ORGANOGERMANE CHEMISTRY.

PREPARATION OF REAGENTS USEFUL IN SYNTHESIS

by

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ABSTRACT

This thesis is divided into three parts. The first part describes the preparation of regioisomerically pure functionalized 2-trimethylgermylalk-1-enes of general structure 26, which are useful in synthesis. The vinylgermane iodide 18, for example, has been shown in our laboratories to be a good synthetic equivalent to the but-1-ene d²,d⁴- and a²,d⁴-synthons 11 and 22, respectively. The preparation of the 2-trimethylgermylalk-1-enes of general structure 26 was accomplished via i) H₂PtCl₆·6H₂O catalyzed addition of Me₃GeH (53) to the carbon–carbon triple bond of 1-trimethylsilylalk-1-ynes 52, and ii) treatment of the resultant product mixtures with p-TsOH·H₂O in dichloromethane.

The second part delineates the new and experimentally simple preparation of Me₃GeLi (149) in THF solution. The novel reagent Me₃GeCu·Me₂S (168) was obtained by treatment of 149 with CuBr·Me₂S. Me₃GeCu·Me₂S (168), in the presence of chlorotrimethylsilane, serves as a good reagent for the conversion of functionalized acyl chlorides of general structure 35 (X = Cl) into the acyltrimethylgermanes 37. Functionalized S-(pyridin-2-yl) thioesters of general structure 35 (X = S-(pyridin-2-yl)) also serve as good substrates for the preparation of acyltrimethylgermanes 37 with reagent 168. The acyltrimethylgermanes 37 are efficiently transformed into the 2-trimethylgermylalk-1-enes 26 via olefination with methylene-triphenylphosphorane.

The third part of this thesis outlines the preparation of the novel (trimethylgermyl)-copper(I) reagents 222–225. The conjugate addition of reagents 222–225, as well as Me₃GeCu·Me₂S (168), to selected unsaturated carbonyl systems was investigated. The substances 229 and 234–238 were synthesized from the corresponding enones via 1,4-addition
of the (trimethylgermyl)copper(I) reagents. The (E)-3-trimethylgermylalk-2-enoate 242 was prepared stereoselectively via 1,4-addition of reagents 168 or 223 onto the corresponding alk-2-ynoate, whereas the (Z) isomer 243 was obtained predominantly when reagent 225 was employed.
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LIST OF ABBREVIATIONS

δ  – chemical shift in part per million from Me₄Si
Δ  – reflux
\( ^{13}\text{C}\) NMR  – carbon nuclear magnetic resonance
\(^{1}\text{H}\) NMR  – proton nuclear magnetic resonance
br  – broad
C-x  – carbon number x
COSY  – \(^{1}\text{H}-{^{1}\text{H}}\) homonuclear correlation spectroscopy
DCI  – desorption chemical ionization
GLC  – gas–liquid chromatography
H-x  – hydrogen number x
HMPA  – hexamethylphosphoramide
HRMS  – high resolution mass spectrometry
J  – coupling constant in hertz
LRMS  – low resolution mass spectrometry
M  – mol-L\(^{-1}\)
MHz  – mega hertz
mmol  – millimole
NOE  – nuclear Overhauser enhancement
ppm  – part per million
RI  – refractive index
THF  – tetrahydrofuran
TLC  – thin layer chromatography
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to my best friend, my sister
1 INTRODUCTION

1.1 GENERAL

Over the past decades, organic chemists have striven to increase their understanding of chemical reactions and, hence, to expand the repertoire of bond forming processes that allow the construction of increasingly more complex molecules. Some of these target molecules are naturally occurring and have important biological activities. Such compounds, though, are often in scarce supply by virtue of a lack of natural sources. Therefore, to prevent depletion of a living species for the sole purpose of isolating biologically valuable compounds, supplying the latter via synthesis would be ecologically warranted. Alternatively, analogs of such compounds may also have important biological activity. Generally, the preparation of such analogs is most conveniently accomplished via synthesis, which requires the preparation of a very large number of diversely functionalized compounds. Since different target organic compounds may differ widely in their structure and functionalization, it would be advantageous to have access to a wide variety of methods to synthesize such target substances.

Due to the fact that the carbon skeletons of target organic compounds often possess structural features such as stereogenic centers, stereodefined unsaturations, and carbocyclic rings, many different types of reactions are required to construct such compounds. To assemble the components required to obtain the synthetic goal, it is generally advantageous to use “building blocks” that contain carbon atoms bearing key required structural features and functional groups. When properly functionalized, such “building blocks” or synthons¹²
become a great asset to the synthetic chemist.

The incorporation of group XIV elements into reagents used for the synthesis of natural products has seen tremendous growth over the last few years, although the scene has been mainly dominated by silicon and tin. The amount of literature that has been published on these subjects is too great to discuss here, but the reader is referred to some excellent reviews. The organic derivatives of these two elements have found widespread applicability in coupling reactions and cyclizations, often forming key steps in natural product syntheses. For some recent examples see references (15)–(22). The popularity of these elements in organic chemistry stems from their compatibility with a wide variety of standard reactions such as reductions, oxidations, alkylations, etc., and to the fact that their (latent) reactivity can be employed when required.

Remarkably, germanium is almost completely absent from the literature on the use of group XIV elements in natural product synthesis. Although some recent reports have appeared, the research in this area is still minimal. In response to the under utilization of organogermane compounds in organic synthesis, it was decided to explore methods that could lead to the preparation of certain classes of functionalized organogermanes that should prove useful in organic synthesis. The details of these investigations and the developments of these new methods are described in this thesis.
1.2 BACKGROUND

A recent report from our laboratories has described the preparation\(^{25}\) of 4-chloro-2-trimethylstannylbut-1-ene (1). This reagent has been shown to serve well as a synthetic equivalent of the donor–acceptor\(^{26}\) but-1-ene d\(^2\),a\(^4\)-synthon 2.\(^{27}\) The usefulness of the bifunctional reagent 1 becomes apparent in the annulation sequence depicted below (Scheme 1). A cyclic enone serves as the synthetic equivalent of the donor–acceptor synthon 3 to produce, after annulation with 2, a bicyclic system such as 4.

\[
\begin{align*}
\text{Cl} \quad \text{SnMe}_3 & \quad \equiv \quad \text{a} \quad \text{d} \\
1 \quad 2 & \quad \equiv \quad \text{a} \quad \text{d} \\
\downarrow & \\
\text{O} & \\
4 & \\
\end{align*}
\]

Scheme 1

Conjunctive reagents have been defined by Trost\(^{28}\) as "...those reagents which are simple building blocks that are incorporated in whole or in part into a more complex system...". Substance 1 may be referred to as a bifunctional conjunctive reagent. To illustrate this concept, when a solution of 1 in THF at \(-78^\circ\text{C}\) is treated with one equivalent of a solution of methyllithium and then with one equivalent of copper cyanide, the corresponding cuprate 5\(^{27}\) is formed (Scheme 2). To this mixture the appropriate enone is added and after
work-up the ketone 6 is isolated. This product is then treated with potassium hydride in THF at room temperature to generate the bicyclic ketone 4.\textsuperscript{27}

![Chemical structure and reaction scheme]

**Scheme 2**

Therefore, in this example, the donor site of 1 was deployed first during the conjugate addition to the enone, and the acceptor site was used in a second step during the intramolecular alkylation.

Recently, in our laboratories, the total synthesis of the diterpenoid (±)-ambliol B (7) was completed.\textsuperscript{23} The retrosynthetic analysis of (±)-ambliol B that formed the basis of this synthesis is outlined in **Scheme 3**. It was thought that 7 could be derived from the bicyclic alcohol 8. Thus, the exocyclic methylidene group in 8 would serve to introduce the gem-dimethyl group, and the vinyl moiety would be used to attach the furan ring. This bicyclic alcohol 8 could, in turn, be obtained via a key annulation sequence which would connect the bifunctional reagent 9 and the enone 10.
Such a sequence can be seen as the theoretical assembly of the donor-donor and acceptor-acceptor synthons 11 and 12 (Scheme 4) that are the synthetic equivalents of the organometallic bifunctional reagent 9 ($M' = \text{metal}$) and the enone 10, respectively. In this sequence of events, the but-1-ene synthon must now be used as the $d_2,d_4$-synthon 11.

To accomplish such a transformation using the 4-halo-2-trimethylstannylbut-1-enes (I,
$X = \text{Cl or } 13, \ X = \text{I}$), it would be necessary to transform one of these substances into the corresponding lithio (14, $M = \text{Li}$) or Grignard (15, $M = \text{Mgl}$) derivatives (Scheme 5). However, treatment\textsuperscript{29} of 1 with lithium 4,4'-di-tert-butylbiphenyl\textsuperscript{30} failed to produce significant quantities of 14. Moreover, treatment of 13 with magnesium turnings in THF heated to reflux failed to produce the expected Grignard reagent 15.\textsuperscript{29} It was rationalized that the labile alkenyl carbon–tin bond interfered with the preparation of the organometallic derivatives 14 and 15.

![Scheme 5](image)

To overcome this problem it was decided to replace the trimethylstannyl moiety with another group that would be stable under the conditions used to generate the organometallic reagent required for the first carbon–carbon bond formation and yet would allow the formation of a vinyl anion at a later stage. To do this is was necessary to find a replacement with a greater alkenyl carbon–metal bond strength. The chemical bond strength, often expressed as the bond dissociation energy, for the carbon–tin bond in $\text{Me}_4\text{Sn}$ has been determined\textsuperscript{31} to be 65 kcal·mol$^{-1}$. Comparatively, the carbon–germanium bond dissociation energy for $\text{Me}_4\text{Ge}$ was found\textsuperscript{31} to be 76 kcal·mol$^{-1}$. It was thought that the greater alkyl carbon–germanium bond strength compared to the alkyl carbon–tin bond strength would be
paralleled in the corresponding alkenyl carbon–metal systems. Therefore, it was envisaged that the trimethylgermyl group would be a good substitute for the trimethylstannyl moiety in the required transformation.

Transmetallation of 1 at low temperature with a solution of methylithium (Scheme 6) generated the corresponding vinyllithium\(^\text{27}\) species 16, which was then treated with bromo-
trimethylgermane to produce 4-chloro-2-trimethylgermylbut-1-ene (17). Following this, the chloride 17 was allowed to react with sodium iodide in acetone to yield the iodide 18. Metal–halogen exchange performed on the iodide 18 using a solution of tert-butyllithium (2 equiv) at -95 °C, followed by treatment of the resultant lithio reagent with one equivalent of copper(I) cyanide, resulted in the formation of the cuprate reagent 19. The successful preparation of 19 allowed the formation of adduct 20 from conjugate addition of 19 to the enone 10. Straightforward iododegermylation$^{32}$ of 20 under standard conditions led to 21. This keto iodide was treated with a solution of n-butyllithium (2 equiv) at low temperature to chemoselectively effect a facile lithium–halogen exchange reaction. The resultant vinyllithium intermediate underwent a ring-closure reaction to provide the alcohol 8. Having this key intermediate in hand, the synthesis of (±)-ambliol B (7)$^{23}$ could be completed.

![Scheme](image)

Following the successful preparation of reagent 19 a related, complementary use of this reagent was developed in our laboratories. In the synthetic sequence depicted in Scheme
7, the reagent 18 serves as the synthetic equivalent to the but-1-ene a²,d⁴-synthon 22 and possesses umpolung²⁶ reactivity when compared to that of synthon 11. Conjugate addition of 19 (prepared from 18, vide supra) to a substituted cyclic enone resulted in the formation of adduct 23. Iododegermylation of 23 under standard conditions, followed by treatment of the resulting vinyl iodide with a catalytic amount of Pd(Ph₃P)₄ in the presence of t-BuOK and t-BuOH generated the bicyclic ring system 24. Thus, this annulation method exhibits a regioselectivity that is opposite to that of the method outlined in Scheme 1.

Scheme 8

The general applicability of this method was shown by the preparation of a number of bicyclic³³,³⁴ and tricyclic³⁴ ring systems. Moreover, the usefulness of this method in organic
synthesis was demonstrated when this 5-membered ring annulation, using the reagent 19, played a key role in the total synthesis of (±)-crinipellin B (25) (Scheme 8). Following the discovery by Marais\textsuperscript{23,29,33} that 4-iodo-2-trimethylgermylbut-1-ene (18) i) can undergo controlled metal–halogen exchange to produce 4-lithio-2-trimethylgermylbut-1-ene and ii) serves as an excellent synthetic equivalent to the but-1-ene d\textsuperscript{2,4} and a\textsuperscript{2,4}-synthons 11 and 22 respectively, it became of interest to consider the possibility of preparing a wide variety of diversely functionalized 2-trimethylgermylalk-1-ene bifunctional reagents of general structure 26. Such substances should prove very useful in organic synthesis.

\[
\text{Me}_3\text{Ge} \quad \text{R}
\]

26

The synthetic sequence initially used to prepare the bifunctional reagent 18 from but-3-yn-1-ol proceeds in satisfactory yield (Scheme 9). However, this synthesis suffers from i) a tedious separation of the regioisomers 27 and 28 formed during the trimethylstannylcupration\textsuperscript{25} of but-3-yn-1-ol and ii) requires the use of two expensive reagents, namely hexamethylditin and bromotrimethylgermane. To overcome these problems, it would be advantageous to prepare compounds of general structure 26 from an alternative precursor such that the intermediacy of the vinylstannane would be avoided.
Examination of the literature revealed that a number of reports have appeared over the last three decades on the preparation of vinylgermanes. Although a certain number of these described the preparation of 2-trialkylgermylalk-1-enes, the latter are usually isolated as an inseparable mixture with the corresponding 1-trialkylgermylalk-1-enes. The following results reported by Oshima and co-workers\textsuperscript{32,35} illustrate well the difficulty (Scheme 10). Germylcupration\textsuperscript{35} of dodec-1-yne afforded, after workup, a 7:3 mixture of the regioisomeric adducts 29 and 30 in 81% yield. Alternatively, when dodec-1-yne was treated with $n$-Pr$_3$GeH in the presence of a catalytic amount of H$_2$PtCl$_6$·6H$_2$O, a 13:87 mixture of the regioisomers 31 and 32 was formed in 93% yield\textsuperscript{32}.
Obviously, it would be advantageous, in the context of using 2-trialkylgermylalk-1-enes in synthesis, to have access to a method that would produce these substances in regioisomerically pure form. Based on the above precedents, it was felt that the preparation of such compounds from terminal alkynes would be troublesome. In the next pages, proposals to prepare regioisomerically pure 2-trimethylgermylalk-1-enes from 1-trimethylsilylalk-1-ynes will be outlined.
1.3 PROPOSALS

The successful preparation and use of the vinylgermane iodide 18 as a synthetic equivalent to the but-1-ene d^2,d^4- and a^2,d^4-synthons 11 and 22, respectively, prompted us to investigate the development of general synthetic methods for the synthesis of functionalized 2-trimethylgermylalk-1-enes. Because of the lack of regioselectivity displayed by reactions in which terminal alkynes were converted directly into 2-trialkylgermylalk-1-enes (see previous section), the possibility of using substituted alkynes of general structure 33 to prepare the desired trimethylgermyl compounds 26 became appealing (Equation 1). What reaction would be employed to add the elements of Me₃GeH across the carbon-carbon triple bond? Would the use of a substituent X be sufficient to effect complete regiocontrol in the addition process? If so, what would the nature of X need to be? What functional groups in R would be compatible with this transformation?

If the first step of this sequence proved to be successful, the second aspect of the overall transformation remained to be examined. Could the X group in 34 be replaced by a hydrogen atom (Equation 1) in the presence of the newly introduced trimethylgermyl group?
Since functionalization of the R group was imperative, what other functional groups would be compatible with this substitution?

An alternative approach to the synthesis of 2-trimethylgermylealk-l-enes was also envisaged. This method, due to the intrinsic nature of the transformations involved, would preclude the formation of regioisomers. Thus, it was postulated that nucleophilic acyl substitution involving reaction of substrates of general structure 35 with a suitable metallo-(trimethylgermane) reagent 36 would generate the corresponding trimethylgermyl ketones 37. The latter compounds could then be olefinated to generate substances 26 (Equation 2). In order for this sequence to be viable, the rate of reaction of reagent 36 with 35 would have to be considerably faster than that of reaction of 36 with 37. What, then, would the requirements be on the nature of X? Could a (trimethylgermyl)copper(I) derivative (36, M = Cu) be used to affect such a transformation? Once again, what functional groups in R would be compatible with such a transformation? Is the olefination of 37 possible?

\[
\begin{align*}
\text{Me}_3\text{GeM} & \quad 36 \quad \text{olefination} \\
\text{R} & \quad 35 \quad ? \quad \text{R} \quad 37 \quad ? \quad \text{R} \quad 26
\end{align*}
\]

As seen in the previous section (Scheme 10), (triethylgermyl)cuprates are known reagents. In contrast, (trimethylgermyl)copper(I) reagents had not been reported prior to the work described in this thesis. If (trimethylgermyl)copper(I) reagents could be prepared, what other synthetic applications would these reagents have?
The utilization of the vinylgermane iodide 18 in the syntheses of (±)-ambliol B (7)\textsuperscript{23} and (±)-crinipellin B (25),\textsuperscript{24} and the possibility of employing 18 and structurally related substances in synthesis were important motivations for the development of methods for the preparation of other functionalized, regioisomerically pure 2-trimethylgermylalk-1-enes. This thesis is divided into three parts and describes the results of research related to the proposed investigations outlined above. The first part describes the preparation of 2-trimethylgermylalk-1-enes from 1-trimethylsilylalk-1-yynes in two experimentally simple steps: platinum catalyzed hydrogermylation of the 1-trimethylsilylalk-1-yynes followed by p-toluenesulfonic acid mediated protodesilylation to afford the 2-trimethylgermylalk-1-enes. The second part details the preparation of acyltrimethylgermanes from the corresponding acyl chlorides using the novel (trimethylgermyl)copper(I)–dimethyl sulfide reagent. The olefination of selected acyltrimethylgermanes into the corresponding 2-trimethylgermylalk-1-enes will also be described. Finally, the third part delineates the preparation of new (trimethylgermyl)cuprate reagents and describes their reaction with selected unsaturated carbonyl systems.
2 DISCUSSION

2.1 SYNTHESIS OF 2-TRIMETHYLGERMYLALK-1-ENES VIA PLATINUM CATALYZED HYDROGERMYLATION OF 1-TRIMETHYLSILYLALK-1-YNES

2.1.1 INTRODUCTORY REMARKS

Recent reports\textsuperscript{23,24,29,33,34} from our laboratories have shown the vinylgermane iodide 18 to be a good synthetic equivalent to the but-1-ene d\textsuperscript{2},d\textsuperscript{4}- and a\textsuperscript{2},d\textsuperscript{4}-synthons 11 and 22, respectively. The usefulness of reagent 18 was demonstrated through the development of two new annulation methods (see Introduction section, Scheme 6, p 7 and Scheme 7, p 9).

The utilization of the vinylgermane iodide 18 in the syntheses of (±)-ambliol B (7)\textsuperscript{23} (see Scheme 6, p 7) and (±)-crinipellin B (25)\textsuperscript{24} (see Scheme 8, p 9) as well as the possibility of using structurally related substances in synthesis, prompted an investigation into the development of a method that would allow the preparation of regioisomerically pure 2-trimethylgermylalk-1-enes of general structure 26.

A survey of the literature revealed that a number of methods for the preparation of 2-
trialkylgermylalk-1-enes and 2-triphenylgermylalk-1-enes have been reported. These methods employ, collectively, four different classes of substrates to achieve the preparation of the 2-trialkylgermylalk-1-enes and 2-triphenylgermylalk-1-enes. A brief description of these methods is presented in the following pages.

Nicholson and Allred reported the preparation of 2-triphenylgermylalk-1-enes in a two step sequence from alkan-2-ones (Equation 3). In this protocol, triphenylgermyllithium was allowed to react with an alkan-2-one to give the corresponding alcohol. This alcohol was then treated with phosphorous tribromide to afford the 2-triphenylgermylalk-1-ene. The overall yield for these two transformations varies from poor to moderate. The applicability of this method for the preparation of functionalized 2-triphenylgermylalk-1-enes is greatly limited by the fact that a powerful nucleophile, triphenylgermyllithium, is required in the first step. Moreover, the conditions used for the dehydration (PBr₃, benzene, reflux 16 h) also limits the number of functional groups that are compatible with the overall method.

A different approach to the preparation of 2-trialkylgermylalk-1-enes was used by Manulkin and co-workers. In this synthetic transformation (Equation 4), a vinyl Grignard reagent is treated with a suitable trialkylgermanium bromide reagent to give the 2-trialkylgermylalk-1-ene. Although the yield for this transformation is good and the formation of regioisomers is precluded, the general applicability of this method is limited by the availability of the regioisomerically pure 2-bromoalk-1-enes, precursors to the Grignard reagents.
2-Trialkylgermylalk-1-enes were also prepared from allenes (Equation 5).\textsuperscript{39,40} In this chemical transformation, H\textsubscript{2}PtCl\textsubscript{6}\textperiodcentered6H\textsubscript{2}O catalyzed addition of a trialkylgermane to an allene 43 resulted in the formation of the desired 2-trialkyldermmylalk-1-ene 42. However, the vinylgermane 44 and the allylgermane 45 were also produced. In fact, the three adducts were obtained as a mixture in an almost equimolar amounts (40–79\% combined yield). Therefore, the low selectivity displayed by this reaction would not allow the preparation of regioisomerically pure 2-trialkyldermmylalk-1-enes.

Terminal alkynes are a fourth class of substrates that have been used to prepare 2-trialkyldermmylalk-1-enes. As presented in the Introduction section (Scheme 10, p 12), germyclupration of a terminal alkyne has been reported by Oshima and co-workers\textsuperscript{35} to result in the formation of regioisomeric adducts. Similarly, platinum\textsuperscript{32,41} or palladium\textsuperscript{42} catalyzed addition of a trialkylgermane to a terminal alkyne 46 (Equation 6) resulted in the formation of a mixture of the regioisomers 42 and 47 (35–97\% combined yield), in which isomer 47 had been predominantly formed.
In light of the literature surveyed, it appears that the methods reported i) have a limited scope and lack generality in the preparation of functionalized 2-trialkylgermylalk-1-enes or ii) yield regioisomeric mixtures of 1- and 2-trialkylgermylalk-1-enes. As outlined in the Proposals (section 1.3, pp 13 ff.), the possibility of effecting regiocontrolled addition of the elements of Me₃GeH to 1-substituted alk-1ynes became an appealing alternative. Support for the possibility of this type of transformation was found in a related reaction reported by Hudrlik and co-workers⁴³ (Scheme 11).

Thus, treatment of 1-trimethylsilyloct-1-yne (48) with methyldichlorosilane (Scheme 11) in the presence of a catalytic amount of H₂PtCl₆•6H₂O, in the absence of solvent (neat), resulted in the formation of adduct 49. Treatment of 49 with methylmagnesium bromide afforded (E)-1,2-bis(trimethylsilyl)oct-1-ene (50) in 96% yield. The regioisomeric purity of
50 was shown to be ≥96% by GLC.\textsuperscript{43} 2-Trimethylsilyloct-1-ene (51) was obtained in 96% yield by heating at reflux a solution of 50 in glacial acetic acid–water (19:1) for 29 h.

\[
\begin{align*}
52 & \quad \text{H}_2\text{PtCl}_6 \cdot 6\text{H}_2\text{O} \\
53 & \quad \text{Me}_3\text{GeH} \\
54 & \quad \text{Me}_3\text{Ge} \\
26 & \quad \text{Me}_3\text{Ge} \\
\end{align*}
\]

The synthetic sequence depicted above (Scheme 11) effects an overall transformation similar to that required for the preparation of the 2-trimethylgermylalk-1-enes. Since the 1-trimethylsilylalk-1-ynes are easily accessible from the corresponding alk-1-ynes in high yields,\textsuperscript{3} it was of interest to determine whether or not the 1-trimethylsilylalk-1-ynes 52 (Equation 7) could be used as substrates for a regioselective hydrogermylation process. In other words, could trimethylgermane (53) be used instead of the methyldichlorosilane in this transformation? If so, this would render the method more versatile, since the utilization of the Grignard reagent would no longer be required. Would the high regioselectivity exhibited in the hydrosilylation be retained in the hydrogermylation leading to the formation of 54 (Equation 7)? If the (E)-2-trimethylgermyl-1-trimethylsilylalk-1-ene 54 could be prepared in a regioisomerically pure form, the removal of the trimethylsilyl group from 54 would have to be addressed. Would it be possible to remove the trimethylsilyl group in the presence of the trimethylgermyl group?

The answer to these questions, as well as the details of the investigations leading to the
successful preparation of the regioisomerically pure 2-trimethylgermylalk-1-enes 26 from the 1-trimethylsilylalk-1-ynes 52 will be disclosed in sections 2.1.4 (p 26 ff.) and 2.1.5 (p 65 ff.) of this thesis.
2.1.2 SYNTHESIS OF 1-TRIMETHYLSILYLALK-1-YNES

In order to prepare the 1-trimethylsilylalk-1-ynes required for this study, the commercially available alk-1-ynes 55–60 shown in Table 1 were chosen as substrates. Table 1 also contains a summary of the conversions of 55–60 into the 1-trimethylsilylalk-1-ynes 61–67.

The 1-trimethylsilylalk-1-ynes were prepared in high yield in a straightforward way. The synthesis of 1-trimethylsilyl-6-(trimethylsilyloxy)hex-1-yne (61) (Table 1, entry 1) for example, was accomplished in the following manner. A solution of hex-5-yn-1-ol (55) in ethereal solvent at low temperature (−78 °C) was treated with a solution of methyllithium followed by addition of chlorotrimethylsilane, and the reaction mixture was warmed to room temperature. After isolation and purification of the crude product, the compound 61 was obtained in 96% yield as a clear colorless oil. Confirmation of the assigned structure was obtained from the \(^1\)H NMR (400 MHz, CDCl\(_3\)) spectrum of 61, which exhibited two nine-proton singlets at \(\delta 0.12\) and 0.09, characteristic of Me\(_3\)Si- functions. Additional evidence was provided by the IR spectrum which exhibited an intense band at 2176 cm\(^{-1}\), diagnostic of Me\(_3\)Si- substituted alkynes, as well as a lack of a broad absorption in the 3200–3600 cm\(^{-1}\) (-OH) region.

The 1-trimethylsilylalk-1-ynes 63–67 were synthesized from the corresponding alk-1-ynes 56–60 in a manner identical with that outlined above. The 1-trimethylsilylalk-1-yne 62 was obtained by treatment of 61 with aqueous hydrochloric acid during the workup of the reaction sequence described above.
Table 1: Preparation of the 1-Trimethylsilylalk-1-ynes 61–67

\[
\text{R} \equiv \text{H} \xrightarrow{1) \text{MeLi or } n-\text{BuLi, THF, } -78 ^\circ\text{C}} \text{R} \equiv \text{SiMe}_3
\]

1) MeLi or n-BuLi, THF, -78 °C
2) TMSCl, -78 °C → rt
3) NaHCO₃/H₂O

<table>
<thead>
<tr>
<th>Entry</th>
<th>Alk-1-yne</th>
<th>1-Trimethylsilylalk-1-yne</th>
<th>Yield (%)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(\text{HO} \equiv \text{SiMe}_3) (\text{55})</td>
<td>(\text{Me}_3\text{SiO} \equiv \text{SiMe}_3) (\text{61})</td>
<td>96</td>
</tr>
<tr>
<td>2(^b)</td>
<td>(\text{HO} \equiv \text{SiMe}_3) (\text{55})</td>
<td>(\text{HO} \equiv \text{SiMe}_3) (\text{62})</td>
<td>82</td>
</tr>
<tr>
<td>3</td>
<td>(\text{HO} \equiv \text{SiMe}_3) (\text{56})</td>
<td>(\text{Me}_3\text{SiO} \equiv \text{SiMe}_3) (\text{63})</td>
<td>96</td>
</tr>
<tr>
<td>4</td>
<td>(n-C_{10}H_{21} \equiv) (\text{57})</td>
<td>(n-C_{10}H_{21} \equiv \text{SiMe}_3) (\text{64})</td>
<td>98</td>
</tr>
<tr>
<td>5</td>
<td>(\text{Cl} \equiv \text{SiMe}_3) (\text{58})</td>
<td>(\text{Cl} \equiv \text{SiMe}_3) (\text{65})</td>
<td>91</td>
</tr>
<tr>
<td>6</td>
<td>(\text{Me}_3\text{Si} \equiv \text{SiMe}_3) (\text{59})</td>
<td>(\text{Me}_3\text{Si} \equiv \text{SiMe}_3) (\text{66})</td>
<td>96</td>
</tr>
<tr>
<td>7</td>
<td>(\text{Me}_3\text{Si} \equiv \text{SiMe}_3) (\text{60})</td>
<td>(\text{Me}_3\text{Si} \equiv \text{SiMe}_3) (\text{67})</td>
<td>71</td>
</tr>
</tbody>
</table>

\(^a\) Yield of isolated and purified product. \(^b\) For the workup, 1 N aqueous HCl was used instead of saturated aqueous NaHCO₃.

The synthesis of 4-(cyclopent-2-en-1-yl)-1-trimethylsilylbut-1-yne (72) was effected via a three step sequence from (cyclopent-2-en-1-yl)acetic acid (68) (Scheme 12). Thus, lithium aluminum hydride reduction of 68 afforded the corresponding alcohol 69 in 96% yield. This alcohol was treated with triphenylphosphine–iodine complex\(^{44}\) in the presence of
imidazole to yield the primary iodide 70 in 92% yield. Finally, the iodide 70 was allowed to react with lithium trimethylsilylacetylide (71) (prepared by treatment of trimethylsilylacetylene with n-butyllithium) in the presence of HMPA. Isolation and purification of the resultant product afforded 4-(cyclopent-2-en-1-yl)-1-trimethylsilylbut-1-yne (72) in 78% yield (69% overall from 68) as a clear colorless oil.

Scheme 12
2.1.3 SYNTHESIS OF TRIMETHYLGERMANE (53)

\[
\text{Me}_3\text{GeBr} \xrightarrow{\text{LiAlH}_4} \text{Me}_3\text{GeH} \quad (8)
\]

Trimethylgermane (53) was prepared using a procedure reported by Coates and Tedder,\textsuperscript{45} with a minor modification. In the original procedure,\textsuperscript{45} a solution of trimethylgermanium bromide in dry dibutyl ether was added to a slurry of lithium aluminum hydride in the same solvent (Equation 8). The heterogeneous mixture was then heated to 75 °C and the volatile liquid (bp 26 °C) was distilled directly from the reaction mixture into a cold (−78 °C) receiving flask. This procedure afforded trimethylgermane (53) in 75% yield.

Since trimethylgermanium bromide required for this reaction is a fairly expensive reagent (≈$5 per gram), it appeared worthwhile to try to improve the yield of this conversion. After some investigation, it was found that raising the distillation temperature to 110 °C resulted in a significantly improved yield. Moreover, the time required to complete the distillation at 110 °C was 3 h as compared to 6–8 h at 75 °C. Examination of the \(^1\text{H}\) NMR spectrum of the acquired liquid revealed the presence of a small amount (5–10%) of dibutyl ether. Distillation of this material (bulb-to-bulb) from −78 °C to 40 °C (directly from the initial receiving flask) afforded essentially pure trimethylgermane (53) in 95% yield. This reaction can be easily carried out on a 20–30 g scale of trimethylgermanium bromide with reproducible yields.
2.1.4 ISOLATION OF THE PRODUCTS OF HYDROGERMYLATION OF 6-TRIMETHYLSILYLHEX-5-YN-1-OL (62) AND THEIR TREATMENT WITH p-TOLUENESULFONIC ACID MONOHYDRATE IN DICHLOROMETHANE

2.1.4.1 HYDROGERMYLATION OF 6-TRIMETHYLSILYLHEX-5-YN-1-OL (62)

6-Trimethylsilylhex-5-yn-1-ol (62) was chosen as the initial substrate for the investigation of the hydrogermylation reaction, since it could be readily prepared from the commercially available hex-5-yn-1-ol (55). This compound also has a moderately high boiling point which would facilitate, in the event, the recovery of any unreacted starting material.

From the chemical transformation involved in the hydrogermylation of 62, it is possible to form four isomers as a result of adding the elements of Me₃GeH (53) across the alkyne function of 62 (Scheme 13). The isomers 73 and 74 arise due to cis addition of Me₃GeH (53) to the carbon–carbon triple bond of 62. Alternatively, the isomers 75 and 76 are the consequence of trans addition of the elements of Me₃GeH (53) across the alkyne function of 62. The regiochemistry of the addition of Me₃GeH (53) can proceed in two different orientations. The trimethylgermyl group can add to the C-substituted end of the alkyne, yielding the isomers 73 and 75. On the other hand, the trimethylgermyl group can add to the Si-substituted end of the triple bond, thus generating isomers the 74 and 76.
Since the objective of this investigation was to develop a method that would ultimately provide 2-trimethylgermylalk-1-enes after removal of the trimethylsilyl group, generation of the isomers 73 and/or 75 from the hydrogermylation of 62 was desired. The regiochemistry of the addition of Me₃GeH (53) to the alkyne function of 62 should be relatively straightforward to establish via ¹H NMR spectroscopic analysis. The ¹H NMR spectra of 73 and 75 should contain a singlet (or a triplet with J = 1–2 Hz) for the vinylic proton. On the other hand, the spectra of 74 and 76 should exhibit a triplet, with a vicinal coupling constant of 5–10 Hz, for the corresponding signal.

Experimentally, hydrogermylations of various types of substrates, with trialkyl-
germanes, have been carried out with H$_2$PtCl$_6$·6H$_2$O in the absence of solvent. These procedures usually result in a vigorous exothermic reaction, accompanied by a significant increase in the temperature of the reaction mixture.

\[
\begin{align*}
\text{H}_2\text{PtCl}_6 \cdot 6\text{H}_2\text{O} & \quad \text{Et}_3\text{GeH} \\
\rightarrow & \quad \text{Et}_3\text{Ge} + \text{Cl} \\
\end{align*}
\]

For example, when a mixture of propargyl chloride and triethylgermane (neat) was treated with a catalytic amount of H$_2$PtCl$_6$·6H$_2$O, a vigorous exothermic reaction occurred to generate the adducts 77 and 78 (Equation 9). Alternatively, hydrogermylations of alkynes with tributylgermane and a catalytic amount of H$_2$PtCl$_6$·6H$_2$O have also been carried out in 1,2-dichloroethane. In a similar transformation, but using a Rh(hfa)(C$_2$H$_4$)$_2$ as catalyst, the hydrogermylation of phenylacetylene (59) with tributylgermane has been performed in dichloromethane to afford a mixture of adducts 79–81 (Equation 10).

\[
\begin{align*}
\text{Ph} & \quad \text{Rh(hfa)(C}_2\text{H}_4)_2 \quad \text{Bu}_3\text{GeH}, \text{CH}_2\text{Cl}_2 \\
\rightarrow & \quad \text{Ph} + \text{GeBu}_3 + \text{Bu}_3\text{Ge} \\
\end{align*}
\]

Since trimethylgermane (53) is a very volatile liquid (bp 26 °C), performing the hydrogermylation in the absence of solvent would not be suitable, since it is likely that due to the (expected) exothermic reaction, the volatile trimethylgermane (53) would be lost. H$_2$PtCl$_6$·6H$_2$O was selected to effect the proposed transformation since it is commercially available and is known to be an effective catalyst for these reactions. It was also decided to perform the reaction in dichloromethane solution to prevent significant temperature increase.

Speier has investigated in detail the nature of the catalyst involved in the
homogeneous catalysis of hydrosilylation by H₂PtCl₆·6H₂O. Although no direct proof of the structure of the soluble complex was obtained, many observations suggest that it is likely to be a Pt(0) species. For example, the reduction of H₂PtCl₆·6H₂O with Me₃GeH (53) to a Pt(0) species probably occurs as depicted in Equation 11.

\[
H₂PtCl₆·6H₂O + 18Me₃GeH \rightarrow Pt(0) + 6Me₃GeCl + 6(Me₃Ge)₂O + 16H₂ \quad (11)
\]

Initial investigations were performed using substrate 62 in dichloromethane and focused on finding experimental conditions that would allow the conversion of the starting material to product within a reasonable length of time. Thus, hydrogermylations of 62 were performed in the presence of approximately two equivalents of Me₃GeH (53) with 1-2% of H₂PtCl₆·6H₂O at 0 and -10 °C initially, in order to minimize the loss of Me₃GeH (53) through evaporation. GLC and TLC analyses of the reaction mixtures revealed that the conversion of the starting material to product was proceeding very slowly.

Scheme 14
In a separate experiment, two equivalents of Me₃GeH (53) were added to a cold (0 °C) solution of 62 (1 equiv) and 1 mol% of H₂PtCl₆·6H₂O and the resultant mixture was allowed to stir at room temperature for 15 h (Scheme 14). GLC analysis of the crude reaction mixture indicated that the starting material had been completely consumed; this analysis also revealed the presence of several products. The two major products constituted approximately 75% and 19% of the mixture, whereas the minor components accounted for the balance of the material at 1–2% each. Preliminary ¹H NMR spectroscopic analysis of this crude mixture revealed that the region of δ 6.5–5.5 contained four distinct signals. These signals were as follows: a triplet at δ 5.7, a singlet at δ 5.8, a singlet at δ 6.2 and finally a triplet at δ = 6.4. The singlet at δ 5.8 and triplet at δ 5.7 were present in a ratio of approximately 4:1, whereas the other two signals at δ 6.2 and 6.4 were present in approximately equal, very small amounts.

Thus, the hydrogermylation of 62 appeared to have generated an approximately 4:1 mixture of regioisomers. The addition of the Me₃Ge- group occurred primarily at the C-substituted end of the alkyne function of 62 (Scheme 14). The poor regioselectivity exhibited by this reaction was disappointing. The platinum catalyzed addition of Me₃GeH (53) to the carbon–carbon triple bond of 62 did not display the high regioselectivity obtained in an analogous reaction, as reported by Hudrlik and co-workers (see Scheme 11, p 19).

\[
\begin{align*}
&\text{Ph} \equiv \text{H} \xrightarrow{\text{H₂PtCl₆·6H₂O}} \text{Ph} \equiv \text{GeBu₃} + \text{Ph} \equiv \text{GeBu₃} \quad (12) \\
&\text{59} \quad + \quad \text{79} \quad (75\%) \quad + \quad \text{80} \quad (2\%) \quad + \quad \text{81} \quad (23\%)
\end{align*}
\]

A mechanism for the hydrogermylation of phenylacetylene (59) catalyzed by
H₂PtCl₆•6H₂O has been proposed by Corriu and Moreau.⁴⁶ This mechanism is based on the observations made by Chalk and Harrod⁴⁹-⁵¹ on the homogeneous catalysis with group VIII metal complexes. Corriu and Moreau⁴⁶ have shown that n-Bu₅GeH adds to phenylacetylene (59) in 1,2-dichloroethane solution at room temperature in the presence of a catalytic amount of H₂PtCl₆•6H₂O to generate three products (Equation 12). The major product (75%) obtained from this reaction, 79, resulted from cis addition of the n-Bu₅GeH, with the Bu₅Ge-group located on the terminal carbon of the alkene product. The second most abundant adduct was 81 (23%), whereas 80 was formed in 2% yield.⁴⁶ The formation of 80 is the result of a trans addition of the elements of n-Bu₅GeH across the alkyne function of 59, while 81 can be produced from one or both of cis and trans modes of addition of n-Bu₅GeH. Although it could be argued that the formation of 80 might arise from a trans to cis isomerization subsequent to the generation of 79, Corriu and Moreau⁴⁶ have shown that this process is slow compared to the rate of addition of n-Bu₅GeH to 59 under comparable experimental conditions.
Scheme 15 depicts a reaction pathway that rationalizes the formation of the adducts 73–76 from the catalyzed hydrogermylation of the 1-trimethylsilylalk-1-yne 62. This reaction scheme is based entirely on the proposals of Corriu and Moreau. Cycle A depicts the cis addition of trimethylgermane (53) to the 1-trimethylsilylalk-1-yne 62, whereas path B accounts for the formation of the adducts resulting from a trans addition of Me₂GeH (53) to the substrate.

The catalytic cycle A proceeds as follows: the active form of the Pt catalyst, 82,
coordinates to the 1-trimethylsilylalk-1-yne 62 to generate the complex 83. Oxidative addition of trimethylgermane (53) to this complex results in the formation of the hexacoordinated complex 84. Intramolecular hydrogen transfer to the carbon–carbon triple bond generates the vinyl platinate 85, which then undergoes reductive elimination to the (E)-2-trimethylgermyl-1-trimethylsilylalk-1-ene 73, simultaneously regenerating the catalytic species 82. Alternatively, migration of the trimethylgermyl group from 84 onto the C-substituted end of the alkyne function, followed by reductive elimination, leads to the same adduct.

The first step of the catalytic cycle B also involves coordination of 62 to the active form of the catalyst 82, generating the complex 83. However, in this case, the trimethylgermane (53) reacts intermolecularly with complex 83 to form the vinyl platinate 86. Hydride transfer from germanium to platinum generates 87, which subsequently undergoes reductive elimination to form the (Z)-1-trimethylgermyl-1-trimethylsilylalk-1-ene 76 and regenerates the catalytic species 82.

TLC analyses of the crude mixture of the newly formed adducts 73–76 (see Scheme 14, p 29) indicated that the products could not be separated by conventional flash chromatography on silica gel. Therefore, protodesilylation of the crude mixture was attempted.

Büchi and Wüest\textsuperscript{52} have shown the dramatic difference in the rate of protodesilylation between the (E/Z)-1-trimethylsilylalk-1-ene 88 and the 2-trimethylsilylalk-1-ene 90 (Scheme 16). When (E/Z)-1-trimethylsilyloct-1-ene (88) was allowed to react with 0.2 equivalent of p-toluenesulfinic acid in wet acetonitrile heated at reflux for 3 h, the oct-1-ene (89) was formed in 85% yield.\textsuperscript{52} Alternatively, treatment of vinylsilane 90 with one equivalent of p-toluene-
sulfuric acid in wet acetonitrile heated at reflux generated less than 5% of the alkene 91 after 18 h.\textsuperscript{52} The remainder of the vinylsilane 90 was recovered unchanged. Consistent with these findings, Hudrlik and co-workers\textsuperscript{43} found that \((E)-1,2\text{-bis(trimethylsilyl)}\text{oct-1-ene} \ (50)\) underwent protodesilylation to yield 2-trimethylsilyloct-1-ene \((51)\) (see Scheme 11, p 19).

\[
\text{Scheme 16}
\]

Although the carbon–silicon bond strength is greater than the corresponding carbon–germanium bond strength \((90 \text{ kcal} \cdot \text{mol}^{-1} \text{ for } \text{Me}_4\text{Si} \text{ vs } 76 \text{ kcal} \cdot \text{mol}^{-1} \text{ for } \text{Me}_4\text{Ge})\textsuperscript{31}\) it was expected that the difference in ease of protiodemetallation between 1-trialkylmetal- and 2-trialkylmetalalk-1-enes would be the dominant factor controlling the outcome of the acidic treatment of 73 and 75 (Scheme 17).
Therefore, treatment of both 73 and 75 under acidic conditions was expected to generate 5-trimethylgermylhex-5-en-1-ol (92) (Scheme 17). On the other hand, the isomers 74 and 76 could potentially give three different types of products. Protodesilylation of 74 and 76 would afford the vinylgermanes 93. Alternatively, protodegermylation of the same substrates would lead to the formation of the corresponding vinylsilanes 94. Finally, both 93 and 94 could undergo further protiodemetallation to afford hex-5-en-1-ol (95).

Protodesilylation of vinylsilanes has been carried out under a variety of acidic conditions. Traditionally strong acids such as hydrochloric acid, hydrobromic acid or hydriodic acid have been used, but other acid systems including p-toluenesulfinic acid in wet acetonitrile heated at reflux and aqueous acetic acid heated at reflux have also been employed to effect this type of process. Since the objective of this study was the preparation of functionalized 2-trimethylgermylalk-1-enes, the use of strong acids in the protodesilylation step was avoided in order to allow for a large number of functional groups to be compatible with this transformation. Moreover, wet acetonitrile was reported to have a poor solubility.
for the substrates, whereas Hudrlik and co-workers noted that the protodesilylation in aqueous acetic acid required extensive heating at reflux. More convenient reaction conditions were therefore sought and the first system investigated was the $p$-toluenesulfonic acid monohydrate in dichloromethane.

Treatment of the mixture of the isomers 73–76 with 1.1 equivalents of $p$-toluenesulfonic acid monohydrate in dichloromethane at room temperature for 15 h effected smoothly the conversion of the starting materials into a single new product (TLC analysis) (Scheme 18). Isolation and flash column chromatography of the crude product, followed by distillation of the acquired oil afforded the newly formed substance as a clear colorless oil in 80% overall yield (from the 1-trimethylsilylalk-1-yne 62). The $^1$H NMR (400 MHz, CDCl$_3$) spectrum of this substance exhibited two characteristic doublets ($J = 2.6$ Hz) at $\delta$ 5.49 and 5.16 integrating for one proton each (terminal alkenyl protons), a two-proton triplet ($J = 6.4$ Hz) at $\delta$ 3.63, a two-proton triplet ($J = 7.4$ Hz) at $\delta$ 2.19, a two-proton multiplet at $\delta$ 1.60–1.50, a two-proton multiplet $\delta$ 1.50–1.40, a broad one-proton signal at $\delta$ 1.31 (exchanges with D$_2$O), as well as a nine-proton singlet at $\delta$ 0.18 for the Me$_3$Ge- group. These data are consistent with the structure 5-trimethylgermylhex-5-en-1-ol (92) (Scheme 18). However, GLC analysis of the acquired oil indicated that the vinylgermane 92 was contaminated with two minor components, each present in 2–3%.
The failure to detect significant amounts (=20% combined yield expected) of the products 93–95 resulting from the protiodemetallation of the isomers 74 and 76, cast doubt on the structural assignments of the isomers 73–76.

Moreover, the high overall yield of the two-step sequence for the generation of 5-trimethylgermylhex-5-en-1-ol (92) from the isomers 73 and 75 was unexpected. Therefore, isolation of the (initially presumed) isomers 73–76 was attempted so that they could be completely characterized and then subjected individually to the protodesilylation conditions.

2.1.4.2 ISOLATION OF THE PRODUCTS OF HYDROGERMYLATION OF 6-TRIMETHYLSILYLHEX-5-YN-1-OL (62)

For the purpose of isolating the different isomeric products from the hydrogermylation of 6-trimethylsilylhex-5-yn-1-ol (62), it was decided to perform the reaction on a larger scale.
under experimental conditions similar with that outlined above. Thus, to a cold (0 °C) stirred solution of 62 (932 mg, 5.47 mmol, 1 equiv) and H₂PtCl₆•6H₂O (57 mg, 0.11 mmol, 0.020 equiv) in dry dichloromethane (27 mL) was added Me₃GeH (53) (974 mg, 8.21 mmol, 1.50 equiv). The cooling bath was removed and the reaction mixture was allowed to stir at room temperature overnight. Isolation and flash column chromatography of the acquired oil on silica gel, afforded 1.32 g (83%) of a mixture of the four isomers 73–76. This liquid was subjected to semi-preparative HPLC (silica Partisil, 10 μm; 22 mm × 250 mm column, 22:3 hexane–ethyl acetate) in four approximately equal portions. These chromatographies resulted in a rough separation to afford three fractions. The corresponding fractions of the separate injections were combined and concentrated under reduced pressure. The first fraction to be eluted, fraction A (retention time 28–40 min), afforded 985 mg of a mixture of two components. The second fraction to be eluted, fraction B (retention time 40–46 min) afforded 105 mg of an oil which was constituted of a mixture of three components (HPLC analysis). The third fraction to be eluted, fraction C (retention time 46–52 min) afforded 75 mg of an oil which was constituted of a mixture of five components (HPLC analysis).

2.1.4.2.1 Isolation and Characterization of (E)-5-Trimethylgermyle-6-trimethylsilylhex-5-en-1-ol (73)

Part of fraction A (~200 mg) was subjected to reversed phase HPLC (C₁₈ μBondapak, 10 μm; 25 mm × 100 mm column, 3:1 methanol–water) in approximately eight equal portions.
The corresponding fractions of the separate injections were combined and concentrated under reduced pressure. The first component to be eluted (retention time 30 min) was distilled to afford 43 mg of a clear colorless oil. This compound, \((E)-5\text{-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73), is the major component formed during the hydrogermylation of 6-trimethylsilylhex-5-yn-1-ol (62).}

The \(^1\text{H NMR spectrum (400 MHz, CDCl}_3\text{) of this liquid exhibited two nine-proton singlets at }\delta 0.17 \text{ and } 0.09, \text{ assigned to the } \text{Me}_3\text{Ge- and Me}_3\text{Si- groups. The spectrum also showed a one-proton singlet at }\delta 5.81 \text{ and a multiplet at }\delta 2.34-2.30 \text{ (allylic methylene protons). The singlet at }\delta 5.81 \text{ can be assigned confidently to a vinylic proton that has no vicinal protons. Therefore, the vinylic proton must be on C-6 and the Me}_3\text{Ge- group must be on C-5. HRMS (DCI, CH}_4\text{) analysis was consistent with the presence of a Si and a Ge atom in the formula C}_{12}\text{H}_{29}^{74}\text{GeO}_{28}\text{Si (M + 1)}^+ \text{ for the proposed structure with a calculated mass of 291.1199 and an experimentally found value of 291.1185.}

After determining the position of the Me}_3\text{Ge- group, the configuration of the double bond needed to be established. This was accomplished through }\text{H NMR NOE difference experiments (see 73). Thus, irradiation of the signal at }\delta 0.09 \text{ (Me}_3\text{Si-) generated an enhancement of the resonances at }\delta 5.81 \text{ (vinylic proton) and 2.34-2.30 (allylic methylene protons). Likewise, irradiation at }\delta 0.17 \text{ (Me}_3\text{Ge-) caused the same two signals to be enhanced. These experiments suggest that the Me}_3\text{Si- and the Me}_3\text{Ge- groups are trans to}
each other so that both of these functions have the vinylic proton and the allylic methylene protons as immediate neighbors. Additional support for this assignment came from observing signal enhancements of the singlets at δ 0.09 and 0.17 (Me$_3$Si- and Me$_3$Ge-) from irradiation of the signal at δ 5.81 (vinylic proton) or from irradiation of the allylic methylene resonance at δ 2.34–2.30. Since the Me$_3$Si- group in the starting material, 6-trimethylsilylhex-5-yn-1-ol (62), was initially located on C-6, the Me$_3$Ge- group in the product 73 must be on C-5 and trans to the Me$_3$Si- moiety.

The second compound to be eluted from the reversed phase HPLC (retention time 33 min) was concentrated under reduced pressure to provide 40 mg of an oil which was still a mixture, but had been enriched with the 33 min component. This sample was resubjected to identical HPLC conditions to afford 13 mg of an oil, fraction D (vide infra), which was 93% pure by GLC analysis. This fraction, which contains the second most abundant product from the hydrogermylation of 6-trimethylsilylhex-5-yn-1-ol (62), was processed further as described in section 2.1.4.2.4 (p 46 ff.).

2.1.4.2.2 Isolation and Characterization of (Z)-5-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75)

The fraction B (105 mg) from the initial HPLC separation (section 2.1.4.2, p 37) was subjected to HPLC (silica Partisil, 10 µm; 22 mm × 250 mm, 9:1 hexane–ethyl acetate). The last component to be eluted (retention time 51 min) was concentrated under reduced pressure
to afford 10.8 mg of an oil which was still a mixture but had been enriched with the 51 min component. This sample was resubjected to HPLC under identical conditions to afford 5.6 mg of an oil which was 92% pure (GLC analysis).

The \(^1\)H NMR spectrum (400 MHz, CDCl\(_3\)) of this liquid exhibited two nine-proton singlets at \(\delta 0.27\) and 0.10, which are assigned to the Me\(_3\)Ge- and Me\(_3\)Si- groups. A two-proton triplet of doublets (\(J = 7.8\) and 1.2 Hz) at \(\delta 2.24\) as well as a one-proton triplet (\(J = 1.2\) Hz) at \(\delta 6.18\) (vinyllic proton) suggest an allylic coupling between the vinyllic proton and the allylic methylene protons. It may therefore be proposed with confidence that this compound has the vinyllic proton on C-6 and, therefore, the Me\(_3\)Ge- group on C-5 (see 75). It may be further concluded that the Me\(_3\)Ge- and the Me\(_3\)Si- groups are cis to each other since compound 73 (vide supra) has the two moieties in a trans relationship. HRMS (DCI, NH\(_3\) + CH\(_4\)) analysis of compound 75 indicated a signal at \(m/z\) 291.1193, which is in good agreement with the calculated value of 291.1199 for C\(_{12}\)H\(_{29}\)GeO\(_2\)Si (M + 1)\(^+\).

\(\text{HO - HSiMe_3} - \text{GeMe_3 75}\)

\(^1\)H NMR NOE difference experiments were performed to establish the relationship between the Me\(_3\)Si- and Me\(_3\)Ge- groups (see 75). Irradiation at \(\delta 6.18\) (vinyllic proton) caused signal enhancements of the resonances at \(\delta 0.10\) (Me\(_3\)Si-) and 2.24 (allylic methylene protons). Alternatively, irradiation of the allylic methylene protons at \(\delta 2.24\) caused the signal at \(\delta 0.27\) (Me\(_3\)Ge-) to be enhanced. Moreover, irradiation at \(\delta 0.27\) (Me\(_3\)Ge-) caused the allylic
methylene signal to be enhanced, whereas irradiation of the Me₃Si- group at δ 0.10 generated an enhancement of the triplet at δ 6.18 (vinyllic proton). These experiments establish the cis relationship between the Me₃Si- and the Me₃Ge- groups.

2.1.4.2.3 Isolation and Characterization of (E)-6-Trimethylgermyl-6-trimethylsilylhex-5-en-l-ol (74)

The fraction C (75 mg) from the initial HPLC separation (section 2.1.4.2, p 37) was subjected to HPLC (silica Partisil, 10 μm; 22 mm × 250 mm, 9:1 hexane–ethyl acetate). The fourth component to be eluted (retention time 54 min) was concentrated under reduced pressure to give an oil which was still a mixture, but had been enriched with the 54 min component. This sample was resubjected twice to HPLC under identical conditions, and the acquired liquid was distilled to afford 13 mg of a clear colorless oil (95% pure by GLC analysis). This sample contained a small (5%) amount of (Z)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75), as determined by GLC and ¹H NMR analyses.

The ¹H NMR (400 MHz, CDCl₃) spectrum of this oil exhibited two nine-proton singlets at δ 0.17 and 0.12 (Me₃Ge- and Me₃Si-), a doublet of triplets (J = 7.0 and 7.0 Hz) at δ 2.21 (allylic methylene protons) and a one-proton triplet (J = 7.0 Hz) at δ 6.43 (vinyllic proton). The multiplicity and coupling constant of the vinyllic proton suggest a vicinal coupling to the allylic methylene protons. Therefore, both the Me₃Ge- and the Me₃Si-moieties must be located on C-6 of the alkene function. HRMS (DCI, NH₃ + CH₄) analysis of
this compound gave a signal at \( m/z \) 291.1190, which is in agreement with the calculated value for \( \text{C}_{12}\text{H}_{29}^{74}\text{GeO}^{28}\text{Si} (M + 1)^+ \) of 291.1199.

\[
\text{HO} \quad \text{Me}_3\text{Si} \quad \text{GeMe}_3
\]

\( 74 \)

\(^1\text{H} \) NMR NOE difference experiments were performed to establish the orientation of the \( \text{Me}_3\text{Si-} \) and \( \text{Me}_3\text{Ge-} \) groups (see 74). Irradiation of the signal at \( \delta \) 6.43 (vinyllic proton) caused enhancements of the resonances at \( \delta \) 2.21 (allylic methylene protons) and 0.17 (\( \text{Me}_3\text{Ge-} \)). Alternatively, irradiation of the allylic methylene protons (\( \delta \) 2.21) caused the signals at \( \delta \) 6.43 (vinyllic proton) and 0.12 (\( \text{Me}_3\text{Si-} \)) to be enhanced. Irradiation of the \( \text{Me}_3\text{Ge-} \) singlet at \( \delta \) 0.17 generated an enhancement of the triplet at \( \delta \) 6.43 (vinyllic proton), whereas irradiation of the singlet at \( \delta \) 0.12 (\( \text{Me}_3\text{Si-} \)) caused the signal at \( \delta \) 2.21 (allylic methylene protons) to be enhanced. These experiments establish the cis relationship between the \( \text{Me}_3\text{Ge-} \) group and the vinyllic proton and at the same time, demonstrate that the \( \text{Me}_3\text{Si-} \) group and the side chain are on the same side of the alkene.

Although the above analysis appears reasonable, it could be argued that the determination of the geometry of the alkene from the NOE experiments hinges ultimately on the assignments of the \( \text{Me}_3\text{Ge-} \) group at \( \delta \) 0.17 and the \( \text{Me}_3\text{Si-} \) at \( \delta \) 0.12. Since these signals are in very close proximity, it was decided to prepare an alkene bearing the same functional groups via a method that would generate a double bond of known geometry and thus ascertain the identity of the two signals.

Following the procedure described by Zweifel and Lewis,\(^{56}\) 1-trimethylsilyldodec-1-
yne (64) (144 mg, 0.60 mmol) was transformed into (E)-1-iodo-1-trimethylsilyldodec-1-ene (96) via hydroalumination and iodination of the resulting vinylalane (Scheme 19). GLC and $^1$H NMR spectroscopic analyses of the crude mixture indicated the presence of the starting alkyne 64 (19%), the expected vinyl iodide 96 (69%) and a small amount (12%) of another product assigned to be (Z)-1-trimethylsilyldodec-1-ene. Flash column chromatography of this mixture using C$_{18}$ silica gel and acetonitrile as eluant afforded 116 mg of an inseparable mixture of (Z)-1-trimethylsilyldodec-1-ene and (E)-1-iodo-1-trimethylsilyldodec-1-ene (96) in a ratio of 1:6. The $^1$H NMR spectrum (200 MHz, CDCl$_3$) of this mixture showed that the major product 96 exhibits a one-proton triplet ($J = 8$ Hz) at $\delta$ 7.14, a two-proton doublet of triplets ($J = 8 \text{ and } 8$ Hz) at $\delta$ 2.04, a sixteen-proton multiplet at $\delta$ 1.42-1.16, a three-proton triplet at $\delta$ 0.86 and a nine-proton singlet at $\delta$ 0.26. The characteristic signals of this material are in good agreement with the spectroscopic data reported by Zweifel and Lewis$^{56}$ for (E)-1-iodo-1-trimethylsilylhex-1-ene. Zweifel and Lewis also reported that metal–halogen exchange of 1-halo-1-trimethylsilylalk-1-enes by treatment with $n$-butyllithium generates the corresponding vinyllithium species, which can subsequently be alkylated without loss of the stereochemical integrity of the alkene function.$^{56}$
Thus, \((E)-1\text{-ido-1-trimethylsilyldodec-1-ene (96)}\) was transformed into \((E)-1\text{-trimethylgermyl-1-trimethylsilyldodec-1-ene (97)}\) via a lithium–halogen exchange, followed by germylation of the corresponding vinyllithium species (Scheme 19). A cold \((-78 °C)\) stirred solution of a mixture of 96 and \((Z)-1\text{-trimethylsilyldodec-1-ene (ratio of 6:1)}\) (56 mg, 0.15 mmol, 1 equiv) in anhydrous THF (2 mL) was treated with a solution of tert-butyllithium (1.62 M in pentane, 0.21 mL, 0.33 mmol, 2.2 equiv) via a syringe. The yellow heterogeneous reaction mixture was stirred at \(-78 °C\) for 15 min and then \(\text{Me}_3\text{GeBr (89 mg, 0.45 mmol, 3.0 equiv)}\) was added. The resulting colorless heterogeneous mixture was stirred at \(-78 °C\) for 15 min, then was warmed to room temperature and was allowed to stir for an additional 10 min. Water (1 mL) and diethyl ether (15 mL) were added. The layers were separated and the organic extract was washed with water (5 mL) and brine (5 mL), was dried over anhydrous magnesium sulfate and then was filtered and concentrated under reduced pressure. The crude oil acquired was flash chromatographed (C_{18} silica gel, methanol) to afford 30 mg (56%) of
the (E)-1-trimethylgermyl-1-trimethylsilyldodec-1-ene (97). The $^1$H NMR (400 MHz, CDCl$_3$) spectrum of this oil exhibited the following signals: $\delta$ 6.44 (t, 1H, $J = 7.0$ Hz), 2.17 (dt, 2H, $J = 7.0$ and 7.0 Hz), 1.48–1.15 (m, 16H), 0.86 (t, 3H, $J = 6.8$ Hz), 0.17 (s, 9H) and 0.12 (s, 9H). The $^1$H NMR chemical shifts for the vinylic proton ($\delta$ 6.44), the Me$_3$Ge- group ($\delta$ 0.17) and the Me$_3$Si- group ($\delta$ 0.12) of (97) are in excellent agreement with those of (E)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74) (vide supra), therefore establishing the geometry of the alkene function of 74.

2.1.4.2.4 Isolation and Characterization of (Z)-6-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76)

![Chemical structure of 76]

The fraction $D$ (13 mg), isolated from the reversed phase HPLC separation of fraction $A$ (see section 2.1.4.2.1, p 38 ff.), was subjected to HPLC (silica µPorasil, 10 µm; 25 mm × 100 mm, 9:1 hexane–ethyl acetate). The major component (retention time 17 min) was separated from a small amount of a more polar impurity (retention time 19 min) and was concentrated under reduced pressure to afford 5.8 mg of a clear colorless oil (98 % pure by GLC analysis).

The $^1$H NMR (400 MHz, CDCl$_3$) spectrum of this liquid possessed a one-proton triplet ($J = 7.4$ Hz) at $\delta$ 5.70 (vinylic proton), a two-proton doublet of triplets ($J = 7.4$ and 7.4 Hz) at $\delta$ 2.12 (allylic methylene protons) and two nine-proton singlets at $\delta$ 0.24 (Me$_3$Ge-) and $-0.04$ (Me$_3$Si-). The multiplicity and coupling constant of the vinylic proton indicated a
vicinal coupling to the allylic methylene protons, therefore locating the Me₃Ge- group on C-6. HRMS (DCI, NH₃ + CH₄) analysis of this compound revealed a signal at m/z 291.1180, in agreement with the calculated value of 291.1173 for C₁₂H₂₉/help>GeO³⁰Si (M + 1)⁺. Since all three other possible isomers 73, 74 and 75 from the hydrogermylation of 6-trimethylsilylhex-5-yn-1-ol (62) had been characterized (vide supra), this compound was assigned structure 76 (see Scheme 13, p 27). To confirm further the configuration of this compound, the following ¹H NMR NOE difference experiments were performed.

Irradiation of the signal at δ 5.70 (vinylic proton) generated an enhancement of the resonances at δ 2.12 (allylic methylene protons) and -0.04 (Me₃Si-). Alternatively, irradiation of the allylic methylene protons at δ 2.12 caused the signal at δ 5.70 to be enhanced (vinylic proton). Irradiation of the singlet at δ 0.24 (Me₃Ge-) generated an enhancement of the signal at δ 2.12 (allylic methylene protons), whereas irradiation of the Me₃Si- group at δ -0.04 caused the triplet due to the vinylic proton (δ 5.70) to be enhanced. These experiments establish the cis relationship between the Me₃Si- group and the vinylic proton and demonstrate that the Me₃Ge- group is on the same side of the alkene as the side chain.
2.1.4.2.5 Summary

The experimentation summarized above established that the hydrogermylation of 6-trimethylsilylhex-5-yn-1-ol (62) with trimethylgermane (53) in the presence of a catalytic amount of \( \text{H}_2\text{PtCl}_6\cdot6\text{H}_2\text{O} \) generates four products. The major product obtained (75%), (\( E \))-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73), arises from the cis addition of \( \text{Me}_3\text{GeH} \) (53) across the alkyne function of 62 (see the formation of 73 from loop A in the catalytic cycle depicted in Scheme 15, p 32). This primary mode of addition was that expected, based on previously described hydrogermylations of alkynes.\(^{32,46}\) The second major product (19%) was (\( Z \))-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76). This product emanates from a trans addition of the elements of \( \text{Me}_3\text{GeH} \) (53) across the alkyne function of 62 (see the formation of 76 from loop B in the catalytic cycle depicted in Scheme 15, p 32). This result is somewhat unexpected since the hydrogermylation of alk-1-ynes in the presence of \( \text{H}_2\text{PtCl}_6\cdot6\text{H}_2\text{O} \) generally provides predominantly, if not exclusively, products of cis addition. Although no reports of hydrogermylation of 1-trimethylsilylalk-1-ynes have been reported to this date, it appears that this class of substrates behaves somewhat differently from the alk-1-ynes.
**Scheme 20** depicts the reaction pathway that would lead to the formation of the other cis addition product, \((E)-6\text{-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74)}\), from the 1-trimethylsilylalk-1-yne 62. Thus, coordination of the active form of the catalyst 82 to the substrate 62 leads to the formation of the complex 83. Oxidative addition of \(\text{Me}_3\text{GeH (53)}\) generates complex 84, which upon transfer of the \(\text{Me}_3\text{Ge- or H fragment yields the vinyl platinates 98 or 99. Reductive elimination from either 98 or 99 generates the alkene 74. Finally, the formation of the other minor product (≈2%), \((Z)-5\text{-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75)}\), arises from a pathway analogous to that of the production of compound 76, that is from a trans addition of the elements of \(\text{Me}_3\text{GeH (53)}\) across the carbon–carbon triple bond of 62 (see **Scheme 15**, p 32).

![Scheme 20](image)

The spectroscopic data presented above support the original assignments for the
structure of compounds 73–76. Therefore, the next step in the attempt to elucidate the transformation was to submit individually the products 73–76 derived from the hydrogermylation of 6-trimethylsilylhex-5-yn-1-ol (62) to the \( p\)-TsOH•H\(_2\)O mediated protodesilylation reaction conditions.

2.1.4.3 TREATMENT OF THE PRODUCTS OF HYDROGERMYLATION OF 6-TRIMETHYLSILYLHEX-5-YN-1-OL (62) WITH \( p\)-TOLUENESULFONIC ACID MONOHYDRATE IN DICHLOROMETHANE

2.1.4.3.1 Protodesilylation of (E)-5-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73) to 5-Trimethylgermylhex-5-en-1-ol (92)

\[
\begin{align*}
\text{Me}_3\text{Si} & \quad \text{H} \\
\text{O} & \quad \text{GeMe}_3 \\
\text{CH}_2\text{Cl}_2 & \quad \text{HO} \\
\text{H} & \quad \text{GeMe}_3 \\
\text{Me}_3\text{Si} & \quad \text{H} \\
\text{O} & \quad \text{GeMe}_3 \\
\text{CH}_2\text{Cl}_2 & \quad \text{HO} \\
\text{H} & \quad \text{GeMe}_3
\end{align*}
\]

A dichloromethane solution of 8.8 mg of (E)-5-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73) (the major product obtained from the hydrogermylation of 62) was treated with 1.2 equivalents of \( p\)-TsOH•H\(_2\)O at room temperature for 1 h. GLC analysis of an aliquot of the reaction mixture revealed that a single product had been formed. After isolation and purification, 6.6 mg of 5-Trimethylgermylhex-5-en-1-ol (92) was obtained (quantitative). The \(^1\)H NMR spectrum of the acquired liquid was identical with that obtained from the hydrogermylation–protodesilylation sequence of 6-trimethylsilylhex-5-yn-1-ol (62) as described in section 2.1.4.1, p 26 ff. As anticipated, the removal of the trimethylsilyl group was effected selectively.
The protodesilylation of (E)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73) can be rationalized using a mechanism similar to that proposed by Koenig and Weber. Thus, when 73 is treated with p-TsOH•H₂O, protonation of the carbon–carbon double bond leads to 100a (Scheme 21). Bond rotation about the carbon–carbon single bond with the least nuclear motion (100a → 100b) permits increasing stabilization of the carbocation from the trimethylsilyl group via hyperconjugation (also referred to as “vertical stabilization”). This property of R₃Si- groups (as well as R₃Ge-, R₃Sn- and R₃Pb-) to stabilize β carbocations is now well recognized. Finally, attack of the nucleophile (TsO⁻) on the trimethylsilyl group, with reformation of the carbon–carbon double bond effects the production of the vinylgermane 92.

2.1.4.3.2 Protodesilylation of (Z)-5-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75) to 5-Trimethylgermylhex-5-en-1-ol (92)

Similarly, a solution of 2.7 mg of (Z)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol
(75) (obtained in trace amounts from the hydrogermylation of 62) in dichloromethane was treated with 1.2 equivalents of p-TsOH•H₂O at room temperature for 1.5 h. GLC analysis of an aliquot of the reaction mixture revealed that the vinylgermane 92 was the sole product formed. After isolation and purification of the crude product, 1.1 mg of 5-trimethylgermyl-hex-5-en-1-ol (92) was obtained (54%). A mechanism similar to that depicted in Scheme 21 (vide supra) can be used to rationalize the protodesilylation of 75 to yield the vinylgermane 92.

2.1.4.3.3 Protidesilylation of (Z)-6-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76) to 5-Trimethylgermylhex-5-en-1-ol (92)

The treatment of (Z)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76) (the second most abundant product from the hydrogermylation of 6-trimethylsilylhex-5-yn-1-ol (62)) with p-TsOH•H₂O will now be discussed. A solution of 76 (9.6 mg) in dichloromethane was treated with 1.2 equivalents of p-TsOH•H₂O at room temperature for 1.5 h. After isolation and purification of the crude product, 5-trimethylgermylhex-5-en-1-ol (92) was obtained in 85% yield. The spectral data derived from this product were identical with those reported in section 2.1.4.1 (p 26). GLC analysis of the crude product, as well as GLC and GLC-MS analyses of the chromatographed product, revealed that a small amount (=2.5%) of (E)-6-trimethylsilylhex-5-en-1-ol (94a) had also been formed during the reaction (vide infra). The structural assignment of this compound was made by comparison of the GLC retention time
and GLC-MS data presented in the next section.

\[
\begin{align*}
\text{93 } R &= \text{GeMe}_3 \\
\text{94 } R &= \text{SiMe}_3
\end{align*}
\]

The results described above were rather surprising and certainly not predicted. Based on the analysis outlined in Scheme 17 (p 35), it was expected that 76 would undergo simple protodesilylation to the vinylgermanes 93 or protiodegermylation to the vinylsilanes 94. The fact that (Z)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76) is transformed almost entirely (>97%) into 5-trimethylgermylhex-5-en-1-ol (92) seems to be the key to the high overall yield of the hydrogermylation–protodesilylation sequence. It therefore appears that upon treatment of 76 with \( p\)-TsOH·H\(_2\)O in dichloromethane at room temperature, the trimethylgermyl group underwent a 1,2 shift. Although this migration was not expected, there is precedent for a related process in the literature involving trialkysilyl chemistry.

\[
\begin{align*}
\text{Me}_3\text{SiCH}_2\text{CD}_2\text{Br} & \quad \text{H}_2\text{C}+\text{CD}_2+\text{Br}^- \quad \text{BrCH}_2\text{CD}_2\text{SiMe}_3 \quad (13)
\end{align*}
\]

Eaborn and co-workers\(^9\) carried out the solvolysis of 101 in aqueous methanol to 50% completion and recovered the bromide. \(^1\)H NMR spectroscopic analysis revealed that the recovered bromide was comprised of a mixture of 101 and 103 (Equation 13). The formation of 103 was rationalized by postulating the reversible ionization of the bromide 101 to a non-classical silacycloprenium ion 102, as depicted in Equation 13. It was also concluded that, under the reaction conditions used, the rate of rearrangement was somewhat faster than that of the solvolysis. Similar results obtained from related experiments have been
rationalized via silacyclopropenium ions.\textsuperscript{60,61}

A possible reaction pathway accounting for the formation of the vinylgermane 92 and the vinylsilane 94a from (Z)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76), rationalized in terms of classical carbocations, is depicted in Scheme 22. Thus, protonation of the alkene function of 76 with \( p\text{-TsOH}\cdot H_2O \) generates the carbocation 104a. Bond rotation about the carbon–carbon single bond of 104a with the least nuclear motion allows increasing stabilization of the carbocation from hyperconjugation by the trimethylgermyl group leading to the formation of 104b. Since the hyperconjugative\textsuperscript{58,62} electron release from the carbon–germanium bond is greater than that from the carbon–silicon bond (the electron release through hyperconjugation for the C–M bond is in the order \( M = Si < Ge << Sn < Pb \)),\textsuperscript{62} it is reasonable to assume that rotation around the carbon–carbon single bond will be such as to favor a stabilization of the carbocation from the trimethylgermyl group. At this point, nucleophilic attack from the tosylate (path a) onto the trimethylgermyl group of 104b with reformation of the carbon–carbon double bond results in the production of the vinylsilane 94a.
Alternatively, the Me₃Ge- group from 104b may undergo a 1,2 shift (path b) to generate the carbocation 105a. This migration would relieve some steric encumbrance from the crowded terminal carbon of 104b, which bears both a Me₃Ge- and a Me₃Si- group. From the carbocation 105a, nucleophilic attack from the tosylate onto the trimethylgermyl group (path c) would produce the vinylsilane 94a, whereas carbon–carbon single bond rotation with the least nuclear motion (path d) would lead to 105b, which can undergo loss of a proton to form 75. Compound 75 can subsequently undergo protodesilylation to 92, as discussed in the previous section. Although no attempts were made to demonstrate the presence of compound 75 in the reaction mixture, the pathway leading to 92 seems nonetheless reasonable. This
does not preclude a possible alternative pathway that would lead to the formation of 92 without going through the intermediacy of 75.

Assuming that i) from 104b the 1,2 shift of the Me₃Ge- group (path b) is fast compared to the attack by the nucleophile (path a), and ii) that from the carbocation 105a rotation (path d) and proton elimination leading to the production of 75 is fast compared to the nucleophilic attack by the tosylate (path c) one would expect the major product to arise via the rearrangement process. This is, in fact, what is experimentally observed: the ratio of the observed products 92 and 94a is 49:1. This shows that the proposed pathways b and d are favored over pathways a and c respectively.

It may be possible to rationalize the preferential formation of 5-trimethylgermylhex-5-en-1-ol (92) over (E)-6-trimethylsilylhex-5-en-1-ol (94a) in terms of counter-ion control. The tosylate anion should be initially located on the same face as the newly introduced proton in 104a. After bond rotation to carbocation 104b, the elimination of the Me₃Ge- group (path a) requires participation of the tosylate anion, which necessitates that the latter moves to the other side of the molecule. On the other hand, the 1,2 shift of the Me₃Ge- group (path b) does not require such a participation of the tosylate and accordingly should be the favored process.

A similar argument may be formulated from carbocation 105a for the preferential proton elimination (path d: 105a ↔ 105b → 75) to form 75, which then undergoes protodesilylation to 92, as opposed to the Me₃Ge- group elimination (path c) to produce 94a.
2.1.4.3.4 Protiodegermylation of \((E)-6\)-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol \((74)\) to \((E)-6\)-Trimethylsilylhex-5-en-1-ol \((94a)\) and \((Z)-6\)-Trimethylsilylhex-5-en-1-ol \((94b)\)

\[
\begin{align*}
\text{Me}_3\text{Si} & \quad \text{GeMe}_3 \\
\text{H} & \quad \text{H} \\
\text{HO} \quad \text{CH}_2\text{Cl}_2 \\
74 \quad \text{p-TsOH} \cdot \text{H}_2\text{O} \\
\text{Me}_3\text{Si} & \quad \text{H} \\
\text{H} & \quad \text{H} \\
\text{HO} \\
94a (E) \\
94b (Z)
\end{align*}
\]

A solution of 6.6 mg of \((E)-6\)-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol \((74)\) (obtained in trace amounts from the hydrogermylation of \((62)\); this sample contained a small (5%) amount of \((Z)-5\)-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol \((75)\)) in dichloromethane was treated with 1.2 equivalents of \(p\)-TsOH•H\(_2\)O at room temperature for 1.25 h. After isolation and purification of the crude product, \(^1\)H NMR (400 MHz, CDCl\(_3\)) spectroscopic, GLC and GLC-MS analyses of the acquired oil revealed the presence of three products, as well as a small amount (5%) of unreacted starting material. The \(^1\)H NMR spectrum of the mixture showed six signals in the region \(\delta\) 6.5–5.1, integrating for a total of two protons, a two-proton triplet at \(\delta\) 3.62, a two-proton multiplet at \(\delta\) 2.26–2.08, a four-proton multiplet at \(\delta\) 1.63–1.40 and five singlets in the \(\delta\) 0.20–0.02 region integrating for a total of nine protons.

The major product (72% by GLC analysis) in the mixture was assigned structure \(94b\), \((Z)-6\)-trimethylsilylhex-5-en-1-ol, formed by protiodegermylation of the starting material \(74\). The assignment was based on the following data: the \(^1\)H NMR spectrum exhibited a doublet of triplets \((J = 14.0\) and 7.0 Hz) at \(\delta\) 6.27, as well as another doublet of triplets \((J = 14.0\) and 1.2 Hz), of equal intensity, at \(\delta\) 5.48. Homonuclear decoupling of the \(\delta\) 6.27 signal resulted in the collapse of the \(\delta\) 5.48 doublet of triplets to a triplet, simultaneously revealing the presence of a small doublet at \(\delta\) 5.49, previously hidden, due to a small amount of \(5\)-trimethylgermyl-
hex-5-en-l-ol (92) present in the mixture (vide infra). The two signals at δ 6.27 and δ 5.48, together with the data given below, suggest a cis arrangement between two vinylic protons of a 1,2-disubstituted alkene. GLC-MS (Cl, NH₃) analysis indicated an ion at 173 (M + 1)⁺, which is consistent with the expected mass for C₉H₂O₂⁺Si (172), as well as diagnostic fragments at 157 (M – CH₃)⁺ and 73 (-Si(CH₃)₃)⁺.

Similarly, the next major component (18%) was assigned structure 94a, (E)-6-trimethylsilylhex-5-en-l-ol, also formed by protiodegermylation of the starting material 74, on the basis of the following data: the ¹H NMR spectrum exhibited a doublet of triplets (J = 18.6 and 6.2 Hz) at δ 6.00 as well as another doublet of triplets (J = 18.6 and 1.5 Hz), of equal intensity, at δ 5.62. These signals are consistent with a trans arrangement between two vinylic protons of a 1,2-disubstituted alkene. GLC-MS (Cl, NH₃) analysis indicated an ion at 173 (M + 1)⁺, in agreement with the expected mass for C₉H₂O₂⁺Si (172), as well as diagnostic fragments at 157 (M – CH₃)⁺ and 73 (-Si(CH₃)₃)⁺.

The minor product (5%) (vide supra) formed during the reaction was 5-trimethylgermylhex-5-en-l-ol (92). The assignment was established as follows: the ¹H NMR spectrum displayed characteristic doublets at δ 5.49 (revealed during the homonuclear decoupling experiment at δ 6.27, vide supra) and 5.16. GLC-MS (Cl, NH₃) indicated an ion at 219 (M + 1)⁺ with an isotopic cluster consistent with the expected distribution for C₉H₂O²⁺Ge (218) and finally, coinjection with an authentic sample on GLC ascertained that this product has a retention time identical with that of 5-trimethylgermylhex-5-en-l-ol (92). The presence of this compound can be linked to the small (5%) amount of (Z)-5-trimethylgermyl-6-trimethylsilylhex-5-en-l-ol (75) in the starting material, incompletely separated from 74 during the
isolation, which underwent protodesilylation (vide supra).

\[
\begin{align*}
&\text{Scheme 23} \\
&\text{The formation of the vinylsilanes } 94\text{a and } 94\text{b from } 74 \text{ can be rationalized in a fashion similar to that used for the formation of the vinylgermane } 92 \text{ from } 73 \text{ (Scheme 21, p 51), following the mechanism proposed by Koenig and Weber.}^{53} \text{ Scheme 23 depicts the proposed transformations. Thus, when } 74 \text{ is treated with } p\text{-TsOH}\cdot H_2O, \text{ protonation of the alkene function leads to the formation of carbocation } 106\text{a. Rotation about the carbon–carbon single bond with the least nuclear motion (path a), simultaneously causing the side chain } R
\end{align*}
\]
and the Me₃Si- group to eclipse each other, allows increased stabilization of the carbocation 106b from the trimethylgermyl group through hyperconjugation. Elimination of the Me₃Ge-group, through nucleophilic attack from the tosylate on 106b, results in the formation of the vinylsilane 94b (path b). The product obtained as a result of pathway b, (Z)-6-trimethylsilyl-hex-5-en-1-ol (94b), is the major component produced from the treatment of 74 under acidic conditions.

As outlined above, no rearranged product was observed from the treatment of 74 with p-TsOH•H₂O. It appears that the carbocation 106b does not undergo a 1,2 Me₃Ge- shift. It is possible that pathway c is not favored since migration of the trimethylgermyl group would require that the side chain R becomes eclipsed the Me₃Si- group going from 106b to 106c. This interaction may be responsible for inhibiting the migration of the Me₃Ge- group.

Alternatively, rotation about the carbon–carbon single bond of 106a (path d) would form 106d. At this time, elimination of the trimethylgermyl group through nucleophilic attack from the tosylate yields vinylsilane 94a (path e). Additional comments are required on the formation of 94a from 106a. Firstly, the formation of 106d, which is stabilized through hyperconjugation from the Me₃Ge- group, alleviates the steric encumbrance between the Me₃Si- group and the side chain R present in both 106a and 106b. Secondly, the carbocation 106d possesses a conformation analogous to that of carbocation 104b which underwent a 1,2 Me₃Ge- shift (Scheme 22, p 55). The “anomalous” behavior of carbocation 106d may be rationalized in terms of counter-ion control. The tosylate anion should be initially located on the same face as the newly introduced proton in 106a, and hence on the same face as the Me₃Ge- group of 106d. Therefore, the tosylate anion may compete effectively for the
elimination of the Me₃Ge- group (path e), instead of undergoing a 1,2 shift (path f). This was not the case for carbocation 104b (see Scheme 22, p 55 and accompanying text).

\[
\begin{align*}
\text{Me} & \quad \text{Me} \\
\text{NH}_2 & \quad + \\
\text{N}_2 & \quad \text{OAc} \\
107 & \quad 108 \\
\end{align*}
\]

\[
\begin{align*}
\text{Me} & \quad \text{Me} \\
\text{OAc} & \quad - \\
\text{N}_2 & \quad - \\
109 & \quad 110 \\
\end{align*}
\]

\[
\begin{align*}
\text{Me} & \quad \text{Me} \\
\text{OH} & \quad + \\
\text{OH} & \quad \text{H} \\
111 & \quad 110 \\
\end{align*}
\]

Scheme 24

Counter-ion control⁶³ has been used successfully to rationalize the outcome of examples in which identical carbocation intermediates lead to different products. This rationale uses ion-pairing to explain the selectivity of certain transformations. The example in Scheme 24 illustrates this concept. Deamination of optically active amine 107 in acetic acid solution in the presence of sodium nitrite generated the optically active acetate 110, which upon hydrolysis, formed the optically active alcohol 111. The optical activity of the alcohol 111 was largely retained. To explain this retention of configuration,⁶³ it has been postulated that the intermediate diazonium acetate 108 decomposes to the ion pair 109, which then recombines to form the acetate 110. The hydrolysis of 110 leads to the optically active alcohol 111.

\[
\begin{align*}
\text{Me}_3\text{Si} & \quad \text{H} \\
\text{HO} & \quad \text{H} \\
94a & \quad 94b \\
\end{align*}
\]

\[
\begin{align*}
\text{H} & \quad \text{H} \\
\text{CH}_2\text{Cl}_2, \ 35^\circ\text{C} & \quad \text{HO} \\
95 & \quad 94a \\
\end{align*}
\]

When the mixture of vinylsilanes 94a and 94b, obtained from the protiodegermylation of (E)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74) (vide supra), was treated with p-
TsOH·H₂O (1.2 equiv) in dichloromethane at 35 °C for 1 h, protodesilylation occurred. GLC analysis of the crude mixture indicated that the substrates had been completely consumed. However, due to the small scale of the reaction (=1 mg) the (expected) product, hex-5-en-1-ol (95), could not be isolated.

\[
\begin{align*}
\text{Me}_3\text{Si} & \quad \text{GeMe}_3 & \equiv & \quad \text{Me}_3\text{Si} & \equiv & \quad \text{H} \\
\text{n-C}_{10}\text{H}_{21} & \quad \text{H} & \quad \text{CH}_2\text{Cl}_2, \text{rt} & \quad \text{Me}_3\text{Si} & \equiv & \quad \text{H} \\
\text{97} & & & \quad \text{CH}_2\text{Cl}_2, 35 ^\circ \text{C} & \quad \text{n-C}_{10}\text{H}_{21} & \quad \text{H} \\
& & & & \quad \text{112 (4:1 Z:E)} & \quad \text{113} \\
\end{align*}
\]

In order to gain further information on the outcome of treating (E)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74) with p-TsOH·H₂O, a similar experiment was carried out employing (E)-1-trimethylgermyl-1-trimethylsilyldodec-1-ene (97) as substrate (Equation 14). Thus, treatment of 97 with 1.2 equivalents of p-TsOH·H₂O in dichloromethane at room temperature for 2.5 h resulted in the formation of the vinylsilanes 112. GLC and \(^1\)H NMR spectroscopic analyses indicated that the vinylsilanes 112 had been formed in a ratio of approximately 4:1, with the Z isomer being the major compound. The signals in the vinylic region of the \(^1\)H NMR spectrum of the crude mixture were similar to those reported for the product mixture derived from protiodegermylation of 74 (vide supra). Periodic GLC analyses of aliquots of the reaction mixture indicated that neither the substrate nor the vinylsilanes 112 underwent E to Z isomerization under the reaction conditions during the time required to effect protiodegermylation. Therefore, both vinylsilanes 112 arose from the same substrate. Moreover, the \(^1\)H NMR spectrum clearly showed that no product originating from the migration of the Me₃Ge- group had been formed during the reaction. When the reaction mixture containing the vinylsilanes 112 was heated to 35 °C for 1 h, protodesilylation
occurred to generate dodec-1-ene (113) (Equation 14). This assignment was based on the 
$^1$H NMR (400 MHz, CDCl$_3$) spectroscopic analysis of the crude oil isolated from the reaction 
mixture. The spectrum exhibited the following signals: $\delta$ 5.80 (ddt, 1H, $J = 17.1$, 10.3 and 6.7 
Hz), 4.98 (ddt, 1H, $J = 17.1$, 2.0 and 2.0 Hz), 4.91 (ddt, 1H, $J = 10.3$, 2.0 and 2.0 Hz), 2.10–
1.98 (m, 2H), 1.45–1.15 (m, 16H), 0.88 (t, 3H, $J = 7.0$ Hz). This experiment, along with 
those derived from the study involving treatment of 74 with acid (vide supra), demonstrates 
that the minor isomer ($E$)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74) obtained from 
the hydrogermylation of 6-trimethylsilylhex-5-yn-1-ol (62) can be chemically “destroyed” to 
form hex-5-en-1-ol (95) and (possibly) removed via chromatography from the desired 5-
trimethylgermylhex-5-en-1-ol (92).

2.1.4.3.5 Summary

The isomers 73–76, products from the hydrogermylation of 6-trimethylsilylhex-5-yn-
1-ol (62), were treated individually with $p$-TsOH$\cdot$H$_2$O in dichloromethane.

As outlined above, ($E$)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73) and ($Z$)-5-
trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75) react chemospecifically, as anticipated, 
with $p$-TsOH$\cdot$H$_2$O in dichloromethane to undergo C–Si bond cleavage to generate 5-
trimethylgermylhex-5-en-1-ol (92).

\[ \text{Me}_3\text{Ge} \quad \text{SiMe}_3 \]

Unexpectedly, (Z)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76) also produced 5-trimethylgermylhex-5-en-1-ol (92) when treated with \( p\text{-TsOH}\cdot\text{H}_2\text{O} \) in dichloromethane. It is postulated that this transformation occurs via an acid mediated 1,2 \( \text{Me}_3\text{Ge} \)- shift (Scheme 22, p 55), to generate eventually (Z)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75). The latter undergoes protodesilylation to give (92).

\[ \text{Me}_3\text{Si} \quad \text{GeMe}_3 \]

Finally, (E)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74) underwent protiodegermylation to a mixture (E)- and (Z)-6-trimethylsilylhex-5-en-1-ols (94a) and (94b). Furthermore, when the reaction mixture containing \( p\text{-TsOH}\cdot\text{H}_2\text{O} \) along with the vinylsilanes 94a and 94b was heated to 35 °C, protodesilylation occurred to generate hex-5-en-1-ol (95).

These transformations proved to be general for a series of diversely functionalized 1-trimethylsilylalk-1-ynes. The results are presented in the following section.
2.1.5 SYNTHESIS OF 2-TRIMETHYLGERMYLALK-1-ENES

The optimized experimental conditions devised as described in the previous section were successfully applied to a number of 1-trimethylsilylalk-1-ynes to generate the corresponding 2-trimethylgermylalk-1-enes.

Table 2 summarizes the conversion of the 1-trimethylsilylalk-1-ynes 61, 63–67, 72 and 114 into the 2-trimethylgermylalk-1-enes 92 and 115–121. The synthesis of 5-chloro-2-trimethylgermylpent-1-ene (117) (Table 2, entry 4), for example, was accomplished in the following manner. A mixture of 5-chloro-1-trimethylsilylpent-1-yne (65) (1 equiv) and \( \text{H}_2\text{PtCl}_6\cdot6\text{H}_2\text{O} \) (=0.02 equiv) in dichloromethane at 0 °C was treated with trimethylgermane (53) (1.5 equiv). The reaction mixture was then stirred at room temperature until complete consumption of the starting material. After isolation, the crude oil was dissolved in dichloromethane and treated with \( p-\text{TsOH}\cdot\text{H}_2\text{O} \) (1.2 equiv) at 30–35 °C for 1 h. Isolation and purification of the crude product afforded 5-chloro-2-trimethylgermylpent-1-ene (117) in 74% overall yield as a clear colorless oil.

The remainder of the 2-trimethylgermylalk-1-enes listed in Table 2 were synthesized from the corresponding 1-trimethylsilylalk-1-ynes in a manner identical with that outlined above. As seen in Table 2, the experimental conditions used for the preparation of the 2-trimethylgermylalk-1-enes are compatible with a wide variety of functional groups. Entries 1 and 2 (Table 2) show that this method accommodates trimethylsilyl ethers. Investigations showed that under similar experimental conditions, substrates bearing a trimethylsilyl ether function underwent hydrogermylation faster than the corresponding substrate with a free hydroxy group.
Table 2: Preparation of the 2-Trimethylgermylalk-1-enes 92, 115–121

\[
\begin{align*}
\text{R} & \quad \text{SiMe}_3 \quad 1) \quad \text{H}_2\text{PtCl}_6 \cdot 6\text{H}_2\text{O} (\text{cat}) \quad \text{Me}_3\text{GeH}, \text{CH}_2\text{Cl}_2, \text{rt} \\
& \quad \quad \quad \quad \text{Me}_3\text{GeH}, \text{CH}_2\text{Cl}_2, \text{rt} \quad \text{GeMe}_3 \\
& \quad \quad \quad \quad 2) \quad \text{p-TsOH} \cdot \text{H}_2\text{O} \\
& \quad \quad \quad \quad \text{CH}_2\text{Cl}_2, 35 \, ^\circ\text{C}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Entry</th>
<th>1-Trimethylsilylalk-1-yne</th>
<th>2-Trimethylgermylalk-1-ene(^a)</th>
<th>Yield (%)(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Me(_3)SiO &amp; &amp; 61 &amp; SiMe(_3) &amp; HO &amp; &amp; GeMe(_3) &amp; 92 &amp; 74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Me(_3)SiO &amp; &amp; 63 &amp; SiMe(_3) &amp; HO &amp; &amp; GeMe(_3) &amp; 115 &amp; 63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>n-C(<em>{10})H(</em>{21}) &amp; &amp; 64 &amp; SiMe(<em>3) &amp; n-C(</em>{10})H(_{21}) &amp; &amp; GeMe(_3) &amp; 116 &amp; 72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Cl &amp; &amp; 65 &amp; SiMe(_3) &amp; Cl &amp; &amp; GeMe(_3) &amp; 117 &amp; 74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Ph &amp; &amp; 66 &amp; SiMe(_3) &amp; Ph &amp; &amp; GeMe(_3) &amp; 118 &amp; 68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6(^c)</td>
<td>Me(_3)Si &amp; &amp; 67</td>
<td>&amp; &amp; Me(_3)SiGe &amp; &amp; GeMe(_3) &amp; 119 &amp; 71</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>&amp; &amp; 72 &amp; SiMe(_3) &amp; &amp; GeMe(_3) &amp; 120 &amp; 72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>&amp; &amp; 114 &amp; SiMe(_3) &amp; &amp; GeMe(_3) &amp; 121 &amp; 68</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Conditions: 1) Me\(_3\)GeH (1.5 equiv), H\(_2\)PtCl\(_6\) \cdot 6H\(_2\)O (=0.02 equiv), CH\(_2\)Cl\(_2\) (1 M), rt 1–21 h. 2) p-TsOH\(\cdot\)H\(_2\)O (1.2 equiv), CH\(_2\)Cl\(_2\) (0.1 M), 30–35 °C 1–7 h. \(^b\) Overall yield of isolated and purified product. \(^c\) The amounts of reagents were doubled for this substrate.
Thus, hydrogermylation followed by protodesilylation of the trimethylsilyl ethers 61 and 63 afforded the alcohols 92 and 115 in 74 and 63% overall yield, respectively. TLC analyses of the product mixtures after hydrogermylation indicated that the trimethylsilyl ether protecting groups had been largely retained. However, the trimethylsilyl ether functions were cleaved during the step involving treatment of the crude product with p-TsOH•H₂O in dichloromethane. Two Me₃Si- groups were removed from each of the substrates 61 and 63 during the protodesilylation step. Since only 1.2 equivalents of p-TsOH•H₂O were used, the acid must therefore have been regenerated within the reaction mixture. It is plausible to envisage that, after protodesilylation of a substrate of general structure depicted in Equation 15, for example, the resulting trimethylsilyl-para-toluenesulfonate was hydrolyzed with water (from the monohydrate of p-TsOH•H₂O or from the CH₂Cl₂ which is not anhydrous) to p-TsOH and trimethylsilanol.⁶⁴

\[
\text{Me}_3\text{Si}^\text{H} + p\text{-TsOH} \rightarrow \text{H} + p\text{-TsOSiMe}_3 \quad + \quad (15)
\]

1-Trimethylsilyldodec-1-yne (64) (entry 3) was transformed into 2-trimethylgermyldodec-1-ene (116) in 72% yield. The two-step sequence leading to the formation of the 2-trimethylgermylalk-1-enes also allows for the presence of a primary chloride (entry 4) as well as a phenyl group (entry 5). 1,6-bis(Trimethylsilyl)hexa-1,5-diyne (67) (entry 6) was smoothly converted into the structurally novel 2,5-bis(trimethylgermyl)hexa-1,5-diene (119) in 71% via the same set of transformations. Substrate 67 underwent a double hydrogermylation followed by protodesilylation and thus required that the amounts of reagents used be doubled.

The presence of an alkene function is also tolerated, as seen in entry 7, in which 72 is
transformed into 120. However, the endocyclic alkene function of 72 isomerized during the platinum catalyzed step leading to the formation of 120. A possible rationale for this isomerization will be presented later (vide infra). Finally, as summarized in entry 8, 5-trimethylsilylpent-4-ynoyltrimethylgermane (114) (the preparation of 114 is described later in section 2.2.2.3, p 97 ff.) was efficiently transformed into the structurally unique 4-trimethylgermynlpent-4-ynoyltrimethylgermane (121), which possesses two Me₃Ge- groups in different chemical environments.

Although the regioselectivity of addition of the Me₃Ge- group varied from one substrate to another (from 5:1 for 64 to 17:1 for 66), the ratio was generally about 12:1 in favor of the Me₃Ge- group having undergone addition at the C-substituted end of the alkyne for the 1-trimethylsilylalk-1-ynes depicted in Table 2.

The formation of 92 from 61 (entry 1), 116 from 64 (entry 3) and 120 from 72 (entry 7) require additional comments.

Firstly, during the purification of 5-trimethylgermylhex-5-en-1-ol (92) (entry 1), two by-products were also isolated in trace amounts. The first component, which was assigned structure 122, 5-trimethylgermyl-6-trimethylsilylhexan-1-ol, was isolated in ≈1.5% yield. The structural assignment was based on the following data. The ¹H NMR (400 MHz, CDCl₃) spectrum of 122 exhibited several distinctive signals, including a one-proton multiplet at δ 1.05–0.98 (H-5), a one-proton doublet of doublets (J = 15.0 and 3.6 Hz) at δ 0.60 (H-6a), a
one-proton doublet of doublets ($J = 15.0$ and $10.4$ Hz) at $\delta 0.48$ (H-6b) and two nine-proton singlets at $\delta 0.06$ and $-0.02$ (Me$_3$Ge- and Me$_3$Si-). Additional evidence for the proposed structure was obtained from homonuclear decoupling experiments. Thus, irradiation of the multiplet at $\delta 1.05-0.98$ (H-5) resulted in the simplification of the signals at $\delta 0.60$ (H-6a) and 0.48 (H-6b) to doublets ($J = 15$ Hz). Alternatively, when H-6a ($\delta 0.60$) was irradiated, H-5 ($\delta 1.05-0.98$) was simplified and at the same time H-6b ($\delta 0.48$) collapsed to a doublet ($J = 10.4$ Hz). Similarly, when H-6b ($\delta 0.48$) was irradiated, H-5 ($\delta 1.05-0.98$) was again simplified and H-6a ($\delta 0.60$) became a doublet ($J = 3.6$ Hz). In addition, HRMS analysis of 122 showed a signal at $m/z$ 292.1270, in good agreement with the calculated value of 292.1278 for C$_{12}$H$_{30}^{74}$GeO$_{28}^{28}$Si.

A possible rationale accounting for the formation of 122 is depicted in Scheme 25. It is conceivable that, during the early stages of the reaction, the hydrogen produced by the reduction of H$_2$PtCl$_6$·6H$_2$O to the active Pt(0) form of the catalyst (see Equation 11 and accompanying text in section 2.1.4.1) hydrogenated a small amount of 61, resulting in the
formation of the vinylsilane 123. Hydrogermylation of the latter substance could then generate 124. Hydrogermylation of alkenes\(^{65}\) are usually slow compared to the hydrogermylation of the corresponding alkynes\(^{46}\) under similar experimental conditions. However, it is possible that vinylsilanes such as 123 are better substrates towards Pt catalyzed addition of trimethylgermane (53) than the parent carbon analogues. Subsequent treatment of 124 with \(p\)-TsOH•H\(_2\)O in dichloromethane would afford 5-trimethylgermyl-6-trimethylsilylhexan-1-ol (122). In spite of the fact that no other by-products related in structure to 122 were isolated from the materials derived from hydrogermylation of the remainder of the substrates depicted in Table 2, it is reasonable to assume that by-products analogous to 122 were formed in trace amounts and were separated during the purification step.

The second by-product that arose from the synthesis of 92 was hex-5-en-1-ol (95), isolated as a mixture with an equal amount of 92 (=3\% combined). The structural assignment related to 95 was based on the examination of the vinylic region of the \(^1\text{H}\) NMR spectrum of this mixture. Thus, the spectrum exhibited the following distinctive signals: a one-proton doublet of doublets of triplets (\(J = 17.0, 10.2\) and 6.8 Hz) at \(\delta 5.79\), a one-proton doublet of doublets (\(J = 17.0\) and 2.0 Hz) at \(\delta 4.99\) and a one-proton doublet of doublets (\(J = 10.2\) and 2.0 Hz) at \(\delta 4.94\). Presumably, hex-5-en-1-ol (95) is produced by protiodemetallation of one of the isomers generated in trace amounts during the hydrogermylation of 61 (for a complete discussion of an identical transformation see section 2.1.4.3.4, p 57 ff.).
Secondly, the preparation of 2-trimethylgermyldodec-1-ene (116) from 1-trimethylsilyldodec-1-yne (64) (Table 2, entry 3) also yielded a small amount (~1.5%) of the corresponding monosubstituted alkene, dodec-1-ene (113). The $^1$H NMR data for this compound are consistent with that reported earlier (see Equation 14 and the accompanying discussion in section 2.1.4.3.4, p 57 ff.). Although the corresponding alk-1-enes were not isolated from the hydrogermylations of the other 1-trimethylsilylalk-1-ynes depicted in Table 2, it can be assumed that the alk-1-enes were generated in trace amounts in all cases and were separated during the purification procedures.

Thirdly, during the transformation of 72 into the product 120 (Table 2, entry 7) the cyclopentene alkene function underwent isomerization. The fact that compound 72 had undergone isomerization was established as follows. GLC analysis of the crude hydrogermylation mixture indicated the presence of one major component. $^1$H NMR spectroscopic analysis of this crude mixture showed that the cyclopentene alkene function of this component had isomerized during the course of the hydrogermylation. This conclusion was based on the examination of the vinylic region of the spectrum which exhibited a one-proton singlet at $\delta$ 5.82 and a one-proton triplet ($J \approx$2 Hz) at $\delta$ 5.33. The singlet ($\delta$ 5.82) was assigned to the vinylic proton geminal to the Me$_3$Si- group in 125a (Scheme 26), whereas the triplet ($\delta$ 5.33) was assigned to the cyclopentene vinylic proton.
During a duplicate experiment, periodic GLC analyses of aliquots of the hydrogermylation mixture of 72 suggested that the starting material also underwent isomerization, to 125b (Scheme 26). After 2 h at room temperature, an aliquot of the reaction mixture was withdrawn. After isolation and purification, GLC and $^1$H NMR spectroscopic analyses of the unreacted 1-trimethylsilylalk-1-yne indicated the presence of two compounds. The vinylic region of the $^1$H NMR spectrum indicated three one-proton signals: $\delta$ 5.73–5.70 (m), $\delta$ 5.67–5.64 (m), 5.33 (t, $J = \approx 2$ Hz). The triplet at $\delta$ 5.33 was attributed to 125b whereas the two multiplet were from 72. After 8 h at room temperature, the hydrogermylation of 72 and 125b was essentially complete. GLC analysis of an aliquot of the mixture at this time indicated that 125 and 125a were present in a 1:12 ratio. TLC analysis of this mixture revealed that it would not be possible to separate 125 from 125a by conventional chromatography. The reaction mixture was therefore allowed to stir at room temperature for an additional 13 h (total of 21 h), at which time the isomerization of 125 into 125a was essentially complete (125:125a 1:30). Protodesilylation of the latter mixture under standard conditions yielded...
essentially pure 120.

Scheme 27

Scheme 27 depicts a pathway, analogous to that proposed by Harrod and Chalk\textsuperscript{49,51} for the isomerization of alkenes by group VIII metal hydrides complexes, that can account for the isomerization of 125 into 125a. Thus, coordination of the active form of the catalyst 80 to the cyclopentene alkene function of 125 would generate the π-complex 126. Oxidative addition of trimethylgermane (53) would give 127, which can subsequently undergo hydrogen transfer to form the alkyl platinate 128. The latter can loose the newly incorporated elements, hydrogen and platinum, but via a different pathway to produce the isomerized π-complex 129. Decomplexation and reductive elimination of trimethylgermane (53) regenerates the catalyst 80 and yields 125a. Although the isomerization of 125 to 125a is a rather facile process, at
no point in this study was the isomerization of the vinylgermane function of the products 92, 115–121 in Table 2 (p 66) ever observed. The isomerization of alkenes using group VIII metals hydrides is a well known process.49,51,66,67

The hydrogermylation of substituted alkenes through reductive elimination of alkyl platinates such as 128 to produce 128a (Scheme 27) under these experimental conditions, although possible, is a slow process65 compared to the hydrogermylation of alkyne functions.

\[
\begin{align*}
\text{X} & \equiv \text{SiMe}_3 & \rightarrow \text{X} \equiv \text{GeMe}_3 \\
(X = \text{Cl, Br, OAc, OSiMe}_3) & & (X = \text{Cl, Br, OAc, OH})
\end{align*}
\]

A perusal of the structures of the 2-trimethylgermylalk-1-enes depicted in Table 2 (p 66) reveals that none of the products are functionalized at the allylic position. This is not coincidental. Although several attempts were made to hydrogermylate propargylic substrates (Equation 16), reaction under standard conditions always gave rise to complex mixtures. Examination of the \(^1\text{H}\) NMR spectrum of the crude reaction mixtures revealed that while the corresponding allylic products \((X = \text{Cl, Br, OAc, OH})\) were present, they were always accompanied by significant amounts of several by-products. Attempts to isolate and characterize these by-products proved unsuccessful. Investigations into the use of this method for the synthesis of 2-trimethylgermylalk-1-enes bearing an allylic functional group were therefore abandoned.

2.1.5.1\ CHARACTERISTIC SPECTRAL DATA OF 2-TRIMETHYLGERMYLALK-1-ENES

The 2-trimethylgermylalk-1-enes prepared in this study possess a number of representative features which are correlated in their spectral data. Table 3 summarizes the charac-
teristic IR, $^1$H and $^{13}$C NMR data of compounds 92 and 115–121.

The carbon–carbon double bond stretching frequency of the 2-trimethylgermylalk-1-enes appears around 1606 cm$^{-1}$ for most compounds in Table 3, whereas it appears at 1599 cm$^{-1}$ for 118 (entry 5). The carbon–carbon double bond stretching frequencies of the 2-trimethylgermylalk-1-enes (≈1606 cm$^{-1}$) is somewhat lower than those of the corresponding carbon analogs, for which the expected frequencies would be around 1660–1630 cm$^{-1}$.68
Table 3: Characteristic Spectral Data of 2-Trimethylgermylalk-1-enes 92, 115–121

![Diagram](image)

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>( \nu \text{ C=C} )</th>
<th>( \delta \text{ ppm} )</th>
<th>( \delta \text{ ppm} )</th>
<th>( \delta \text{ ppm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( \nu \text{ C=C} )</td>
<td>H-a(^d)</td>
<td>H-b(^d)</td>
<td>Me(_3)Ge-</td>
</tr>
<tr>
<td>1</td>
<td>HO(CH(_2)_4) 92</td>
<td>1606</td>
<td>5.49</td>
<td>5.16</td>
<td>0.18</td>
</tr>
<tr>
<td>2</td>
<td>HO(CH(_2)_2) 115</td>
<td>1606</td>
<td>5.61</td>
<td>5.32</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>n-C(_{10})H(_21) 116</td>
<td>n/a</td>
<td>5.48</td>
<td>5.14</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>Cl(CH(_2)_3) 117</td>
<td>1607</td>
<td>5.53</td>
<td>5.22</td>
<td>0.20</td>
</tr>
<tr>
<td>5</td>
<td>Ph 118</td>
<td>1599</td>
<td>5.84</td>
<td>5.47</td>
<td>0.29</td>
</tr>
<tr>
<td>6</td>
<td>Me(_3)GeC(=CH(_2))(CH(_2)_2) 119</td>
<td>1607</td>
<td>5.52</td>
<td>5.18</td>
<td>0.20</td>
</tr>
<tr>
<td>7</td>
<td>c-C(_5)H(_7)(CH(_2)_2) 120</td>
<td>1606</td>
<td>5.51</td>
<td>5.33</td>
<td>0.20</td>
</tr>
<tr>
<td>8</td>
<td>Me(_3)GeCO(CH(_2)_2) 121</td>
<td>n/a</td>
<td>5.44</td>
<td>5.17</td>
<td>0.19</td>
</tr>
</tbody>
</table>

\( ^a \) 400 MHz, CDCl\(_3\). \( ^b \) 75 MHz, CDCl\(_3\). \( ^c \) in cm\(^{-1}\). \( ^d \) These assignments were made by correlation with the \(^1\)H NMR NOE difference experiments performed on 92 (see text). \( ^e \) c-C\(_5\)H\(_7\)(CH\(_2\)_2) = \[Chemical\] Image

The \(^1\)H NMR spectra of the 2-Trimethylgermylalk-1-enes display three distinctive signals: the two alkenyl proton resonances due to H-a and H-b as well as the singlets due to the methyl protons from the Me\(_3\)Ge- group. The protons H-a and H-b give rise to doublets with a small mutual coupling constant (=2.5 Hz). Since the H-a and H-b signals could not be assigned on the sole basis of their chemical shifts and coupling constants, \(^1\)H NMR NOE difference experiments were performed on 5-Trimethylgermylhex-5-en-1-ol (92).
Irradiation of the signal at $\delta$ 5.49 (H-a) generated an enhancement at $\delta$ 5.16 (H-b) as well as at $\delta$ 2.19 (allylic methylene protons). Alternatively, when the allylic methylene protons were irradiated ($\delta$ 2.19) an enhancement was observed at $\delta$ 5.49 (H-a) and at $\delta$ 0.18 ($\text{Me}_3\text{Ge}$-). These experiments demonstrate that H-a is the alkenyl proton trans to the $\text{Me}_3\text{Ge}$- group. When the signal at $\delta$ 5.16 (H-b) was irradiated, a signal enhancement was observed at $\delta$ 5.49 (H-a) and at $\delta$ 0.18 ($\text{Me}_3\text{Ge}$-). Furthermore, irradiation of the signal at $\delta$ 0.18 ($\text{Me}_3\text{Ge}$-) caused the signals at $\delta$ 5.16 (H-b) and at $\delta$ 2.19 (allylic methylene protons) to be enhanced. The latter experiments establish that the alkenyl proton H-b and the $\text{Me}_3\text{Ge}$- are cis to each other.

The assignments of H-a and H-b for the compounds 115–121 depicted in Table 3 were made by correlation with the data obtained from the $^1$H NMR NOE difference experiments for 5-trimethylgermylhex-5-en-1-ol (92). The signals for H-a, the protons trans to the $\text{Me}_3\text{Ge}$- group, appear between $\delta$ 5.61–5.44, whereas the resonances derived from the protons H-b, (cis to the $\text{Me}_3\text{Ge}$- group) appear between $\delta$ 5.33–5.14. The signals of H-a and H-b are somewhat deshielded in 1-phenyl-1-trimethylgermylethene (118) (entry 5). Thus, for 118, H-a appears at $\delta$ 5.84, whereas H-b resonates at $\delta$ 5.47. The protons of the $\text{Me}_3\text{Ge}$- group for the compounds depicted in Table 3 appear as a singlet between $\delta$ 0.18–0.20, except for 118 in which the $\text{Me}_3\text{Ge}$- protons resonate at $\delta$ 0.29.
Each of the $^{13}$C NMR spectra of the 2-trimethylgermylalk-1-enes depicted in Table 3 also exhibit three distinctive signals: the resonances due to the two alkenyl carbons C-1 and C-2 and the signal derived from the methyl carbons of the Me$_3$Ge- group. The signals from the terminal alkenyl carbons (C-1) appear within the region $\delta$ 125–121, whereas the C-2 alkenyl carbons give rise to resonances between $\delta$ 155 and 150. In each case, the alkenyl carbons C-1 and C-2 were assigned by examination of the intensity of their signals in the $^{13}$C NMR spectra. The alkenyl carbon C-1 bearing two protons exhibits a more intense signal, due to a faster relaxation,$^{69}$ than the adjacent alkenyl carbon C-2, which has no attached protons. The signals of the methyl carbons of the Me$_3$Ge- group in the $^{13}$C spectra appears near $\delta$ –1.8, except for compound 118 which exhibits the corresponding signal at $\delta$ –1.1.
2.1.6 CONCLUSIONS

The aim of this study was to develop a method that would allow the efficient preparation of diversely functionalized 2-trimethylgermylalk-1-enes from the corresponding 1-trimethylsilylalk-1-yynes.

The 1-trimethylsilylalk-1-yynes are easily prepared from the corresponding alk-1-yynes in high yield. 1-Trimethylsilylalk-1-yynes serve as good substrates for the H\textsubscript{2}PtCl\textsubscript{6}\cdot6H\textsubscript{2}O catalyzed addition of Me\textsubscript{3}GeH to the carbon–carbon triple bond. Although the regioselectivity of this type of addition was generally only moderate (=12:1), this lack of selectivity turned out to be of no consequence.

The isomers of general structure I–IV were formed as a result of the hydrogermylation of the 1-trimethylsilylalk-1-yynes. The major component produced from this transformation was isomer I, whereas isomer II was the second most abundant. Isomers III and IV were generated in trace amounts.

Isomers I and III upon treatment with p-TsOH\cdotH\textsubscript{2}O in dichloromethane undergo
protodesilylation to afford the 2-trimethylgermylalk-1-ene. Isomer II, when treated under identical experimental conditions, undergoes a 1,2 Me₃Ge- shift followed by protodesilylation to also produce the 2-trimethylgermylalk-1-ene. Isomer IV undergoes sequential protodegermylation and protodesilylation to the corresponding alk-1-ene when treated with p-TsOH•H₂O in dichloromethane.

This two-step procedure for the conversion of 1-trimethylsilylalk-1-ynes into 2-trimethylgermylalk-1-enes is experimentally simple, accommodates a variety of functional groups and provides the products regioisomerically pure.
2.2 SYNTHESIS OF ACYLTRIMETHYLGERMANES VIA ADDITION OF (TRI-METHYLGERMYL)COPPER(I)-DIMETHYL SULFIDE TO ACYL ELECTR- PHILES AND THEIR OLEFINATION TO 2-TRIMETHYLGERMYLALK-1-ENES

2.2.1 INTRODUCTORY REMARKS

As outlined in the Proposals (section 1.3, p 13 ff.), an approach to the synthesis of 2-trimethylgermylalk-1-enes, alternative to that involving catalyzed hydrogermylation of 1-trimethylsilylalk-1-yne, was envisaged. This method, due to the inherent nature of the transformations involved, would preclude the formation of regioisomers.

It was postulated that olefination of acyltrimethylgermanes of general structure 37 (Equation 17) would generate the corresponding 2-trimethylgermylalk-1-enes 26. The first objective of this study was, therefore, to prepare the key acyltrimethylgermanes. A survey of the literature revealed that a number of methods have been reported for the preparation of acyltrialkylgermanes. A brief summary of these methods, which can be separated into four categories, is presented in the following pages.

\[
\begin{array}{c}
\text{37} \quad \overset{\text{olefination}}{\longrightarrow} \quad \text{26} \\
\end{array}
\]  
(17)

In the first category, Yamamoto and co-workers\textsuperscript{70} reported the preparation of the acyltrimethylgermanes 131 (Equation 18) and 132 (Equation 19) via a Pd-catalyzed acyl substitution with hexamethyldigermane (130). In this protocol, treatment of benzoyl chloride (Equation 18) with Me\textsubscript{3}GeGeMe\textsubscript{3} (130) and a catalytic amount of Pd(0) at 90 °C for 6.5 h provided the acyltrimethylgermane 131 in 69% yield. Alternatively, when octanoyl chloride
(Equation 19) was allowed to react under similar conditions, the acyltrimethylgermane 132 was generated in 15% after 38 h at 90 °C. These results suggest that an aryloyl chloride is a much better substrate in this reaction than an alkanoyl chloride. Therefore, this method appears to be unsuitable for the preparation of diversely functionalized acyltrimethylgermanes.

\[
\begin{align*}
\text{O} & \quad \text{Pd, 90 °C, 6.5 h} & \quad \text{O} \\
\text{Ph} & \quad \text{Me}_3\text{GeGeMe}_3 & \quad \text{Ph} \\
\text{Cl} & \quad \text{130} & \quad \text{GeMe}_3 \\
\text{131 (69%)} &
\end{align*}
\]

\[
\begin{align*}
\text{O} & \quad \text{Pd, 90 °C, 38 h} & \quad \text{O} \\
\text{C}_7\text{H}_{15} & \quad \text{Me}_3\text{GeGeMe}_3 & \quad \text{C}_7\text{H}_{15} \\
\text{Cl} & \quad \text{130} & \quad \text{GeMe}_3 \\
\text{132 (15%)} &
\end{align*}
\]

In the second category, a sequence of transformations generates a precursor to the acyltrimethylgermane in which the carbonyl group is masked. Hydrolysis of the latter function affords the final product. An example utilizing this strategy is depicted in Equation 20. Soderquist and Hassner\textsuperscript{71} reported that lithiation of the dienol ether 133 with tert-butyllithium, followed by treatment of the corresponding lithio species with Me\textsubscript{3}GeCl, afforded 134 in 53% yield. Subsequent hydrolysis of the latter in a dilute hydrochloric acid–acetone mixture, gave the unsaturated acyltrimethylgermane 135 in 69% yield.

\[
\text{CH}_2=\text{CHCHO} \quad 1) \quad \text{t-BuLi} \\
\text{OMe} \quad 2) \quad \text{Me}_3\text{GeCl} \\
\text{H} \quad \text{GeMe}_3 \\
\text{133} \quad \text{134 (53%)} \\
\text{HCl / H}_2\text{O} \quad \text{acetone} \\
\text{OMe} \quad \text{GeMe}_3 \\
\text{GeMe}_3 \\
\text{133} \quad \text{134 (53%)}
\]

A similar approach was used by Brook and co-workers.\textsuperscript{72} Thus, when the dithiane 136 (Equation 21) was deprotonated with n-butyllithium and the resulting lithio species treated with Et\textsubscript{3}GeBr, the substituted dithiane 137 was obtained in 70% yield. Subsequent
hydrolysis of 137 with HgCl₂ in aqueous THF heated at reflux afforded the acyltriethylgermane 138 in 63% yield.

\[
\begin{align*}
\text{136} & \xrightarrow{1) n-BuLi} \text{137 (70\%)} & \xrightarrow{2) \text{Et₃GeBr}} \text{138 (63\%)}
\end{align*}
\]

**Equation 22** depicts a somewhat different, but related, method devised by Yoshida and co-workers⁷³ for the synthesis of acyltrimethylgermanes. In this protocol, the methyl ether 139 was treated with n-butyllithium and the resultant carbanion was allowed to react with decanal to form the alkoxide 140. The latter underwent in situ carbon–silicon bond cleavage (Peterson reaction)⁷⁴ to form the enol ethers 141 (E/Z = 1:1) in 76% yield. This compound was subsequently hydrolyzed in aqueous acid to generate the acyltrimethylgermane 142 in 96% yield.

\[
\begin{align*}
\text{OMe} & \xrightarrow{1) n-BuLi} \text{R-SiMe₃} & \xrightarrow{2) RCHO} \text{141 (76\%)} & \xrightarrow{\text{H₂O}^+} \text{142 (96\%)}
\end{align*}
\]

\( R = C_9H_{19} \)

Although the above three methods (**Equations 20–22**) have, collectively, the potential to accomplish the preparation of a certain number of acyltrialkylgermanes, in poor to good overall yield, they all suffer from one limitation: a carbanion intermediate is formed at one stage during the sequence of transformations. The strongly nucleophilic and basic nature of such anions seriously limits the type of functional groups that could be introduced into the acyltrialkylgermanes.
In the third category, a Claisen rearrangement is used to introduce the carbonyl function of the acyltrimethylgermane. Yamamoto and co-workers have shown that when the enol ether 143 (Equation 23) was treated with a chiral organoaluminum reagent, rearrangement occurred to generate the optically active acyltrimethylgermane 144 in 73% yield (91% ee). Although this method provides good yields of the acyltrimethylgermane, it is limited to the preparation of γ,δ-enones.

\[
\begin{align*}
143 & \xrightarrow{\text{AlR}_3^*} 144 \\
& \text{(73%)}
\end{align*}
\]

Finally, the fourth category of transformations employs the addition of a trialkylgermyllithium reagent to a carbonyl electrophile (Equation 24). In this protocol, described by Sato and co-workers, treatment of 3-phenylpropanal with triethylgermyllithium afforded the alcohol 145 in 76% yield. Oxidation of the latter compound using the conditions of Swern generated the acyltriethylgermane 146 in 72% yield.

\[
\begin{align*}
\text{PhCHO} & \xrightarrow{\text{Et}_3\text{GeLi}} \text{OH} \\
145 & \xrightarrow{\text{Swern oxidation}} 146 \\
& \text{(76%)} \quad \text{(72%)}
\end{align*}
\]

A similar method was developed by Vyazankin and co-workers, in which triethylgermyllithium was allowed to react with N,N-dialkylamides (Equation 25). For example, when the amide 147 was treated with triethylgermyllithium, the acyltriethylgermane 138 was obtained in 88% yield. While the methods depicted in Equations 24 and 25 provide the acyltriethylgermanes in good yields, they require the use of the triethylgermyllithium reagent, which is a powerful nucleophile. The use of such a nucleophile again limits the possible
functional groups that can be present in the acyltrialkylgermanes.

\[
\text{Ph}\text{NEt}_2 + \text{Et}_3\text{GeLi} \rightarrow \text{Ph}\text{GeEt}_3
\] (25)

Vyazankin and co-workers\(^7\) noted that adding one equivalent of copper(I) iodide to triethylgermyllithium formed the corresponding copper reagent. When the (triethylgermyl)copper(I) reagent (148) (Equation 26) was allowed to react with benzoyl chloride at \(-30 \, ^\circ C\), the acyltriethylgermane 138 was formed in 60\% yield. No additional examples were reported.

\[
\text{PhCl} + \text{Et}_3\text{GeCu} \rightarrow \text{Ph}\text{GeEt}_3
\] (26)

In light of this report, the utilization of a trimethylgermylcopper(I) reagent to effect the synthesis of acyltrimethylgermanes from acyl chlorides became appealing (Equation 27). Three questions then arose: i) can the nucleophilic substitution of an acyl chloride be effected by a reagent such as trimethylgermylcopper(I) (36) to generate the corresponding acyltrimethylgermane 37, ii) is the transformation general, or to put it in other words, what functional groups, other than phenyl, are compatible with this transformation (since functionalization of the side chain was imperative) and iii) can the method be developed to provide the required products in high yields? The trimethylgermylcopper(I) reagent would certainly be a milder nucleophile than the corresponding lithio species and the experimental conditions would then possibly allow for a large number of functional groups to be present in the acyl chloride.
In order to prepare the trimethylgermylcopper(I) reagent (36), the corresponding lithio species 149 was required (Equation 28). Examination of the literature revealed that only two methods had been reported for the preparation of the trimethylgermyllithium (149).

Bulten and Noltes\textsuperscript{79} have developed a general method for the preparation of solutions of \( R_3 \text{GeM} \) (\( R = \text{alkyl}, M = \text{alkali metal} \)) in HMPA. For example, in this protocol, when a solution of hexamethyldigermane (130) in HMPA was stirred with lithium metal, trimethylgermyllithium (149) was generated quantitatively (Equation 29).

Alternatively, a solution of \( \text{Me}_3\text{GeLi} \) (149) has been prepared in pentane by Schumann and co-workers.\textsuperscript{80} Thus, when bis(trimethylgermyl)mercury (150) was treated with lithium metal in pentane, \( \text{Me}_3\text{GeLi} \) (149) was obtained in 12\% yield (Equation 30).

Although both methods (Equations 29 and 30) depicted above provide access to \( \text{Me}_3\text{GeLi} \) (149), the latter protocol, using bis(trimethylgermyl)mercury (150) (Equation 30), is clearly unsatisfactory due to the low yield of this reaction. On the other hand, the former method (Equation 29) generates \( \text{Me}_3\text{GeLi} \) (149), quantitatively, in HMPA solution. The
Me₃GeLi (149) needs to be converted in situ into the corresponding copper reagent 36 (see Equation 28) for reaction with the acyl chloride. Since most reactions involving organo-copper reagents are performed in ethereal solvents, it was unclear what effects a co-solvent such as HMPA would have on the outcome of the reaction. The details of the investigations describing the development of a new method for the in situ preparation of the Me₃GeLi (149) in ethereal solvent will be disclosed in the following section.

Finally, if the preparation of the acyltrimethylgermanes proved successful, their conversion into the corresponding 2-trialkylgermylalk-1-enes remained to be accomplished. Examination of the literature revealed that one example of olefination of an acyltriphenylgermane into the corresponding 2-triphenylgermylalk-1-ene had been reported. Brook and Fieldhouse⁸¹ reported that when the acyltriphenylgermane 151 was treated with Ph₃P=CH₂, the 2-triphenylgermylalk-1-ene 152 was formed in 72% yield (Equation 31). Would the olefination depicted in Equation 31 be applicable to the synthesis of the functionalized acyltrimethylgermanes?

The answer to the questions raised in the previous pages, as well as the details of the investigations leading to the successful preparation of the acyltrimethylgermanes of general
structure 37 and their olefination into the 2-trimethylgermylalk-1-enes 26 will be disclosed in the following sections.
2.2.2 SYNTHESIS OF ACYLTRIMETHYLGERMANES FROM ACYL CHLORIDES

2.2.2.1 SYNTHESIS OF ACYL CHLORIDES

In order to prepare the acyl chlorides required for this study, the commercially available carboxylic acids 153–156 shown in Table 4 were chosen as substrates. Table 4 also contains a summary of the conversions of 153–156 into the acyl chlorides 157–160.

Table 4: Preparation of the Acyl Chlorides 157–160

<table>
<thead>
<tr>
<th>Entry</th>
<th>Alkanoic Acid</th>
<th>Acyl Chloride</th>
<th>Yield (%)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>C$<em>9$H$</em>{19}$COOH</strong> (153)</td>
<td><strong>C$<em>9$H$</em>{19}$C=OCl</strong> (157)</td>
<td>98</td>
</tr>
<tr>
<td>2</td>
<td><strong>C$_6$H$_5$CH$_2$COOH</strong> (154)</td>
<td><strong>C$_6$H$_5$CH$_2$C=OCl</strong> (158)</td>
<td>94</td>
</tr>
<tr>
<td>3</td>
<td><strong>C$<em>9$H$</em>{19}$CH$_2$COOH</strong> (155)</td>
<td><strong>C$<em>9$H$</em>{19}$CH$_2$C=OCl</strong> (159)</td>
<td>92</td>
</tr>
<tr>
<td>4</td>
<td><strong>C$<em>9$H$</em>{19}$CH$_3$C=OCl</strong> (156)</td>
<td><strong>C$<em>9$H$</em>{19}$CH$_3$C=OCl</strong> (160)</td>
<td>62$^b$</td>
</tr>
</tbody>
</table>

$^a$ Yield of isolated and purified product. $^b$ Volatile liquid.

The acyl chlorides depicted in Table 4 were prepared in a straightforward manner.
The synthesis of decanoyl chloride (157), for example, was accomplished as follows. Decanoic acid (153) was treated with an excess of thionyl chloride and the reaction mixture was heated at reflux for 0.5 h. After the mixture had been cooled to room temperature, removal of the excess thionyl chloride under reduced pressure, followed by distillation (bulb-to-bulb 70–80 °C/0.06 Torr, lit. bp 94–96 °C/5 Torr) of the residue, afforded decanoyl chloride (157) in 98% yield as a clear colorless oil.

The acyl chlorides 158–160 were obtained in a manner identical with that outlined above. Although the acyl chlorides 157 and 159 are commercially available, they were prepared by this simple method since the corresponding alkanoic acids were readily available.

Two additional substrates were prepared for this study. The first, 5-trimethylsilylpent-4-ynoyl chloride (164), was synthesized from pent-4-yn-1-ol (161) via a three step sequence, reported by Utimoto and co-workers, as outlined in Scheme 28. A solution of 161 in ethereal solvent was treated sequentially with a solution of n-butyllithium and chlorotrimethylsilane. Subsequent treatment of the mixture with aqueous acid afforded 5-trimethylsilylpent-4-yn-1-ol (162) in 74% yield. Jones oxidation of the latter compound gave 5-trimethylsilylpent-4-ynoic acid (163) in 66% yield. This alkanoic acid was treated with thionyl chloride, as described above, to generate 5-trimethylsilylpent-4-ynoyl chloride (164) in 97% yield.
The second substrate, ((4-methoxybenzyl)oxy)acetyl chloride (167), was prepared via a three step sequence from (4-methoxyphenyl)methanol (165), via a procedure reported by Kukla and Fortunato for a related substrate, as outlined in Scheme 29. Treatment of an excess of (4-methoxyphenyl)methanol (165) with sodium hydride, followed by addition of ethyl bromoacetate and subsequent saponification of the mixture, resulted in the formation of ((4-methoxybenzyl)oxy)acetic acid (166) in 59% yield. Attempted formation of the acyl chloride 167 from 166 under standard conditions (thionyl chloride, reflux) failed to generate the expected product. However, a procedure to form acyl chlorides under neutral conditions reported by Beeby proved to be successful. Thus, treatment of the alkanoic acid 166 with a solution of potassium hydroxide in ethanol formed a precipitate, the potassium salt of 166, which was collected by suction filtration. This salt was subsequently treated with oxalyl chloride in dry diethyl ether to afford ((4-methoxybenzyl)oxy)acetyl chloride (167) in 92% yield from 166.
Scheme 29

2.2.2.2 PREPARATION OF TRIMETHYLGERMYLLITHIUM (149) AND (TRIMETHYLGERMYL)-
copper(I)—DIMETHYL SULFIDE (168)

As outlined in the Introductory Remarks (section 2.2.1, p 81 ff.), the reported procedures\textsuperscript{79,80} for the preparation of Me\textsubscript{3}GeLi (149) were unsuitable for the present study. Following initial investigations performed by Dr. Guy Plourde from our laboratories, attention was focused on the development of a satisfactory preparation of Me\textsubscript{3}GeLi (149) for which the following protocol was devised. Treatment of 1.4 equivalents of Me\textsubscript{3}GeH (53) in THF (=0.18 M solution of Me\textsubscript{3}GeH in THF) with 1.2 equivalents of a solution of tert-butyllithium at 0 °C for 20 min afforded a clear and colorless solution (Scheme 30). Indications that metallation had occurred were the rapid disappearance of the initial yellow color, caused by the presence of tert-butyllithium in THF.
In order to assess the extent of the formation of the lithium reagent 149, it was decided to form the corresponding copper reagent 168 in situ, and to treat the latter with an acyl electrophile (Scheme 30). Thus, addition of 1.2 equivalents of CuBr•Me₂S to the resultant solution of Me₃GeLi (149) ("inverse" addition method) at -78 °C, followed by stirring of this mixture at -78 °C for 45 min, resulted in the formation of a dark red–black solution of the reagent Me₃GeCu•Me₂S (168). This solution was treated with one equivalent of decanoyl chloride (157), the resultant reaction mixture was stirred for an hour at -78 °C, and then was treated with an aqueous solution of NH₄Cl–NH₄OH. Isolation and flash chromatography of the crude product afforded two compounds.

The first component to be eluted, obtained in 22% yield, was assigned structure 169 (Scheme 30). This assignment was established as follows. The ¹H NMR (400 MHz, CDCl₃) spectrum of 169 exhibited a one-proton doublet of doublets (J = 14.0 and 6.3 Hz) at δ 7.27, a one-proton doublet of doublets (J = 14.0 and 1.5 Hz) at δ 4.86, a one-proton doublet of
doublets \((J = 6.3 \text{ and } 1.5 \text{ Hz})\) at \(\delta 4.54\), a two-proton triplet \((J = 7.5 \text{ Hz})\) at \(\delta 2.36\), a two-proton multiplet at \(\delta 1.69-1.57\), a twelve-proton multiplet at \(\delta 1.37-1.16\) and a three-proton broad triplet \((J = 6.8 \text{ Hz})\) at \(\delta 0.86\). Additional evidence supporting the structural assignment of 169 was provided by the IR spectrum, which showed an intense band at 1758 cm\(^{-1}\) \((\nu \text{ C=O})\) as well as a band of medium intensity at 1648 cm\(^{-1}\) \((\nu \text{ C=C})\) for the vinyl ester function. These frequencies are in good agreement with the literature values for this type of functionality.\(^{87}\)

The second compound to be eluted, obtained in 31\% yield, was decanoyltrimethylgermane (170) (Scheme 30). The \(^1\)H NMR (400 MHz, CDCl\(_3\)) spectrum of 170 exhibited a two-proton triplet \((J = 7.4 \text{ Hz})\) at \(\delta 2.58\), a two-proton multiplet at \(\delta 1.57-1.45\), a twelve-proton multiplet at \(\delta 1.39-1.18\), a three-proton broad triplet \((J = 6.8 \text{ Hz})\) at \(\delta 0.85\) and a nine-proton singlet at \(\delta 0.31\). Additional evidence to support the structural assignment of 170 was provided by the IR spectrum, which contained a band at 1658 cm\(^{-1}\) for the acyl germane carbonyl, as well as from HRMS analysis, which exhibited a signal at \(m/z\) 274.1354, in good agreement with the calculated value of 274.1352 for C\(_{13}\)H\(_{28}\)\(^{74}\)GeO.

Two conclusions were drawn from the experiment depicted in Scheme 30. First, the formation of an acyltrimethylgermane via addition of (trimethylgermyl)copper(I)–dimethyl sulfide reagent (168) to an acyl chloride is possible and, second, the lithiation of Me\(_3\)GeH (53) is incomplete, as indicated by the generation of the by-product 169 (vide infra).
Scheme 31 depicts a rationale for the formation of 169. Under the reaction conditions used for the lithiation of Me₃GeH (53), competitive fragmentation of THF by tert-butyl-lithium generates isobutane, ethylene and the lithium enolate of acetaldehyde 171. Upon addition of decanoyl chloride (157) to the reaction mixture, 171 reacts with 157 to form 169 and lithium chloride.

Further investigations pertaining to the lithiation of Me₃GeH (53) showed that deprotonation of 53 with tert-butyllithium did not occur when diethyl ether was used as solvent or in the absence of solvent (neat), even at room temperature. Moreover, the formation of Me₃GeLi (149) in THF with tert-butyllithium did not occur below -15 °C. In order to minimize the fragmentation of THF by tert-butyllithium, the lithiation of Me₃GeH (53) was performed in the presence of a minimum amount of THF.

Thus, treatment of a cold (-10 °C) solution of 1.2 equivalents of trimethylgermane
(53) in anhydrous THF (=2.5 M solution of Me₃GeH in THF) with 1 equivalent of a solution of tert-butyllithium for 5 min generated Me₃GeLi (149) (Equation 32). In order to quantify the yield of 149, the following experiment was carried out. The solution of Me₃GeLi (149) was diluted with additional anhydrous THF (final concentration of ≈0.6 M with respect to Me₃GeH), was then cooled to −78 °C and 1.2 equivalents of 1-bromodecane were added. After the mixture had been warmed to room temperature, an internal standard was added and the mixture was treated with water and diethyl ether (for complete experimental details, see section 3.3.2.1.3, p 222). GLC analysis of an aliquot of this mixture revealed that 1-trimethylgermyldecane (172) (Equation 32), and, therefore, Me₃GeLi (149), had been formed in >97% yield. The remaining 2–3% can be accounted for by the formation of the lithium enolate of acetaldehyde 171 (vide infra), from the reaction of tert-butyllithium with THF (see Scheme 31).

\[
\begin{align*}
\text{Et}_3\text{GeH} & \xrightarrow{\text{t-BuLi, TMEDA}} \text{Et}_3\text{GeLi} \\
\text{THF, 0 °C, 30 min} & \\
(33)
\end{align*}
\]

During the course of these investigations, a preparation of Et₃GeLi via a related method was reported by Takeda and co-workers.⁸⁹ In this protocol, a solution of one equivalent of Et₃GeH in THF (=1 M solution of Et₃GeH in THF) was treated with 1.1 equivalents of a solution of tert-butyllithium and 1.1 equivalents of N,N,N',N'-tetramethyl-ethylenediamine (TMEDA) at 0 °C for 30 min to generate Et₃GeLi quantitatively (Equation 33). However, since 1.1 equivalents of tert-butyllithium were employed, it is likely that under the experimental conditions used the excess reagent (=0.1 equivalent) reacted with THF to form the lithium enolate of acetaldehyde 171 (see Scheme 31).
2.2.2.3 SYNTHESIS OF ACYLTRIMETHYLGERMANES

As described in the previous section, the formation of decanoyltrimethylgermane (170) via reaction of Me₃GeCu•Me₂S (168) with decanoyl chloride (157) is possible. Further investigations were therefore conducted with the same substrate, in an effort to improve the yield of decanoyltrimethylgermane (170) using this method.

Table 5: Optimization of the Experimental Conditions for the Formation of Decanoyltrimethylgermane (170)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Me₃GeCu•Me₂S (equiv)</th>
<th>T (°C), time</th>
<th>Yield⁸</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2ᵇᶜᵈ</td>
<td>-78, 1 h</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td>1.2ᶜ</td>
<td>-78, 0.3 h</td>
<td>43</td>
</tr>
<tr>
<td>3</td>
<td>1.2ᶜ</td>
<td>-78, 1 h; -30, 2 h</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>2.2ᶜ</td>
<td>-78, 1 h; -30, 2 h</td>
<td>71</td>
</tr>
<tr>
<td>5</td>
<td>1.5ᵈ</td>
<td>-78, 1 h; -30, 2 h</td>
<td>81</td>
</tr>
<tr>
<td>6</td>
<td>1.5ᵈ / 1 equiv TMSCl</td>
<td>-78, 1 h; -30, 2 h</td>
<td>92</td>
</tr>
</tbody>
</table>

⁸ Yield of isolated and purified product. ᵇ Preparation of Me₃GeLi under non-optimum conditions; see text. ᵇ Preparation of Me₃GeCu•Me₂S via the “inverse” addition method; see text. ᵇ Preparation of Me₃GeCu•Me₂S via the “normal” addition method; see text.

Table 5 summarizes the key experimental modifications that rendered the transformation synthetically useful. Entry 1 displays the initial conditions under which 170 was synthesized in 31% yield. This experiment was used to assess the formation of the Me₃GeLi
(149), via lithiation of Me₃GeH (53), in a solution of THF (see previous section, 2.2.2.2, p 92 ff.). In entry 2, the product was obtained in 43% yield, using the optimized preparation of Me₃GeLi (149) (see previous section, 2.2.2.2, p 92 ff.) and, consequently, the formation of the by-product 169 was significantly reduced.

The yield of decanoyltrimethylgermane (170) increased dramatically when the reaction mixture was stirred for 1 h at -78 °C, was warmed to -30 °C and then was allowed to stir for an additional 2 h (entry 3). This result suggests that the conversion of the starting material is incomplete at -78 °C. When the same experiment was repeated using 2.2 equivalents of Me₃GeCu•Me₂S (168) (entry 4), the yield of 170 was unchanged.

In entry 5, the reagent Me₃GeCu•Me₂S (168) was prepared via a protocol very similar to that previously described, but with a minor modification. In entries 1–4, the reagent 168 was obtained by addition of solid CuBr•Me₂S to a solution of the Me₃GeLi (149) in THF at -78 °C (“inverse” addition), as described in the previous section (2.2.2.2, p 92 ff.). In entry 5, the Me₃GeCu•Me₂S (168) was prepared by addition, via a cannula, of a solution of reagent 149 to a suspension of CuBr•Me₂S in THF at -78 °C (“normal” addition). While both of these preparations should generate the same reagent, Me₃GeCu•Me₂S (168), it appears that the “normal” addition method affords decanoyltrimethylgermane (170) in better yield than the “inverse” addition method. The fact that 1.5 equivalents of 168 were used in entry 5, as opposed to 1.2 equivalents, is not likely to be responsible for the increase in yield (compare, for example, entries 3 and 4). The reasons for the different yields of 170 obtained from the
preparation of Me$_3$GeCu•Me$_2$S (168) via the “normal” and “inverse” addition methods remain unclear.

\[ \text{Li}^+ \text{O}^- \xrightarrow{\text{TMSCI}} \text{OTMS} + \text{LiCl} \quad (34) \]

The optimized preparation of Me$_3$GeLi (149) virtually eliminated the formation of 169 in the reactions summarized in entries 2–5. However, GLC analyses of aliquots of the crude reaction mixtures indicated the presence of trace amounts (≈2–3%) of 169. In an attempt to completely inhibit the production of 169, the solution of Me$_3$GeCu•Me$_2$S (168) was treated with chlorotrimethylsilane prior to the addition of decanoyl chloride (157). It was anticipated that the lithium enolate of acetaldehyde 171 would react with chlorotrimethylsilane to form the corresponding vinyl silyl ether 173 (Equation 34) and, consequently, suppress the formation of 169. Thus, when a solution of 1.5 equivalents of Me$_3$GeCu•Me$_2$S (168) and one equivalent of chlorotrimethylsilane in THF were treated with one equivalent of the acyl chloride 157 (Table 5, entry 6), decanoyltrimethylgermane (170) was obtained in 92% yield. GLC analysis of an aliquot of the crude reaction mixture showed that the formation of 169 had been completely inhibited. Additional benefits of chlorotrimethylsilane as an additive in the formation of acyltrimethylgermanes in high yield will be discussed on the following pages. The experimental conditions outlined above to prepare decanoyltrimethylgermane (170) proved to be general for a number of diversely functionalized acyl chlorides, as described below.

The acyl chlorides 157, 158, 174, 167, 175–177, 159, 160 and 164 depicted in Table 6 were chosen as substrates. Table 6 also contains a summary of the conversions of these
acyl chlorides into the acyltrimethylgermanes 170, 178–185 and 114.

The substrates 157–160, 164 and 167 were synthesized as described previously (section 2.2.2, p 89 ff.), whereas the acyl chlorides 174–177 are commercially available.
Table 6: Preparation of the Acyltrimethylgermanes 170, 178–184 and 114

![Chemical reaction diagram]

1) Me₃GeCu•Me₂S

<table>
<thead>
<tr>
<th>Entry</th>
<th>Acyl Chloride</th>
<th>Acyltrimethylgermane</th>
<th>Yield (%)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>without additive</td>
</tr>
<tr>
<td>1</td>
<td>C₆H₁₉</td>
<td>C₅H₁₉</td>
<td>81</td>
</tr>
<tr>
<td>2</td>
<td>[Chemical structure]</td>
<td>[Chemical structure]</td>
<td>n/a</td>
</tr>
<tr>
<td>3</td>
<td>c-C₆H₁₁</td>
<td>c-C₆H₁₁</td>
<td>n/a</td>
</tr>
<tr>
<td>4</td>
<td>4-MeO(C₆H₄)CH₂OCH₂</td>
<td>4-MeO(C₆H₄)CH₂OCH₂</td>
<td>n/a</td>
</tr>
<tr>
<td>5</td>
<td>(C₆H₅)CH₂OCH₂</td>
<td>(C₆H₅)CH₂OCH₂</td>
<td>63&lt;sup&gt;e,f&lt;/sup&gt;</td>
</tr>
<tr>
<td>6</td>
<td>Cl(CH₂)₄</td>
<td>Cl(CH₂)₄</td>
<td>n/a</td>
</tr>
<tr>
<td>7</td>
<td>Cl(CH₂)₂</td>
<td>Cl(CH₂)₂</td>
<td>23</td>
</tr>
<tr>
<td>8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>ClCO(CH₂)₄</td>
<td>Me₃GeCO(CH₂)₄</td>
<td>33&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>9&lt;sup&gt;e,i&lt;/sup&gt;</td>
<td>HC≡C(CH₂)₂</td>
<td>Me₃SiC≡C(CH₂)₂</td>
<td>0&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>10</td>
<td>Me₃SiC≡C(CH₂)₂</td>
<td>Me₃SiC≡C(CH₂)₂</td>
<td>n/a</td>
</tr>
</tbody>
</table>

<sup>a</sup> Yield of isolated and purified product.  
<sup>b</sup> 1.5 equiv of Me₃GeCu•Me₂S, prepared via the "normal" addition method, were used unless otherwise stated.  
<sup>c</sup> One equiv of TMSCl was used unless otherwise stated.  
<sup>d</sup> 2.5–4 equiv of TMSBr were used.  
<sup>e</sup> Me₃GeCu•Me₂S was prepared via the "inverse" addition method.  
<sup>f</sup> 2.2 equiv of Me₃GeCu•Me₂S were used.  
<sup>g</sup> 2.5 equiv of pyridine and 2 equiv of dry methanol were added prior to work-up.
The results summarized in entry 1 of Table 6 for the synthesis of decanoyltrimethylgermane (170) have already been discussed in detail (see Table 5, p 97 and accompanying text). The synthesis of (cyclopent-2-en-1-yl)acetyltrimethylgermane (178) (entry 2) was accomplished in the following manner. A cold (-78 °C) solution of Me₃GeCu‚Me₂S (168) (1.5 equiv) prepared via the "normal" addition method (vide supra) in dry THF (≈0.18 M) was treated sequentially with chlorotrimethylsilane (1 equiv) and (cyclopent-2-en-1-yl)acetyl chloride (158). The reaction mixture was stirred at -78 °C for 1 h, then was warmed to -30 °C and was allowed to stir for an additional 2 h. After isolation and purification of the crude product, (cyclopent-2-en-1-yl)acetyltrimethylgermane (178) was obtained in 88% yield as a light yellow oil.

The remainder of the acyltrimethylgermanes listed in Table 6, except for 185, were synthesized from the corresponding acyl chlorides in a manner similar to or identical with that outlined above. In an effort to further understand the (additional) benefits of using chlorotrimethylsilane as additive, a number of selected substrates were also allowed to react with Me₃GeCu›Me₂S (168) in the absence of chlorotrimethylsilane, whereas two of these substrates were also allowed to undergo reaction with 168 in the presence of bromotrimethylsilane as additive.

The acyl chloride 174, which bears a "bulky" cyclohexyl group α to the carbonyl, was smoothly converted into the corresponding acyltrimethylgermane under standard experimental conditions (entry 3).

This transformation is also compatible with benzylic ethers. ((4-Methoxybenzyl)oxy)-acetyl chloride (167) (entry 4) was converted into ((4-methoxybenzyl)oxy)acetyltrimethyl-
germane (180) in 82% yield. On the other hand, treatment of (benzylloxy)acetyl chloride (175) (entry 5) with Me₃GeCu•Me₂S (168) prepared via the “inverse” addition method (vide supra) without additive afforded (benzylloxy)acetyltrimeethylgermane (181) in 63% yield. Alternatively, when 175 was allowed to react with Me₃GeCu•Me₂S (168) (prepared via the “normal” addition method) in the presence of chlorotrimethylsilane, the yield of 181 was increased to 89%. Attempted conversion of 175 into 181 with 2.2 equivalents of Me₃GeCu•Me₂S (168) (prepared via the “inverse” addition method) using bromotrimethylsilane as additive failed to produce any of the “expected” product.

5-Chloropentanoyl chloride (176) (entry 6) was efficiently (90% yield) converted into 5-chloropentanoyltrimeethylgermane (182) under standard experimental conditions. Reaction of 3-chloropropanoyltrimeethylgermane (177) with reagent 168 (entry 7) in the absence of additive afforded 3-chloropropanoyltrimeethylgermane (183) in only 23% yield. On the other hand, treatment of 177 with 168 in the presence of 4.5 equivalents of chlorotrimethylsilane gave the acyltrimethylgermane 183 in 35% yield. When the same reaction was performed using 2.2 equivalents of Me₃GeCu•Me₂S (168) and bromotrimethylsilane (4.5 equiv) as additive, 183 was generated in 58% yield.

When adipoyl chloride (159) (entry 8) was treated with three equivalents of Me₃GeCu•Me₂S (168) (prepared via the “inverse” addition method) without chlorotrimethylsilane, the structurally novel hexanediolbis(trimethylgermane) (184) was obtained in 33% yield. On the other hand, when 159 was allowed to react with 168 (3 equiv) in the presence of two equivalents of chlorotrimethylsilane, the product 184 was generated in 92% yield. Since 159 possesses two acyl chloride functions which can undergo reaction with 168, the
amounts of reagents for this substrate were doubled.

Treatment of pent-4-ynoyl chloride (160) (entry 9) with approximately one equivalent of \( \text{Me}_3\text{GeCu} \cdot \text{Me}_2\text{S} \) (168) at \(-78^\circ\text{C}\) for 2.5–3 h, with or without chlorotrimethylsilane, failed to produce the expected pent-4-ynoyltrimethylgermane (185). Remarkably, reaction of 168 with 5-trimethylsilylpent-4-ynoyl chloride (164), the \( \text{Me}_3\text{Si}\)-substituted analog of 160, under standard conditions generated 5-trimethylsilylpent-4-ynoyltrimethylgermane (114) in 82\% yield (entry 10).

The reactions summarized in entries 5, 7, 8 and 9 of Table 6 require additional comments. During the purification of (benzyloxy)acetyltrimethylgermane (181) (entry 5), formed by reaction of 175 with \( \text{Me}_3\text{GeCu} \cdot \text{Me}_2\text{S} \) (168) \textit{in the absence} of chlorotrimethylsilane, a by-product was isolated in \(-2.5\%\) yield. This material was assigned structure 186, \((E)-2\text{-benzyloxy-1-(benzyloxy)acetoxy-1-trimethylgermylene}\).

![Structure 186](image)

The assignment was based on the following data. The \(^1\text{H NMR}\) (400 MHz, \(\text{CDCl}_3\)) spectrum exhibited a ten-proton multiplet at \(\delta\) 7.52–7.23 (aromatic protons), a one-proton singlet at \(\delta\) 5.87 (vinyllic proton), three two-proton singlets at \(\delta\) 4.84, 4.62 and 4.19 as well as a nine-proton singlet at \(\delta\) 0.27 (\(\text{Me}_3\text{Ge}\)-). Additional evidence was provided by the IR spectrum of 186 which showed a strong band at 1760 cm\(^{-1}\) (v C=O), together with HRMS
analysis which showed a signal at $m/z$ 416.1043, a value identical with that calculated for $C_{21}H_{26}^{74}GeO_4$. To establish the geometry of the alkene function, $^1H$ NMR NOE difference experiments were performed. Thus, irradiation of the singlet at $\delta$ 5.87 (vinyllic proton) caused the resonances at $\delta$ 4.84 (benzylic protons) and 0.27 (Me$_3$Ge-) to be enhanced. Alternatively, when the Me$_3$Ge- signal ($\delta$ 0.27) was irradiated, the vinyllic proton ($\delta$ 5.87) was enhanced. These experiments establish the cis relationship between the vinyllic proton and the Me$_3$Ge-group.

A possible rationale accounting for the formation of 186 is depicted in Scheme 32. Thus, during the course of the reaction of Me$_3$GeCu•Me$_2$S (168) with 181, the reagent 168 may have served as a base to form a small amount of the copper enolate 187, together with Me$_3$GeH (53), from the acyltrimethylgermane 181. This enolate could then undergo O-acylation with 175, still present in the reaction mixture, to afford the enol acetate 186.

\[ R - CO - GeMe_3 \quad \overset{Me_3GeCu•Me_2S}{\text{168}} \quad \rightarrow \quad R - CH = CH - GeMe_3 \]

\[ R = C_6H_5CH_2O \]

\[ \rightarrow \quad R - CH = CH - GeMe_3 + \quad Me_3GeH \]

\[ \quad \overset{O}{\text{175}} \quad \rightarrow \quad R - CO - R \quad + \quad CuCl \]

\[ \quad \text{Scheme 32} \]
When (benzyloxy)acetyl chloride (175) was allowed to react with 168 (Table 6, entry 5) in the presence of bromotrimethylsilane, none of the expected acyltrimethylgermane 181 was formed. The only product that was isolated from the complex mixture was assigned structure 188, 2-benzyloxy-1-trimethylsilyloxy-1,1-bis(trimethylgermyl)ethane, which was obtained in 52% yield.

This assignment was based on the following data. The $^1$H NMR (400 MHz, CDCl$_3$) spectrum exhibited a 5-proton multiplet at $\delta$ 7.45–7.35, a two-proton singlet at $\delta$ 4.43, a two-proton singlet at $\delta$ 3.77, an eighteen-proton singlet at $\delta$ 0.15 as well as a nine-proton singlet at $\delta$ 0.07. Additional evidence to support the structural assignment of 188 was provided from HRMS analysis which indicated a signal at $m/z$ 443.0686 ($M - CH_3$)$^+$. This data is consistent with the calculated value of 443.0682 for C$_{17}$H$_{33}$Ge$_{74}$GeO$_{28}$Si.

![Scheme 33](image-url)
Scheme 33 depicts a possible reaction pathway that rationalizes the formation of 188. During the course of the reaction of 181 with 168, bromotrimethylsilane could have acted as a Lewis acid to form (reversibly) the oxonium ion 189 from the initially formed acyltrimethylgermane 181, thus enhancing the electrophilic character of the carbonyl carbon. Subsequent nucleophilic addition of the Me₃GeCu•Me₂S (168) to 189 would generate the trimethylsilyl ether 188.

Scheme 34

The data derived from the reaction of 168 with 175 (Table 6, entry 5) also shed some light on the possible role of chlorotrimethylsilane as additive. A mechanistic pathway rationalizing the role of chlorotrimethylsilane in the formation of the acyltrimethylgermane 181 is depicted in Scheme 34. The small amount of the (postulated) copper enolate 187 produced from the acyltrimethylgermane 181 could be trapped efficiently by chlorotrimethylsilane, as opposed to reacting with the acyl chloride substrate (compare Scheme 34 with Scheme 32), to produce the enol trimethylsilyl ether 190. After complete conversion of the acyl chloride into product, treatment of the reaction mixture with aqueous NH₄Cl/NH₄OH would hydrolyze...
to regenerate the product \( \text{181} \). Several attempts to isolate and characterize the (postulated) enol trimethylsilyl ether \( \text{190} \) proved unsuccessful.

\[
\begin{align*}
\text{I} & : \quad \text{Ph}_3\text{Ge} = \text{R} \\
\text{II} & : \quad \text{Ph}_3\text{Ge}^+ \text{R} \\
\text{III} & : \quad \text{Ph}_3\text{Ge}^+ \cdot \text{C}_- \text{R} \\
\text{IV} & : \quad \text{Ph}_3\text{Ge}^+ \cdot \text{O}^\delta^- - \text{R}
\end{align*}
\]

The notable tendency of acyltrimethylgermanes to undergo enolization (or enolate anion formation) may be understood by examining the properties associated with the acylgermane function. Yates and Agolini\(^\text{90}\) have shown that benzoyltriphenylgermane (\( \text{I} \) (\( \text{R} = \text{phenyl} \)) and related substances have an increased amount of electron density at the carbonyl oxygen, compared to the carbon analog. This increase was attributed to a larger contribution of the canonical form (\( \text{II} \)), due to a strong inductive effect of germanium\(^\text{91}\) on the carbonyl carbon–germanium bond. Trotter and Harrison\(^\text{92}\) suggested that a third resonance form (\( \text{III} \)), in which there is no formal bond between the germanium and the carbonyl carbon, may contribute to the structural representation of the acylgermanes. The contribution from this resonance form was suggested by a single crystal X-ray crystallographic analysis of a related substance (\( \text{R} = \text{Me} \)), in which the carbonyl carbon–germanium bond is abnormally long at 2.01 Å, compared to the phenyl carbon–germanium bond length of 1.95 Å. Thus, it was suggested that compounds such as acetyltriphenylgermane (\( \text{R} = \text{Me} \)) would be best illustrated by (\( \text{IV} \)), which represents both the increased electron availability at the carbonyl carbon and the lengthened germanium–carbonyl carbon bond.\(^\text{92}\)
During the chromatographic purification of 3-chloropropanoyltrimethylgermane (183), synthesized by reaction of reagent 168 with 3-chloropropanoyl chloride (177) in the absence of any additive (Table 6, entry 7, p 101), an additional fraction, which was constituted of two compounds, was obtained in 10% yield. An analytically pure sample of each component was obtained by subjecting this mixture to reversed phase HPLC (C_{18} Bondapak 10 μm, 25 mm × 100 mm column, 3:2 acetonitrile–water). The first component to be eluted (retention time 53 min) was assigned structure 191, (E)- or (Z)-1-(3-chloropropanoyl)oxy)-1,3-bis(trimethylgermyl)prop-1-ene. The structural assignment of 191 was based on the following data. The $^1$H NMR (400 MHz, CDCl$_3$) spectrum exhibited a one-proton triplet ($J = 9.2$ Hz) at δ 5.80 (H-2), a two-proton triplet ($J = 6.8$ Hz) at δ 3.75 (H-3'), a two-proton triplet ($J = 6.8$ Hz) at δ 2.82 (H-2'), a two-proton doublet ($J = 9.2$ Hz) at δ 1.58 (H-3), as well as two nine-proton singlets at δ 0.30 and 0.16 for the Me$_3$Ge- groups. Additional evidence to support the structural assignment of 191 was provided by the IR spectrum, which showed a band at 1741 cm$^{-1}$ (ν C=O). In addition, HRMS analysis indicated a signal at $m/z$ of 383.9985 which is in good agreement with the calculated value of 383.9967 for C$_{12}$H$_{25}$Cl$_7$Ge$_2$O$_2$.

The second component to be eluted (retention time 57 min) was assigned structure 192, (Z)- or (E)-1-((3-chloropropanoyl)oxy)-1,3-bis(trimethylgermyl)prop-1-ene. This assignment was based on the following data. The $^1$H NMR (400 MHz, CDCl$_3$) spectrum exhibited a one-proton triplet ($J = 8.8$ Hz) at δ 5.34 (H-2), a two-proton triplet ($J = 6.6$ Hz)
at δ 3.77 (H-3'), a two-proton triplet (J = 6.6 Hz) at δ 2.86 (H-2'), a two-proton doublet (J = 8.8 Hz) at δ 1.64 (H-3), as well as two nine-proton singlets at δ 0.25 and 0.13 for the Me₃Ge-groups. Additional evidence was provided by the IR spectrum which showed a band at 1742 cm⁻¹ (ν C=O). In addition, HRMS analysis indicated a signal at m/z 383.9975, which is in good agreement with the calculated value of 383.9967 for C₁₂H₂₅³⁵Cl⁷⁴Ge₂O₂.

Although the geometry of the alkene functions of compounds 191 and 192 was not established, it is obvious from the data presented above that 191 and 192 are constitutionally identical and must, therefore, be geometric isomers. Compounds 191 and 192 are, in part, structurally related to 186 and thus, are likely to be formed via a pathway similar to that depicted in Scheme 32 (p 105) for the production of 186. In addition, 191 and 192 possess an allylic Me₃Ge- group which results from the substitution of the chloride by a Me₃Ge-function.

When 3-chloropropanoyl chloride (177) was allowed to react with Me₃GeCu•Me₂S (168) in the presence of bromotrimethylsilane (Table 6, entry 7, p 101), an additional fraction was isolated during the purification of 3-chloropropanoyltrimethylgermane (183). GLC and \(^1\)H NMR analyses showed that this fraction was constituted of a mixture of compounds, but contained a major (=75%) component. The major component was assigned structure 193, 3-chloro-1,1-bis(trimethylgermyl)-1-(trimethylsilyloxy)propane. The structural assignment of 193 was based on the following data. The \(^1\)H NMR (400 MHz, CDCl₃) spectrum exhibited a two-proton multiplet at δ 3.55–3.48, a two-proton multiplet at δ 2.40–2.32, an eighteen-
proton singlet at δ 0.20 as well as a nine-proton singlet at δ 0.12. The compound 193 is structurally related to 188 and thus, it is postulated to be formed via a pathway identical with that depicted in Scheme 33 (p 106) for the production of 188.

During the purification of hexanedioylbis(trimethylgermane) (184), synthesized by treatment of adipoyl chloride (159) with Me₃GeCu•Me₂S (168) in the absence of any additive (Table 6, entry 8, p 101), a by-product was isolated. This component, which was assigned structure 194, 2-hydroxy-2-trimethylgermyl(cyclopentanecarbonyl)trimethylgermane, was obtained in 6% yield. This assignment was based on the following data. The ¹H NMR (400 MHz, CDCl₃) spectrum exhibited a one-proton broad signal (exchanges with D₂O) at δ 3.92 (-OH), a one-proton doublet of doublets (J = 11.0 and 8.6 Hz) at δ 3.11, a two-proton multiplet at δ 2.10–1.95, a two-proton multiplet at δ 1.85–1.75, a one-proton multiplet at δ 1.72–1.61, a one-proton multiplet at δ 1.59–1.52, a nine-proton singlet at δ 0.34 as well as a nine-proton singlet at δ 0.10. Additional evidence was provided by the IR spectrum which showed bands at 3464 (-OH) and 1634 cm⁻¹ (ν C=O), together with HRMS analysis which indicated a signal at m/z 348.0359, in good agreement with the calculated value of 348.0365 for C₁₂H₂₅⁷²Ge⁷⁴GeO₂.

A mechanistic pathway accounting for the formation of 194 is depicted in Scheme 35. During the course of the formation of 184, the Me₃GeCu•Me₂S (168) may have served as a base to generate a small amount of the copper enolate 195 and Me₃GeH (53) from the
compound 184. This enolate can undergo ring closure to the copper alkoxide 196, which upon work-up produces the alcohol 194. In order to gain further information on the production of 194, the following experiment was performed. A solution of 184 (1 equiv) in dry methanol was treated with sodium methoxide (1 equiv) at room temperature, and then was allowed to stir for 15 h. TLC analysis of an aliquot of the mixture indicated that the conversion of 184 into 194 was essentially complete (>95%). However, due to the small scale on the reaction (=10 mg), isolation and purification of the crude oil obtained afforded the alcohol 194 in 30% yield. The spectral data derived from 194 were identical with that reported above.

![Scheme 35](image)

Scheme 35

The experiments described above, along with the data derived from the reaction of substrates 175 and 177 with reagent 168 (Table 6, entries 5 and 7, p 101), indicate that the acyltrimethylgermanes partially undergo enolate formation under the experimental conditions
used. This enolization results in the formation of by-products through O-acylation or aldol condensation in the case of the reaction in which adipoyl chloride (159) is the substrate.

Treatment of pent-4-ynoyl chloride (160) (Table 6, entry 9, p 101) with approximately one equivalent of Me₃GeCu•Me₂S (168), with or without chlorotrimethylsilane, failed to produce pent-4-ynoyltrimethylgermane (185). Pent-4-ynoyl chloride (160) was chosen as a substrate to investigate the possibility of effecting a chemoselective reaction of the Me₃GeCu•Me₂S (168) with an acyl chloride function in the presence of another potentially reactive function (alk-1-yne) within the same substrate. Although neither of the two attempts afforded the expected acyltrimethylgermane 185, isolation and characterization of the by-products formed under these experimental conditions gave some insights into the chemoselectivity of the overall reaction.

Treatment of pent-4-ynoyl chloride (160) with Me₃GeCu•Me₂S (168) in the presence of chlorotrimethylsilane gave a complex mixture of products. The crude oil obtained was subjected to flash column chromatography on silica gel to afford two components. The first compound, which was assigned structure 197, 2-(bis(trimethylgermyl)methyl)-1-((trimethylsilyl)oxy)cyclobutene, was obtained in 10% yield. The structural assignment was based on the following data. The ¹H NMR (400 MHz, CDCl₃) spectrum exhibited a two-proton triplet (J = 3.2 Hz) at δ 2.47, a two-proton triplet (J = 3.2 Hz) at δ 1.89, a one-proton singlet at δ 1.29, a
nine-proton singlet at δ 0.16 as well as an eighteen-proton singlet at δ 0.15. Additional evidence was provided by the IR spectrum which showed a band at 1681 cm$^{-1}$ (v C=O). HRMS analysis of 197 indicated a signal at $m/z$ 390.0660, which is consistent with the calculated value of 390.0655 for C$_{14}$H$_{92}$Ge$_{74}$GeO$_{28}$Si.

The second component, which was assigned structure 198, 4-trimethylgermylpent-4-enamide, was isolated in 42% yield. This assignment was based on the following data. The $^1$H NMR (400 MHz, CDCl$_3$) spectrum exhibited a two-proton broad signal at δ 5.62–5.40, a one-proton doublet ($J = 2.0$ Hz) at δ 5.53, a one-proton doublet ($J = 2.0$ Hz) at δ 5.22, a two-proton multiplet at δ 2.53–2.47, a two-proton multiplet at δ 2.37–2.30 as well as a nine-proton singlet at δ 0.21. Additional evidence was provided by the IR spectrum of 198 which showed two broad bands at 3365 and 3193 cm$^{-1}$ (-NH$_2$) along with another band at 1667 cm$^{-1}$ (v C=O). HRMS analysis of this component indicated a signal at $m/z$ 217.0513, in good agreement with the calculated value of 217.0522 for C$_8$H$_7$GeNO.

A rationale accounting for the formation of 2-(bis(trimethylgermyl)methyl)-1-((trimethylsilyl)oxy)cyclobutene (197) and 4-trimethylgermylpent-4-enamide (198) is depicted in Scheme 36. Thus, in one possible pathway, cis addition$^{93-95}$ of Me$_3$GeCu-Me$_2$S (168) to the alkyne function of 160 results in the formation of the vinylcopper species 199, which bears the Me$_3$Ge- group on the terminal carbon of the alkene function (path a). The adduct 199 can undergo ring closure to generate the cyclobutenone 200. Conjugate addition of
Me₃GeCu•Me₂S (168) to the enone function of 200 generates the copper enolate 201 which can subsequently react with chlorotrimethylsilane to form the enol trimethylsilyl ether 197.

Scheme 36

Alternatively, cis addition of Me₃GeCu•Me₂S (168) to the alkyne function of 160, in a manner regio-opposite to that producing 199, results in the formation of the vinylcopper species 202 (path b) in which the Me₃Ge- group is located on the internal carbon of the alkene.
function. Upon work-up (aqueous NH₄Cl/NH₄OH), nucleophilic substitution of the acyl chloride function by NH₃ and protonation of the vinylcopper species affords 198.

![Chemical Structures](image)

The reaction mixture derived from treatment of pent-4-ynoyl chloride (160) with Me₃GeCu•Me₂S (168) in the absence of chlorotrimethylsilane was treated with pyridine and dry methanol immediately prior to work-up. This treatment would transform any unreacted acyl chloride into the corresponding methyl ester, as opposed to a primary amide (vide supra), and consequently, would facilitate the isolation and purification procedures. The crude oil (a complex mixture) obtained was subjected to flash column chromatography to afford three fractions.

¹H NMR spectroscopic, GLC and GLC-MS analyses of the first fraction (obtained in 9% yield) suggested that it was constituted of two components, which were assigned structures 203, 5-(3-trimethylgermylbut-3-en-1-yl)-4-(bis(trimethylgermyl)methyl)pent-4-eno-5-lactone (=80% by GLC analysis) and 204, (E)-5-(4-trimethylgermylbut-3-en-1-yl)-4-(bis(trimethylgermyl)methyl)pent-4-eno-5-lactone (=20%). These assignments were based on the following data and by correlation with the ¹H NMR spectroscopic data derived from 205 (vide infra). The ¹H NMR (400 MHz, CDCl₃) spectrum showed four signals in the δ 5.95–5.15 region integrating for a total of two protons: δ 5.92 (m, 0.2H, H-3"–204), δ 5.83 (d,
0.2H, $J = 18.2$ Hz, H-$4^\prime$-204), $\delta$ 5.52 (d, 0.8H, $J = 1.8$ Hz, H-$4^\prime$-203) and $\delta$ 5.22 (d, 0.8H, $J = 1.8$ Hz, H-$4^\prime$-203); then a two-proton triplet ($J = 3.2$ Hz, H-$3^\prime$-203 + 204) at $\delta$ 2.79, a four-proton multiplet at $\delta$ 2.60–2.38 (H-$1^\prime$ and H-$2^\prime$-203 + 204), a two-proton triplet ($J = 3.2$ Hz, H-$3^\prime$-203 + 204) at $\delta$ 2.08, a one-proton singlet at $\delta$ 1.34 (H-$1^\prime$-203 + 204) and three singlets in the $\delta$ 0.26–0.15 region integrating for a total of 27 protons. The doublet ($J = 18.2$ Hz) at $\delta$ 5.83 indicates a trans coupling of a 1,2-disubstituted alkene with the signal at $\delta$ 5.92 consistent with the proposed structure for 204. On the other hand, the doublets ($J = 1.8$ Hz) at $\delta$ 5.52 and 5.22 are characteristic of terminal alkenyl protons in the 2-trimethylgermylalk-1-ene moiety of 203. GLC-MS analysis showed that both components have a mass of 516, and the isotopic clusters are consistent with the calculated isotopic distribution for C$_{19}$H$_{38}$Ge$_3$O$_2$.

The second fraction (obtained in 16% yield) was constituted of a single component which was assigned structure 205, 5-(but-3-yn-1-yl)-4-(bis(trimethylgermyl)methyl)pent-4-eno-5-lactone. This assignment was based on the following data. The $^1$H NMR (400 MHz, CDCl$_3$) spectrum exhibited a two-proton triplet ($J = 3.0$ Hz) at $\delta$ 2.79 (H-2), a two-proton multiplet at $\delta$ 2.62–2.55 (H-$1^\prime$), a two-proton multiplet at $\delta$ 2.53–2.46 (H-$2^\prime$), a two-proton triplet ($J = 3.0$ Hz) at $\delta$ 2.06 (H-3), a one-proton triplet ($J = 2.6$ Hz) at $\delta$ 1.96 (H-$4^\prime$), a one-proton singlet at $\delta$ 1.34 (H-$1^\prime$) as well as an eighteen-proton singlet at $\delta$ 0.17 (Me$_3$Ge-).
These assignments were supported by the following decoupling experiments. Thus, irradiation of the triplet at $\delta$ 2.79 (H-2) resulted in the collapse of the signal at $\delta$ 2.06 (H-3) to a singlet. Similarly, irradiation of H-3 ($\delta$ 2.06) caused H-2 ($\delta$ 2.79) to collapse to a singlet. When the multiplet at $\delta$ 2.62–2.55 (H-1") was irradiated, the resonance at $\delta$ 2.53–2.46 (H-2") was simplified to a doublet ($J = 2.6$ Hz). Irradiation of the multiplet at $\delta$ 2.53–2.46 (H-2") caused the signals at $\delta$ 2.62–2.55 (H-1") and 1.96 (H-4") to collapse to singlets. Finally, when the triplet at $\delta$ 1.96 (H-4") was irradiated the multiplet at $\delta$ 2.53–2.46 (H-2") was simplified. Additional evidence was provided by the IR spectrum which showed bands at 3313 ($\nu$ alkynyl C-H), 2140 ($\nu$ C≡C) and 1757 cm$^{-1}$ ($\nu$ C=O), together with HRMS analysis which indicated a signal at $m/z$ 398.0521, in good agreement with the calculated value of 398.0522 for C$_{16}$H$_{28}$Ge$_{72}$GeO$_2$.

The third fraction, which consisted of a single component, was obtained in 4% yield and was assigned structure 206, methyl 4-trimethylgermylpent-4-enoate. This assignment was based on the data derived from the $^1$H NMR (400 MHz, CDCl$_3$) spectrum, which exhibits a one-proton doublet ($J = 2.0$ Hz) at $\delta$ 5.50, a one-proton doublet ($J = 2.0$ Hz) at $\delta$ 5.20, a three-proton singlet at $\delta$ 3.67, a four-proton multiplet at $\delta$ 2.52–2.39 as well as a nine-proton singlet at $\delta$ 0.22.
Scheme 37
Possible mechanistic pathways rationalizing the formation of compounds 203–206 are depicted in Scheme 37. Thus, in one possible pathway, cis addition of the reagent Me₃GeCuMe₂S (168) to the alkyne function of pent-4-ynoyl chloride (160) results in the formation of the vinylcopper species 199 (path a). Intermolecular acylation of the latter with 160 generates the enone 207, which can subsequently undergo further conjugate addition with Me₃GeCuMe₂S (168) to produce the copper enolate 208. This enolate can undergo intramolecular acyl substitution to form the six-membered ring lactone 205. Germycupration of the carbon–carbon triple bond of 205 affords the regioisomeric vinylgermanes 203 and 204 upon work-up.

The formation of methyl 4-trimethylgermylpent-4-enoate (206) can be rationalized via pathway b, depicted in Scheme 37. Addition of Me₃GeCuMe₂S (168) to the alkyne function of pent-4-ynoyl chloride (160) affords the vinylcopper species 202. Treatment of the latter intermediate with dry methanol prior to work-up affords methyl 4-trimethylgermylpent-4-enoate (206).

The data presented above, along with that derived from the reaction of pent-4-ynoyl chloride (160) with Me₃GeCuMe₂S (168) in the presence of chlorotrimethylsilane as additive (see Scheme 36, p 115), demonstrate somewhat surprisingly that reagent 168 adds preferentially, if not exclusively, to the alkyne moiety of a substrate bearing both a terminal alkyne and an acyl chloride function. Interestingly, when the alkynyl H was replaced by a Me₃Si-group, the chemoselectivity of addition of Me₃GeCuMe₂S (168) was completely reversed from that observed for 160, affording the “normal” addition product (compare entries 9 and 10 in Table 6, p 101).
2.2.2.4 CHARACTERISTIC SPECTRAL DATA OF ACYLTRIMETHYLGERMANES

The acyltrimethylgermanes prepared in this study exhibit a number of characteristic spectral features. Table 7 summarizes some of the IR, $^1$H and $^{13}$C NMR data derived from compounds 114, 170, 178–184.

Table 7: Characteristic Spectral Data of the Acyltrimethylgermanes 114, 170, 178–184

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>$\nu$ C=O</th>
<th>$^1$H$^a$</th>
<th>$^{13}$C$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Me$_3$SiC≡C(CH$_2$)$_4$</td>
<td>1660</td>
<td>0.33</td>
<td>242.9</td>
</tr>
<tr>
<td>2</td>
<td>n-C$<em>{8}$H$</em>{19}$</td>
<td>1658</td>
<td>0.31</td>
<td>245.9</td>
</tr>
<tr>
<td>3</td>
<td>$\alpha$-C$_5$H$_7$CH$_2$</td>
<td>1657</td>
<td>0.31</td>
<td>245.4</td>
</tr>
<tr>
<td>4</td>
<td>$\alpha$-C$<em>6$H$</em>{11}$</td>
<td>1654</td>
<td>0.31</td>
<td>247.2</td>
</tr>
<tr>
<td>5</td>
<td>4-MeO(C$_6$H$_4$)CH$_2$OCH$_2$</td>
<td>1667</td>
<td>0.32</td>
<td>244.8</td>
</tr>
<tr>
<td>6</td>
<td>(C$_6$H$_5$)CH$_2$OCH$_2$</td>
<td>1668</td>
<td>0.34</td>
<td>244.8</td>
</tr>
<tr>
<td>7</td>
<td>Cl(CH$_2$)$_4$</td>
<td>1657</td>
<td>0.32</td>
<td>244.9</td>
</tr>
<tr>
<td>8</td>
<td>Cl(CH$_2$)$_2$</td>
<td>1661</td>
<td>0.34</td>
<td>242.5</td>
</tr>
<tr>
<td>9</td>
<td>Me$_3$GeCO(CH$_2$)$_4$</td>
<td>1657</td>
<td>0.31</td>
<td>245.1</td>
</tr>
</tbody>
</table>

$^a$ 400 MHz, CDCl$_3$. $^b$ 75 MHz, CDCl$_3$. $^c$ $\text{c-C}_5\text{H}_7\text{CH}_2 = \begin{array}{c} \text{C} \\ \text{C} \end{array}$

The carbonyl stretching frequencies of the acyltrimethylgermanes depicted in Table 7
appear in the 1668–1654 cm\(^{-1}\) region. These absorptions are found at frequencies lower than those of the corresponding carbon analogs, for which the expected frequencies would be approximately 1730–1700 cm\(^{-1}\).\(^{96}\) The lowering in the carbonyl stretching frequencies of acylgermanes has been attributed to a strong inductive effect of the germanium atom, resulting in an increase in the electron density at the carbonyl oxygen.\(^{90,92}\)

![Chemical Structure](image)

The \(^1\)H NMR spectra of the acyltrimethylgermanes exhibit singlets for the Me\(_2\)Ge-group at approximately \(\delta 0.32\) for the compounds depicted in Table 7. The \(^{13}\)C spectra of the acyltrimethylgermanes display two distinctive signals. The resonances due to the carbonyl carbons appear within the region \(\delta 248–242\), and the signals derived from the methyl carbons of the Me\(_2\)Ge- groups appear near \(\delta -3.0\), except for compound 179, which exhibits the corresponding signal at \(\delta -2.2\). Finally, the acyltrimethylgermanes are pale yellow oils. This color is consistent with that of other reported acylgermanes and is due to the n–\(\pi^*\) transition of the carbonyl group occurring in the visible region.\(^{97}\) The shifted absorption, compared to the corresponding carbon analogs, has been rationalized in terms of inductive effects.\(^{97}\)
2.2.3 SYNTHESIS OF ACYLTRIMETHYLGERMANES FROM S-(PYRIDIN-2-YL) THIOESTERS

As described in section 2.2.2.3 (p 97 ff.), the reaction of acyl chlorides with \( \text{Me}_3\text{GeCu·Me}_2\text{S} \) (168) in the absence of an additive generally produced small amounts of enol ester by-products. These substances are thought to be produced by formation of enolate anions from the initial products (acyltrimethylgermanes), followed by \( O \)-acylation of these intermediates with the acyl chloride substrates.

\[
\text{O} \\
\text{R} \\
\text{R} \text{GeMe}_3 \\
\text{O}
\]

In an effort to circumvent the formation of such by-products, investigations were directed towards the conversion of \( S \)-(pyridin-2-yl) thioesters into acyltrimethylgermanes. It was hoped that the less reactive electrophilic substrates, \( S \)-(pyridin-2-yl) thioesters, would not form by-products resulting from \( O \)-acylation as readily as their acyl chlorides counterparts.

2.2.3.1 SYNTHESIS OF \( S \)-(PYRIDIN-2-YL) THIOESTERS

In order to prepare the \( S \)-(pyridin-2-yl) thioesters chosen for this study, the carboxylic acids 153, 156, 166 and 209 shown in Table 8 were employed as substrates. Table 8 also contains a summary of the conversion of the carboxylic acids 153, 156, 166 and 209 into the \( S \)-(pyridin-2-yl) thioesters 210–213. In particular, compound 211 was synthesized to deter-
mine whether the chemoselectivity of the reaction of Me₃GeCu•Me₂S (168) would be altered from that of the parent pent-4-ynoyl chloride (160) (exclusive addition on the alkyne function of 160; see Table 6, entry 9, p 101 and accompanying text). On the other hand, 213 was selected in an attempt to improve the efficiency of the synthesis of 3-chloropropanoyltrimethylgermane (183) (see Table 6, entry 7, p 101).

**Table 8: Preparation of the S-(Pyridin-2-yl) Thioesters 210–213**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Alkanoic Acid</th>
<th>S-(Pyridin-2-yl) Thioester</th>
<th>Yield (%)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C₉H₁₉COOH</td>
<td>C₉H₁₉S&lt;sub&gt;2&lt;/sub&gt;N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>C≡CHCOOH</td>
<td>C≡CHS&lt;sub&gt;2&lt;/sub&gt;N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>C₆H₄COOH</td>
<td>C₆H₄O&lt;sub&gt;2&lt;/sub&gt;S&lt;sub&gt;2&lt;/sub&gt;N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>83</td>
</tr>
<tr>
<td>4</td>
<td>ClC≡CHCOOH</td>
<td>ClC≡CHS&lt;sub&gt;2&lt;/sub&gt;N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>56&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Yield of isolated and purified product. <sup>b</sup> This compound decomposed readily when stored at room temperature.
The synthesis of S-(pyridin-2-yl) decanethioate (210) (Table 8, entry 1), for example, was accomplished in the following manner. A solution of decanoic acid (153) (1 equiv) in acetonitrile was treated sequentially with triphenylphosphine (=1.1 equiv) and 2,2'-disulfane-diyl-dipyridine98 (=1.1 equiv) and the resultant mixture was stirred for 1 h at room temperature. After isolation and purification of the crude product, S-(pyridin-2-yl) decanethioate (210) was obtained in 78% yield as a light yellow oil. The remainder of the S-(pyridin-2-yl) thioesters listed in Table 8 were prepared from the corresponding alkanoic acids in a manner identical with that outlined above.

2.2.3.2 SYNTHESIS OF ACYLTRIMETHYLGERMANES

Table 9 contains a summary of the conversion of the S-(pyridin-2-yl) thioesters 210, 212 and 213 into the acyltrimethylgermanes 170, 180 and 183. For example, the synthesis of decanoyltrimethylgermane (170) (entry 1) was accomplished in the following manner. A cold (~78 °C) stirred solution of Me₃GeCu·Me₂S (168) (=1.5 equiv), prepared via the "inverse" addition method (see section 2.2.2.2, p 92 ff.), in dry THF was treated with one equivalent of S-(pyridin-2-yl) decanethioate (210). The reaction mixture was stirred at ~78 °C for 1 h, then was warmed to ~30 °C and was allowed to stir for an additional 2 h. After isolation and purification of the crude product, decanoyltrimethylgermane (170) was obtained in 64% yield, along with 10% of 210 which was recovered unchanged.

The acyltrimethylgermanes 180 and 183 listed in Table 9 were prepared in a manner identical with that outlined above from the corresponding S-(pyridin-2-yl) thioesters. Table 9 also summarizes the yields of acyltrimethylgermanes obtained from the related conversions using the corresponding acyl chlorides as substrates (taken from Table 6, p 101).
Decanoyltrimethylgermane (170) (entry 1) was synthesized in 64% yield from S-(pyridin-2-yl) decanethioate 210, whereas 170 was obtained in 81% yield from the corresponding acyl chloride 157 under similar experimental conditions. Treatment of 212 with Me₃GeCu•Me₂S (168) resulted in the formation of 180 in 62% yield (entry 2). S-(Pyridin-2-yl) 3-chloropropanethioate 213 (entry 3) was converted into 3-chloropropanoyltrimethylgermane (183) in 23% yield, a yield identical with that obtained from a similar reaction involving 3-chloropropanoyl chloride (177) as the substrate. Finally, treatment of S-(pyridin-2-yl) pent-4-yethioate (211) (entry 4) gave none of the expected pent-4-ynoyltrimethylgermane (185), an outcome analogous with that observed from pent-4-ynoyl chloride (160).

Purification of the crude oil (complex mixture) obtained from the reaction of 211 with 168

Table 9: Preparation of the Acyltrimethylgermanes 170, 180 and 183

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>Acyltrimethylgermane</th>
<th>Yield (%)a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>n-C₉H₁₉</td>
<td>170</td>
<td>64</td>
</tr>
<tr>
<td>2</td>
<td>4-MeO(C₆H₄)CH₂OCH₂</td>
<td>180</td>
<td>62</td>
</tr>
<tr>
<td>3</td>
<td>Cl(CH₂)₂</td>
<td>183</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>HC≡C(CH₂)₂</td>
<td>185</td>
<td>0</td>
</tr>
</tbody>
</table>

a Yield of isolated and purified product. b The Me₃GeCu•Me₂S (168) reagent was prepared via the “inverse” addition method (see section 2.2.2.2, p 92 ff.). c Yields taken from Table 6, p 101.
provided the products 198 and 205 in small amounts. The spectral data of these materials were identical with those reported in section 2.2.2.3, p 97 ff.

The data presented above suggest that, for the synthesis of acyltrimethylgermanes by reaction with Me₃GeCu•Me₂S (168), acyl chlorides are better substrates than S-(pyridin-2-yl) thioesters, at least under the experimental conditions investigated. Moreover, many acyl chlorides are commercially available or are more readily prepared than the S-(pyridin-2-yl) thioesters from the parent carboxylic acids.
2.2.4 OLEFINATION OF ACYLTRIMETHYLGERMANES TO 2-TRIMETHYLGERMYLALK-1-ENES

As outlined in the Introductory Remarks (section 2.2.1, p 81 ff.), following the successful development of a method for the preparation of acyltrimethylgermanes, the olefination of the latter compounds into the corresponding 2-trimethylgermylalk-1-enes remained to be accomplished.

Brook and Fieldhouse\textsuperscript{81} reported the conversion of an acyltriphenylgermane to the corresponding 2-triphenylgermylalk-1-ene using a Wittig reagent (see Equation 31 in the Introductory Remarks, section 2.2.1, p 81 ff.). It was therefore decided to investigate the applicability of this transformation to the conversion of functionalized acyltrimethylgermanes into the corresponding 2-trimethylgermylalk-1-enes.

Table 10 contains a summary of the conversion of selected acyltrimethylgermanes (170, 114, 180, 182, 184) into the 2-trimethylgermylalk-1-enes 214–218.
Table 10: Preparation of the 2-Trimethylgermylalk-1-enes 214–218

![Chemical structure diagram]

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>R&lt;sub&gt;1&lt;/sub&gt;</th>
<th>Solvent</th>
<th>Yield (%)&lt;sup&gt;a&lt;/sup&gt;</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>C&lt;sub&gt;9&lt;/sub&gt;H&lt;sub&gt;19&lt;/sub&gt; 170</td>
<td>C&lt;sub&gt;9&lt;/sub&gt;H&lt;sub&gt;19&lt;/sub&gt; 214</td>
<td>THF</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>Me&lt;sub&gt;3&lt;/sub&gt;SiC≡C(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt; 114</td>
<td>Me&lt;sub&gt;3&lt;/sub&gt;SiC≡C(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt; 215</td>
<td>benzene</td>
<td>86&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>3</td>
<td>4-MeO(C&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;)CH&lt;sub&gt;2&lt;/sub&gt;OCH&lt;sub&gt;2&lt;/sub&gt; 180</td>
<td>4-MeO(C&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;)CH&lt;sub&gt;2&lt;/sub&gt;OCH&lt;sub&gt;2&lt;/sub&gt; 216</td>
<td>THF</td>
<td>91</td>
</tr>
<tr>
<td>4</td>
<td>Cl(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;4&lt;/sub&gt; 182</td>
<td>Cl(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;4&lt;/sub&gt; 217</td>
<td>diethyl ether</td>
<td>84</td>
</tr>
<tr>
<td>5</td>
<td>Me&lt;sub&gt;3&lt;/sub&gt;Ge(C=O)(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;4&lt;/sub&gt; 184</td>
<td>Me&lt;sub&gt;3&lt;/sub&gt;Ge(C=CH&lt;sub&gt;2&lt;/sub&gt;)(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;4&lt;/sub&gt; 218</td>
<td>benzene</td>
<td>85&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Yield of isolated and purified product using 1.2 equiv of Ph<sub>3</sub>P=CH<sub>2</sub> (unless otherwise noted).  
<sup>b</sup> 1.6 equiv of Ph<sub>3</sub>P=CH<sub>2</sub> were used.  
<sup>c</sup> Using 2.5 equiv of Ph<sub>3</sub>P=CH<sub>2</sub> were used.

For example, the synthesis of 2-trimethylgermylundec-1-ene (214) (entry 1) was accomplished in the following manner. A mixture of methylenetriphenylphosphorane (1.2 equiv) in dry THF, prepared by treating methyltriphenylphosphonium bromide (1.25 equiv) with a solution of n-BuLi (1.2 equiv), was allowed to react with decanoyltrimethylgermane (170) (1 equiv) at room temperature for 20 min. After isolation and purification of the crude product, 2-trimethylgermylundec-1-ene (214) was obtained in 90% yield. The <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) spectrum of 214 exhibited a one-proton doublet (J = 2.8 Hz) at δ 5.48, a one-proton doublet (J = 2.8 Hz) at δ 5.14, a two-proton triplet (J = 7.6 Hz) at δ 2.16, a fourteen-proton multiplet at δ 1.44–1.16, a three-proton triplet (J = 7.0 Hz) at δ 0.86 as well as a nine-proton singlet at δ 0.19. Additional structural evidence was provided by the IR spectrum
which showed a band at 1604 cm\(^{-1}\) (v C=C), together with HRMS analysis which indicated a signal at \(m/z\) 257.1329 (M – CH\(_3\))\(^+\), in good agreement with the calculated value of 257.1325 for C\(_{13}\)H\(_{27}\)\(^{74}\)Ge.

The 2-trimethylgermylalk-1-enes 215–218 listed in **Table 10** were prepared from the corresponding acyltrimethylgermanes in a manner analogous with that outlined above. Thus, treatment of 5-trimethylsilylpent-4-ynoyltrimethylgermane (114) (entry 2) with 1.6 equivalents of methylenetriphenylphosphorane in dry benzene afforded 2-trimethylgermyl-6-trimethylsilylhex-5-yn-1-ene (215) in 86% yield. When the same reaction was performed in THF or with 1.2 equivalents of methylenetriphenylphosphorane, the yield of 215 decreased by =10%. It is noteworthy that 2-trimethylgermyl-6-trimethylsilylhex-5-yn-1-ene (215) possesses a 2-trimethylgermylalk-1-ene as well as a 1-trimethylsilylalk-1-yne function. Using the method developed as described in section 2.1 of this thesis (p 16 ff.), the 1-trimethylsilylalk-1-yne function of 215 could be submitted (theoretically) to the platinum catalyzed hydrogermylation conditions to produce, sequentially, a second vinylgermane function.

Treatment of the acyltrimethylgermane 180 (entry 3) with 1.2 equivalents of methylenetriphenylphosphorane in dry THF afforded the 2-trimethylgermylalk-1-ene 216 in 91% yield. Interestingly, product 216 bears an ether function in the allylic position, a type of compound that could not be synthesized via the method involving platinum catalyzed hydrogermylation of 1-trimethylsilylalk-1-ynes (see section 2.1.5, p 65 ff.). 5-Chloropentanoyltrimethylgermane (182) (entry 4) was converted into 6-chloro-2-trimethylgermylhex-1-ene (217) in 84% yield using dry diethyl ether as solvent. When the olefination of 182 was effected in THF, 217 was obtained in 80% yield, whereas with benzene as solvent the yield of
217 was essentially the same as with diethyl ether (83%).

Finally, treatment of hexanedioylbis(trimethylgermane) (184) with 2.5 equivalents of methylenetriphenylphosphorane in benzene afforded 2,7-bis(trimethylgermyl)octa-1,7-diene (218) in 85% yield. Since substrate 184 underwent a double olefination reaction, the amount of reagent employed was increased. When the olefination of 184 was effected in diethyl ether, the yield of 218 was lowered slightly (82%).

The vinylgermane 216 can serve as an ether-protected form of an allylic bifunctional reagent. Thus, 1-((4-methoxybenzyl)oxy)-2-trimethylgermylprop-2-ene (216) was treated with DDQ in a dichloromethane–water mixture at room temperature. After isolation and purification of the crude product, 2-trimethylgermylprop-2-en-1-ol (219) was obtained in 75% yield. Substance 219 has been employed as a precursor for the preparation of the synthetically useful bifunctional reagent 2-(trimethylgermyl)allylcopper(I)–dimethyl sulfide.  

![Diagram of the reaction](https://example.com/diagram.png)
2.2.5 CONCLUSIONS

The aim of this study was to develop a method for the preparation of functionalized acyltrimethylgermanes and, subsequently, to convert the latter compounds into the corresponding 2-trimethylgermylalk-1-enes.

The acyl chlorides required as substrates for this study are easily synthesized from the alkanoic acids precursors. A new and, more importantly, experimentally simple method was devised for the preparation of MesGeLi (149) in high yield in THF solution. The novel reagent Me₃GeCu•Me₂S (168) was obtained by treatment of a solution of MesGeLi (149) with CuBr•Me₂S.

Me₃GeCu•Me₂S (168) serves as a good reagent for the conversion of functionalized acyl chlorides into the corresponding acyltrimethylgermanes of general structure 37. The formation of the acyltrimethylgermanes is accompanied by the production of small amounts of by-products, apparently originating from the enolization of the acyltrimethylgermanes. The formation of these by-products can be completely inhibited by addition of chlorotrimethylsilane to the reaction mixture prior to addition of the substrate. The reaction of S-(pyridin-2-yl) thioesters with Me₃GeCu•Me₂S (168) provides the corresponding acyltrimethylgermanes. The yields are comparable or lower than that obtained with the parent acyl chlorides.
Finally, the acyltrimethylgermanes 37 are efficiently converted into the corresponding 2-trimethylgermylalk-1-enes of general structure 26 via olefination with methylenetriphenylphosphorane.
2.3 CONJUGATE ADDITION OF (TRIMETHYLGEMYL)COPPER(I)–DIMETHYL SULFIDE (168) AND LITHIUM (TRIMETHYLGEMYL)CUPRATES TO SELECTED UNSATURATED CARBONYL SYSTEMS

2.3.1 INTRODUCTORY REMARKS

Following the successful preparation of Me₃GeCu•Me₂S (168) (section 2.2.2.2, p 92 ff.), and the demonstration that 168 serves as useful reagent for the synthesis of functionalized acyltrimethylgermanes (section 2.2.2.3, p 97 ff.), it became of interest to undertake the preparation of additional (trimethylgermyl)cupper(I) reagents. In addition, as outlined in the Proposals (section 1.3, p 13 ff.), given that (trimethylgermyl)cupper(I) reagents could be prepared, what synthetic applications would these reagents have?

A survey of the literature showed that three reports have appeared describing the preparation and use of triphenyl- and (triethylgermyl)cupper(I) reagents. In contrast, (trimethylgermyl)cupper(I) reagents had not been reported prior this work. A brief summary of these reports will be presented below.

In the first report, as outlined in the Introductory Remarks from the previous section (2.2.1, p 81 ff.), Vyazankin and co-workers described the use of Et₃GeCu to convert an acyl chloride into the corresponding acyltriethylgermane (see Equation 26).

\[
\begin{align*}
\text{OAc} & \quad \text{(Et₃Ge)₂CuLi} & \quad \text{THF, -23 °C} & \quad \text{GeMe₃} & \quad \text{(35)} \\
\text{220} & \quad \text{221 (80%)} 
\end{align*}
\]

Takeda and co-workers, in the second report, utilized (Et₃Ge)₂CuLi for the preparation of allylgermanes. In this protocol, for example, a cold (–23 °C) solution of
(Et₃Ge)₂CuLi (1 equiv) in THF was treated with the allylic acetate 220 (1 equiv) to afford the allylgermane 221 in 80% yield (Equation 35).

In the third report, Oshima and co-workers,³⁵ outlined the use of (Et₃Ge)₂CuLi in the synthesis of vinylgermanes, as depicted in Scheme 10 (p 12) of the Introduction.

\[
\begin{align*}
\text{Ph} & \equiv \text{H} \\
\text{Ph} & \equiv \text{GeBu₃} + \text{Bu₃Ge}
\end{align*}
\]

Oshima and co-workers,³⁵ also employed (Ph₃Ge)₂Cu(CN)Li₂ in the formation of vinylgermanes from alk-1-yynes. For example, in this protocol, a solution of (Ph₃Ge)₂Cu(CN)Li₂ (1.5 equiv) in THF at 0 °C was treated sequentially with phenylacetylene (59) (1 equiv) and n-butanol (4.6 equiv) as a proton source,³⁵ to afford the regioisomeric vinylgermanes 79 and 81, as a mixture, in 85% yield (Equation 36).

As outlined above, the triphenyl- and (triethylgermyl)copper(I) reagents have been used sparingly with a limited number of substrates. In an effort to develop the use of organogermanes reagents in synthesis, a number of new (trimethylgermyl)copper(I) reagents have been prepared. The following pages describes the preparation of these reagents as well as their conjugate addition to selected α,β-unsaturated carbonyl systems.
2.3.2 PREPARATION OF THE (TRIMETHYLGERMYL)CUPRATES 222–225

Following the development of the new and experimentally simple formation of Me$_3$GeLi (149) (section 2.2.2.2, p 92 ff.), the preparation of the (trimethylgermyl)cuprates reagents 222–225 was easily accomplished.

For example, the formation of lithium bis(trimethylgermyl)cuprate (222) was accomplished as follows. A cold (−10 °C) solution of Me$_3$GeLi (149) (2 equiv) in dry THF was transferred to a cold (−78 °C) stirred suspension of CuBr•Me$_2$S (1 equiv) in dry THF via a cannula. The resultant mixture was stirred at −78 °C for 1 h to afford a clear golden solution of the reagent 222, which was then ready to use.

The (trimethylgermyl)cuprate reagents 223–225 were prepared in a manner analogous to that described above, using CuCN as the copper(I) source. A yellow opaque solution of reagent 223 in THF was obtained by mixing together a 1:1 molar ratio of Me$_3$GeLi (149) and CuCN, whereas treatment of one equivalent of CuCN with 2 equivalents of Me$_3$GeLi (149) in THF generated a clear colorless solution of reagent 224. When a suspension of CuCN (1 equiv) in THF was treated with one equivalent each of solutions of Me$_3$GeLi (149) and MeLi, the dilithium methyl(trimethylgermyl)cyanocuprate (225) was obtained as a clear colorless solution.

The formulae depicting the (trimethylgermyl)cuprates 222–225 are intended to indicate the stoichiometry of the reagents used for their preparation and not an actual structural representation or state of aggregation. While reagents 222–225 will be treated as
monomeric species, in order to facilitate the discussion of the results, the reader should keep in mind that they possibly possess some degree of aggregation like their carbocuprate analogs.\textsuperscript{102-104}
2.3.3 ADDITION OF (TRIMETHYLGERMYL)COPPER(I)-DIMETHYL SULFIDE (168) AND (TRIMETHYLGERMYL)CUPRATES 222–225 TO CYCLIC ENONES

In order to evaluate the effectiveness of Me₃GeCu·Me₂S (168) and the (trimethylgermyl)cuprates reagents 222–225 to undergo conjugate addition, cyclohex-2-en-1-one (226), l-carvone (227) and isophorone (228) were chosen as substrates.

2.3.3.1 CONJUGATE ADDITION TO CYCLOHEX-2-EN-1-ONE (226)

Initial investigations were performed using cyclohex-2-en-1-one (226) as substrate. Table 11 contains a summary of the conversion of 226 into 3-trimethylgermylcyclohexanone (229) with reagents 168 and 222–225.
Table 11: Conjugate Addition of Reagents 168 and 222–225 to Cyclohex-2-en-1-one (226)

```
<table>
<thead>
<tr>
<th>Entry</th>
<th>Reagent</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Me₃GeCu•Me₂S 168</td>
<td>77</td>
</tr>
<tr>
<td>2</td>
<td>(Me₃Ge)₂CuLi 222</td>
<td>86</td>
</tr>
<tr>
<td>3</td>
<td>Me₃GeCu(CN)Li 223</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>(Me₃Ge)₂Cu(CN)Li₂ 224</td>
<td>85</td>
</tr>
<tr>
<td>5</td>
<td>Me₃Ge(Me)Cu(CN)Li₂ 225</td>
<td>87</td>
</tr>
</tbody>
</table>
```

*a 1.3 equiv of reagent were used unless otherwise stated. b Yield of isolated and purified product. c 0.65 equiv of reagent was used.

For example, the conjugate addition of Me₃GeCu•Me₂S (168) to 226 (entry 1) was accomplished as follows. A cold (−78 °C) solution of reagent 168 (1.3 equiv) in dry THF was treated with cyclohex-2-en-1-one (226) (1 equiv). The resultant black mixture was stirred at −78 °C for 0.5 h, and then was treated with aqueous NH₄Cl–NH₄OH (pH 8–9). Isolation and purification of the crude product obtained afforded 3-trimethylgermylcyclohexanone (229) in 77% yield. The ¹H NMR (400 MHz, CDCl₃) spectrum derived from 229 exhibits a three-proton multiplet at δ 2.41–2.24, a two-proton multiplet at δ 2.20–2.10, a one-proton multiplet at δ 1.86–1.78, a one-proton ddddd (J = 12.8, 12.8, 12.8, 5.0 and 3.8 Hz) at δ 1.71, a one-proton dddd (J = 12.8, 12.8 and 3.6 Hz) at δ 1.46, a one-proton dddd (J = 13.6, 12.8, 3.4 and 3.4 Hz) at δ 1.30, as well as a nine-proton singlet at δ 0.10. The IR spectrum derived
from 229 showed a band at 1713 cm\(^{-1}\) (\(\nu\) C=O), whereas HRMS analysis indicated a signal at \(m/z\) 216.0565, which is consistent with the calculated value of 216.0569 for C\(_9\)H\(_{18}\)\(^{74}\)GeO.

The conjugate addition of the other (trimethylgermyl)cuprate reagents 222–225 listed in Table 11 to cyclohex-2-en-1-one (226) was effected in a manner similar to that described above. It is noteworthy that reagents 222 (entry 2) and 224 (entry 4), which possess two Me\(_3\)Ge- ligands, were employed in sub-stoichiometric amounts (0.65 equivalent) with 226 to afford the adduct 229 in 86 and 85% yield respectively. These results demonstrate that both ligands are transferable in a conjugate addition reaction to an enone and, thus, “throwing away” a valuable (Me\(_3\)Ge-) ligand is precluded. Similarly, this concept of “ligand economy” instigated the preparation of reagent 225, which possesses an expendable non-transferable ligand (Me-).\(^{105}\) Thus, when 1.3 equivalents of reagent 225 were treated with one equivalent of the enone 226, the adduct 229 was obtained in 87% yield (entry 5).

\[
\begin{align*}
\text{O} & \quad \xrightarrow{\text{Me}_3\text{MLi}} \quad \text{O} + \text{HO-}\text{MMe}_3 \\
226 & \quad \text{solvent, -78 °C} & 229 & \quad M = \text{Ge} \\
   & \quad 229a & \quad M = \text{Si} \\
   & \quad 229b & \quad M = \text{Sn} \\
   & \quad 230 & \quad M = \text{Ge} \\
   & \quad 230a & \quad M = \text{Si} \\
   & \quad 230b & \quad M = \text{Sn}
\end{align*}
\]

<table>
<thead>
<tr>
<th>M</th>
<th>Solvent</th>
<th>THF-HMPA</th>
<th>&gt;99</th>
<th>&lt;1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>THF-HMPA</td>
<td>&gt;99</td>
<td>:</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Sn</td>
<td>THF</td>
<td>&gt;99</td>
<td>:</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Sn</td>
<td>Et(_2)O</td>
<td>1</td>
<td>:</td>
<td>9</td>
</tr>
<tr>
<td>Ge</td>
<td>THF</td>
<td>1</td>
<td>:</td>
<td>3.8</td>
</tr>
</tbody>
</table>

\textbf{Scheme 38}
Still\textsuperscript{106,107} has shown that Me\textsubscript{3}MLi (M = Si, Sn) reagents undergo smooth 1,4-addition to cyclohex-2-en-1-one (226) in a THF–HMPA solvent mixture or in THF respectively, to produce exclusively the adduct 229\textsubscript{a} and 229\textsubscript{b}, respectively (Scheme 38). Alternatively, when a solution of Me\textsubscript{3}SnLi in diethyl ether was treated with 226, the allylic alcohol 230\textsubscript{b} was formed predominantly.\textsuperscript{107}

Therefore, it could be argued that Me\textsubscript{3}GeLi (149) might also add in a 1,4-fashion to the enone 226 in THF solution. When cyclohex-2-en-1-one (226) was allowed to react with Me\textsubscript{3}GeLi (149) in THF at –78 °C for 5 min, a mixture of two compounds was obtained in a ratio of 1:3.8 (GLC analysis). Isolation and purification of the crude oil obtained afforded compound 229 in 20% yield as well as product 230 in 59% yield. The \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) spectrum of 230 exhibited the following signals: a one-proton ddd (\( J = 9.8, 3.8 \) and 3.0 Hz) at \( \delta 5.75 \) (vinyllic proton), a one-proton ddd (\( J = 9.8, 1.4 \) and 1.4 Hz) at \( \delta 5.69 \), a one-proton multiplet at \( \delta 2.08–1.98 \), a three-proton multiplet at \( \delta 1.94–1.72 \), a two-proton multiplet at \( \delta 1.68–1.50 \), a one-proton broad signal at \( \delta 1.27 \) (-OH) as well as a nine-proton singlet at \( \delta 0.17 \) (Me\textsubscript{3}Ge-). The IR spectrum derived from 230 showed a broad signal at 3425 cm\textsuperscript{-1} (-OH) and HRMS analysis indicated a signal at \( m/z \) 216.0567, in good agreement with the calculated value of 216.0569 for C\textsubscript{9}H\textsubscript{18}\textsuperscript{74}GeO.

Thus, under the experimental conditions used, the chemoselectivity of addition of Me\textsubscript{3}SiLi and Me\textsubscript{3}SnLi is higher than that derived from addition of Me\textsubscript{3}GeLi (149). The selectivity of addition of reagents 168 and 222–225 (Table 11) to 226 is also superior to that of Me\textsubscript{3}GeLi (149), evident from the exclusive formation of 229.
2.3.3.1.1 Mechanistic Considerations

Attempts to gain insight into the mechanistic picture of cuprate addition to α,β-unsaturated ketones has generated a lot of research over the past years. Several different proposals, such as single electron transfer\textsuperscript{108} between the organocopper an the enone substrate, as well as formation of a charge transfer complex between the reactants,\textsuperscript{109} have been put forth. Another proposal delineates the reversible formation of an intermediate $d,\pi^*$ cuprate–enone complex\textsuperscript{110} in the conjugate addition of organocopper(I) reagents to enones. The latter proposal is summarized in Scheme 39 and depicts, for example, the conjugate addition of $(\text{Me}_3\text{Ge})_2\text{CuLi}$ (222) to cyclohex-2-en-1-one (226).

\begin{center}
\includegraphics[width=\textwidth]{Scheme39}
\end{center}

\textbf{Scheme 39}

Initially, complexation of the cuprate reagent 222 to the enone moiety of 226 generates the $d,\pi^*$ intermediate 231a. Subsequently, C–Cu bond formation perpendicular to the plane of the p orbital system (231b) leads to the copper(III) intermediate 232. Reductive
elimination generates the copper(I) species $RCu$ as well as the enolate $233a$. The latter enolate can undergo conformational change to $233b$, thus changing the $R$ group from an axial to a more stable equatorial orientation. Protonation of the enolate during work-up affords 3-trimethylgermylcyclohexanone ($229$).

2.3.3.2 CONJUGATE ADDITION TO $l$-CARVONE ($227$)

$l$-Carvone ($227$) was the next substrate selected for the conjugate addition of the (trimethylgermyl)copper(I) reagents $168$ and $223-225$. In this transformation, the four diastereomeric adducts $234-237$ can be formed. The diastereomeric pair $234$ and $235$ is the result of a syn addition of the $\text{Me}_3\text{Ge}^-$ group with respect to the isopropenyl moiety in $227$, whereas the $236$ and $237$ pair arises from an anti addition of the $\text{Me}_3\text{Ge}^-$ group. Each member of a pair shares an epimeric relationship at the carbon bearing the methyl group.
The reagent \((\text{Me}_3\text{Ge})_2\text{Cu}(\text{CN})\text{Li}_2\) (224) was employed to effect the initial conjugate addition to \(l\)-carvone (227). Thus, treatment of a solution of reagent 224 (0.6 equiv) in THF with the enone 227 (1 equiv) at \(-78^\circ\text{C}\) for 1 h resulted in the formation of a complex mixture. Periodic TLC analyses of aliquots of the reaction mixture indicated that the conversion of the starting material was incomplete after 1 h and was no longer progressing.

In a separate experiment, a solution of reagent 224 (0.65 equiv) in THF was treated sequentially with chlorotrimethylsilane (1.3 equiv) and the enone 227 (1 equiv) at \(-78^\circ\text{C}\). TLC analysis of an aliquot of the reaction mixture after 0.5 h at \(-78^\circ\text{C}\) indicated that the conversion of starting material to product (enol trimethylsilyl ether) was incomplete. Therefore, the mixture was warmed gradually to 0 °C over a 0.5 h period, at which time the conversion of the starting material appeared to be complete (TLC analysis). After isolation, GLC analysis of an aliquot of the crude oil indicated that two products had been formed in a ratio of 1.4:1. This oil was dissolved in THF and the solution was treated with 1 M hydrochloric acid (few drops) at room temperature for 1 h in order to hydrolyze the enol...
trimethylsilyl ether function. Isolation and purification of the crude product gave a clear and colorless oil in 86% yield. $^1$H NMR (400 MHz, C$_6$D$_6$) spectroscopic analysis of this oil indicated the presence of four products, evident from the four singlets in the region $\delta$ 0.10 and $\delta$ -0.02 in a ratio of 1.1:2.5:1:3.9, attributed to the Me$_3$Ge- group of the four diastereomeric products 234–237, respectively. In order to ascertain the identity and stereochemistry of each products, it was decided to isolate the four compounds 234–237.

2.3.3.2.1 Isolation and Characterization of the Four Diastereomers 234–237

Two samples (=100 mg each) of the mixture obtained as described above were subjected to HPLC (silica Partisil, 10 µm; 22 mm × 250 mm column, 99:1 hexane–ethyl acetate) individually. These chromatographies resulted in a rough separation to afford three fractions. The corresponding fractions of the separate injections were combined and concentrated under reduced pressure. The first fraction to be eluted, fraction A (retention time 42–45 min), afforded 45 mg of an oil which consisted of a mixture of two components (compounds 237 and 235). The second fraction to be eluted, fraction B (retention time 53–62 min), afforded 28 mg of an oil which was mostly one component (compound 236). Fractions A and B were processed further as described below. The third fraction to be eluted (retention time 65–78 min) afforded 28 mg of compound 234 as a clear colorless oil.

![Structural formula of compound 234](image)

The $^1$H NMR (400 MHz, CDCl$_3$) spectrum of this oil exhibited the following charac-
teristic signals: two one-proton singlets at δ 4.75 and 4.73 (H-9a, H-9b), a three-proton singlet at δ 1.73 (Me-10), a three-proton doublet (J = 7.2 Hz) at δ 1.12 (Me-7) as well as a nine-proton singlet at δ 0.15 (Me$_3$Ge-). The proton H-2 was evident as a quadruplet of doublets (J = 7.2 and 4.0 Hz) at δ 2.55 with a 7.2 Hz coupling to the Me-7. The COSY spectrum allowed the assignment of proton H-3 (δ 1.39 ddd, J = 13.4, 4.0 and 3.8 Hz) through the correlation of its signal to that of proton H-2 (the majority of the signals could be assigned from the data derived from the COSY spectrum; see Experimental section Table 23, p 277). Proton H-6a was evident as a doublet of doublets (J = 13.0 and 13.0 Hz) at δ 2.50 and, consequently, a trans-diaxial relationship between H-5 and H-6a with a 13.0 Hz coupling constant, was established. The COSY spectrum allowed the assignment of proton H-5 (δ 2.42–2.32 m) through the correlation of its signal to that of proton H-6a.

$^1$H NMR NOE difference experiments were performed to establish the stereochemistry of this compound. Thus, irradiation of the doublet at δ 1.12 (Me-7) caused the signal at δ 2.50 (H-6a) to be enhanced. When the resonance for H-5 (δ 2.42–2.32) was irradiated an enhancement was observed for H-3 (δ 1.39). Similarly, irradiation of the signal at δ 1.39 (H-3) caused the signal at δ 2.42–2.32 (H-5) to be enhanced. These experiments, along with the data derived from the $^1$H NMR and COSY spectra presented above, are consistent with the structural assignment for compound 234.
Fraction A (45 mg) from the first HPLC separation (vide supra) was subjected to reversed phase HPLC (C<sub>18</sub> µBondapak, 10 µm; 8 mm × 100 mm column, acetonitrile–water step gradient) in four approximately equal portions. The combined first fractions to be eluted (retention time 56 min) afforded 23 mg of compound 237 as a clear colorless oil.

The <sup>1</sup>H NMR (400 MHz, C<sub>6</sub>D<sub>6</sub>) spectrum derived from this oil exhibits the following characteristic signals: a two-proton singlet at δ 4.73 (H-9a, H-9b), a three-proton singlet (Me-10) at δ 1.52 (part of the δ 1.56–1.47 multiplet), a three-proton doublet (J = 6.2 Hz) at δ 1.07 (Me-7) as well as a nine-proton singlet at δ 0.10 (Me<sub>3</sub>Ge-). The proton H-6b was evident as a doublet of doublets (J = 13.6 and 11.2 Hz) at δ 2.07 and, consequently, a trans-diaxial arrangement between H-6a and H-5 was established. The COSY spectrum allowed the assignment of proton H-5 (part of δ 2.35–2.25 m) through the correlation of its signal to that of proton H-6b (the majority of the signals could be assigned from the data derived from the COSY spectrum; see Experimental section Table 24, p 279). The proton H-3 was evident as the highest field one-proton signal (ddd, J = 6.2, 4.6 and 4.6 Hz) at δ 1.38. These coupling constants indicate that H-3 is not part of a trans-diaxial arrangement and, therefore, must be in an equatorial orientation. The COSY spectrum allowed the assignment of the proton H-2 through the correlations of its signal (part of δ 2.35–2.25 m) to that of proton H-3 and Me-7.
\(^1\)H NMR NOE difference experiments were performed to establish the stereochemistry of compound 237. Thus, irradiation of the doublet at \(\delta 1.07\) (Me-7) caused a quadruplet of doublets \((J = 6.2\) and 6.2 Hz\) at \(\delta 2.31\) (H-2) to be enhanced. This experiment was performed to differentiate the resonance derived from H-2 from the multiplet expected from H-5 (vide infra), both of which are part of the \(\delta 2.35-2.25\) multiplet. When the signal for H-6b \((\delta 2.07)\) was irradiated, an enhancement was observed at \(\delta 2.31\) (qd, \(J = 6.2\) and 6.2 Hz) for H-2. On the other hand, irradiation of the singlet derived from the Me\(_3\)Ge- group \((\delta 0.10)\) caused the multiplet at \(\delta 2.32-2.25\) to be enhanced (H-5). This signal was different from the multiplet observed in the non-irradiated spectrum for H-2 and H-5 together. These experiments, along with the data derived from the \(^1\)H NMR and COSY spectra, are consistent with the structural assignment for compound 237.

The combined second fractions to be eluted (retention time 59 min) from the reversed phase HPLC of fraction A (vide supra) afforded 9.8 mg of compound 235 as a clear colorless oil. The \(^1\)H NMR (400 MHz, C\(_6\)D\(_6\)) spectrum of this oil exhibited the following characteristic
signals: two one-proton doublets ($J = 1.4$ Hz) at $\delta$ 4.69 and 4.64 (H-9a, H-9b), a three-proton singlet at $\delta$ 1.50 (Me-10), a three-proton doublet ($J = 6.6$ Hz) at $\delta$ 1.08 (Me-7) as well as a nine-proton singlet at $\delta$ 0.04 (Me$_3$Ge-). The proton H-2 was evident as a doublet of quadruplets ($J = 13.2$ and 6.6 Hz) at $\delta$ 1.92. The COSY spectrum allowed the assignment of H-3 through the correlation of its signal ($\delta$ 0.77 ddd, $J = 13.2$, 13.2 and 3.2) to that of proton H-2 (the majority of the signals could be assigned from the data derived from the COSY spectrum; see Experimental section Table 25, p 281). The 13.2 Hz coupling constant between protons H-2 and H-3 indicates a trans-diaxial arrangement. The proton H-4b was assigned through the correlation of its signal ($\delta$ 1.22 ddd, $J = 13.2$, 13.2 and 11.8 Hz) to that of proton H-3. These coupling constants indicate that H-4b possesses two neighboring protons in trans-diaxial arrangements. The proton H-6b was evident as a doublet of doublets ($J = 13.2$ and 12.4 Hz) at $\delta$ 1.97 and, thus, a trans-diaxial arrangement between protons H-5 and H-6b was established. The COSY spectrum allowed the assignment of proton H-5 through the correlation of its signal ($\delta$ 2.21–2.11 m) to that of proton H-6b.

\[ \text{H NMR NOE difference experiments were performed in order to establish the stereochemistry of compound 235. Thus, irradiation of the resonance for H-4b (}\delta 1.22)\text{ caused the signals for H-2 (}\delta 1.92)\text{ and H-6b (}\delta 1.97)\text{ to be enhanced. When the multiplet at } \delta 2.21–2.11 (\text{H-5}) \text{ was irradiated the signal at } \delta 0.77 (\text{H-3}) \text{ was enhanced. Similarly, irradiation} \]
of H-3 (δ 0.77) resulted in an enhancement of the resonance for H-5 (δ 2.21–2.11). The results of these experiments, along with the data derived from the 1H NMR and COSY spectra, are consistent with the structural assignment for compound 235.

Fraction B (28 mg) from the initial chromatography was resubjected to HPLC under identical conditions (silica Partisil, 10 μm; 22 mm × 250 mm column, 99:1 hexane–ethyl acetate) to afford 8.2 mg of compound 236 as a clear colorless oil.

![Image of compound 236]

The 1H NMR (400 MHz, CDCl₃) spectrum derived from this oil exhibits the following characteristic signals: two one-proton singlets at δ 4.94 and 4.86 (H-9a, H-9b), a three-proton singlet at δ 1.50 (Me-10), a three-proton doublet (J = 6.8 Hz) at δ 1.07 (Me-7) as well as a nine-proton singlet at δ 0.05 (Me₃Ge-). The proton H-2 was evident as a doublet of quadruplets (J = 11.0 and 6.8 Hz) at δ 2.01. The COSY spectrum allowed the assignment of proton H-3 through the correlation of its signal (δ 1.12 ddd, J = 11.0, 11.0 and 3.6 Hz) to that of proton H-2 (the majority of the signals could be assigned from the data derived from the COSY spectrum; see Experimental section Table 26, p 284). The large coupling constants (J = 11.0 and 11.0 Hz) associated with the signal due to H-3 indicate that this proton is in a trans-diaxial arrangement with two neighboring protons. The COSY spectrum also allowed the assignment of the following protons through sequential correlations of their signals: H-4b (δ 1.38 ddd, J = 13.8, 11.0 and 4.6 Hz, correlation with H-3), H-5 (δ 2.41–2.34 m,
correlation with H-4b) and H-6b (δ 2.11 dd, J = 14.2 and 6.0 Hz, correlation with H-5).

\[ \text{[Diagram of molecule 236]} \]

$^1$H NMR NOE difference experiments were performed to establish the stereochemistry of compound 236. Thus, irradiation of H-9a (δ 4.94) caused the resonance for H-3 (δ 1.12) to be enhanced. When the signal for H-4b (δ 1.38) was irradiated, the resonances at H-2 (δ 2.01) and H-6b (δ 2.11) were enhanced. The results of these experiments, along with the data derived from the $^1$H NMR and COSY spectra, are consistent with the structural assignment for compound 236.

2.3.3.2.2 Conjugate Addition of Reagents 168 and 223–225 to l-Carvone (227)

Table 12 contains a summary of the conjugate addition of reagents 168 and 223–225 to l-carvone (227). The reaction of Me₃GeCu•Me₂S (168) with 227 (entry 1), for example, was accomplished in the following manner. A cold (−78 °C) solution of reagent 168 (1.3 equiv) in dry THF was sequentially treated with chlorotrimethylsilane (1.3 equiv) and 227 (1 equiv). The reaction mixture was stirred at −78 °C for 0.5 h, then was allowed to warm to 0 °C over a 0.5 h period. After isolation, the crude oil was dissolved in THF and the solution was treated with 1 M hydrochloric acid (few drops) at room temperature for 1 h. $^1$H NMR (400 MHz, C₆D₆) spectroscopic analysis of the crude mixture indicated that the addition of the Me₃Ge- group occurred predominantly (1.4:1) in a fashion syn to the isopropenyl moiety.
(234 + 235). After isolation and purification, the products 234-237 were obtained as a mixture in 82% yield.

**Table 12: Conjugate Addition of Reagents 168 and 223-225 to l-Carvone (227)**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reagent&lt;sup&gt;a&lt;/sup&gt;</th>
<th>234 + 235</th>
<th>236 + 237</th>
<th>Yield (%)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Me₃GeCu•Me₂S 168</td>
<td>1.4 :</td>
<td>1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>Me₃GeCu(CN)Li 223</td>
<td>1.4 :</td>
<td>1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>(Me₃Ge)&lt;sub&gt;2&lt;/sub&gt;Cu(CN)Li&lt;sub&gt;2&lt;/sub&gt; 224</td>
<td>1 : 1.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Me₃Ge(Me)Cu(CN)Li&lt;sub&gt;2&lt;/sub&gt; 225</td>
<td>1 : 3.9&lt;sup&gt;c&lt;/sup&gt;</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> 1.3 equiv of reagent were employed, except for reagent 224 for which 0.65 equiv was utilized. <sup>b</sup> Yield of isolated and purified product mixture (234-237). <sup>c</sup> Ratio determined from <sup>1</sup>H NMR (400 MHz, C<sub>6</sub>D<sub>6</sub>) spectroscopic analysis of the crude mixture (integration of the Me<sub>3</sub>Ge- singlets).

The remainder of the reagents listed in Table 12 were employed in a manner similar with that outlined above. For the conversion summarized in entry 2, the stereoselectivity of addition of the Me₃Ge- group, using Me₃GeCu(CN)Li (223), was comparable with that of reagent 168 affording predominantly (1.4:1) products of syn addition in 80% yield. When reagent 224 (entry 3) was employed (see previous discussion), the selectivity was reversed: the addition of the Me₃Ge- group occurred to give mainly (1.4:1) the anti adducts (236 +
237). The yield of the mixture obtained was 86%. In the reaction summarized in entry 4, conjugate addition of reagent 225 to l-carvone (227) afforded predominantly (3.9:1) the products of anti addition (236 + 237) (overall yield, 90%). The epimeric ratio at the α-carbon varied for the different experiments, but was generally ≈2.5:1 for the syn adducts, with the epimer 235 predominating, whereas for the anti adducts the ratio was ≈3:1, with the epimer 237 being dominant.

The results summarized in Table 12 require additional comments. It is well documented that cuprate additions to enones bearing a substituent at C-5, such as l-carvone (227), result largely in the formation of adducts with the newly introduced group anti to the C-5 substituent. As shown in Table 12, the ratios obtained for the different trimethylgermylcuprates indicate that the reactions of these reagents with l-carvone (227) proceed with poor stereoselectivity. The reasons for this lack of selectivity remain unclear.

2.3.3.3 CONJUGATE ADDITION TO ISOPHORONE (228)

Isophorone (228) was selected as substrate for the conjugate addition of the (trimethylgermyl)cuprates to evaluate their ability to undergo addition to a sterically hindered substrate. Table 13 contains a summary of the conjugate addition of reagents 224 and 225 to isophorone (228). The effect of certain additives on the production of 238 was also evaluated.
Table 13: Conjugate Addition of Reagents 224 and 225 to Isophorone (228)

![Chemical structure](image)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reagent$^a$</th>
<th>Additive</th>
<th>Yield (%)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1$^c$</td>
<td>(Me₃Ge)$_2$Cu(CN)Li₂ 224</td>
<td>HMPA (2.6 equiv)</td>
<td>42</td>
</tr>
<tr>
<td>2$^d$</td>
<td>Me₃Ge(Me)Cu(CN)Li₂ 225</td>
<td>none</td>
<td>33</td>
</tr>
<tr>
<td>3$^e$</td>
<td>Me₃Ge(Me)Cu(CN)Li₂ 225</td>
<td>TMSCl (1.2 equiv)</td>
<td>33</td>
</tr>
<tr>
<td>4$^f$</td>
<td>Me₃Ge(Me)Cu(CN)Li₂ 225</td>
<td>TMSBr (4 equiv)</td>
<td>66</td>
</tr>
</tbody>
</table>

$^a$ 0.64 equiv of reagent 224 was used whereas 1.2–1.3 equiv of reagent 225 were employed.

$^b$ Yield of isolated and purified product. $^c$ Conditions: -78 °C 1 h, then HMPA, -78 → 0 °C.

$^d$ Conditions: -78 → 0 °C. $^e$ Conditions: -78 → -30 °C. $^f$ Conditions: -78 → -15 °C.

A solution of 224 (0.64 equiv) in dry THF (entry 1) was treated with isophorone (228) (1 equiv) at -78 °C. After the reaction mixture had been stirred at -78 °C for 1 h, HMPA (2.6 equiv) was added. The mixture was allowed to stir for an additional 0.5 h, then was warmed to 0 °C over 0.5 h to afford the product 238 in 42% yield. When 1.2 equivalents of a solution of reagent 225 was treated with 1 equivalent of 228 at -78 °C for 1h, then was warmed to 0 °C over 0.75 h, the adduct 238 was formed in 33% yield (entry 2). Entry 3 summarizes a similar experiment in which 1.2 equivalents of chlorotrimethylsilane were used as additive, prior to the addition of isophorone (238), to afford 238 in 33% yield after hydrolysis of the intermediate enol trimethylsilyl ether. A solution of reagent 225 (1.3 equiv) was treated sequentially with bromotrimethylsilane (4 equiv) and 228 (1 equiv) at -78 °C (entry 4). The reaction mixture was stirred at -78 °C for 1 h, then was allowed to warm...
slowly to -30 °C over 2 h. After hydrolysis of the intermediate enol trimethylsilyl ether, the product 238 was obtained in 66% yield.

The results summarized in Table 13 suggest that neither HMPA nor chlorotrimethylsilane are very effective additives in this transformation. On the other hand, bromotrimethylsilane served as an effective additive for the production of 238, increasing the yield from 33% to 66% under similar experimental conditions (compare entries 2 and 4).
As outlined in the previous section, (trimethylgermyl)copper(I)-dimethyl sulfide (168) and the (trimethylgermyl)cuprates serve as efficient reagents for the conjugate addition to cyclohex-2-en-l-ones. The possibility of employing these reagents for the preparation of (E)- and/or (Z)-3-trimethylgermylalk-2-enoates of general structure 240, via addition to alk-2-ynoates of general structure 239, was envisaged.

2.3.4.1 ADDITION TO ETHYL BUT-2-YNOATE (241)

The 1,4-addition of the Me₃Ge- group onto the conjugated carbonyl system of 241 can result in the formation of one or both of two adducts, ethyl (E)- and/or (Z)-3-trimethylgermylbut-2-enoate (242) and (243), respectively. The (E) isomer 242 was expected to be the major product resulting from the germylcupration of 241 by analogy with the literature precedents for the stannylcupration of alk-2-ynoates.
The initial investigation was carried out using Me₃GeCu(CN)Li (223) and the commercially available ethyl but-2-ynoate (241) was selected as substrate (Equation 37). Thus, a cold (−78 °C) solution of 1.3 equivalents of reagent 223 in THF, prepared as described above (section 2.3.2, p 136 ff.), was treated with one equivalent of ethyl but-2-ynoate (241). The reaction mixture was stirred at −78 °C for 20 min, then was treated sequentially with glacial acetic acid (=4 equiv) and NH₄Cl/NH₄OH (pH 8–9). GLC analysis of the crude product indicated that a single substance (>99% by GLC) had been formed. Isolation and purification of the crude product obtained afforded a clear colorless oil in 90% yield. The ¹H NMR (400 MHz, CDCl₃) spectrum derived from this oil exhibits the following signals: a one-proton quadruplet \((J = 1.8 \text{ Hz})\) at \(\delta 5.95\), a two-proton quadruplet \((J = 7.2 \text{ Hz})\) at \(\delta 4.14\), a three-proton doublet \((J = 1.8 \text{ Hz})\) at \(\delta 2.26\), a three-proton triplet \((J = 7.2 \text{ Hz})\) at \(\delta 1.27\) as well as a nine-proton singlet at \(\delta 0.23\). The IR spectrum of this oil showed bands at 1718 (v C=O) and 1614 cm⁻¹ (v C=C), whereas HRMS (DCI, NH₃ + CH₄) analysis indicated a signal at \(m/z\) 233.0597, a value identical with that calculated for C₉H₁₉⁷⁴GeO₂ (M + 1)⁺.

¹H NMR NOE difference experiments were performed to establish the geometry of the
alkene function of the isolated compound. Thus, irradiation of the resonance for the vinylic proton ($\delta$ 5.95) caused the signal for the Me$_3$Ge- group ($\delta$ 0.23) to be enhanced. When the singlet for the Me$_3$Ge- group ($\delta$ 0.23) was irradiated, enhancements were observed for the vinylic proton ($\delta$ 5.95) and the alkenyl methyl ($\delta$ 2.26). Irradiation of the doublet at $\delta$ 2.26 (alkenyl methyl) caused the resonances for the Me$_3$Ge- group ($\delta$ 0.23) and the methylene protons ($\delta$ 4.14) to be enhanced. These experiments, along with the spectral data presented above are consistent with the structural assignment for ethyl (E)-3-trimethylgermylbuto-2-enoate (242).

**Table 14**: Addition of (Trimethylgermyl)copper(I) Reagents to Ethyl But-2-ynoate (241)

![Chemical structure](image)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reagent$^a$</th>
<th>Ratio$^b$ 242 : 243</th>
<th>Yield$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Me$_3$GeCu*Me$_2$S 168</td>
<td>$&gt;99 : &lt;1$</td>
<td>81</td>
</tr>
<tr>
<td>2</td>
<td>Me$_3$GeCu(CN)Li 223</td>
<td>$&gt;99 : &lt;1$</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>(Me$_3$Ge)$_2$CuLi 222</td>
<td>1.7 : 1</td>
<td>90$^d$</td>
</tr>
<tr>
<td>4</td>
<td>Me$_3$Ge(MeCu(CN)Li$_2$ 225</td>
<td>1 : 3.9</td>
<td>(E) 17, (Z) 69</td>
</tr>
</tbody>
</table>

$^a$ ≈1.3 equiv of reagent were employed except for reagent 222, for which 0.66 equiv was used. $^b$ Ratio determined by GLC analysis of an aliquot of the crude product. $^c$ Yield of isolated and purified product unless otherwise stated. $^d$ Isolated as a mixture of (E/Z) isomers.

Table 14 summarizes the reaction of reagents 168, 223, 222 and 225 with ethyl but-2-
ynoate (241). The reaction of 241 with reagents 168, 222 and 225 was effected in manner similar to that outlined above for Me₃GeCu(CN)Li (223) (entry 2). Treatment of a solution of ≈1.3 equivalents of Me₃GeCu·Me₂S (168) (entry 1) in THF with one equivalent of 241 afforded the (E) isomer 242 in 81% yield. In the reaction summarized in entry 3, when a solution of reagent 222 (0.66 equiv) was treated with 241 (1 equiv), a mixture of isomers 242 and 243 (vide infra) was obtained in 90% yield (1.7:1, E:Z).

Treatment of a solution of reagent 225 (1.3 equiv) (entry 4) with 241 (1 equiv) gave a mixture of products 242 and 243, in a ratio of 1:3.9 respectively (GLC analysis). The crude oil obtained was subjected to flash chromatography to afford two fractions. The first fraction to be eluted, compound 243 (vide infra), was obtained in 69% yield as a clear colorless oil. The second fraction to be eluted afforded ethyl (E)-3-trimethylermethylbut-2-enoate (242) in 17% yield. The structural assignment for 243 was based on the following data. The ¹H NMR (400 MHz, CDCl₃) spectrum exhibited a one-proton quadruplet (J = 1.6 Hz) at δ 6.28, a two-proton quadruplet (J = 7.2 Hz) at δ 4.13, a three-proton doublet (J = 1.6 Hz) at δ 2.01, a three-proton triplet (J = 7.2 Hz) at δ 1.26 as well as a nine-proton singlet at δ 0.29. The IR spectrum of this oil showed bands at 1718 (v C=O) and 1610 cm⁻¹ (v C=C). In addition, HRMS analysis indicated a signal at m/z 217.0291, in good agreement with the calculated value of 217.0284 for C₈H₁₅³⁴GeO₂ (M – CH₃)⁺.
$^1$H NMR NOE difference experiments were performed to establish the geometry of the alkene function of 243. Thus, irradiation of the alkenyl methyl doublet ($\delta$ 2.01) caused an enhancement of the signals for the vinylic proton ($\delta$ 6.28) and the Me$_3$Ge- group ($\delta$ 0.29). When the singlet at $\delta$ 0.29 (Me$_3$Ge-) was irradiated, the resonances at $\delta$ 4.13 (methylene protons) and 2.01 (alkenyl methyl) were enhanced. The results of these experiments, along with the spectral data presented above, are consistent with the structural assignment for ethyl (Z)-3-trimethylgermylbut-2-enoate (243).

The experimental conditions outlined above did not allow a completely stereoselective preparation of ethyl (Z)-3-trimethylgermylbut-2-ynoate (243). However, compound 243 can be obtained as a single stereoisomer, in a synthetically useful yield ($\approx$70%), via facile chromatographic separation from the corresponding (E) isomer (see entry 4, Table 14).

2.3.4.1.1 Mechanistic Considerations

A possible reaction pathway rationalizing the formation of stereoisomers 242 and 243 is depicted in Scheme 40. Thus, cis addition$^{93-95}$ of a (trimethylgermyl)copper(I) reagent to the alkyne function of 241 generates the alkenylcopper intermediate 244. Protonation of the latter intermediate (path a) produces the (E) isomer 242. The formation of 242 via path a is predominant for the reagents Me$_2$GeCu•Me$_2$S (168) and Me$_2$GeCu(CN)Li (223) (see entries 1 and 2 in Table 14, p 158). Alternatively, 244 can isomerize (path b) to the (postulated)
Allenolate species 245 (a similar intermediate has been proposed to rationalize the formation of alkyl (Z)-2-trimethylstannylalk-2-enoates\(^{113}\) from reaction of \(\text{Me}_3\text{SnCu(SPh)Li}\) with alkyl alk-2-ynoates). Protonation of the allenolate 245 from the same side as the \(\text{Me}_3\text{Ge}\) group leads to the formation of 242. On the other hand, protonation of the allenolate from the opposite side of the \(\text{Me}_3\text{Ge}\) group generates 243.

![Scheme 40](image)

**Scheme 40**

Pathways a and b are probably both in effect with reagents \((\text{Me}_3\text{Ge})_2\text{CuLi}\) (222) and \(\text{Me}_3\text{Ge}(\text{Me})\text{Cu(CN)Li}_2\) (225) (see Table 14, entries 3 and 4). Interestingly, the nature of W seem to have a profound influence on the ease of formation of the allenolate 245. Under identical experimental conditions, while reagents 168 and 223 appear to generate a stable intermediate 244, reagents 222 and 225 seem to undergo (at least in part) isomerization to the (postulated) allenolate intermediate 245.
2.3.4.2 SYNTHESIS OF METHYL \((E)\)-6-CHLORO-3-TRIMETHYLGERMYLHEX-2-ENOATE (248)

The preparation of trifunctional reagents of general structure 246, which should prove useful in synthesis, can possibly be achieved through the germycupration of functionalized alk-2-ynoates. The stereocontrolled conversion of methyl 6-chlorohex-2-ynoate\(^\text{115}\) (247) into methyl \((E)\)-6-chloro-3-trimethylgermylhex-2-enoate (248) illustrates this concept (Equation 38).

\[
\begin{align*}
1) \text{Me}_3\text{GeCu(CN)Li} & \quad \text{THF, } -78 \, ^\circ\text{C} \\
2) \text{AcOH} & \quad \text{247} \\
3) \text{NH}_4\text{Cl} / \text{NH}_4\text{OH} & \quad \text{248 (92\%)} \\
\end{align*}
\]

A cold (\(-78 \, ^\circ\text{C}\)) solution of 1.3 equivalents of Me\(_3\)GeCu(CN)Li (223) in THF was treated with one equivalent of 247. The reaction mixture was stirred at \(-78 \, ^\circ\text{C}\) for 30 min, then was treated sequentially with glacial acetic acid (1.6 equiv) and aqueous NH\(_4\)Cl/NH\(_4\)OH (pH 8–9). Isolation and purification of the crude product obtained gave methyl \((E)\)-6-chloro-3-trimethylgermylhex-2-enoate (248) in 92% yield.
Conversion of 248, and other structurally related substances, into trifunctional reagents (of general structure 246) should be accomplished in a straightforward manner via functional group interconversions.
2.3.5 CONCLUSIONS

The novel (trimethylgermyl)cuprates 222–225 have been prepared by treatment of solutions of Me₃GeLi (149) in THF with copper(I) salts. These (trimethylgermyl)cuprates serve as excellent reagents in the conjugate addition of the Me₃Ge- group to cyclohex-2-en-1-ones.

\[(\text{Me}_3\text{Ge})_2\text{CuLi} \quad \text{Me}_3\text{GeCu(CN)Li} \quad (\text{Me}_3\text{Ge})_2\text{Cu(CN)Li}_2 \quad \text{Me}_3\text{Ge(Me)Cu(CN)Li}_2\]

Reagents Me₃GeCu•Me₂S (168) and Me₃GeCu(CN)Li (223) undergo stereocontrolled cis addition to the alkyne function of ethyl but-2-ynoate (241) at low temperature to produce ethyl (E)-2-trimethylgermylbut-2-enoate (242) in high yield. The completely stereoselective synthesis of ethyl (Z)-2-trimethylgermylbut-2-enoate (243) could not be achieved under the experimental conditions used. However, facile chromatographic separation of the mixture of (E/Z) isomers produced affords the (Z) isomer 243 in a synthetically useful yield (≈70%).

Finally, stereocontrolled germylecupration of functionalized alkynoates, followed by functional group interconversions, should provide convenient access to trifunctional reagents of general structure 246.
3 EXPERIMENTAL

3.1 GENERAL

3.1.1 DATA ACQUISITION AND METHODS

Unless otherwise stated all glassware was dried at ≈140 °C in an oven or flame dried prior to use, and all reactions were performed under an atmosphere of dry argon. The Teflon cannulae (purchased from Canlab, 0.38 mm × 0.23 mm, catalogue # R5360-111 and 0.97 mm × 0.30 mm, catalogue # R5360-117) and stainless steel needles used to handle various anhydrous solvents and reagents were oven dried. The plastic syringes were flushed with dry argon prior to use. The glass microliter syringes were dried under reduced pressure (vacuum pump), stored in a desiccator and flushed with dry argon prior to use.

The following cooling baths were used to maintain sub-zero temperatures: −10 °C and −30 °C: aqueous CaCl₂–solid CO₂ (16.5 and 34.8 g CaCl₂/100 g water, respectively);¹¹⁶ −78 °C: acetone–solid CO₂.

Solvent removal or concentration refers to solvent removal under reduced pressure (water aspirator) via a Büchi rotary evaporator at ≈15 Torr.

Thin layer chromatography (TLC) was performed using commercial aluminum-backed silica gel 60 F₂₅₄ plates from E. Merck, type 5554, 0.2 mm. Reversed phase TLC was carried out on commercially available glass backed plates from Whatman, type KC₁₈/KC₁₈F. Visualization was accomplished using ultraviolet light (254 nm) and/or iodine, followed by heating the plates after staining with an appropriate reagent. The following stains were used:
1) phosphomolybdic acid in ethanol from Aldrich Chemical Co. Inc., 2) cerium sulfate-
ammonium molybdate in aqueous H$_2$SO$_4$ (0.40 g Ce(SO$_4$)$_2$, 20 g (NH$_4$)$_6$Mo$_7$O$_{24}$$\cdot$4H$_2$O, 400
mL 10% aqueous H$_2$SO$_4$), 3) anisaldehyde in H$_2$SO$_4$-ethanol (20 mL anisaldehyde, 20 mL
concentrated H$_2$SO$_4$, 400 mL ethanol), 4) basic aqueous KMnO$_4$ (3 g KMnO$_4$, 20 g K$_2$CO$_3$, 5
mL 5% aqueous NaOH, 300 mL water). Flash chromatography$^{117}$ was performed using 230–
400 mesh silica gel 60 from E. Merck. Reversed phase chromatography was performed using
C$_{18}$ functionalized$^{118}$ silica gel 60 with an appropriate solvent system applied to the technique
described by Still.$^{117}$ TLC grade flash chromatography was performed using Sigma type H
silica gel 10–40 µm, no binder, following the technique described by Taber.$^{119}$

Gas–liquid chromatography (GLC) was performed on Hewlett-Packard model 5830A,
5880A or 5890 gas chromatographs, all three equipped with flame ionization detectors and
fused capillary columns, either 25 m × 0.20 mm coated with 5% phenylmethyl silicone or
Stabilwax 30 m × 0.25 mm × 0.25 µm.

High performance liquid chromatography (HPLC) was performed using a Waters
600E Multisolvent Delivery System connected in series, to 1) a Waters 486 Tunable
Absorbance Detector and 2) a Waters 410 Differential Refractometer. The following columns
were used: 1) Waters µPorasil silica 10 µm, 8 mm × 100 mm; 2) Waters µBondapak 10 µm, 8
mm × 100 mm and 25 mm × 100 mm; 3) Whatman Magnum 20 Partisil silica 10 µm, 20 mm ×
250 mm.

Unless otherwise noted, distillations refer to bulb-to-bulb distillations; the temperature
is indicated in parentheses and is uncorrected. Melting points were recorded on a Fisher-
Johns melting point apparatus and are uncorrected.
Proton nuclear magnetic resonance (1H NMR) spectra were recorded on Bruker models AC-200 (200.1 MHz) or WH-400 (400.1 MHz) spectrometers using deuteriochloroform (CDCl₃) or deuteriobenzene (C₆D₆) as solvents. Signal positions (δ) are given in parts per million from tetramethylsilane and were measured relative to the residual signal of chloroform (δ 7.24) or benzene (δ 7.15). The following abbreviations are used to describe the multiplicity: br = broad, d = doublet, m = multiplet, q = quartet, s = singlet, t = triplet. Coupling constants (J values) are given in Hertz (Hz). Data are reported in the following format: chemical shift (ppm), multiplicity, number of protons, coupling constants (Hz) and assignment (when known). In some instances the assignments are supported by COSY (1H-1H homonuclear correlation spectroscopy) and 1H NMR NOE (nuclear Overhauser enhancement) difference experiments. These experiments were carried out using the Bruker WH-400 spectrometer.

Carbon nuclear magnetic resonance (13C NMR) spectra were recorded on Varian XL-300 (75.4 MHz) or Bruker AMX-500 (125.7 MHz) spectrometers, using deuteriochloroform or deuteriobenzene as solvents. Signal positions are given in parts per million from tetramethylsilane and were measured relative to the signal of deuteriochloroform (δ 77.0) or deuteriobenzene (δ 128.0). Attached proton test (APT) experiments were used to differentiate methyl and methine from methylene and quaternary carbons.

Infrared (IR) spectra were recorded on a Perkin Elmer 1710 Fourier transform spectrophotometer with internal calibration using sodium chloride plates for liquids and potassium bromide pellets for solid samples.

Low and high resolution electron impact (EI) mass spectra were recorded on Kratos
MS 50 or MS 80 mass spectrometers at 70 eV. The molecular ion \((M^+)\) masses are given unless otherwise stated. Low and high resolution desorption chemical ionization (DCI) spectra were recorded on a Delsi Nermag R10-10 C mass spectrometer using \(\text{CH}_4\), isobutane or a \(\text{NH}_3 + \text{CH}_4\) mixture and masses are given as \((M + 1)^+\) unless otherwise stated. Gas–liquid chromatography–low resolution mass spectrometry was performed on a Carlo Erba model 4160 capillary gas chromatograph (15 m \(\times\) 0.25 mm fused silica column coated with DB-5) and a Kratos MS 80 mass spectrometer, interfaced with a hollow capillary tube. The following masses were used to calculate the mass of the ions in the high resolution mass spectra (HRMS): \(^1\text{H} 1.007825, \ ^{12}\text{C} 12.000000, \ ^{14}\text{N} 14.003074, \ ^{16}\text{O} 15.994915, \ ^{28}\text{Si} 27.976927, \ ^{30}\text{Si} 29.973770, \ ^{32}\text{S} 31.972070, \ ^{35}\text{Cl} 34.968852, \ ^{37}\text{Cl} 36.965903, \ ^{72}\text{Ge} 71.922079, \ ^{74}\text{Ge} 73.921177. \) All compounds subjected to HRMS were homogeneous by TLC and/or GLC analyses.

Elemental analyses were performed on a Carlo Erba CHN model 1106 or on a Fisons EA model 1108 elemental analyzer, by the UBC Microanalytical Laboratory.
3.1.2 SOLVENTS AND REAGENTS

All solvents and reagents were purified using established procedures.\textsuperscript{120} Diethyl ether, dibutyl ether and tetrahydrofuran (THF) were heated at reflux over and distilled from sodium–benzophenone ketyl radical. Dichloromethane and benzene were heated at reflux over and distilled from calcium hydride. The five aforementioned solvents were distilled under an atmosphere of argon and used immediately. Acetonitrile, HMPA and $N,N$-dimethylformamide were heated at reflux over and distilled from calcium hydride under an atmosphere of argon and stored under argon in bottles sealed with a Sure/Seal (Aldrich Chemical Co. Inc.). Magnesium turnings were added to methanol and the mixture was heated at reflux under an atmosphere of argon. The methanol was distilled from the formed magnesium methoxide and stored under argon over 4Å molecular sieves in bottles sealed with a Sure/Seal (Aldrich Chemical Co. Inc.). Chlorotrimethylsilane was heated at reflux over and distilled from calcium hydride and was used immediately. Bromotrimethylsilane was distilled (bulb-to-bulb) from calcium hydride and was used immediately. Petroleum ether refers to a mixture of hydrocarbon with a boiling range of 35–60 °C. All others solvents were used without further purification.

Solutions of mehylithium in diethyl ether, $n$-butyllithium in hexanes and tert-butyllithium in pentane were obtained from Aldrich Chemical Co. Inc., and were standardized using the procedure of Kofron and Baclawski.\textsuperscript{121}

Copper(I) bromide–dimethyl sulfide complex was prepared by the method described by Wuts\textsuperscript{122} and was stored in a desiccator under an atmosphere of dry argon.

Methyltriphenylphosphonium bromide was heated at 110–120 °C (using an oil bath)
under reduced pressure (0.05 Torr) for 3 h and then was stored under an atmosphere of argon.

Aqueous ammonium chloride–ammonium hydroxide (NH₄Cl–NH₄OH, pH 8–9) was prepared by the addition of 50 mL of concentrated aqueous ammonium hydroxide to 950 mL of saturated aqueous ammonium chloride solution.

All other reagents are commercially available and were used without further purification.
3.2 SYNTHESIS OF 2-TRIMETHYLGEMYLALK-1-ENES VIA PLATINUM CATALYZED HYDROGERMYLATION OF 1-TRIMETHYLSILYLALK-1-YNES

3.2.1 SYNTHESIS OF 1-TRIMETHYLSILYLALK-1-YNES

3.2.1.1 General Procedure 1: Preparation of the 1-Trimethylsilylalk-1-ynes 61 and 63

To a cold (−78 °C) stirred solution of the alk-1-yne (1 equiv) in dry THF (0.2–0.3 M) was added a solution of MeLi in diethyl ether (2.2–2.3 equiv). The resultant mixture was stirred at −78 °C for 1.25–2 h. Chlorotrimethylsilane (2.5–2.6 equiv) was added, the cooling bath was removed and the mixture was allowed to stir at rt for at least 1.5 h. Ice-cold saturated aqueous NaHCO3 (=10 mL per mmol of alkyne) was added. The mixture was diluted with diethyl ether (=10 mL per mmol of alkyne) and the layers were separated. Ice was added to the aqueous layer and the latter was extracted with diethyl ether (2 × ≈3 mL per mmol of alkyne). The pooled organic extracts were washed with an ice–water mixture (≈3 mL per mmol of alkyne) and with ice-cold brine (2 × ≈3 mL per mmol of alkyne), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The oil thus obtained was distilled to provide the desired 1-trimethylsilylalk-1-yne.

3.2.1.1.1 Synthesis of 1-Trimethylsilyl-6-(trimethylsilyloxy)hex-1-yne (61)

Following general procedure 1, to a solution of hex-5-yn-1-ol (55) (1.10 g, 11.2
mmol, 1 equiv) in dry THF (57 mL) was added a solution of MeLi (1.40 M in diethyl ether, 17.6 mL, 24.6 mmol, 2.20 equiv). The thick mixture was stirred at -78 °C for 2 h, then chlorotrimethylsilane (3.04 g, 28.0 mmol, 2.50 equiv) was added. The resulting solution was warmed to rt and was allowed to stir for an additional 1.5 h. The crude oil acquired was distilled (60–69 °C/0.04 Torr) to yield 2.61 g (96%) of the title compound as a clear colorless oil.

\[ \text{H NMR (400 MHz, CDCl}_3\text{): } \delta 3.58 (t, 2H, J = 6.2 \text{ Hz, } -\text{CH}_2\text{O}-), 2.22 (t, 2H, J = 6.8 \text{ Hz, } -\text{CH}_2\text{C}=\text{C}-), 1.68–1.50 (m, 4H), 0.12 (s, 9H, -C≡CSi(CH}_3\text{)}_3\text{), 0.09 (s, 9H, } -\text{OSi(CH}_3\text{)}_3\text{).} \]

\[ \text{C NMR (75.4 MHz, CDCl}_3\text{): } \delta 107.1 (-\text{C≡CSi(CH}_3\text{)}_3\text{), 84.4 (-C≡CSi(CH}_3\text{)}_3\text{), 62.0 (-CH}_2\text{O}-), 31.7 (-\text{CH}_2\text{CH}_2\text{O}-), 24.9 (-\text{CH}_2\text{CH}_2\text{C}=\text{C}-), 19.5 (-\text{CH}_2\text{C}=\text{C}-), 0.1 (-C≡CSi(CH}_3\text{)}_3\text{), -0.6 (-OSi(CH}_3\text{)}_3\text{).} \]

IR (film): 2176, 1251, 1106, 841, 760 cm\(^{-1}\).

HRMS for C\(_{12}\)H\(_{26}\)O\(^{28}\)Si\(_2\): calcd 242.1522, found 242.1513.

Anal. calcd for C\(_{12}\)H\(_{26}\)OSi\(_2\): C 59.43, H 10.81; found: C 59.10, H 10.71.

### 3.2.1.1.2 Synthesis of 1-Trimethylsilyl-4-(trimethylsilyloxy)but-1-yne (63)

![Structure of 1-Trimethylsilyl-4-(trimethylsilyloxy)but-1-yne](image)

Following general procedure 1, to a solution of but-3-yn-1-ol (56) (2.51 g, 35.8 mmol, 1 equiv) in dry THF (120 mL) was added a solution of MeLi (1.40 M in diethyl ether, 59 mL, 82 mmol, 2.3 equiv). The resulting solution was stirred at -78 °C for 1.25 h, then chloro-
trimethylsilane (10.1 g, 93.0 mmol, 2.60 equiv) was added. The mixture was warmed to rt and was allowed to stir overnight. The crude oil acquired was distilled (bp 85 °C/12 Torr) to yield 7.36 g (96%) of the title compound as a clear colorless oil.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 3.67 (t, 2H, $J = 7.2$ Hz, -OCH$_2$-), 2.43 (t, 2H, $J = 7.2$ Hz, -CH$_2$C≡C-), 0.13 (s, 9H, -C≡CSi(CH$_3$)$_3$), 0.11 (s, 9H, -OSi(CH$_3$)$_3$).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 103.9 (-C≡CSi(CH$_3$)$_3$), 85.5 (-C≡CSi(CH$_3$)$_3$), 61.2 (-CH$_2$O-), 24.1 (-CH$_2$C≡C-), 0.0 (-C≡CSi(CH$_3$)$_3$), −0.5 (-OSi(CH$_3$)$_3$).

IR (film): 2179, 1252, 1104, 843, 760 cm$^{-1}$.

HRMS for C$_{10}$H$_{22}$O$^{28}$Si$_2$: calcd 214.1209, found 214.1202.

Anal. calcd for C$_{10}$H$_{22}$OSi$_2$: C 56.01, H 10.34; found: C 55.75, H 10.45.

3.2.1.2 SYNTHESIS OF 6-TRIMETHYLSILYLHEX-5-YN-1-OL (62)

![structure](image)

To a cold (−78 °C) stirred solution of hex-5-yn-1-ol (55) (1.47 g, 15.0 mmol, 1 equiv) in dry THF (134 mL) was added a solution of MeLi (1.46 M in diethyl ether, 22.6 mL, 33.0 mmol, 2.20 equiv). The reaction mixture was warmed to 0 °C and was allowed to stir for 2 h at 0 °C, after which time it became a white opaque mixture. Chlorotrimethylsilane (4.07 g, 37.5 mmol, 2.50 equiv) was added, then the cooling bath was removed and the solution was allowed to stir at rt for 2.5 h. The reaction mixture was treated with 1 M hydrochloric acid (50 mL) and ethyl acetate (300 mL) was added. The layers were separated and the aqueous portion was extracted with ethyl acetate (2 × 100 mL). The combined organic extracts were
washed with brine (2 × 100 mL), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil thus acquired was subjected to flash chromatography (100 g TLC grade silica gel, 7:3 petroleum ether–ethyl acetate) and distilled (68–82 °C/0.05 Torr) to afford 2.11 g (82%) of the title compound as a clear colorless oil.

\[ \text{^1H NMR (400 MHz, CDCl}_3\text{): } \delta 3.66 (t, 2H, } J = 6.2 \text{ Hz, } \text{-CH}_2\text{OH}, 2.25 (t, 2H, } J = 6.8 \text{ Hz, } \text{-CH}_2\text{C}C\text{-}, 1.71-1.55 (m, 4H, } -(\text{CH}_2)_2\text{CH}_2\text{OH}, 1.42 (br s, 1H, exchanges with } \text{D}_2\text{O, } \text{-OH}, 0.12 (s, 9H, } \text{Si(CH}_3\text{)_3}). \]

\[ \text{^13C NMR (75.4 MHz, CDCl}_3\text{): } \delta 107.1 (-\text{-C}C\text{-Si(CH}_3\text{)_3}), 84.6 (-\text{-C}C\text{-Si(CH}_3\text{)_3}, 61.9 (-\text{-CH}_2\text{OH}), 31.6 (-\text{-CH}_2\text{CH}_2\text{OH), 24.8 (-\text{-CH}_2\text{CH}_2\text{C}C\text{-), 19.5 (-\text{-CH}_2\text{C}C\text{-), 0.0 (-Si(CH}_3\text{)_3}).} \]

IR (film): 3348, 2957, 2175, 1250, 1047, 844, 760 cm\(^{-1}\).

HRMS for C\(_8\)H\(_{15}\)O\(_2\)Si (M – CH\(_3\))\(^+\): calcd 155.0892, found 155.0892.

Anal. calcd for C\(_9\)H\(_{18}\)OSi: C 63.47, H 10.65; found: C 63.33, H 10.52.

3.2.1.3 General Procedure 2: Preparation of the 1-Trimethylsilylalk-1-ynes 64–66

To a cold (−78 °C) stirred solution of the alk-1-yne (1 equiv) in dry ethereal solvent (diethyl ether or THF, 0.1–0.25 M) was added a solution of MeLi in diethyl ether or n-BuLi in hexanes (1.1–1.25 equiv) via a syringe. The resulting solution was stirred at −78 °C for 1.5–2 h, then chlorotrimethylsilane (1.3–1.5 equiv) was added. The reaction mixture was stirred at −78 °C for a short period of time, then the cooling bath was removed and the mixture was
allowed to stir at rt for at least 1 h. Saturated aqueous NaHCO$_3$ (=2 mL per mmol of alkyne) was added. The mixture was diluted with diethyl ether (=10 mL per mmol of alkyne) and the layers were separated. The organic layer was washed with saturated aqueous NaHCO$_3$ (1 × =2 mL per mmol of alkyne) and the pooled aqueous layers were extracted with diethyl ether (2 × =3 mL per mmol of alkyne). The combined organic extracts were washed with water (2 × =3 mL per mmol of alkyne) and brine (1 × =3 mL per mmol of alkyne), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The oil thus acquired was distilled to provide the desired 1-trimethylsilylalk-1-yne.

3.2.1.3.1 Synthesis of 1-Trimethylsilyldodec-1-yne (64)

Following general procedure 2, to a solution of dodec-1-yne (57) (1.04 g, 6.27 mmol, 1 equiv) in dry THF (63 mL) was added a solution of n-BuLi (1.58 M in hexanes, 4.76 mL, 7.53 mmol, 1.20 equiv). The reaction mixture was stirred at -78 °C for 2 h, then chlorotrimethylsilane (1.02 g, 9.41 mmol, 1.50 equiv) was added. The resultant solution was warmed to rt and was allowed to stir overnight. The crude oil obtained was distilled (72–77 °C/0.04 Torr) to afford 1.46 g (98%) of the title compound as a clear colorless oil.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 2.19 (t, 2H, J = 7.2 Hz, -CH$_2$C≡C-), 1.49 (quintuplet, 2H, J = 7.2 Hz, -CH$_2$CH$_2$C≡C-), 1.40–1.33 (br m, 3H), 1.33–1.20 (br s, 11H), 0.86 (br t, 3H, J = 6.8 Hz, -CH$_2$CH$_3$), 0.12 (s, 9H, -Si(CH$_3$)$_3$).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 107.5 (-C≡CSi(CH$_3$)$_3$), 84.1 (-C≡CSi(CH$_3$)$_3$), 32.0, 29.62,
29.57, 29.4, 29.1, 28.8, 28.7, 22.7, 19.9 (-CH=CH-C=), 14.1 (-CH2CH3), 0.1 (-Si(CH3)3).

IR (film): 2176, 1250, 843, 760 cm⁻¹.

HRMS for C15H3028Si: calcd 238.2117, found 238.2123.

Anal. calcd for C15H30Si: C 75.54, H 12.68; found: C 75.29, H 12.77.

3.2.1.3.2 Synthesis of 5-Chloro-1-trimethylsilylpent-1-yne (65)

Following general procedure 2, to a solution of 5-chloropent-1-yne (58) (5.05 g, 49.2 mmol, 1 equiv) in dry diethyl ether (200 mL) was added a solution of MeLi (1.40 M in diethyl ether, 43.9 mL, 61.5 mmol, 1.25 equiv). The resultant mixture was stirred at -78 °C for 1.5 h. Chlorotrimethylsilane (8.02 g, 73.8 mmol, 1.50 equiv) was added and the mixture was stirred for an additional 45 min at -78 °C. The cooling bath was removed and the solution was stirred at rt overnight. The crude oil obtained was distilled (bp 108–112 °C/70 Torr) to provide 7.82 g (91%) of the title compound as a clear colorless oil.

1H NMR (400 MHz, CDCl3): δ 3.62 (t, 2H, J = 6.6 Hz, -CH2C=), 2.39 (t, 2H, J = 6.6 Hz, -CH2C=), 1.94 (quintuplet, 2H, J = 6.6 Hz, -CH2CH2CH2-), 0.13 (s, 9H, -Si(CH3)3).

13C NMR (75.4 MHz, CDCl3): δ 105.1 (-C≡CSi(CH3)3), 85.5 (-C≡CSi(CH3)3), 43.4, 31.3, 17.2, 0.0 (-Si(CH3)3).

IR (film): 2177, 1250, 844, 761 cm⁻¹.
HRMS for C₈H₁₅³⁵Cl²⁸Si: calcd 174.0632, found 174.0624.

Anal. calcd for C₈H₁₅ClSi: C 54.99, H 8.65; found: C 55.18, H 8.80.

### 3.2.1.3.3 Synthesis of 1-Phenyl-2-trimethylsilylacetylene (66)

![Chemical structure of 1-Phenyl-2-trimethylsilylacetylene (66)](image_url)

Following general procedure 2, to a solution of phenylacetylene (59) (2.64 g, 25.9 mmol, 1 equiv) in dry THF (130 mL) was added a solution of n-BuLi (1.59 M in hexanes, 17.9 mL, 28.5 mmol, 1.10 equiv). The solution was stirred at -78 °C for 1 h, after which time a white suspension formed. The mixture was stirred for an additional hour, then chlorotrimethylsilane (3.65 g, 33.6 mmol, 1.30 equiv) was added. The resulting solution was warmed to rt and was allowed to stir for 1 h. The crude oil obtained was distilled (110–120 °C/11 Torr) to provide 4.31 g (96%) of the title compound as a clear colorless oil.

¹H NMR (400 MHz, CDCl₃): δ 7.50–7.42 (m, 2H), 7.32–7.26 (m, 3H), 0.24 (s, 9H, -Si(CH₃)₃).

¹³C NMR (75.4 MHz, CDCl₃): δ 131.9, 128.4, 128.2, 123.1 (aromatic ipso carbon), 105.1 (-C≡CSi(CH₃)₃), 94.0 (-C≡CSi(CH₃)₃), 0.0 (-Si(CH₃)₃).

IR (film): 3081, 2961, 2900, 2160, 1599, 1489, 1445, 864, 758, 691, 645 cm⁻¹.

HRMS for C₁₁H₁₄²⁸Si: calcd 174.0865, found 174.0866.

Anal. calcd for C₁₁H₁₄Si: C 75.79, H 8.10; found: C 75.51, H 8.03.
3.2.1.4 SYNTHESIS OF 1,6-BIS(TRIMETHYLSILYL)HEXA-1,5-DIYNE (67)

To a cold (−78 °C) stirred solution of hexa-1,5-diyne (60) (558 mg, 7.15 mmol, 1 equiv) in dry THF (36 mL) was added a solution of MeLi (1.40 M in diethyl ether, 12.3 mL, 17.2 mmol, 2.40 equiv). The resulting solution was stirred at −78 °C for 0.5 h, then chlorotrimethylsilane (2.02 g, 18.6 mmol, 2.60 equiv) was added. The reaction mixture was warmed to rt and was allowed to stir for an additional hour. Saturated aqueous NaHCO$_3$ (25 mL) was added. The mixture was diluted with diethyl ether (175 mL), the layers were separated and the organic layer was washed with another portion of saturated aqueous NaHCO$_3$ (25 mL). The pooled aqueous layers were extracted with diethyl ether (2 × 20 mL). The combined organic extracts were washed with water (20 mL) and brine (20 mL), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude solid thus acquired was recrystallized from a pentane–methanol mixture to afford 1.14 g (71%) of the title compound as colorless crystals (mp 46–46.5 °C).

$^1$H NMR (400 MHz, CDCl$_3$): δ 2.41 (s, 4H, -CH$_2$CH$_2$-), 0.13 (s, 18H, 2 × -Si(CH$_3$)$_3$).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): δ 105.1 (-C≡CSi(CH$_3$)$_3$), 85.5 (-C≡CSi(CH$_3$)$_3$), 20.0 (-CH$_2$-), 0.1 (-Si(CH$_3$)$_3$).

IR (KBr pellet): 2180, 1249, 1023, 844, 759, 637 cm$^{-1}$.

HRMS for C$_{12}$H$_{22}$Si$_2$: calcd 222.1260, found 222.1258.

Anal. calcd for C$_{12}$H$_{22}$Si$_2$: C 64.78, H 9.97; found: C 64.50, H 10.11.
3.2.1.5 SYNTHESIS OF 2-(Cyclopent-2-en-1-yl)ethanol (69), 1-(Cyclopent-2-en-1-yl)-2-iodoethane (70) AND 4-(Cyclopent-2-en-1-yl)-1-trimethylsilylbut-1-yn (72)

\[ \text{69} \]
\[ \text{70} \]
\[ \text{72} \]

a) 2-(Cyclopent-2-en-1-yl)ethanol (69)

To a cold (0 °C) stirred slurry of LiAlH\(_4\) (1.15 g, 30.3 mmol, 1.20 equiv) in dry diethyl ether (225 mL) was added dropwise, via a cannula, a solution of (cyclopent-2-en-1-yl)acetic acid (68) (3.18 g, 25.2 mmol, 1 equiv) in diethyl ether (25 mL). The heterogeneous mixture was allowed to stir at rt for 1.5 h, then 1 M hydrochloric acid (=55 mL total) was cautiously added until the pH of the aqueous layer reached ≈3. Diethyl ether (200 mL) was added and the layers were separated. The aqueous layer was extracted with diethyl ether (3 × 50 mL). The combined organic extracts were washed with water (25 mL), saturated aqueous NaHCO\(_3\) (25 mL), and brine (2 × 25 mL), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil thus obtained was distilled (118–128 °C/11 Torr) to afford 2.72 g (96%) of 2-(cyclopent-2-en-1-yl)ethanol (69) as a clear colorless oil.

\(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta\) 5.73–5.70 (m, 1H, vinylic proton), 5.68–5.65 (m, 1H, vinylic proton), 3.73–3.63 (m, 2H, -CH\(_2\)OH), 2.80–2.70 (m, 1H, allylic methine proton), 2.39–2.21 (m, 2H), 2.05 (dtd, 1H, \(J = 13.2, 8.4\) and \(4.8\) Hz), 1.72–1.63 (m, 1H), 1.60–1.51 (m, 1H), 1.46–1.37 (m, 1H), 1.32 (br s, 1H, exchanges with D\(_2\)O, -OH).
$^{13}$C NMR (75.4 MHz, CDCl$_3$): δ 134.6 (vinyllic carbon), 130.5 (vinyllic carbon), 61.6 (-CH$_2$OH), 42.0 (allylic methine carbon), 38.8, 31.8, 29.7.

IR (film): 3338, 3051, 2931, 1614, 1433, 1359, 1059, 720 cm$^{-1}$.

HRMS for C$_7$H$_{12}$O: calcd 112.0888, found 112.0890.

b) 1-(Cyclopent-2-en-1-yl)-2-iodoethane (70)

To a stirred mixture of dry diethyl ether–acetonitrile (3:1, 236 mL total) at rt was added sequentially triphenylphosphine (19.2 g, 73.1 mmol, 3.10 equiv) and imidazole (4.98 g, 73.1 mmol, 3.10 equiv). The clear colorless solution was cooled to 0 °C and iodine (18.6 g, 73.1 mmol, 3.10 equiv) was added in three approximately equal portions. After the mixture had been stirred for 20 min at 0 °C, the mustard-yellow suspension was treated, via a cannula, with a solution of 2-(cyclopent-2-en-1-yl)ethanol (69) (2.64 g, 23.6 mmol, 1 equiv) in dry diethyl ether (10 mL). The reaction mixture was stirred for an additional 20 min, then was treated with saturated aqueous Na$_2$S$_2$O$_3$ (150 mL). Diethyl ether (200 mL) was added and the layers were separated. The organic layer was washed with saturated aqueous Na$_2$S$_2$O$_3$ (6 x 25 mL). The pooled aqueous layers were extracted with diethyl ether (3 x 25 mL). The combined organic extracts were washed with 10% aqueous CuSO$_4$ (2 x 25 mL), water (2 x 25 mL), and brine (2 x 25 mL), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The residue was passed through a column of Florisil (85 g, elution with petroleum ether, 200 mL) and the eluate was concentrated under reduced pressure. The crude oil thus acquired was distilled (118–128 °C/11 Torr) to yield 4.82 g (92%) of 1-(cyclopent-2-en-1-yl)-2-iodoethane (70) as a clear colorless oil.
$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 5.77–5.73 (m, 1H, vinylic proton), 5.65–5.61 (m, 1H, vinylic proton), 3.25–3.12 (m, 2H, -CH$_2$I), 2.80–2.70 (m, 1H, allylic methine proton), 2.40–2.22 (m, 2H), 2.05 (dtd, 1H, $J = 12.8, 8.4$ and $5.2$ Hz), 1.99–1.90 (m, 1H), 1.85–1.76 (m, 1H), 1.42–1.33 (m, 1H).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 133.2 (vinylic carbon), 131.2 (vinylic carbon), 46.4 (allylic methine carbon), 39.9, 31.9, 29.0, 4.9 (-CH$_2$I).

IR (film): 3050, 2931, 1614, 1427, 1231, 1181, 720 cm$^{-1}$.

HRMS for C$_7$H$_{11}$I: calcd 221.9906, found 221.9904.

c) 4-(Cyclopent-2-en-1-yl)-1-trimethylsilylbut-1-yne (72)

To a cold (−78 °C) stirred solution of trimethylsilylacetylene (1.73 g, 17.6 mmol, 1.50 equiv) in dry THF (14 mL) was added a solution of n-BuLi (1.55 M in hexanes, 9.10 mL, 14.1 mmol, 1.20 equiv). The reaction mixture was stirred at −78 °C for 5 min, then was warmed to 0 °C and was allowed to stir at 0 °C for an additional 10 min. A solution of 1-(cyclopent-2-en-1-yl)-2-iodoethane (70) (2.60 g, 11.7 mmol, 1 equiv) in dry HMPA (12 mL) was added dropwise over 30 min via a cannula. The resulting mixture was stirred at 0 °C for 30 min, then was treated with water (10 mL). Diethyl ether (120 mL) was added and the layers were separated. The aqueous layer was extracted with diethyl ether (3 × 50 mL). The pooled organic extracts were washed with 10% aqueous CuSO$_4$ (3 × 25 mL), saturated aqueous Na$_2$S$_2$O$_3$ (25 mL), water (2 × 20 mL), and brine (2 × 20 mL), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil thus obtained was distilled. A forerun (distillation temperature 80–120 °C/39 Torr) was collected in a first bulb (155 mg, volatile material as indicated by GLC
analysis). The remainder of the material was collected in a second bulb (distillation temperature 120–140 °C/39 Torr) to afford 1.76 g (78%) of 4-(cyclopent-2-en-1-yl)-1-trimethylsilylbut-1-ylene (72) as a clear colorless oil.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 5.73–5.70 (m, 1H, vinylic proton), 5.67–5.64 (m, 1H, vinylic proton), 2.80–2.68 (m, 1H, allylic methine proton), 2.38–2.19 (m, 4H), 2.03 (dtd, 1H, $J = 13.2, 8.4$ and 5.0 Hz), 1.67–1.58 (m, 1H), 1.53–1.44 (m, 1H), 1.43–1.34 (m, 1H), 0.12 (s, 9H, -Si(CH$_3$)$_3$).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 134.3 (vinylic carbon), 130.7 (vinylic carbon), 107.5 (-C≡Si(CH$_3$)$_3$), 84.1 (-C≡Si(CH$_3$)$_3$), 44.8 (allylic methine carbon), 34.8, 31.9, 29.4, 18.3 (-CH$_2$C≡C-), 0.1 (-Si(CH$_3$)$_3$).

IR (film): 3053, 2957, 2176, 1614, 1250, 843, 760 cm$^{-1}$.

HRMS for C$_{12}$H$_{20}$Si: calcd 192.1334, found 192.1334.

Anal. calcd for C$_{12}$H$_{20}$Si: C 74.92, H 10.48; found: C 75.10, H 10.38.
3.2.2 SYNTHESIS OF TRIMETHYLGERMANE (53)

\[ \text{Me}_3\text{GeH} \]

53

The apparatus for this reaction was as follows: a 250 mL three-necked flask was equipped with a stir bar, two septa and a water-cooled condenser (15 cm). The condenser was surmounted with a short-path distillation apparatus fitted with a 100 mL receiving flask. This distillation apparatus must have a drip end that can reach deep inside the 100 mL flask. An argon flow through the system was created using an inlet (needle) on one neck of the reaction flask, and a bleed was created on the short path distillation apparatus by inserting a needle through a septum covering the outlet side arm. All joints were sealed with Teflon tape. The 100 mL receiving flask was immersed deep inside a dry ice–acetone bath.

To a cold (0 °C) stirred slurry of LiAlH₄ (2.5 g, 65 mmol, 0.5 equiv) in dry dibutyl ether (100 mL) in the three-necked flask, was added a solution of bromotrimethylgermane (25.7 g, 130 mmol, 1 equiv, freshly distilled from CaH₂) in dry dibutyl ether (17 mL) via a cannula. The mixture was stirred for 5 min at 0 °C, then was heated to 110 °C, with an oil bath, and stirred at this temperature for 3 h while distilling the volatile liquid into the receiving flask cooled to −78 °C. The distilled liquid generally contained 5–10% of dibutyl ether. This liquid was then redistilled (bulb-to-bulb distillation) from −78 °C to 40 °C, under an atmosphere of argon, to afford 14.70 (95%) of essentially pure trimethylgermane (53). The volatile liquid was transferred to a 25 mL round bottom flask fitted with a Teflon Mininert Valve (purchased from the Aldrich Chemical Co. Inc.) and stored at −25 °C in a freezer.

\(^1\text{H NMR (400 MHz, CDCl}_3\): \( \delta \) 3.83 (deciplet, 1H, \( J = 3.6 \text{ Hz}, \text{HGe(CH}_3)_3\)), 0.22 (d, 9H,
$J = 3.6$ Hz, HGe(CH$_3$)$_3$).

$^{13}$C NMR (50.3 MHz, CDCl$_3$): $\delta$ −3.5 (HGe(CH$_3$)$_3$).
3.2.3 ISOLATION OF THE PRODUCTS OF HYDROGERMYLATION OF 6-TRIMETHYLSILYLHEX-5-YN-1-OL (62) AND THEIR TREATMENT WITH p-TOLUENESULFONIC ACID MONOHYDRATE IN DICHLOROMETHANE

3.2.3.1 SYNTHESIS, ISOLATION AND CHARACTERIZATION OF (E)- AND (Z)-5-TRIMETHYLGERMYL-6-TRIMETHYLSILYLHEX-5-EN-1-OLS (73) AND (75), AND (E)- AND (Z)-6-TRIMETHYLGERMYL-6-TRIMETHYLSILYLHEX-5-EN-1-OLS (74) AND (76)

To a stirred solution of 6-trimethylsilylhex-5-yn-1-ol (62) (932 mg, 5.47 mmol, 1 equiv) in CH₂Cl₂ (27 mL) at rt was added H₂PtCl₆•6H₂O (57 mg, 0.11 mmol, 0.020 equiv). The orange solution was cooled to 0°C, stirred for 5 min and Me₃GeH (53) (974 mg, 8.21 mmol, 1.50 equiv) was added via a precooled gas-tight syringe (cooled by running cold water on the barrel). The cooling bath was removed and the reaction mixture was allowed to stir at rt overnight. The black solution was treated with saturated aqueous NaHCO₃ (5 mL) and diethyl ether (150 mL) and the layers were separated. The organic layer was washed with saturated aqueous NaHCO₃ (25 mL) and water (25 mL). The combined aqueous portions were extracted with diethyl ether (2 x 25 mL). The pooled organic extracts were washed with brine (2 x 25 mL), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil thus obtained was subjected to flash chromatography (80 g TLC grade silica gel, 17:3 petroleum ether–ethyl acetate) to afford 1.32 g (83%) of the four title compounds as a mixture.

The acquired liquid was subjected to HPLC (silica Partisil, 10 μm; 22 mm x 250 mm column, 22:3 hexane–ethyl acetate, 9 mL/min, RI detector, UV-vis detector λ = 254 nm) in
four approximately equal portions. This chromatography resulted in a rough separation to afford three fractions, which were concentrated under reduced pressure. The first fraction to be eluted, fraction A (retention time 28–40 min), afforded 985 mg of a mixture of two components. The second fraction to be eluted, fraction B (retention time 40–46 min), afforded 105 mg of an oil which was constituted of a mixture of three components (HPLC analysis). The third fraction to be eluted, fraction C (retention time 46–52 min), afforded 75 mg of an oil which was constituted of a mixture of five components (HPLC analysis).

**a) Isolation and Characterization of (E)-5-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73)**

Part of fraction A (≈200 mg) was submitted to reversed phase HPLC (C
\textsubscript{18} μBondapak, 10 μm; 25 mm × 100 mm column, 3:1 methanol–water, 9 mL/min, UV-vis detector λ = 230 nm) in eight approximately equal portions. The first component to be eluted (retention time 30 min) was concentrated under reduced pressure and then was distilled (72–80 °C/0.04 Torr) to provide 43 mg of pure (E)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73) as a clear colorless oil.

\[ \begin{align*}
\text{Me}_3\text{Si} & \quad \text{Me}_3 \text{Ge} \\
\text{HO} & \quad \text{H} \\
1 & \quad 2 \\
3 & \quad 4 \\
5 & \quad \text{GeMe}_3 \\
6 & \\
\end{align*} \]

\textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): δ 5.81 (s, 1H, vinylic proton), 3.63 (t, 2H, \( J = 6.6 \) Hz, -CH\textsubscript{2}OH), 2.34–2.30 (m, 2H, allylic protons), 1.60–1.53 (m, 2H, -CH\textsubscript{2}CH\textsubscript{2}OH), 1.43–1.35 (m, 2H, homoallylic protons), 1.21 (br s, 1H, exchanges with D\textsubscript{2}O,
-OH), 0.17 (s, 9H, -Ge(CH$_3$)$_3$), 0.09 (s, 9H, -Si(CH$_3$)$_3$).

Additional $^1$H NMR data, derived from NOE difference experiments, are given in Table 15.

$^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 166.7 (C-5), 138.8 (C-6), 62.9 (C-1), 37.4, 33.0, 26.6, 0.6, -1.2.

IR (film): 3318, 2937, 1566, 1411, 1247, 1066, 823, 756, 597 cm$^{-1}$.

HRMS (DCI, CH$_3$) for C$_{12}$H$_{29}$GeO$_2$Si (M + 1)$^+$: calcd 291.1199, found 291.1185.

Anal. calcd for C$_{12}$H$_{29}$GeOSi: C 49.87, H 9.76; found: C 49.83, H 9.79.

Table 15: $^1$H NMR Data from Nuclear Overhauser Enhancement Difference Experiments for (E)-5-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73)

<table>
<thead>
<tr>
<th>Assignments</th>
<th>$^1$H NMR$^a$</th>
<th>Observed NOEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-x</td>
<td>δ ppm (mult, J (Hz))</td>
<td></td>
</tr>
<tr>
<td>H-6$^b$</td>
<td>5.81 (s)</td>
<td>-Ge(CH$_3$)$_3$, -Si(CH$_3$)$_3$</td>
</tr>
<tr>
<td>H-1</td>
<td>3.63 (t, J = 6.6)</td>
<td></td>
</tr>
<tr>
<td>H-4$^b$</td>
<td>2.34–2.30 (m)</td>
<td>H-2, H-3, -Ge(CH$_3$)$_3$, -Si(CH$_3$)$_3$</td>
</tr>
<tr>
<td>H-2</td>
<td>1.60–1.53 (m)</td>
<td></td>
</tr>
<tr>
<td>H-3</td>
<td>1.43–1.35 (m)</td>
<td></td>
</tr>
<tr>
<td>-OH</td>
<td>1.21 (br s)</td>
<td></td>
</tr>
<tr>
<td>-Ge(CH$_3$)$_3$</td>
<td>0.17 (s)</td>
<td>H-1, H-2, H-3, H-4, H-6</td>
</tr>
<tr>
<td>-Si(CH$_3$)$_3$</td>
<td>0.09 (s)</td>
<td>H-4, H-6</td>
</tr>
</tbody>
</table>

$^a$ 400 MHz, CDCl$_3$. $^b$ Irradiation of this signal generated the corresponding NOEs in the right hand column.

The second component to be eluted from the reversed phase HPLC (retention time 33
188 min), was concentrated under reduced pressure to provide 40 mg of an oil which was still a mixture, but had been enriched with the 33 min component. This sample was resubjected to identical HPLC conditions to afford 13 mg of an oil, fraction D, which was 93% pure by GLC analysis.

b) Isolation and Characterization of (Z)-5-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75)

The fraction B (105 mg) from the initial HPLC separation was subjected to HPLC (silica Partisil, 10 μm; 22 mm × 250 mm column, 9:1 hexane–ethyl acetate, 9 mL/min, RI detector, UV-vis detector λ = 254 nm). The last component to be eluted (retention time 51 min) was concentrated under reduced pressure to afford 10.8 mg of an oil which was still a mixture, but had been enriched with the 51 min component. This sample was resubjected to HPLC under identical conditions to afford 5.6 mg of (Z)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75) (92% pure by GLC analysis).

\[ ^1H \text{NMR (400 MHz, CDCl}_3): \delta 6.18 (t, 1H, } J = 1.2 \text{ Hz, vinylic proton), 3.63 (t, 2H, } J = 6.6 \text{ Hz, -CH}_2\text{OH), 2.24 (td, 2H, } J = 7.8 \text{ and 1.2 Hz, allylic protons), 1.57–1.50 (m, 2H, -CH}_2\text{CH}_2\text{OH), 1.43–1.36 (m, 2H, homoallylic protons), 1.23 (br s, 1H, exchanges with D}_2\text{O, -OH), 0.27 (s, 9H, -Ge(CH}_3)_3, 0.10 (s, 9H, -Si(CH}_3)_3.} \]

Additional \(^1\text{H NMR data, derived from NOE difference experiments, are given in Table 16.} \]
$^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 163.9 (C-5), 140.9 (C-6), 62.9 (C-1), 44.4, 32.4, 25.8, 0.83, 0.81.

IR (film): 3325, 2928, 1564, 1461, 1249, 1067, 826, 595 cm$^{-1}$.

HRMS (DCI, NH$_3$ + CH$_4$) for C$_{12}$H$_{29}$GeO$_2$Si (M + 1)$^+$: calcd 291.1199, found 291.1193.

Table 16: $^1$H NMR Data from Nuclear Overhauser Enhancement Difference Experiments for (Z)-5-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75)

<table>
<thead>
<tr>
<th>Assignments</th>
<th>$^1$H NMR$^a$</th>
<th>Observed NOEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-x</td>
<td>$\delta$ ppm (mult, $J$ (Hz))</td>
<td></td>
</tr>
<tr>
<td>H-6$^b$</td>
<td>6.18 (t, $J = 1.2$)</td>
<td>H-3, H-4, -Si(CH$_3$)$_3$</td>
</tr>
<tr>
<td>H-1</td>
<td>3.63 (t, $J = 6.6$)</td>
<td></td>
</tr>
<tr>
<td>H-4$^b$</td>
<td>2.24 (td, $J = 7.8, 1.2$)</td>
<td>H-1, H-2, H-3, H-4, -Ge(CH$_3$)$_3$</td>
</tr>
<tr>
<td>H-2</td>
<td>1.57–1.50 (m)</td>
<td></td>
</tr>
<tr>
<td>H-3</td>
<td>1.43–1.36 (m)</td>
<td></td>
</tr>
<tr>
<td>-OH</td>
<td>1.23 (br s)</td>
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<tr>
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<td>0.27 (s)</td>
<td>H-4</td>
</tr>
<tr>
<td>-Si(CH$_3$)$_3$</td>
<td>0.10 (s)</td>
<td>H-6</td>
</tr>
</tbody>
</table>

$^a$ 400 MHz, CDCl$_3$. $^b$ Irradiation of this signal generated the corresponding NOEs in the right hand column.
c) Isolation and Characterization of (E)-6-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74)

The fraction C (75 mg) from the initial HPLC separation was subjected to HPLC (silica Partisil, 10 μm; 22 mm × 250 mm column, 9:1 hexane–ethyl acetate, 9 mL/min, RI detector, UV-vis detector λ = 254 nm). The fourth component to be eluted (retention time 54 min) was concentrated under reduced pressure to give an oil which was still a mixture, but had been enriched with the 54 min component. This sample was resubjected twice to HPLC under identical conditions and then was distilled (80–89 °C/0.04 Torr) to afford 13 mg of (E)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74) (95% pure by GLC analysis). This sample contained a small amount (5%) of (Z)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75).

\[ 74 \]

\[ \text{Me}_3\text{Si} \quad \text{GeMe}_3 \]

\[ \text{HO} \quad \text{C} \quad \text{H} \]

\[ 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \]

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Table 17: $^1$H NMR Data from Nuclear Overhauser Enhancement Difference Experiments for (E)-6-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74)

![Chemical Structure](image)

<table>
<thead>
<tr>
<th>Assignments</th>
<th>$^1$H NMR$^a$</th>
<th>Observed NOEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-x</td>
<td>$\delta$ ppm (mult, $J$ (Hz))</td>
<td></td>
</tr>
<tr>
<td>H-5$^b$</td>
<td>6.43 (t, $J = 7.0$)</td>
<td>H-4, -Ge(CH$_3$)$_3$</td>
</tr>
<tr>
<td>H-1</td>
<td>3.64 (t, $J = 6.4$)</td>
<td></td>
</tr>
<tr>
<td>H-4$^b$</td>
<td>2.21 (dt, $J = 7.0, 7.0$)</td>
<td>H-1, H-2, H-3, H-5, -Si(CH$_3$)$_3$</td>
</tr>
<tr>
<td>H-2</td>
<td>1.61–1.54 (m)</td>
<td></td>
</tr>
<tr>
<td>H-3</td>
<td>1.49–1.43 (m)</td>
<td></td>
</tr>
<tr>
<td>-OH</td>
<td>1.24 (br s)</td>
<td></td>
</tr>
<tr>
<td>-Ge(CH$_3$)$_3$$^b$</td>
<td>0.17 (s)</td>
<td>H-5</td>
</tr>
<tr>
<td>-Si(CH$_3$)$_3$$^b$</td>
<td>0.12 (s)</td>
<td>H-4</td>
</tr>
</tbody>
</table>

$^a$ 400 MHz, CDCl$_3$. $^b$ Irradiation of this signal generated the corresponding NOEs in the right hand column.

d) Isolation and Characterization of (Z)-6-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76)

![Chemical Structure](image)

The fraction D (13 mg) from the reversed phase HPLC separation of fraction A, was subjected to HPLC (silica µPorasil, 10 µm; 25 mm × 100 mm column, 9:1 hexane–ethyl...
acetate, 10 mL/min, RI detector, UV-vis detector λ = 254 nm). The major component (retention time 17 min) was separated from a small amount of a more polar impurity (retention time 19 min) and was concentrated under reduced pressure to afford 5.8 mg of (Z)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76), which was now 98% pure by GLC analysis.

$^1$H NMR (400 MHz, CDCl$_3$): δ 5.70 (t, 1H, $J = 7.4$ Hz, vinylic proton), 3.64 (t, 2H, $J = 6.6$ Hz, -CH$_2$OH), 2.12 (dt, 2H, $J = 7.4$ and 7.4 Hz, allylic protons), 1.65–1.61 (m, 4H, -(CH$_2$)$_2$CH$_2$OH), 1.34–1.20 (br s, 1H, exchanges with D$_2$O, -OH), 0.24 (s, 9H, -Ge(CH$_3$)$_3$), −0.04 (s, 9H, -Si(CH$_3$)$_3$).

Additional $^1$H NMR data, derived from NOE difference experiments, are given in Table 18.

$^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 138.9 (C-6), 136.5 (C-5), 62.8 (C-1), 33.6, 28.8, 26.7, 0.1, −1.3.

IR (film): 3316, 2953, 1612, 1413, 1247, 1055, 852, 595 cm$^{-1}$.

HRMS (DCI, NH$_3$ + CH$_4$) for C$_{12}$H$_{29}$GeO$_3$Si (M + 1)$^+$: calcd 291.1173, found 291.1180.

Anal. calcd for C$_{12}$H$_{28}$GeOSi: C 49.87, H 9.76; found C 49.74, H 9.80.
Table 18: $^1$H NMR Data from Nuclear Overhauser Enhancement Difference Experiments for (Z)-6-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76)

<table>
<thead>
<tr>
<th>Assignments</th>
<th>$^1$H NMR$^a$</th>
<th>Observed NOEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-x</td>
<td>$\delta$ ppm (mult, $J$ (Hz))</td>
<td></td>
</tr>
<tr>
<td>H-5$^b$</td>
<td>5.70 (t, $J = 7.4$)</td>
<td>H-3, H-4, -Si(CH$_3$)$_3$</td>
</tr>
<tr>
<td>H-1</td>
<td>3.64 (t, $J = 6.6$)</td>
<td></td>
</tr>
<tr>
<td>H-4$^b$</td>
<td>2.12 (dt, $J = 7.4, 7.4$)</td>
<td>H-1, H-5</td>
</tr>
<tr>
<td>H-2, H-3</td>
<td>1.65–1.61 (m)</td>
<td></td>
</tr>
<tr>
<td>-OH</td>
<td>1.34–1.20 (br s)</td>
<td></td>
</tr>
<tr>
<td>-Ge(CH$_3$)$_3$ $^b$</td>
<td>0.24 (s)</td>
<td>H-4</td>
</tr>
<tr>
<td>-Si(CH$_3$)$_3$ $^b$</td>
<td>-0.04 (s)</td>
<td>H-5</td>
</tr>
</tbody>
</table>

$^a$ 400 MHz, CDCl$_3$. $^b$ Irradiation of this signal generated the corresponding NOEs in the right hand column.
3.2.3.2 Treatment of (E)- and (Z)-5-Trimethylgermyl-6-Trimethylsilylhex-5-en-1-ols (73) and (75), and (E)- and (Z)-6-Trimethylgermyl-6-Trimethylsilylhex-5-en-1-ols (74) and (76) with p-Toluenesulfonic Acid Monohydrate in Dichloromethane

3.2.3.2.1 Protodesilylation of (E)-5-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73) to 5-Trimethylgermylhex-5-en-1-ol (92)

To a stirred solution of (E)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (73) (8.8 mg, 0.030 mmol, 1 equiv) in CH$_2$Cl$_2$ (0.5 mL) at rt was added p-TsOH$\cdot$H$_2$O (6.9 mg, 0.036 mmol, 1.2 equiv). The heterogeneous mixture was stirred at rt for 1 h, then was treated with saturated aqueous NaHCO$_3$ (1 mL) and diethyl ether (20 mL). The layers were separated and the organic extract was washed with water (2 mL) and brine (3 mL), was dried over anhydrous magnesium sulfate, and then was filtered and concentrated under reduced pressure. The crude oil thus acquired was subjected to flash chromatography (4 g silica gel, 7:3 petroleum ether–diethyl ether) and distilled (84–90 °C/8 Torr) to afford 6.6 mg (100%) of 5-trimethylgermylhex-5-en-1-ol (92) as a clear colorless oil. Spectral data were identical with those reported in section 3.2.4.1.1 (p 200 ff.).
3.2.3.2.2 Protodesilylation of (Z)-5-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75) to 5-
Trimethylgermylhex-5-en-1-ol (92)

To a stirred solution of (Z)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75) (92% 
pure by GLC analysis, 2.7 mg, 0.0093 mmol, 1 equiv) in CH$_2$Cl$_2$ (0.5 mL) at rt was added 
p-TsOH•H$_2$O (2.1 mg, 0.011 mmol, 1.2 equiv). The heterogeneous mixture was stirred at rt for 
1.5 h, then was treated with saturated aqueous NaHCO$_3$ (1 mL) and diethyl ether (15 mL). 
The layers were separated and the organic extract was washed with water (1 mL) and brine (2 
ml), was dried over anhydrous magnesium sulfate and then was filtered and concentrated 
under reduced pressure. The oil thus acquired was subjected to flash chromatography (4 g 
silica gel, 17:3 petroleum ether–ethyl acetate) to afford 1.1 mg (54%, as a single product) of 
5-trimethylgermylhex-5-en-1-ol (92) as a clear colorless oil. The spectral data were identical 
with those reported in section 3.2.4.1.1 (p 200 ff.).

3.2.3.2.3 Protodesilylation of (Z)-6-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76) to 5-
Trimethylgermylhex-5-en-1-ol (92)

To a stirred solution of (Z)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (76) (9.6 
mg, 0.033 mmol, 1 equiv) in CH$_2$Cl$_2$ (0.5 mL) at rt was added p-TsOH•H$_2$O (7.6 mg, 0.040
mmol, 1.2 equiv). The heterogeneous mixture was stirred at rt for 1.5 h, then was treated with saturated aqueous NaHCO₃ (1 mL) and diethyl ether (15 mL). The layers were separated and the organic extract was washed with water (1 mL) and brine (1 mL), was dried over anhydrous magnesium sulfate and then was filtered and concentrated under reduced pressure. The oil thus acquired was subjected to flash chromatography (4 g silica gel, 17:3 petroleum ether–ethyl acetate) to afford 6.1 mg (85%) of 5-trimethylgermylhex-5-en-1-ol (92) as a clear colorless oil. The spectral data were identical with those reported in section 3.2.4.1.1 (p 200 ff.). GLC analysis of the crude mixture as well as GLC and GLC–MS analyses of the chromatographed product revealed the presence of a small amount (=2.5%) of (E)-6-trimethylsilylhex-5-en-1-ol (94a) (vide infra) also formed during the reaction.

3.2.3.2.4 Protiodegermylation of (E)-6-Trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74) to (E)- and (Z)-6-Trimethylsilylhex-5-en-1-ol (94a) and (94b)

![Chemical Structure](image)

To a stirred solution of (E)-6-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (74) (6.6 mg, 0.023 mmol, 1 equiv) in CH₂Cl₂ (0.5 mL) at rt was added p-TsOH•H₂O (5.2 mg, 0.027 mmol, 1.2 equiv). The heterogeneous mixture was stirred at rt for 1.25 h, then was treated with saturated aqueous NaHCO₃ (1 mL) and diethyl ether (15 mL). The layers were separated and the organic extract was washed with water (1 mL) and brine (1 mL), was dried over anhydrous magnesium sulfate, and then was filtered and concentrated under reduced
pressure. The oil thus acquired was subjected to flash chromatography (4 g silica gel, 17:3 petroleum ether–ethyl acetate) to afford 4.4 mg of a clear colorless oil. $^1$H NMR (400 MHz, CDCl$_3$) spectroscopic, GLC and GLC–MS (Cl, NH$_3$) analyses of the mixture revealed the presence of three products, as well as a small amount (=5%) of unreacted starting material. The $^1$H NMR spectrum showed 6 signals in the 6.50–5.10 ppm region integrating for a total of 2 protons, a triplet at 3.62 ppm (2H), a multiplet at 2.26–2.08 ppm (2H), a multiplet at 1.63–1.40 ppm (4H) and 5 singlets in the 0.20–0.02 ppm region integrating for a total of 9 protons.

\[
\text{Me}_3\text{Si} \quad \text{H} \\
\text{HO} \quad \text{94b}
\]

The major product (=72%) was assigned structure 94b, (Z)-6-trimethylsilylhex-5-en-1-ol, formed by protiodegermylation of the starting material, based on the following data. $^1$H NMR: $\delta$ 6.27 (dt, 1H, $J$ = 14.0 and 7.0 Hz), 5.48 (dt, 1H, $J$ = 14.0 and 1.2 Hz). Homonuclear decoupling of the 6.27 signal resulted in the collapse of the 5.48 ppm doublet of triplets to a triplet, also revealing a small doublet previously hidden (vide infra). GLC-MS indicated an ion at 173 (M + 1)$^+$, as well as diagnostic fragments at 157 (M – CH$_3$)$^+$ and 73 (-Si(CH$_3$)$_3$)$^+$.

\[
\text{H} \quad \text{SiMe}_3 \\
\text{HO} \quad \text{94a}
\]

Similarly, the next major component (18%) was assigned structure 94a, (E)-6-trimethylsilylhex-5-en-1-ol, based on the following data. $^1$H NMR: $\delta$ 6.00 (dt, 1H, $J$ = 18.6
and 6.2 Hz), 5.62 (dt, 1H, $J = 18.6$ and 1.5 Hz). GLC-MS indicated an ion at 173 (M + 1)$^+$, as well as diagnostic fragments at 157 (M − CH$_3$)$^+$ and 73 (-Si(CH$_3$)$_3$)$^+$. The minor product (≈5%) formed during the reaction was 5-trimethylgermylhex-5-en-1-ol (92). The assignment was established based on the following: characteristic doublets at 5.49 (revealed during the decoupling experiment at 6.27 ppm) and 5.16 ppm in the $^1$H NMR spectrum, GLC-MS indicated an ion 219 (M + 1)$^+$ with an isotopic cluster consistent with the expected isotopic distribution and finally, coinjection with an authentic sample on GLC ascertained that this product has a retention time identical with that of 5-trimethylgermylhex-5-en-1-ol (92). The presence of this compound can be linked to the small (5%) amount of (Z)-5-trimethylgermyl-6-trimethylsilylhex-5-en-1-ol (75) in the starting material, incompletely separated from 74 during the isolation, which underwent protodesilylation (vide supra).
3.2.4 SYNTHESIS OF 2-TRIMETHYLGERMYLALK-1-ENES

3.2.4.1 GENERAL PROCEDURE 3: PREPARATION OF THE 2-TRIMETHYLGERMYLALK-1-ENES

To a stirred solution of the appropriate 1-trimethylsilylalk-1-yne (1 equiv) in dry CH₂Cl₂ (1 M solution) at rt was added H₂PtCl₆•6H₂O (=0.02 equiv unless otherwise noted). The mixture was cooled to 0 °C, stirred for 5 min and Me₃GeH (53) (1.50 equiv unless otherwise noted) was added via a precooled gas-tight syringe (cooled by running cold water on the barrel). The reaction mixture was warmed to rt and stirred until the conversion of the starting material appeared to be complete (1–21 h) by TLC or GLC analysis of an aliquot of the reaction mixture. The mixture was filtered through a short column of Florisil or silica gel (=3 g per mmol of 1-trimethylsilylalk-1-yne) and the column was eluted with CH₂Cl₂ or diethyl ether (=30 mL per mmol of 1-trimethylsilylalk-1-yne). The eluate was concentrated under reduced pressure. The dark oil thus obtained was dissolved in CH₂Cl₂ (0.1 M, nonanhydrous; reaction not performed under inert atmosphere) and p-TsOH•H₂O (1.20 equiv unless otherwise noted) was added. The stirred heterogeneous mixture was heated, using an oil bath, at 30–34 °C until the protiodesilylation appeared to be complete (1–7 h) by GLC analysis of an aliquot of the reaction mixture. After the mixture had been cooled, it was diluted with diethyl ether (=20 mL per mmol of 1-trimethylsilylalk-1-yne) and saturated aqueous NaHCO₃ (=3 mL per mmol of 1-trimethylsilylalk-1-yne) was added. The layers were separated and the aqueous portion was extracted with diethyl ether (2 x ≈3 mL per mmol of 1-trimethylsilylalk-1-yne). The pooled organic extracts were washed with water (≈3 mL per mmol of 1-trimethylsilylalk-1-yne), and brine (≈3 mL per mmol of 1-trimethylsilylalk-1-yne),
were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil was flash chromatographed and the acquired oil was distilled to afford the desired 2-trimethylgermylalk-1-ene.

3.2.4.1.1 Synthesis of 5-Trimethylgermylhex-5-en-1-ol (92) and 5-Trimethylgermyl-6-trimethylsilylhexan-1-ol (122)

Following general procedure 3, to a stirred solution of 1-trimethylsilyl-6-(trimethylsilyloxy)hex-1-yne (61) (305 mg, 1.26 mmol, 1 equiv) in dry CH$_2$Cl$_2$ (1.2 mL), was added sequentially H$_2$PtCl$_6$$\cdot$6H$_2$O (13 mg, 0.025 mmol, 0.019 equiv) and Me$_3$GeH (53) (224 mg, 1.89 mmol, 1.50 equiv). The orange solution was stirred at rt for 1 h. The mixture was filtered through a short column of silica gel (elution with diethyl ether) and the eluate was concentrated under reduced pressure. The dark oil thus acquired was dissolved in CH$_2$Cl$_2$ (12 mL) and p-TsOH$\cdot$H$_2$O (287 mg, 1.51 mmol, 1.20 equiv) was added. The heterogeneous mixture was heated at 30 °C and stirred for 1.5 h. The crude oil obtained was subjected to flash chromatography (30 g TLC grade silica gel, 17:3 then 4:1 petroleum ether–ethyl acetate) to afford three fractions which were concentrated under reduced pressure. The first fraction to be eluted afforded 5.8 mg of 5-trimethylgermyl-6-trimethylsilylhexan-1-ol (122) as a clear colorless oil.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 3.61 (t, 2H, $J$ = 6.6 Hz, -CH$_2$OH), 1.56–1.18 (m, 7H), 1.05–
0.98 (m, 1H, -CHGe(CH$_3$)$_3$), 0.60 (dd, 1H, $J = 15.0$ and 3.6 Hz, -CH$_a$H$_b$Si(CH$_3$)$_3$),
0.48 (dd, 1H, $J = 15.0$ and 10.4 Hz, -CH$_a$H$_b$Si(CH$_3$)$_3$), 0.06 (s, 9H), -0.02 (s, 9H).

Additional $^1$H NMR data, derived from homonuclear decoupling experiments, are given in

**Table 19.**

$^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 63.0 (-CH$_2$OH), 34.1, 33.3, 25.0, 22.9 (-CHGe(CH$_3$)$_3$),
17.5 (-CH$_2$Si(CH$_3$)$_3$), 0.8, -3.0.

IR (film): 3328, 2952, 1413, 1248, 1060, 839, 751, 692 cm$^{-1}$.

HRMS for C$_{12}$H$_30^{74}$GeO$^{28}$Si: calcd 292.1278, found 292.1270.

**Table 19: $^1$H NMR Data from Homonuclear Decoupling Experiments for 5-Trimethylgermyl-
6-trimethylsilylhexan-1-ol (122)**

<table>
<thead>
<tr>
<th>Assignments</th>
<th>$^1$H NMR$^a$</th>
<th>Simplified Signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-1</td>
<td>3.61 (t, $J = 6.6$)</td>
<td></td>
</tr>
<tr>
<td>H-2,3,4, -OH</td>
<td>1.56–1.18 (m)</td>
<td></td>
</tr>
<tr>
<td>H-5$^b$</td>
<td>1.05–0.98 (m)</td>
<td>1.49–1.41 (H-4) portion of 1.56–1.18 m, H-6a (d, 15.0) H-6b (d, 15.0)</td>
</tr>
<tr>
<td>H-6a$^b$</td>
<td>0.60 (dd, $J = 15.0$, 3.6)</td>
<td>H-5 (dt; 10.4, 6.0), H-6b (d, 10.4)</td>
</tr>
<tr>
<td>H-6b$^b$</td>
<td>0.48 (dd, $J = 15.0$, 10.4)</td>
<td>H-5 (td; 6.0, 3.6), H-6a (d, 3.6)</td>
</tr>
<tr>
<td></td>
<td>0.06 (s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.02 (s)</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ 400 MHz, CDCl$_3$. $^b$ Irradiation of this signal simplified the corresponding signals in the right hand column.
The second fraction to be eluted was distilled (118–124 °C/24 Torr) to afford 202 mg (74%) of 5-trimethylgermylhex-5-en-1-ol (92) as a clear colorless oil.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 5.49 (d, 1H, $J = 2.6$ Hz, vinylic proton trans to -Ge(CH$_3$)$_3$), 5.16 (d, 1H, $J = 2.6$ Hz, vinylic proton cis to -Ge(CH$_3$)$_3$), 3.63 (t, 2H, $J = 6.4$ Hz, -CH$_2$OH), 2.19 (t, 2H, $J = 7.4$ Hz, -CH$_2$C(=CH$_2$)-), 1.60–1.50 (m, 2H, -CH$_2$CH$_2$OH), 1.50–1.40 (m, 2H, -CH$_2$CH$_2$C(=CH$_2$)-), 1.31 (br s, 1H, exchanges with D$_2$O, -OH), 0.18 (s, 9H, -Ge(CH$_3$)$_3$).

Additional $^1$H NMR data, derived from NOE difference experiments, are given in Table 20.

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 153.8 (-C(=CH$_2$)-), 121.5 (-C(=CH$_2$)-), 62.6 (-CH$_2$OH), 37.0, 32.4, 24.9, -1.9 (-Ge(CH$_3$)$_3$).

IR (film): 3328, 3046, 2937, 1833, 1606, 1413, 1236, 1062, 916, 825, 760, 599 cm$^{-1}$.

HRMS for C$_8$H$_{17}^{74}$GeO (M – CH$_3$)$^+$: calcd 203.0491, found 203.0482.

**Table 20:** $^1$H NMR Data from Nuclear Overhauser Enhancement Difference Experiments for 5-Trimethylgermylhex-5-en-1-ol (92)

![Chemical Structure](image)

<table>
<thead>
<tr>
<th>Assignments</th>
<th>$^1$H NMR$^a$</th>
<th>Observed NOEs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H-x</strong></td>
<td>$\delta$ ppm (mult, $J$ (Hz))</td>
<td></td>
</tr>
<tr>
<td>H-6a$^b$</td>
<td>5.49 (d)</td>
<td>H-3, H-4, H-6b</td>
</tr>
<tr>
<td>H-6b$^b$</td>
<td>5.16 (d)</td>
<td>H-6a, -Ge(CH$_3$)$_3$</td>
</tr>
<tr>
<td>H-1</td>
<td>3.63 (t, $J = 6.4$)</td>
<td></td>
</tr>
<tr>
<td>H-4$^b$</td>
<td>2.19 (t, $J = 7.4$)</td>
<td>H-2, H-3, H-6a, -Ge(CH$_3$)$_3$</td>
</tr>
<tr>
<td>H-2</td>
<td>1.60–1.50 (m)</td>
<td></td>
</tr>
<tr>
<td>H-3</td>
<td>1.50–1.40 (m)</td>
<td></td>
</tr>
<tr>
<td>-OH</td>
<td>1.31 (br s)</td>
<td></td>
</tr>
<tr>
<td>-Ge(CH$_3$)$_3$$^b$</td>
<td>0.18 (s)</td>
<td>H-2, H-3, H-4, H-6b</td>
</tr>
</tbody>
</table>

$^a$ 400 MHz, CDCl$_3$. $^b$ Irradiation of this signal generated the corresponding NOEs in the right hand column.

The third fraction to be eluted afforded 8.5 mg and was shown, by GLC analysis, to be a mixture of four compounds. $^1$H NMR analysis of the mixture suggested that it was comprised mainly of two components, hex-5-en-1-ol (95) and 5-trimethylgermylhex-5-en-1-ol (92), in about equal amounts. Spectral data for hex-5-en-1-ol (95) are as follows:

$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 5.79 (ddt, 1H, $J = 17.0$, 10.2 and 6.8 Hz, -CH=CH$_2$), 4.99 (dd, 1H, $J = 17.0$ and 2.0 Hz, -CH=CH$_3$H$_b$), 4.94 (dd, 1H, $J = 10.2$ and 2.0 Hz, -CH=CH$_3$H$_b$), 3.63 (t, 2H, $J = 6.4$ Hz, -CH$_2$OH), 2.07 (dt, 2H, $J = 6.8$ and 6.8 Hz, -CH$_2$OH).
-CH₂CH=CH₂), 1.58–1.40 (m, 4H, -CH₂CH₂CH₂OH), 1.28 (br s, 1H, exchanges with D₂O -OH).

3.2.4.1.2 Synthesis of 3-Trimethylgermylbut-3-en-1-ol (115)

Following general procedure 3, to a stirred solution of 1-trimethylsilyl-4-(trimethylsilyloxy)but-1-yne (63) (279 mg, 1.30 mmol, 1 equiv) in dry CH₂Cl₂ (1.3 mL) was added sequentially H₂PtCl₆•6H₂O (8.8 mg, 0.017 mmol, 0.013 equiv) and Me₃GeH (53) (232 mg, 1.95 mmol, 1.50 equiv). The orange solution was stirred at rt for 1 h and was then filtered through a short column of silica gel (elution with diethyl ether). The eluate was concentrated under reduced pressure. The dark oil thus obtained was dissolved in CH₂Cl₂ (13 mL) and p-TsOH•H₂O (297 mg, 1.56 mmol, 1.20 equiv) was added. The heterogeneous mixture was heated at 30–32 °C and stirred for 1.5 h. The crude oil acquired was flash chromatographed (20 g TLC grade silica gel, 17:3 petroleum ether–diethyl ether) and distilled (95–102 °C/9 Torr) to afford 155 mg (63%) of the title compound as a clear colorless oil.

¹H NMR (400 MHz, CDCl₃): δ 5.61 (d, 1H, J = 2.4 Hz, vinylic proton trans to -Ge(CH₃)₃), 5.32 (d, 1H, J = 2.4 Hz, vinylic proton cis to -Ge(CH₃)₃), 3.65 (td, 2H, J = 6.4 and 6.4 Hz, -CH₂OH), 2.46 (t, 2H, J = 6.4 Hz, -CH₂C(=CH₂)-), 1.41 (br t, 1H, J = 6.4 Hz, exchanges with D₂O, -OH), 0.21 (s, 9H, -Ge(CH₃)₃).

¹³C NMR (75.4 MHz, CDCl₃): δ 150.3 (-C(=CH₂)-), 124.6 (-C(=CH₂)-), 61.1 (-CH₂OH), 40.4 (-CH₂C(=CH₂)-), -1.9 (-Ge(CH₃)₃).
IR (film): 3365, 3048, 2971, 1606, 1417, 1237, 1047, 920, 825, 760 cm\(^{-1}\).

HRMS for C\(_{7}\)H\(_{16}\)GeO (M – CH\(_{3}\))\(^{+}\): calcd 175.0178, found 175.0179.

Anal. calcd for C\(_{7}\)H\(_{16}\)GeO: C 44.53, H 8.54; found: C 44.64, H 8.70.

3.2.4.1.3 Synthesis of 2-Trimethylgermyldodec-1-ene (116)

![Structure of 2-Trimethylgermyldodec-1-ene (116)]

Following general procedure 3, to a stirred solution of 1-trimethylsilyldodec-1-yne (64) (314 mg, 1.32 mmol, 1 equiv) in dry CH\(_{2}\)Cl\(_{2}\) (1.3 mL) was added sequentially H\(_{2}\)PtCl\(_{6}\)•6H\(_{2}\)O (12 mg, 0.024 mmol, 0.018 equiv) and Me\(_{3}\)GeH (53) (235 mg, 1.98 mmol, 1.50 equiv). The heterogeneous mixture was stirred at rt for 3.5 h. The green solution which contained a fine black suspension was filtered through Florisil (elution with CH\(_{2}\)Cl\(_{2}\)) and the eluate was concentrated under reduced pressure. The dark oil thus acquired was dissolved in CH\(_{2}\)Cl\(_{2}\) (13 mL) and p-TsOH•H\(_{2}\)O (301 mg, 1.58 mmol, 1.20 equiv) was added. The heterogeneous mixture was heated at 34 °C and stirred for 1.5 h. The crude liquid was flash chromatographed (40 g of C\(_{18}\) silica gel, 3:2 acetonitrile–methanol) to afford two fractions which were concentrated under reduced pressure. The first fraction to be eluted afforded 3.9 mg and was shown, by GLC analysis, to be a mixture of several compounds. \(^1\)H NMR spectroscopic analysis of the mixture suggested that the major component of this mixture was dodec-1-ene (113).

\(^1\)H NMR (400 MHz, CDCl\(_{3}\)): \(\delta\) 5.80 (ddt, 1H, \(J = 17.1, 10.3\) and 6.7 Hz), 4.98 (ddt, 1H, \(J = 17.1, 2.0\) and 2.0 Hz), 4.91 (ddt, 1H, \(J = 10.3, 2.0\) and 2.0 Hz), 2.10–1.98 (m, 2H),
1.45–1.15 (m, 16H), 0.88 (t, 3H, J = 7.0 Hz).

The second fraction to be eluted was distilled (102–110 °C/0.2 Torr) to afford 269 mg (72%) of the title compound as a clear colorless oil.

$^1$H NMR (400 MHz, CDCl$_3$): δ 5.48 (d, 1H, J = 2.7 Hz, vinylic proton trans to -Ge(CH$_3$)$_3$), 5.14 (d, 1H, J = 2.7 Hz, vinylic proton cis to -Ge(CH$_3$)$_3$), 2.16 (br t, 2H, J = 7.6 Hz, -CH$_2$C(=CH$_2$)-), 1.42–1.33 (br m, 3H), 1.33–1.20 (br s, 13H), 0.86 (br t, 3H, J = 6.8 Hz, -CH$_2$CH$_3$), 0.18 (s, 9H, -Ge(CH$_3$)$_3$).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): δ 154.4 (-C(=CH$_2$)-), 121.3 (-C(=CH$_2$)-), 37.6, 32.1, 29.8 (2 overlapping signals), 29.7, 29.52, 29.49, 29.1, 22.8, 14.2 (-CH$_2$CH$_3$), −1.8 (-Ge(CH$_3$)$_3$).

IR (film): 3050, 2926, 1467, 1236, 824, 759 cm$^{-1}$.
HRMS for C$_{15}$H$_{32}$Ge: calcd 286.1716, found 286.1724.

Anal. calcd for C$_{15}$H$_{32}$Ge: C 63.21, H 11.32; found: C 62.89, H 11.60.

3.2.4.1.4 Synthesis of 5-Chloro-2-trimethylgermylpent-l-ene (117)

![Chemical Structure 117](image)

Following general procedure 3, to a stirred solution of 5-chloro-1-trimethylsilylpent-l-yne (65) (256 mg, 1.47 mmol, 1 equiv) in dry CH$_2$Cl$_2$ (1.5 mL) was added sequentially H$_2$PtCl$_6$·6H$_2$O (10 mg, 0.020 mmol, 0.014 equiv) and Me$_3$GeH (53) (261 mg, 2.20 mmol, 1.50 equiv). The heterogeneous mixture was stirred at rt for 3.5 h. The green solution which contained a fine black suspension was filtered through Florisil (elution with CH$_2$Cl$_2$) and the
eluate was concentrated under reduced pressure. The dark oil thus obtained was dissolved in CH₂Cl₂ (15 mL) and p-TsOH•H₂O (335 mg, 1.76 mmol, 1.20 equiv) was added. The heterogeneous mixture was heated at 30 °C and stirred for 2.5 h. The crude oil acquired was flash chromatographed (20 g TLC grade silica gel, petroleum ether) and distilled (103–112 °C/16 Torr) to afford 243 mg (74%) of the title compound as a clear colorless oil.

¹H NMR (400 MHz, CDCl₃): δ 5.53 (d, 1H, J = 2.4 Hz, vinylic proton trans to -Ge(CH₃)₃), 5.22 (d, 1H, J = 2.4 Hz, vinylic proton cis to -Ge(CH₃)₃), 3.51 (t, 2H, J = 6.6 Hz, -CH₂Cl), 2.32 (br t, 2H, J = 7.4 Hz, -CH₂C(=CH₂)-), 1.86 (tt, 2H, J = 7.4 and 6.6 Hz, -CH₂CH₂CH₂-), 0.20 (s, 9H, -Ge(CH₃)₃).

¹³C NMR (75.4 MHz, CDCl₃): δ 152.2 (-C(=CH₂)-), 122.5 (-C(=CH₂)-), 44.3, 34.2, 31.6, -1.9 (-Ge(CH₃)₃).

IR (film): 3048, 2970, 1839, 1607, 1237, 920, 826, 601 cm⁻¹.

HRMS for C₇H₁₄Cl²⁷⁴Ge (M - CH₃)⁺: calcd 206.9996, found 206.9999.

Anal. calcd for C₈H₁₇ClGe: C 43.43, H 7.74; found: C 43.60, H 7.90.

3.2.4.1.5 Synthesis of 1-Phenyl-1-trimethylgermylthene (118)

Following general procedure 3, to a stirred solution of 1-phenyl-2-trimethylsilyl-acetylene (66) (201 mg, 1.15 mmol, 1 equiv) in dry CH₂Cl₂ (1.2 mL) was added H₂PtCl₆•6H₂O (16 mg, 0.030 mmol, 0.026 equiv). The mixture soon became green and
contained a fine black suspension. After cooling to 0 °C, Me₃GeH (53) (205 mg, 1.73 mmol, 1.50 equiv) was added and the mixture became bright yellow. The heterogeneous mixture was stirred at rt for 4 h, during which time it became green again. The mixture was filtered through Florisil (elution with CH₂Cl₂) and the eluate was concentrated under reduced pressure. The dark oil thus obtained was dissolved in CH₂Cl₂ (12 mL) and p-TsOH•H₂O (263 mg, 1.38 mmol, 1.20 equiv) was added. The suspension was heated at 30 °C and stirred for 7 h. The crude liquid acquired was subjected to flash chromatography (25 g TLC grade silica gel, petroleum ether) and distilled (105–108 °C/8 Torr) to afford 174 mg (68%) of the title compound as a clear colorless oil.

¹H NMR (400 MHz, CDCl₃): δ 7.31–7.27 (m, 2H), 7.23–7.19 (m, 3H), 5.84 (d, 1H, J = 2.4 Hz, vinylic proton trans to -Ge(CH₃)₃), 5.47 (d, 1H, J = 2.4 Hz, vinylic proton cis to -Ge(CH₃)₃), 0.29 (s, 9H, -Ge(CH₃)₃).

¹³C NMR (75.4 MHz, CDCl₃): δ 154.1 (–C(=CH₂)–), 144.4 (aromatic ipso carbon), 128.2, 126.4 (2 overlapping signals), 124.2 (–C(=CH₂)–), −1.1 (–Ge(CH₃)₃).

IR (film): 3055, 2974, 1599, 1573, 1490, 1412, 1237, 924, 827, 778, 705, 601 cm⁻¹.

HRMS for C₁₁H₁₆²⁷⁴Ge: calcd 222.0464, found 222.0470.

Anal. calcd for C₁₁H₁₆Ge: C 59.83, H 7.30; found: C 59.60, H 7.25.
3.2.4.1.6 Synthesis of 2,5-bis(Trimethylgermyl)hexa-1,5-diene (119)

Following general procedure 3, to a stirred solution of 1,6-bis(trimethylsilyl)hexa-1,5-diyne (67) (250 mg, 1.12 mmol, 1 equiv) in dry CH$_2$Cl$_2$ (1.1 mL) was added sequentially H$_2$PtCl$_6$·6H$_2$O (22 mg, 0.043 mmol, 0.038 equiv) and Me$_3$GeH (53) (400 mg, 3.37 mmol, 3.00 equiv). The heterogeneous mixture was stirred at rt for 4.5 h. The green solution which contained a fine black suspension was filtered through Florisil (elution with CH$_2$Cl$_2$) and the eluate was concentrated under reduced pressure. The dark oil thus acquired was dissolved in CH$_2$Cl$_2$ (11 mL) and p-TsOH·H$_2$O (513 mg, 2.70 mmol, 2.40 equiv) was added. The suspension was heated at 30 °C and stirred for 5 h. The crude oil obtained was flash chromatographed (20 g TLC grade silica gel, petroleum ether) and distilled. A forerun (distillation temperature 50–70 °C/9 Torr) was collected in a first bulb (26 mg, volatile material as indicated by GLC analysis). The remainder of the liquid was collected in a second bulb (distillation temperature 88–98 °C/9 Torr) to afford 251 mg (71%) of the title compound as a clear colorless oil.

$^1$H NMR (400 MHz, CDCl$_3$): δ 5.52 (d, 2H, $J = 2.4$ Hz, 2 × vinylic proton trans to -Ge(CH$_3$)$_3$), 5.18 (d, 2H, $J = 2.4$ Hz, 2 × vinylic proton cis to -Ge(CH$_3$)$_3$), 2.26 (s, 4H, -CH$_2$CH$_2$), 0.20 (s, 18H, 2 × -Ge(CH$_3$)$_3$).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): δ 153.8 (-C(=CH$_2$)-), 121.4 (-C(=C$_2$H$_2$)-), 36.9 (-CH$_2$-), −1.8 (-Ge(CH$_3$)$_3$).
IR (film): 3048, 2972, 1838, 1612, 1412, 1236, 916, 825, 759, 598 cm\(^{-1}\).

HRMS (DCI, NH\(_3\) + CH\(_4\)) for C\(_{12}\)H\(_{27}\)Ge\(_{74}\)Ge (M + 1): calcd 317.0545, found 317.0541.

Anal. calcd for C\(_{12}\)H\(_{26}\)Ge\(_2\): C 45.68, H 8.31; found: C 45.47, H 8.27.

3.2.4.1.7 Synthesis of 4-(Cyclopent-1-en-1-yl)-2-trimethylgermylbut-1-ene (120)

Following general procedure 3, to a stirred solution of 4-(cyclopent-2-en-1-yl)-1-trimethylsilylbut-1-yne (72) (228 mg, 1.19 mmol, 1 equiv) in dry CH\(_2\)Cl\(_2\) (1.2 mL) was added sequentially H\(_2\)PtCl\(_6\)-6H\(_2\)O (9.0 mg, 0.017 mmol, 0.015 equiv) and Me\(_3\)GeH (53) (211 mg, 1.78 mmol, 1.50 equiv). The heterogeneous mixture was stirred at rt for 21 h. The green solution which contained a fine black suspension was filtered through Florisil (elution with CH\(_2\)Cl\(_2\)) and the eluate was concentrated under reduced pressure. The dark oil thus acquired was dissolved in CH\(_2\)Cl\(_2\) (12 mL) and p-TsOH\(\cdot\)H\(_2\)O (270 mg, 1.42 mmol, 1.20 equiv) was added. The heterogeneous mixture was heated at 30 °C and stirred for 2 h. The crude oil obtained was filtered through a short column of silica gel (2.5 g, elution with petroleum ether, 50 mL), and the eluate was concentrated under reduced pressure. The crude oil thus acquired was distilled. A forerun was collected in a first bulb (31 mg, distillation temperature 70–100 °C/17 Torr). The remainder of the material was collected in a second bulb (distillation temperature 130–150 °C/17 Torr) to afford 205 mg (72%) of the title compound as a clear colorless oil.
$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 5.51 (d, 1H, $J = 2.6$ Hz, vinylic proton trans to -Ge(CH$_3$)$_3$), 5.33 (t, 1H, $J = 1.8$ Hz, cyclopentene vinylic proton), 5.16 (d, 1H, $J = 2.6$ Hz, vinylic proton cis to -Ge(CH$_3$)$_3$), 2.39–2.12 (m, 8H), 1.87–1.80 (m, 2H), 0.20 (s, 9H, -Ge(CH$_3$)$_3$).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 153.9 (-C(=CH$_2$)-), 144.5 (C-1'), 123.3 (C-2'), 121.1 (-C(=CH$_2$)-), 35.5, 35.2, 32.4, 30.6, 23.4, −1.9 (-Ge(CH$_3$)$_3$).

IR (film): 3046, 2907, 1835, 1651, 1606, 1439, 1236, 916, 824, 759, 599 cm$^{-1}$.

HRMS for C$_{12}$H$_{22}$Ge: calcd 240.0933, found 240.0935.

Anal. calcd for C$_{12}$H$_{22}$Ge: C 60.33, H 9.28; found: C 60.13, H 9.20.

3.2.4.1.8 Synthesis of 4-Trimethylgermylpent-4-enoyltrimethylgermane (121)

Following general procedure 3, to a stirred solution of 5-trimethylsilylpent-4-ynoyltrimethylgermane (114) (see section 3.3.2.3.10, p 246 for the preparation of 114; 296 mg, 1.09 mmol, 1 equiv) in dry CH$_2$C$_2$ (1.1 mL) was added sequentially H$_2$PtCl$_6$·6H$_2$O (9.0 mg, 0.017 mmol, 0.016 equiv) and Me$_3$GeH (53) (194 mg, 1.63 mmol, 1.50 equiv). The orange solution was stirred at rt for 6 h. The mixture was filtered through a short column of silica gel (elution with diethyl ether) and the eluate was concentrated under reduced pressure. The dark oil thus obtained was dissolved in CH$_2$Cl$_2$ (11 mL) and p-TsOH·H$_2$O (249 mg, 1.31 mmol, 1.20 equiv) was added. The heterogeneous mixture was heated at 32–34 °C for 1 h. The crude oil acquired was subjected to flash chromatography (35 g TLC grade silica gel, 97:3
petroleum ether–diethyl ether) and distilled (75–85 °C/0.1 Torr) to afford 235 mg (68%) of the title compound as a light yellow oil.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 5.44 (d, 1H, $J = 2.0$ Hz, vinylic proton trans to -Ge(CH$_3$)$_3$), 5.17 (d, 1H, $J = 2.0$ Hz, vinylic proton cis to -Ge(CH$_3$)$_3$), 2.75–2.71 (m, 2H), 2.40–2.36 (m, 2H), 0.32 (s, 9H, -COGe(CH$_3$)$_3$), 0.19 (s, 9H, -C(=CH$_2$)Ge(CH$_3$)$_3$).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 244.4 (-COGe(CH$_3$)$_3$), 152.5 (-C(=CH$_2$)-), 121.2 (-C(=CH$_2$)-), 48.3 (-CH$_2$CO-), 28.8 (-CH$_2$C(=CH$_2$)-), −2.1 (-C(=CH$_2$)Ge(CH$_3$)$_3$), −2.9 (-COGe(CH$_3$)$_3$).

IR (film): 3049, 2974, 1840, 1658, 1412, 1237, 1053, 828, 602 cm$^{-1}$.

HRMS for C$_{10}$H$_{21}$Ge$_7^4$GeO (M – CH$_3$)$^+$: calcd 303.0025, found 303.0027.

Anal. calcd for C$_{11}$H$_{24}$Ge$_2$O: C 41.61, H 7.62; C 41.40, H 7.83.
3.3 SYNTHESIS OF ACYLTRIMETHYLGERMANES VIA ADDITION OF (TRI-METHYLGERMYL)COPPER(I)-DIMETHYL SULFIDE TO ACYL ELECTROPHILES, AND THEIR OLEFINATION TO 2-TRIMETHYLGERMYLALK-L-ENES

3.3.1 SYNTHESIS OF ACYL CHLORIDES

3.3.1.1 GENERAL PROCEDURE 4: PREPARATION OF THE ACYL CHLORIDES 157–160 AND 164

To the appropriate carboxylic acid (1 equiv) was added SOCl₂ (2–8 equiv). The mixture was heated at reflux for 0.5–3 h, then the excess SOCl₂ was removed via distillation under reduced pressure. The crude oil thus obtained was distilled to afford the desired acyl chloride.

3.3.1.1.1 Synthesis of Decanoyl Chloride (157)

Following general procedure 4, to decanoic acid (153) (2.00 g, 11.6 mmol, 1 equiv) was added SOCl₂ (2.76 g, 23.2 mmol, 2.00 equiv). The mixture was heated at reflux for 0.5 h. The crude oil obtained was distilled (70–80 °C/0.06 Torr, lit. bp 94–96 °C/5 Torr) to afford 2.16 g (98%) of the title compound as a clear colorless oil. Decanoyl chloride (157) is commercially available, but it was prepared by this simple method since decanoic acid (153) was readily available.
3.3.1.1.2 Synthesis of (Cyclopent-2-en-1-yl)acetyl Chloride (158)

Following general procedure 4, to (cyclopent-2-en-1-yl)acetic acid (154) (1.84 g, 14.6 mmol, 1 equiv) was added SOCl₂ (3.46 g, 29.1 mmol, 2.00 equiv). The mixture was heated at reflux for 0.75 h. The crude oil obtained was distilled (90–110 °C/9 Torr, lit. bp 65 °C/18 Torr) to afford 1.99 g (94%) of the title compound as a clear colorless oil.

3.3.1.1.3 Synthesis of Adipoyl Chloride (159)

Following general procedure 4, to adipic acid (155) (2.00 g, 13.7 mmol, 1 equiv) was added SOCl₂ (6.51 g, 54.7 mmol, 4 equiv). The mixture was heated at reflux for 3 h. The crude oil obtained was distilled (76–86 °C/0.05 Torr, lit. bp 105–107 °C/2 Torr) to afford 2.30 g (92%) of the title compound as a clear colorless oil. Adipoyl chloride (159) is commercially available, but it was prepared by this simple method since adipic acid (155) was readily available.
3.3.1.4 Synthesis of Pent-4-ynoyl Chloride (160)

\[
\text{\textbf{160}}
\]

Following general procedure 4, to pent-4-ynoic acid (156) (990 mg, 10.1 mmol, 1 equiv) was added SOCl\textsubscript{2} (2.40 g, 20.2 mmol, 2 equiv). The mixture was heated at reflux for 0.75 h. The crude oil obtained was distilled (62–72 °C/23 Torr, lit. bp 46–48 °C/19 Torr\textsuperscript{124}) to afford 733 mg (62%) of the title compound as a volatile clear colorless oil.

3.3.1.5 Synthesis of 5-Trimethylsilylpent-4-yn-1-ol (162), 5-Trimethylsilylpent-4-ynoic Acid (163) and 5-Trimethylsilylpent-4-ynoyl Chloride (164)

\[\text{Me}_3\text{Si} \quad \text{162} \quad \text{Me}_3\text{Si} \quad \text{163} \quad \text{Me}_3\text{Si} \quad \text{164}\]

\textit{a) 5-Trimethylsilylpent-4-yn-1-ol (162)}

To a cold (–78 °C) stirred solution of pent-4-yn-1-ol (161) (2.29 g, 27.2 mmol, 1 equiv) in dry THF (270 mL) was added a solution of \textit{n}-BuLi (1.60 M in hexanes, 37.4 mL, 59.9 mmol, 2.20 equiv) via a syringe over 10 min. The resulting thick slurry was stirred at –78 °C for 2 h, then chlorotrimethylsilane (7.39 g, 68.0 mmol, 2.50 equiv) was added via a syringe. The solution was stirred at –78 °C for 5 min, then was warmed to rt and was allowed to stir for an additional 0.5 h. Water (100 mL) was added and the mixture was stirred overnight. Diethyl ether (100 mL) was added and the layers were separated. The aqueous portion was extracted with diethyl ether (2 × 100 mL). The pooled organic extracts were
washed with brine (2 x 50 mL), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil thus acquired was subjected to flash chromatography (200 g silica gel, 3:2 diethyl ether–petroleum ether) and distilled (130–140 °C/11 Torr) to afford 3.53 g (74%) of 5-trimethylsilylpent-4-yn-1-ol (162) as a clear colorless oil.

**1H NMR (400 MHz, CDCl₃):** δ 3.74 (t, 2H, J = 6.2 Hz, -CH₂OH), 2.33 (t, 2H, J = 6.8 Hz, -CH₂C≡C-), 1.75 (tt, 2H, J = 6.8 and 6.2 Hz, -CH₂CH₂CH₂-), 1.56 (br s, 1H, exchanges with D₂O, -OH), 0.12 (s, 9H, -Si(CH₃)₃).

**13C NMR (75.4 MHz, CDCl₃):** δ 106.6 (-C≡CSi(CH₃)₃), 85.3 (-C≡CSi(CH₃)₃), 61.9 (-CH₂OH), 31.1 (-CH₂CH₂CH₂-), 16.5 (-CH₂C≡C-), 0.1 (-Si(CH₃)₃).

**IR (film):** 3327, 2958, 2176, 1250, 843, 761 cm⁻¹.

**HRMS for C₇H₁₃O²⁸Si (M – CH₃):** calcd 141.0736, found 141.0730.

**Anal. calcd for C₈H₁₆OSi: C 61.48, H 10.32; found: C 61.25, H 10.23.**

**b) 5-Trimethylsilylpent-4-ynoic Acid (163)**

To a stirred solution of CrO₃ (7.20 g, 72.0 mmol, 3.75 equiv) in 1.5 M aqueous H₂SO₄ (115 mL) at 0 °C, was added a solution of 5-trimethylsilylpent-4-yn-1-ol (162) (3.00 g, 19.2 mmol, 1 equiv) in acetone (230 mL) over 3 h. The reaction mixture was allowed to slowly warm up to rt and was stirred overnight. Diethyl ether (100 mL) was added and the aqueous layer was saturated with NaCl. The layers were separated and the aqueous portion was extracted with diethyl ether (3 x 100 mL). The combined organic extracts were washed with water (8 x 50 mL) and brine (2 x 100 mL), were dried over anhydrous magnesium sulfate,
and then were filtered and concentrated under reduced pressure. The crude oil thus acquired was subjected to flash chromatography (325 g silica gel, 85:15:1 petroleum ether–ethyl acetate–acetic acid) to afford a beige solid. This solid was sublimed (42–44 °C/0.007 Torr) to afford 2.16 g (66%) of 5-trimethylsilylpent-4-ynoic acid (163) as a colorless solid (mp 47.5–48.0 °C).

\[ ^1H \text{ NMR (400 MHz, CDCl}_3 \]: } \delta 11.00–10.40 (br s, 1H, exchanges with D\textsubscript{2}O, -CO\textsubscript{2}H), 2.62–2.49 (m, 4H, -CH\textsubscript{2}CH\textsubscript{2}-), 0.12 (s, 9H, -Si(CH\textsubscript{3})\textsubscript{3}).

\[ ^{13}C \text{ NMR (75.4 MHz, CDCl}_3 \]: } \delta 178.4 (-CO\textsubscript{2}H), 104.5 (-C≡CSi(CH\textsubscript{3})\textsubscript{3}), 85.7

\[ (-\text{C≡CSi(CH}_3)_3 \), 33.4 (-\text{CH}_2\text{CO}_2H), 15.4 (-\text{CH}_2\text{C=}-), 0.0 (-\text{Si(CH}_3)_3 \).

IR (KBr pellet): 3600–2300, 2178, 1718, 1430, 1296, 1255, 1212, 1014, 844, 761 cm\textsuperscript{-1}.

HRMS for C\textsubscript{8}H\textsubscript{14}O\textsubscript{2}Si: calcd 170.0763, found 170.0758.

Anal. calcd for C\textsubscript{8}H\textsubscript{14}O\textsubscript{2}Si: C 56.43, H 8.29; found: C 56.37, H 8.20.

c) 5-Trimethylsilylpent-4-ynoyl Chloride (164)

Following general procedure 4, to 5-trimethylsilylpent-4-ynoic acid (163) (150 mg, 0.88 mmol, 1 equiv) was added SOCl\textsubscript{2} (0.84 g, 7.1 mmol, 8.0 equiv). The mixture was heated at reflux for 0.75 h. The crude oil obtained was distilled (80–85 °C/11 Torr) to afford 161 mg (97%) of 5-trimethylsilylpent-4-ynoyl chloride (164) as a clear colorless oil.

\[ ^1H \text{ NMR (400 MHz, CDCl}_3 \]: } \delta 3.09 (t, 2H, J = 7.2 Hz), 2.58 (t, 2H, J = 7.2 Hz), 0.13 (s, 9H, -Si(CH\textsubscript{3})\textsubscript{3}).

\[ ^{13}C \text{ NMR (75.4 MHz, CDCl}_3 \]: } \delta 172.1 (-COCl), 102.6 (-C≡CSi(CH\textsubscript{3})\textsubscript{3}), 86.8

\[ (-\text{C≡CSi(CH}_3)_3 \), 45.8 (-\text{CH}_2\text{COCl}), 16.0 (-\text{CH}_2\text{C=}-), -0.1 (-\text{Si(CH}_3)_3 \).
IR (film): 2182, 1801, 1252, 844, 761 cm\(^{-1}\).

LRMS for C\(_7\)H\(_{10}\)\(^{35}\)ClO\(^{28}\)Si (M – CH\(_3\))\(^+\): calcd 173, found 173.

3.3.1.2 **SYNTHESIS OF ((4-METHOXYBENZYL)OXY)ACETIC ACID (166) AND ((4-METHOXYBENZYL)OXY)ACETYL CHLORIDE (167)**

![Structures 166 and 167](image)

**a) ((4-Methoxybenzyl)oxy)acetic Acid (166)**

To stirred neat (4-methoxyphenyl)methanol (165) (78.7 g, 570 mmol, 6.30 equiv) at rt was added, portionwise, NaH (dry powder 98%, 4.56 g, 190 mmol, 2.10 equiv) over 1 h. The resulting thick slurry was heated at 60 °C and stirred for 3 h. Ethyl bromoacetate (15.1 g, 90.4 mmol, 1 equiv) was added dropwise over 10 min. The mixture was stirred at 60 °C for an additional 2 h. After the solution had been cooled, methanol (30 mL), water (20 mL) and KOH (5.58 g, 99.5 mmol, 1.10 equiv) were added. The reaction mixture was heated at 60 °C and stirred overnight (this reaction was not performed under an atmosphere of argon). After the solution had been cooled, water (200 mL) and diethyl ether (100 mL) were added. The layers were separated and the aqueous portion was extracted with diethyl ether (8 x 100 mL). The aqueous layer was acidified with concentrated hydrochloric acid (25 mL) and was extracted with diethyl ether (100 mL). The aqueous layer was saturated with NaCl, and then was extracted with diethyl ether (2 x 200 mL). The combined organic extracts were washed with brine (50 mL), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude solid (16.1 g) thus obtained was dissolved in
2:1 benzene–petroleum ether (160 mL total) at rt and was stored in the refrigerator for 48 h to allow crystallization. The crystals were collected by suction filtration and washed with ice-cold pentane (3 × 30 mL) to afford 10.5 g (59%) of ((4-methoxybenzyl)oxy)acetic acid (166) as a colorless solid (mp 52.5–53.5 °C, lit. mp 49–52 °C\(^{125}\)).

\(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta 10.00–8.50\) (br s, 1H, -CO\(_2\)H), 7.26 (d, 2H, \(J = 8.6\) Hz), 6.88 (d, 2H, \(J = 8.6\) Hz), 4.56 (s, 2H), 4.09 (s, 2H), 3.79 (s, 3H, -OCH\(_3\)).

\(^13\)C NMR (75.4 MHz, CDCl\(_3\)): \(\delta 175.5\) (-CO\(_2\)H), 159.5, 129.8, 128.5, 113.9, 73.0 (-CH\(_2\)OCH\(_2\)CO-), 66.1 (-CH\(_2\)OCH\(_2\)CO-), 55.2 (-OCH\(_3\)).

IR (KBr pellet): 3600–2500, 1727, 1614, 1584, 1253, 1178, 1097, 1028, 819 cm\(^{-1}\).

HRMS for C\(_{10}\)H\(_{12}\)O\(_4\): calcd 196.0736, found 196.0739.

Anal. calcd for C\(_{10}\)H\(_{12}\)O\(_4\): C 61.22, H 6.16; found: C 61.16, H 6.10.

\(b\) ((4-Methoxybenzyl)oxy)acetyl Chloride (167)

To a stirred solution of ((4-methoxybenzyl)oxy)acetic acid (166) (1.84 g, 9.38 mmol, 1 equiv) in absolute ethanol (38 mL) at rt was added a solution of KOH\(^{86}\) (2.69 M in ethanol, 3.49 mL, 9.38 mmol, 1 equiv; this reaction was not performed under an atmosphere of argon). The thick slurry was stirred at rt for 20 min, then the solvent was removed under reduced pressure. The solid obtained was triturated in acetone (40 mL), and the solvent was removed under reduced pressure. The residual solid was suspended in dry diethyl ether (27 mL; under an atmosphere of argon) and was cooled to 0 °C. Dry \(N,N\)-dimethylformamide (2 drops) and oxalyl chloride (3.57 g, 28.1 mmol, 3.00 equiv) were sequentially added. The heterogeneous mixture was stirred at 0 °C for 2 h, then was filtered through a dry sintered glass funnel under
an atmosphere of argon. The solvent was removed from the filtrate via distillation under reduced pressure at rt, and the crude oil thus obtained was distilled (92–96 °C/0.02 Torr) to afford 1.85 g (92%) of ((4-methoxybenzyl)oxy)acetyl chloride (167) as a clear colorless oil. This compound was either used immediately or kept overnight in a freezer (−25 °C) under an argon atmosphere and used the following day. Storage of this compound at rt, even for a few hours resulted in decomposition of the material.

\[ ^1H \text{NMR (400 MHz, CDCl}_3): \delta 7.26 (d, 2H, } J = 8.8 \text{ Hz), 6.88 (d, 2H, } J = 8.8 \text{ Hz), 4.58 (s, 2H), 4.37 (s, 2H), 3.80 (s, 3H, -OCH}_3). \]

\[ ^13C \text{NMR (75.4 MHz, CDCl}_3): \delta 171.9 (-CO-), 159.6, 129.8, 128.0, 113.9, 74.4 \]

\(-\text{CH}_2\text{OCH}_2\text{CO-}, 73.0 (-\text{CH}_2\text{OCH}_2\text{CO-}), 55.1 (-\text{OCH}_3). \]

IR (film): 1801, 1614, 1515, 1251, 1127, 1034, 937, 746 cm\(^{-1}\). 

LRMS for C\textsubscript{10}H\textsubscript{11}\textsuperscript{35}ClO\textsubscript{3}: calcd 214, found 214.
3.3.2 SYNTHESIS OF ACYLTRIMETHYLGERMANES FROM ACYL CHLORIDES

3.3.2.1 SYNTHESIS OF TRIMETHYLGERMYLTHIUM (149)

3.3.2.1.1 Preparation of the Trimethylgermylthium Reagent (149)

\[
\text{Me}_3\text{GeLi} \quad 149
\]

To cold (−10 °C) dry THF (0.6 mL) was added Me\(_3\)GeH (53) (202 mg, 1.70 mmol, 1.20 equiv to give an ≈2.5 M solution of Me\(_3\)GeH in THF) via a precooled syringe (cooled by running cold water on the barrel). A solution of t-BuLi (1.69 M in pentane, 837 µL, 1.41 mmol, 1 equiv) was added via a syringe, and the resulting yellow solution was stirred at −10 °C for 5 min to afford a clear colorless solution. The solution of Me\(_3\)GeLi (149) thus obtained was used immediately. For a large scale preparation of Me\(_3\)GeLi (149) see section 3.3.2.4, p 247.

3.3.2.1.2 Treatment of Trimethylgermylthium with 1-Bromodecane: Synthesis of 1-Trimethylgermyldecane (172)

\[
\begin{array}{c}
\text{GeMe}_3 \\
\text{172}
\end{array}
\]

A cold (−10 °C) stirred solution of Me\(_3\)GeLi (149) (1.25 mmol, 1.25 equiv) in dry THF (0.5 mL), prepared as described above (section 3.3.2.1.1, p 221), was diluted with dry THF (2 mL) and the solution was cooled to −78 °C. 1-Bromodecane (221 mg, 1.00 mmol, 1 equiv, freshly distilled from CaH\(_2\)) was added via a syringe. The reaction mixture was stirred
at −78 °C for 5 min, then was warmed to rt and was allowed to stir for an additional 15 min. The mixture was diluted with diethyl ether (15 mL), then water (0.5 mL) was added and the layers were separated. The organic extract was washed with brine (2 mL), was dried over anhydrous magnesium sulfate, and then was filtered and concentrated under reduced pressure. The crude oil thus obtained was distilled (48–54 °C/0.06 Torr) to afford 241 mg (93%) of the title compound as a clear colorless oil.

\textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): 8 1.40–1.18 (br s, 16H), 0.86 (br t, 3H, J = 6.8 Hz, -CH\textsubscript{2}CH\textsubscript{3}), 0.67 (br dd, 2H, J = 8.2 and 7.8 Hz, -CH\textsubscript{2}Ge(CH\textsubscript{3})\textsubscript{3}), 0.07 (s, 9H, -Ge(CH\textsubscript{3})\textsubscript{3}).

\textsuperscript{13}C NMR (75.4 MHz, CDCl\textsubscript{3}): 8 33.3, 32.0, 29.72, 29.68, 29.43, 29.40, 25.1, 22.7, 16.9, 14.2 (-CH\textsubscript{2}CH\textsubscript{3}), -2.3 (-Ge(CH\textsubscript{3})\textsubscript{3}).

IR (film): 2925, 823, 598 cm\textsuperscript{-1}.

HRMS (DCI, NH\textsubscript{3} + CH\textsubscript{4}) for C\textsubscript{12}H\textsubscript{27}\textsuperscript{74}Ge (M - CH\textsubscript{3})\textsuperscript{+}: calcd 245.1325, found 245.1328.

Anal. calcd for C\textsubscript{13}H\textsubscript{30}Ge: C 60.29, H 11.68; found: C 60.47, H 11.65.

3.3.2.1.3 Determination of the Yield of Trimethylgermyllithium (149) Formation from Trimethylgermane (53) via the Internal Standard Method

A cold (−10 °C) stirred solution of Me\textsubscript{3}GeLi (149) (1.25 mmol, 1 equiv) in dry THF (0.5 mL), prepared as described above (section 3.3.2.1.1, p 221), was diluted with THF (2 mL) and the solution was cooled to −78 °C. 1-Bromodecane (323 mg, 1.50 mmol, 1.20 equiv, freshly distilled from CaH\textsubscript{2}) was added via a syringe. The reaction mixture was stirred at −78 °C for 15 min, then was warmed to rt and was allowed to stir for an additional 45 min. The internal standard n-tridecane (191.5 ± 1.2 mg) was added via a syringe calibrated by
delivering 250 μL of tridecane multiple times. The mixture was treated with water (1 mL) and diethyl ether (1 mL) was added. The GLC was calibrated using a mixture prepared as follows: 64 mg of n-tridecane and 107 mg of 1-trimethylgermyldecane (172). An aliquot of the reaction mixture was injected and it was determined that 1-trimethylgermyldecane (172) had been formed in >97% yield.

3.3.2.2 PREPARATION OF (TRIMETHYLGERMYL)COPPER(I)–DIMETHYL SULFIDE (168)

\[ \text{Me}_3\text{GeCu}\cdot\text{Me}_2\text{S} \]

a) Via Addition of the Solution of Me\(_3\)GeLi (149) to a Suspension of CuBr•Me\(_2\)S in THF

(“Normal” Addition Method)

A cold (−10 °C) stirred solution of Me\(_3\)GeLi (149) (1.41 mmol, 1 equiv) in dry THF (0.6 mL), prepared as described above (section 3.3.2.1.1, p 221), was transferred via a cannula to a cold (−78 °C) stirred suspension of CuBr•Me\(_2\)S (290 mg, 1.41 mmol, 1 equiv) in dry THF (6 mL). The flask that initially contained the Me\(_3\)GeLi (149) was rinsed with dry THF (2 × 0.5 mL) and the rinses were transferred via a cannula to the suspension of CuBr•Me\(_2\)S. The suspension was stirred at −78 °C for 1 h to afford a dark red–black solution of the title reagent (=0.18 M). The reagent 168 was then ready to use. For a large scale preparation of Me\(_3\)GeCu•Me\(_2\)S (168) using this procedure see section 3.3.2.4, p 247.

b) Via Addition of Solid CuBr•Me\(_2\)S to the Solution of Me\(_3\)GeLi (149) in THF (“Inverse” Addition Method)

A cold (−10 °C) stirred solution of Me\(_3\)GeLi (149) (4.40 mmol, 1 equiv) in dry THF (1.8 mL), prepared as described above (section 3.3.2.1.1, p 221), was diluted with dry THF
(23 mL) and the solution was cooled to -78 °C. After the solution had been stirred for 10 min, solid CuBr•Me₂S (905 mg, 4.40 mmol, 1 equiv) was added in one portion. The suspension was stirred at -78 °C for 1 h to afford a dark red-black solution of the title reagent (=0.18 M). The reagent 168 was then ready to use.

3.3.2.3 GENERAL PROCEDURE 5: PREPARATION OF THE ACYLTRIMETHYLGEMANES FROM ACYL CHLORIDES

To a cold (-78 °C) stirred solution of Me₃GeCu•Me₂S (168) (1.0–3.0 equiv) in dry THF (=0.18 M), prepared as described above (section 3.3.2.2, p 223), was added a solution of the appropriate acyl chloride (1 equiv) in dry THF, via a cannula, to generate a final concentration of ≈0.1 M of the acyl chloride. The reaction mixture was stirred at -78 °C for 1 h, was then warmed to -30 °C and was allowed to stir for an additional 2 h. The black mixture was poured into a stirred aqueous NH₄Cl-NH₄OH solution (pH 8–9, ≈15 mL per mmol of acyl chloride) and diethyl ether (≈30 mL per mmol of acyl chloride) was added. The two-phase system was stirred vigorously open to the atmosphere until the aqueous layer was deep blue. The layers were separated and the aqueous portion was extracted with diethyl ether (2 × ≈10 mL per mmol of acyl chloride). The combined organic extracts were washed with water (2 × ≈10 mL per mmol of acyl chloride) and brine (≈10 mL per mmol of acyl chloride), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil thus acquired was subjected to flash chromatography and the acquired oil was distilled to provide the desired acyltrimethylgermane.
3.3.2.3.1 Synthesis of Decanoyltrimethylgermane (170)

![Chemical Structure]

\( \text{170} \)

a) With Chlorotrimethylsilane as Additive

Following general procedure 5, to a cold (−78 °C) stirred solution of Me\(_3\)GeCu•Me\(_2\)S (168) (1.47 mmol, 1.50 equiv) in dry THF (8.5 mL total), prepared via the “normal” addition method (section 3.3.2.2(a), p 223), was added chlorotrimethylsilane (107 mg, 0.98 mmol, 1 equiv) via a syringe. After the mixture had been stirred for 5 min at −78 °C, a solution of decanoyl chloride (157) (187 mg, 0.98 mmol, 1 equiv) in dry THF (2 mL) was added via a cannula. The oil acquired was subjected to flash chromatography (30 g TLC grade silica gel, 24:1 petroleum ether–diethyl ether) and the derived oil was distilled (86–94 °C/0.04 Torr) to afford 247 mg (92%) of the title compound as a light yellow oil.

\(^1\)H NMR (400 MHz, CDCl\(_3\)): \( \delta \) 2.58 (t, 2H, \( J = 7.4 \) Hz, -CH\(_2\)CO-), 1.57–1.45 (m, 2H), 1.39–1.18 (m, 12H), 0.85 (br t, 3H, \( J = 6.8 \) Hz, -CH\(_2\)CH\(_3\)), 0.31 (s, 9H, -Ge(CH\(_3\))\(_3\)).

\(^{13}\)C NMR (75.4 MHz, CDCl\(_3\)): \( \delta \) 245.9 (-CO-), 49.7 (-CH\(_2\)CO-), 31.9, 29.5, 29.4, 29.30, 29.27, 22.7, 22.3, 14.1 (-CH\(_2\)CH\(_3\)), −2.9 (−Ge(CH\(_3\))\(_3\)).

IR (film): 1658, 1466, 1237, 829, 603 cm\(^{-1}\).

HRMS for C\(_{13}\)H\(_{28}\)\(^74\)GeO: calcd 274.1352, found 274.1354.

Anal. calcd for C\(_{13}\)H\(_{28}\)GeO: C 57.20, H 10.34; found: C 56.90, H 10.45.
b) Without Additive

Following general procedure 5, to a cold (−78 °C) stirred solution of Me₃GeCu•Me₂S (168) (1.59 mmol, 1.50 equiv) in dry THF (8.7 mL total), prepared via the “normal” addition method (section 3.3.2.2(a), p 223), was added a solution of decanoyl chloride (157) (202 mg, 1.06 mmol, 1 equiv) in dry THF (2 mL) via a cannula. The oil acquired was subjected to flash chromatography (25 g TLC grade silica gel, 24:1 petroleum ether–diethyl ether) and the acquired oil was distilled to afford 234 mg (81%) of the title compound as a light yellow oil. The spectral data were identical with those reported above.

3.3.2.3.2 Synthesis of (Cyclopent-2-en-1-yl)acetyltrimethylgermane (178)

Following general procedure 5, to a cold (−78 °C) stirred solution of Me₃GeCu•Me₂S (168) (1.69 mmol, 1.50 equiv) in dry THF (9.2 mL total), prepared via the “normal” addition method (section 3.3.2.2(a), p 223), was added chlorotrimethylsilane (122 mg, 1.13 mmol, 1 equiv) via a syringe. After the mixture had been stirred for 5 min, a solution of (cyclopent-2-en-1-yl)acetyl chloride (158) (163 mg, 1.13 mmol, 1 equiv) in dry THF (2 mL) was added via a cannula. The oil acquired was subjected to flash chromatography (35 g TLC grade silica gel, 24:1 petroleum ether–diethyl ether) and the derived oil was distilled (120–130 °C/12 Torr) to afford 225 mg (88%) of the title compound as a light yellow oil.

¹H NMR (400 MHz, CDCl₃): δ 5.73–5.68 (m, 1H, vinylic proton), 5.60–5.56 (m, 1H, vinylic proton), 3.16–3.06 (m, 1H, allylic methine proton), 2.71 (dd, 1H, J = 16.7 and 6.4
Hz, -CH₃H₂CO-), 2.62 (dd, 1H, J = 16.7 and 7.9 Hz, -CH₃H₂CO-), 2.36–2.20 (m, 2H), 2.07 (dtd, 1H, J = 12.9, 8.4 and 5.4 Hz), 1.34–1.24 (m, 1H), 0.31 (s, 9H, -Ge(CH₃)₃).

¹³C NMR (75.4 MHz, CDCl₃): δ 245.4 (-CO-), 134.1 (vinylic carbon), 130.9 (vinylic carbon), 55.7 (-CH₂CO-), 39.5 (allylic methine carbon), 31.7, 29.9, -3.0 (-Ge(CH₃)₃).

IR (film): 3053, 2910, 1657, 1238, 830, 605 cm⁻¹.

HRMS for C₁₀H₁₈⁷⁴GeO: calcd 228.0569, found 228.0570.

3.3.2.3.3 Synthesis of (Cyclohexanecarbonyl)trimethylgermane (179)

Following general procedure 5, to a cold (−78 °C) stirred solution of Me₃GeCu•Me₂S (168) (2.10 mmol, 1.50 equiv) in dry THF (11.9 mL total), prepared via the “normal” addition method (section 3.3.2.2(a), p 223), was added chlorotrimethylsilane (153 mg, 1.40 mmol, 1 equiv). After the solution had been stirred for 5 min at −78 °C, a solution of cyclohexanecarbonyl chloride (174) (206 mg, 1.40 mmol, 1 equiv) in dry THF (2 mL) was added via a cannula. The oil acquired was subjected to flash chromatography (40 g TLC grade silica gel, 24:1 petroleum ether–diethyl ether) and the derived oil was distilled (120–130 °C/10 Torr) to afford 282 mg (88%) of the title compound as a light yellow oil.

¹H NMR (400 MHz, CDCl₃): δ 2.63–2.54 (m, 1H, -CH(COGe(CH₃)₃)-), 1.85–1.58 (m, 5H), 1.34–1.10 (m, 5H), 0.31 (s, 9H, -Ge(CH₃)₃).
\(^{13}\)C NMR (75.4 MHz, CDCl\(_3\)): \(\delta\) 247.2 (-CO-), 56.5 (-CHCO-), 26.5, 26.0, 25.5, -2.2 (-Ge(CH\(_3\))\(_3\)).

IR (film): 1654, 1450, 1236, 1137, 830, 604 cm\(^{-1}\).

HRMS for C\(_{10}\)H\(_{20}\)GeO: calcd 230.0726, found 230.0732.

Anal. calcd for C\(_{10}\)H\(_{20}\)GeO: C 52.48, H 8.81; found: C 52.64, H 8.98.

3.3.2.3.4 Synthesis of ((4-Methoxybenzyl)oxy)acetyltrimethylgermane (180)

\[
\text{MeO} \bigg\| \text{O} \bigg\| \text{O} \bigg\| \text{GeMe}_3
\]

Following general procedure 5, to a cold (-78 °C) stirred solution of Me\(_3\)GeCu•Me\(_2\)S (168) (1.60 mmol, 1.50 equiv) in dry THF (9.2 mL total), prepared via the "normal" addition method (section 3.3.2.2(a), p 223), was added chlorotrimethylsilane (116 mg, 1.07 mmol, 1 equiv) via a syringe. After the mixture had been stirred for 5 min, a solution of ((4-methoxybenzyl)oxy)acetyl chloride (167) (229 mg, 1.07 mmol, 1 equiv) in dry THF (1.5 mL) was added via a cannula. The oil acquired was subjected to flash chromatography (30 g TLC grade silica gel, 17:3 petroleum ether–diethyl ether) and the derived oil was distilled (120–130 °C/0.06 Torr) to afford 259 mg (82%) of the title compound as a light yellow oil.

\(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta\) 7.25 (d, 2H, \(J = 8.6\) Hz, aromatic protons), 6.87 (d, 2H, \(J = 8.6\) Hz, aromatic protons), 4.50 (s, 2H), 4.00 (s, 2H), 3.79 (s, 3H, -OCH\(_3\)), 0.32 (s, 9H, -Ge(CH\(_3\))\(_3\)).

\(^{13}\)C NMR (75.4 MHz, CDCl\(_3\)): \(\delta\) 244.8 (-CO-), 159.3, 129.4, 129.3, 113.7, 80.7
(-CH₂OCH₂CO-), 73.0 (-CH₂OCH₂CO-), 55.1 (-OCH₃), -2.7 (-Ge(CH₃)₃).

IR (film): 1667, 1614, 1515, 1303, 1250, 1175, 1117, 1036, 830, 607 cm⁻¹.

HRMS for C₁₃H₂₀⁷⁴GeO₃: calcd 298.0624, found 298.0628.

Anal. calcd for C₁₃H₂₀GeO₃: C 52.59, H 6.79; found: C 52.47, H 6.56.

3.3.2.3.5 Synthesis of (Benzyloxy)acetyltrimethylgermane (181)

\[ \text{181} \]

a) With Chlorotrimethylsilane as Additive

Following general procedure 5, to a cold (−78 °C) stirred solution of Me₃GeCu·Me₂S (168) (1.42 mmol, 1.50 equiv) in dry THF (8.1 mL total), prepared via the “normal” addition method (section 3.3.2.2(a), p 223), was added chlorotrimethylsilane (103 mg, 0.94 mmol, 1 equiv) via a syringe. After the mixture had been stirred at −78 °C for 5 min, a solution of benzyloxyacetyl chloride (175) (174 mg, 0.94 mmol, 1 equiv) in dry THF (1.5 mL) was added via a cannula. The oil acquired was subjected to flash chromatography (26 g TLC grade silica gel, 9:1 petroleum ether–diethyl ether) and the oil derived was distilled (130–140 °C/0.05 Torr) to afford 224 mg (89%) of the title compound as a light yellow oil.

\(^1\text{H NMR (400 MHz, CDCl}_3\)): \(\delta \ 7.33 \ (\text{br s, 5H, aromatic protons}), \ 4.56 \ (\text{s, 2H}), \ 4.03 \ (\text{s, 2H}), \ 0.34 \ (\text{s, 9H, -Ge(CH}_3)_3\)).

\(^{13}\text{C NMR (75.4 MHz, CDCl}_3\)): \(\delta \ 244.8 \ (-\text{CO-}), \ 137.2 \ (\text{aromatic ipso carbon}), \ 128.4, \ 127.81, \ 127.75, \ 81.1 \ (-\text{CH}_2\text{OCH}_2\text{CO-}), \ 73.4 \ (-\text{CH}_2\text{OCH}_2\text{CO-}), \ -2.6 \ (-\text{Ge(CH}_3)_3\)).
IR (film): 3033, 2911, 1668, 1455, 1236, 1123, 833, 739, 699, 606 cm⁻¹.

HRMS for C₁₁H₁₅⁷⁴GeO₂ (M – CH₃)⁺: calcd 253.0284, found 253.0283.

Anal. calcd for C₁₂H₁₈GeO₂: C 54.01, H 6.80; found: C 54.13, H 6.82.

b) Without Additive

Following general procedure 5, to a cold (−78 °C) stirred solution of Me₃GeCu•Me₂S (168) (4.40 mmol, 2.20 equiv) in dry THF (26.8 mL total), prepared via the “inverse” addition method (section 3.3.2.2(b), p 223), was added benzylxyacetyl chloride (175) (369 mg, 2.00 mmol, 1 equiv) via a syringe. The reaction mixture was stirred at −78 °C for 1.5 h, then was treated with aqueous NH₄Cl–NH₄OH (pH 8–9, 6 mL) and diethyl ether (10 mL) was added to the mixture. The cooling bath was removed and the mixture was stirred vigorously at rt, open to the atmosphere, until the aqueous layer was deep blue. The crude oil obtained was subjected to flash chromatography (50 g TLC grade silica gel, 9:1 then 3:1 petroleum ether–diethyl ether) to afford four fractions which were concentrated under reduced pressure. The first fraction to be eluted afforded 337 mg (63%) of (benzyloxy)acetyltrimethylgermane (181). The spectral data were identical with those reported above. The second fraction to be eluted afforded 8.9 mg of an unidentified compound. The third fraction to be eluted afforded 22 mg (2.6%) of (E)-2-benzyloxy-1-(benzyloxy)acetoxy-1-trimethylgermylene (186). An analytically pure sample of this compound was obtained by resubjecting this material to flash chromatography (5 g TLC grade silica gel, 17:3 petroleum ether–diethyl ether).
$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 7.52–7.23 (m, 10H, aromatic protons), 5.87 (s, 1H, -CH=\text{C}(\text{Ge(CH}_3)_3))-), 4.84 (s, 2H, -\text{CH}_2\text{OCH} = \text{C}(\text{Ge(CH}_3)_3))-), 4.62 (s, 2H, -\text{CH}_2\text{OCH}_2\text{CO}-), 4.19 (s, 2H, -\text{CH}_2\text{CO}-), 0.27 (s, 9H, -\text{Ge(CH}_3)_3)

Additional $^1$H NMR data, derived from NOE difference experiments, are given in Table 21.

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 168.4 ($\text{-CO-}$), 142.0 ($\text{-CH=\text{C}(\text{Ge(CH}_3)_3)}$), 137.1, 136.7, 134.2, 128.5, 128.4, 128.14, 128.08, 127.9, 127.4, 74.4, 73.1, 66.8, $-1.4$ ($\text{-Ge(CH}_3)_3$).

IR (film): 3032, 2909, 1760, 1647, 1238, 1202, 1117, 830, 738, 698, 606 cm$^{-1}$.

HRMS for C$_{21}$H$_{26}$$^{74}$GeO$_4$: calcd 416.1043, found 416.1043.
Table 21: \(^1\)H NMR Data from Nuclear Overhauser Enhancement Difference Experiments for (E)-2-Benzylxy-1-(benzyloxy)acetoxy-1-trimethylgermylethene (186)

<table>
<thead>
<tr>
<th>Assignments</th>
<th>(^1)H NMR(^a)</th>
<th>Observed NOEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-x</td>
<td>(\delta) ppm (mult, (J) (Hz))</td>
<td></td>
</tr>
<tr>
<td>Aromatic</td>
<td>7.52–7.23 (m)</td>
<td></td>
</tr>
<tr>
<td>H-2(^b)</td>
<td>5.87 (s)</td>
<td>H-1&quot; , -Ge(CH(_3))(_3)</td>
</tr>
<tr>
<td>H-1(^{1b})</td>
<td>4.84 (s)</td>
<td>H-2, H-2&quot;</td>
</tr>
<tr>
<td>H-2(^b)</td>
<td>4.62 (s)</td>
<td>H-1', H-3'</td>
</tr>
<tr>
<td>H-1(^b)</td>
<td>4.19 (s)</td>
<td>H-2'</td>
</tr>
<tr>
<td>-Ge(CH(_3))(_3)(^b)</td>
<td>0.27 (s)</td>
<td>H-2</td>
</tr>
</tbody>
</table>

\(^a\) 400 MHz, CDCl\(_3\). \(^b\) Irradiation of this signal generated the corresponding NOEs in the right hand column.

The fourth fraction to be eluted afforded 4.2 mg of an unidentified compound.

c) With Bromotrimethylsilane as Additive

Following general procedure 5, to a cold (−78 °C) stirred solution of \(\text{Me}_3\text{GeCu}\cdot\text{Me}_2\text{S} (168)\) (2.40 mmol, 2.20 equiv) in dry THF (14 mL total), prepared via the “inverse” addition method (section 3.3.2.2(b), p 223), was added a solution of bromotrimethylsilane (659 mg, 4.30 mmol, 3.93 equiv, freshly distilled from CaH\(_2\)) in THF (1 mL) via a cannula. After the mixture had been stirred for 5 min, a solution of (benzyloxy)acetyl chloride (175) (202 mg,
1.09 mmol, 1 equiv) in dry THF (1 mL) was added via a cannula. The reaction mixture was stirred at -78 °C for 2.5 h, then was treated with aqueous NH₄Cl–NH₄OH (pH 8–9, 7 mL) and diethyl ether (10 mL) was added to the mixture. The cooling bath was removed and the heterogeneous mixture was vigorously stirred, open to the atmosphere, until the aqueous layer was deep blue. The crude oil obtained was subjected to flash chromatography (16 g TLC grade silica gel, 19:1 petroleum ether–diethyl ether) to afford four fractions which were concentrated under reduced pressure. The first fraction to be eluted afforded 262 mg (52%) of 2-benzyloxy-1-trimethylsilyloxy-1,1-bis(trimethylgermyl)ethane (188).

![Chemical Structure](image_url)

**1H NMR (400 MHz, CDCl₃):** δ 7.45–7.35 (m, 5H, aromatic protons), 4.43 (s, 2H), 3.77 (s, 2H), 0.15 (s, 18H, 2 × -Ge(CH₃)₃), 0.07 (s, 9H, -Si(CH₃)₃).

**13C NMR (75.4 MHz, CDCl₃):** δ 138.3 (aromatic ipso carbon), 128.2, 127.9, 127.4, 76.9 (C₆H₅CH₂OCH₂–), 74.3 (-C(Ge(CH₃)₃)₂OSi(CH₃)₃–), 73.0 (C₆H₅CH₂–), 2.6 (-Si(CH₃)₃), -1.6 (-Ge(CH₃)₃).

**IR (film):** 1498, 1455, 1402, 1351, 1248, 1111, 1065, 976, 838, 599 cm⁻¹.

**HRMS for C₁₇H₃₃²⁷Ge⁻⁷⁴GeO₂²²⁺Si (M – CH₃):** calcd 443.0682, found 443.0686.

**Anal. calcd for C₁₈H₃₆Ge₂O₂Si: C 47.23, H 7.93; found: C 47.19, H 7.71.**

The following three fractions to be eluted afforded only trace amounts of unidentified compounds.
3.3.2.3.6 Synthesis of 5-Chloropentanoyltrimethylgermane (182)

Following general procedure 5, to a cold (−78 °C) stirred solution of Me₃GeCu•Me₂S (168) (1.81 mmol, 1.50 equiv) in dry THF (9.8 mL total), prepared via the “normal” addition method (section 3.3.2.2(a), p 223), was added chlorotrimethylsilane (131 mg, 1.21 mmol, 1 equiv) via a syringe. After the mixture had been stirred for 5 min, a solution of 5-chloropentanoyl chloride (176) (186 mg, 1.21 mmol, 1 equiv) in dry THF (2 mL) was added via a cannula. The crude oil acquired was subjected to flash chromatography (20 g TLC grade silica gel, 19:1 petroleum ether–diethyl ether) and the resultant oil was distilled (145–155 °C/15 Torr) to afford 256 mg (90%) of the title compound as a light yellow oil.

$^1$H NMR (400 MHz, CDCl₃): δ 3.49 (t, 2H, J = 6.4 Hz, -CH₂Cl), 2.64 (t, 2H, J = 7.0 Hz, -CH₂CO-), 1.78–1.62 (m, 4H), 0.32 (s, 9H, -Ge(CH₃)₃).

$^{13}$C NMR (75.4 MHz, CDCl₃): δ 244.9 (-CO-), 48.4, 44.6, 31.9, 19.5, −3.0 (-Ge(CH₃)₃).

IR (film): 1657, 1238, 830, 605 cm⁻¹.

HRMS for C₈H₁₇ClGeO: calcd 238.0180, found 238.0179.

Anal. calcd for C₈H₁₇ClGeO: C 40.50, H 7.22; found: C 40.80, H 7.40.
3.3.2.3.7 Synthesis of 3-Chloropropanoyltrimethylgermane (183)

\[ \text{Cl} - \text{O} - \text{GeMe}_3 \]

183

\( \text{O} \)

a) With Bromotrimethylsilane as Additive

Following general procedure 5, to a cold (-78 °C) stirred solution of \( \text{Me}_3\text{GeCu} \cdot \text{Me}_2\text{S} \) (168) (4.70 mmol, 2.20 equiv) in dry THF (26.5 mL total), prepared via the “inverse” addition method (section 3.3.2.2(b), p 223), was added a solution of bromotrimethylsilane (815 mg, 5.32 mmol, 2.50 equiv) in dry THF (3 mL) via a cannula. After the mixture had been stirred for 5 min, a solution of 3-chloropropanoyl chloride (177) (271 mg, 2.13 mmol, 1 equiv) in dry THF (2 mL) was added via a cannula. The reaction mixture was stirred at -78 °C for 2.25 h, then was treated with aqueous \( \text{NH}_4\text{Cl} - \text{NH}_4\text{OH} \) (pH 8-9, 8 mL) and diethyl ether (10 mL) was added to the mixture. The cooling bath was removed and the heterogeneous mixture was stirred vigorously, open to the atmosphere, until the aqueous layer was deep blue. The combined dried organic extracts were concentrated via distillation of the solvent at atmospheric pressure. The crude oil obtained was subjected to flash chromatography (50 g TLC grade silica gel, 24:1 petroleum ether–diethyl ether) to afford two fractions which were concentrated via distillation of the solvent at atmospheric pressure. The first fraction to be eluted afforded 65 mg of an oil as a mixture of compounds. \(^1\text{H} \) NMR spectroscopic and GLC analysis suggested that this material was mainly composed (≈75%) of 3-chloro-1,1-bis-(trimethylgermyl)-1-(trimethylsilyloxy)propane (193).
1H NMR (400 MHz, CDCl3):  δ 3.55–3.48 (m, 2H, -CH2Cl), 2.40–2.32 (m, 2H, -CH2CH2Cl), 0.20 (s, 18H, 2 x -Ge(CH3)3), 0.12 (s, 9H, -Si(CH3)3).

The second compound to be eluted was distilled. A forerun was collected in a first bulb (distillation temperature 20–40 °C/9 Torr) to afford 31 mg of volatile material (by GLC analysis). The remainder of the oil was collected in a second bulb (distillation temperature 105–115 °C/9 Torr) to afford 261 mg (58%) of 3-chloropropanoyltrimethylgermane (183) as a light yellow oil.

1H NMR (400 MHz, CDCl3): δ 3.69 (t, 2H, J = 6.8 Hz, -CH2CO-), 3.09 (t, 2H, J = 6.8 Hz, -CH2CO-), 0.34 (s, 9H, -Ge(CH3)3).

13C NMR (75.4 MHz, CDCl3): δ 242.5 (-CO-), 51.1 (-CH2Cl), 37.4 (-CH2CO-), -3.3 (-Ge(CH3)3).

IR (film): 1661, 1326, 1239, 832, 668, 606 cm⁻¹.

HRMS for C6H13ClGeO: calcd 209.9867, found 209.9872.

Anal. calcd for C6H13ClGeO: C 34.45, H 6.26; found: C 34.46, H 6.36.

b) Without Additive

Following general procedure 5, to a cold (−78 °C) stirred solution of Me3GeCu•Me2S (168) (2.59 mmol, 1.50 equiv) in dry THF (14.1 mL total), prepared via the "inverse" addition method (section 3.3.2.2(b), p 223), was added a solution of 3-chloropropanoyl chloride (177) (220 mg, 1.73 mmol, 1 equiv) in dry THF (3 mL) via a cannula. The reaction mixture was
stirred at -78 °C for 3 h, then was treated with aqueous NH₄Cl–NH₄OH (pH 8–9, 8 mL) and diethyl ether (10 mL) was added to the mixture. The cooling bath was removed and the heterogeneous mixture was stirred vigorously, open to the atmosphere, until the aqueous layer was deep blue. The crude oil obtained was subjected to flash chromatography (29 g TLC grade silica gel, 32:1 petroleum ether–diethyl ether) to afford two fractions which were concentrated under reduced pressure. The first fraction to be eluted afforded 34 mg of a mixture of two compounds. An analytically pure sample of each compound was obtained by HPLC separation (vide infra). The second fraction to be eluted afforded 82 mg (23%) of 3-chloropropanoyltrimethylgermane (183). The spectral data were identical with those reported above. The mixture of two compounds (fraction one) was subjected to reversed phase HPLC (C₁₈ µBondapak 10 µm, 25 mm × 100 mm column; 3:2 acetonitrile–water, 10 mL/min, UV-vis detector λ = 254 nm) to give two fractions which were concentrated under reduced pressure. The first fraction to be eluted, retention time 53 min, afforded 3.5 mg of (E)- or (Z)-1-((3-chloropropanoyl)oxy)-1,3-bis(trimethylgermyl)prop-1-ene (191).

\[\text{1}^H\text{ NMR (400 MHz, CDCl}_3\text{): } \delta 5.80 (t, 1H, J = 9.2 Hz, -CH=\text{C}(\text{Ge}(\text{CH}_3)_3))-), 3.75 (t, 2H, J = 6.8 Hz, -CH_2Cl), 2.82 (t, 2H, J = 6.8 Hz, -CH_2CO)-, 1.58 (d, 2H, J = 9.2 Hz, -CH_2Ge(\text{CH}_3)_3), 0.30 (s, 9H, -CH=\text{C}(\text{Ge}(\text{CH}_3)_3))-), 0.16 (s, 9H, -CH_2Ge(\text{CH}_3)_3).\]

\[\text{13}^C\text{ NMR (75.4 MHz, CDCl}_3\text{): } \delta 169.8 (-\text{CO}-), 152.7 (-\text{CH}=\text{C}(\text{Ge}(\text{CH}_3)_3))-), 129.5 (-\text{CH}=\text{C}(\text{Ge}(\text{CH}_3)_3))-), 39.0, 37.4, 17.2 (-\text{CH}_2Ge(\text{CH}_3)_3), -0.7, -2.3.\]
IR (film): 1741, 1238, 1146, 827, 603 cm$^{-1}$.

HRMS for C$_{12}$H$_{25}^{35}$Cl$^{74}$Ge$_2$O$_2$: calcd 383.9967, found 383.9985.

The second fraction to be eluted, retention time 57 min, afforded 7.4 mg of (Z)- or (E)-1-((3-chloropropanoyl)oxy)-1,3-bis(trimethylgermyl)prop-1-ene (192).

\[
\begin{align*}
\text{Cl} & \quad \text{O} & \quad \text{GeMe}_3 \\
\text{O} & \quad \text{GeMe}_3
\end{align*}
\]

$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 5.34 (t, 1H, $J = 8.8$ Hz, -CH=Ge(CH$_3$)$_3$-), 3.77 (t, 2H, $J = 6.6$ Hz, -CH$_2$Cl), 2.86 (t, 2H, $J = 6.6$ Hz, -CH$_2$CO-), 1.64 (d, 2H, $J = 8.8$ Hz, -CH$_2$Ge(CH$_3$)$_3$), 0.25 (s, 9H, -CH=C(Ge(CH$_3$)$_3$)-), 0.13 (s, 9H, -CH$_2$Ge(CH$_3$)$_3$).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 168.5 (-CO-), 153.1 (-CH=C(Ge(CH$_3$)$_3$)-), 126.5 (-CH=C(Ge(CH$_3$)$_3$)-), 39.1, 37.5, 16.4 (-CH$_2$Ge(CH$_3$)$_3$), -1.0, -2.2.

IR (film): 1742, 1629, 1237, 1148, 825, 602 cm$^{-1}$.

HRMS for C$_{12}$H$_{25}^{35}$Cl$^{74}$Ge$_2$O$_2$: calcd 383.9967, found 383.9975.

3.3.2.3.8 Synthesis of Hexanediroylbis(trimethylgermane) (184)

\[
\begin{align*}
\text{Me}_3\text{Ge} & \quad \text{O} & \quad \text{O} & \quad \text{GeMe}_3 \\
\text{O} & \quad \text{GeMe}_3
\end{align*}
\]

a) With Chlorotrimethylsilane as Additive

Following general procedure 5 (amounts of reagents and solvents were doubled for this substrate), to a cold (-78 °C) stirred solution of Me$_3$GeCu•Me$_2$S (168) (3.53 mmol, 3.00
equiv) in dry THF (21.4 mL total), prepared via the "normal" addition method (section 3.3.2.2(a), p 223), was added chlorotrimethylsilane (256 mg, 2.35 mmol, 2.00 equiv) via a syringe. After the solution had been stirred for 5 min, a solution of adipoyl chloride (159) (215 mg, 1.18 mmol, 1 equiv) in dry THF (2 mL) was added via a cannula. The crude oil acquired was subjected to flash chromatography (50 g TLC grade silica gel, 17:3 petroleum ether–diethyl ether) and the derived liquid was distilled (110–120 °C/0.05 Torr) to afford 375 mg (92%) of the title compound as a light yellow oil.

\[ ^{1}H\text{ NMR (400 MHz, CDCl}_{3}\text{): }\delta 2.69\text{--2.56 (m, 4H, }2\times\text{-CH}_{2}\text{CO-}, 1.53\text{--1.44 (m, 4H, }2\times\text{-CH}_{2}\text{CH}_{2}\text{CO-}, 0.31 (s, 18H, }2\times\text{-Ge(CH}_{3}\text{)}_{3}\text{).} \]

\[ ^{13}C\text{ NMR (75.4 MHz, CDCl}_{3}\text{): }\delta 245.1 (-CO-), 49.2 (-CH}_{2}\text{CO-), 21.8 (-CH}_{2}\text{CH}_{2}\text{CO-), -3.0 (-Ge(CH}_{3}\text{)}_{3}\text{).} \]

IR (film): 1657, 1237, 830, 604 cm\(^{-1}\).

HRMS for C\(_{12}\)H\(_{26}\)Ge\(_{2}\)O\(_{2}\): calcd 350.0356, found 350.0355.

Anal. calcd for C\(_{12}\)H\(_{26}\)Ge\(_{2}\)O\(_{2}\): C 41.47, H 7.54; found: C 41.58, H 7.58.

\(b\) Without Additive

Following general procedure 5 (amounts of reagents and solvents were doubled for this substrate), to a cold (−78 °C) stirred solution of Me\(_{3}\)GeCu•Me\(_{2}\)S (168) (3.45 mmol, 3.00 equiv) in dry THF (18.4 mL total), prepared via the "inverse" addition method (section 3.3.2.2(b), p 223), was added a solution of adipoyl chloride (159) (210 mg, 1.15 mmol, 1 equiv) in dry THF (2 mL) via a cannula. The crude oil obtained was subjected to flash chromatography (60 g TLC grade silica gel, 29:20:1 petroleum ether–CH\(_{2}\)Cl\(_{2}\)–diethyl ether)
to afford 229 mg of a mixture of 2 components. The mixture was resubjected to flash chromatography (25 g TLC grade silica gel, 9:1 petroleum ether–diethyl ether) to afford two fractions, which were concentrated under reduced pressure. The first fraction to be eluted was distilled (105–115 °C/0.07 Torr) to afford 25 mg (6%) of 2-hydroxy-2-trimethylgermyl-(cyclopentanecarbonyl)trimethylgermane (194) as a light yellow oil.

![Image](image)

1H NMR (400 MHz, CDCl₃): δ 3.92 (br s, 1H, exchanges with D₂O, -OH), 3.11 (dd, 1H, J = 11.0 and 8.6 Hz, -CH(COGe(CH₃)₃)-), 2.10–1.95 (m, 2H), 1.85–1.75 (m, 2H), 1.72–1.61 (m, 1H), 1.59–1.52 (m, 1H), 0.34 (s, 9H, -COGe(CH₃)₃), 0.10 (s, 9H, -C(OH)Ge(CH₃)₃–).

13C NMR (75.4 MHz, CDCl₃): δ 254.4 (-CO-), 79.1 (-C(OH)Ge(CH₃)₃–), 62.8 (-CH(COGe(CH₃)₃)-), 37.7, 26.9, 22.5, –2.8, –3.7.

IR (film): 3464, 2969, 1634, 1358, 1291, 1236, 1031, 826, 602 cm⁻¹.

HRMS for C₁₂H₂₆²⁷²⁷Ge: calcd 348.0365, found 348.0359.

The second fraction to be eluted was distilled to afford 131 mg (33%) of hexanediol-bis(trimethylgermane) (184). Spectral data were identical with those reported above.
3.3.2.3.9 Attempts at Synthesizing Pent-4-ynoyltrimethylgermane (185)

\[
\begin{align*}
\text{GeMe}_3
\end{align*}
\]

\[185\]

\(a)\) With Chlorotrimethylsilane as Additive

Following general procedure 5, to a cold \((-78 \, ^\circ\text{C})\) stirred solution of \(\text{Me}_3\text{GeCu}\cdot\text{Me}_2\text{S} (168) (0.92 \, \text{mmol, 1.06 equiv})\) in dry THF (5 mL total), prepared via the “inverse” addition method (section 3.3.2.2(b), p 223), was added chlorotrimethylsilane (99 mg, 0.91 mmol, 1.05 equiv) via a syringe. After the mixture had been stirred for 5 min, a solution of pent-4-ynoyl chloride (160) (101 mg, 0.87 mmol, 1 equiv) in dry THF (1 mL) was added via a cannula. The reaction mixture was stirred for 3 h at \(-78 \, ^\circ\text{C}\). The crude oil obtained was subjected to flash chromatography (5 g TLC grade silica gel, petroleum ether then ethyl acetate) to afford two fractions which were concentrated under reduced pressure. The first fraction to be eluted was distilled \((70–80 \, ^\circ\text{C}/0.08 \, \text{Torr})\) to afford 34 mg \((10\%)\) of 2-(bis(trimethylgermyl)methyl)-1-((trimethylsilyl)oxy)cyclobutene (197) as a clear colorless oil.

\[
\begin{align*}
\text{OSiMe}_3
\end{align*}
\]

\[197\]

\(^1\text{H NMR (400 MHz, CDCl}_3\):} \delta 2.47 \,(t, 2\text{H}, J = 3.2 \, \text{Hz}), 1.89 \,(t, 2\text{H}, J = 3.2 \, \text{Hz}), 1.29 \,(s, 1\text{H,} -\text{CH(}\text{Ge(CH}_3)_3\text{)})_2, 0.16 \,(s, 9\text{H,} -\text{Si(CH}_3)_3\text{)}, 0.15 \,(s, 18\text{H,} 2 \times -\text{Ge(CH}_3)_3\text{}).

\(^{13}\text{C NMR (75.4 MHz, CDCl}_3\):} \delta 137.3 \,(\text{vinyllic carbon}), 117.2 \,(\text{vinyllic carbon}), 31.7, 24.9,
19.0 (-CH(Ge(CH₃)₃)₂), 0.7 (-Si(CH₃)₃), 0.1 (-Ge(CH₃)₃).

IR (film): 1681, 1296, 1185, 1151, 1026, 924, 884, 845, 598 cm⁻¹.

HRMS for C₁₄H₃₂⁷²Ge⁷⁴GeO²₈Si: calcd 390.0655, found 390.0660.

The second fraction to be eluted afforded 78 mg (42%) of 4-trimethylgermylpent-4-enamide (198) as a colorless solid. An analytically pure sample of this compound was obtained by sublimation (35–36 °C/0.007 Torr; mp 52.5–54.5 °C).

![198](image)

**1H NMR (400 MHz, CDCl₃):** δ 5.62–5.40 (br s, 2H, -NH₂), 5.53 (d, 1H, J = 2.0 Hz, vinylic proton trans to -Ge(CH₃)₃), 5.22 (d, 1H, J = 2.0 Hz, vinylic proton cis to -Ge(CH₃)₃), 2.53–2.47 (m, 2H), 2.37–2.30 (m, 2H), 0.21 (s, 9H, -Ge(CH₃)₃).

**1³C NMR (75.4 MHz, CDCl₃):** δ 175.3 (-CO-), 152.4 (-C(=CH₂)-), 121.7 (-C(=CH₂)-), 34.8, 32.1, -2.1 (-Ge(CH₃)₃).

IR (KBr pellet): 3365, 3193, 3050, 2972, 1667, 1631, 1236, 921, 826, 599 cm⁻¹.

HRMS for C₆H₁₇⁷⁴GeNO: calcd 217.0522, found 217.0513.

Anal. calcd for C₆H₁₇GeNO: C 44.52, H 7.94, N 6.49; found: C 44.78, H 7.95, N 6.44.

**b) Without Additive**

Following general procedure 5, to a cold (–78 °C) stirred solution of Me₃GeCu·Me₂S (168) (0.94 mmol, 1 equiv) in dry THF (5 mL total), prepared via the “inverse” addition method (section 3.3.2.2(b), p 223), was added a solution of pent-4-ynoyl chloride (160) (110
mg, 0.94 mmol, 1 equiv) in dry THF (1 mL) via a cannula. The reaction mixture was stirred at \(-78^\circ C\) for 2.5 h, then pyridine (187 mg, 2.36 mmol, 2.50 equiv) and dry methanol (61 mg, 1.90 mmol, 2.00 equiv) were added sequentially. The cooling bath was removed, and the mixture was allowed to stir for an additional 15 min. The mixture was poured into aqueous NH\(_4\)Cl–NH\(_4\)OH (pH 8–9, 5 mL) and diethyl ether (10 mL) was added to the mixture. The heterogeneous mixture was stirred vigorously, open to the atmosphere, until the aqueous layer was deep blue. The crude oil of the complex mixture obtained was subjected to flash chromatography (35 g TLC grade silica gel, 49:1, then 24:1, petroleum ether–diethyl ether) to afford three major fractions, which were concentrated under reduced pressure. The first substantial fraction to be eluted afforded 23 mg (9%) of a mixture of two compounds. \(^1\)H NMR, GLC and GLC–MS analyses of this mixture suggested that it was composed of 5-(3-trimethylgermylbut-3-en-1-yl)-4-(bis(trimethylgermyl)methyl)pent-4-eno-5-lactone (203) (=80% by GLC analysis) as well as of (E)-5-(4-trimethylgermylbut-3-en-1-yl)-4-(bis(trimethylgermyl)methyl)pent-4-eno-5-lactone (204) (=20%) based on the following: \(^1\)H NMR (400 MHz, CDCl\(_3\)) spectrum showed four signals in the 5.95–5.15 ppm region integrating for a total of two protons: 5.92 (m, 0.2H, H-3\(^{-}\)-204), 5.83 (d, 0.2H, \(J = 18.2\) Hz, H-4\(^{-}\)-204), 5.52 (d, 0.8H, \(J = 1.8\) Hz, H-4\(^{-}\)-203) and 5.22 (d, 0.8H, \(J = 1.8\) Hz, H-4\(^{-}\)-203); then 2.79 (t, 2H, \(J = 3.2\) Hz, H-3\(^{-}\)-203 + 204), 2.60–2.38 (m, 4H, H-1\(^{-}\) and H-2\(^{-}\)-203 + 204), 2.08 (t, 2H, \(J = 3.2\) Hz, H-3\(^{-}\)-203 + 204), 1.34 (s, 1H, H-1\(^{\prime}\)-203 + 204) and three singlets in the 0.26–0.15 ppm region integrating for a total of 27 protons. GLC-MS showed both components to have molecular ions of 516 whose isotopic clusters are consistent with the calculated isotopic distribution for C\(_{19}\)H\(_{38}\)Ge\(_3\)O\(_2\).
The second sizable fraction to be eluted was distilled (98–107 °C/0.07 Torr) to afford 30 mg (16%) of 5-(but-3-yn-1-yl)-4-(bis(trimethylgermyl)methyl)pent-4-eno-5-lactone (205) as a clear colorless oil.

\begin{align*}
\text{\textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3})}: & \delta 2.79 \text{ (t, 2H, } J = 3.0 \text{ Hz, -CH\textsubscript{2}CO-)}, \text{2.62–2.55 (m, 2H, } \\
& \text{-CH\textsubscript{2}CH\textsubscript{2}C=CH), 2.53–2.46 (m, 2H, -CH\textsubscript{2}C=CH), 2.06 (t, 2H, } J = 3.0 \text{ Hz, } \\
& \text{-CH\textsubscript{2}CH\textsubscript{2}CO-)}, 1.96 \text{ (t, 1H, } J = 2.6 \text{ Hz, -C=CH), 1.34 (s, 1H, -CH(Ge(CH\textsubscript{3})\textsubscript{3})\textsubscript{2}}, \\
& 0.17 \text{ (s, 18H, 2 x -Ge(CH\textsubscript{3})\textsubscript{3}).}
\end{align*}

Additional \textsuperscript{1}H NMR data, derived from homonuclear decoupling experiments, are given in Table 22.

\textsuperscript{13}C NMR (75.4 MHz, CDCl\textsubscript{3}): $\delta$ 168.9 (-CO-), 133.3 (vinyllic carbon), 126.9 (vinyllic carbon), 82.3 (-C=CH), 69.2 (-C=CH), 33.2, 31.2, 26.8, 19.9 (-CH(Fe(CH\textsubscript{3})\textsubscript{3})\textsubscript{2}), 14.3 (-CH\textsubscript{2}C=CH), -0.1 (-Ge(CH\textsubscript{3})\textsubscript{3}).
IR (film): 3313, 2970, 2140, 1757, 1682, 1269, 1236, 1144, 823, 600 cm⁻¹.

HRMS for C₁₀H₂₈²⁷Ge²⁷GeO₂: calcd 398.0522, found 398.0521.

**Table 22: **[^1]H NMR Data from Homonuclear Decoupling Experiments for 5-(But-3-yn-1-yl)-4-(bis(trimethylgermyl)methyl)pent-4-eno-5-lactone (205)

<table>
<thead>
<tr>
<th>Assignments</th>
<th>¹H NMR[^a] (δ ppm (mult, J Hz))</th>
<th>Simplified Signals (mult, J Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-2[^b]</td>
<td>2.79 (t, 3.0)</td>
<td>H-3 (s)</td>
</tr>
<tr>
<td>H-1&quot;[^b]</td>
<td>2.62–2.55 (m)</td>
<td>H-2&quot; (d, 2.6)</td>
</tr>
<tr>
<td>H-2&quot;[^b]</td>
<td>2.53–2.46 (m)</td>
<td>H-1&quot; (s), H-4&quot; (s)</td>
</tr>
<tr>
<td>H-3[^b]</td>
<td>2.06 (t, 3.0)</td>
<td>H-2 (s)</td>
</tr>
<tr>
<td>H-4[^b]</td>
<td>1.96 (t, 2.6)</td>
<td>H-2&quot; (m)</td>
</tr>
<tr>
<td>H-1'</td>
<td>1.34 (s)</td>
<td></td>
</tr>
<tr>
<td>-Ge(CH₃)₃</td>
<td>0.17</td>
<td></td>
</tr>
</tbody>
</table>

[^a] 400 MHz, CDCl₃.  
[^b] Irradiation of this signal simplified the corresponding signals in the right hand column.

The third substantial fraction to be eluted afforded 9 mg (4%) of methyl 4-trimethylgermylpent-4-enoate (206) as a clear colorless oil.
^1H NMR (400 MHz, CDCl₃): δ 5.50 (d, 1H, J = 2.0 Hz, vinylic proton trans to -Ge(CH₃)₃),
5.20 (d, 1H, J = 2.0 Hz, vinylic proton cis to -Ge(CH₃)₃),
3.67 (s, 3H, -OCH₃),
2.52–2.39 (m, 4H, -CH₂CH₂-),
0.22 (s, 9H, -Ge(CH₃)₃).

3.3.2.3.10 Synthesis of 5-Trimethylsilylpent-4-ynoylttrimethylgermane (114)

Following general procedure 5, to a cold (-78 °C) stirred solution of Me₃GeCu*SMe (168) (1.79 mmol, 1.50 equiv) in dry THF (9.8 mL total), prepared via the "normal" addition method (section 3.3.2.2(a), p 223), was added chlorotrimethylsilane (130 mg, 1.19 mmol, 1 equiv) via a syringe. After the mixture had been stirred for 5 min, a solution of 5-trimethylsilylpent-4-ynoyl chloride (164) (225 mg, 1.19 mmol, 1 equiv) in dry THF (2 mL) was added via a cannula. The oil acquired was subjected to flash chromatography (40 g TLC grade silica gel, 26:1 petroleum ether–diethyl ether) and the derived oil was distilled (68–76 °C/0.05 Torr) to afford 265 mg (82%) of the title compound as a light yellow oil.

^1H NMR (400 MHz, CDCl₃): δ 2.89–2.83 (m, 2H), 2.45–2.38 (m, 2H), 0.33 (s, 9H,
-Ge(CH₃)₃), 0.11 (s, 9H, -Si(CH₃)₃).

^13C NMR (75.4 MHz, CDCl₃): δ 242.9 (-CO-), 106.1 (-C≡CSi(CH₃)₃), 84.8 (-C≡CSi(CH₃)₃),
47.9 (-CH₂CO-), 12.9 (-CH₂C≡C-), 0.0 (-Si(CH₃)₃), −3.1 (-Ge(CH₃)₃).

IR (film): 2177, 1660, 1251, 843, 760, 606 cm⁻¹.

HRMS for C₁₁H₂₂⁷⁴GeO²⁸Si: calcd 272.0652, found 272.0644.

Anal. calcd for C₁₁H₂₂GeOSi: C 48.76, H 8.18; found: C 48.79, H 8.16.

3.3.2.4 LARGE SCALE PREPARATION OF ((4-METHOXYBENZYL)OXY)ACETYLTRIMETHYL-GERMANE (180)

![180](image)

To cold (−10 °C) stirred dry THF (25 mL) was added cold (0 °C) Me₃GeH (53) (8.55 g, 72.0 mmol, 1.80 equiv) via a cannula. A solution of t-BuLi (1.77 M in pentane, 33.9 mL, 60.0 mmol, 1.50 equiv) was added via a syringe over 3 min (Warning! Gas evolution!). The resulting yellow solution was stirred at −10 °C for 5 min to afford a clear colorless solution. This solution was transferred via a cannula to a cold (−78 °C) stirred suspension of CuBr•Me₂S (12.34 g, 60.0 mmol, 1.50 equiv) in dry THF (325 mL). The flask that initially contained the Me₃GeLi (149) was rinsed with dry THF (2 × 10 mL) and the rinses were transferred via a cannula to the suspension of CuBr•Me₂S. The mixture was stirred at −78 °C for 1 h to afford a dark red–black solution. Chlorotrimethylsilane (4.35 g, 40.0 mmol, 1 equiv) was added via a syringe. After the mixture had been stirred for 5 min, a solution of ((4-methoxybenzyl)oxy)acetyl chloride (167) (8.59 g, 40.0 mmol, 1 equiv) in dry THF (30 mL) was added via a cannula. The black reaction mixture was stirred at −78 °C for 1 h, then was warmed to −30 °C and was allowed to stir for an additional 2 h. The mixture was poured
into a stirred solution of aqueous NH₄Cl–NH₄OH (pH 8–9, 400 mL) and diethyl ether (400 mL) was added to the mixture. The heterogeneous mixture was stirred vigorously, open to the atmosphere, until the aqueous layer was deep blue. The layers were separated and the aqueous portion was extracted with diethyl ether (3 × 200 mL). The combined organic extracts were washed with water (2 × 100 mL) and brine (100 mL), were dried over anhydrous magnesium sulfate and then were filtered and concentrated under reduced pressure. The crude oil obtained was subjected to chromatography (Prep LC 500, two silica gel cartridges (57 mm × 300 mm) in tandem, 23:2 petroleum ether–diethyl ether, 250 mL/min) and the acquired oil was distilled to afford 9.76 g (82%) of the title compound as a clear colorless oil. The spectral data were identical with those reported above (section 3.3.2.3.4, p 228).
3.3.3 SYNTHESIS OF S-(PYRIDIN-2-YL) THIOESTERS

3.3.3.1 GENERAL PROCEDURE 6: PREPARATION OF THE S-(PYRIDIN-2-YL) THIOESTERS

To a stirred solution of the appropriate carboxylic acid (1 equiv) in dry acetonitrile (0.3 M solution) at rt was added sequentially triphenylphosphine (1.0–1.1 equiv) and 2,2'-disulfanediyldipyridine (1.0–1.1 equiv). The yellow solution was stirred at rt 0.5–1 h, then the solvent was removed under reduced pressure. The residue was flash chromatographed to afford the desired S-(pyridin-2-yl) thioester.

3.3.3.1.1 Synthesis of S-(Pyridin-2-yl) Decanethioate (210)

Following general procedure 6, to a solution of decanoic acid (153) (1.02 g, 5.92 mmol, 1 equiv) in dry acetonitrile (20 mL) was sequentially added triphenylphosphine (1.55 g, 5.92 mmol, 1.00 equiv) and 2,2'-disulfanediyldipyridine (1.31 g, 5.92 mmol, 1.00 equiv). The reaction mixture was stirred at rt for 0.5 h. The residue was subjected to flash chromatography (140 g silica gel, 2:1 petroleum ether–diethyl ether) to afford 1.23 g (78%) of the title compound as a light yellow oil.

\(^1\)H NMR (400 MHz, CDCl₃): \(\delta\) 8.59 (ddd, 1H, \(J = 4.8, 1.8\) and 1.0 Hz), 7.71 (td, 1H, \(J = 7.8\) and 1.8 Hz), 7.59 (dt, 1H, \(J = 7.8\) and 1.0 Hz), 7.25 (ddd, 1H, \(J = 7.8, 4.8\) and 1.0 Hz), 7.26 (t, 2H, \(J = 7.4\) Hz, -CH₂CO-), 1.70 (quintuplet, 2H, \(J = 7.4\) Hz, -CH₂CH₂CO-), 1.48–1.19 (m, 12H), 0.85 (t, 3H, \(J = 7.8\) Hz, -CH₃).
$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 196.1 (-CO-), 151.4, 150.0, 136.7, 129.8, 123.1, 43.9, 31.6, 29.1, 29.0 (2 overlapping signals), 28.6, 25.1, 22.4, 13.8 (-CH$_2$CH$_3$).

IR (film): 1708, 1573, 1563, 1451, 1421, 1120, 990, 766 cm$^{-1}$.

HRMS for C$_{15}$H$_{23}$NOS: calcd 265.1500, found 265.1496.

Anal. calcd for C$_{15}$H$_{23}$NOS: C 67.88, H 8.73, N 5.28; found: C 67.84, H 8.91, N 5.16.

3.3.3.1.2 Synthesis of S-(Pyridin-2-yl) Pent-4-ynethioate (211)

Following general procedure 6, to a solution of pent-4-ynoic acid (156) (343 mg, 3.50 mmol, 1 equiv) in dry acetonitrile (12 mL) was added sequentially triphenylphosphine (1.01 g, 3.85 mmol, 1.10 equiv) and 2,2'-disulfanediyldipyridine (848 mg, 3.85 mmol, 1.10 equiv). The reaction mixture was stirred at rt for 0.5 h. The residue was subjected to flash chromatography (140 g silica gel, 7:3 petroleum ether–ethyl acetate) to afford 624 mg (56%) of the title compound as a light yellow oil.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 8.60 (ddd, 1H, $J = 4.8, 1.8$ and 1.0 Hz), 7.72 (ddd, 1H, $J = 7.6, 7.6$ and 1.8 Hz), 6.70 (ddd, 1H, 7.6, 1.0 and 1.0 Hz), 7.27 (ddd, 1H, $J = 7.6, 4.8$ and 1.0 Hz), 2.92 (t, 2H, $J = 7.4$ Hz, -CH$_2$CH$_2$C≡CH), 2.56 (td, 2H, $J = 7.4$ and 2.6 Hz, -CH$_2$C≡CH), 1.99 (t, 1H, $J = 2.6$ Hz, -C≡CH).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 194.3 (-CO-), 150.7, 150.2, 137.0, 129.9, 123.5, 81.4 (-C≡CH), 69.5 (-C≡CH), 42.3 (-CH$_2$CH$_2$C≡CH), 14.2 (-CH$_2$C≡CH).
IR (film): 3293, 2121, 1703, 1573, 1563, 1451, 1422, 1051, 974, 769 cm\(^{-1}\).

HRMS (DCI, isobutane) for C\(_{10}\)H\(_{10}\)NOS (M + 1): calcd 192.0483, found 192.0484.

Anal. calcd for C\(_{10}\)H\(_9\)NOS: C 62.80, H 4.74, N 7.32; found: C 62.58, H 4.61, N 7.51.

3.3.3.1.3 Synthesis of S-(Pyridin-2-yl) ((4-Methoxybenzyl)oxy)ethanethioate (212)

Following general procedure 6, to a solution of ((4-methoxybenzyl)oxy)acetic acid (166) (694 mg, 3.53 mmol, 1 equiv) in dry acetonitrile (12 mL) was added sequentially triphenylphosphine (1.02 g, 3.89 mmol, 1.10 equiv) and 2,2'-disulfanediyldipyridine (857 mg, 3.89 mmol, 1.10 equiv). The reaction mixture was stirred at rt for 1 h. The residue was subjected to flash chromatography (140 g silica gel, 3:2 petroleum ether–ethyl acetate) to afford 851 mg (83%) of the title compound as a light yellow oil.

\(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta\) 8.64 (ddd, 1H, \(J = 4.8, 2.0\) and \(1.0\) Hz), 7.73 (ddd, 1H, \(J = 7.8, 7.8\) and 2.0), 7.58 (ddd, 1H, \(J = 7.8, 1.0\) and \(1.0\) Hz), 7.33 (d, 2H, \(J = 8.6\) Hz), 7.28 (ddd, 1H, \(J = 7.8, 4.8\) and \(1.0\) Hz), 6.89 (d, 2H, \(J = 8.6\) Hz), 4.65 (s, 2H), 4.23 (s, 2H), 3.80 (s, 3H, -OCH\(_3\)).

\(^13\)C NMR (75.4 MHz, CDCl\(_3\)): \(\delta\) 197.6 (-CO-), 159.4, 150.7, 150.3, 137.0, 130.4, 129.5, 128.5, 123.4, 113.7, 74.3, 73.7, 55.0 (-OCH\(_3\)).

IR (film): 1708, 1613, 1574, 1563, 1515, 1451, 1422, 1250, 1121, 1076, 1034, 769 cm\(^{-1}\).

HRMS (DCI, isobutane) for C\(_{15}\)H\(_{16}\)NO\(_3\)S (M + 1): calcd 290.0851, found 290.0850.
3.3.3.1.4 Synthesis of \( S-(\text{Pyridin-2-yl}) 3\)-Chloropropanethioate (213)

![Structure of 213](image)

Following general procedure 6, to a solution of 3-chloropropanoic acid (209) (380 mg, 3.50 mmol, 1 equiv) in dry acetonitrile (12 mL) was added sequentially triphenylphosphine (1.01 g, 3.85 mmol, 1.10 equiv) and 2,2'-disulfanediyldipyridine (848 mg, 3.85 mmol, 1.10 equiv). The reaction mixture was stirred at rt for 0.5 h. The residue was subjected to flash chromatography (50 g TLC grade silica gel, 3:2 petroleum ether–ethyl acetate) to afford 395 mg (56%) of the title compound as a light yellow oil.

\(^{1}H\) NMR (400 MHz, CDCl\(_3\)): \( \delta \) 8.61 (ddd, 1H, \( J = 4.8, 2.0 \) and 1.0 Hz), 7.74 (ddd, 1H, \( J = 7.6, 7.6 \) and 2.0 Hz), 7.61 (ddd, 1H, \( J = 7.6, 1.0 \) and 1.0 Hz), 7.29 (ddd, 1H, \( J = 7.6, 4.8 \) and 1.0 Hz), 7.38 (t, 2H, \( J = 6.8 \) Hz), 3.14 (t, 2H, \( J = 6.8 \) Hz).

\(^{13}C\) NMR (75.4 MHz, CDCl\(_3\)): \( \delta \) 193.2 (CO), 150.21, 150.17, 137.4, 130.1, 123.8, 46.1, 38.3.

IR (film): 1708, 1573, 1563, 1451, 1421, 1050, 969, 768 cm\(^{-1}\).

LRMS for \( C_8H_8^{35}ClNOS \): calcd 201, found 201.

Due to the fact that this compound was unstable, satisfactory HRMS and elemental analysis could not be obtained.
3.3.4 SYNTHESIS OF ACYLTRIMETHYLGERMANES FROM S-(PYRIDIN-2-YL) THIOESTERS

3.3.4.1 GENERAL PROCEDURE 7: PREPARATION OF THE ACYLTRIMETHYLGERMANES FROM S-(PYRIDIN-2-YL) THIOESTERS

To a cold (−78 °C) stirred solution of Me₃GeCu•Me₂S (168) (1.0–1.5 equiv) in dry THF, prepared via the “inverse” addition method (section 3.3.2.2(b), p 223), was added a solution of the appropriate S-(pyridin-2-yl) thioester (1 equiv) in dry THF, via a cannula, to generate a final concentration of ≈0.1 M solution of the S-(pyridin-2-yl) thioester. The reaction mixture was stirred at −78 °C for 1 h, then was warmed to −30 °C and was allowed to stir for an additional 2 h. The black mixture was poured into a stirred aqueous NH₄Cl–NH₄OH solution (pH 8–9, ≈15 mL per mmol of S-(pyridin-2-yl) thioester) and diethyl ether (≈30 mL per mmol of S-(pyridin-2-yl) thioester) was added to the mixture. The two-phase system was stirred vigorously, open to the atmosphere, until the aqueous layer was deep blue and an orange precipitate was present. The solid was removed by filtration of the mixture through a plug of glass wool in a funnel. The layers of the filtrate were separated and the aqueous portion was extracted with diethyl ether (2 × ≈10 mL per mmol of S-(pyridin-2-yl) thioester). The combined organic extracts were washed with water (2 × ≈10 mL per mmol of S-(pyridin-2-yl) thioester) and brine (≈10 mL per mmol of S-(pyridin-2-yl) thioester), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil thus acquired was subjected to flash chromatography to provide the desired acyltrimethylgermane.
3.3.4.1.1 Synthesis of Decanoyltrimethylgermane (170)

Following general procedure 7, to a cold (−78 °C) stirred solution of Me$_3$GeCu•Me$_2$S (168) (1.28 mmol, 1.47 equiv) in dry THF (7.5 mL total) was added a solution of S-(pyridin-2-yl) decanethioate (210) (232 mg, 0.87 mmol, 1 equiv) in dry THF (1 mL) via a cannula. The crude oil obtained was subjected to flash chromatography (10 g TLC grade silica gel, 24:1 then 2:1 petroleum ether–diethyl ether) to afford two fractions which were concentrated under reduced pressure. The first fraction to be eluted was distilled to afford 153 mg (64%) of the title compound as a light yellow oil. The spectral data were identical with those reported above (section 3.3.2.3.1. p 225). The second compound to be eluted afforded 23 mg (10%) of unreacted S-(pyridin-2-yl) decanethioate (210).

3.3.4.1.2 Synthesis of ((4-Methoxybenzyl)oxy)acetyltrimethylgermane (180)

Following general procedure 7, to a cold (−78 °C) stirred solution of Me$_3$GeCu•Me$_2$S (168) (0.80 mmol, 1.5 equiv) in dry THF (4.3 mL total) was added a solution of S-(pyridin-2-y1) ((4-methoxybenzyl)oxy)ethanethioate (212) (156 mg, 0.54 mmol, 1 equiv) in dry THF (1 mL) via a cannula. The crude oil obtained was subjected to flash chromatography (10 g TLC grade silica gel, 17:3 petroleum ether–diethyl ether) and distilled to afford 89 mg (62%) of the
title compound as a light yellow oil. The spectral data were identical with those reported above (section 3.3.2.3.4, p 228).

3.3.4.1.3 Synthesis of 3-Chloropropanoyltrimethylgermane (183)

Following general procedure 7, to a cold (−78 °C) stirred solution of Me₃GeCu•Me₂S (168) (0.80 mmol, 1.5 equiv) in dry THF (4.3 mL total) was added a solution of S-(pyridin-2-yl) 3-chloropropanethioate (213) (107 mg, 0.54 mmol, 1 equiv) in dry THF (1 mL) via a cannula. The reaction mixture was stirred at −78 °C for 3 h, then was poured into a stirred aqueous NH₄Cl–NH₄OH solution (pH 8–9, 12 mL). The dried organic extracts were concentrated via distillation at atmospheric pressure. The crude oil obtained was subjected to flash chromatography (10 g TLC grade silica gel, gradient elution from 32:1 to 17:3 petroleum ether–diethyl ether) to afford 26 mg (23%) of the title compound as a light yellow oil. Spectral data were identical with those reported above (section 3.3.2.3.7(a), p 235).

3.3.4.1.4 Attempt at Synthesizing Pent-4-ynoyltrimethylgermane (185)

A cold (−78 °C) stirred solution of Me₃GeCu•Me₂S (168) (0.50 mmol, 1 equiv) in dry THF (5 mL total), prepared via the “inverse” addition method (section 3.3.2.2(b), p 223), was transferred via a cannula, to a cold (−78 °C) stirred solution of S-(pyridin-2-yl) pent-4-yno-
thioate (211) (192 mg, 1.00 mmol, 2.00 equiv) in dry THF (5 mL). The flask that initially contained the Me₂GeCu·Me₂S (168) was rinsed with dry THF (2 × 1 mL), and the rinses were transferred via a cannula to the solution of 5-(pyridin-2-yl) pent-4-ynethioate (211). The reaction mixture was stirred at -78 °C for 3 h, then was poured into a stirred aqueous NH₄Cl-NH₄OH solution (pH 8–9, 10 mL) and diethyl ether (20 mL) was added to the mixture. The heterogeneous mixture was stirred vigorously, open to the atmosphere, until the aqueous layer was deep blue. The yellow precipitate was removed by filtration of the mixture through a plug of glass wool in a funnel. The layers of the filtrate were separated and the aqueous portion was extracted with diethyl ether (2 × 10 mL). The combined organic extracts were washed with water (2 × 5 mL) and brine (5 mL), were dried over anhydrous magnesium sulfate and were filtered and concentrated under reduced pressure. The crude oil thus obtained was subjected to flash chromatography (7.5 g TLC grade silica gel, 32:1 petroleum ether–diethyl ether, then 1:1 petroleum ether–ethyl acetate and finally ethyl acetate) to afford 5 fractions which were concentrated under reduced pressure. The first fraction to be eluted afforded 26 mg of 5-(but-3-yn-1-yl)-4-(bis(trimethylgermyl)methyl)pent-4-eno-5-lactone (205). Spectral data were identical with those reported above (3.3.2.3.9(b), p 241). The next two fractions to be eluted afforded only trace amounts of unidentified compounds. The fourth fraction to be eluted afforded 27 mg of 2,2'-disulfanediyldipyridine. The fifth fraction to be eluted afforded 29 mg of a mixture of compounds. ¹H NMR spectroscopy analysis suggested that the major component (≈50%) was 4-trimethylgermylpent-4-enamide (198). Spectral data were identical with those reported above (3.3.2.3.9, p 241).
3.3.5 SYNTHESIS OF 2-TRIMETHYLGERMYLALK-1-ENES VIA WITTIG OLEFINATION OF ACYLTRIMETHYLGERMANES

3.3.5.1 GENERAL PROCEDURE 8: PREPARATION OF THE 2-TRIMETHYLGERMYLALK-1-ENES

To a stirred suspension of methyltriphenylphosphonium bromide (1.25–2.60 equiv) in dry solvent (0.07–0.2 M) was added a solution of n-BuLi in hexanes (1.20–2.50 equiv) via a syringe. The yellow mixture was stirred for 20–30 min, then a solution of the appropriate acyltrimethylgermane (1 equiv) in dry solvent was added, via a cannula, to generate a final concentration 0.04–0.1 M of the acyltrimethylgermane. The reaction mixture was stirred for 15–20 min then was treated with anhydrous methanol (2–3 drops). Petroleum ether or diethyl ether (=30 mL per mmol of acyltrimethylgermane) was added. The precipitate formed was removed by filtration of the mixture through Celite and the collected material was washed with petroleum ether or diethyl ether (=20 mL per mmol of acyltrimethylgermane). The filtrate was concentrated under reduced pressure and the crude oil thus acquired was flash chromatographed and the derived oil was distilled to afford the desired 2-trimethylgermylalk-1-ene as a clear colorless oil.

3.3.5.1.1 Synthesis of 2-Trimethylgermylundec-1-ene (214)

Following general procedure 8, to a cold (0 °C) stirred suspension of methyltriphenylphosphonium bromide (873 mg, 2.44 mmol, 1.25 equiv) in dry THF (15 mL) was added a
solution of n-BuLi (1.60 M in hexanes, 1.47 mL, 2.35 mmol, 1.20 equiv). The mixture was stirred at 0 °C for 10 min, then was warmed to rt and was allowed to stir for an additional 20 min. A solution of decanoyltrimeethylgermane (170) (534 mg, 1.95 mmol, 1 equiv) in dry THF (5 mL) was added via a cannula. The reaction mixture was stirred at rt for 20 min. The crude oil acquired was subjected to flash chromatography (50 g silica gel, 49:1 petroleum ether–diethyl ether) and the derived oil was distilled (80–90 °C/0.1 Torr) to afford 476 mg (90%) of the title compound as a clear colorless oil.

\[^{1}H \text{NMR (400 MHz, CDCl}_3\): \delta 5.48 (d, 1H, J = 2.8 Hz, vinylic proton trans to -Ge(CH}_3)_3\), 5.14 (d, 1H, J = 2.8 Hz, vinylic proton cis to -Ge(CH}_3)_3\), 2.16 (t, 2H, J = 7.6 Hz, -CH}_2C(=CH}_2)-), 1.44–1.16 (m, 14H), 0.86 (t, 3H, J = 7.0 Hz, -CH}_2CH}_3), 0.19 (s, 9H, -Ge(CH}_3)_3\).

\[^{13}C \text{NMR (75.4 MHz, CDCl}_3\): \delta 154.5 (-C(=CH}_2)-), 121.2 (-C(=CH}_2)-), 37.5, 31.9, 29.64, 29.57, 29.43, 29.37, 29.0, 22.7, 14.1 (-CH}_2CH}_3), -1.8 (-Ge(CH}_3)_3\).

IR (film): 3047, 2926, 1604, 1466, 1236, 916, 824, 759, 599 cm\(^{-1}\).

HRMS for C\(_{13}\)H\(_{74}\)Ge (M – CH\(_3\))\(^+\): calcd 257.1325, found 257.1329.


3.3.5.1.2 Synthesis of 2-Trimethylgermyl-6-trimethylysilylhex-5-yn-1-ene (215)

Following general procedure 8, to a stirred suspension of methyltriphenylphosphonium
bromide (435 mg, 1.22 mmol, 1.63 equiv) in dry benzene (9 mL) at rt was added a solution of
n-BuLi (1.59 M in hexanes, 0.74 mL, 1.2 mmol, 1.6 equiv). The mixture was stirred at rt for
30 min. A solution of 5-trimethylsilylpent-4-ynoyltrimethylgermane (114) (203 mg, 0.75
mmol, 1 equiv) in dry benzene (2 mL) was added via a cannula. The reaction mixture was
stirred at rt for 20 min. The crude oil acquired was subjected to flash chromatography (38 g
silica gel, petroleum ether) and the derived oil was distilled (135–145 °C/11 Torr) to afford
173 mg (86%) of the title compound as a clear colorless oil.

\[ ^1H \text{NMR (400 MHz, CDCl}_3\]:} \delta 5.52 (d, 1H, \( J = 2.0 \) Hz, vinylic proton trans to -Ge(CH\(_3\))\(_3\)),
5.21 (d, 1H, \( J = 2.0 \) Hz, vinylic proton cis to -Ge(CH\(_3\))\(_3\)), 2.42–2.27 (m, 4H,
-CH\(_2\)CH\(_2\)-), 0.20 (s, 9H, -Ge(CH\(_3\))\(_3\)), 0.12 (s, 9H, -Si(CH\(_3\))\(_3\)).

\[ ^{13}C \text{NMR (75.4 MHz, CDCl}_3\]:} \delta 152.1 (-C(=CH\(_2\))-), 122.2 (-C(=CH\(_2\))-), 107.1
(-C=CSi(CH\(_3\))\(_3\)), 84.7 (-C=CSi(CH\(_3\))\(_3\)), 35.9 (-CH\(_2\)C(=CH\(_2\))-), 19.6 (-CH\(_2\)C=C-),
0.2 (-Si(CH\(_3\))\(_3\)), -2.0 (-Ge(CH\(_3\))\(_3\)).

IR (film): 3050, 2964, 2177, 1609, 1411, 1250, 921, 843, 760, 600 cm\(^{-1}\).

HRMS for C\(_{11}\)H\(_{21}\)^{74}Ge\(^{28}\)Si (M – CH\(_3\))\(^{+}\): calcd 255.0624, found 255.0629.

Anal. calcd for C\(_{12}\)H\(_{24}\)GeSi: C 53.58, H 8.99; found: C 53.30, H 8.95.
3.3.5.1.3 Synthesis of 1-((4-Methoxybenzyl)oxy)-2-trimethylgermylprop-2-ene (216) and 2-
Trimethylgermylprop-2-en-1-ol (219)

\[ \text{MeO} \hspace{1cm} \text{HO} \]

\[ \text{216} \hspace{1cm} \text{219} \]

\( a \) 1-((4-Methoxybenzyl)oxy)-2-trimethylgermylprop-2-ene (216)

Following general procedure 8, to a cold (0 °C) stirred suspension of methyltriphenyl-
phosphonium bromide (709 mg, 1.98 mmol, 1.25 equiv) in dry THF (10 mL) was added a
solution of \( n \)-BuLi (1.60 M in hexanes, 1.19 mL, 1.90 mmol, 1.20 equiv). The mixture was
stirred at 0 °C for 10 min, then was warmed to rt and was allowed to stir for an additional 10
min. A solution of ((4-methoxybenzyl)oxy)acetyltrimethylgermane (180) (472 mg, 1.59
mmol, 1 equiv) in dry THF (6 mL) was added via a cannula. The reaction mixture was stirred
at rt for 15 min. The crude oil acquired was subjected to flash chromatography (25 g TLC
grade silica gel, 23:4 petroleum ether–diethyl ether) and the derived oil was distilled (88–98
°C/0.007 Torr) to afford 429 mg (91%) of 1-((4-methoxybenzyl)oxy)-2-trimethylgermylprop-
2-ene (216) as a clear colorless oil.

\[ \text{H NMR} (400 \text{ MHz, CDCl}_3): \delta \text{7.25 (d, 2H, } J = 8.8 \text{ Hz), 6.86 (d, 2H, } J = 8.8 \text{ Hz), 5.74 (dt,}
1\text{H, } J = 2.6 \text{ and } 1.4 \text{ Hz), 5.32 (dt, 1H, } J = 2.6 \text{ and } 1.4 \text{ Hz), 4.40 (s, 2H,}
\text{-C}_6\text{H}_4\text{CH}_2\text{O-), 4.11 (t, 2H, } J = 1.4 \text{ Hz, -CH}_2\text{C(=CH}_2\text{-), 3.79 (s, 3H, } -\text{OCH}_3\text{, 0.22}
\text{(s, 9H, -Ge(CH}_3\text{)3).} \]

\[ \text{C NMR} (75.4 \text{ MHz, CDCl}_3): \delta \text{159.0, 150.8 (-C(=CH}_2\text{-), 130.5, 129.2, 122.9 (-C(=CH}_2\text{-),} \]
113.6, 74.7, 71.6, 55.2 (-OCH₃), -2.0 (-Ge(CH₃)₃).

IR (film): 1614, 1515, 1250, 1088, 1039, 824, 602 cm⁻¹.

HRMS for C₁₄H₂₂⁷⁴GeO₂: calcd 296.0832, found 296.0838.

Anal. calcd for C₁₄H₂₂GeO₂: C 57.02, H 7.52; found: C 56.80, H 7.65.

b) 2-Trimethylgermylprop-2-en-1-ol (219)

To a stirred solution of 1-((4-methoxybenzyl)oxy)-2-trimethylgermylprop-2-ene (216) (52 mg, 18 mmol, 1 equiv) in a CH₂Cl₂–water (18:1, 2.11 mL total) mixture was added DDQ⁹⁹ (44 mg, 19 mmol, 1.1 equiv; this reaction was not performed under an atmosphere of argon). The brown–green reaction mixture was stirred at rt for 40 min. The solids were removed by filtration of the mixture through Celite and the collected material was washed with CH₂Cl₂ (5 mL). The filtrate was concentrated under reduced pressure. The crude oil thus acquired was subjected to flash chromatography (5 g TLC grade silica gel, 9:1 CH₂Cl₂–diethyl ether) to afford 23 mg (75%) of 2-trimethylgermylprop-2-en-1-ol (219)¹²⁷ as a clear colorless oil.

¹H NMR (400 MHz, CDCl₃): δ 5.73 (d, 1H, J = 2.2 Hz, vinylic proton trans to -Ge(CH₃)₃), 5.28 (d, 1H, J = 2.2 Hz, vinylic proton cis to -Ge(CH₃)₃), 4.28 (s, 2H, -CH₂OH), 1.32 (br s, 1H, exchanges with D₂O, -OH), 0.22 (s, 9H, -Ge(CH₃)₃).

¹³C NMR (75.4 MHz, CDCl₃): δ 153.1 (-C(=CH₂)-), 120.1 (-C(=CH₂)-), 66.7 (-CH₂-), -2.2 (-Ge(CH₃)₃).

IR (film): 3306, 827 cm⁻¹.

HRMS for C₅H₁₁⁷⁴GeO (M – CH₃)⁺: calcd 161.0022, found 161.0028.
Anal. calcd for C$_6$H$_{14}$GeO: C 41.24, H 8.07; found: C 41.30, H 8.13.

3.3.5.1.4 Synthesis of 6-Chloro-2-trimethylgermylhex-1-ene (217)

![Image of compound 217]

Following general procedure 8, to a cold (0 °C) stirred suspension of methyltriphenylphosphonium bromide (625 mg, 1.75 mmol, 1.25 equiv) in dry diethyl ether (25 mL) was added a solution of n-BuLi (1.60 M in hexanes, 1.05 mL, 1.68 mmol, 1.20 equiv). The mixture was stirred at 0 °C for 10 min, then was warmed to rt and was allowed to stir for an additional 20 min. After the yellow mixture had been cooled to 0 °C, a solution of 5-chloropentanoyltrimethylgermane (182) (332 mg, 1.40 mmol, 1 equiv) in dry diethyl ether (6 mL) was added via a cannula. The reaction mixture was stirred at 0 °C for 15 min. The crude oil acquired was subjected to flash chromatography (38 g silica gel, petroleum ether) and the derived oil was distilled (115–125 °C/9 Torr) to afford 278 mg (84%) of the title compound as a clear colorless oil.

$^1$H NMR (400 MHz, CDCl$_3$): δ 5.50 (d, 1H, $J = 2.4$ Hz, vinylic proton trans to -Ge(CH$_3$)$_3$), 5.18 (d, 1H, $J = 2.4$ Hz, vinylic proton cis to -Ge(CH$_3$)$_3$), 3.52 (t, 2H, $J = 6.8$ Hz, -CH$_2$Cl), 2.20 (t, 2H, $J = 7.6$ Hz, -CH$_2$C(=CH$_2$))-), 1.76 (quintuplet, 2H, $J = 6.8$ Hz, -CH$_2$CH$_2$Cl), 1.58–1.50 (m, 2H, -CH$_2$CH$_2$C(=CH$_2$)-), 0.20 (s, 9H, -Ge(CH$_3$)$_3$).

$^{13}$C NMR (75.4 MHz, CDCl$_3$): δ 153.4 (-C(=CH$_2$)-), 121.9 (-C(=CH$_2$)-), 44.9, 36.5, 32.2, 26.0, -1.9 (-Ge(CH$_3$)$_3$).

IR (film): 3047, 2943, 1605, 1413, 1236, 918, 825, 599 cm$^{-1}$. 
HRMS for C_9H_16^{35}Cl^{74}Ge (M – CH_3)^+: calcd 221.0152, found 221.0145.


3.3.5.1.5 Synthesis of 2,7-bis(Trimethylgermyl)octa-1,7-diene (218)

Following general procedure 8, to a stirred suspension of methyltriphenylphosphonium bromide (1.17 g, 3.28 mmol, 2.60 equiv) in dry benzene (26 mL) at rt was added a solution of n-BuLi (1.59 M in hexanes, 1.98 mL, 3.15 mmol, 2.50 equiv). The mixture was stirred at rt for 30 min. A solution of hexanedioylbis(trimethylgermane) (184) (438 mg, 1.26 mmol, 1 equiv) in dry benzene (6 mL) was added via a cannula. The reaction mixture was stirred at rt for 15 min. The crude oil acquired was subjected to flash chromatography (50 g silica gel, petroleum ether) and the derived oil was distilled (70–80 °C/0.3 Torr) to afford 368 mg (85%) of the title compound as a clear colorless oil.

^1H NMR (400 MHz, CDCl_3): δ 5.49 (d, 2H, J = 2.6 Hz, 2 × vinylic proton trans to -Ge(CH_3)_3), 5.15 (d, 2H, J = 2.6 Hz, 2 × vinylic proton cis to -Ge(CH_3)_3), 2.18 (m, 4H, 2 × -CH_2C(=CH_2)-), 1.39 (m, 4H, 2 × -CH_2CH_2C(=CH_2)-), 0.19 (s, 18H, 2 × -Ge(CH_3)_3).

^13C NMR (75.4 MHz, CDCl_3): δ 154.2 (C(=CH_2)), 121.4 (C(=CH_2)), 37.3, 28.7, -1.8 (-Ge(CH_3)_3).

IR (film): 3047, 2928, 1605, 1236, 917, 824, 759, 599 cm^{-1}. 

HRMS (DCI, isobutane) for $\text{C}_{14}\text{H}_{31}^{72}\text{Ge}^{74}\text{Ge} (\text{M} + 1)^+$: calcd 345.0859, found 345.0867.

Anal. calcd for $\text{C}_{14}\text{H}_{30}\text{Ge}_2$: C 48.94, H 8.80; found: C 49.20, H 8.98.
3.4 CONJUGATE ADDITION OF (TRIMETHYLGERMYL)COPPER(1)-
DIMETHYL SULFIDE (168) AND LITHIUM (TRIMETHYLGERMYL)CUPRATES
222-225 TO SELECTED UNSATURATED CARBONYL SYSTEMS

3.4.1 PREPARATION OF THE (TRIMETHYLGERMYL)CUPRATES 222–225

3.4.1.1 PREPARATION OF THE LITHIUM BIS(TRIMETHYLGERMYL)CUPRATE (222)

\((\text{Me}_3\text{Ge})_2\text{CuLi}\)

222

A cold (−10 °C) solution of \(\text{Me}_3\text{GeLi}\) (1.40 mmol, 1 equiv) in dry THF (0.6 mL), prepared as described above (section 3.3.2.1.1, p 221), was transferred via a cannula to a cold (−78 °C) stirred suspension of \(\text{CuBr}^\cdot\text{Me}_2\text{S}\) (144 mg, 0.70 mmol, 0.50 equiv) in dry THF (9 mL). The flask that initially contained the \(\text{Me}_3\text{GeLi}\) solution was rinsed with dry THF (2 × 1.2 mL) and the rinses were transferred via a cannula to the suspension of \(\text{CuBr}^\cdot\text{Me}_2\text{S}\). The suspension was stirred at −78 °C for 1 h to afford a clear golden solution. The reagent 222 was then ready to use.

3.4.1.2 PREPARATION OF THE LITHIUM (TRIMETHYLGERMYL)CYANOCUPRATE (223)

\(\text{Me}_3\text{GeCu(CN)Li}\)

223

A cold (−10 °C) solution of \(\text{Me}_3\text{GeLi}\) (1.52 mmol, 1 equiv) in dry THF (0.6 mL), prepared as described above (section 3.3.2.1.1, p 221), was transferred via a cannula to a cold (−78 °C) stirred suspension of \(\text{CuCN}\) (136 mg, 1.52 mmol, 1 equiv) in dry THF (9 mL). The flask that initially contained the \(\text{Me}_3\text{GeLi}\) solution was rinsed with dry THF (2 ×
1.2 mL) and the rinses were transferred via a cannula to the suspension of CuCN. The suspension was stirred at -78 °C for 1 h to afford a yellow opaque solution. The reagent 223 was then ready to use.

3.4.1.3 PREPARATION OF THE DILITHIUM BIS(TRIMETHYLGERMYL)CYANOCUPRATE (224)

\[(\text{Me}_3\text{Ge})_2\text{Cu(CN)Li}_2\]

224

A cold (-10 °C) solution of Me$_3$GeLi (149) (1.52 mmol, 1 equiv) in dry THF (0.6 mL), prepared as described above (section 3.3.2.1.1, p 221), was transferred via a cannula to a cold (-78 °C) stirred suspension of CuCN (68 mg, 0.76 mmol, 0.50 equiv) in dry THF (9 mL). The flask that initially contained the Me$_3$GeLi solution was rinsed with dry THF (2 x 1.2 mL) and the rinses were transferred via a cannula to the suspension of CuCN. The suspension was stirred at -78 °C for 1 h to afford a clear colorless solution. The reagent 224 was then ready to use.

3.4.1.4 PREPARATION OF THE DILITHIUM METHYL(TRIMETHYLGERMYL)CYANOCUPRATE (225)

\[\text{Me}_3\text{Ge(Me)Cu(CN)Li}_2\]

225

To a cold (-10 °C) stirred solution of Me$_3$GeLi (149) (1.43 mmol, 1 equiv) in dry THF (0.6 mL), prepared as described above (section 3.3.2.1.1, p 221), was added a solution of MeLi (1.37 M in diethyl ether, 1.04 mL, 1.43 mmol, 1 equiv). This solution was transferred via a cannula to a cold (-78 °C) stirred suspension of CuCN (128 mg, 1.43 mmol, 1 equiv) in dry THF (9 mL). The flask that initially contained the Me$_3$GeLi solution was rinsed with dry THF (2 x 1.2 mL) and the rinses were transferred via a cannula to the
suspension of CuCN. The suspension was stirred at -78 °C for 1 h to afford a clear colorless solution. The reagent 225 was then ready to use.
3.4.2 ADDITION OF (TRIMETHYLGERMYL)COPPER(I)-DIMETHYL SULFIDE (168) AND (TRIMETHYLGERMYL)CUPRATES 222–225 TO CYCLIC ENONES

3.4.2.1 General Procedure 9: Synthesis of 3-Trimethylgermylcyclohexanone (229) from Cyclohex-2-en-1-one (226)

![Chemical Structure](image)

To a cold (−78 °C) stirred solution of the appropriate (trimethylgermyl)copper(I) reagent (0.65–1.3 equiv) in dry THF was added a solution of cyclohex-2-en-1-one (226) (1 equiv) in dry THF to generate a final concentration of ≈0.08 M of the enone. The resulting mixture was stirred at −78 °C for 0.5 h, then was poured into stirred aqueous NH₄Cl–NH₄OH (pH 8–9, ≈20 mL per mmol of enone) and diethyl ether (≈40 mL per mmol of enone) was added to the mixture. The heterogeneous mixture was stirred vigorously, open to the atmosphere, until the aqueous layer was deep blue. The layers were separated and the aqueous portion was extracted with diethyl ether (2 × ≈10 mL per mmol of enone). The combined organic extracts were washed with water (2 × ≈10 mL per mmol of enone) and brine (≈10 mL per mmol of enone), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil acquired was subjected to flash chromatography and the resultant oil was distilled (150–160 °C/12 Torr) to afford the title compound as a clear colorless oil.
\textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): \(\delta\) 2.41–2.24 (m, 3H), 2.20–2.10 (m, 2H), 1.86–1.78 (m, 1H), 1.71 (dddd, 1H, \(J = 12.8, 12.8, 12.8, 5.0\) and 3.8 Hz), 1.46 (dddd, 1H, \(J = 12.8, 12.8, 12.8\) and 3.6 Hz), 1.30 (dddd, 1H, \(J = 13.6, 12.8, 3.4\) and 3.4 Hz), 0.10 (s, 9H, -Ge(CH\textsubscript{3})\textsubscript{3}).

\textsuperscript{13}C NMR (75.4 MHz, CDCl\textsubscript{3}): \(\delta\) 212.5 (-CO-), 43.6, 41.9, 29.7, 28.6 (-CH(Ge(CH\textsubscript{3})\textsubscript{3}))-), 27.0, -4.5 (-Ge(CH\textsubscript{3})\textsubscript{3}).

IR (film): 1713, 1228, 823, 600 cm\textsuperscript{-1}.

HRMS for C\textsubscript{9}H\textsubscript{18}GeO: calcd 216.0569, found 216.0565.

Anal. calcd for C\textsubscript{9}H\textsubscript{18}GeO: C 50.32, H 8.45; found: C 50.30, H 8.30.

3.4.2.1.1 Preparation of 3-Trimethylgermylcyclohexanone (229) Using (Trimethylgermyl)\textsuperscript{-}copper(I)–Dimethyl Sulfide (168)

Following general procedure 9, to a cold (-78 °C) stirred solution of Me\textsubscript{3}GeCu•Me\textsubscript{2}S (168) (1.48 mmol, 1.30 equiv) in dry THF (12.1 mL), prepared as described above (section 3.3.2.2, p 223), was added a solution of cyclohex-2-en-1-one (226) (109 mg, 1.14 mmol, 1 equiv) in dry THF (2.5 mL). The black mixture was stirred at -78 °C for 0.5 h. The crude oil acquired was subjected to flash chromatography (13 g silica gel, 9:1 petroleum ether–diethyl ether) and the resultant liquid was distilled to afford 189 mg (77%) of 3-trimethylgermylcyclohexanone (229). The spectral data were identical with those reported above.
3.4.2.1.2 Preparation of 3-Trimethylgermylcyclohexanone (229) Using Lithium Bis-(trimethylgermyl)cuprate (222)

![Diagram of 3-Trimethylgermylcyclohexanone (229)]

Following general procedure 9, to a cold (−78 °C) stirred solution of (Me₃Ge)₂CuLi (222) (0.70 mmol, 0.65 equiv) in dry THF (12.1 mL), prepared as described above (section 3.4.1.1, p 265), was added a solution of cyclohex-2-en-1-one (226) (104 mg, 1.08 mmol, 1 equiv) in dry THF (2.5 mL). The black mixture was stirred at −78 °C for 0.5 h. The crude oil acquired was subjected to flash chromatography (11 g silica gel, 17:3 petroleum ether–diethyl ether) and the derived oil was distilled to afford 198 mg (86%) of 3-trimethylgermylcyclohexanone (229). The spectral data were identical with those reported above.

3.4.2.1.3 Preparation of 3-Trimethylgermylcyclohexanone (229) Using Lithium (Trimethylgermyl)cyanocuprate (223)

Following general procedure 9, to a cold (−78 °C) stirred solution of Me₃GeCu(CN)Li (223) (1.52 mmol, 1.30 equiv) in dry THF (12.1 mL), prepared as described above (section 3.4.1.2, p 265), was added a solution of cyclohex-2-en-1-one (226) (113 mg, 1.17 mmol, 1
equiv) in dry THF (2.5 mL). The orange mixture was stirred at -78 °C for 0.5 h. The crude oil acquired was subjected to flash chromatography (10 g TLC grade silica gel, 17:3 petroleum ether-diethyl ether) and the resultant oil was distilled to afford 227 mg (90%) of 3-trimethylgermylcyclohexanone (229). The spectral data were identical with those reported above.

3.4.2.1.4 Preparation of 3-Trimethylgermylcyclohexanone (229) Using Dilithium Bis-(trimethylgermyl)cyanocuprate (224)

Following general procedure 9, to a cold (-78 °C) stirred solution of (Me₃Ge)₂Cu(CN)Li₂ (224) (0.70 mmol, 0.65 equiv) in dry THF (12.1 mL), prepared as described above (section 3.4.1.3, p 266), was added a solution of cyclohex-2-en-1-one (226) (113 mg, 1.17 mmol, 1 equiv) in dry THF (2.5 mL). The orange solution was stirred at -78 °C for 0.5 h. The crude oil acquired was subjected to flash chromatography (14 g silica gel, 17:3 petroleum ether-diethyl ether) and the derived oil was distilled to afford 213 mg (85%) of 3-trimethylgermylcyclohexanone (229). The spectral data were identical with those reported above.
3.4.2.1.5 Preparation of 3-Trimethylgermylcyclohexanone (229) Using Dilithium Methyl-(trimethylgermyl)cyanocuprate (225)

Following general procedure 9, to a cold (−78 °C) stirred solution of Me$_3$Ge(Me)Cu(CN)Li$_2$ (225) (1.43 mmol, 1.30 equiv) in dry THF (12.1 mL), prepared as described above (section 3.4.1.4, p 266), was added a solution of cyclohex-2-en-1-one (226) (106 mg, 1.10 mmol, 1 equiv) in dry THF (2.5 mL). The clear colorless solution was stirred at −78 °C for 0.5 h. The crude oil acquired was subjected to flash chromatography (13 g silica gel, 17:3 petroleum ether–diethyl ether) and the resultant liquid was distilled to afford 207 mg (87%) of 3-trimethylgermylcyclohexanone (229). The spectral data were identical with those reported above.

3.4.2.2 ADDITION OF TRIMETHYLGEMYLLITHIUM (149) TO CYCLOHEX-2-EN-1-ONE (226)

3.4.2.2.1 Synthesis of l-Trimethylgermylcyclohex-2-en-1-ol (230)

A cold (−10 °C) stirred solution of Me$_3$GeLi (149) (2.07 mmol, 1.30 equiv) in dry THF (0.9 mL), prepared as described above (section 3.3.2.1.1, p 221), was transferred via a
cannula to cold (−78 °C) stirred dry THF (16 mL). The flask that initially contained the Me₃GeLi solution was rinsed with dry THF (2 × 1 mL) and the rinses were transferred via a cannula to the cold (−78 °C) stirred dry THF. After the solution had been stirred for 5 min, a solution of cyclohex-2-en-1-one (226) (153 mg, 1.59 mmol, 1 equiv) in dry THF (2 mL) was added via a cannula. The reaction mixture was stirred at −78 °C for 5 min, then was poured into a stirred solution of NH₄Cl-NH₄OH (pH 8–9, 20 mL) and diethyl ether (30 mL) was added to the mixture. The layers were separated and the aqueous portion was extracted with ethyl acetate (2 × 10 mL). The combined organic extracts were washed with water (2 × 10 mL) and brine (10 mL), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil acquired was subjected to flash chromatography (35 g TLC grade silica gel, 49:1 CH₂Cl₂–diethyl ether) to afford two fractions which were concentrated under reduced pressure. The first fraction to be eluted afforded 69 mg (20%) of 3-trimethylgermylcyclohexanone (229). The spectral data were identical with those reported above (section 3.4.2.1, p 268). The second fraction to be eluted was distilled (130–140 °C/9 Torr) to afford 202 mg (59%) of 1-trimethylgermylcyclohex-2-en-1-ol (230) as a clear colorless oil.

¹H NMR (400 MHz, CDCl₃): δ 5.75 (ddd, 1H, J = 9.8, 3.8 and 3.0 Hz, -CH=CHCH₂−), 5.69 (ddd, 1H, J = 9.8, 1.4 and 1.4 Hz, -CH=CHCH₂−), 2.08–1.98 (m, 1H), 1.94–1.72 (m, 3H), 1.68–1.50 (m, 2H), 1.27 (s, 1H, exchanges with D₂O, -OH), 0.17 (s, 9H, -Ge(CH₃)₃).

¹³C NMR (75.4 MHz, CDCl₃): δ 131.4 (vinyllic carbon), 128.4 (vinyllic carbon), 67.7 (tetra-substituted carbon), 34.0, 25.0, 18.3, −4.6 (-Ge(CH₃)₃).
IR (film): 3435, 3016, 2932, 1234, 823, 737, 602 cm$^{-1}$.

HRMS for C$_9$H$_{18}$GeO: calcd 216.0569, found 216.0567.

Anal. calcd for C$_9$H$_{18}$GeO: C 50.32, H 8.45; found: C 50.36, H 8.52.

3.4.2.3 GENERAL PROCEDURE 10: SYNTHESIS OF (2$R$,3$S$,5$S$)-, (2$S$,3$S$,5$S$)-, (2$R$,3$R$,5$S$)- AND (2$S$,3$R$,5$S$)-5-ISOPROPENYL-2-METHYL-3-TRIMETHYLGERMYLCYCLOHEXANONE (234)-(237) FROM l-CARVONE (227)

To a cold (−78 °C) stirred solution of the appropriate (trimethylgermyl)copper(I) reagent (1.3 equiv) in dry THF, was added chlorotrimethylsilane (1.3 equiv) via a syringe. After the mixture had been stirred for 5 min, a solution of l-carvone (227) (1 equiv) in dry THF was added via a cannula. The reaction mixture was stirred at −78 °C for 0.5 h, then was warmed to 0 °C over a 0.5 h period. The mixture was poured into stirred aqueous NH$_4$Cl-NH$_4$OH (pH 8–9, ≈20 mL per mmol of enone) and diethyl ether (≈20 mL per mmol of enone) was added to the mixture. The heterogeneous mixture was stirred vigorously, open to the atmosphere, until the aqueous layer was deep blue. The layers were separated and the aqueous portion was extracted with diethyl ether (2 × ≈10 mL per mmol of enone). The combined organic extracts were washed with water (2 × ≈10 mL per mmol of enone) and brine (≈10 mL per mmol of enone), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil acquired was dissolved
in THF (=0.07 M; this reaction was not performed under an atmosphere of argon) and 1 M hydrochloric acid (6 drops) was added. After the mixture had been stirred at rt for 1 h, diethyl ether (=20 mL per mmol of enone) was added, the organic layer was dried over anhydrous magnesium sulfate, and then was filtered and concentrated under reduced pressure. The crude oil obtained was subjected to flash chromatography and the derived oil was distilled to afford a mixture of the four diastereomeric 5(S)-isopropenyl-2-methyl-3-trimethylgermylcyclohexanones (234)–(237) as a clear colorless oil.

3.4.2.3.1 Isolation and Characterization of the Four Diastereomeric 5(S)-Isopropenyl-2-methyl-3-trimethylgermylcyclohexanones (234)–(237)

a) Isolation and Characterization of (2R,3S,5S)-5-Isopropenyl-2-methyl-3-trimethylgermylcyclohexanone (234)

Two samples (=100 mg each) of a mixture of the four diastereomeric 5(S)-isopropenyl-2-methyl-3-trimethylgermylcyclohexanones were subjected to HPLC (silica Partisil, 10 μm; 22 mm × 250 mm column, 99:1 hexane–ethyl acetate, 9 mL/min, RI detector) individually. These chromatographies resulted in a rough separation to afford three fractions, which were concentrated under reduced pressure. The corresponding fractions of the two samples were pooled, and the isolated amounts are derived from the pooled fractions. The
first fraction to be eluted, fraction A (retention time 42–52 min), afforded 45 mg of an oil which consisted of a mixture of two components (compounds 237 and 235). The second fraction to be eluted, fraction B (retention time 53–62 min) afforded 28 mg of an oil which was mostly one component (compound 236). The third fraction to be eluted (retention time 65–78 min) afforded 28 mg of (2R,3S,5S)-5-isopropenyl-2-methyl-3-trimethylgermylcyclohexanone (234) as a clear colorless oil.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 4.75 (s, 1H, H-9a), 4.73 (s, 1H, H-9b), 2.55 (qd, 1H, $J = 7.2$ and 4.0 Hz, H-2), 2.50 (dd, 1H, $J = 13.0$ and 13.0 Hz, H-6a), 2.42–2.32 (m, 1H, H-5), 2.24 (ddd, 1H, $J = 13.0$, 1.8 and 1.8 Hz, H-6b), 1.77–1.60 (m, 5H, H-4a, H-4b and -CH$_3$-10), 1.39 (ddd, 1H, $J = 13.4$, 4.0 and 3.8 Hz, H-3), 1.12 (d, 3H, $J = 7.2$ Hz, -CH$_3$-7), 0.15 (s, 9H, -Ge(CH$_3$)$_3$).

Detailed $^1$H NMR data, derived from COSY and NOE difference experiments, are given in Table 23.

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 215.5 (−CO−), 147.7 (−$C(=\text{CH}_2)$−), 109.6 (−$C(=\text{CH}_2)$−), 49.8, 46.3, 42.4 (secondary carbon), 32.2, 26.8 (secondary carbon), 20.5, 14.7, −2.7 (−$\text{Ge(CH}_3)_3$).

IR (film): 3083, 2970, 1708, 1645, 1237, 891, 824, 599 cm$^{-1}$.

HRMS for C$_{13}$H$_{24}$$^{74}$GeO: calcd 270.1039, found 270.1041.
Table 23: $^1$H NMR Data from $^1$H–$^1$H Homonuclear Correlation Spectroscopy and Nuclear Overhauser Enhancement Difference Experiments for (2R,3S,5S)-5-Isopropenyl-2-methyl-3-trimethylgermylcyclohexan-1-one (234)

![Image of the molecule](Image)

<table>
<thead>
<tr>
<th>Assignments H-(x)</th>
<th>$^1$H NMR(^a)</th>
<th>COSY Correlations</th>
<th>Observed NOEs</th>
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<tr>
<td>H-9a</td>
<td>4.75 (s)</td>
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<tr>
<td>H-9b</td>
<td>4.73 (s)</td>
<td>-CH(_2)-10</td>
<td></td>
</tr>
<tr>
<td>H-2</td>
<td>2.55 (qd, 7.2, 4.0)</td>
<td>H-3, -CH(_3)-7</td>
<td></td>
</tr>
<tr>
<td>H-6a</td>
<td>2.50 (dd, 13.0, 13.0)</td>
<td>H-5, H-6b</td>
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<tr>
<td>H-5(^b)</td>
<td>2.42–2.32 (m)</td>
<td>H-4a, H-4b, H-6a, H-6b</td>
<td>H-3, H-4b, H-9b</td>
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<tr>
<td>H-6b</td>
<td>2.24 (ddd, 13.0, 1.8)</td>
<td>H-4b, H-5, H-6a</td>
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<tr>
<td>-CH(_3)-10</td>
<td>1.73 part of 1.77–1.60 (m)</td>
<td>H-9a, H-9b</td>
<td></td>
</tr>
<tr>
<td>H-4b</td>
<td>1.66–1.60 part of 1.77–1.60 (m)</td>
<td>H-3, H-4a, H-5, H-6b</td>
<td></td>
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<tr>
<td>H-3(^b)</td>
<td>1.39 (ddd, 13.4, 4.0, 3.8)</td>
<td>H-2, H-4a, H-4b</td>
<td>H-2, H-5</td>
</tr>
<tr>
<td>-CH(_3)-7(^b)</td>
<td>1.12 (d, 7.2)</td>
<td>H-2</td>
<td>H-2, H-6a</td>
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<tr>
<td>-Ge(CH(_3))(_3)(^b)</td>
<td>0.15 (s)</td>
<td></td>
<td>H-2, H-3, H-4b, -CH(_3)-7</td>
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</table>

\(^a\) 400 MHz, CDCl\(_3\). \(^b\) Irradiation of this signal generated the corresponding NOEs in the right hand column.
b) Isolation and Characterization of (2S,3R,5S)- and (2S,3S,5S)-5-Isopropenyl-2-methyl-3-trimethylgermylcyclohexanone (237) and (235)

Fraction A (45 mg) was subjected to reversed phase HPLC (C$_{18}$ µBondapak, 10 µm; 8 mm × 100 mm column, 40:60 to 65:35 acetonitrile–water, 5% step increments/10 min, 1 mL/min, UV-vis detector $\lambda = 254$ nm) in four approximately equal portions. The combined first fractions to be eluted (retention time 56 min) were distilled (72–82 °C/0.007 Torr) to afford 23 mg of (2S,3R,5S)-5-isopropenyl-2-methyl-3-trimethylgermylcyclohexanone (237).

$^1$H NMR (400 MHz, C$_6$D$_6$): $\delta$ 4.73 (s, 2H, H-9a and H-9b), 2.43 (dd, 1H, $J$ = 13.6, 4.8 and 2.0 Hz, H-6a), 2.35–2.25 (m, 2H, H-2 and H-5), 2.07 (dd, 1H, $J$ = 13.6 and 11.2 Hz, H-6b), 1.82 (dddd, 1H, $J$ = 13.6, 5.2, 4.6 and 2.0 Hz, H-4a), 1.56–1.47 (m, 4H, H-4b and -CH$_3$-10), 1.38 (ddd, 1H, $J$ = 6.2, 4.6 and 4.6 Hz, H-3), 1.07 (d, 3H, $J$ = 6.2 Hz, -CH$_3$-7), 0.10 (s, 9H, -Ge(CH$_3$)$_3$).

Detailed $^1$H NMR data, derived from COSY and NOE difference experiments, are given in Table 24.

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 212.8 (-CO-), 147.3 (-C(=CH$_2$)-), 110.3 (-C(=CH$_2$)-), 47.8, 45.4 (secondary carbon), 44.6, 32.4 (secondary carbon), 32.2, 20.9, 14.9, −0.8 (-Ge(CH$_3$)$_3$).

IR (film): 3075, 2972, 1713, 1646, 1238, 892, 826, 596 cm$^{-1}$. 
HRMS for C\textsubscript{13}H\textsubscript{24}\textsuperscript{74}GeO: calcd 270.1039, found 270.1037.

Anal. calcd for C\textsubscript{13}H\textsubscript{24}GeO: C 58.06, H 9.00; found: C 58.00, H 9.00.

**Table 24:** \textsuperscript{1}H NMR Data from \textsuperscript{1}H--\textsuperscript{1}H Homonuclear Correlation Spectroscopy and Nuclear Overhauser Enhancement Difference Experiments for (2\textit{S},3\textit{R},5\textit{S})-5-Isopropenyl-2-methyl-3-trimethylgermylcyclohexanone (237)

![Chemical Structure](image)

<table>
<thead>
<tr>
<th>Assignments</th>
<th>\textsuperscript{1}H NMR\textsuperscript{a}</th>
<th>COSY Correlations</th>
<th>Observed NOEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-9a and H-9b</td>
<td>4.73 (s)</td>
<td>-CH\textsubscript{3}-10</td>
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<tr>
<td>H-6a</td>
<td>2.43 (ddd, 13.6, 4.8, 2.0)</td>
<td>H-4a, H-5, H-6b</td>
<td></td>
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<tr>
<td>H-2 and H-5</td>
<td>2.35–2.25 (m)</td>
<td>H-3, H-4a, H-4b, H-6a, H-6b, -CH\textsubscript{3}-7</td>
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</tr>
<tr>
<td>H-6b\textsuperscript{b}</td>
<td>2.07 (dd, 13.6, 11.2)</td>
<td>H-5, H-6a</td>
<td>H-2, H-6a, H-9, -CH\textsubscript{3}-10</td>
</tr>
<tr>
<td>H-4a</td>
<td>1.82 (dddd, 13.6, 5.2, 4.6, 2.0)</td>
<td>H-3, H-4b, H-5, H-6a</td>
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<tr>
<td>H-4b and -CH\textsubscript{3}-10</td>
<td>1.56–1.47 (m)</td>
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</tr>
<tr>
<td>H-3\textsuperscript{b}</td>
<td>1.38 (ddd, 6.2, 4.6, 4.6)</td>
<td>H-2, H-4a, H-4b</td>
<td>H-2, H-4a</td>
</tr>
<tr>
<td>-CH\textsubscript{3}-7\textsuperscript{b}</td>
<td>1.07 (d, 6.2)</td>
<td>H-2</td>
<td>H-2, H-3, -Ge(CH\textsubscript{3})\textsubscript{3}</td>
</tr>
<tr>
<td>-Ge(CH\textsubscript{3})\textsubscript{3}</td>
<td>0.10 (s)</td>
<td></td>
<td>H-3, H-4a, H-5, -CH\textsubscript{3}-7</td>
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</tbody>
</table>

\textsuperscript{a} 400 MHz, C\textsubscript{6}D\textsubscript{6}. \textsuperscript{b} Irradiation of this signal generated the corresponding NOEs in the right hand column.
The combined second fractions to be eluted (retention time 59 min) afforded 9.8 mg of (2S,3S,5S)-5-isopropenyl-2-methyl-3-trimethylgermylcyclohexanone (235).

\(^1\)H NMR (400 MHz, C\(_6\)D\(_6\)): \(\delta \) 4.69 (d, 1H, \(J = 1.4 \text{ Hz}, \text{H-9a}\)), 4.64 (d, 1H, \(J = 1.4 \text{ Hz}, \text{H-9b}\)), 2.48 (ddd, 1H, \(J = 12.4, 3.5 \text{ and } 2.4 \text{ Hz}, \text{H-6a}\)), 2.21-2.11 (m, 1H, H-5), 1.97 (dd, 1H, \(J = 13.2 \text{ and } 12.4 \text{ Hz}, \text{H-6b}\)), 1.92 (dq, 1H, \(J = 13.2 \text{ and } 6.6 \text{ Hz}, \text{H-2}\)), 1.69 (dddd, 1H, \(J = 13.2, 3.2, 2.4 \text{ Hz}, \text{H-4a}\)), 1.50 (s, 3H, -CH\(_3\)-10), 1.22 (ddd, 1H, \(J = 13.2, 3.2 \text{ and } 2.4 \text{ Hz}, \text{H-4b}\)), 1.08 (d, 3H, \(J = 6.6 \text{ Hz}, \text{-CH}_3\)-7), 0.77 (ddd, 1H, \(J = 13.2, 13.2 \text{ and } 3.2 \text{ Hz}, \text{H-3}\)), 0.04 (s, 9H, -Ge(CH\(_3\)_3)).

Detailed \(^1\)H NMR data, derived from COSY and NOE difference experiments, are given in Table 25.

\(^{13}\)C NMR (75.4 MHz, C\(_6\)D\(_6\)): \(\delta \) 210.4 (-CO-), 147.9 (-C(=CH\(_2\))-), 109.6 (-C(=C\(_\text{H}_2\))-), 49.5, 46.75 (secondary carbon), 46.70, 35.2, 34.0 (secondary carbon), 20.4, 14.7, -2.4 (-Ge(CH\(_3\)_3)).

IR (film): 3080, 2972, 1713, 1645, 1237, 891, 824, 597 cm\(^{-1}\).

HRMS for C\(_{13}\)H\(_{24}\)\(^{74}\)GeO: calcd 270.1039, found 270.1043.
Table 25: $^1$H NMR Data from $^1$H–$^1$H Homonuclear Correlation Spectroscopy and Nuclear Overhauser Enhancement Difference Experiments for (2S,3S,5S)-5-Isopropenyl-2-methyl-3-trimethylgermylcyclohexanone (235)

![Chemical Structure](image)

<table>
<thead>
<tr>
<th>Assignments</th>
<th>$^1$H NMR$^a$</th>
<th>COSY Correlations</th>
<th>Observed NOEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-9a</td>
<td>4.69 (d, 1.4)</td>
<td>-CH$_3$-10</td>
<td></td>
</tr>
<tr>
<td>H-9b</td>
<td>4.64 (d, 1.4)</td>
<td>-CH$_3$-10</td>
<td></td>
</tr>
<tr>
<td>H-6a</td>
<td>2.48 (ddd, 12.4, 3.5, 2.4)</td>
<td>H-4a, H-5, H-6b</td>
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<tr>
<td>H-5$^b$</td>
<td>2.21–2.11 (m)</td>
<td>H-4a, H-4b, H-6a, H-6b</td>
<td>H-3, H-4a, H-6a, H-9b, -CH$_3$-10</td>
</tr>
<tr>
<td>H-6b</td>
<td>1.97 (dd, 13.2, 12.4)</td>
<td>H-5, H-6a</td>
<td></td>
</tr>
<tr>
<td>H-2</td>
<td>1.92 (dq, 13.2, 6.6)</td>
<td>H-3, -CH$_3$-7</td>
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</tr>
<tr>
<td>H-4a</td>
<td>1.69 (dddd, 13.2, 3.2, 3.2, 2.4)</td>
<td>H-3, H-4b, H-5, H-6a</td>
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</tr>
<tr>
<td>-CH$_3$-10</td>
<td>1.50 (s)</td>
<td>H-9a, H-9b</td>
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<tr>
<td>H-4b$^b$</td>
<td>1.22 (ddd, 13.2, 13.2, 11.8)</td>
<td>H-3, H-4a, H-5</td>
<td>H-2, H-4a, H-6b</td>
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<tr>
<td>-CH$_3$-7$^b$</td>
<td>1.08 (d, 6.6)</td>
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<td>H-3$^b$</td>
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<td>H-4a, H-5, -CH$_3$-7</td>
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<tr>
<td>-Ge(CH$_3$)$_3$</td>
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</table>

$^a$ 400 MHz, C$_6$D$_6$. $^b$ Irradiation of this signal generated the corresponding NOEs in the right hand column. $^e$ This signal appeared negative as a result of a possible relay NOE from H-2.
c) Isolation and Characterization of (2R,3R,5S)-5-Isopropenyl-2-methyl-3-trimethylgermylcyclohexanone (236)

Fraction B (28 mg) from the initial chromatography was resubjected to HPLC under identical conditions (silica Partisil, 10 μm; 22 mm x 250 mm column, 99:1 hexane–ethyl acetate, 9 mL/min, RI detector) and the acquired liquid was distilled (60–70 °C/0.007 Torr) to afford 8.2 mg of (2R,3R,5S)-5-isopropenyl-2-methyl-3-trimethylgermylcyclohexanone (236).

\[\begin{align*}
1^H \text{ NMR (400 MHz, } \text{C}_6\text{D}_6): & \delta 4.94 (s, 1H, H-9a), 4.86 (s, 1H, H-9b), 2.58 (ddd, 1H, J = 14.2, 4.4 \text{ and } 2.0 \text{ Hz, H-6a}), 2.41–2.34 (m, 1H, H-5), 2.11 (dd, 1H, J = 14.2 \text{ and } 6.0 \text{ Hz, H-6b}), 2.01 (dq, 1H, J = 11.0 \text{ and } 6.8 \text{ Hz, H-2}), 1.69 (ddd, 1H, J = 13.8, 4.6, 3.6 \text{ and } 2.0 \text{ Hz, H-4a}), 1.50 (s, 3H, -CH}_3-10\text{), 1.38 (ddd, 1H, J = 13.8, 11.0 \text{ and } 4.6 \text{ Hz, H-4b}), 1.12 (ddd, 1H, J = 11.0, 11.0 \text{ and } 3.6 \text{ Hz, H-3), 1.07 (d, 3H, J = 6.8 Hz, -CH}_3-7\text{), 0.05 (s, 9H, -Ge(CH}_3)_3\text{).}
\end{align*}\]

Detailed $^1$H NMR data, derived from COSY and NOE difference experiments, are given in Table 26.

$^{13}C \text{ NMR (75.4 MHz, } \text{C}_6\text{D}_6): \delta 210.8 (-CO-), 146.5 (-C(=CH}_2\text{-), 112.9 (-C(=CH}_2\text{-), 47.2, 44.5 \text{ (secondary carbon), 44.0, 30.1, 29.9 \text{ (secondary carbon), 21.9, 15.6, 2.5 (-Ge(CH}_3)_3\text{).}}$
IR (film): 3080, 2971, 1708, 1645, 1451, 1237, 986, 824, 597 cm\(^{-1}\).

HRMS for C\(_{13}\)H\(_{24}\)\(^{74}\)GeO: calcd 270.1039, found 270.1031.
Table 26: $^1$H NMR Data from $^1$H–$^1$H Homonuclear Correlation Spectroscopy and Nuclear Overhauser Enhancement Difference Experiments for (2R,3R,5S)-5-isopropenyl-2-methyl-3-trimethylgermylcylohexanone (236)

![Chemical Structure](image)

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<thead>
<tr>
<th>Assignments</th>
<th>$^1$H NMR$^a$</th>
<th>COSY Correlations</th>
<th>Observed NOEs</th>
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<td></td>
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<td>H-9b</td>
<td>4.86 (s)</td>
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</tr>
<tr>
<td>H-6a</td>
<td>2.58 (ddd, 14.2, 4.4, 2.0)</td>
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<tr>
<td>H-5</td>
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<tr>
<td>H-6b</td>
<td>2.11 (dd, 14.2, 6.0)</td>
<td>H-5, H-6a</td>
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<tr>
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<td>2.01 (dq, 11.0, 6.8)</td>
<td>H-3, -CH$_3$-7</td>
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<tr>
<td>H-4a</td>
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<td>H-3, H-4b, H-5, H-6a</td>
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</tr>
<tr>
<td>-CH$_3$-10</td>
<td>1.50 (s)</td>
<td>H-9a, H-9b</td>
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<tr>
<td>H-4b$^b$</td>
<td>1.38 (ddd, 13.8, 11.0, 4.6)</td>
<td>H-3, H-4a, H-5</td>
<td>H-2, H-4a, H-5, H-6b</td>
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<tr>
<td>H-3</td>
<td>1.12 (ddd, 11.0, 11.0, 3.6)</td>
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<tr>
<td>-CH$_3$-7</td>
<td>1.07 (d, 6.8)</td>
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<tr>
<td>-Ge(CH$_3$)$_3$</td>
<td>0.05 (s)</td>
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</table>

$^a$ 400 MHz, C$_6$D$_6$. $^b$ Irradiation of this signal generated the corresponding NOEs in the right hand column.
3.4.2.3.2 Preparation of the Diastereomeric Mixture of Four $5(S)$-Isopropenyl-2-methyl-3-trimethylgermylcyclohexanones (234)–(237) Using (Trimethylgermyl)copper(I)–Dimethyl Sulfide (168)

Following general procedure 10, to a cold (−78 °C) stirred solution of Me$_3$GeCu·Me$_2$S (168) (1.43 mmol, 1.30 equiv) in dry THF (12.1 mL), prepared as described above (section 3.3.2.2, p 223), was added sequentially chlorotrimethylsilane (155 mg, 1.43 mmol, 1.30 equiv) via a syringe and a solution of $l$-carvone (227) (165 mg, 1.10 mmol, 1 equiv) in dry THF (2.5 mL) via a cannula. The crude oil acquired was subjected to flash chromatography (30 g TLC grade silica gel, 9:1 petroleum ether–diethyl ether) and the derived oil was distilled (95–105 °C/0.5 Torr) to afford 243 mg (82%) of the diastereomeric mixture of four $5(S)$-isopropenyl-2-methyl-3-trimethylgermylcyclohexanones (234)–(237). $^1$H NMR spectroscopic analysis indicated a 2.4:1:3.4:1.5 ratio of the 2$S$,3$R$:2$R$,3$R$:2$S$,3$S$:2$S$,3$S$ diastereomers.
3.4.2.3.3 Preparation of the Diastereomeric Mixture of Four 5(5)-Isopropenyl-2-methyl-3-trimethylgermylcyclohexanones (234)–(237) Using Lithium (Trimethylgermyl)cyanocuprate (223)

Following general procedure 10, to a cold (−78 °C) stirred solution of Me₃GeCu(CN)Li (223) (1.39 mmol, 1.30 equiv) in dry THF (12.1 mL), prepared as described above (section 3.4.1.2, p 265), was added sequentially chlorotrimethylsilane (151 mg, 1.39 mmol, 1.30 equiv) via a syringe and a solution of \( \alpha \)-carvone (227) (161 mg, 1.07 mmol, 1 equiv) in dry THF (2.5 mL) via a cannula. The crude oil acquired was subjected to flash chromatography (30 g TLC grade silica gel, 9:1 petroleum ether–diethyl ether) and the derived oil was distilled (100–110 °C/0.1 Torr) to afford 230 mg (80%) of the diastereomeric mixture of four 5(5)-isopropenyl-2-methyl-3-trimethylgermylcyclohexanones (234)–(237). \(^1\)H NMR spectroscopic analysis indicated a 2.2:1:3.1:1.3 ratio of the 2S,3R:2R,3R:2S,3S:2R,3S diastereomers.
3.4.2.3.4 Preparation of the Diastereomeric Mixture of Four 5(S)-Isopropenyl-2-methyl-3-
trimethylgermylcyclohexanones (234)–(237) Using Diliithium Bis(trimethylgermyl)cyano-
cuprate (224)

![Image of molecule](image_url)

Following general procedure 10, to a cold (−78 °C) stirred solution of
(Me₃Ge)₂Cu(CN)Li₂ (224) (0.69 mmol, 0.65 equiv) in dry THF (12.1 mL), prepared as
described above (section 3.4.1.3, p 266), was added sequentially chlorotrimethylsilane (150
mg, 1.38 mmol, 1.30 equiv) via a syringe and a solution of /-carvone (227) (160 mg, 1.06
mmol, 1 equiv) in dry THF (2.5 mL) via a cannula. The crude oil acquired was subjected to
flash chromatography (15 g TLC grade silica gel, 9:1 petroleum ether–diethyl ether) and the
resultant oil was distilled (98–108 °C/0.06 Torr) to afford 246 mg (86%) of the
diastereomeric mixture of four 5(S)-isopropenyl-2-methyl-3-trimethylgermylcyclohexanones
(234)–(237). ¹H NMR spectroscopic analysis indicated a 3.9:1:2.5:1.1 ratio of the
3.4.2.3.5 Preparation of the Diastereomeric Mixture of Four 5(S)-Isopropenyl-2-methyl-3-
trimethylgermylcyclohexanones (234)–(237) Using Dilithium Methyl(trimethylgermyl)cyano-
cuprate (225)

Following general procedure 10, to a cold (-78 °C) stirred solution of
Me₃Ge(Me)Cu(CN)Li₂ (225) (1.38 mmol, 1.30 equiv) in dry THF (12.1 mL), prepared as
described above (section 3.4.1.4, p 266), was added sequentially chlorotrimethylsilane (150
mg, 1.38 mmol, 1.30 equiv) via a syringe and a solution of l-carvone (227) (160 mg, 1.06
mmol, 1 equiv) in dry THF (2.5 mL) via a cannula. The crude oil acquired was subjected to
flash chromatography (15 g TLC grade silica gel, 9:1 petroleum ether–diethyl ether) and the
derived oil was distilled (95–105 °C/0.07 Torr) to afford 259 mg (90%) of the diastereomeric
mixture of four 5(S)-isopropenyl-2-methyl-3-trimethylgermylcyclohexanones (234)–(237). ¹H
NMR spectroscopic analysis indicated a 12:3.9:3.1:1 ratio of the 2S,3R:2R,3R:2S,3S:2R,3S
diastereomers.
3.4.2.4 General Procedure 11: Synthesis of 3,5,5-Trimethyl-3-trimethylgermyl-cyclohexanone (238) from Isophorone (228)

To a cold (−78 °C) stirred solution of the appropriate (trimethylgermyl)copper(I) reagent (0.64–1.3 equiv) in dry THF was added a solution of isophorone (228) (1 equiv) in dry THF via a cannula to generate a final concentration of ≈0.08 M of the isophorone (228). The mixture was stirred at −78 °C, then was warmed to the indicated temperature and was allowed to stir for an additional period of time. The mixture was poured into stirred aqueous NH₄Cl–NH₄OH (pH 8–9, ≈20 mL per mmol of enone) and diethyl ether was added (≈40 mL per mmol of enone) to the mixture. The heterogeneous mixture was stirred vigorously, open to the atmosphere, until the aqueous layer was deep blue. The layers were separated and the aqueous portion was extracted with diethyl ether (2 × ≈10 mL per mmol of enone). The combined organic extracts were washed with water (2 × ≈10 mL per mmol of enone) and brine (≈10 mL per mmol of enone), were dried over anhydrous magnesium sulfate, and then were filtered and concentrated under reduced pressure. The crude oil acquired was subjected to flash chromatography to afford the title compound as a clear colorless oil.

¹H NMR (400 MHz, CDCl₃): δ 2.35 (d, 1H, J = 13.0 Hz), 2.23 (d, 1H, J = 13.0 Hz), 2.10 (ddd, 1H, J = 13.0, 2.0 and 2.0 Hz), 2.00 (ddd, 1H, 13.0, 2.0 and 2.0 Hz), 1.74 (d, 1H, J = 13.0 Hz), 1.46 (ddd, 1H, J = 13.0, 2.0 and 2.0 Hz), 1.13 (s, 3H), 1.05 (s,
3H), 1.02 (s, 3H), 0.10 (s, 9H, -Ge(CH₃)₃).

¹³C NMR (75.4 MHz, CDCl₃): δ 213.0 (-CO-), 54.4, 47.8, 44.9, 39.1 (quaternary carbon), 34.2 (-CH₃), 29.1 (-CH₃), 28.4 (quaternary carbon), 22.7 (-CH₃), -5.6 (-Ge(CH₃)₃).

IR (film): 1713, 1273, 1238, 823, 597 cm⁻¹.

HRMS for C₁₂H₂₄GeO: calcd 258.1039, found 258.1032.

Anal. calcd for C₁₂H₂₄GeO: C 56.10, H 9.42; found: C 56.48, H 9.47.

3.4.2.4.1 Preparation of 3,5,5-Trimethyl-3-trimethylgermylcyclohexanone (238) Using Dilithium Bis(trimethylgermyl)cyanocuprate (224)

Following general procedure 11, to a cold (−78 °C) stirred solution of (Me₃Ge)₂Cu(CN)Li₂ (224) (0.32 mmol, 0.64 equiv) in dry THF (4.8 mL), prepared as described above (section 3.4.1.3, p 266), was added a solution of isophorone (228) (69 mg, 0.50 mmol, 1 equiv) in dry THF (1.5 mL) via a cannula. After the mixture had been stirred at −78 °C for 1 h, dry HMPA (0.23 mL) was added via a syringe. The mixture was allowed to stir for an additional 0.5 h at −78 °C, then it was warmed to 0 °C over a 0.5 h period. The crude oil obtained was subjected to flash chromatography (18 g silica gel, 4:1 then 3:2 petroleum ether–diethyl ether) to afford two fractions, which were concentrated under reduced pressure. The first fraction to be eluted afforded 54 mg (42%) of 3,5,5-trimethyl-3-
trimethylgermylcyclohexanone (238) as a clear colorless oil. The spectral data were identical with those reported above. The second fraction to be eluted afforded 30 mg (43%) of unreacted isophorone (228).

3.4.2.4.2 Preparation of 3,5,5-Trimethyl-3-trimethylgermylcyclohexanone (238) Using Dilithium Methyl(trimethylgermyl)cyanocuprate (225)

Following general procedure 11, to a cold (−78 °C) stirred solution of Me₃Ge(Me)Cu(CN)Li₂ (225) (0.59 mmol, 1.20 equiv) in dry THF (5 mL), prepared as described above (section 3.4.1.4, p 266), was added a solution of isophorone (228) (68 mg, 0.49 mmol, 1 equiv) in dry THF (1.2 mL) via a cannula. The orange mixture was stirred at −78 °C for 1 h, then was warmed to 0 °C over a 45 min period. The crude oil obtained was subjected to flash chromatography (18 g silica gel, 4:1 then 3:2 petroleum ether–diethyl ether) to afford two fractions which were concentrated under reduced pressure. The first fraction to be eluted afforded 42 mg (33%) of 3,5,5-trimethyl-3-trimethylgermylcyclohexanone (238) as a clear colorless oil. The spectral data were identical with those reported above. The second fraction to be eluted afforded 25 mg (37%) of unreacted isophorone (228).
3.4.2.4.3 Preparation of 3,5,5-Trimethyl-3-trimethylgermylcyclohexanone (238) Using Dilithium Methyl(trimethylgermyl)cyanocuprate (225) and Chlorotrimethylsilane as Additive

Following general procedure 11, to a cold (−78 °C) stirred solution of Me₃Ge(Me)Cu(CN)Li₂ (225) (0.60 mmol, 1.20 equiv) in dry THF (5 mL), prepared as described above (section 3.4.1.4, p 266), was added chlorotrimethylsilane (65 mg, 0.60 mmol, 1.20 equiv) via a syringe. After the mixture had been stirred for 5 min, a solution of isophorone (228) (69 mg, 0.50 mmol, 1 equiv) in dry THF (1.2 mL) was added via a cannula. The orange mixture was stirred at −78 °C for 1 h, then was warmed to −30 °C over a 30 min period and was allowed to stir for an additional 1 h. The crude oil obtained was dissolved in THF (5 mL) and 1 M hydrochloric acid (2 drops) was added. The mixture was stirred at rt for 1 h and diethyl ether (5 mL) was added. The mixture was dried over anhydrous magnesium sulfate, and then was filtered and concentrated under reduced pressure. GLC analysis of the crude mixture revealed the presence of ≈20% of unreacted isophorone (228). The crude oil acquired was subjected to flash chromatography (10 g silica gel, 4:1 petroleum ether–diethyl ether) to afford 42 mg (33%) of 3,5,5-trimethyl-3-trimethylgermylcyclohexanone (238) as a clear colorless oil. The spectral data were identical with those reported above.
3.4.2.4.4 Preparation of 3,5,5-Trimethyl-3-trimethylgermylcyclohexanone (238) Using Dilithium Methyl(trimethylgermyl)cyanocuprate (225) and Bromotrimethylsilane as Additive

Following general procedure 11, to a cold (−78 °C) stirred solution of Me₃Ge(Me)Cu(CN)Li₂ (225) (1.51 mmol, 1.30 equiv) in dry THF (13.1 mL), prepared as described above (section 3.4.1.4, p 266), was added bromotrimethylsilane (0.70 g, 4.6 mmol, 4.0 equiv) via a cannula. After the mixture had been stirred for 5 min, a solution of isophorone (228) (160 mg, 1.16 mmol, 1 equiv) in dry THF (2 mL) was added via a cannula. The red-brown mixture was stirred at −78 °C for 1 h, then was warmed to −15 °C over a 2 h period. The crude oil obtained was dissolved in THF (15 mL) and 1 M hydrochloric acid (6 drops) was added. The mixture was stirred at rt for 1 h and diethyl ether (15 mL) was added. The mixture was dried over anhydrous magnesium sulfate, and then was filtered and concentrated under reduced pressure. The crude oil acquired was subjected to flash chromatography (25 g TLC grade silica gel, 4:1 petroleum ether–diethyl ether) and the derived oil was distilled (86–96 °C/0.05 Torr) to afford 198 mg (66%) of 3,5,5-trimethyl-3-trimethylgermylcyclohexanone (238) as a clear colorless oil. The spectral data were identical with those reported above.
3.4.3 ADDITION OF (TRIMETHYLGERMYL)COPPER(I)-DIMETHYL SULFIDE (168) AND (TRIMETHYLGERMYL)CUPRATES TO ACETYLENIC ESTERS

3.4.3.1 GENERAL PROCEDURE 12: SYNTHESIS OF ETHYL (E)-3-TRIMETHYLGERMYLBUT-2-ENOATE (242) FROM ETHYL BUT-2-YNOATE (241)

To a cold (−78 °C) stirred solution of the appropriate (trimethylgermyl)copper(I) reagent (0.66–1.32 equiv) in dry THF was added a solution of ethyl but-2-ynoate (241) (1 equiv) in dry THF via a cannula. The reaction mixture was stirred at −78 °C for 20–30 min, then acetic acid (1.5–3.9 equiv) was added via a syringe. The thick mixture was stirred for an additional 5 min, then was poured into stirred aqueous NH₄Cl-NH₄OH (pH 8–9, ≈20 mL per mmol of alkynoate) and diethyl ether (≈25 mL per mmol of alkynoate) was added to the mixture. The layers were separated and the aqueous portion was extracted with diethyl ether (2 × ≈10 mL per mmol of alkynoate). The combined organic extracts were washed with water (2 × ≈10 mL per mmol of alkynoate) and brine (2 × =10 mL per mmol of alkynoate), were dried over anhydrous magnesium sulfate and then were filtered and concentrated under reduced pressure. The crude oil acquired was subjected to flash chromatography and the derived oil was distilled (110–120 °C/11 Torr) to afford the title compound as a clear colorless oil.
$^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 5.95 (q, 1H, $J = 1.8$ Hz, vinylic proton), 4.14 (q, 2H, $J = 7.2$ Hz, -CH$_2$CH$_3$), 2.26 (d, 3H, $J = 1.8$ Hz, vinylic methyl), 1.27 (t, 3H, $J = 7.2$ Hz, -CH$_2$CH$_3$), 0.23 (s, 9H, -Ge(CH$_3$)$_3$).

Additional $^1$H NMR data, derived from NOE difference experiments, are given in Table 27.

$^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ 165.3 (C=O or C-3), 165.2 (C=O or C-3), 124.8 (C-2), 59.5 (-CH$_2$), 18.2, 14.3, -3.0 (-Ge(CH$_3$)$_3$).

IR (film): 1718, 1614, 1367, 1340, 1239, 1181, 1117, 1040, 826, 603 cm$^{-1}$.

HRMS (DCI, NH$_3$ + CH$_4$) for C$_9$H$_{19}$GeO$_2$ (M + 1)$^+$: calcd 233.0597, found 233.0597.

Anal. calcd for C$_9$H$_{18}$GeO$_2$: C 46.83, H 7.86; found: C 47.10, H 7.70.

Table 27: $^1$H NMR Data from Nuclear Overhauser Enhancement Difference Experiments for Ethyl (E)-3-Trimethylgermylbut-2-enoate (242)

<table>
<thead>
<tr>
<th>Assignments</th>
<th>$^1$H NMR$^a$</th>
<th>Observed NOEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-x</td>
<td>$\delta$ ppm (mult, $J$ (Hz))</td>
<td>-Ge(CH$_3$)$_3$</td>
</tr>
<tr>
<td>H-2$^b$</td>
<td>5.95 (q, 1.8)</td>
<td>H-2, -CH$_3$-2'</td>
</tr>
<tr>
<td>H-1$^b$</td>
<td>4.14 (q, 7.2)</td>
<td>H-1', -Ge(CH$_3$)$_3$</td>
</tr>
<tr>
<td>-CH$_3$-4$^b$</td>
<td>2.26 (d, 1.8)</td>
<td>-CH$_3$-4</td>
</tr>
<tr>
<td>-CH$_3$-2'</td>
<td>1.27 (t, 7.2)</td>
<td></td>
</tr>
<tr>
<td>-Ge(CH$_3$)$_3$</td>
<td>0.23 (s)</td>
<td>H-2, -CH$_3$-4</td>
</tr>
</tbody>
</table>

$^a$ 400 MHz, CDCl$_3$. $^b$ Irradiation of this signal generated the corresponding NOEs in the right hand column.
3.4.3.1.1 Preparation of Ethyl (E)-3-Trimethylgermylbut-2-enoate (242) Using Trimethylgermylcopper(I)–Dimethyl Sulfide (168)

Following general procedure 12, to a cold (−78 °C) stirred solution of Me₃GeCu•Me₂S (168) (1.11 mmol, 1.32 equiv) in dry THF (6.5 mL), prepared as described above (section 3.3.2.2, p 223), was added a solution of ethyl but-2-ynoate (241) (95 mg, 0.85 mmol, 1 equiv) in dry THF (1 mL) via a cannula. The black mixture was stirred at −78 °C for 30 min, then acetic acid (80 mg, 1.3 mmol, 1.5 equiv) was added via a syringe. The crude oil obtained was subjected to flash chromatography (20 g TLC grade silica gel, 32:1 petroleum ether–diethyl ether) and the derived liquid was distilled to afford 158 mg (81%) of ethyl (E)-3-trimethylgermylbut-2-enoate (242) as a clear colorless oil. The spectral data were identical with those reported above.

3.4.3.1.2 Preparation of Ethyl (E)-3-Trimethylgermylbut-2-enoate (242) Using Lithium (Trimethylgermyl)cyanocuprate (223)

Following general procedure 12, to a cold (−78 °C) stirred solution of
Me₃GeCu(CN)Li (223) (1.11 mmol, 1.30 equiv) in dry THF (10 mL), prepared as described above (section 3.4.1.2, p 265), was added a solution of ethyl but-2-ynoate (241) (97 mg, 0.86 mmol, 1 equiv) in dry THF (1.5 mL) via a cannula. The light orange mixture was stirred at -78 °C for 20 min, then acetic acid (0.20 g, 3.3 mmol, 3.9 equiv) was added via a syringe. The crude oil obtained was subjected to flash chromatography (10 g TLC grade silica gel, 32:1 petroleum ether–diethyl ether) and the derived oil was distilled to afford 180 mg (90%) of ethyl (E)-3-trimethylgermylbut-2-enoate (242) as a clear colorless oil. The spectral data were identical with those reported above.

3.4.3.2 SYNTHESIS OF ETHYL (Z)-3-TRIMETHYLGERMYL BUT-2-ENOATE (243) FROM ETHYL BUT-2-YNOATE (241) USING DILITHIUM METHYL(TRIMETHYLGERMYL) CYANOCUPRATE (225)

To a cold (-78 °C) stirred solution of Me₃Ge(Me)Cu(CN)Li₂ (225) (1.11 mmol, 1.30 equiv) in dry THF (10 mL), prepared as described above (section 3.4.1.4, p 266), was added a solution of ethyl but-2-ynoate (241) (96 mg, 0.86 mmol, 1 equiv) in dry THF (1.5 mL) via a cannula. The reaction mixture was stirred at -78 °C for 30 min, then acetic acid (0.13 g, 2.2 mmol, 2.6 equiv) was added via a syringe. The heterogeneous mixture was stirred for an additional 5 min, then was poured into stirred aqueous NH₄Cl–NH₄OH (pH 8–9, 15 mL) and diethyl ether (20 mL) was added to the mixture. The heterogeneous mixture was stirred vigorously, open to the atmosphere, until the aqueous layer was deep blue. The layers were
separated and the aqueous portion was extracted with diethyl ether (2 x 10 mL). The combined organic extracts were washed with water (2 x 10 mL) and brine (2 x 10 mL), were dried over anhydrous magnesium sulfate and then were filtered and concentrated under reduced pressure. The crude oil obtained was subjected to flash chromatography (20 g TLC grade silica gel, 49:1 petroleum ether–diethyl ether) to afford two fractions, which were concentrated under reduced pressure. The first fraction to be eluted afforded 137 mg (69%) of the ethyl (Z)-3-trimethylgermylbut-2-enoate (243) as a clear colorless oil. An analytically pure sample was obtained by distillation (100–110 °C/10 Torr).

\[ ^1H \text{NMR (400 MHz, CDCl}_3\): } \delta 6.28 (q, 1H, J = 1.6 Hz, vinylic proton), 4.13 (q, 2H, J = 7.2 Hz, -CH}_2CH_3), 2.01 (d, 3H, J = 1.6 Hz, vinylic methyl), 1.26 (t, 3H, J = 7.2 Hz, -CH}_2CH_3), 0.29 (s, 9H, -Ge(CH}_3)_3). \]

Additional \(^1H\) NMR data, derived from NOE difference experiments, are given in Table 28.

\[ ^13C \text{NMR (75.4 MHz, CDCl}_3\): } \delta 166.5 (C=O or C-3), 166.0 (C=O or C-3), 128.4 (C-2), 59.8 (-CH}_2-), 26.2, 14.3, –0.8 (-Ge(CH}_3)_3). \]

IR (film): 1718, 1610, 1326, 1196, 1046, 832 cm\(^{-1}\).

HRMS for C\(_9\)H\(_{18}\)GeO\(_2\) (M – CH\(_3\))\(^+\): calcd 217.0284, found 217.0291.

Anal. calcd for C\(_9\)H\(_{18}\)GeO\(_2\): C 46.83, H 7.86; found: C 46.94, H 7.87.
Table 28: $^1$H NMR Data from Nuclear Overhauser Enhancement Difference Experiments for Ethyl (Z)-3-Trimethylgermylbut-2-enoate (243)

\[
\text{Assignments} \quad \text{H-x} \quad \begin{array}{c} \text{$^1$H NMR$^a$} \\ \delta \text{ ppm (mult, } J \text{ (Hz))} \end{array} \quad \text{Observed} \\
\text{H-2$^b$} \quad 6.28 (q, 1.6) \quad \text{H-1'} \\
\text{H-1$^b$} \quad 4.13 (q, 7.2) \quad \text{H-2, -CH$_3$-2'} \\
\text{-CH$_3$-4$^b$} \quad 2.01 (d, 1.6) \quad \text{H-2, -Ge(CH$_3$)$_3$} \\
\text{-CH$_3$-2'} \quad 1.26 (t, 7.2) \quad \text{H-1', -CH$_3$-4} \\
\text{-Ge(CH$_3$)$_3$} \quad 0.29 (s) \quad \text{H-1', -CH$_3$-4} \\
\]

$^a$ 400 MHz, CDCl$_3$. $^b$ Irradiation of this signal generated the corresponding NOEs in the right hand column.

The second fraction to be eluted afforded 33 mg (17%) of ethyl (E)-3-trimethylgermylbut-2-enoate (242) as a clear colorless oil. The spectral data were identical with those reported above (see section 3.4.3.1, p 294).
3.4.3.3 Synthesis of ethyl (E)- and (Z)-3-trimethylgermylbut-2-enoate (242) and (243) from ethyl but-2-ynoate (241) using lithium bis(trimethylgermyl)cuprate (222)

To a cold (–78 °C) stirred solution of (Me₃Ge)₂CuLi (222) (0.56 mmol, 0.66 equiv) in dry THF (10 mL), prepared as described above (section 3.4.1.1, p 265), was added a solution of ethyl but-2-ynoate (241) (95 mg, 0.85 mmol, 1 equiv) in dry THF (1.5 mL) via a cannula. The light yellow mixture was stirred at –78 °C for 30 min, then acetic acid (80 mg, 1.3 mmol, 1.5 equiv) was added via a syringe. The black mixture was stirred for an additional 5 min, then was poured into stirred aqueous NH₄Cl–NH₄OH (pH 8–9, 15 mL) and diethyl ether (20 mL) was added to the mixture. The layers were separated and the aqueous portion was extracted with diethyl ether (2 × 10 mL). The combined organic extracts were washed with water (2 × 10 mL) and brine (2 × 10 mL), were dried over anhydrous magnesium sulfate and then were filtered and concentrated under reduced pressure. The crude oil obtained was subjected to flash chromatography (10 g TLC grade silica gel, 32:1 petroleum ether–diethyl ether) to afford 176 mg (90%) of a mixture of ethyl (E)- and (Z)-3-trimethylgermylbut-2-enoate (242) and (243) (1.7:1, E:Z) as a clear colorless oil. The spectral data were identical with those reported above (section 3.4.3.1, p 294 and section 3.4.3.2, p 297 respectively).
3.4.3.4 SYNTHESES OF METHYL (E)-6-CHLORO-3-TRIMETHYLGEMYLHEX-2-ENOATE (248)

To a cold (-78 °C) stirred solution of Me₃GeCu(CN)Li (223) (1.24 mmol, 1.30 equiv) in dry THF (11 mL), prepared as described above (section 3.4.1.2, p 265), was added a solution of methyl 6-chlorohex-2-ynoate (247)¹¹⁵ (154 mg, 0.96 mmol, 1 equiv) in dry THF (1.5 mL) via a cannula. The reaction mixture was stirred at -78 °C for 30 min, then acetic acid (90 mg, 1.5 mmol, 1.6 equiv) was added via a syringe. The mixture was stirred for an additional 5 min, then was poured into stirred aqueous NH₄Cl-NH₄OH (pH 8–9, 15 mL) and diethyl ether (20 mL) was added to the mixture. The layers were separated and the aqueous portion was extracted with diethyl ether (2 × 10 mL). The combined organic extracts were washed with water (2 × 10 mL) and brine (10 mL), were dried over anhydrous magnesium sulfate and then were filtered and concentrated under reduced pressure. The crude oil acquired was subjected to flash chromatography (20 g TLC grade gel, 24:1 petroleum ether–diethyl ether) to afford 248 mg (92%) of the title compound as a clear colorless oil.

¹H NMR (400 MHz, CDCl₃): δ 6.02 (s, 1H, vinylic proton), 3.70 (s, 3H, -OCH₃), 3.56 (t, 2H, J = 6.6 Hz, -CH₂Cl), 2.86 (t, 2H, J = 8.0 Hz, -CH₂CH₂CH₂Cl), 1.86 (tt, 2H, J = 8.0 and 6.6 Hz, -CH₂CH₂Cl), 0.29 (s, 9H, -Ge(CH₃)₃).

¹³C NMR (75.4 MHz, CDCl₃): δ 168.7 (C=O or C-3), 165.0 (C=O or C-3), 125.5 (C-2), 50.9 (-OCH₃), 44.9, 32.1, 29.9, -2.1 (-Ge(CH₃)₃).
IR (film): 1718, 1607, 1434, 1347, 1181, 1156, 828, 603 cm$^{-1}$.

HRMS for $\text{C}_9\text{H}_{16}{ }^{35}\text{Cl}{ }^{74}\text{GeO}_2$ (M – CH$_3$)$^+$: calcd 265.0051, found 265.0048.

Anal. calcd for $\text{C}_{10}\text{H}_{19}\text{ClGeO}_2$: C 43.00, H 6.86; found: C 42.98, H 6.68.
4 FOOTNOTES AND REFERENCES


Transl.) 1968, 38, 2225-2227.


A similar rationale for the catalytic protodesilylation of vinylsilanes with p-toluene-sulfinic acid has been invoked: see reference (52).

See reference (68), pp 104-105.
Isolation of 5-trimethylsilylpent-4-ynoic acid (163) via extraction with 1 M aqueous NaOH resulted in cleavage of the alkynyl Me₃Si-group.


The electronegativity of carbon is 2.55, whereas that of germanium is 2.01, a difference comparable to that between chlorine and carbon (3.16 vs 2.55).


See reference (68), p 195.


(115) Todd W. Schindeler is gratefully acknowledged for a generous gift of a sample of methyl 6-chlorohex-2-ynoate (247).


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