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Department of Chemistry
The University of British Columbia
Vancouver, Canada
Date Sept. 27th, 1993
ABSTRACT

Six di- and mono- aryl substituted dibenzobarrelene derivatives were synthesized for studies of the di-π-methane rearrangement in both solution and the solid state. The starting materials and their photoproducts were characterized by spectroscopic methods. The photoproduct ratios of these dibenzobarrelene derivatives in the di-π-methane rearrangement, in both the solution and solid state, were determined. Based on the X-ray crystal structures and Molecular Mechanics calculations (MMX), the regioselectivities of these dibenzobarrelene substrates in the multi-channel di-π-methane rearrangement were discussed in terms of electronic effects and intramolecular steric effects.

A series of α-adamantyl acetophenone derivatives were synthesized for the structure-reactivity correlation studies in the solid state Norrish type II photoreactions. The structure assignments of both the starting substrates and the diastereomeric photoproducts were primarily based on NMR techniques, such as HETCOR and NOE experiments. The X-ray crystal structures of four α-adamantyl acetophenones were determined, and their solid state reactivities were discussed relative to the proposed ideal geometric requirements for hydrogen abstraction.

Chiral crystals of carboxylic acid-amine salts were synthesized for solid state asymmetric induction studies. Some of these chiral salts were made from a prochiral, carboxylic acid group-containing α-adamantyl acetophenone (119) and optically pure chiral amines. The solid state photolyses of these chiral salts afforded photoproducts in optially active form (12%-97% e.e.). The solid state structure-reactivity was discussed based on X-ray crystal structures of crystals of these starting chiral salts.
The absolute configuration correlation between a chiral crystalline salt $169n$ and its major photoproduct $159s$ was established, which revealed that salt $169n$ reacted stereospecifically via a topochemically allowed pathway to give a single diastereomer of photoproduct $159s$.

A macrocyclic diketone $108b$ was synthesized. It was found that this diketone did not undergo the Norrish type II reaction in the crystalline state. The hydrogen abstraction geometry of this diketone was analysed based on its crystal structure, and the distances between $\gamma$-hydrogens and the carbonyl oxygens were found to be beyond the proposed maximum abstracting distance of 3.0 Å.

Pyrazinone $197$ and pyrazinethione $199$ were synthesized for the solid state [4 + 4] photocycloaddition reactions. It was found that pyrazinone $197$ gave high optical yield of the photoproduct $198$ (95% e.e.); this result was discussed based on the crystal structure of the substrate $197$. Pyrazinethione $199$ was found photochemically unreactive.
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3.16 The Distance between the Carbonyl Carbon and the $\gamma$-Carbons in Diketones 92 and 108b
ACKNOWLEDGEMENT

I would like to thank my research supervisor Professor John R. Scheffer for his valuable guidance and encouragement on my research and study throughout the years, and I appreciate his understanding and patience in helping me writing my Ph.D. thesis.

I would like to thank Professor James Trotter and members of his research group, Dr. Steve Rettig, Dr. Ray Jones and Dr. Bozena Borecka, for the X-ray crystallographic analysis. My thanks also go to Professor Menehem Kaftory and Mr. Taiyu Fu for the X-ray crystallographic analysis.

Thanks to all my friends for every thing they have done for me, and special thanks to Mardy Leibovitch, Anna Gudmundsdottir and Brian Patrick for proof-reading my thesis.

Finally, I would like to express my appreciation for all the help from the NMR, Mass and Elemental Analysis laboratories, and also from the Chemistry departmental staff in various aspects.
DEDICATION

To my parents, my wife and my son
INTRODUCTION

Chapter 1  Introduction

The occurrence of photoreactions in the crystalline state was recognized long ago and was first reported in the early 19th century. Despite this long history, early solid state photochemical study was greatly restricted owing to the lack of knowledge about molecular structure, especially crystal structure. With the development of X-ray crystallography, there has been a resurgence of interest in the study of solid state photochemistry. Although this field is still in its infancy, solid state photochemistry has been growing very rapidly for the last 30 years.

Solid state photochemical reactions have often been used in the study of reaction mechanisms and structure-reactivity correlations. The restriction of internal molecular motions in the solid state can reveal intimate details of reaction mechanisms by favoring or disfavoring certain photochemical processes. X-ray crystallography and other solid state spectroscopic techniques, such as magic angle spinning solid state $^{13}$C NMR, ESR and FT-IR, provide chemists with penetrating insights into the structural details of the reactants, intermediates and products.

In addition to the crystalline state, organic reactions are conducted in other organized media, such as polymer matrices, micelles, liquid crystals, zeolites and inclusion complexes. Among these varied organized media, the crystalline state has the highest degree of order. There are many advantages in conducting reactions in the crystalline state over those in other organized media. In the crystalline state, molecules
are often packed in their lowest energy conformations, while in other media, there may be many interconvertible molecular conformations involved. Many organic compounds tend to crystallize in different forms, i.e. polymorphs, which possess different space groups as a result of different packing arrangements. Polymorphs sometimes react differently in the solid state, and this has led to the discovery of new reactions and reaction mechanisms. However, a problem involved in solid state chemistry is the inability to predict and control crystal packing so as to get the desired molecular arrangement. The factors that control crystal packing are not yet well understood. To some extent, solid state chemistry is still at the "show and tell" stage.

1.1. Crystal Engineering

High quality organic crystals are required for X-ray diffraction analyses and for use as solid state starting materials for photochemical reactions. Many methods of growing organic crystals have been reported by Etter and coworkers, including examples of crystal growth with controlled morphology, controlled growth of metastable crystals and growth of polymorphic crystal forms. It has been recognized that hydrogen bonding plays a very important role in crystal packing. Etter et al. also reported the use of triphenylphosphine oxide as a crystallization aid to grow large and high quality organic crystals. Triphenylphosphine oxide itself forms high quality crystals easily and it induces many organic compounds to crystallize readily as large, blocky crystals that have sharp edges and well-defined crystal faces. Triphenylphosphine oxide is a good hydrogen bond acceptor and is known to form complexes in solution with a wide variety of organic molecules. These complexes are stabilized by strong hydrogen bonds between the oxygen atom of the triphenylphosphine oxide and an N-H or O-H hydrogen atom of the substrate. For organic compounds that form poor quality crystals or are available in only
small amounts, triphenylphosphine oxide complexation is a good method for converting them into useful crystals.

Besides crystals of high quality, solid state photochemical reactions require crystals that are packed with proper inter- and/or intramolecular arrangements, so as to take part in the anticipated reactions. During the past thirty years, many efforts have been made by chemists to study the factors that govern crystal packing. The control of crystal growth in certain pre-determined arrangements was termed "crystal engineering" by Schmidt. The most intensive investigation over the years on this topic was the study of substituent effects on the molecular packing arrangement of olefins. Among various substituents studied, chlorine was found to be a steering agent for aromatic olefins toward a favorable molecular orientation for solid state photodimerization reactions. Attractive intermolecular Cl···Cl interactions were proposed as being responsible for the close molecular packing.

Crystal structure prediction has been approached by both theoretical calculations and experimental methods. The atom-atom potential method and the close-packing model for molecular crystals have been proposed by Kitaigorodskii to understand and predict crystal packing. Many methods of crystal design have also been reported, such as the formation of solid solutions, mixed crystals, donor-acceptor complexes and clathration. However, knowledge about crystal engineering is still limited at this stage.

1.2. The Topochemical Postulate

The first topochemical postulate for solid state chemical reactions was proposed by Kohlschutter in 1918. He suggested that reactions in crystals proceed with a
minimum of atomic and molecular movement. A topochemical reaction is then considered to take place under the constraining influence of the crystal lattice, and this suggests that only reactions requiring minimum motion would be permitted in the solid state. This fundamental topochemical postulate was further modified many years later by chemists as a result of their studies of different solid state reactions. Most notable was the pioneering work by Schmidt and coworkers in the 1960s on the solid state \([2 + 2]\) photocycloaddition reaction of \textit{trans}-cinnamic acid derivatives. As a result of Schmidt's systematic investigations, some important principles were established for solid state reactions. He proposed that the reactivity of each substrate in the crystalline state is governed by the molecular packing in the crystal lattice, which determines the orientation and distance between the two reacting double bonds. The photochemical reactions of \textit{trans}-cinnamic acid in solution and solid state are given in Scheme 1.01.11,12,13

As shown in Scheme 1.01, photolysis of \textit{trans}-cinnamic acid (1) in solution gives \textit{cis}-cinnamic acid (2), and no dimerization reaction is observed. In the solid state, \textit{trans}-cinnamic acid crystallizes in three polymorphic forms, namely \(\alpha\), \(\beta\) and \(\gamma\). In the \(\alpha\) form, the molecules are packed with a head-to-tail pattern, and the center-to-center distance between the two nearest double bonds is 3.8 \(\text{Å}\). Irradiation of the \(\alpha\) form crystals afforded a \([2 + 2]\) photocycloaddition reaction product, \(\alpha\)-truxillic acid (3), which is a centrosymmetric dimer. The molecules in the metastable \(\beta\) form are packed head-to-head with a nearest-neighbor contact between two double bonds of 3.9 \(\text{Å}\). The mirror-symmetric \(\beta\)-truxillic acid (4) was formed upon photolysis of the \(\beta\) form \textit{trans}-cinnamic acid in the solid state. The \(\gamma\) form, in which the nearest two double bonds make contact at 4.7 \(\text{Å}\), is photostable. This photostability was interpreted as being due to lattice constraints which do not permit the potentially reactive centers to move sufficiently close together to form a photodimer. Interestingly, the metastable \(\beta\) form underwent a thermal
Scheme 1.01  The Photochemical Reactions of trans-Cinnamic Acid

phase transition to give the more stable α form in the solid state at about 50 °C. The irradiation of β form crystals at high temperature (> 50 °C) afforded both α and β-truxillic acid; in this case, Schmidt suggested that the photoprodct α-truxillic acid was formed via the α form trans-cinnamic acid, which was generated during the reaction process by the phase transition of the β form.12 This example demonstrates both the
topochemical control of solid state reactions and the reactivity differences among polymorphs. After their systematic studies on the [2 + 2] photocycloaddition reactions of trans-cinnamic acid and its derivatives, Schmidt and co-workers proposed that the center-to-center distance of two neighboring double bonds should be less than 4.2 Å in order for them to take part in the photocycloaddition reaction.6,11,12,13

According to Schmidt and coworkers,6 a parallel alignment of the two reacting double bonds is also important for the [2 + 2] photocycloaddition reaction to take place. There are examples where the distance between the centers of adjacent double bonds is within the proposed reaction limit, but the double bonds are not parallel to each other. As a result, no photodimerization reaction was observed in the solid state.7 However, a few cases have also been reported where the reacting double bonds were not exactly parallel but the photodimerization reaction was observed. For example, in crystals of 7-methoxycoumarin, the reactive double bonds are rotated by about 65 ° with respect to each other, and the center-to-center distance between them is 3.83 Å. In spite of this unfavorable arrangement, photodimerization did occur.14 Exceptions such as this should not be considered as serious violations of Schmidt's original concepts, but should be integrated into the original basic idea, thereby widening its scope.

Following Schmidt's investigations of [2 + 2] photocycloaddition reactions, another general concept called the "reaction cavity" was introduced by Cohen as an aid in interpreting the course of a variety of solid state reactions.15 This concept considers the space occupied by the reacting molecules as the reaction cavity. Therefore the proposed reaction cavity is the space surrounded by the neighboring molecules, and the shape of the cavity is determined by the packing of the crystal. According to Cohen,15 the atomic movements during a reaction course produce pressure on the cavity wall, which may
cause a distortion of the surface of the reaction cavity, and such distortions in shape would be restricted by the closely packed crystal lattice. This concept predicts that in a solid state reaction where two pathways are available, lattice control favors the one which involves a minimal change or distortion of the surface of the reaction cavity. This reaction cavity concept is further depicted in Scheme 1.02.

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Transition States</th>
<th>Products</th>
</tr>
</thead>
</table>

![Scheme 1.02](image)

**Scheme 1.02**  The Reaction Cavity Concept: Before Reaction (Full Line) and The Transition State (Broken Line)

In Scheme 1.02, there are two reaction pathways, I and II, that occur via the transition states B' and C' respectively. For reaction I, the shape and size of the transition state B' resemble those of the reaction cavity, but for reaction II, there is a large shape
change in the transition state C'. According to the reaction cavity concept, reaction I is topochemically feasible, and reaction II is energetically unfavorable.

Other attempts to account for solid state reaction selectivity, such as "steric compression", "free volume" and "local stress" have also been proposed. These concepts have been reviewed elsewhere and will not be discussed in this thesis.

1.3. Solid State Reactivity and Selectivity

The topochemical principle states that reactions in the solid state prefer to occur with a minimum amount of atomic and molecular movement. This implies that a certain amount of motion in the crystal lattice is tolerable. Many solid state organic reactions involve considerable molecular movement, and as a result, the crystal lattices are destroyed at the end. However, there are examples of single crystal-to-single crystal photochemical transformations which represent the ultimate topochemical reactions with minimum molecular motion. The photodimerization reaction of 2-benzyl-5-benzylidene-cyclopentanone and the crystallographic molecular conformations of both monomer 5 and dimer 6 are shown in Scheme 1.03.

The crystallographic configurations shown for compound 5 and its dimer 6 reveal that the dimerization process requires very little motion of the atoms. As a result, in this solid state photochemical reaction, not only did the crystals of the starting compound 5 convert quantitatively to dimer 6, but also the crystals remained single throughout the process.
Scheme 1.03  Single Crystal-to-Single Crystal Photodimerization Reaction of 2-Benzyl-5-benzylidenecyclopentanone and the Crystallographic Conformations of the Corresponding Molecules of Monomer (solid lines) and Dimer (dotted lines)

Most solid state organic reactions that have been studied so far are induced by light or other irradiation. This is because irradiation can penetrate the surface of the crystal and reach the reactive site without disruption of the crystal packing. Thermal solid state reactions, on the other hand, often involve considerable heat-induced molecular motions during the activation process, and this frequently causes melting of the crystals. For this reason, solid state photochemical reactions are generally more specific and selective than solid state thermal processes.
As mentioned above, organic molecules in the crystalline state are often packed in their most stable conformations. The solid state reaction is then limited to taking place via this lowest energy conformation. In solution, however, owing to conformational flexibility, reactions often occur from higher energy conformations. The influence of the ground state conformation on the excited state behavior of cyclohexenones in the solid state was elucidated by Scheffer and coworkers.\textsuperscript{19,20} Examples are shown in Scheme 1.04.

**Scheme 1.04**  The Photolysis of Cyclohexenone 7

The photolysis of cyclohexenone 7 in solution leads to the intramolecular [2 + 2] cycloaddition reaction to give cage compound 8. On the other hand, the irradiation of cyclohexenone 7 in the crystalline state gives photorearrangement product 9. Thus,
completely different reactions are found in the solution and solid state photolyses. It was found by X-ray diffraction analysis that cyclohexenone 7 crystallizes in conformations unsuitable for intramolecular [2 + 2] photocycloaddition; instead, intramolecular hydrogen transfer is a topochemically allowed process. The above solid state photoreactions were suggested to be governed by the ground state conformations under lattice control.\textsuperscript{19,20}

Solid state photoinduced decarbonylation reactions have been reported to occur with high regioselectivity, and two examples are given in Scheme 1.\textsuperscript{05,21,22} The photodecarbonylation reaction of 1,1,3-triphenylacetone 10 was proposed to involve the formation of two radical intermediates, 11 and 12, in equal amounts accompanied by the elimination of carbon monoxide. Following this, radical coupling between intermediates 11 and 12 gives photoproducts 13, 14 and 15. Quinkert and co-workers reported\textsuperscript{21} that the photolysis of ketone 10 in solution leads to the formation of products 13, 14 and 15 in a statistical 1:2:1 ratio. In the solid state, the irradiation of 1,1,3-triphenylacetone (10) gives product 14 exclusively. Cohen suggested that the proposed radical intermediates 11 and 12 are formed in close proximity, and that direct coupling between these two radicals leads to product 14 because the strong lattice effect or the so-called "cage effect" restricts the diffusion of these two radical intermediates, so that there was no chance for radicals of the same type to react with each other in a solid state reaction.\textsuperscript{15}
The photolysis of indanone 16 in solution resulted in smooth decarbonylation to give isomeric benzocyclobutanes 18 and 19 in a ratio of 11:89. However, the solid state photolysis led to a striking increase in the formation of the cis isomer 18. Quinkert suggested that this photodecarbonylation reaction involves a biradical intermediate 17; in solution, the internal rotations and inversion at radical centers lead mainly to the
sterically less hindered trans isomer 19. In the solid state, on the other hand, the crystal lattice effect was proposed to have a strong influence on the rate and direction of phenyl group rotation at the radical centers, and this led to the formation in the solid state of the more sterically hindered cis isomer 18 as the major photoproduct.22

1.4. The Di-π-methane Rearrangement

The di-π-methane rearrangement is one of the most thoroughly studied organic photoreactions. It was conceptually developed by Zimmerman in the 1960s.23 The phrase "di-π-methane" denotes a general reactant structure of two π-bonds that are separated by a methane carbon or sp³ hybridized carbon atom. The simplest di-π-methane system is 1,4-pentadiene (20). The proposed di-π-methane rearrangement mechanism is shown in Scheme 1.06, and diene 20 is used to depict the skeletal change during this rearrangement.23

![Scheme 1.06](image)

Scheme 1.06  The Postulated Di-π-methane Rearrangement Mechanism

As depicted in Scheme 1.06, Zimmerman postulated that the excited state of 1,4-pentadiene (20) bridges to form a new sigma bond and afford a cyclopropylidicarbiny 1,4-diradical 21, which proceeds onward to 1,3-diradical 22. The final ring closure yields vinylcyclopropane (23). The diradicals 21 and 22, first proposed by Zimmerman, are
approximations of species along the reaction pathway and do not necessarily represent true intermediates. However, these radical species have proved very useful in understanding, rationalizing and even predicting the course of reactions that will be discussed later. Two examples are given in Scheme 1.07 and represent acyclic and cyclic variants of the di-\(\pi\)-methane rearrangement.

Generally speaking, acyclic systems, such as compound 24, undergo the di-\(\pi\)-methane rearrangement via the singlet excited state, whereas cyclic systems, such as compound 26, react via the triplet excited state. Both aliphatic and aromatic \(\pi\)-bonds are capable of participating in the di-\(\pi\)-methane rearrangement.

1.4.1. Reaction Mechanism

Although the di-\(\pi\)-methane rearrangement has been extensively studied for three decades, the reaction mechanism remains uncertain. The first mechanism was postulated
by Zimmerman and is shown in Scheme 1.06. Two diradical intermediates were proposed in this mechanism, and many efforts have been made to confirm their existence by theoretical calculations and experimental approaches. Good evidence came from the independent generation of these diradical species. In one example, the cyclopropylidicarbinyl diradical, i.e. the first type of diradical (diradical 21 in Scheme 1.06), was generated by Zimmerman via nitrogen extrusion from the appropriate azoalkane\textsuperscript{26} (Scheme 1.08).

\[ \text{Scheme 1.08} \quad \text{The Denitrogenation Reaction of Azoalkane 28} \]

It was observed that the ground state diradical species 30, which was presumably generated by the thermolysis of azo compound 28, led to Grob fragmentation and cycloreversion to the corresponding barrelene 29 quantitatively. The direct photolysis (via the singlet excited state) of compound 28 afforded three compounds, labelled 29, 31 and 32. In the triplet-sensitized irradiation of 28, the di-\(\pi\)-methane product semibullvalene (31) was formed exclusively.\textsuperscript{26} This example provided evidence that diradical 30 could lead to both the starting material and the product of the above di-\(\pi\)-
methane rearrangement. However, the question arises whether the generated diradicals are indeed the same as the ones involved in the di-π-methane rearrangement. Recent studies by Adam et al. suggest that the di-π-methane rearrangement and the photochemical denitrogenation of azoalkanes are disjointed chemical events.27,28

Turning to the second type of diradicals proposed in the Zimmerman mechanism (diradical 22 in Scheme 1.06), it was suggested by Zimmerman that for the triplet di-π-methane rearrangement of bicyclic barrelene systems, these species are true intermediates.23a This conclusion was based on photochemical studies of the deuterium labelled barrelene system.29,30

The photolysis of deuterium labelled barrelene system. The photolysis of barrelene (33) is outlined in Scheme 1.09, where the bridgehead deuterium labels are depicted by filled circles. It was found that the triplet-sensitized irradiation of barrelene (33) led to the formation of
semibullvalenes 37 and 38 in a 1:1 ratio. This was considered to be the result of radical coupling reactions occurred in the diradical resonance structures 35 and 36. Therefore, this diradical was taken to be true intermediate of modest lifetime.\textsuperscript{23a} Furthermore, photochemical studies by Paquette on deuterium labelled dibenzobarrelenes and benzonorbornadienes also strongly suggest the direct intervention of the second type of diradical species during the di-\pi-methane reaction process.\textsuperscript{31,32}

Schaffner and co-workers\textsuperscript{33} studied the di-\pi-methane reaction process using spectroscopic methods. The low temperature di-\pi-methane rearrangement of a naphthobarrelene-like compound was monitored by ESR and IR spectroscopy, and the experimental results suggested the existence of diradical intermediates.\textsuperscript{33}

A question raised from studies of the aryl di-\pi-methane rearrangement is whether there is any need for the formation of the first type of cyclopropyldicarbinyl diradical in this reaction. As shown in Scheme 1.10, the formation of diradical 42 results in the loss of aromaticity in the aryl moiety. Alternatively, a 1,2-aryl shift mechanism, with the direct formation of the second type of 1,3-diradical, was proposed by Paquette and co-workers.\textsuperscript{34,35} This mechanism is depicted in Scheme 1.10. Although both of the above-mentioned mechanisms have explained some di-\pi-methane reactions, knowledge about the diradical intermediates is still insufficient, and there is still more to be learned about the nature of this photorearrangement.
1.4.2. Regioselectivity of the Di-\(\pi\)-methane Rearrangement

A part of this thesis will deal with the regioselectivity of the di-\(\pi\)-methane rearrangement, therefore, this topic will be discussed in this section. The di-\(\pi\)-methane rearrangement is very susceptible to control of its regioselectivity by substituents. As an important part of di-\(\pi\)-methane photochemistry, regioselectivity studies have played a significant role in understanding and establishing the reaction mechanisms.

The regioselectivity of the di-\(\pi\)-methane rearrangement of acyclic 1,4-dienes has been investigated systematically by Zimmerman and co-workers.\(^{23}\) As an example, the di-\(\pi\)-methane rearrangement of unsymmetrically substituted diene 43 is shown in Scheme 1.11.
As reported by Zimmerman,\textsuperscript{36} direct irradiation of 1,1-diphenyl-3,3,5-trimethyl-1,4-hexadiene (43) afforded compound 48 as the only photoprodut. As depicted in Scheme 1.11, Zimmerman suggested that there are two alternative ring-opening processes, "a" and "b", that convert the initially formed diradical 44 into diradical species 45 and 47, respectively. Process "a" utilizes the odd electron at the benzhydryl center, and the resulting formation of diradical 45 leads to the loss of benzhydryl delocalization. In contrast, process "b" uses the less stabilized odd electron and goes on to form diradical 47, which still possesses the delocalization energy.\textsuperscript{23,36}

In the example discussed above, there is only one pathway that leads to the initial cyclopropyl dicarbinyl diradical species, and it is the second step that is thought to determine the regioselectivity. However, in the di-\pi-methane rearrangement of some
cyclic systems, there is more than one pathway that can lead to formation of the first diradical. Paquette and co-workers, for example, have studied the reaction regioselectivity of benzonorbornadienes very intensively.\textsuperscript{37-45} Examples of aryl-substituted benzonorbornadiene photochemistry are shown in Schemes 1.12 and 1.13.

![Chemical structure diagram]

<table>
<thead>
<tr>
<th>X</th>
<th>52</th>
<th>55</th>
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<tbody>
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</tr>
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<td>NO\textsubscript{2}</td>
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</tr>
<tr>
<td>COMe</td>
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<td>0</td>
</tr>
<tr>
<td>COOEt</td>
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</tr>
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<td>F</td>
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</tr>
<tr>
<td>NH\textsubscript{2}</td>
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<td>70</td>
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</tbody>
</table>

**Scheme 1.12** The Di-\(\pi\)-methane Rearrangement of 7-Substituted Benzonorbornadienes
As shown in Scheme 1.12, the di-π-methane rearrangements of 7-substituted benzonorbornadienes are dual channel reactions. It was found that electron-withdrawing groups, like X= CN, NO₂, COMe and COOEt, direct the benzo-vinyl bridging to the para position of the aryl ring, and thus give product 52 exclusively. In contrast, electron-donating groups direct the di-π-methane rearrangement via the meta benzo-vinyl bonding process to give compound 55 as the major photoproduct. Paquette suggested that, in this case, the initial bridging step is the source of the regioselectivity. The observed regioselectivity was then explained by Paquette to be due to the difference in the triplet excited state electron densities at the para and meta positions, the assumption being that initial benzo-vinyl bridging occurs preferentially at the position with higher electron density. Molecular orbital calculations provided by Houk et al. indicate that, for substitution by electron-withdrawing groups, the electron density is higher at the para position than that at the meta position, while substitution with electron donating groups results in a higher electron density at the meta position.

The regioselectivities of the di-π-methane rearrangement of 6-substituted benzonorbornadienes have also been studied by Paquette and co-workers. The product ratios listed in Scheme 1.13 indicate a preference for ortho bridging with both electron-withdrawing and donating groups. It was suggested by Paquette that the relative rates of benzo-vinyl bridging are again the source of the observed regioselectivity, and that the electron distribution in the triplet excited state might control the rates of the initial bond formation step. Molecular orbital perturbation theory indicated that the calculated triplet electron density is higher at the ortho carbon than that at the meta carbon for both electron-withdrawing and donating groups.
Scheme 1.13  The Regioselectivities of the Di-π-methane Rearrangement of 6-Substituted Benzonorbornadienes

1.4.3. Photochemistry of Dibenzobarrelene and Derivatives

Studies of the regioselectivity of the di-π-methane rearrangement of 9-substituted
dibenzobarrelene derivatives have been reported by several groups, and some of the results are listed in Scheme 1.14.\textsuperscript{46,47}

![Scheme 1.14](image)

<table>
<thead>
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<th>X</th>
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<tbody>
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<td>Me</td>
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<td>29</td>
</tr>
<tr>
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</tr>
</tbody>
</table>

**Scheme 1.14**  Regioselectivity Studies of the Di-$\pi$-methane Rearrangement of 9-Substituted Dibenzobarrenes

Both Wright et al.\textsuperscript{46} and Iwamura et al.\textsuperscript{47} suggested that the stabilities of the initially formed diradicals 64 and 67 determine the regioselectivity. Iwamura\textsuperscript{47} put forward the idea that the substituents affect the stability of the initially formed
intermediates in the same way as the effect of substituents on the equilibrium between cycloheptatriene and the corresponding norcaradiene (Scheme 1.15). As shown in Scheme 1.15, Hoffmann et al. proposed that a substituent on the cyclopropane ring of norcaradiene influences the strength of the opposite bonds, and \( \pi \) electron acceptors, such as \( \text{COOMe}, \text{CN} \) and \( \text{CHO} \), strengthen the \( \text{C}_1-\text{C}_6 \) bond so as to shift the equilibrium to the norcaradiene side; in contrast, \( \pi \) electron donors, such as \( \text{OMe} \) and \( \text{OAc} \), weaken the \( \text{C}_1-\text{C}_6 \) bond and shift the equilibrium to the cycloheptatriene side.

\[ \text{Cycloheptatriene} \quad \text{Norcaradiene} \]

Scheme 1.15 The Valence Isomerization of Cycloheptatriene and Norcaradiene

The product ratios from the di-\( \pi \)-methane rearrangement of some vinyl-substituted dibenzobarrelenes are listed in Scheme 1.16 (page 25). It was suggested that the stability of the first-formed diradical species 71 and 74 is directly related to the regioselectivity, and that both the polar nature and the radical-stabilizing ability of the substituents are important in determining regioselectivity.

Dibenzobarrelene and its derivatives have been found to undergo three types of photochemical reactions: the di-\( \pi \)-methane rearrangement, the tri-\( \pi \)-methane rearrangement and an intramolecular [2 + 2] photocycloaddition reaction.
It was first reported by Ciganek in 1966 that the direct or sensitized irradiation of 11,12-disubstituted dibenzobarrelenes causes di-π-methane rearrangement to give the dibenzosemibullvalene type photoproducts. Subsequent studies revealed that the di-π-methane rearrangement of dibenzobarrelenes is a triplet-specific reaction. In contrast, the direct irradiation (via the singlet excited state) of some dibenzobarrelene derivatives has been reported to give dibenzocyclooctatetraene (COT) type photoproducts. Based on the well-established benzo- and naphthobarrelene reaction mechanisms, it has

<table>
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<th>X</th>
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<th>73</th>
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<td>100</td>
</tr>
</tbody>
</table>
been proposed that this reaction involves an initial intramolecular \([2 + 2]\) photocycloaddition through the singlet excited state followed by thermal reorganization of the resulting cage compound (Scheme 1.17).\(^{53-56}\)

\[\text{Scheme 1.17 The } [2 + 2] \text{ Photocycloaddition of Dibenzobarrelenes} \]

The term "tri-\(\pi\)-methane rearrangement" was recently introduced by Zimmerman et al., and was used to describe the interactions among three \(\pi\) moieties within one molecule during a photorearrangement.\(^{57}\) An observation of the tri-\(\pi\)-methane rearrangement was reported by Scheffer et al.; the postulated reaction mechanism is depicted in Scheme 1.18.\(^{58}\) The tri-\(\pi\)-methane rearrangement was considered to be a singlet photochemical reaction. Steric crowding was suggested as the reason why these dibenzobarrelenes undergo the tri-\(\pi\)-methane rearrangement rather than the \([2 + 2]\) photocycloaddition reaction. Because there are four substituents on the barrelene unit, the \([2 + 2]\) photocycloaddition of compound 80 will lead to a more sterically congested intermediate than the tri-\(\pi\)-methane rearrangement intermediate 84.\(^{58}\)
Scheme 1.18 The Tri-$\pi$-methane Rearrangement

1.5. Norrish type II Reaction

Ketones are known to undergo photoinduced Norrish type reactions.\textsuperscript{60} The Norrish type II reaction is an intramolecular $\gamma$ hydrogen abstraction reaction by an excited carbonyl group, which has been shown to give a 1,4-diradical intermediate followed by cyclization (Yang reaction) and/or cleavage reactions.\textsuperscript{60} The suggested reaction mechanism is shown in Scheme 1.19.
The Norrish type II reaction is potentially very useful as a method of building highly strained ring systems, but most of the research work has centered on the mechanistic aspects. The nature of the 1,4-diradical intermediate has been extensively investigated.\textsuperscript{61} One of the recent goals of research on this reaction has been the determination of the geometrical requirements for initial hydrogen abstraction. Four geometric parameters have been proposed by Scheffer, Trotter and co-workers as being most important in determining hydrogen abstractability, and these are shown in Scheme 1.20.\textsuperscript{63,64} The first is the distance $d$ between the carbonyl oxygen and the $\gamma$ hydrogen. The second, the angle between the carbonyl carbon, the carbonyl oxygen and the $\gamma$ hydrogen, is defined as $\Delta$. Third, the angle between the O-H vector (carbonyl oxygen and $\gamma$ hydrogen) and the carbonyl mean plane is defined as $\omega$. Fourth, the angle between the
carbonyl oxygen, the γ hydrogen and the γ carbon is shown as θ. The theoretically ideal values of these parameters for hydrogen abstraction have been suggested\textsuperscript{63,64} to be $d \leq 3.0 \text{ Å}$, $\Delta = 90^\circ$, $\omega = 0^\circ$, $\theta = 180^\circ$.

Scheme 1.20  Representation of Hydrogen Abstraction Geometry

Many Norrish type II reactions have been studied in the solid state.\textsuperscript{8} It was found that the chairlike abstraction geometry proposed by Wagner\textsuperscript{62} is not essential in the crystalline state, and the photolyses of α-cycloalkylacetophenones in the solid state revealed three types of γ-hydrogen abstraction geometries - chairlike, boatlike and half-chairlike.\textsuperscript{64} Recent studies on the solid state Norrish type II reaction of macrocyclic diketones revealed that these reactions are very stereoselective in the solid state, and the reactivity has been interpreted as being dependant on the molecular conformations.\textsuperscript{65-67} An example of conformation control of stereoselectivity is given in Scheme 1.21.
It was reported that diketone 92 crystallizes in two different crystal forms (dimorphs) of different conformations, and striking differences in reactivity between the dimorphs were found in the solid state Norrish type II reactions. As shown in Scheme 1.21, the photolysis of diketone 92 in solution led mainly to the formation of Norrish type II cleavage product 95 (50% yield). In the solid state irradiations, the platelike crystals of diketone 92 gave rise to stereoselective formation of cis-cyclobutanol 93 (>95% yield), and the needlelike crystals of diketone 92 afforded trans-cyclobutanol 94 with greater than 90% stereoselectivity. Very little cleavage product 95 was detected in the solid state reactions. This was explained as being the result of conformational differences between the dimorphs.66
1.6. Asymmetric Synthesis

There are many methods of obtaining optically active compounds, such as isolation of natural products (i.e. the chiral pool), resolution of racemates and asymmetric synthesis. Asymmetric synthesis is defined as a process which converts a prochiral unit in a substrate molecule into a chiral unit in such a manner that the stereoisomeric products are produced in unequal amounts. During the last two decades, there has been growing interest in asymmetric synthesis, including asymmetric synthesis via photochemical reactions.

Asymmetric synthesis can be achieved by conducting a reaction in a chiral environment, and such a chiral influence on a prochiral or racemic reactant will lead to diastereomeric transition states of different energy. As a result, enantiomerically (or diastereomerically) enriched products will be generated. There are many ways of introducing a chiral environment into a photochemical reaction, and these include the use of resolved chiral reactants, chiral solvents, chiral sensitizers, chiral auxiliaries and circularly polarized light. Asymmetric syntheses via photochemical reactions in solution usually give photoproducts with low optical purities.

The methodology of using crystal chirality to generate molecular chirality was recognized by Schmidt, and the first example of a topochemical asymmetric synthesis using chiral crystals was reported by Penzien and Schmidt in 1969. It was demonstrated that the gas-solid reaction between crystals of 4,4'-dimethylchalcone (space group P2₁₂₁₂₁) and gaseous bromine gives the corresponding dibromide product in up to 25% optical yield. Schmidt termed this process, which proceeds from a prochiral starting material to a chiral product without using any chiral reagent, an "absolute asymmetric
synthesis\textsuperscript{	extregistered}. The first absolute asymmetric synthesis \textit{via} a solid state photochemical reaction was also reported by Schmidt and co-workers in 1973\textsuperscript{71}. Following Schmidt's work, there have been a few reports on absolute asymmetric syntheses \textit{via} solid state photochemical reactions, and two of them with high optical yield are shown in Scheme 1.22.

\begin{center}
\begin{tikzpicture}[scale=0.8]
  \node[draw,shape=circle,fill=black] (a) at (0,0) {96};
  \node[draw,shape=circle,fill=black] (b) at (2,2) {97};
  \node[draw,shape=circle,fill=black] (c) at (-2,0) {98};
  \node[draw,shape=circle,fill=black] (d) at (0,4) {99};
  \draw [->] (a) -- (1,1) node[above] {hv} -- (b);
  \draw [->] (c) -- (-1,1) node[above] {hv} -- (d);
  \draw (a) -- (1,0) node[below] {crystal \ P2\textsubscript{1}2\textsubscript{1}2\textsubscript{1}};
  \draw (c) -- (-1,0) node[below] {crystal \ E=COO\textsubscript{iPr}};
  \draw (96) -- (97) node[right] {>95\% ee};
  \draw (98) -- (99) node[right] {93\% ee};
\end{tikzpicture}
\end{center}

\textbf{Scheme 1.22}  Examples of Absolute Asymmetric Syntheses

It was found by Scheffer and co-workers that the achiral dibenzobarrelene diester 96 crystallizes in the chiral P2\textsubscript{1}2\textsubscript{1}2\textsubscript{1} space group, and the solid state di-\pi-methane rearrangement of these crystals gives product 97 in >95\% optical yield\textsuperscript{72}. Also shown in
Scheme 1.22 is the reported photolysis of chiral crystals derived from pro-chiral N,N-diisopropyl phenylglyoxylamide (98) to afford the Norrish type II reaction product β-lactam 99 with 93% optical yield and 74% chemical yield.73

However, the impetus for prochiral molecules to crystalize in chiral space groups is rare, which is only given by nature, and is presently beyond the reach of crystal engineering. Therefore the synthetic application of absolute asymmetric synthesis is greatly limited. Instead, solid state asymmetric syntheses that use a resolved chiral molecule to grow crystals of the starting material have attracted much recent attention. This crystal engineering is based on the fact that resolved chiral molecules are required to crystallize in chiral space groups. Chiral molecules used for solid state asymmetric synthesis can be made from prochiral substrate molecules (which will undergo a photochemical reaction upon irradiation) and chiral auxiliaries (or the so called chiral handles). These chiral handles can be removed afterwards. Toda and co-workers reported so-called wheel-and-axle type chiral auxiliaries for solid state asymmetric synthesis, which can form inclusion complexes with substrate molecules through hydrogen bonding.74,75 One example is given in Scheme 1.23.75
Scheme 1.23  Solid State Asymmetric Synthesis via [2 + 2] photocycloaddition Reaction

As shown in Scheme 1.23, it was reported that the chiral host molecule 1,4-bis[3-(o-chlorophenyl)-3-hydroxy-3-phenylprop-1-ynyl]benzene (103) and cyclohexenone 100 form a 1:2 inclusion complex, and that irradiation of this inclusion complex leads, via [2 + 2] cycloaddition, to the formation of dimer 101 with 46.5% e.e.\(^75\)

Although optically active carboxylic acids and amines have long been used in the resolution of racemic mixtures by forming diastereomeric salts,\(^76\) the idea of using carboxylic acid-amine salts in asymmetric synthesis was reported only recently by Scheffer and coworkers.\(^77,78\) This so called "ionic chiral handle approach", involves the formation of ionically bonded chiral salts between pro-chiral substrate molecules and optically pure amines. The resulting salts are crystalline and have high melting point, which are required for solid state photolysis. Furthermore, the ionic chiral handles are very easy to attach and remove from the substrate molecules through simple acid-base
chemistry. As shown in Scheme 1.24, the di-π-methane rearrangement of chiral salts 104 led to the formation of products 105 and 106, which were subsequently converted to 105a and 106a, respectively. Enantiomerically enriched photoproduct 105a was isolated with optical yields ranging from 14% to 80%.

<table>
<thead>
<tr>
<th>Y</th>
<th>ee %</th>
<th>ee %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proline</td>
<td>80%</td>
<td>0%</td>
</tr>
<tr>
<td>Strychnine</td>
<td>14%</td>
<td>0%</td>
</tr>
<tr>
<td>Proline Methyl Ester</td>
<td>58%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Scheme 1.24  Solid State Asymmetric Synthesis Utilizing the Ionic Chiral Handle Approach
1.7. Research Objectives

As discussed earlier, solid state photochemistry is still in its infancy, and more research work is needed for a better understanding of crystal lattice effects on chemical reactivity. The overall objective of the present research is concentrated on developing structure-reactivity correlations. This will be achieved by conducting photochemical reactions in both the solution and solid states; X-ray diffraction analysis of the starting materials and the photoproducts will be used as an essential method to interpret the solid state reactivity.

The solid state photochemical studies on the macrocyclic diketones have provided valuable information on structure-reactivity correlations.\textsuperscript{65,66} As a continuation of this work, the first research project was designed to introduce aromatic rings into the above-mentioned macrocyclic diketones, so as to make more rigid molecules for study of their solution and solid state Norrish type II reactivity. The diketones that have been studied (107, \( n = 3-10 \)) and the compounds proposed for the first research project (108a-c) are given in Scheme 1.25.
A second project is the study of substituent effects on the regioselectivity of the di-π-methane rearrangement of dibenzobarrelene derivatives. The di-π-methane rearrangement of vinyl- and bridgehead- substituted dibenzobarrelenes has been studied in both solution and the solid state, but no work has been reported on the photochemistry of aryl- substituted dibenzobarrelenes. This project was therefore designed to study the di-π-methane rearrangement of diaryl-substituted dibenzobarrelene derivatives (109-112) as shown in Scheme 1.26.

As depicted in Scheme 1.26, the 1,5-disubstituted dibenzobarrelene derivatives 109-112 can in principle undergo the di-π-methane rearrangement and lead to two photoproducts. The stereoelectronic effects of the substituents and lattice control of regioselectivity could be studied by conducting solution and solid state photolyses.
Scheme 1.26 The Di-π-methane Rearrangement of 1,5-Disubstituted Dibenzobarrelene Derivatives

The third project of study is concerned with solid state asymmetric synthesis via the Norrish type II reaction. This project is aimed to extend and explore the recently-reported method of making optically active salts for photoreactions.\textsuperscript{77,78} As shown in Scheme 1.27, prochiral α-adamantyl phenyl ketone with a p-carboxyl group (119, 120) was designed to form different salts with optically active amines, and the resulting salts would be certain to form crystals in chiral space groups. The chiral crystals will be used in a solid state asymmetric synthesis via the Norrish type II reaction. After the reaction, the optically active amines will be removed, and the enantiomERICALLY-enriched photoproducts (122) are anticipated (Scheme 1.27). The asymmetric induction ability of each ionic chiral handle will be correlated with the crystal structure of the salt, and this will provide us with an insight into the structure-reactivity relationships involved. We
also plan to study the absolute configuration correlation between chiral crystals of the starting materials and crystals of the optically active photoproducts, so as to study molecular or group movements during solid state photoreactions.

\( \alpha \)-Adamantyl acetophenones (119, 120) are prochiral molecules that give chiral Norrish type II Yang cyclization products, whereas the cleavage products would be achiral. The photochemistry of \( \alpha \)-adamantyl acetophenones has been studied both in solution and the solid state, and no cleavage products were found.\(^{72}\) Because of the exclusive photocyclization reaction, \( \alpha \)-adamantyl acetophenones 119 and 120 were chosen for asymmetric induction studies.

\[
\begin{align*}
\text{hv} &\rightarrow \text{work-up} \\
\text{solid} &\rightarrow \text{122}
\end{align*}
\]

\[
\begin{align*}
\text{119} & \quad R = H \\
\text{120} & \quad R = \text{CH}_3
\end{align*}
\]

Scheme 1.27  The Solid State Asymmetric Synthesis via the Norrish Type II Reactions of Crystalline Chiral Salts
RESULTS AND DISCUSSION

Chapter 2 Studies on the Di-π-methane Rearrangement

2.1. The Preparation of Dibenzobarrelene Derivatives

These starting materials possess a skeleton that is formally named "9,10-dihydro-9,10-ethenoanthracene", and the numbering is shown in Scheme 2.01. The origin of this nomenclature stems from the anthracene ring system; however, this skeleton is known more commonly as "dibenzobarrelene". Throughout the thesis, the two names will be used interchangeably.

Scheme 2.01 The Dibenzobarrelene Skeleton

The synthesis of dibenzobarrelene derivatives was first reported by Diels and Alder in 1931.\textsuperscript{79} This short and productive method is still widely used to synthesize substituted dibenzobarrelenes (Scheme 2.02).
The synthesis of dibenzobarrelene itself was reported later utilizing the Diels-Alder reaction of 1,2-dichloroethylene with anthracene followed by dehalogenation as shown in Scheme 2.03.

Scheme 2.02  The First Synthesis of a Dibenzobarrelene Derivative

Scheme 2.03  The Synthesis of Dibenzobarrelene
All of the dibenzobarrelene derivatives studied in this thesis were prepared by the Diels-Alder reaction of the corresponding substituted anthracenes with dimethyl acetylenedicarboxylate. The syntheses are shown in Schemes 2.04-2.06.

Scheme 2.04  The Synthesis of 1,5-Disubstituted Dibenzobarrelenes 109-112

\[
\begin{align*}
\text{X} = \text{Cl} & \quad 124 \\
\text{CN} & \quad 125 \\
\text{COOMe} & \quad 126 \\
\text{OMe} & \quad 127
\end{align*}
\]

Scheme 2.05  The Synthesis of Dibenzobarrelene Derivatives 130 and 131

\[
\begin{align*}
\text{X} = \text{Y} = \text{Cl} & \quad 128 \\
\text{X} = \text{Cl}, \text{ Y} = \text{H} & \quad 129
\end{align*}
\]
Scheme 2.06  The Synthesis of 1,5-Disubstituted Anthracenes 124-127
The commercially available 1,5-dichloro-9,10-anthraquinone (132) was reduced to 1,5-dichloroanthracene (124). This was accomplished by using zinc powder with continuous addition of acetic acid to produce hydrogen to reduce the carbonyl groups. The same method was used for the reduction of 1,8-dichloro-9,10-anthraquinone, 1-chloro-9,10-anthraquinone and 1,5-dicarboxy-9,10-anthraquinone (zinc powder in aqueous ammonia). The 1,5-dimethoxy-9,10-anthraquinone (136) was reduced with sodium borohydride in iso-propanol. This type of reduction was suggested to involve two reduction-dehydration sequences via the successive formation of 9,10-dihydroxy-9,10-dihydroanthracene (137), anthrone (138) and 9-hydroxy-9,10-dihydroanthracene (139) (Scheme 2.07).

The Diels-Alder reactions were carried out in refluxing xylenes (mixed, Aldrich, bp 137-144 °C), and these reactions gave moderate to very high yields (from 24% to
92%) of the products. An excess of dimethyl acetylenedicarboxylate was used in these reactions, because it has been reported that this compound can undergo a dimerization reaction by itself.\textsuperscript{83} This dimer was in fact found in the above-mentioned Diels-Alder reactions.

The dibenzobarrelenes 109, 110, 111 and 112 are all $C_2$-symmetric molecules, and their $^1H$ NMR spectra showed characteristic singlet bridgehead hydrogen (H9, H10) signals at chemical shifts ranging from 5.9 to 7 ppm. These bridgehead hydrogens are flanked by electronegative substituents, and as a result, the proton signals are shifted downfield compared with the bridgehead hydrogens of compound 123 (Table 2.01).

\textbf{Table 2.01} The $^1H$ NMR (400 MHz, CDCl$_3$) Chemical Shifts of Bridgehead Hydrogens of 1,5-Disubstituted Dibenzobarrelenes

<table>
<thead>
<tr>
<th>Compound</th>
<th>X</th>
<th>Chemical Shift, H9 &amp; H10 (δ ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>H</td>
<td>5.50*</td>
</tr>
<tr>
<td>109</td>
<td>Cl</td>
<td>5.96</td>
</tr>
<tr>
<td>110</td>
<td>CN</td>
<td>5.98</td>
</tr>
<tr>
<td>111</td>
<td>COOME</td>
<td>6.93</td>
</tr>
<tr>
<td>112</td>
<td>OMe</td>
<td>5.92</td>
</tr>
</tbody>
</table>

* Ref. 84.
As shown in Table 2.01, there is a very large downfield shift of the bridgehead hydrogens in dibenzobarrelene 111 compared with those in the unsubstituted analog 123, and this large downfield shift ($\Delta \delta = 1.43$ ppm) is believed to be caused by the anisotropic deshielding effect of the carbomethoxy group. The downfield shift of bridgehead hydrogen signals caused by the other substituents (Cl, CN and OMe) are around 0.4 ppm ($\Delta \delta = 0.4$ ppm). The dibenzobarrelene derivatives 130 and 131 showed two bridgehead hydrogen signals (two singlets), and their chemical shifts are listed in Table 2.02. In each case, the proton at the 9-position is more deshielded than that at the 10-position and leads to a higher chemical shift. As expected, the chemical shifts of the 10-position hydrogen in the above two compounds remain the same as that of the unsubstituted analog 123 (Table 2.02). It was also found that the proton signal of H9 in 1,8-dichloro-substituted compound 130 shifted twice as much as the H9 in monosubstituted analog 131 ($\Delta \delta = 0.97$ ppm vs $\Delta \delta = 0.46$ ppm). This substituent effect on the chemical shift of bridgehead hydrogens seems to be additive.

Table 2.02  The $^1$H NMR (400 MHz, CDCl$_3$) Chemical Shifts of Bridgehead Hydrogens of Dibenzobarrelenes 130 and 131

<table>
<thead>
<tr>
<th>Compound</th>
<th>X</th>
<th>Y</th>
<th>H9 (\delta ppm)</th>
<th>H10 (\delta ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>H</td>
<td>H</td>
<td>5.50*</td>
<td>5.50*</td>
</tr>
<tr>
<td>130</td>
<td>Cl</td>
<td>Cl</td>
<td>6.47</td>
<td>5.50</td>
</tr>
<tr>
<td>131</td>
<td>Cl</td>
<td>H</td>
<td>5.96</td>
<td>5.50</td>
</tr>
</tbody>
</table>

* Ref. 84.
All of these compounds were characterized by spectroscopic and elemental analyses, and adducts 109, 110, 112 and 130 were further analysed by X-ray crystallography. The results were in agreement with the proposed structures.

For solid state photochemical reactions, high quality crystals are desirable. The dibenzobarrelene derivatives were found to form crystals from several solvents. In most cases, acetone was a good solvent from which to grow large single crystals. These compounds are found having high melting points (≥ 160°, Table 2.03), which are suitable for solid state reactions. The higher the melting point, the less probable that a solid sample will melt during a photochemical reaction.

### Table 2.03  Crystal Preparation from Dibenzobarrelene Derivatives

<table>
<thead>
<tr>
<th>Compound Number</th>
<th>Substituent &amp; Position</th>
<th>Crystallization Solvent</th>
<th>Melting Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>1,5-di Cl</td>
<td>acetone</td>
<td>206-207.5</td>
</tr>
<tr>
<td>110</td>
<td>1,5-di CN</td>
<td>acetone</td>
<td>272-273</td>
</tr>
<tr>
<td></td>
<td></td>
<td>xylene</td>
<td>272-273</td>
</tr>
<tr>
<td>111</td>
<td>1,5-di COOMe</td>
<td>acetone</td>
<td>220-221</td>
</tr>
<tr>
<td>112</td>
<td>1,5-di OMe</td>
<td>acetone</td>
<td>239-240</td>
</tr>
<tr>
<td>130</td>
<td>1,8-di Cl</td>
<td>acetone</td>
<td>227-228</td>
</tr>
<tr>
<td>131</td>
<td>1-Cl</td>
<td>acetone</td>
<td>160-161</td>
</tr>
</tbody>
</table>

2.2. **The Photochemical Reactions of Dibenzobarrelene Derivatives**

The photochemical behavior of dibenzobarrelene and some of its analogs was first studied by Ciganek in 1966. He reported that the direct or sensitized irradiation of
a series of 11,12-disubstituted dibenzobarrelenes in solution gave the corresponding
dibenzosemibullvalene derivatives as the di-\(\pi\)-methane rearrangement products. An
example is given in Scheme 2.08. Subsequent studies showed that the di-\(\pi\)-methane
rearrangement is a triplet-specific reaction, and that triplet-sensitized irradiation of
dibenzobarrelenes always brings about the di-\(\pi\)-methane rearrangement to give the
dibenzosemibullvalene type photoproducts.\(^{23,46,47,58}\)

![Scheme 2.08 The Di-\(\pi\)-methane Rearrangement of Dibenzobarrelene 123](image)

The solid state photochemical reactions of dibenzobarrelene derivatives have been
studied by Scheffer, Trotter and co-workers for the past several years.\(^{85-87}\) As discussed
in the introduction section, most of these compounds undergo the di-\(\pi\)-methane
rearrangement to give dibenzosemibullvalene type photoproducts. It has been
demonstrated that the crystal lattice has significant effects on the reactivity and
selectivity of the di-\(\pi\)-methane rearrangement of dibenzobarrelene derivatives.\(^{72}\) Novel
photoproducts have also been reported from the solid state photoreactions of
dibenzobarrelene derivatives.\(^{58}\)

To study the effect of substituents and lattice control on the regioselectivity of the
photochemical transformation of aryl-substituted dibenzobarrelenes, substrates 109-112,
130 and 131 were photolyzed in solution and in the solid state. The product ratios will be discussed in the following sections, and the crystal structures of some substrates and photoproducts will be analyzed and correlated with the reactivity.

Direct and acetone-sensitized irradiation of dibenzobarrelenes 109, 110, 111 and 112 was first carried out in solution. Two photoproducts were detected by GC and/or \(^1\)H NMR analysis in each case. The photoproducts from the preparative photolysis of substrates 109, 111 and 112 were isolated by using column chromatography. The photoproducts from substrate 110 could not be separated by column chromatography, and their identification will be discussed later. The four reactants were found to undergo the di-\(\pi\)-methane rearrangement to give dibenzosemibullvalene type photoproducts as shown in Scheme 2.09; no COT type photoproducts, via the [2 + 2] photocycloaddition or the tri-\(\pi\)-methane rearrangement, were observed.

\[ \begin{align*}
\text{Type A} & \quad \text{Type B} \\
\text{X= Cl} & \quad 109 \quad 109A \quad 109B \\
\text{CN} & \quad 110 \quad 110A \quad 110B \\
\text{COOMe} & \quad 111 \quad 111A \quad 111B \\
\text{OMe} & \quad 112 \quad 112A \quad 112B \\
\end{align*} \]

Scheme 2.09 The Di-\(\pi\)-methane Rearrangement of 1,5-Di-substituted Dibenzobarrelene Derivatives 109-112
For regioselectivity studies of the di-π-methane rearrangement, it is desirable to isolate and characterize each of the photoproducts. However, there are examples in the literature where the di-π-methane rearrangement products could not be separated because of their very close structural similarity.\cite{85,87,88} Efforts were made to isolate these photoproducts. Since the TLC analysis showed that both the starting material and the corresponding photoproducts (Scheme 2.09) have very close \( R_f \) values, the preparative scale photolyses were conducted until no starting material remained. As a result, the final isolation was concerned with only two compounds, which proved to be partially separable. Very low polarity eluent was used in the careful and slow column chromatography. Three pairs of photoproducts (109A & 109B, 111A & 111B and 112A & 112B) were successfully isolated by column chromatography; photoproducts 110A and 110B could not be so separated.

2.3. The Characterization of Photoproducts

The structures of these photoproducts were assigned by spectroscopic methods, particularly \(^1\)H NMR spectroscopy and NOE experiments. The structure of photoproduct 109B was further confirmed by X-ray diffraction analysis. These dibenzosemibullvalene type di-π-methane rearrangement photoproducts have characteristic proton signals, and the assignment of each regioisomer was primarily based on the NOE experiments. For simplicity of description, the two dibenzosemibullvalene type photoproducts are defined as type A and type B (Scheme 2.09). The difference between the two regioisomers is the position of the methine hydrogen on the cyclopropane ring. In type A dibenzosemibullvalenenes, this methine proton is at the 8d-position, whereas the methine proton in type B products is at the 8b-position. The numbering system of dibenzosemibullvalene is given in Scheme 2.10.
Spectroscopic studies of dibenzosemibullvalene type photoproducts have been reported by Ciganek, Wright et al., Iwamura et al. and Scheffer et al. Among various spectroscopic methods, $^1$H NMR was found to be particularly useful in assigning structures. In the case of 11,12-disubstituted dibenzobarrelene derivatives, the di-$\pi$-methane rearrangement results in dibenzosemibullvalene type photoproducts that have two kinds of methine protons. One is at the 4b-position, and the other is at the 8b-position. These two benzylic methine protons have been reported to have characteristic chemical shift values: the 4b-proton appears at $\delta = 5.0-5.1$ ppm as a singlet, and the methine proton on the cyclopropane ring at the 8b-position (or 8d-position, refer to Schemes 2.11, 2.09 and 2.10) gives rise to a singlet at $\delta = 4.2-4.5$ ppm. Because the 4b-proton is deshielded by both aromatic rings, it has a larger chemical shift $\delta$ value than that at the 8b-position.
The structures of the photoproducts were initially deduced from their $^1$H NMR spectra. Type A photoproducts were assigned such that the methine proton on the cyclopropane ring (H8d) has a higher chemical shift $\delta$ value than that of the corresponding methine proton (H8b) in type B photoproducts. The assigned structures of both types of photoproducts and the chemical shifts of their methine protons are listed in Tables 2.04 and 2.05.

The chemical shifts of the methine protons in the assigned type A dibenzosemibullvalene photoproducts are listed in Table 2.04. Compared with the two methine protons in unsubstituted analog 140, the methine protons in type A molecules (H8d and H4b) are both very close to electronegative groups on the aromatic rings. As a result of deshielding, these proton signals are shifted downfield. The 8d-protons are shifted downfield from 0.12 ppm to 0.78 ppm (i.e., $\Delta\delta = 0.12-0.78$ ppm). The 4b-protons have also shifted downfield, with $\Delta\delta$ values ranging from 0.15 ppm to 0.94 ppm.
Table 2.04  The $^1$H NMR (400 MHz, CDCl$_3$) Chemical Shifts of Methine Protons in Type A Photoproducts

<table>
<thead>
<tr>
<th>Compound Number</th>
<th>X</th>
<th>Chemical Shift H8d (δ ppm)</th>
<th>Chemical Shift H4b (δ ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>H</td>
<td>4.49*</td>
<td>5.03*</td>
</tr>
<tr>
<td>109A</td>
<td>Cl</td>
<td>4.66</td>
<td>5.28</td>
</tr>
<tr>
<td>110A</td>
<td>CN</td>
<td>4.81</td>
<td>5.40</td>
</tr>
<tr>
<td>111A</td>
<td>COOMe</td>
<td>5.27</td>
<td>5.97</td>
</tr>
<tr>
<td>112A</td>
<td>OMe</td>
<td>4.61</td>
<td>5.18</td>
</tr>
</tbody>
</table>

* Ref. 50.

The chemical shifts of the methine protons in the assigned type B dibenzosemibullvalene photoproducts are listed in Table 2.05. Compared with the two methine protons in unsubstituted analog 140, the 4b-hydrogens, which have a similar chemical environment as that in the type A products, are shifted downfield ($\Delta$δ figures ranging from 0.20 ppm to 0.96 ppm). In contrast, the 8b-protons are far away from the two electronegative aromatic substituents and have relatively small downfield shifts compared with the chemical shift of H8b in compound 140 (for products 109B, 110B and 111B, $\Delta$δ = 0.02, 0.21 and 0.26 ppm respectively). The H8b signal in product 112B even had an upfield shift ($\Delta$δ = 0.09 ppm, relative to compound 140).
Table 2.05   The $^1$H NMR (400 MHz, CDCl$_3$) Chemical Shifts of Methine Protons in Type B photoproducts

<table>
<thead>
<tr>
<th>Compound Number</th>
<th>X</th>
<th>Chemical Shift H8b (δ ppm)</th>
<th>Chemical Shift H4b (δ ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>H</td>
<td>4.49*</td>
<td>5.03*</td>
</tr>
<tr>
<td>109B</td>
<td>Cl</td>
<td>4.51</td>
<td>5.32</td>
</tr>
<tr>
<td>110B</td>
<td>CN</td>
<td>4.70</td>
<td>5.45</td>
</tr>
<tr>
<td>111B</td>
<td>COOMe</td>
<td>4.75</td>
<td>5.99</td>
</tr>
<tr>
<td>112B</td>
<td>OMe</td>
<td>4.40</td>
<td>5.23</td>
</tr>
</tbody>
</table>

* Ref. 50.

Recall that type A photoproducts were assigned with larger chemical shift δ values of the methine proton on the cyclopropane ring (H8d) than those of the corresponding methine protons (H8b) in type B photoproducts. Based on these assignments and the chemical shift figures listed in Tables 2.04 and 2.05, a general trend was found where the chemical shifts of 4b-Hs in type B photoproducts are larger than those of the corresponding 4b-Hs in type A photoproducts. Even though the chemical shift differences are small, ranging from 0.03 ppm to 0.05 ppm, they are distinguishable in the high resolution $^1$H NMR spectrum (Scheme 2.12). A general methine proton signal pattern of both types of photoproducts can be further illustrated with a $^1$H NMR
spectrum of a mixture of type A and type B photoproducts. As shown in Scheme 2.12, in the region from 4 to 7 ppm where there are four methine proton signals (4 singlets), the two inner singlets belong to type A product 112A, and the outer two singlets come from the type B product 112B.

Scheme 2.12 The Partial $^1$H NMR Spectrum (400 MHz, CDCl$_3$) of a Mixture of Photoproducts 112A and 112B
NOE experiments were conducted to corroborate the structural assignments for type A and type B photoproducts. Once again, it is the methine proton on the cyclopropane ring in these two types of molecules that gives a different response in the NOE experiments. In type A products, H8d is not close enough to any aromatic protons to give a signal enhancement. In contrast, H8b in type B molecules is very close to H8 on the adjacent aromatic ring. As a result, irradiation of the 8b-proton gives an aromatic hydrogen signal enhancement (Scheme 2.13).

\[ E = \text{CO}_2\text{Me} \]

**Scheme 2.13** Description of NOE Experiments on Type A and B Photoproducts*

* NOE experiments were conducted only on some of the above shown methine protons.

In addition, irradiation on 4b-Hs in both type A and B molecules resulted in aromatic proton signal enhancement. This is because the 4b-Hs are close to H4 in both types of photoproducts. Examples of the NOE experiments on photoproducts 111A and 111B are depicted in Schemes 2.14 and 2.15.
Scheme 2.14 NOE Experiments on Photoprodct 111A (a) Irradiation of Proton H4b (b) Irradiation of Proton H8d (c) Off-resonance Spectrum
Scheme 2.15  NOE Experiments on Photoproduct 111B (a) Irradiation of Proton H4b (b) Irradiation of Proton H8b (c) Off-resonance Spectrum
An X-ray diffraction analysis of photoproduct 109B was conducted to verify the structure assignment deduced from $^1$H NMR and NOE experiments. It turned out that the X-ray crystal structure of product 109B matches the structure assigned by NOE experiments. An ORTEP drawing of photoproduct 109B is given in Scheme 2.16. The only reason for selecting photoproduct 109B for X-ray diffraction analysis is that this product forms very high quality single crystals as required by X-ray crystallography.

Scheme 2.16 The ORTEP Drawing of Photoproduct 109B
It should be mentioned that since photoproducts 110A and 110B could not be separated from each other, the $^1$H NMR spectrum of the mixture was obtained, and the signals were assigned based on the above discussed $^1$H NMR and NOE experiments. The product ratio was also obtained from $^1$H NMR integrations of a reaction mixture.

2.4. The Regioselectivities in Solution

Turning to the regioselectivity studies in solution, compound 109 was selected to be irradiated in different solvents to test solvent effects on the photoproduct ratios. The product ratio was determined by quantitative GC analysis (column DB-17). Despite their very close R$_f$ values on TLC, the starting material (109) and the photoproducts (109A and 109B) are well separated by GC. The GC retention times for compounds 109, 109A and 109B are 14.5, 16.2 and 18.3 min respectively, with good baseline separation. The GC detector response was calibrated with pure samples of compounds 109, 109A and 109B. As shown in Table 2.06, the photolysis of compound 109 in the nonpolar solvent hexane gives the highest product ratio of 109A to 109B, which is 79:21, and the product ratio decreases in polar solvents. It was also found that the product ratio in the solid state photolysis is higher than those in polar solvents, and is close to the ratio in the non-polar solvent hexane. In polar solvents, the product ratios were observed to be very similar.

In regioselectivity studies of the di-π-methane rearrangement, there are mainly two types of controlling effects, namely electronic effects and steric effects. The electronic effect was often interpreted in terms of electronegativity, electron-withdrawing or donating ability and radical stabilizing ability of substituents.$^{23,47}$ Steric effects have been reported in the photolysis of dibenzobarrelene derivatives, in both solution and the
Table 2.06 The Photolysis of Dibenzobarrelene Derivative 109 in Different Media

<table>
<thead>
<tr>
<th>Medium</th>
<th>109A (%)</th>
<th>109B (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexane</td>
<td>79</td>
<td>21</td>
</tr>
<tr>
<td>Acetone</td>
<td>69</td>
<td>31</td>
</tr>
<tr>
<td>Benzene</td>
<td>68</td>
<td>32</td>
</tr>
<tr>
<td>Methanol</td>
<td>66</td>
<td>34</td>
</tr>
<tr>
<td>Acetonitrile</td>
<td>62</td>
<td>38</td>
</tr>
<tr>
<td>Solid State</td>
<td>78</td>
<td>22</td>
</tr>
</tbody>
</table>

solid state. An example is the photolysis of tetrasubstituted dibenzobarrelene 80 (page 27), which was reported to undergo the tri-π-methane rearrangement instead of the [2 + 2] photocycloaddition reaction. This was suggested to be due to a steric effect.58

According to the generally accepted di-π-methane reaction mechanism (Scheme 1.26, page 38), it has been postulated that the initial bond formation step controls the regioselectivity;23 therefore the relative stability of diradical species 113 and 116 are important in determining the product ratio.

The product ratios of the four 1,5-disubstituted dibenzobarrelene derivatives 109-112 in solution photolysis are listed in Table 2.07, which shows that photolysis of substrates 109 and 111 (X = Cl and COOMe) leads to the formation of type A major products, whereas the irradiation of compounds 110 and 112 (X = CN and OMe) gives rise to type B molecules as the major photoproducts. The electron-withdrawing substituents COOMe and CN were expected to have the same effect on the product ratio; i.e., lead to the same major photoproduct, however, the CN substituent gave different results.
Table 2.07  The Solution Photolysis of 1,5-Disubstituted Dibenzo[barrelene Derivatives 109-112

<table>
<thead>
<tr>
<th>Substrate</th>
<th>X</th>
<th>Medium</th>
<th>Type A Product (%)</th>
<th>Type B Product (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>109a</td>
<td>Cl</td>
<td>CH3CN</td>
<td>69</td>
<td>31</td>
</tr>
<tr>
<td>110b</td>
<td>CN</td>
<td>CDCl₃</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>111a</td>
<td>COOMe</td>
<td>CH₃CN</td>
<td>65</td>
<td>35</td>
</tr>
<tr>
<td>112b</td>
<td>OMe</td>
<td>CDCl₃</td>
<td>14</td>
<td>86</td>
</tr>
</tbody>
</table>

a Product Ratio Determined by GC.  b Product Ratio Determined by ¹H NMR.

2.5. The Perturbation Molecular Orbital Theory and Regioselectivity

The effect of aromatic substituents on the regioselectivity of the di-π-methane rearrangement of benzonorbornadienes has been studied by Paquette and co-workers, and an electronic effect was proposed to explain the regioselectivity. As shown in Scheme 2.17 (please also refer to Scheme 1.13 on page 22), Paquette et al. reported that in the di-π-methane rearrangement of compound 56, ortho-bridging is favored for both electron-withdrawing and electron-donating group substitution. This result was explained by using perturbation molecular orbital theory, which indicated that in the triplet state the electron density at the ortho carbon is higher than that at the meta carbon for both electron-withdrawing and electron-donating group substitution. The basic idea of perturbation molecular orbital theory is that the aromatic substituents polarize the frontier molecular orbitals of the aromatic ring. As a result, the atomic orbital coefficients are largest at the ortho position. It was postulated that strong electron-donating substituents mainly polarize the HOMO, and strong electron-accepting groups primarily polarize the LUMO. Weak electron-donating groups such as halogens
only weakly polarize the HOMO. Therefore, halogen-substituted benzonorbornadiene was expected to show low regioselectivity.\textsuperscript{38,40,41}

Scheme 2.17 The Regioselectivity of Benzonorbornadiene 56 in the Di-\(\pi\)-methane Rearrangement

Scheme 2.18 The Two Reaction Pathways in the Di-\(\pi\)-methane Rearrangement of 1,5-Disubstituted Dibenzobarrelenes

As we can see from Scheme 2.18, the substitution pattern is similar in 1,5-disubstituted dibenzobarrelenes (109-112) compared with that in benzonorbornadiene 56. Applying Paquette's explanation, type B compounds should be the major photoproducts.
In fact, compounds 110 and 112 (X = CN, OMe) fit this theory. Substrate 111 (X = COOMe) gave a product ratio of 65:35, favoring the type A product. This suggests that, in addition to the electronic effect used by Paquette, there might be other effects involved. For instance, since the carbomethoxy group (COOMe) is bulky, it is possible that diradical 111a is more stable than 111b, because the two ester groups (E1 and E2) are very close to each other in 111b, and steric hindrance might exist (Scheme 2.19). The observed product ratio is then considered to be the net result of different effects (will be discussed in the following sections 2.6, 2.7 and 2.8). The dichloro-substituted compound 109 led to the type A compound as the major photoproduct (via meta bridging), and similar unusual regioselectivities were reported by Paquette et al. in the di-π-methane rearrangement of fluoro-substituted benzonorbomadienes.40,41 It is worth pointing out that the dibenzobarrelene derivatives and their photoproducts are more sterically crowded than the corresponding benzonorbomadienes and their photoproducts, therefore both electronic and steric effects should be taken into consideration.

Scheme 2.19  The Diradical Species 111a and 111b
2.6. Diradical Stability Control of Regioselectivity

As discussed earlier, the initially formed cyclopropyldicarbinyl diradical intermediates are important in determining regioselectivity. Zimmerman et al. reported that, in the di-π-methane rearrangement, the carbinyl carbons of the cyclopropyldicarbinyl diradical intermediates have been noted to be electron rich; electron-withdrawing and/or delocalizing groups were reported to stabilize the diradical intermediates and therefore determine the regioselectivity. The resonance structures of the two diradical intermediates, 113 and 116 in our case, are shown in Scheme 2.20. It can be seen that diradical 116 is not resonance stabilized by the substituents, whereas the diradical species 113 is resonance stabilized by substituents Cl, CN, COOMe and OMe, and therefore favors the formation of type B photoproducts. On the other hand, diradical 113 is destabilized by the electron-donating group OMe (polar effect), and in this case, type A photoproduct (via diradical 116) is favored. However, the experimental results are quite different from the above predictions. These radical stability considerations, together with the experimental results, are summarized in Table 2.08.

Table 2.08  Diradical Resonance Stabilization Control of Regioselectivity

<table>
<thead>
<tr>
<th>X</th>
<th>Diradical 113</th>
<th>Favored Product</th>
<th>Observed Major Product (solution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>Resonance Stabilized</td>
<td>109B</td>
<td>109A (69%)</td>
</tr>
<tr>
<td>CN</td>
<td>Resonance Stabilized</td>
<td>110B</td>
<td>110B (80%)</td>
</tr>
<tr>
<td>COOMe</td>
<td>Resonance Stabilized</td>
<td>111B</td>
<td>111A (65%)</td>
</tr>
<tr>
<td>OMe</td>
<td>Destabilized</td>
<td>112A</td>
<td>112B (86%)</td>
</tr>
</tbody>
</table>

(Polar Effect)
2.7. The Regioselectivities in the Solid State

The dibenzobarrelene skeleton is a conformationally rigid tricyclic system, and conformational changes of the substituents are more significant than changes in shape of the structural skeleton. Examples of solid state steric control of regioselectivity by substituents in dibenzobarrelene derivatives have been reported from our group, in which both the intramolecular and intermolecular interactions have been interpreted as playing important roles in determining regioselectivity.58,87,88
2.7.1. Solid State Photoproduct Ratio

The dibenzobarrelene derivatives 109-112 were photolysed in the solid state. By comparing the GC retention time and $^1$H NMR spectra of the photoproducts with those obtained from the solution reaction, it was found that these compounds (109-112) also undergo the di-$\pi$-methane rearrangement in the solid state and lead to the formation of type A and type B dibenzosemibullvalene products. The product ratios were determined by GC and $^1$H NMR integrations and are listed in Table 2.09.

Table 2.09 The Solid State Photolysis of 1,5-Disubstituted Dibenzobarrelene Derivatives 109-112

<table>
<thead>
<tr>
<th>Substrate</th>
<th>X</th>
<th>Type A Product (%)</th>
<th>Type B Product (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>109$^a$</td>
<td>Cl</td>
<td>78 (69)$^c$</td>
<td>22 (31)</td>
</tr>
<tr>
<td>110$^b$</td>
<td>CN</td>
<td>30 (20)</td>
<td>70 (80)</td>
</tr>
<tr>
<td>111$^a$</td>
<td>COOMe</td>
<td>45 (65)</td>
<td>55 (35)</td>
</tr>
<tr>
<td>112$^b$</td>
<td>OMe</td>
<td>57 (14)</td>
<td>43 (86)</td>
</tr>
</tbody>
</table>

$^a$ Product ratio determined by GC. $^b$ Product ratio determined by $^1$H NMR. $^c$ Solution product ratios given in parentheses.

2.7.2. Crystal Structures of Dibenzobarrelenes 109, 110 and 112

The solid state photoproduct ratios were found to be different from those in solution. In particular, substrates 111 and 112 gave different major photoproducts in the solid state compared with their solution product ratios. In order to study solid state structure-reactivity correlations, the crystal structures of substrates 109, 110 and 112 were determined by X-ray diffraction methods, and their ORTEP drawings are shown in
Schemes 2.21 and 2.22. The crystal quality of compound 111 was not good enough for X-ray analysis.

Scheme 2.21  The ORTEP Diagrams for Dibenzobarrelenes 109 (a) and 110 (b)
Scheme 2.22  The ORTEP Diagram for Dibenzobarrelene 112*

* There are two molecules with similar conformations, and only one is shown here.

2.7.3. Solid State Conformation and Regioselectivity

In solution, the two carbomethoxy groups attached at C(11) and C(12) of a dibenzobarrelene molecule are free to undergo conformational change, therefore they are equivalent and have no contribution to the regioselectivity. In the solid state, however, these two carbomethoxy groups might be crystallized in different conformations, and may affect the regioselectivity. Such a situation has been reported.88
By examining the crystal structures of dibenzobarrelenes 109, 110 and 112, the conformation of the two carbomethoxy groups were found to be different. As depicted in Scheme 2.23, it was found that the distance between one carbonyl oxygen (O1) and its neighbouring bridgehead hydrogen (H9) is shorter than the distance between the other carbonyl oxygen (O2) and the corresponding bridgehead hydrogen (H10). This is common to all the three substrates (109, 110 and 112) analysed by X-ray crystallography.

![Diagram of dibenzobarrelene molecules](image)

<table>
<thead>
<tr>
<th>Compound</th>
<th>X1, X2</th>
<th>(d) (O1(\cdots)H9) (Å)</th>
<th>(d) (O2(\cdots)H10) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>Cl, Cl</td>
<td>2.66</td>
<td>2.98</td>
</tr>
<tr>
<td>110</td>
<td>CN, CN</td>
<td>2.59</td>
<td>3.02</td>
</tr>
<tr>
<td>112</td>
<td>OMe, OMe</td>
<td>2.53</td>
<td>3.11</td>
</tr>
</tbody>
</table>

**Scheme 2.23**  The Carbonyl Oxygen and Bridgehead Hydrogen Distances in Crystals of Dibenzobarrelenes 109, 110 and 112

The solid state conformations of the carbomethoxy groups can also be differentiated by their dihedral angles. Dihedral angle \(\phi 1\) is defined as that between the
\[ \pi \text{-orbital on the carbonyl carbon } C(13) \text{ and the } C(11)=C(12) \text{ bond } \pi \text{-orbitals, i.e.,} \]

\[ \text{between } O1-C(13)-C(12)-C(11). \phi 2 \text{ is the dihedral angle between } O2-C(14)-C(11)-C(12). \phi 1 = \phi 2 = 0^\circ \text{ denotes the fully conjugated conformation of this ene-dioate system (Scheme 2.24). As depicted in Scheme 2.24, the idea that the ene-dioate conformations affect solid state reaction regioselectivity was first proposed by Scheffer et al., stating that the initial benzo-vinyl bridging would be favored at the vinyl carbon that is less conjugated to its attached ester group, and the resulting radical will be delocalized at the other vinyl carbon that is more conjugated to its attached ester group.}^{88} \]

Scheme 2.24 Effect of Ene-Dioate Conjugation on Reaction Regioselectivity (Ref. 88)
The $\phi_1$ and $\phi_2$ values calculated from the crystal structures of dibenzobarrelene 109, 110 and 112 are listed in Table 2.10. In general, $\phi_1$ and $\phi_2$ are different and deviate from $0^\circ$. The smaller the $\phi$ angle, the better the conjugation of the carbonyl group with the C(11)-C(12) double bond.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\phi_1$ (°)</th>
<th>$\phi_2$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>31.5</td>
<td>64</td>
</tr>
<tr>
<td>110</td>
<td>27.1</td>
<td>70.8</td>
</tr>
<tr>
<td>112</td>
<td>2.1</td>
<td>80.7</td>
</tr>
</tbody>
</table>

As listed in Table 2.10, all the four $\phi_2$ values are greater than the corresponding $\phi_1$ values, and this implies that initial bond formation should be favored at vinyl carbon C(11) (Scheme 2.23). There are two initial bond formation pathways involved with carbon C(11); one is ortho-bridging via C(11)-C(10a), the other is meta-bridging via C(11)-C(4a). Because these two pathways lead to different photoproducts, this dihedral angle consideration does not predict a preference for the formation of either of the regioisomeric photoproducts (see further discussion on pages 78-79).

2.8. The Steric Effect and MMX Calculations for the Regioselectivity

Further examination of the molecular conformations in the crystalline state provided us with more interesting data. It was found that the substituents on the aromatic rings are very close to the bridgehead hydrogens (H9 & H10), and these distances are listed in Table 2.11.
Table 2.11 The Distances Between Bridgehead Hydrogens and the Substituents

![Diagram of a molecule with桥头氢原子和取代基之间的距离示意图]

<table>
<thead>
<tr>
<th>Compound Number</th>
<th>X1, X2</th>
<th>(d(X1\cdots H9)) (Å)</th>
<th>(d(X2\cdots H10)) (Å)</th>
<th>Sum of Van der Waals Radii (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>Cl, Cl</td>
<td>2.76</td>
<td>2.81</td>
<td>2.95</td>
</tr>
<tr>
<td>110</td>
<td>CN, CN</td>
<td>2.66</td>
<td>2.66</td>
<td>2.90</td>
</tr>
<tr>
<td>112</td>
<td>OMe, OMe</td>
<td>2.54</td>
<td>2.59</td>
<td>2.72</td>
</tr>
</tbody>
</table>

The data listed in Table 2.11 indicate that moderately severe nonbonded interactions exist between the bridgehead hydrogens and the aryl substituents, because all the distances are less than the sum of van der Waals radii\(^89\). The interaction between nonbonded atoms may be attractive or repulsive depending on the interatomic distance. The attractive interaction between them is very small when the two atoms are separated by a large distance, and this attractive interaction increases steadily as the distance decreases, and finally reaches a maximum at the distance of the sum of the van der Waals radii. This interaction becomes strongly repulsive as the atoms approach each other with a separation less than the sum of the van der Waals radii (Scheme 2.25).\(^90\)

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Two examples were reported where intramolecular nonbonded interactions were released during the di-π-methane rearrangement, via specific pathways and leading to sterically favored photoproducts. In one example, MMX calculations were performed to find the most stable conformations of two diastereomeric diradical intermediates. To study the steric effect in our case, MMX calculations (MMX PC Model, Serena Software, Bloomington, Indiana, 1988) on the minimum energy conformation of substrates 109, 110 and 112 (crystal structures available for comparison) and their cyclopropyldicarbiny1 diradical intermediates were conducted, and the results are shown in Schemes 2.26-2.28 respectively.
Scheme 2.26  The Calculated Cl⋯H Distances (by MMX) in Substrate 109 and Diradical Intermediates 109a and 109b

<table>
<thead>
<tr>
<th>Structure</th>
<th>(d) [H9⋯Cl(1)] (Å)</th>
<th>(d) [H10⋯Cl(2)] (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>2.76 (2.76)*</td>
<td>2.76 (2.81)*</td>
</tr>
<tr>
<td>109a</td>
<td>2.99</td>
<td>2.70</td>
</tr>
<tr>
<td>109b</td>
<td>2.88</td>
<td>2.73</td>
</tr>
</tbody>
</table>

note: Distances less than the sum of van der Waals radii (2.95 Å) are underlined.

* From the X-ray crystallographic method.

First, the MMX calculation gives the Cl⋯H distance in 109 as 2.76 Å for both bridgehead hydrogens (Scheme 2.26), which is very close to the distances given by the crystal structure (2.76 Å and 2.81 Å respectively, Table 2.11). Second, the consideration of diradical intermediates reveals that, in 109a, there is only one Cl⋯H repulsion [Cl(2)⋯H10], whereas the other was released by the initial bond formation (meta
bridging). In contrast, there are still two nonbonded interactions in diradical 109b. Therefore, under this steric effect consideration, intermediate 109a should be favored.

Scheme 2.27 The Calculated C−H Distances (by MMX) in Substrate 110 and Diradical Intermediates 110a and 110b

<table>
<thead>
<tr>
<th>Structure</th>
<th>(d[H9\cdots C(1a)]) (Å)</th>
<th>(d[H10\cdots C(5a)]) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>2.62 (2.66)*</td>
<td>2.62 (2.66)*</td>
</tr>
<tr>
<td>110a</td>
<td>2.84</td>
<td>2.55</td>
</tr>
<tr>
<td>110b</td>
<td>2.74</td>
<td>2.59</td>
</tr>
</tbody>
</table>

note: Distances less than the sum of van der Waals radii (2.90 Å) are underlined.
* From the X-ray crystallographic method.
nonbonded interactions were released in either of the intermediates. From the steric effect point of view, no conclusion can be drawn on the relative stability of each diradical intermediate.

Scheme 2.28

<table>
<thead>
<tr>
<th>Structure</th>
<th>$d$ (H9···O1) (Å)</th>
<th>$d$ (H10···O2) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>2.52(2.54,2.55)*</td>
<td>2.54 (2.56,2.59)*</td>
</tr>
<tr>
<td>112a</td>
<td>2.75</td>
<td>2.44</td>
</tr>
<tr>
<td>112b</td>
<td>2.65</td>
<td>2.48</td>
</tr>
</tbody>
</table>

Scheme 2.28  The Calculated O···H Distances (by MMX) in Substrate 112 and Diradical Intermediates 112a and 112b

note: Distances less than the sum of van der Waals radii (2.72 Å) are underlined.

* From the X-ray crystallographic method.

As shown in Scheme 2.28, in the photolysis of dibenzobarrelene 112, the formation of diradical intermediate 112a results in the release of the nonbonded
interaction between atoms H9 and O1, which implies that diradical 112a (via meta-bridging) is the sterically favored intermediate.

In summary, both the X-ray crystallographic analyses and MMX calculations on the substrates 109, 110 and 112 reveal that there are two nonbonded interactions between the bridgehead hydrogens of each substrate molecule and its aromatic substituents. In two cases (substrate 109 and 112), one of the two nonbonded interactions could be released by preferentially forming diradical intermediates 109a and 112a (both via meta-bridging). However, it should be pointed out that the MMX calculation is very rough, particularly due to the carbon radical parameters used in this calculation, which are not based on experimental data (experimental data for carbon radicals are not available). It should also be pointed out that because of the rigidity of the dibenzobarrelene framework, the above nonbonded interactions exist both in solution phase and solid state, therefore, the above argument applies both in solution and solid state photoreactions. The predicted major photoproducts (by MMX calculations) and experimental results are listed in Table 2.12.

Table 2.12 The MMX Calculation Results and the Observed Regioselectivities

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Major Product Predicted</th>
<th>Major Product Solution</th>
<th>Major Product Solid State</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>109A</td>
<td>109A (69%)</td>
<td>109A (78%)</td>
</tr>
<tr>
<td>112</td>
<td>112A</td>
<td>112B (86%)</td>
<td>112A (57%)</td>
</tr>
</tbody>
</table>

If we apply the dihedral angle consideration [favor initial bonding via C(11), p 72] and the MMX calculation results (favor meta-bridging) on dibenzobarrelenes 109 and
112, the initial bond formation via carbons C(11) and C(4a) is predicted to be favored in the solid state photoreaction for substrates 109 and 112 (see also Scheme 2.23, p 70).

In conclusion, in the regioselectivity studies of the di-π-methane rearrangement of dibenzobarrelenes 109-112, the observed solution and solid state regioselectivities could not be explained by any single controlling effect discussed above; the observed regioselectivities might be due to a combination of several different controlling factors. The predicted major photoproducts by different controlling effects and the observed major photoproducts are summarized in Table 2.13.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Favored Photoproduct</th>
<th>Observed Major Product</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perturbation Theory</td>
<td>Diradical Stability</td>
</tr>
<tr>
<td>109</td>
<td>109B</td>
<td>109B</td>
</tr>
<tr>
<td>110</td>
<td>110B</td>
<td>110B</td>
</tr>
<tr>
<td>111</td>
<td>111B</td>
<td>111B</td>
</tr>
<tr>
<td>112</td>
<td>112B</td>
<td>112A</td>
</tr>
</tbody>
</table>

2.9. **Photochemistry of 1,8-Dichlorodibenzobarrelene Derivative 130**

Preparative photolysis of 1,8-Dichlorodibenzobarrelene 130 was conducted in acetone. This was probably not an acetone sensitized reaction, because compound 130 has moderate absorption under the photolysis condition (Pyrex filter). Two photoproducts, 141 and 142, were isolated by column chromatography and characterized by spectroscopic methods, and they were identified as dibenzosemibullvalene type
photoproducts (Scheme 2.29). $^1$H NMR and NOE experiments were mainly used to assign the structures of the two regioisomeric photoproducts. The chemical shifts of the methine protons in each photoproduct are listed in Table 2.14, and the NOE experiment results are given in Table 2.15.

Scheme 2.29 The Di-π-methane Rearrangement of 1,8-Disubstituted Dibenzobarrelene 130

Table 2.14 The $^1$H NMR (400 MHz, CDCl$_3$) Chemical Shifts of the Methine Protons in Photoproducts 141 and 142

<table>
<thead>
<tr>
<th>Compound Number</th>
<th>Chemical Shifts H8d (δ ppm)</th>
<th>Chemical Shifts H4b (δ ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>4.49*</td>
<td>5.03*</td>
</tr>
<tr>
<td>141</td>
<td>4.66</td>
<td>5.14</td>
</tr>
<tr>
<td>142</td>
<td>4.44</td>
<td>5.45</td>
</tr>
</tbody>
</table>

* Ref. 50.
Table 2.15 The NOE Experiment Results for Photoproducts 141 and 142

<table>
<thead>
<tr>
<th>NOE Experiment</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation of H4b in 141</td>
<td>Aromatic Proton Signal Enhanced</td>
</tr>
<tr>
<td>Irradiation of H8d in 141</td>
<td>Aromatic Proton Signal Not Enhanced</td>
</tr>
<tr>
<td>Irradiation of H4b in 142</td>
<td>Aromatic Proton Signal Not Enhanced</td>
</tr>
<tr>
<td>Irradiation of H8d in 142</td>
<td>Aromatic Proton Signal Enhanced</td>
</tr>
</tbody>
</table>

Analytical photolysis of 1,8-dichlorodibenzobarrelene derivative 130 were conducted in acetone, benzene and the crystalline state. The product ratios were determined by GC, and are given in Table 2.16. In both solution and the solid state, compound 142 was formed (via meta bridging) as the major photoproduct.

Table 2.16 The Product Ratio from the Photolysis of Compound 130

<table>
<thead>
<tr>
<th>Medium</th>
<th>141 (%)</th>
<th>142 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetone</td>
<td>36</td>
<td>64</td>
</tr>
<tr>
<td>Benzene</td>
<td>29</td>
<td>71</td>
</tr>
<tr>
<td>Solid State</td>
<td>8</td>
<td>92</td>
</tr>
</tbody>
</table>

We consider the solution results first. According to the theory of electronic control proposed by Paquette et al., the photolysis of dibenzobarrelene derivative 130 should favor initial ortho bridging to give product 141. However, the experimental result shows that compound 142 is the major photoproduct.

Turning to the radical stability consideration, diradical intermediate 130b (Scheme 2.30) is resonance stabilized by the chlorine substituent Cl(1), whereas diradical
130a is not resonance stabilized by the chlorine substituents. Therefore product 141 via intermediate 130b is also favored under the radical stability consideration.

MMX calculations were carried out on substrate 130 and the diradical intermediates 130a and 130b (Scheme 2.30). Once again it was found, by MMX calculations and X-ray crystallographic analysis, that the distances between the bridgehead hydrogen H9 and the aromatic substituents Cl(1) and Cl(2) are less than the sum of the van der Waals radii (2.95 Å). According to the MMX calculations, the formation of diradical intermediate 130a releases one van der Waals repulsion, whereas both of the van der Waals repulsions still exist in diradical intermediate 130b. Therefore, this steric effect consideration favors the formation of intermediate 130a, via meta bridging, and leads to the observed major photoproduct 142.
<table>
<thead>
<tr>
<th>Structure</th>
<th>(d) [H9(\cdots)Cl(1)] (Å)</th>
<th>(d) [H9(\cdots)Cl(2)] (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>2.75 (2.85)*</td>
<td>2.74 (2.83)*</td>
</tr>
<tr>
<td>130a</td>
<td>2.97</td>
<td>2.73</td>
</tr>
<tr>
<td>130b</td>
<td>2.86</td>
<td>2.68</td>
</tr>
</tbody>
</table>

* Distance measured from X-ray crystal structure.
Note: Distances less than the sum of van der Waals radii (2.95 Å) are underlined.

**Scheme 2.30** The Calculated H\(\cdots\)Cl Distances (by MMX) for Dibenzobarrelene 130 and Intermediates 130a and 130b

Turning to the solid state, as depicted in Scheme 2.31, the two carbomethoxy groups in substrate 130 crystallized in different conformations. The dihedral angle \(\phi_1\) [O1-C(13)-C(12)-C(11)] is 2.7°, and \(\phi_2\) [O2-C(14)-C(11)-C(12)] is 86°. These data indicate that one carbonyl [C(13)=01] is in conjugation with the vinyl group, and the other carbonyl [C(14)=02] is out of conjugation with the vinyl group. According to the above-mentioned idea by Scheffer et al.,\textsuperscript{88,92} initial bridging is expected at vinyl carbon C(11), which is connected to the less conjugated carbonyl group [C(14)=O2]. This solid state conformation consideration also favors the formation of photoproduct 142 via *meta* bridging [i.e., C(11)-C4a and C(11)-C(10a)]. The crystal structure of substrate 130 is given in Scheme 2.32.
Scheme 2.31  The Dihedral Angles of Dibenzobarrelene 130

Scheme 2.32  The Stereo Diagram of Dibenzobarrelene 130
In summary (Table 2.17), the MMX calculations and solid state ene-dioate conjugation arguments both favor initial bond formation at the meta position to give compound 142 (via intermediate 130a) as the major photoproduct. Because the ene-dioate conjugation is under lattice control, it is not surprising that the solid state reaction is more selective than that in solution. However, both the electron perturbation theory, postulated by Paquette et al.,38,40,41 and the diradical stability consideration favor ortho bridging which leads to photoproduct 141. We suggest that, in this case, steric control is more important than the electronic control of the regioselectivity.

Table 2.17 The Predicted and Observed Regioselectivities in the Di-π-methane Rearrangement of Substrate 130

<table>
<thead>
<tr>
<th>Effect</th>
<th>Favored Product</th>
<th>Observed Major Photoproduct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perturbation Theory</td>
<td>141</td>
<td>Solution</td>
</tr>
<tr>
<td>Radical Stability</td>
<td>141</td>
<td>142</td>
</tr>
<tr>
<td>MMX Calculation</td>
<td>142</td>
<td>142 (92%)</td>
</tr>
<tr>
<td>Dihedral Angle</td>
<td>142</td>
<td>(64%, acetone)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(71%, benzene)</td>
</tr>
</tbody>
</table>
2.10. Photolysis of Monochloro-substituted Dibenzobarrelene Derivative 131

The Monochloro-substituted dibenzobarrelene 131 was chosen for regioselectivity studies because the di-π-methane rearrangement of this substrate could give four photoproducts via four possible different initial bond formation pathways (Scheme 2.33). However, these photoproducts were found to be very difficult to separate by column chromatography, and were also found to give broad, overlapping GC signals. Among the four possible photoproducts, only one was isolated (compound 143) from a solution photolysis, whose structure was assigned by an X-ray diffraction analysis (Scheme 2.34). The multi-channel regioselectivity of this di-π-methane rearrangement remains to be sorted out.

Scheme 2.33 The Four Possible Photoproducts from the Di-π-methane Rearrangement of Compound 131
Scheme 2.34  The ORTEP Drawing of Photoproduct 143
Chapter 3  The Studies of Substrates that undergo the Norrish Type II Reaction

3.1.  The Preparation of α-Adamantyl Acetophenones

Scheme 3.01  The Preparation of α-Adamantyl Acetophenones

All the α-adamantyl acetophenones studied were synthesized by a Friedel-Crafts reaction between the corresponding 1-adamantylacetyl chloride and fluorobenzene. This reaction resulted in the formation of α-adamantyl-p-fluoro acetophenones, which underwent a subsequent nucleophilic aromatic substitution reaction with KCN to give the
corresponding nitrile derivatives. These nitrile derivatives were hydrolysed to afford the corresponding carboxylic acid derivatives, which were finally converted to the ester forms. The synthetic pathways are outlined in Scheme 3.01.

Table 3.01 The NMR Signals of α-Adamantyl Acetophenones

<table>
<thead>
<tr>
<th>Compound #</th>
<th>R</th>
<th>X</th>
<th>δ H2 (ppm)</th>
<th>δ C1 (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>148</td>
<td>H</td>
<td>F</td>
<td>2.70\textsuperscript{b}</td>
<td>198.53</td>
</tr>
<tr>
<td>149</td>
<td>H</td>
<td>CN</td>
<td>2.72\textsuperscript{b}</td>
<td>198.88</td>
</tr>
<tr>
<td>119</td>
<td>H</td>
<td>COOH</td>
<td>2.80\textsuperscript{b}</td>
<td>201.00</td>
</tr>
<tr>
<td>150</td>
<td>H</td>
<td>COOMe</td>
<td>2.75\textsuperscript{b}</td>
<td>199.88</td>
</tr>
<tr>
<td>152</td>
<td>CH$_3$</td>
<td>F</td>
<td>2.70\textsuperscript{c}</td>
<td>198.47</td>
</tr>
<tr>
<td>153</td>
<td>CH$_3$</td>
<td>CN</td>
<td>2.78\textsuperscript{c}</td>
<td>198.79</td>
</tr>
<tr>
<td>120</td>
<td>CH$_3$</td>
<td>COOH</td>
<td>2.72\textsuperscript{c}</td>
<td>199.52</td>
</tr>
<tr>
<td>154</td>
<td>CH$_3$</td>
<td>COOMe</td>
<td>2.72\textsuperscript{c}</td>
<td>199.74</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Solvent CDC$_3$. \textsuperscript{b} 400 MHz. \textsuperscript{c} 200 MHz. \textsuperscript{d} 50 MHz.

These α-adamantyl acetophenones are all new compounds, which were initially characterized by spectroscopic analyses. In addition, X-ray diffraction analyses have been conducted on four of the above eight α-adamantyl acetophenones (120, 148, 149 and 153). These eight α-adamantyl acetophenones have characteristic $^1$H NMR and $^{13}$C NMR signals, which are listed in Table 3.01. In general, the two α-hydrogens (H2) in each substrate give a singlet $^1$H NMR signal at ca. $\delta = 2.7$ ppm, with the area ratio
indicating two protons. The carbonyl carbon Cl appears at ca. \( \delta = 200 \) ppm in the \(^{13}\)C NMR spectra.

In the Results and Discussion section, trivial names for these adamantyl-substituted ketones are used for simplicity and clarity; their IUPAC nomenclatures are given in the Experimental section.

### 3.2. The Photochemistry of \( \alpha \)-Adamantyl Acetophenones

The photochemical behavior of \( \alpha \)-adamantyl acetophenones has been well documented.\(^{72,96-100}\) Because of the synthetic interest in bicyclic compounds with bridgehead double bonds, Gagosian and co-workers attempted to generate adamantene by the Norrish type II cleavage reaction of 1-adamantyl acetone \((155, \text{Scheme 3.02})\). However, it was found that irradiation of 1-adamantyl acetone gave only the Norrish type II cyclization products \(157\) and \(158\), and no cleavage product adamantene \((156)\) was found (Scheme 3.02).\(^{96,97}\) The absence of adamantene was attributed to the fact that adamantene is a high energy, unstable olefin whose formation would have to proceed via a very high energy reaction pathway. The Norrish type II cyclization products \(157\) and \(158\) are usually called cis and trans cyclobutanols. The designation cis and trans was based on the stereochemistry of the hydroxyl group on the cyclobutane ring relative to the methine hydrogen on the adjacent ring junction carbon. Thus cyclization product \(157\) is called cis because the hydroxyl group and the methine hydrogen are on the same side of the cyclobutane ring; product \(158\) is termed trans because the hydroxyl group and the methine hydrogen are on opposite sides of the cyclobutane ring.
A subsequent report by Lewis et al. on the photolysis of α-adamantyl acetophenone also showed the absence of the Norrish type II cleavage product adamantene (156), and this reaction only gave two cyclization reaction products.⁹⁸ In recent years, the photochemistry of α-adamantyl acetophenone and derivatives have been studied by Scheffer, Trotter and co-workers,⁷²,⁹⁹,¹⁰⁰ both in solution and the solid state. As before, no cleavage products were found. α-Adamantyl acetophenones are achiral molecules that give chiral cyclization products, whereas the cleavage products would be
achiral. Because of the exclusive photocyclization reaction, \( \alpha \)-adamantyl acetophenones are good substrates for asymmetric induction studies via the Norrish type II reaction.

It should be pointed out that adamantene (156) has been reported as being generated in low yield from the photolysis of 1-adamantyl phenylacetate and 2-adamantyl phenylacetate, and this short lived species was trapped by solvent molecules.\(^{101}\) However these two adamantyl esters are different from the \( \alpha \)-adamantyl acetophenone derivatives discussed above, which are ketones.

### 3.3. The Photolysis of \( \alpha \)-adamantyl-4-carbomethoxy acetophenone (150)

\[
\text{hv} \rightarrow \text{acetone} \quad \text{150} \quad \text{159}
\]

\[
77.5\% \quad \text{COOCH}_3
\]

\[
\text{160} \quad \text{161} \quad \text{162}
\]

\[
14\% \quad 3\% \quad 3.7\%
\]

**Scheme 3.03** The Preparative Photolysis of Ketone 150
The preparative photolysis of ketone 150 was conducted in acetone until no starting material remained. Four photoproducts were isolated through column chromatography (Scheme 3.03).

These four photoproducts were characterized by spectroscopic analysis. The cis and trans cyclobutanols 160 and 159 are the Norrish type II cyclization products. Product 161 was formed via a non-photochemical dehydration reaction of the cyclobutanols 159 and 160, and similar dehydration reactions have been reported.95,96 In addition, another unusual photoproduct 162 was formed in low yield (3.7%). The mechanism of the formation of product 162 is postulated in Scheme 3.04.
A similar reaction was suspected by Lewis et al. in 1974. They reported that photolysis of cyclohexyl phenyl ketone $163$ resulted in the formation of products $164$ and $165$, plus an unusual photoproduct $166$ (Scheme 3.05).$^{102}$

As explained by Lewis et al., the IR, $^1$H NMR and MS spectra of unknown product $166$ were indicative of an $\alpha$-tetralone structure, and product $166$ was suspected to be tetralone $163c$, which might be formed by an unusual reaction of the biradical intermediate $163a$ as shown in Scheme 3.06.$^{102}$
Scheme 3.06   A Possible Mechanism of Forming Product 163c (Ref. 102)

However, Lewis et al. also reported in the same paper that the spectra of the unknown product 166 and an authentic sample of compound 163c were similar but not identical. Therefore 163c was ruled out as the structure for unknown compound 166.102 It should be pointed out that only IR, MS and $^1$H NMR data for compound 166 were reported by Lewis et al.102 In our case, with more advanced high resolution NMR techniques combined with IR and MS spectroscopies, photoproduct 162 is suggested to have a structure similar to that of compound 163c. The proposed structure of product 162 and selected informative spectral data are outlined below.
b) MS m/e: 310 (M+). Relative Intensity: 100%.
c) IR (KBr) ν_max: 1722 cm⁻¹ (carbonyl, ester), 1693 cm⁻¹ (carbonyl, ketone).
d) ¹H NMR δ ppm: 8.09 (d, J = 8.1 Hz, 1 H, Hb), 8.07 (s, 1 H, Hc), 7.87 (d, J = 8.1 Hz, 1 H, Ha).
e) ¹³C NMR δ ppm: 197.59 (C=O, ketone), 166.63 (C=O, ester). Total 20 Carbon Signals.
f) APT experiment: No. of carbons with one or three protons attached, 8
   No. of carbons with zero or two protons attached, 12

The assignment of structure to cyclobutanol 159 was based upon spectroscopic analysis and an X-ray diffraction study. The structure assignment of similar compounds has been reported by Lewis et al. Lewis reported the differentiation of cis and trans cyclobutanols by NMR chemical shift reagent studies on the methine proton at the cyclobutane ring (H4 on 167, Scheme 3.07). However, because of the complicated proton signals in the high field region, the proton assignment by Lewis et al. is not very
convincing without other complementary NMR experiments (such as NOE, COSY and HETCOR).

![Scheme 3.07](image)

**Scheme 3.07** Structures of *Trans* Cyclobutans 159, 167 and 168

In this thesis, the structure assignment of product 159 was primarily derived from an X-ray crystal structure analysis on salt 159s, which was chemically correlated with *trans* cyclobutanol 159 (Scheme 3.08). The crystal structure diagrams of salt 159s are shown in Schemes 3.20-3.21 (pages 121-122).

![Scheme 3.08](image)

**Scheme 3.08** A Structure Correlation Between Salt 159s and Photoproduct 159
Returning to the proton NMR signal assignment on the methine proton H4 in photoproducts 159 and 167 (Scheme 3.07), the \(^1\)H NMR of product 159 (Scheme 3.09) showed a broad doublet at \(\delta = 2.91\) ppm, and a similar signal was reported in the \(^1\)H NMR spectrum of analog 167 (\(\delta = 2.9\) ppm) by Lewis et al.\(^9\) They assigned this signal to the methine hydrogen H4 in compound 167 (Scheme 3.07).

However, the \(^{13}\)C APT and HETCOR experiments on photoproduct 159 revealed that this broad doublet (\(\delta = 2.91\) ppm) is a one hydrogen signal from a methylene group, not from a methine proton. Since we have the crystal structure data on salt 159s, calculations were conducted on the distances between the hydroxyl oxygen and its neighboring hydrogens. It was found that, in the salt form 159s, the O1—H4 distance is quite far (3.29 Å). The O1—H10a distance (2.35 Å) is the shortest, which is less than the sum of van der Waals radii (2.72 Å). Based on this information, it is suggested that the observed broad doublet, in the proton NMR spectrum of product 159 (\(\delta = 2.91\) ppm, Scheme 3.09), is the signal from hydrogen H10a. Because hydrogen H10a is very close to the electronegative oxygen atom O1, its NMR signal is shifted significantly downfield compared with the rest of methylene hydrogens in this molecule. Since a detailed discussion on the characterization of another trans photoproduct 168 (Scheme 3.07), together with all the \(^1\)H NMR, \(^{13}\)C NMR (APT), HETCOR and NOE spectra, are shown on pages 140-142, these spectra for product 159 will not be shown here.
Scheme 3.09  The $^1$H NMR Spectrum (500 MHz, CDCl$_3$) of Photoproduc}

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3.4. Asymmetric Synthesis Studies in the Solid State

Optically active molecules are required to crystallize in chiral space groups. An optically active molecule that is reacting in the solid state therefore senses a chiral environment that is caused by both the chiral center as well as the chiral crystalline medium. Optically active substrate molecules for asymmetric induction studies are often made up of two components that are chemically bonded. One component is a prochiral molecule which is going to undergo a chemical transformation to yield a product with one or more chiral centers. The other component is a resolved chiral molecule which is used as a chiral handle. After the reaction, this chiral handle will be removed and the optical activity of the product can then be determined. For asymmetric synthesis in solution, where the asymmetric induction is exerted solely by the chiral center, the chiral handle should be close to the reacting center in order for it to sense a chiral environment. In contrast, for solid state asymmetric synthesis, the chiral handle can be attached farther away from the reaction site, and it is then only used to ensure a chiral crystalline lattice. Since the chiral handle is far away from the site of reaction, there might be no asymmetric induction in the solution reaction.

As discussed in the Introduction section, the strategy of using ionic chiral handles was recently reported from our group. These chiral handles, which join with substrate molecules via ionic bonds to form carboxylic acid-amine type salts, are easy to introduce and remove through simple acid-base chemistry. In addition, the resulting high melting salts can induce high selectivity solid state photoreactions; moreover, if it exists, single crystal-to-single crystal photoreaction can be revealed. Solid state asymmetric syntheses of this type involve the preparation of chiral salts, solid state photolysis, optical
activity determination and absolute configuration correlation. Each topic will be discussed separately.

3.4.1. The Preparation of Chiral Salts from Carboxylic Acid 119

Table 3.02  The Preparation of Chiral Salts from Carboxylic Acid 119

<table>
<thead>
<tr>
<th>Entry</th>
<th>Salt #</th>
<th>Chiral Amine</th>
<th>Solvent</th>
<th>Crystal Morphology</th>
<th>Melting Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>169p</td>
<td>L-prolinol</td>
<td>acetone</td>
<td>plates</td>
<td>116-118</td>
</tr>
<tr>
<td>2</td>
<td>169n</td>
<td>L-prolinol</td>
<td>acetone</td>
<td>needles</td>
<td>128-130</td>
</tr>
<tr>
<td>3</td>
<td>170</td>
<td>D-prolinol</td>
<td>acetone</td>
<td>needles</td>
<td>128-130</td>
</tr>
<tr>
<td>4</td>
<td>171</td>
<td>R-(+)-α-phenylethyl amine</td>
<td>acetone</td>
<td>needles*</td>
<td>235-236</td>
</tr>
<tr>
<td>5</td>
<td>172</td>
<td>hydroquinine</td>
<td>DMSO</td>
<td>needles*</td>
<td>222-224</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>L-proline</td>
<td>acetone</td>
<td>oil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ethanol</td>
<td>oil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>chloroform</td>
<td>oil</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>(1S,2R)-(+)−ephedrine</td>
<td>acetone</td>
<td>oil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ethanol</td>
<td>oil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>chloroform</td>
<td>oil</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>L-proline t-butyl ester</td>
<td>acetone</td>
<td>oil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ethanol</td>
<td>oil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>chloroform</td>
<td>oil</td>
<td></td>
</tr>
</tbody>
</table>

* Crystals are not suitable for X-ray diffraction analysis.
The chiral crystalline salts were prepared by reaction of prochiral carboxylic acid 119 with several optically active amines (Table 3.02). It was found that the reaction of substrate 119 with L-prolinol [S-(+)-2-pyrrolidinemethanol] in acetone gave two crystal forms with different melting points. The plate form crystals formed first; after filtration, the needle-shaped crystals formed from the mother liquor. The differences between these dimorphs will be discussed in more detail later. The reactions of compound 119 with R-(+)-α-phenylethyl amine and hydroquinine gave very fine needles which were not suitable for X-ray diffraction analysis. The reactions of carboxylic acid 119 with three amines (entries 6, 7 and 8) afforded non-crystalline products.

The characterization of the newly formed salts was performed by first measuring their melting points. The melting points of all the salts are different from those of their precursors, i.e. the carboxylic acid 119 and the corresponding amine. Secondly, the solid state IR spectra were analysed. Salt formation resulted in a characteristic change in the carboxylic acid OH stretch band at ca. 3200-2500 cm\(^{-1}\), which was replaced by the less intense amonium NH band; also indicative was the disappearance of the strong carboxylic acid carbonyl band (1686 cm\(^{-1}\)) and the appearance of a carboxylate anion stretch at 1650-1550 cm\(^{-1}\) of medium intensity.

Informative data also came from the FAB mass spectra of these salts, which gave the (M + 1)+ peak in each case. In addition, the \(^1\)H NMR, \(^{13}\)C NMR, APT experiment and elemental analysis were all in agreement with the proposed structures. X-ray diffraction analysis of salts 169p and 169n were also carried out to reveal more structural features which will be discussed later. Crystals of salt 172 were formed very rapidly and, as a result, solvent and/or substrate molecules might have been trapped inside the crystal. Because of its low solubility in organic solvents, it was difficult to further purify salt 172. 

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by recrystallization. Salt 172 did not pass the elemental analysis, but the FAB mass spectrum did give the correct (M + 1)+ peak.

3.4.2. The Photolysis of Chiral Salts 169-172

The irradiation of crystalline chiral salts was conducted at −40 °C. No colour change or melting of the crystals was observed during the reaction. Afterwards, the reaction mixture was acidified with dilute hydrochloric acid, extracted with diethyl ether, and the extracts were treated with excess of diazomethane. This ether solution was then rotary evaporated and the resulting oil was chromatographed. Usually three compounds could be isolated from this oily mixture. These three compounds are products 159 and 160, which are methyl esters of the corresponding solid state photoproducts (159-salt and 160-salt, Scheme 3.10, page 104), and compound 150, which is the ester form of the unreacted starting salt molecules. Since chiral crystals are used for the solid state photolysis, products 159 and 160 might be enantiomerically enriched or optically pure. The determination of their enantiomeric excess will be discussed in the following section.

Salts 169p, 169n, 170 and 171 underwent photochemical reactions smoothly in the solid state at low temperature, whereas salt 172 was photochemically unreactive (Table 3.03). Salt 172 crystallized as thin needles, which were not suitable for X-ray diffracton analysis that would provide us with the intramolecular packing. It can be speculated that the γ-hydrogens in salt 172 might be too far away from the carbonyl oxygen to permit abstraction,63,64 or the crystal packing disfavors the diradical coupling reaction if a solid state intramolecular hydrogen abstraction reaction does exist.

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Scheme 3.10 Solid State Photolysis of Chiral Salts and Work-up
Table 3.03 The Photolysis of Salts 169-172a

<table>
<thead>
<tr>
<th>Entry</th>
<th>Salt #</th>
<th>Temp. (°C)</th>
<th>Time (h)</th>
<th>Conversion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 p</td>
<td>169p</td>
<td>0</td>
<td>60</td>
<td>&gt;99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-40</td>
<td>24</td>
<td>79</td>
</tr>
<tr>
<td>2 n</td>
<td>169n</td>
<td>-40</td>
<td>24</td>
<td>87</td>
</tr>
<tr>
<td>3</td>
<td>170</td>
<td>-40</td>
<td>24</td>
<td>69</td>
</tr>
<tr>
<td>4</td>
<td>171</td>
<td>-40</td>
<td>48</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>172</td>
<td>-40</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>60</td>
<td>trace</td>
</tr>
</tbody>
</table>

a The crystal integrity was retained in all cases. Crystals in Entries 1-4 turned opaque after photolysis.

3.4.3. Enantiomeric Excess Determination

During the past ten years, there has been an increasing demand, particularly from the pharmaceutical industry, for accurate, reliable and convenient methods of measuring enantiomeric purity. Many methods and reagents have been developed for this purpose. Some commonly used methods for enantiomeric excess determination are optical rotation measurement, chiral GC, chiral HPLC and NMR-based methods.

The enantiomeric excess determination of photoproducts 159 and 160 was first conducted by using chiral GC. Racemic compounds 159 and 160 were initially analysed on chiral GC (column Cyclodex-B, J & W Scientific), but it was not possible to separate the enantiomers. The 1H NMR chiral shift reagent method was subsequently used to determine the enantiomeric purity. Chiral lanthanide shift reagents Eu(hfc)3 and Yb(hfc)3 were used, and it was found that Yb(hfc)3 gave better results.

The determination of enantiomeric purity was carried out on a Bruker 400 NMR spectrometer at room temperature. This experiment was first conducted on a racemic
mixture of compound 159, by adding chiral shift reagent Yb(hfc)₃ in a 1:1 mixture of CDCl₃/CCl₄. The signal monitored was the aromatic proton H2' at 7.41 ppm. The two enantiomeric proton signals reached almost baseline separation once the molar ratio of compound 159 and the chiral shift reagent Yb(hfc)₃ reached 1:1 (Scheme 3.11). As shown in Scheme 3.11, the two enantiomeric proton signals were separated by 0.19 ppm (Δδ = 0.19 ppm), and broadened as well.
Scheme 3.11  NMR Chiral Shift Reagent Study on the Racemic Mixture of Product 159 (a) Before Adding Yb(hfc)$_3$  (b) During Yb(hfc)$_3$ Addition  (c) Yb(hfc)$_3$/159 Molar Ratio Reached 1:1

The enantiomeric excesses in photoproducts 159 and 160 from the photolysis of salts 169n, 169p and 170 are listed in Table 3.04. Salts 169n and 170 gave high optical yields in the major photoproduct 159 upon solid state irradiation, whereas the solution photolysis of salt 169n yielded the photoproducts without any enantiomeric excess.

Table 3.04  The Enantiomeric Excesses of Photoproducts 159 and 160 from the Photolysis of Chiral Salts

<table>
<thead>
<tr>
<th>Salt</th>
<th>Conversion %</th>
<th>Reaction Medium**</th>
<th>159/160</th>
<th>159 ee%*</th>
<th>160 ee%</th>
</tr>
</thead>
<tbody>
<tr>
<td>169n</td>
<td>87</td>
<td>Crystal</td>
<td>5.5:1</td>
<td>97(+)</td>
<td>37(−)</td>
</tr>
<tr>
<td>170</td>
<td>69</td>
<td>Crystal</td>
<td>5.5:1</td>
<td>97(−)</td>
<td>20(+</td>
</tr>
<tr>
<td>169p</td>
<td>79</td>
<td>Crystal</td>
<td>5.5:1</td>
<td>12(−)</td>
<td>17(−)</td>
</tr>
<tr>
<td>169n</td>
<td>40</td>
<td>Chloroform</td>
<td>1.6:1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* Estimated error ±3%. Sign of optical rotation of predominant enantiomer shown in parentheses. ** Photolysis temperature: crystals at -40°C, chloroform solution at 22°C.
Salt 169n, made up with acid 119 and S-(+)-2-pyrrolidinemethanol (L-prolinol), led to the formation of the (+)-enantiomer of product 159 upon solid state photolysis. In contrast, salt 170, prepared from acid 119 and R-(-)-2-pyrrolidinemethanol (D-prolinol), resulted in the formation of the (−)-enantiomer of photoproduct 159.

3.4.4. The Structure-Reactivity Analysis of Salt 169n

The X-ray analysis of salt 169n made it possible to further examine its solid state reactivity. The packing diagram and ORTEP drawings of salt 169n are shown in Schemes 3.12 and 3.13. According to the X-ray crystallographic analysis, salt 169n crystallizes in a chiral space group P212121, and there is only one independent molecule in the asymmetric unit. The absolute configuration of the reactant anion in salt 169n can be defined by the sign of a dihedral angle, defined in this case as that between the reacting carbonyl group and the neighboring α and β carbons [O=C-C(α)-C(β)].104 Since this dihedral angle in the crystals of salt 169n is negative (−82°C), the corresponding reactant anion is assigned as having the S absolute configuration.

The distances between the carbonyl oxygen O12 and the 6 γ-hydrogens were calculated, based on the crystal structure. It was found that only H2B (Table 3.05) is within the proposed hydrogen abstraction distance of 3.0 Å.63,64 The hydrogen abstraction geometric parameters are listed in Table 3.05.
### Table 3.05 The Hydrogen Abstraction Geometric Parameters of Salt 169n

<table>
<thead>
<tr>
<th>γ-H</th>
<th>d (C=O⋯H) (Å)</th>
<th>Δ(°)</th>
<th>ω(°)</th>
<th>Θ(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2B</td>
<td>2.70</td>
<td>87.0</td>
<td>45.9</td>
<td>118.5</td>
</tr>
<tr>
<td>H9A</td>
<td>3.14</td>
<td>53.5</td>
<td>53.0</td>
<td>114.3</td>
</tr>
<tr>
<td>H2A</td>
<td>3.47</td>
<td>81.0</td>
<td>20.7</td>
<td>69.9</td>
</tr>
<tr>
<td>H9B</td>
<td>4.05</td>
<td>33.9</td>
<td>32.8</td>
<td>58.0</td>
</tr>
<tr>
<td>H8B</td>
<td>4.74</td>
<td>51.7</td>
<td>8.6</td>
<td>74.5</td>
</tr>
<tr>
<td>H8A</td>
<td>4.91</td>
<td>35.1</td>
<td>12.8</td>
<td>64.5</td>
</tr>
</tbody>
</table>

### Scheme 3.12 The Packing Diagram for Salt 169n
Scheme 3.13  The Absolute Configuration of Salt 169n  (a) Stereo View  (b) The Labeling of Atoms
It should be pointed out that the atom labeling in the crystal structure of salt 169n is different from that used before (IUPAC labeling). In the following discussion, the crystal labeling (Scheme 3.13) is followed.

Scheme 3.14  The Conformations of Salt 169n and the Diradical Intermediate 173

According to the proposed Norrish type II reaction mechanism, in the photolysis of salt 169n, the γ-hydrogen abstraction (most probably H2B) by the carbonyl oxygen (O12) leads to the formation of a 1,4-diradical intermediate 173. The radical coupling reaction of intermediate 173 will give the trans and cis cyclobutanols 159s and 160s (Schemes 3.14, 3.15 and 3.16).
In molecules of salt 169n (Scheme 3.14), there are two diastereotopic carbonyl faces (*re* and *si*). The crystal structure diagrams (Schemes 3.12 and 3.13) reveal that the carbonyl *re* face is closer to the reacting γ-hydrogen H2B and the γ-carbon C2 than the corresponding *si* face. It can be postulated that, in the solid state, these two faces remain in approximately the same position in biradical 173 as in the starting material 169n. In the diradical intermediate 173, there are another two diastereotopic faces on the radical-bearing carbon C2 (Scheme 3.14), which can also be defined as *re* and *si* faces by following the sequence rule. Now let's discuss the formation of the two photoproducts *trans* cyclobutanol 159s and *cis* cyclobutanol 160s (Schemes 3.15 and 3.16).
Scheme 3.16  The Radical Coupling Reactions via Pathways 3 and 4
As shown in Scheme 3.15, a single bond formation via the radical coupling reaction leads to the cyclobutanol type photoproducts. There are four possible pathways for forming a single bond between the two radicals in the intermediate 173 (pathways 1 and 2 are shown in Scheme 3.15, pathways 3 and 4 are shown in Scheme 3.16). Pathway 1 is the bond formation between the \( p \) orbital lobe on C12 at the \( re \) face and the \( p \) orbital lobe on C2 at the \( re \) face (C12 \( re \) + C2 \( re \)), to give \( cis \)-cyclobutanol 160s in C3(R) absolute configuration. This product is called C3(R)-diastereomer of \( cis \)-cyclobutanol 160s for the simplicity of description, because the chiral carbon C3 has the R configuration. Pathway 2, C12 \( re \) + C2 \( si \), gives \( trans \)-cyclobutanol 159s in C3(R) absolute configuration; pathway 3, C12 \( si \) + C2 \( re \), leads to \( trans \)-cyclobutanol 159s in C3(S) absolute configuration; pathway 4, C12 \( si \) + C2 \( si \), yields \( cis \)-cyclobutanol 160s in C3(S) absolute configuration. Among these four possible pathways, pathway 1 involves the least motion, therefore the C3(R)-diastereomer of \( cis \)-cyclobutanol 160s is the topoclectronically favored photoproduct. In contrast, pathways 2, 3 and 4 require certain molecular motions to bring the corresponding \( p \) orbital lobes into position for bond formation. The molecular movement required for pathway 2 can be described in three ways. The first is the rotation of the adamantyl group around the C1-C11 single bond [rotation (a), Schemes 3.15 and 3.17], while the position of the phenone-salt moiety is fixed; the second one is the rotation of the phenone-salt moiety around the C1-C11 single bond [rotation (b), Scheme 3.17], while the adamantyl group position is fixed; the third one is the combination of rotations (a) and (b). Adamantane itself is a symmetric molecule with a spherical shape. There is a symmetry axis (C\(_3\) symmetry) through the center of the molecule, and this C\(_3\) symmetric axis of the 1-adamantyl group coincides with the C1-C11 single bond in the starting salt 169n. Therefore the rotation of adamantyl group around the C1-C11 bond in the reaction process is considered to be of least hindrance, because this movement does not require much void space. To some
extent, this movement is similar to the rotation of a sphere on its central axis, and is pictured in Scheme 3.17. On the other hand, the rotation of the phenone-salt moiety around the C1-C11 bond [rotation (b)] is similar to the swing of a long bar, which requires more void space (Scheme 3.17). In view of the close crystal packing, rotation (a) is more favored than rotation (b) in the solid state.

Scheme 3.17 The Rotations (a) and (b) for Pathway 2
Turning to pathways 3 and 4, in which the C12 si face is involved in forming the C12-C2 single bond, in addition to the motions discussed above for pathway 2, extra molecular movements are required to bring the C12 si face into position for bond formation.

Scheme 3.18 The Rotations (c) and (d) for Pathways 3 and 4
formation. There are also three types of possible group movements for setting the C12 surface in position. One is the rotation (ca. 180°) of the adamantyl moiety around the C11-C12 single bond while the position of the phenone-salt moiety is fixed [rotation (c)]. The second one is the rotation (ca. 180°) of the phenone-salt moiety around the C11-C12 single bond [rotation (d)], while the position of the adamantyl moiety is fixed. The third one is the combination of rotations (c) and (d). By examining the stereo packing diagram (Scheme 3.12), it can be seen that both pathways should be sterically hindered by the surrounding molecules. Rotation of the adamantyl moiety around C11-C12 requires certain void space. Rotation of the long phenone-salt moiety, however, requires more void space. Rotations (c) and (d) are shown in Scheme 3.18.

Among the four possible rotations discussed above, rotation (a) is highly probable to be involved in the solid state photoreaction, because it does not require much void space; whereas rotations (b), (c) and (d) could be prohibited by the close crystal packing arrangement. To have an idea about how close the molecules are packed in the crystals of salt 169n, some intermolecular distances are listed in Table 3.06.

<table>
<thead>
<tr>
<th>Nonbonded Atoms</th>
<th>Distance (Å)</th>
<th>Sum of van der Waals Radii (Å)</th>
<th>Nonbonded Atoms</th>
<th>Distance (Å)</th>
<th>Sum of van der Waals Radii (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1...H20</td>
<td>2.61</td>
<td>2.72</td>
<td>C23...H8A</td>
<td>3.11</td>
<td>2.92</td>
</tr>
<tr>
<td>N21...H15</td>
<td>2.86</td>
<td>2.75</td>
<td>C4...H7</td>
<td>3.13</td>
<td>2.92</td>
</tr>
<tr>
<td>H15...H21B</td>
<td>2.44</td>
<td>2.40</td>
<td>C8...H4B</td>
<td>3.13</td>
<td>2.92</td>
</tr>
<tr>
<td>C15...H22A</td>
<td>2.88</td>
<td>2.92</td>
<td>C7...H4B</td>
<td>3.14</td>
<td>2.92</td>
</tr>
<tr>
<td>C15...H6A</td>
<td>3.02</td>
<td>2.92</td>
<td>C15...H21B</td>
<td>3.16</td>
<td>2.92</td>
</tr>
<tr>
<td>C24...H8A</td>
<td>3.07</td>
<td>2.92</td>
<td>C19...H4A</td>
<td>3.19</td>
<td>2.92</td>
</tr>
</tbody>
</table>
As shown in Table 3.06, some intermolecular distances between non-bonded atoms are very short, which are close to the sum of van der Waals radii; two distances (underlined) are even shorter than the sum of van der Waals radii. These data indicate that the molecules are very closely packed in crystals of salt \textit{169n}; therefore, rotations (b), (c) and (d) are not very likely to happen during the solid state photolysis of salt \textit{169n}.

For the summary, based on the above analysis, it is suggested that the diradical coupling pathways 3 and 4, which require the topochemically disfavored rotations (c) and/or (d), will not occur in the solid state photoreaction. Pathway 2, which involves the topochemically allowed rotation (a), will occur in the photolysis and give \textit{trans}-cyclobutanol photoproduct. Pathway 1, which involves the least motion among the four possible pathways, will lead to \textit{cis}-cyclobutanol as the major photoproduct. In other words, it is predicted that only two photoproducts out of the possible four (Scheme 3.15 and 3.16) will be formed; the C3(R)-diastereomer of \textit{cis}-cyclobutanol \textit{160s} is predicted to be the major photoproduct, and the C3(R)-diastereomer of \textit{trans}-cyclobutanol \textit{159s} is predicted to be the minor photoproduct.

It should be pointed out that the rotations (a)-(d) can go both directions, either clockwise or counter-clockwise, and only one direction was shown for each rotation in Schemes 3.17 and 3.18.

### 3.4.5. The Structure-Reactivity Correlation for Salt 169n

It was found experimentally that the solid state photolysis of salt \textit{169n} gave the \textit{trans}-cyclobutanol \textit{159} as the major photoproduct (\textit{trans/cis} ratio 5.5:1, Table 3.04, page
107), instead of the predicted major photoproduct cis-cyclobutanol 160. To explain this result, molecular mechanics calculation (MMX) on the energy minima of products 159, and 160 was conducted for comparison. The MMX calculation results indicate that the trans-cyclobutanol 159 is the thermodynamically favored photoproduct.

<table>
<thead>
<tr>
<th>Photoproduct</th>
<th>trans-cyclobutanol 159</th>
<th>cis-cyclobutanol 160</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Energy</td>
<td>78.20 kcal/mol</td>
<td>79.82 kcal/mol</td>
</tr>
</tbody>
</table>

Another explanation for the observed product ratio is that the formation of cis-product 160s (Scheme 3.15) has to compete with the reverse hydrogen abstraction reaction. The biradical intermediate 173 can return to the parent ketone 169n, form cis-product 160s, or undergo rotation (a) to give the trans-product 159s. The formation of cis-product 160s is probably not competitive with the other two processes.

Experimental results in Table 3.04 also indicate the formation of a single diastereomer of 159s, because the ester form 159 (the ester form of product 159s) has very high enantiomeric purity (97% e.e.). Among the four possible pathways (Schemes 3.15 and 3.16), two pathways (2 and 3) lead to trans photoproduct 159s; and these two pathways give different diastereomers of product 159s, which are related to the two enantiomers of product 159. This implies that for the trans photoproduct 159s formation, there is only one pathway involved; or in other words, only one of the two diastereotopic faces of radical C12 (in the intermediate 173) was actually reacted in the formation of the trans-cyclobutanol 159s. Pathway 2 is the predicted reaction process, based on topochemical consideration. This prediction can be verified by determining the absolute configuration of photoproduct 159s obtained from the solid state photolysis of salt 169n.
There are also two pathways (pathways 1 and 4, Schemes 3.15 and 3.16) that lead to cis-cyclobutanol 160s, and each pathway gives a different diastereomer of 160s. The experimental results, that ester 160 was formed in low optical yield (< 40% e.e., Table 3.04), indicate that both the topochemically favored pathway 1 and disfavored pathway 4 were followed. It is difficult to explain why both of the diastereotopic faces on radical C12 were reacted to form cis-product 160s, and only one diastereotopic face was involved in forming trans-product 159s. However, a similar example has been reported from our group in which the solid state photolysis of a chiral crystal gave two photoproducts, one in high optical yield (100%), the other racemic.91a

3.4.6. The Absolute Configuration Correlation Between Salt 169n and Its Major Photoproduct 159s

Since the irradiation of salt 169n led to the formation of photoproduct 159 in high optical yield (97% ee), the absolute configuration correlation is very helpful in understanding the solid state reaction pathways. The absolute configuration of salt 169n is known (Schemes 3.12 and 3.13), and this correlation relies on obtaining the absolute configuration of the photoproduct 159 or 159s. Since there is no heavy atoms in product 159, it would be difficult to determine the absolute configuration of the crystals of a pure enantiomer of product 159. Indeed, the X-ray diffraction analysis was conducted on crystals containing photoproduct 159s. These plate-like crystals were formed upon recrystallization of a reaction mixture after the solid state photolysis of salt 169n. These plates are packed in a chiral space group (P212121), and there are three different molecules in the asymmetric unit - a trans photoproduct 159s, an unreacted starting material 169n and a water molecule (perhaps present in the recrystallization solvent, acetone). The absolute configuration of the trans photoproduct 159s was directly
deduced from the crystal structure, based on the absolute configuration of the optically pure molecule S-(+)-2-pyrrolidinemethanol. The absolute configuration of product 159s was determined to be C3(R) as shown in Scheme 3.19. The crystal structure ORTEP drawing and crystal packing diagram of this C3(R) diastereomer of product 159s are shown in Schemes 3.20 and 3.21.

Scheme 3.19  The Absolute Configuration of Photoproduct 159s

Scheme 3.20  The ORTEP Drawing of Photoproduct 159s
Turing back to the starting salt 169n, there are two diastereomeric faces in the reacting radical carbon C12, in which the \textit{re} face was proposed to be the one that is involved in the reaction to give a pure C3(R)-diastereomer of the major photoproduct 159s \textit{via} pathway 2. This prediction is supported by the X-ray absolute structure analysis of the solid state photoproduct 159s, which is also a C3(R) absolute configuration.
3.4.7. The Structure-Reactivity Correlation for Salt 169p

The chiral salt made from acid 119 and S-(+)-2-pyrrolidinemethanol crystallizes in dimorphic forms. One is the needle-shaped crystal 169n, the other is the plate-form crystal 169p (Table 3.02, page 101).

The X-ray diffraction analysis of crystal 169p revealed that there are two independent molecules in the asymmetric unit. In these two molecules, the absolute configurations of the reactant anions are assigned according to the sign of the O=C-C(α)-C(β) dihedral angle as mentioned before. The crystal structure shows that one anion has the R absolute configuration (dihedral angle + 85°C), while the other has the S absolute configuration (dihedral angle − 82°C). These two reactant anions have opposite absolute configurations, even though they are both associated with an S-(+)-pyrrolidinemethanol-derived cation. The conformations of these two molecules are very similar to each other, but not identical. The hydrogen abstraction parameters, ORTEP drawing and packing diagrams are depicted in Schemes 3.22 and 3.23.

Table 3.07 Hydrogen Abstraction Geometric Parameters of Salt 169p

<table>
<thead>
<tr>
<th>γ-H</th>
<th>d (C=O⋯H) (Å)</th>
<th>Δ(°)</th>
<th>ω(°)</th>
<th>θ(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2b</td>
<td>2.70</td>
<td>84.5</td>
<td>53.5</td>
<td>114.6</td>
</tr>
<tr>
<td>H2a</td>
<td>3.31</td>
<td>84.7</td>
<td>26.2</td>
<td>78.8</td>
</tr>
<tr>
<td>H9a</td>
<td>3.43</td>
<td>47.5</td>
<td>47.8</td>
<td>108.9</td>
</tr>
<tr>
<td>H9b</td>
<td>4.28</td>
<td>30.2</td>
<td>28.7</td>
<td>57.0</td>
</tr>
<tr>
<td>H8a</td>
<td>4.59</td>
<td>56.5</td>
<td>7.8</td>
<td>79.8</td>
</tr>
<tr>
<td>H8b</td>
<td>4.89</td>
<td>38.7</td>
<td>10.4</td>
<td>62.0</td>
</tr>
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</table>
Molecule with a S absolute configuration anion

<table>
<thead>
<tr>
<th>γ-H</th>
<th>d (C=O···H) (Å)</th>
<th>Δ(°)</th>
<th>Θ(°)</th>
<th>ω(°)</th>
</tr>
</thead>
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<tr>
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<td>82.6</td>
<td>53.9</td>
<td>115.0</td>
</tr>
<tr>
<td>H32a</td>
<td>3.24</td>
<td>83.1</td>
<td>25.9</td>
<td>78.3</td>
</tr>
<tr>
<td>H39a</td>
<td>3.50</td>
<td>46.0</td>
<td>44.7</td>
<td>109.4</td>
</tr>
<tr>
<td>H39b</td>
<td>4.36</td>
<td>29.9</td>
<td>26.4</td>
<td>56.8</td>
</tr>
<tr>
<td>H38a</td>
<td>4.66</td>
<td>57.4</td>
<td>7.9</td>
<td>81.3</td>
</tr>
<tr>
<td>H38b</td>
<td>4.99</td>
<td>39.8</td>
<td>9.1</td>
<td>61.3</td>
</tr>
</tbody>
</table>

Scheme 3.22  The Crystal Structure of Salt 169p
It was found that, in each of the two independent molecules, there is only one γ-hydrogen which is within the proposed abstracting distance of 3.0 Å.\textsuperscript{63,64} It can be seen from the crystal structure that in one molecule (the S absolute configuration anion), the γ-hydrogen is close to the carbonyl \textit{re} face, whereas in the other molecule (the R absolute configuration anion), the reacting γ-hydrogen is close to the carbonyl \textit{si} face. Following the previous discussion concerning salt \textit{169n}, it can be proposed that, in the case of salt \textit{169p}, there are two stereospecific photoreactions leading to the major photoproduct.
*trans*-cyclobutanol 159s. One photoreaction (S configuration anion) gives the C3(R)-diastereomer of photoproduct 159s, while the other (R configuration anion) leads to the C3(S)-diastereomer. Because the two competing reactions, which are under the influence of a chiral environment, have diastereomeric transition states of presumably unequal energy, one diastereomer should be formed in greater amounts than the other, and this accounts for the observed low enantiomeric excess in the final product 159 (12% ee). However, we cannot rule out the possibility that salt 169p reacts non-stereospecifically. As previously discussed, solid state photolysis of salt 169n afforded *cis*-cyclobutanol 160 non-stereospecifically. Also reported from our group, photoreactions in chiral crystals do not always proceed with high enantioselectivity.91a

3.4.8. The Solution Photolysis of Chiral Salt 169n

Chiral salt 169n was photolysed in chloroform solution. It was found that photoproducts 159 and 160 were formed in racemic form (Table 3.04, page 107). This is probably due to the fact that, as a result of dissociation, the chiral handle is relatively far away from the reacting center, as well as to the conformational freedom that the reactant anion has in solution. It appears, therefore, that the role of the ionic chiral handle in the solid state is mainly to ensure a chiral space group. Similar results, that the solution photolysis of substrates with ionic chiral handles gave racemic photoproducts, have also been reported.77,78

3.5. The Quantum Yield Measurement for Ketone 150

The type II quantum yields of *α*-adamantyl ketones have been reported by Gagosian et al.,97 Lewis et al.98 and Scheffer et al.100 In this thesis, the *α*-adamantyl
ketone 150 was selected for quantum yield studies. A known method was followed, and the measured quantum yields of ketone 150 in the Norrish type II reaction are listed in Table 3.08.

**Table 3.08** The Quantum Yields* of α-Adamantyl Ketones

<table>
<thead>
<tr>
<th>Ketone</th>
<th>X</th>
<th>Φtotal</th>
<th>Φtrans</th>
<th>Φcis</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>-C₆H₄COOMe</td>
<td>0.043</td>
<td>0.033</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>155</td>
<td>Me</td>
<td>0.0133</td>
<td>0.0033</td>
<td>0.010</td>
<td>97</td>
</tr>
<tr>
<td>167</td>
<td>-C₆H₅</td>
<td>0.04</td>
<td>-----</td>
<td>-----</td>
<td>98</td>
</tr>
<tr>
<td>174</td>
<td>-C₆H₄Cl</td>
<td>0.05</td>
<td>-----</td>
<td>-----</td>
<td>100</td>
</tr>
</tbody>
</table>

* All data obtained from benzene solution.

The total type II reaction quantum yield of ketone 150 (0.043) is very close to those of its analogs 167 (0.04) and 174 (0.05). In order to compare the photoreactivity in both solution and solid phases, solid state quantum yield of ketone 150 was determined by following two recently reported methods. However, the data obtained were not self-consistent; this might be due to the design of the experimental methods, and will not be discussed in this thesis.

3.6. **Photochemistry of α-(3-methyl)-adamantyl ketones**

Before discussing the photochemical reactions of α-(3-methyl)-adamantyl ketones, it is necessary to briefly review the photochemical reactions of α-adamantyl...
ketones. An example is selected for discussion (150).

As shown above, ketone 150 is a symmetric molecule. There is a plane of symmetry (C2-C1"-C2"-C3" plane), and there is also a C3 axis in the 1-adamantyl group which makes all six γ-hydrogens equivalent. As a result, the solution photolysis of ketone 150 leads to the formation of only one diradical intermediate (150a, Scheme 3.04) and two Norrish type II cyclization products, 159 and 160 (Scheme 3.03).

In contrast, an extra methyl group substituted at the adamantyl ring in the 3" position makes the six γ-hydrogens non-equivalent. For example, the photolysis of α-(3-methyl)-adamantyl ketone 154 in solution could lead to the formation of two different types of diradical intermediates and six possible Norrish type II cyclization products (Scheme 3.24, page 129). Note that intermediates 154B and 154C are enantiotopic diradical species, and lead to diastereotopic photoproducts.

Therefore, α-(3-methyl)-adamantyl ketones should be good candidates for solid state stereoselectivity studies. In addition, chiral salts like 169n could be made from the carboxylic acid 120 (Scheme 3.01) for solid state asymmetric induction studies.
Scheme 3.24 The Six Possible Photoproducts from the Norrish Type II Reaction of α-(3-Methyl)-Adamantyl Ketone 154
The photolysis of ketone **154** was conducted in acetonitrile solution, and a column chromatographic separation was conducted after the photoreaction in order to isolate each photoproduct. However, difficulties were encountered in the isolation of these stereoisomeric products, which are structurally very similar. Only three photoproducts (168, 176 and 180) were isolated from the reaction mixture (partial separation). The characterization of these three products is discussed below.

### 3.6.1. The Characterization of Photoproduct 180

High resolution mass spectroscopic analysis revealed the formula of product **180** to be C_{21}H_{24}O_{2}, which is two hydrogens and one oxygen less than that of the starting ketone **154**. This suggested that product **180** might be a dehydration product of the Norrish type II cyclization products, and have one of the three possible structures shown in Scheme 3.25. As references, a similar dehydration product **161** was found in the solution photolysis of α-adamantyl ketone **150** (Scheme 3.03, page 92), and two other dehydration products were also reported.95,96

![Scheme 3.25: The Three Possible Structures for Product 180](image)

**A**

**B**

**C**

Ar = -C_{6}H_{4}COOMe

**Scheme 3.25**  The Three Possible Structures for Product **180**
It was found that B and C are enantiotopic structures, by constructing molecular models. The difference between structures A and B is that there is a plane of symmetry in structure A (C1-C4-C5 plane), and 16 carbon signals out of 21 carbons are expected from structure A in the $^{13}$C NMR spectrum. In contrast, there is no plane of symmetry in structure B, therefore 19 carbon signals are expected. Also in the $^{13}$C APT experiment, five methine and methyl carbon signals are expected for structure A, and six methine and methyl carbon signals are expected for structure B. The $^{13}$C NMR and APT spectra of product 180 are shown in Schemes 3.26 and 3.27, in which, total 19 carbon signals and 6 methine and methyl signals are found. Therefore product 180 was assigned as having the structure B.

19 Carbon Signals

Scheme 3.26  The $^{13}$C NMR Spectrum (50 MHz, CDCl$_3$) of Product 180
3.6.2. The Characterization of Photoproduct 176

The mass spectrum of photoproduct 176 gave a parent mass which is the same as that of the starting ketone 154. This indicates that product 176 might be one of the six possible Norrish type II photoproducts listed in Scheme 3.24. Besides, the IR, $^1$H NMR, $^{13}$C NMR and APT spectra are all indicative of a Norrish type II cyclization product. The characterization of these six diastereomeric photoproducts shown in Scheme 3.24 (page 129) are mainly dependent on (a) the assignment of the position of the methyl substituent position, (b) the cis and trans cyclobutanol assignment.
Scheme 3.28  The Assigned Structure of Photoproduct 176

The cis and trans isomers can be differentiated by NOE experiments. For instance, NOE irradiation of proton H4 (Schemes 3.08 and 3.28) will enhance the aromatic hydrogen H2' signal in trans isomer only. The methyl substituent position can also be assigned by NOE experiments.

To find hydrogen H4 in the $^1$H NMR spectrum, it is necessary to locate carbon C4 in $^{13}$C NMR first. Then the H4 signal can be determined by a 2-D $^{13}$C-$^1$H HETCOR experiment. In the characterization of product 176, the signal due to carbon C4 was located based on the $^1$H NMR, $^{13}$C NMR, APT and HETCOR experiments, and these spectra are shown in Schemes 3.29-3.31.

First of all, the $^{13}$C NMR and APT spectra were used to differentiate the methyl and methine carbons from the remaining carbons in the molecule. Secondly, the HETCOR experiment revealed the positions of two methyl carbons (one on the adamantyl moiety, the other in the ester group), which were correlated with two three-proton peaks (Scheme 3.30); and also the aromatic methine carbons can be easily
recognized by their chemical shifts. Now this leaves only three methine carbon signals to be determined. Among these 3 methine carbons, one is C4, and the other two are two carbons out of the following three - C5, C7 & C9. Among these methine carbons, only C4 is a β-carbon relative to the electron-withdrawing hydroxyl group on the cyclobutane ring, therefore C4 should have the biggest chemical shift value. Based on this argument, carbon C4 is assigned at 66.3 ppm, and hydrogen H4 is then assigned at 2.36 ppm based on the HETCOR spectrum (Scheme 3.30).

The following NOE experiments led to the structure assignment for photoproduct 176 (Scheme 3.28). Irradiation of H4 resulted in enhancement of the signals due to the methyl group (1.1% enhancement) and H2b (5.8%). Irradiation of the methyl group enhanced H4 (6.9%) and H2' (7.4%). (Scheme 3.31)

<table>
<thead>
<tr>
<th>NOE experiment</th>
<th>Result</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation of CH₃</td>
<td>H4 enhanced by 6.9%</td>
<td>CH₃ attached to C5</td>
</tr>
<tr>
<td></td>
<td>H2' enhanced by 7.4%</td>
<td></td>
</tr>
<tr>
<td>Irradiation of H₄</td>
<td>CH₃ enhanced by 1.1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H2b enhanced by 5.8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No enhancement on H2'</td>
<td>Not a cis cyclobutanol</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Must be a trans cyclobutanol</td>
</tr>
</tbody>
</table>
Scheme 3.29  The $^1$H NMR and $^{13}$C APT Spectra of Product 176
Scheme 3.30  The Structure of Product 176 and Its Partial HETCOR Spectrum
Scheme 3.31  The NOE Spectra of Product 176  (a) Irradiation of Proton H4
(b) Irradiation of Methyl Group  (c) Off-resonance Spectrum
3.6.3. The Characterization of Photoproduct 168

![Chemical Structure of 168]

Scheme 3.32  The Assigned Structure of Photoproduct 168

To characterize product 168, the same procedure that was used in characterizing product 176 was employed. For the simplicity, only the key steps are discussed below. For a detailed analysis, please refer to the characterization of product 176 on page 132. The structure of product 168, which is shown in Scheme 3.32, was assigned after the following experimental results and analysis:

a) The NMR signal assignments for the ring junction carbon C4 and the attached hydrogen H4 were based on the $^1$H NMR, $^{13}$C NMR, APT and HETCOR spectra. The related spectra and signal assignments are shown in Schemes 3.33 and 3.34.
b) NOE experiments were conducted to determine the cis or trans nature of photoprodut 168, and to determine the methyl substituent position on the adamantyl group. The NOE spectra are shown in Scheme 3.35.

<table>
<thead>
<tr>
<th>NOE experiment</th>
<th>Result</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation of H4</td>
<td>H2' signal enhanced by 2.7%</td>
<td>Trans Cyclobutanol</td>
</tr>
<tr>
<td>Irradiation of Me</td>
<td>H2' &amp; H4 signals not enhanced</td>
<td>Me not attached to C5</td>
</tr>
<tr>
<td>at 0.76 ppm</td>
<td>H10a signal* not enhanced</td>
<td>Me not attached to C9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Me attached to C7</td>
</tr>
</tbody>
</table>

* The H10a signal was assigned based on the structure assignment of a similar photoprodut 159. Please see page 97 for analysis.
Scheme 3.33  (a) $^1$H NMR Spectrum (500 MHz, CDCl$_3$) of Product 168  (b) The Partial Expansion of the above $^1$H NMR Spectrum
Scheme 3.34  (a) Partial HETCOR Spectrum  (b) APT Spectrum of Photoprodut 168
Scheme 3.35  NOE Spectra of Photoproduct 168 (a) Irradiation of Proton H4  
(b) Irradiation of Methyl Group  (c) Off-resonance Spectrum
3.7. The Solid State Photolysis of Chiral Crystals of α-(3-Methyl)-Adamantyl Ketone 153

The X-ray diffraction analysis of α-(3-methyl)-adamantyl ketone 153 reveals that this achiral molecule crystallizes in a chiral space group by spontaneous resolution (space group $P2_12_12_1$), and also that only one $\gamma$-hydrogen (H6a, Table 3.09) is within the proposed reacting distance of 3.0Å.63,64 In total, there are 6 $\gamma$-hydrogens attached to 3 different $\gamma$-carbons. Abstraction of different hydrogens will result in the formation of different photoproducts, as was discussed for the photolysis of ketone 154 (Scheme 3.24, page 129). Therefore ketone 153 is not only a good candidate for solid state absolute asymmetric induction studies, but also a very good candidate for solid state regioselectivity studies. The molecular structure of ketone 153 in the crystal is shown in Scheme 3.36.
**Table 3.09**  Hydrogen Abstraction Geometric Parameters of Ketone 153

<table>
<thead>
<tr>
<th>γ-H</th>
<th>$d (\text{C=O} \cdots \text{H}) ,(\text{Å})$</th>
<th>$\Delta(\text{o})$</th>
<th>$\omega(\text{o})$</th>
<th>$\Theta(\text{o})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H6a</td>
<td>2.73</td>
<td>74.4</td>
<td>62.6</td>
<td>110.0</td>
</tr>
<tr>
<td>H6b</td>
<td>3.13</td>
<td>81.8</td>
<td>37.7</td>
<td>84.2</td>
</tr>
<tr>
<td>H4b</td>
<td>3.76</td>
<td>36.4</td>
<td>36.0</td>
<td>103.9</td>
</tr>
<tr>
<td>H2a</td>
<td>4.50</td>
<td>59.6</td>
<td>11.3</td>
<td>86.1</td>
</tr>
<tr>
<td>H4a</td>
<td>4.53</td>
<td>23.3</td>
<td>20.1</td>
<td>57.1</td>
</tr>
<tr>
<td>H2b</td>
<td>4.93</td>
<td>41.4</td>
<td>8.9</td>
<td>60.1</td>
</tr>
</tbody>
</table>

**Scheme 3.36**  The ORTEP Drawing of Ketone 153
3.7.1. The Solid State Photolysis of Ketone 153

Chiral crystals of ketone 153 were photolyzed at room temperature for a few days (96 hours). The reaction conversion was found to be 15%. A major photoproduct 181 was isolated (93% of the total photoproducts). The remaining 7% of mixed photoproducts was not further analysed, because of separation difficulties.

3.7.2. The Characterization of Photoproduct 181

Photoproduct 181 was determined to be a Norrish type II cyclization product by spectroscopic analysis. The structural assignment procedures are outlined below, and the assigned structure is given in Scheme 3.37.

Scheme 3.37 The Assigned Structure of Photoproduct 181

a) The NMR signal assignments for the ring junction carbon C4 and the attached hydrogen H4 were based on the $^1$H NMR, $^{13}$C NMR, APT and HETCOR spectra. The related spectra and signal assignments are shown below in Schemes 3.38 to 3.40.
Scheme 3.38  The $^1$H NMR Spectrum (500 MHz, CDCl$_3$) of Product 181
Scheme 3.39  The $^{13}$C APT Spectrum (50 MHz, CDCl$_3$) of Product 181
Scheme 3.40  The Partial HETCOR Spectrum of Photoprodct 181
b) NOE experiments were conducted to determine the cis or trans arrangement of the substituents on the cyclobutane ring, and to determine the methyl substituent position on the adamantyl group. The NOE experimental results are shown in Table 3.10.

**Table 3.10** The NOE Results for Photoproduct 181

<table>
<thead>
<tr>
<th>Proton Irradiated</th>
<th>Proton Signal Enhanced (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3'</td>
<td>H2'(4.3%)</td>
</tr>
<tr>
<td>H2'</td>
<td>H3'(4.7%), H2a(18%), H9(8.5%)</td>
</tr>
<tr>
<td>H2a</td>
<td>H2'(9.6%), H2b(15%)</td>
</tr>
<tr>
<td>H4</td>
<td>H2b(3.9%)</td>
</tr>
<tr>
<td>H9</td>
<td>H2'(4.0%)</td>
</tr>
<tr>
<td>H2b</td>
<td>H2a(21%), H4(6.2%)</td>
</tr>
<tr>
<td>CH₃</td>
<td>No proton listed above was enhanced</td>
</tr>
<tr>
<td></td>
<td>some CH₂ signals were enhanced</td>
</tr>
</tbody>
</table>

* The percentage enhancement is given in brackets.

The methyl substituent position was assigned after the assignment of the two bridgehead methine protons H5 and H9. The above NOE results indicate that H5 is next to H4, and H9 is close to the aromatic proton H2'. Therefore the only position left for the methyl group is at the bridgehead C7 position. This assignment was further confirmed by irradiation of the methyl group, which failed to enhance either H4 or H2'. If this methyl group were attached at carbon C9, the aromatic proton H2' signal would have been enhanced, as was reported in a similar compound.⁹⁵
Photoprodut 181 was assigned as a *cis* cyclobutanol, based on the NOE experiment result that the irradiation of H4 did not enhance the signal due to aromatic hydrogen H2'.

3.7.3. The Structure-Reactivity Correlation for Ketone 153

Scheme 3.41  Solid State Photolysis of Ketone 153
According to the X-ray structure analysis, the closest γ-hydrogen to the carbonyl oxygen (O1) is hydrogen H6a on carbon C6 (Table 3.09, page 144). The H6a—O1 distance is 2.73 Å, which is within the proposed γ-hydrogen abstraction distance of 3.0 Å.63,64 In the solid state photolysis, the abstraction of γ-hydrogen H6a by the carbonyl oxygen O1 will result in the formation of a 1,4-diradical intermediate 153A (Scheme 3.41). In this diradical intermediate 153A, one radical will be on the carbonyl carbon C11, and the other radical will be on the γ-carbon C6. The radical coupling reaction will lead to the formation of both cis and trans photoproducts 181 and 153B. As shown in Scheme 3.41, the formation of cis-cyclobutanol 181 involves the single bond formation between the p orbital lobe on the C11 si face and the p orbital lobe on the C6 si face (C11 si + C6 si). Since this process requires the least molecular motion, cis-cyclobutanol 181 is the topochemically favored photoproduct. The formation of the corresponding trans isomer 153B, via process C11 si + C6 re, requires rotation [rotation (e) and/or rotation (f), Scheme 3.42] around the C1-C12 single bond in order to bring the corresponding p orbital lobes (on the two radical-bearing γ-carbons C6 and C11) into position for bonding.

As shown in Scheme 3.42, rotation (e) involves rotation of the adamantyl group around the C1-C12 single bond, while the position of the phenone moiety is fixed. This rotation is topochemically disfavored, because the rotation of a methyl-substituted adamantyl group is an unsymmetric operation, which requires more void space to accommodate the methyl substituent compared with the rotation of the unsubstituted adamantyl group in salt 169n [rotation (a), Scheme 3.16]. As shown in Table 3.11, this methyl substituent makes close contact with atoms from its surrounding molecules (C13, H17, H18 and H19 are the four atoms in this methyl group), therefore, rotation (e) should be sterically hindered. Rotation (f) is to rotate the phenone moiety around the C1-C12
single bond, which is also a topochemically disfavored process (Scheme 3.42). Because both rotations (e) and (f) are sterically disfavored, *trans*-cyclobutanol 153B should be a minor photoproduct. The experimental results reveal that ketone 153 gives a *cis* major solid state photoproduct (93%), and salt 169n leads to a *trans* major photoproduct (85%). The difference between rotation (e) in ketone 153 and rotation (a) in salt 169n is proposed to account for the observed difference in stereochemistry.

![Scheme 3.42 Description of Rotations (e) and (f)]
Table 3.11  Selected Intermolecular Distances between the Methyl Group and Its Surrounding Molecules in Crystals of 153

<table>
<thead>
<tr>
<th>Nonbonded Atoms</th>
<th>Distance (Å)</th>
<th>Sum of van der Waals Radii (Å)</th>
<th>Nonbonded Atoms</th>
<th>Distance (Å)</th>
<th>Sum of van der Waals Radii (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1···H19</td>
<td>2.92</td>
<td>2.72</td>
<td>C17···H19</td>
<td>3.40</td>
<td>2.92</td>
</tr>
<tr>
<td>O1···H17</td>
<td>3.49</td>
<td>2.72</td>
<td>C11···H19</td>
<td>3.41</td>
<td>2.92</td>
</tr>
<tr>
<td>N1···H18</td>
<td>2.74</td>
<td>2.75</td>
<td>C12···H19</td>
<td>3.51</td>
<td>2.92</td>
</tr>
<tr>
<td>N1···H19</td>
<td>3.30</td>
<td>2.75</td>
<td>H1···H18</td>
<td>2.77</td>
<td>2.40</td>
</tr>
<tr>
<td>C13···H23</td>
<td>3.08</td>
<td>2.92</td>
<td>H1···H17</td>
<td>2.80</td>
<td>2.40</td>
</tr>
<tr>
<td>C14···H19</td>
<td>3.17</td>
<td>2.92</td>
<td>H2···H19</td>
<td>2.81</td>
<td>2.40</td>
</tr>
</tbody>
</table>

The photoreaction of ketone 153 in the solid state showed high regioselectivity in the abstraction of γ-hydrogens. The formation of product 181 is consistent with γ-hydrogen abstraction exclusively from γ-carbon C6. The hydrogen abstraction from other γ-carbons is expected to give different stereoisomers.

The photolysis of chiral crystals of ketone 153 also leads to the formation of product 181 in optically active form; the optical rotation is measured to be $[\alpha]_D = -29^\circ$ (at room temperature, in 10 mg/ml chloroform solution). The enantiomeric excess determination for photoproduct 181, with a chiral HPLC column and NMR chiral shift reagents, was not successful.
3.8. The Hydrogen Abstraction Reaction of Ketones 120, 148, and 149

The above three α-adamantyl acetophenones were found to be photostable in the solid state, but they all reacted in the solution photolysis. The X-ray structure analysis revealed that each ketone has at least one γ-hydrogen in a position suitable for hydrogen abstraction, based on the postulate by Scheffer, Trotter and coworkers.\textsuperscript{63,64} The postulated ideal parameters and the actual data from the above ketones are listed in Table 3.12.

Most of the γ-hydrogen-carbonyl oxygen distances listed in Table 3.12 are within the proposed reacting distance (ca. 3 Å).\textsuperscript{63,64} Even though there are some deviations between the proposed ideal parameters (especially the θ and ω values) and the actual data listed in Table 3.12, these three ketones are still considered to be able to undergo solid state hydrogen abstraction reactions, because similar hydrogen abstraction geometries were also found in ketones 153, 169n and 169p (which are photochemically reactive ketones).
Table 3.12 The Hydrogen Abstraction Geometric Parameters of Ketones 148, 149 and 120

<table>
<thead>
<tr>
<th>Ketone #</th>
<th>R, X</th>
<th>γ-H</th>
<th>d (Å)</th>
<th>Δ(°)</th>
<th>ω(°)</th>
<th>θ(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C=O...H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>148</td>
<td>H, F</td>
<td>H16</td>
<td>2.64</td>
<td>80.0</td>
<td>59.6</td>
<td>112.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H20</td>
<td>2.79</td>
<td>72.4</td>
<td>62.9</td>
<td>106.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H19</td>
<td>3.07</td>
<td>82.5</td>
<td>39.6</td>
<td>88.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H15</td>
<td>3.12</td>
<td>85.0</td>
<td>31.4</td>
<td>81.3</td>
</tr>
<tr>
<td>149</td>
<td>H, CN</td>
<td>H10</td>
<td>2.57</td>
<td>93.9</td>
<td>33.3</td>
<td>120.5</td>
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<tr>
<td></td>
<td></td>
<td>H7</td>
<td>3.02</td>
<td>61.32</td>
<td>58.9</td>
<td>115.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H9</td>
<td>3.40</td>
<td>84.32</td>
<td>9.8</td>
<td>67.1</td>
</tr>
<tr>
<td>120</td>
<td>CH₃,COOH</td>
<td>H2</td>
<td>2.50</td>
<td>99.2</td>
<td>14.3</td>
<td>121.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H10</td>
<td>2.57</td>
<td>89.6</td>
<td>44.4</td>
<td>120.2</td>
</tr>
<tr>
<td>Proposed Parameter</td>
<td>Ref. 63, 64</td>
<td></td>
<td>≤ 3.0</td>
<td>90</td>
<td>0</td>
<td>180</td>
</tr>
</tbody>
</table>

It was reported by Trotter et al. that the distances between carbonyl carbon and γ-carbon in several reactive α-cycloalkyl acetophenones were around 3.2 Å. Similar distances were also found in the above-discussed three ketones. A stereodiagram of ketone 120 is shown in the appendix. A possible explanation, for the observed solid state photostability of ketones 120, 148 and 149, is that the hydrogen abstraction did occur in these ketones in the solid state; but the corresponding diradical intermediate reversed to the starting material instead of forming photoproducts. This might be due to such an unfavorable crystal packing that disallow the two radical-bearing carbons to get close and form a single bond. However, what causes the solid state photostability of these three ketones is still unclear and deserves further investigation.

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3.9. The Synthesis and Photochemistry of \( \alpha \)-Cyclohexyl Acetophenone Derivatives

Literature procedures were followed to synthesize \( \alpha \)-cyclohexyl acetophenones 182-185,93-95 which were characterized by spectroscopic analyses. The synthetic pathways are outlined in Scheme 3.43.

Scheme 3.43  The Synthesis of \( \alpha \)-Cyclohexyl Acetophenones 182-185

The solution phase photolysis of 1-(4-carbomethoxyphenyl)-2-cyclohexyl ethanone (185) is known to give both Norrish type II cyclization and cleavage photoproducts as shown in Scheme 3.44.93,95,100
Scheme 3.44 The Norrish Type II Reaction of Ketone 185

Two chiral salts (189 and 190) were made from the corresponding carboxylic acid (184) of ketone 185 in order to study the solid state asymmetric induction as well as the cleavage-cyclization reaction ratio upon solid state photolysis. The preparation of the chiral salts is shown in Table 3.13.

<table>
<thead>
<tr>
<th>Salt #</th>
<th>Chiral Amine</th>
<th>Recrystallization Solvent</th>
<th>Crystal Morphology</th>
<th>Melting Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>189</td>
<td>L-prolinol</td>
<td>acetone</td>
<td>needle</td>
<td>125.5-127.5</td>
</tr>
<tr>
<td>190</td>
<td>R(−)-α-phenylethyl amine</td>
<td>acetone</td>
<td>needle</td>
<td>160-162</td>
</tr>
</tbody>
</table>
However, these two chiral salts were found to be photochemically unreactive in the solid state. In addition, crystals of both salts were not suitable for X-ray diffraction analysis. This project was not continued.

### 3.10. The Synthesis and Photoreactivity of Diketone 108b

As shown in Scheme 3.45, there are three macrocyclic diketones (108a-c) proposed for this project. The synthesis of diketones 108a and 108b has been reported by Schimelpfenig and co-workers\textsuperscript{110}, and was accomplished by the high dilution Dieckmann condensation of the corresponding esters of \textit{p}-phenylene-dicarboxylic acids. Schimelpfenig et al. have also reported the synthesis of several other macrocyclic diketones by conducting the Dieckmann condensation reaction in very dilute solutions.\textsuperscript{111-113}

Macrocyclic diketone 108b was prepared by following the reported method via the Dieckmann condensation reaction.\textsuperscript{110} A small change was made to the original procedure, which was the use of a syringe pump to add the reactant solution to the reaction vessel, instead of using a dropping funnel. This change may be responsible for the increase in the product yield, which went from 8.2\% (reported) to 18\% (observed). As outlined in Scheme 3.46, the synthesis of macrocyclic diketone 108b involves two Friedel-Crafts acylation reactions, two Wolff-Kishner reductions and a final Dieckmann condensation reaction.\textsuperscript{110,114,115}
Scheme 3.45  The Macrocyclic Diketones 108a-c

Diketone 108b was characterized by spectroscopic methods, such as IR, UV, $^1$H NMR and $^{13}$C NMR, as well as by X-ray diffraction analysis. The ORTEP diagram is given in Scheme 3.47. Solid state DSC analysis of this compound gave an endothermic peak at 124.2 °C, which corresponded to the melting point, and no other phase transition peak was observed.
Scheme 3.46  The Synthesis of Macrocyclic Diketone 108b
The analytical scale photolysis (λ ≥ 290 nm) of diketone 108b was conducted in acetonitrile solution. The formation of three photoproducts was detected by GC, and the GC-MS analysis showed that these photoproducts have the same parent mass as that of the starting diketone 108b. Therefore, these products were considered to be formed from the Norrish type II cyclization and cleavage reactions. No effort was made to isolate and characterize these photoproducts, because this diketone (108b) was not photochemically reactive in the solid state. As depicted in Table 3.14, the distances between the γ-
hydrogens and the two carbonyl oxygens are beyond the proposed reactive limit (ca. 3 Å), and the shortest distance found is 4.6 Å. These unsuitable distances are considered to account for the observed photostability of diketone 108b in the solid state.

Table 3.14 The Hydrogen Abstraction Geometric Parameters of Diketone 108b

<table>
<thead>
<tr>
<th>γ-H</th>
<th>d(C=O•••H) (Å)</th>
<th>Δ(°)</th>
<th>ω(°)</th>
<th>θ(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H5</td>
<td>4.7</td>
<td>56.3</td>
<td>9.4</td>
<td>61.9</td>
</tr>
<tr>
<td>H6</td>
<td>4.6</td>
<td>56.7</td>
<td>10.3</td>
<td>64.1</td>
</tr>
<tr>
<td>H15*</td>
<td>5.0</td>
<td>31.2</td>
<td>3.5</td>
<td>67.9</td>
</tr>
<tr>
<td>H16*</td>
<td>4.8</td>
<td>48.4</td>
<td>12.7</td>
<td>78.5</td>
</tr>
</tbody>
</table>

* The asterisk mark was used in the crystal structure for atom labeling.

The ring size of macrocyclic diketone 108b is comparable to that of the 26-membered cyclic diketone 92 (Scheme 1.21, page 30), for which both of the dimorphs were found to be reactive in the solid state. The reacting γ-hydrogens in diketone 92 were reported as being 2.7 Å and 2.8 Å away from the corresponding carbonyl oxygen. The hydrogen abstraction geometric parameters for diketone 92 are listed in Table 3.15.

Table 3.15 The Hydrogen Abstraction Geometric Parameters of Diketone 92

<table>
<thead>
<tr>
<th>Plate Form Crystals</th>
<th>γ-H</th>
<th>d(C=O•••H) (Å)</th>
<th>Δ(°)</th>
<th>ω(°)</th>
<th>θ(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H5</td>
<td>3.3</td>
<td>52.9</td>
<td>51.7</td>
<td>114.7</td>
<td></td>
</tr>
<tr>
<td>H6</td>
<td>3.9</td>
<td>59.0</td>
<td>41.7</td>
<td>75.5</td>
<td></td>
</tr>
<tr>
<td>H19*</td>
<td>3.9</td>
<td>86.3</td>
<td>33.6</td>
<td>44.7</td>
<td></td>
</tr>
<tr>
<td>H20*</td>
<td>2.8</td>
<td>82.1</td>
<td>52.0</td>
<td>113.2</td>
<td></td>
</tr>
</tbody>
</table>
Needle Form Crystals

<table>
<thead>
<tr>
<th>γ-H</th>
<th>d(C=O⋯H) (Å)</th>
<th>Δ(°)</th>
<th>ω(°)</th>
<th>θ(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H5</td>
<td>3.8</td>
<td>63.9</td>
<td>39.1</td>
<td>50.2</td>
</tr>
<tr>
<td>H6</td>
<td>2.7</td>
<td>84.6</td>
<td>48.6</td>
<td>115.0</td>
</tr>
<tr>
<td>H19*</td>
<td>3.8</td>
<td>63.1</td>
<td>43.9</td>
<td>74.2</td>
</tr>
<tr>
<td>H20*</td>
<td>3.1</td>
<td>56.1</td>
<td>54.7</td>
<td>117.0</td>
</tr>
</tbody>
</table>

* The asterisk mark was used in the crystal structure for atom labeling.

The study of diketone 92 was reported by Scheffer and co-workers (Ref. 65, 66).

Differences were found between diketones 108b and 92 by comparing Tables 3.14 and 3.15. For instance, all the γ-hydrogens in diketone 108b are 4.6 Å or more away from the carbonyl oxygen, whereas the γ-hydrogens in diketone 92 are less than 4 Å away from the carbonyl oxygen. The distance between the carbonyl carbon and the γ-carbon was postulated to be a possible factor in determining the reactivity, and this distance in reactive α-cycloalkyl acetophenone derivatives was reported to be about 3.2 Å.109 The carbonyl carbon and γ-carbon distances of diketones 92 and 108b are listed in Table 3.16, from which the distance in diketone 108b was found about 0.7 Å longer than that in diketone 92; this distance in diketone 92 is approximately the same as reported.109

Table 3.16 The Distance between the Carbonyl Carbon and the γ-Carbons in Diketones 92 and 108b

<table>
<thead>
<tr>
<th>Diketone</th>
<th>d (C1⋯C4) (Å)</th>
<th>d (C1⋯C11* or C13*)a (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>108b</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>92, plates</td>
<td>3.1</td>
<td>3.2</td>
</tr>
<tr>
<td>92, needles</td>
<td>3.2</td>
<td>3.0</td>
</tr>
</tbody>
</table>

a C1⋯C11* refers to diketone 92, C1⋯C13* refers to diketone 108b.
The differences discussed above might be due to the fact that diketone 108b is a more rigid molecule compared with diketone 92, because there are two rigid benzene rings in diketone 108b. Further analysis of the molecular conformations in crystals of diketones 108b and 92 reveal that the relative positions of carbonyl carbon (C1) with respect to γ-carbon (C4) in diketone 108b are quite different from those in diketone 92 (Scheme 3.48). The crystal structures of diketones 108b and 92 are shown in Schemes 3.49 and 3.50.

![Dihedral Angle Comparison](image)

<table>
<thead>
<tr>
<th>Dihedral Angle</th>
<th>108b</th>
<th>92</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-C2-C3-C4</td>
<td>178°</td>
<td>63° (plates), 69° (needles)</td>
</tr>
<tr>
<td>C1-C2'-C3'-C4'</td>
<td>173°</td>
<td>67° (plates), 58° (needles)</td>
</tr>
</tbody>
</table>

Scheme 3.48 The Comparison of Molecular Conformations in Diketones 108b and 92

As shown in Scheme 3.48, it was found that the four-carbon chains (i.e., C1-C2-C3-C4 and C1-C2'-C3'-C4') in diketone 108b have transoid conformations, which can be recognized by their large dihedral angles. In contrast, the corresponding four-carbon chains in diketone 92 have cisoid conformations (with relatively small dihedral angles). The dihedral angle is defined such that cis 2-butene has a dihedral angle of 0° between
the four carbon atoms and trans 2-butene has a dihedral angle of 180°. The C1-C4 distance in a transoid conformation is longer than that in a cisoid conformation, and as a result, the corresponding carbonyl oxygen and γ-hydrogens are separated further apart in the transoid conformation. The two rigid phenyl groups in diketone 108b are considered to be responsible for this unfavorable transoid conformation for the hydrogen abstraction reaction.

The above discussion suggests that the distances between carbonyl oxygen and the corresponding γ-hydrogens in diketones 108a and 108c would also not be within the proposed reactive distance (3 Å), therefore we decided not to investigate these two compounds.

Scheme 3.49  The Stereodiagram of Diketone 108b
Scheme 3.50  The Stereodiagrams of Diketone 92  (a) the Needle Form  (b) the Plate Form

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Chapter 4  The Study of Compounds that Undergo the [4 + 4] Photocycloaddition Reaction

This research project is in collaboration with Prof. M. Kaftory's group at the Technion-Israel Institute of Technology, Haifa, Israel. The work done in our group was intended to determine the optical purity of solid state photoproducts and to synthesize a new substrate for further studies on an absolute configuration correlation.

The solid state photolysis of 1-methyl-5,6-diphenyl-2-pyrazinone (197) was reported to cause a photochemical [4 + 4] cycloaddition reaction and form a dimer (198) in quantitative yield (Scheme 4.01). This reaction was found to occur only in the solid state.$^{116,117}$

\[ \text{Scheme 4.01  The [4 + 4] PhotocycloadditionReaction of Compound 197} \]

The crystal structures of pyrazinone 197 and its dimer 198 were reported by Kaftory.$^{118}$ He reported that pyrazinone 197 crystallizes in dimorphic forms, and both
dimorphs are in chiral space groups by spontaneous resolution, either in a P2₁ space
group (the light sensitive modification) or in a P2₁2₁2₁ space group (the light stable
modification). The solid state photolysis of the light sensitive chiral crystals (in P2₁
space group) might lead to the formation of optically enriched or optically pure
photodimer 198.

4.1. The Determination of Enantiomeric Excess for Photodimer 198

The enantiomeric excess of the solid state photoproduct 198 was determined with
the use of chiral HPLC. A chiral HPLC column was used in this experiment. Some
parameters are given below.

Chiral Column: Chiralcel OD, Chiral Technologies Inc.
Detector: UV detector at λ = 261 nm.
Solvents: Isopropanol 10%, Hexane 90%.
Flow Rate: 1 ml/min.

Crystals of pyrazinone 197 from one recrystallization batch were found to give
the same enantiomer of photoproduct 198 upon solid state photolysis. Since no racemic
sample of product 198 could be obtained directly from the solid state photolysis of
pyrazinone 197, a mixed sample was prepared by mixing the (-)-enantiomer of
photodimer 198 with the corresponding (+)-enantiomer. The corresponding HPLC trace
for this sample is given in Scheme 4.02.
Another sample of the (+)-enantiomer of photodimer 198 was also injected into this chiral HPLC column, and the trace is shown in Scheme 4.03.
It was found that the signal peak of the (+)-enantiomer of photodimer 198 is sharper than the signal peak of the (-)-enantiomer, but both enantiomers gave signals with long tails; no baseline separation of signals was achieved in this experiment. The estimated experimental error is ±5%, and the optical purity of the (+)-enantiomer sample shown in Scheme 4.03 is estimated to be 95% (±5%). The optical rotation of this sample is measured as $[\alpha]_D = +208.0^\circ$ (at room temperature, in 10 mg/ml chloroform solution).
4.2. The Solid State Reaction Mechanism

The crystal packing and molecular conformation of pyrazinone 197 have been reported and discussed by Kaftory. It was found that there are two independent molecules in the asymmetric unit, and also it was postulated by Kaftory that there are two different pathways in this [4 + 4] photocycloaddition reaction, i.e., the molecules within a stack form two types of molecular pairs, which consist of a reference molecule and a second molecule above or below it. As described in Scheme 4.04, one reaction pathway involves the top side of molecule A reacting with the bottom side of molecule B (atoms shown in bold), i.e., pathway (AB); the other pathway involves the top side of molecule B and the bottom side of molecule A [pathway (BA)]. As pointed out by Kaftory, there are small differences in the intermolecular distances between C2 and C4 of these two pathways (Scheme 4.04), and each pathway leads to a different enantiomer of photodimer 198 (Scheme 4.05). 

The previously discussed enantiomeric excess in the photodimer 198 (95% ± 5% e.e.) indicates that probably only one of the two reaction pathways is involved in the photocycloaddition reaction (within the experimental error). In order to determine which pathway is involved, the absolute configurations of both substrate 197 and photoproduct 198 need to be known. However, difficulties were encountered in determining the absolute configuration by anomalous dispersion X-ray crystallography, because there is no heavy atom in molecules of the substrate 197 and photoproduct 198. Since photodimer 198 is not thermally stable (it reverses to monomer upon heating), it was not possible to make derivatives from photodimer 198 so as to determine its absolute configuration. Instead, a sulfur derivative (199) from the monomer 197 was synthesized,
hoping that substrate 199 will act the same as its analog 197. The photochemical reactivity of pyrazinethione 199 is discussed in the following section.

Scheme 4.04  Two Types of Overlap Diagrams for the Two Independent Molecules in Pyrazinone 197 (Reprinted from Ref. 118)

Scheme 4.05  Possible Mechanism for the Photodimerization of Crystals of Pyrazinone 197 (Reprinted from Ref. 118)
4.3. The Synthesis and Photochemical Reactivity of Pyrazinethione 199

Pyrazinethione 199 was prepared from its analog 197 by following a known procedure (Scheme 4.06).119

Scheme 4.06 The Synthesis of Pyrazinethione 199

It was expected that the introduction of a sulfur atom would help to solve its absolute configuration by using sulfur as a heavy atom in anomalous dispersion X-ray crystallography, if pyrazinethione 199 is packed in a chiral crystal space group. However, it was found that pyrazinethione 199 crystallizes in an achiral space group P1, and the crystal structure is shown in Scheme 4.07.120 The X-ray crystallographic analysis revealed that the potential reactive centers are separated by 4.1 Å and 5.6 Å, and the second distance is beyond the proposed reacting distance of 4.1 Å.6,11,12,13

It was found that pyrazinethione 199 was not photochemically reactive both in solution and the solid state. This project is still under investigation.
Scheme 4.07  The Crystal Structure of Pyrazinethione
Chapter 5  EXPERIMENTAL

5.1.  General Considerations

Infrared Spectra (IR)

Infrared spectra were recorded on a Perkin-Elmer 1700 Fourier transform infrared spectrometer, with the absorption maxima ($v_{max}$) of the spectral bands reported in reciprocal centimeters (cm$^{-1}$). Solid samples were prepared as KBr pellets by grinding 100-150 mg of KBr and 1-5 mg of sample together and compressing the mixture in a Perkin-Elmer evacuated die (186-0002) with a Carver Laboratory Press (Model B, 17,000 psi). Liquid samples were run neat as a thin film between two sodium chloride plates.

Nuclear Magnetic Resonance (NMR) Spectra

Proton nuclear magnetic resonance ($^1$H NMR) spectra were recorded on Bruker AC-200 (200 MHz), Varian XL-300 (300 MHz) and Bruker WP-400 (400 MHz) spectrometers at ambient temperature in deuterochloroform unless otherwise noted. Signal positions are reported as chemical shift ($\delta$) in parts per million (ppm) with tetramethylsilane (TMS) as an internal standard. The multiplicity of the signals, number of protons, coupling constants ($J$) in Hz and assignments are given in parentheses following the chemical shifts. The multiplicities of the signals are abbreviated as follows: $s$ = singlet, $d$ = doublet, $t$ = triplet, $q$ = quartet and $m$ = multiplet.

Carbon nuclear magnetic resonance spectra ($^{13}$C NMR) were recorded on Bruker AC-200 (50.3 MHz), Varian XL-300 (75.4 MHz) and Bruker AMX-500 (125.8 MHz)
spectrometers. All spectra were run under broad band proton decoupling $^{13}\text{C}-^{1}\text{H}$. Chemical shifts ($\delta$) are reported in ppm. Assignments, where given, were supported by APT (attached proton test) and/or HETCOR (Heteronuclear Chemical Shift Correlation Spectroscopy, $^{13}\text{C}-^{1}\text{H}$) experiments. HETCOR experiments were performed on a Bruker AMX-500 (500 MHz) spectrometer. NOE (Nuclear Overhauser Effect) experiments were performed on a Bruker WP-400 (400 MHz) spectrometer.

Mass Spectra (MS)

Low and high resolution mass spectra were obtained on a Kratos MS 50 instrument operating at 70 eV. Coupled gas chromatography-mass spectral analysis (GC-MS) were performed on a Kratos MS 80RFA spectrometer connected to a Carlo-Erba 4160 gas chromatograph. Ionization for the above was achieved by electron bombardment at 70 electron volts (EI). Desorption chemical ionization (DCI) spectra were done on a Delsi Nermag R10-10C spectrometer using ammonia as the CI gas. Fast atom bombardment (FAB) spectra were recorded on an AEI MS-9 mass spectrometer with xenon bombardment of an 3-nitrobenzyl alcohol matrix of the sample. Mass to charge ratios ($m/e$) are reported with relative intensities in parentheses. Molecular ions are designated as $M^+$. 

Ultraviolet Spectra (UV)

Ultraviolet spectra were recorded on a Perkin Elmer Lambda-4B UV/Vis spectrophotometer. Spectral grade acetonitrile (BDH) was used without further purification. Wavelengths ($\lambda$) in nanometers (nm) are reported and the extinction coefficients ($\epsilon$) are given in brackets.
**Melting Points (mp)**

Melting points were determined on a Fisher-Johns hot stage apparatus and are uncorrected.

**Microanalysis**

Elemental analyses were performed by the departmental microanalyst, Mr. P. Borda.

**Optical Rotations (α)**

Optical rotations (α) were measured on a JASCO J-710 spectrophotometer in spectral grade chloroform (BDH). Values are reported as specific rotation [α]D, at room temperature 22 °C. Sample concentrations were approximately 10 mg/ml. Optical rotations were detected at λ = 589 nm, correspondent to the sodium D-line.

**Gas Liquid Chromatography**

Gas liquid chromatography (GLC or GC) analyses were performed on a Hewlett Packard 5890 A gas chromatograph fitted with a flame ionization detector and equipped with a Hewlett Packard 3392 A integrator. The fused silica capillary columns used were DB-1 (15 m × 0.25 mm, J & W Scientific Inc.), DB-17 (15 m × 0.25 mm, J & W Scientific Inc.) and Carbowax 20 M (20 m × 0.21 mm, Hewlett Packard).
Chromatography

Analytical thin layer chromatography (TLC) was performed on pre-coated silica gel plates (E. Merck, type 5554). Preparative column chromatography was carried out by the flash method\textsuperscript{121} using 230-400 mesh silica gel (E. Merck). The eluting solvents are specified in each preparation.

High Performance Liquid Chromatography (HPLC)

High performance liquid chromatography analyses were conducted on a Waters 600 E system controller connected to a tunable UV detector (Waters 486). A silica 80 mm x 10 mm column was used for conventional analyses. A chiral column (Chiracel OD, 250 mm x 4.6 mm, Chiral Technologies Inc.) was used to determine enantiomeric excesses (e.e.).

X-ray Crystallographic Analyses

X-ray crystal structures were determined on a Rigaku AFC6S 4-circle diffractometer using single crystal X-ray diffraction analysis by Dr. Steve Rettig, Dr. Ray Jones, Mr. Taiyu Fu and Prof. James Trotter of the UBC Chemistry Department.

Solvents and Reagents

Spectral grade solvents were used for spectroscopic and photochemical studies. Unless otherwise specified, all the solvents and reagents were used directly without
further purification. When necessary, literature procedures\textsuperscript{122} were followed to further purify the reagent or solvent.

5.2. The Synthesis of 9,10-Dihydro-9,10-ethenoanthracene Derivatives

1,5-Dichloroanthracene (124)

Compound 124 was prepared by the reduction of 1,5-dichloro-9,10-anthraquinone (132) according to the known procedure.\textsuperscript{81} Thus, a mixture of 1,5-dichloroanthraquinone (5.54 g, 20 mmol, Aldrich) and zinc powder (15.3 g, 0.24 mol, BDH) in 100 ml of pyridine was heated to reflux with magnetic stirring, and 80\% acetic acid (38 ml, 0.5 mol) was added dropwise over 5 h. The reaction mixture (colour changed from red to yellow) was stirred under reflux for an additional 0.5 h, allowed to cool to room temperature; the excess of zinc powder was removed by filtration and the filtrate was poured into ice-cold hydrochloric acid (400 ml, 3 M). After stirring for 15 minutes, the resulting solid was removed by filtration. Recrystallization of the crude solid from ethanol afforded yellow needles (3.16 g, yield 64\%), mp 187-188 °C (lit.\textsuperscript{81,123} 178-182 °C, 185 °C).

IR (KBr) $\nu_{\text{max}}$: 1619, 1302, 1164, 874, 780, 721 cm$^{-1}$.

MS $m/e$ (rel. intensity): 250 (M$^+$ + 4, 10), 248 (M$^+$ + 2, 66), 246 (M$^+$, 100), 211 (7), 176 (36).

$^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ ppm: 8.88 (s, 2 H, H9 & H10), 8.03 (m, 2 H), 7.63 (m, 2 H), 7.43 (m, 2 H).
Dimethyl 1,5-Dichloro-9,10-dihydro-9,10-ethenoanthracene-11,12-dicarboxylate (109)

Compound 109 was synthesized by the Diels-Alder addition reaction. Thus, 1,5-dichloroanthracene 124 (1.0 g, 4 mmol) and dimethyl acetylenedicarboxylate (dimethyl 2-butyne-1,4-dioate, 1.72 g, 12 mmol, Aldrich) were dissolved in 30 ml of xylenes (mixed, Aldrich) and refluxed for 7 h. The reaction mixture was cooled to room temperature, and the white solid obtained after filtration was recrystallized from acetone to afford colourless prisms (0.85 g, yield 54%), mp 206-207.5 °C.

IR (KBr) $\nu_{\text{max}}$: 1736 (C=O), 1713 (C=O), 1455, 1287, 1274, 1144, 1070 cm$^{-1}$.

UV (CH$_3$CN) $\lambda_{\text{max}}$: 219 nm ($\varepsilon$ 48000).

MS $m/e$ (rel. intensity): 390 (M$^+$ + 2, 30), 388 (M$^+$, 47), 357 (11), 328 (100), 301 (29), 270 (45), 246 (54).

$^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ ppm: 6.95-7.35 (m, 6 H, Ar-H), 5.96 (s, 2 H, H9 & H10), 3.82 (s, 6 H, 2 COOCH$_3$).

$^{13}$C NMR (CDCl$_3$, 50 MHz) $\delta$ ppm: 165.27 (C=O), 146.82, 145.52, 141.20, 129.83, 126.89, 126.39, 122.66, 52.61, 49.40.

Anal. Calcd for C$_{20}$H$_{14}$Cl$_2$O$_4$: C, 61.72; H, 3.63; Cl, 18.22. Found: C, 61.76; H, 3.64; Cl, 18.10.

The structure of this compound was further supported by an X-ray diffraction analysis. The crystal data are as follows: C$_{20}$H$_{14}$Cl$_2$O$_4$ crystallized in space group $P2_1/n$. 

180
\[ a = 7.672 \text{ (1) Å}, \ b = 8.217 \text{ (2) Å}, \ c = 29.042 \text{ (2) Å}, \ \beta = 92.41 \text{ (1)°}, \ V = 1829.2 \text{ (4) Å}^3, \ Z = 4, \ D_{\text{calc}} = 1.413 \text{ g/cm}^3, \ R = 0.040. \]

**1,5-Dicyano-9,10-anthraquinone (133)**

Compounds 133, 134, 135 and 126 were made according to the literature procedure.\(^{124}\) A mixture of 1,5-dichloro-9,10-anthraquinone (132) (8.43 g, 30 mmol, Aldrich), cuprous cyanide (6.75 g, 76 mmol, Aldrich) and phenylacetonitrile (78 ml, Aldrich) was refluxed for 70 min. The insoluble solid, obtained after filtration, was washed with benzene and digested with boiling 4 M nitric acid (40 ml) to give 133 (3.7 g, yield 47%), which was used in the next step without further purification.

IR (KBr) \( \nu_{\text{max}} \): 2229 (C\(-\equiv\)N), 1670 (C=O), 1562, 1324, 1290 \text{ cm}^{-1}.

**1,5-Dicarboxy-9,10-anthraquinone (134) and 1,5-Dicarboxyanthracene (135)\(^{124}\)**

Water (20 ml) was added to a solution of 133 (3.7 g, 14 mmol) in concentrated sulfuric acid (43 ml) under ice-cooling. After being heated to 160 °C for 1.5 h, the mixture was poured into 65 ml of water to give compound 134 as a dark brown solid, which was subsequently dissolved in 20% aqueous ammonia solution (100 ml) and treated with zinc powder (7 g) with stirring at 85-95 °C. Stirring was continued for 5 h at the same temperature with occasional addition of zinc powder and ammonia solution. The reaction mixture was filtered and the filtrate was decolorized with charcoal, acidified with 12 M hydrochloric acid to afford 135 (1.7 g, yield 94%). mp > 360 °C.

IR (KBr) \( \nu_{\text{max}} \): 3062, 1685 (C=O), 1610, 1544, 1273 \text{ cm}^{-1}.

MS \( m/e \) (rel. intensity): 266 (M\(^+\), 100), 247 (18), 222 (33).
\(^1\)H NMR (CDCl\(_3\), 400 MHz) \(\delta\) ppm: 9.68 (s, 2 H, H9 & H10), 8.39 (m, 2 H), 8.25 (m, 2 H), 7.62 (m, 2 H).

1,5-Dicarbomethoxyanthracene (126)\(^{124}\)

The above prepared di-acid 135 (1.7 g, 13 mmol) was mixed with sodium methoxide-methanol solution (from 0.5 g of sodium and 32 ml of methanol) and this solution was refluxed for 2 h. Freshly distilled dimethyl sulfate (3.5 g, 28 mmol, Aldrich) was added dropwise to the solution. After refluxing for 22 h, the reaction mixture was concentrated under reduced pressure. Water (15 ml) was added and compound 126 (1.4 g, yield 48%) was obtained as a yellow solid after filtration. Another type of esterification reaction was conducted in methanol with a catalytic amount of concentrated sulfuric acid. This was refluxed for 48 h to afford a 90% yield of diester 126, mp 200-202 °C (lit.\(^ {124}\) 200-201 °C).

IR (KBr) \(v_{\text{max}}\): 2949, 1703(C=O), 1261, 1216, 1142 cm\(^{-1}\).

MS \(m/e\) (rel. intensity): 294 (M\(^+\), 100), 263 (39), 235 (22).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \(\delta\) ppm: 9.65 (s, 2 H, H9 & H10), 8.30 (m, 4 H), 7.52 (m, 2 H), 4.07 (s, 6 H, 2 COOCH\(_3\)).

Dimethyl 1,5-Dicarbomethoxy-9,10-dihydro-9,10-ethanoanthracene-11,12-dicarboxylate (111)
Compound 111 was synthesized by the Diels-Alder reaction. Thus, diester 126 (1.79 g, 6.1 mmol) and dimethyl acetylenedicarboxylate (2.0 g, 14 mmol, Aldrich) were dissolved in 25 ml of xylenes (mixed, Aldrich) and refluxed for 8 h. The reaction mixture was cooled to room temperature and the white solid collected after filtration was recrystallized from acetone to give compound 111 (2.44 g, yield 92%), mp 220-221 °C.

IR (KBr) ν_max: 2954, 1739 (CD), 1718 (C=O), 1436, 1277 (broad, OCH₃), 1146 cm⁻¹.

UV (CH₃CN) λ_max : 220 nm (ε 21800), 299 nm (ε 5150).

MS m/e (rel. intensity): 436 (M⁺, 41), 405 (18), 376 (100), 345 (39), 329 (13), 318 (19), 317 (20), 287 (15), 259 (12).

¹H NMR (CDCl₃, 400 MHz) δ ppm: 7.60-7.68 (m, 4 H), 7.08 (m, 2 H), 6.93 (s, 2 H, H9 & H10), 3.97 (s, 6 H, 2 COOCH₃), 3.80 (s, 6 H, 2 COOCH₃).

¹³C NMR (CDCl₃, 50 MHz) δ ppm: 166.90 (C=O), 165.56 (C=O), 147.09, 145.83, 145.22, 128.48, 127.18, 125.98, 125.37, 52.48, 52.11, 48.80.


1,5-Dicyanoanthracene (125)

The procedure for preparing 1,8-dicyanoanthracene²⁵ was followed. Thus, 1,5-dichloroanthracene (124) (9.37 g, 38 mmol) and cuprous cyanide (11.33 g, 126 mmol, Aldrich) were slurried in 100 ml of distilled quinoline and refluxed for 24 h under nitrogen. The warm black solution was poured into 1 M HCl (840 ml), producing a black solid which was filtered and washed with water. The solid product was partitioned between 1 M aqueous ammonia (420 ml) and dichloromethane (420 ml) and stirred vigorously for 6 h. The aqueous layer was then discarded. This procedure was repeated 5
times until the aqueous layer was no longer blue. Rotary evaporation of the organic layer left a brown oil, which was chromatographed with dichloromethane to afford pure 125 as a yellow solid (4.08 g, yield 47%), mp > 300 °C.

IR (KBr) νmax: 2220 cm⁻¹ (C≡N).

MS m/e (rel. intensity): 229 (M+ + 1, 25), 228 (M+, 100), 201 (15), 174 (5).

¹H NMR (CDCl₃, 400 MHz) δ ppm: 8.93 (s, 2 H, H₉ & H₁₀), 8.38 (m, 2 H), 8.08 (m, 2 H), 8.08 (m, 2 H), 7.65 (m, 2 H).

**Dimethyl 1,5-Dicyano-9,10-dihydro-9,10-ethenoanthracene-11,12-dicarboxylate (110)**

![Diagram](attachment:image.png)

The Diels-Alder addition of compound 125 (1.24 g, 5.4 mmol) with dimethyl acetylenedicarboxylate (0.92 g, 6.5 mmol, Aldrich) was conducted in refluxing xylenes (25 ml) for 26 h. The solvent was evaporated under reduced pressure and the residue was chromatographed with dichloromethane and petroleum ether (50/50, v/v) to afford 110 (1.28 g, yield 63%), which was recrystallized from xylenes to give colourless plates, mp 272-273 °C.

IR (KBr) νmax: 2954, 2230 (C≡N), 1718 (C=O), 1631, 1432, 1288, 1067 cm⁻¹.

UV (CH₃CN) λmax: 297 nm (ε 7600).

MS m/e (rel. intensity): 370 (M+, 22), 339 (7), 311 (25), 252 (21), 228 (19), 91 (100), 77 (39).
\(^1\)H NMR (CDCl\(_3\), 400 MHz) \(\delta\) ppm: 7.72 (m, 2 H), 7.39 (m, 2 H), 7.22 (m, 2 H), 5.98 (s, 2 H, H9 & H10), 3.85 (s, 6 H, 2 COOCH\(_3\)).

\(^{13}\)C NMR (CDCl\(_3\), 50 MHz) \(\delta\) ppm: 164.37, 146.76, 146.20, 143.83, 129.12, 128.90, 128.52, 126.87, 116.44, 108.69, 52.96, 50.36.

Anal. Calcd for C\(_{22}\)H\(_{14}\)N\(_2\)O\(_4\): C, 71.35; H, 3.81; N, 7.56. Found: C, 71.11; H, 3.71; N, 7.36.

The structure of this compound was further supported by an X-ray diffraction analysis. The crystal data are as follows: C\(_{22}\)H\(_{14}\)N\(_2\)O\(_4\) crystallized in space group P2\(_1\)/n, \(a = 7.864\) (2) \(\text{\AA}\), \(b = 27.588\) (2) \(\text{\AA}\), \(c = 8.760\) (2) \(\text{\AA}\), \(\beta = 101.88\) (2)°, \(V = 1859.9\) (6) \(\text{\AA}^3\), \(Z = 4\), \(D_{\text{calcd}} = 1.322\) g/cm\(^3\), \(R = 0.035\).

1,5-Dimethoxy-9,10-anthraquinone (136)

Sodium metal (2.0 g, 87 mmol) was added to anhydrous methanol (100 ml) and reacted for 20 min. 1,5-Dichloro-9,10-anthraquinone (10.0 g, 36 mmol, Aldrich) was then added to this solution and this was refluxed for 24 h. The yellow solid collected after filtration was recrystallized from glacial acetic acid to afford 136 (8.25 g, yield 85%), mp 236-238 °C (lit.\(^1\)26 238-240 °C).

IR (KBr) \(\nu_{\text{max}}\): 2840, 1663 (C=O), 1588, 1466, 1442, 1334, 1286, 1263 cm\(^{-1}\).

MS \(m/e\) (rel. intensity): 269 (M\(^+\) + 1, 17), 268 (M\(^+\), 100), 251 (15), 239 (19), 237 (33), 221 (13), 209 (21), 152 (29).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \(\delta\) ppm: 7.90 (m, 2 H), 7.70 (m, 2 H), 7.28 (m, 2 H), 4.03 (s, 6 H, 2 OCH\(_3\)).
1,5-Dimethoxyanthracene (127)

The procedure for the reduction of 1,4-dimethoxy-9,10-anthraquinone\textsuperscript{82} was followed to reduce 1,5-dimethoxy-9,10-anthraquinone (136). To a mixture of 1,5-dimethoxy-9,10-anthraquinone (1.2 g, 4.5 mmol) and 18 ml of diglyme at 5 °C was added sodium borohydride (0.72 g) in portions over 15 min, and this mixture was stirred at 5-15 °C for 2 h before it was added to 60 ml of ice-water. After adding 15 ml of diethyl ether and 4.8 ml of glacial acetic acid, the reaction mixture was heated at 90-100 °C for 4 h and then cooled overnight, whereupon yellow solid 127 (0.9 g, yield 84\%) was obtained after filtration, mp 229-230 °C (lit.\textsuperscript{127} 229-230 °C).

IR (KBr) $v_{\text{max}}$: 2959, 1627, 1545, 1468, 1441, 1403, 1353, 1309, 1257 cm\textsuperscript{-1}.

MS $m/e$ (rel. intensity): 239 (M$^+$ + 1, 18), 238 (M$^+$, 100), 223 (47), 195 (37), 152 (29), 119 (14).

$^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ ppm: 8.78 (s, 2 H, H$_9$ & H$_{10}$), 7.63 (m, 2 H), 7.35 (m, 2 H), 6.75 (m, 2 H), 4.08 (s, 6 H, 2 OCH$_3$).

Dimethyl 1,5-Dimethoxy-9,10-dihydro-9,10-ethenoanthracene-11,12-dicarboxylate (112)

![Chemical Structure](image)

The Diels-Alder addition of compound 127 (318 mg, 1.34 mmol) with dimethyl acetylenedicarboxylate (0.23 g, 1.6 mmol, Aldrich) was conducted in refluxing xylenes.
(10 ml) for 8 h. The solvent was evaporated under reduced pressure and the residue was chromatographed with 40% diethyl ether in petroleum ether (v/v) to afford 112 (122 mg, yield 24%), which was further recrystallized from acetone to give colourless prisms, mp 239-240 °C.

IR (KBr) ν\text{max}: 2952, 1713 (C=O), 1632, 1591, 1483, 1438, 1297, 1270, 1090 cm\textsuperscript{-1}.

UV (CH\textsubscript{3}CN) λ\text{max} : 284 nm (ε 3520).

MS m/e (rel. intensity): 381 (M\textsuperscript{+} + 1, 13), 380 (M\textsuperscript{+}, 46), 322 (21), 321 (100), 320 (84), 293 (19), 292 (11), 289 (20), 263 (13), 262 (24), 247 (12), 238 (31), 223 (21), 219 (14), 195 (21), 176 (14), 152 (27), 106 (25), 105 (10), 91 (50), 44 (32).

\textsuperscript{1}H NMR (CDCl\textsubscript{3}, 400 MHz) δ ppm: 7.07 (m, 2 H), 6.95 (m, 2 H), 6.60 (m, 2 H), 5.92 (s, 2 H, H\textsubscript{9} & H\textsubscript{10}), 3.82 (s, 6 H), 3.78 (s, 6 H).

\textsuperscript{13}C NMR (CDCl\textsubscript{3}, 50 MHz) δ ppm: 166.08, 154.63, 147.74, 146.29, 131.88, 126.28, 116.77, 108.71, 55.76, 52.32, 45.93.

Anal. Calcd for C\textsubscript{22}H\textsubscript{20}O\textsubscript{6}: C, 69.45; H, 5.30. Found: C, 69.51; H, 5.23.

The structure of this compound was further supported by an X-ray diffraction analysis. The crystal data are as follows: C\textsubscript{22}H\textsubscript{20}O\textsubscript{6} crystallized in space group P\textbar, a = 14.900 (2) Å, b = 15.128 (9) Å, c = 8.809 (3) Å, α = 105.03 (3)°, β = 90.22 (2)°, γ = 82.79 (3), V = 1092 (2) Å\textsuperscript{3}, Z = 4, D\textsubscript{calcd} = 1.329 g/cm\textsuperscript{3}, R = 0.076.

1,8-Dichloroanthracene (128)

Compound 128 was prepared by the reduction of 1,8-dichloro-9,10-anthraquinone according to the literature procedure.\textsuperscript{81} A mixture of 1,8-dichloro-9,10-anthraquinone (11.08 g, 40 mmol, Aldrich) and zinc powder (30.6 g, 0.48 mol, BDH) in 200 ml of pyridine was heated to reflux with magnetic stirring, and 80% acetic acid (76 ml) was
added dropwise over 5 h. The reaction mixture (colour changed from red to yellow) was stirred under reflux for an additional 30 min, allowed to cool to room temperature, the excess of zinc powder was removed by filtration and the filtrate was added into ice-cold hydrochloric acid (800 ml, 3 M). After stirring for 15 min, the resulting solid was obtained after filtration. Recrystallization of the crude solid from ethanol afforded yellow needles (4.2 g, yield 43%), mp 149-151 °C (lit. 150-153 °C).

IR (KBr) \( \nu_{\text{max}} \): 1439, 1211, 954, 872, 732 cm\(^{-1}\).

MS \( m/e \) (rel. intensity): 250 (M\(^+\) + 4, 13), 248 (M\(^+\) + 2, 73), 247 (M\(^+\) + 1, 20), 246 (M\(^+\), 100), 213 (18), 178 (30), 176 (55).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 9.21 (s, 1 H, H9), 8.42 (s, 1 H, H10), 7.90 (m, 2 H), 7.60 (m, 2 H), 7.36 (m, 2 H).

**Dimethyl 1,8-Dichloro-9,10-dihydro-9,10-ethenoanthracene-11,12-dicarboxylate (130)**

![Structure of 130]

Compound 130 was synthesized by the Diels-Alder addition reaction. 1,8-Dichloroanthracene (2.72 g, 10.9 mmol) and dimethyl acetylenedicarboxylate (2.3 g, 16 mmol, Aldrich) were dissolved in 25 ml of xylenes (mixed, Aldrich) and refluxed for 12 h. The reaction mixture was cooled to room temperature and the white solid obtained after filtration was recrystallized from acetone to afford colourless prisms (2.91 g, yield 68%), mp 227-228 °C.
IR (KBr) $\nu_{\text{max}}$: 2956, 1735 (C=O), 1704 (C=O), 1633, 1578, 1455, 1446, 1435, 1345, 1327, 1286, 1256, 1144, 1062 cm$^{-1}$.

UV (CH$_3$CN) $\lambda_{\text{max}}$: 217 nm ($\epsilon$ 26000).

MS $m/e$ (rel. intensity): 390 (M$^+$ + 2, 39), 388 (M$^+$, 64), 330 (47), 331 (28), 329 (41), 328 (60), 270 (34), 250 (36), 246 (54), 200 (31), 176 (40).

$^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ ppm: 7.28 (m, 2 H), 7.08 (m, 2 H), 6.97 (m, 2 H), 6.47 (s, 1 H, H9), 5.50 (s, 1 H, H10), 3.82 (s, 3 H, 12-COOCH$_3$), 3.78 (s, 3 H, 11-COOCH$_3$).

$^{13}$C NMR (CDCl$_3$, 50 MHz) $\delta$ ppm: 165.40, 165.18, 147.43, 146.18, 146.08, 140.59, 130.16, 126.86, 126.39, 122.27, 52.87, 52.67, 52.58, 46.02.

Anal. Calcd for C$_{20}$H$_{14}$Cl$_2$O$_4$: C, 61.72; H, 3.63; Cl, 18.22. Found: C, 61.86; H, 3.73; Cl, 18.36.

The structure of this compound was further supported by an X-ray diffraction analysis. The crystal data are as follows: C$_{20}$H$_{14}$Cl$_2$O$_4$ crystallized in space group $P\overline{1}$, $a$ = 8.1058 (5) Å, $b$ = 14.7882 (8) Å, $c$ = 7.8659 (6) Å, $\alpha$ = 100.934 (5)$^\circ$, $\beta$ = 103.279 (5)$^\circ$, $\gamma$ = 90.865 (4)$^\circ$, $V$ = 899.3 (1) Å$^3$, $Z$ = 2, $D_{\text{calcd}}$ = 1.437 g/cm$^3$, $R$ = 0.036.

1-Chloroanthracene (129)

Compound 129 was prepared by the reduction of 1-chloro-9,10-anthraquinone.$^{81}$ A mixture of 1-chloro-9,10-anthraquinone (9.7 g, 40 mmol, Aldrich) and zinc powder (30.6 g, 0.48 mol, BDH) in 200 ml of pyridine was heated to reflux with magnetic stirring, and 80% acetic acid (76 ml) was added dropwise over 5 h. The reaction mixture (colour changed from red to yellow) was stirred under reflux for an additional 30 min, allowed to cool to room temperature, the excess of zinc powder was removed by filtration and the filtrate was added into ice-cold hydrochloric acid (800 ml, 3 M). After
stirring for 15 min, the resulting solid was collected by filtration. Recrystallization of the crude solid from ethanol afforded yellow needles (8.2 g, yield 85%), mp 80-81 °C (lit.81 79-80 °C).

IR (KBr) $\nu_{\text{max}}$: 3050, 1618, 1527, 1450, 1426, 1364, 1308, 1228, 1163 cm$^{-1}$.

MS $m/e$ (rel. intensity): 214 (M$^+$ + 2, 31), 213 (M$^+$ + 1, 16), 212 (M$^+$, 100), 176 (25), 106 (27), 88 (48), 75 (25).

$^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ ppm: 8.83 (s, 1 H, H9), 8.40 (s, 1 H, H10), 8.06 (m, 1 H), 7.96 (m, 1 H), 7.89 (m, 1 H), 7.55 (m, 1 H), 7.50 (m, 2 H), 7.30 (m, 1 H).

Dimethyl 1-Chloro-9,10-dihydro-9,10-ethenoanthracene-11,12-dicarboxylate (131)

![Diagram of compound 131](image)

Compound 131 was synthesized by the Diels-Alder addition reaction. 1-Chloroanthracene (3.0 g, 14.2 mmol) and dimethyl acetylenedicarboxylate (3.02 g, 21.3 mmol, Aldrich) were dissolved in 28 ml of xylenes (mixed, Aldrich) and refluxed for 12 h. The reaction mixture was cooled to room temperature and the white solid obtained after filtration was recrystallized from acetone to afford colourless plates (3.7 g, yield 74%), mp 160-161 °C.

IR (KBr) $\nu_{\text{max}}$: 3008, 2953, 1728 (C=O), 1703 (C=O), 1630, 1577, 1456, 1434, 1343, 1282, 1206, 1148, 1132, 1111, 1061, 1017 cm$^{-1}$.

UV (CH$_3$CN) $\lambda_{\text{max}}$: 220 nm ($\varepsilon$ 13200).
MS m/e (rel. intensity): 356 (M+ + 2, 23), 354 (M+, 67), 326 (12), 323 (12), 297 (23), 296 (45), 295 (72), 294 (100), 267 (28), 263 (16), 236 (50), 216 (27), 212 (55), 200 (37), 100 (50).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \(\delta\) ppm: 7.45 (m, 1 H), 7.38 (m, 1 H), 7.25 (m, 1 H), 7.03 (m, 3 H), 6.91 (m, 1 H), 5.96 (s, 1 H, H9), 5.50 (s, 1 H, H10), 3.81 (s, 3 H, 12-COOCH\(_3\)), 3.79 (s, 3 H, 11-COOCH\(_3\)).

\(^1\)C NMR (CDCl\(_3\), 50 MHz) \(\delta\) ppm: 165.66, 165.51, 147.25, 146.54, 146.29, 143.58, 142.71, 141.35, 129.73, 126.60, 126.08, 125.73, 124.30, 123.93, 122.17, 52.68, 52.50, 49.12.


5.3. Photochemical Procedures

5.3.1. Analytical Photolyses

All analytical runs for both the solution and solid state irradiations were conducted using a minimum of 3 samples, and for each photolysis at least 3 gas chromatographic (GC) runs were performed. GC detector response was calibrated with appropriate internal standards and compounds to be detected. Some of the photoproduct ratios were determined by \(^1\)H NMR integration of the appropriate signals. Average results are reported. The overall precision of the reported results obtained from both GC and \(^1\)H NMR was ± 3%.
Solid State Irradiations

Analytical runs were carried out by irradiating single crystals or polycrystalline samples (powders) in 3 mm sealed Pyrex or quartz tubes under a nitrogen atmosphere. The irradiations were conducted at $\lambda \geq 290$ nm or $\lambda \geq 200$ nm using a 450 W Hanovia medium pressure mercury lamp housed in a Pyrex or quartz jacket respectively, or at 337 nm using the output from a Molectron UV 22 pulsed nitrogen laser (330 mW average power). Solid state conversions to products were limited to $\leq 20\%$ for the product ratio studies.

Solution State Irradiations

The solution state analytical runs were conducted in 3 mm Pyrex tubes which were sealed after three freeze-pump-thaw cycles. Conversion to products was limited to $\leq 20\%$ (7% for the quantum yield studies). The irradiation sources were the same as those used for solid state photolyses.

5.3.2. Preparative Scale Photolyses

Solid State Irradiations

For irradiations at room temperature, solid samples were placed in Pyrex test tubes (10 × 100 mm) and sealed under nitrogen. The degassing procedure was conducted on the vacuum line to pump off the air and then fill the tube with the nitrogen gas.

Low temperature photolyses were conducted in a Pyrex glass cooling bath filled with ethanol and cooled with a Cryocool CC-100-II Immersion Cooling System (Neslab Instruments Inc.). Solid samples were sandwiched between two pieces of microscope...
plates and this was placed in a polyethylene bag filled with nitrogen gas and irradiated with a 450 W Hanovia medium pressure mercury lamp.

**Solution State Irradiations**

The following procedure for a preparative scale solution photolysis is typical.

A solution of compound 109 (776 mg, 2.0 mmol) in 200 ml of acetone (spectral grade, BDH) was placed in a 250 ml Pyrex immersion well. The solution was degassed with high purity nitrogen gas for 45 min. with constant stirring, and a positive pressure of nitrogen was maintained throughout the irradiation. The solution was photolysed with a 450 W Hanovia medium pressure lamp for 5 h until all the starting material had disappeared as shown by GC. After irradiation, the solvent was removed in vacuo, and the residue was chromatographed (4% diethyl ether in petroleum ether). Photoproduct 109A (430 mg, yield 55%) was isolated first, followed by a mixture of photoproducts 109A and 109B (200 mg), and finally pure photoproduct 109B (136 mg, yield 18%).

**Spectral Characteristics of Photoproducts 109A and 109B**

Dimethyl 1,5-Dichloro-4b,8b,8c,8d-tetrahydro-dibenzo[a,f]cyclopropa[cd]-pentalene-8b,8c-dicarboxylate (109A)

![Diagram of 109A]

\[ E = \text{CO}_2\text{Me} \]

193
mp: 127-128 °C.

IR (KBr) $\nu_{\text{max}}$: 2957, 2361, 1736 (C=O), 1572, 1436, 1377, 1341, 1304, 1256, 1242, 1211, 1142, 1093, 1055, 1015 cm$^{-1}$.

MS $m/e$ (rel. intensity): 390 (M$^+$ + 2, 25), 388 (M$^+$, 38), 332 (17), 331 (42), 330 (75), 329 (68), 328 (100), 303 (18), 301 (28), 272 (22), 270 (31), 251 (17), 200 (34), 100 (24).

$^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ ppm: 7.03-7.43 (m, 6 H), 5.28 (s, 1 H, H4b), 4.66 (s, 1 H, H8d), 3.88 (s, 3 H), 3.72 (s, 3 H).

$^{13}$C NMR (CDCl$_3$, 50 MHz) $\delta$ ppm: 168.49, 167.55, 150.48, 146.51, 135.55, 133.32, 131.43, 129.11, 128.84, 128.06, 127.82 (2 C), 124.78, 120.08, 66.34, 57.29, 55.06, 52.98, 52.56, 47.99.

Anal. Calcd for C$_{20}$H$_{14}$Cl$_2$O$_4$: C, 61.72; H, 3.63; Cl, 18.22. Found: C, 61.71; H, 3.66; Cl, 18.15.

NOE: Irradiated at 4.66 ppm (H8d), no aromatic hydrogen signal enhancement was observed.

Dimethyl 1,5-Dichloro-4b,8b,8c,8d-tetrahydro-dibenzo[a,f]cyclopropa[cd]-pentene-8c,8d-dicarboxylate (109B)
IR (KBr) $v_{\text{max}}$: 2945, 2360, 1737 (C=O), 1726 (C=O), 1572, 1457, 1438, 1385, 1344, 1300, 1272, 1229, 1200, 1181, 1141, 1096, 1043 cm$^{-1}$.

MS $m/e$ (rel. intensity): 390 (M$^+ + 2$, 37), 388 (M$^+$, 53), 332 (16), 331 (33), 330 (71), 329 (53), 328 (100), 303 (25), 302 (17), 301 (43), 300 (17), 299 (19), 297 (29), 272 (22), 270 (32), 251 (27), 200 (49), 100 (26).

$^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ ppm: 7.03-7.50 (m, 6 H), 5.32 (s, 1 H, H4b), 4.51 (s, 1 H, H8b), 3.86 (s, 3 H), 3.75 (s, 3 H).

$^{13}$C NMR (CDCl$_3$, 50 MHz) $\delta$ ppm: 168.71, 167.33, 151.39, 146.75, 136.87, 131.79, 131.46, 129.39, 128.84, 128.54, 127.96, 127.80, 124.16, 120.14, 65.34, 57.46, 54.07, 53.00, 52.49, 49.30.

Anal. Calcd for C$_{20}$H$_{14}$Cl$_2$O$_4$: C, 61.72; H, 3.63; Cl, 18.22. Found: C, 61.79; H, 3.71; Cl, 18.15.

NOE: Irradiated at 4.51 ppm (H8b) and 5.32 ppm (H4b), aromatic hydrogen signals were enhanced in both cases.

X-ray crystallographic analysis further confirmed the proposed structure. The X-ray diffraction data are as follows: C$_{20}$H$_{14}$Cl$_2$O$_4$, crystallized in space group Pn$a$2$_1$, $a = 14.867$ (1) Å, $b = 8.109$ (1) Å, $c = 14.9437$ (6) Å, $V = 1801.6$ (4) Å$^3$, $Z = 4$, $D_{\text{calc}} = 1.435$ g/cm$^3$, $R = 0.027$.

The Photolysis of Dimethyl 1,5-Dicarbomethoxy-9,10-dihydro-9,10-ethenoanthracene-11,12-dicarboxylate (111)

Preparative scale irradiation of substrate 111 (600 mg, 1.4 mmol) was conducted in acetone for 2 h with the complete consumption of compound 111. The two photoproducts were partially separated by column chromatography. Photoproduct 111A (274 mg, yield 46%) was eluted with 5% acetone in petroleum ether (v/v), and
photoproduct 111B (268 mg, yield 45%) was eluted with 10% acetone in petroleum ether (v/v); their spectral characteristics are as follows:

Tetramethyl-4b,8b,8c,8d-tetrahydro-dibenzo[a,f]cyclopropa[cd]pentalene-1,5,8b,8c-tetracarboxylate (111A)

mp: 128-129 °C.

IR (KBr) νmax: 2960, 2360, 1742 (C=O), 1718 (C=O), 1591, 1444, 1383, 1337, 1284, 1260, 1225, 1200, 1173, 1151, 1133, 1069, 1037 cm⁻¹.

MS m/e (rel. intensity): 436 (M⁺, 31), 405 (14), 378 (13), 377 (53), 376 (100), 372 (17), 349 (19), 346 (15), 345 (33), 318 (21), 317 (21), 294 (12), 287 (13), 260 (10), 259 (11), 200 (15), 187 (13).

¹H NMR (CDCl₃, 400 MHz) δ ppm: 7.10-7.85 (m, 6 H), 5.97 (s, 1 H, H₄b), 5.27 (s, 1 H, H₈d), 4.02 (s, 3 H), 3.95 (s, 3 H), 3.93 (s, 3 H), 3.75 (s, 3 H).

¹³C NMR (CDCl₃, 50 MHz) δ ppm: 204.02, 169.02, 168.22, 166.67, 166.59, 151.60, 151.27, 136.72, 135.58, 130.84, 129.52, 129.19, 127.74, 127.58, 127.43, 126.45, 123.12, 67.82, 56.83, 54.70, 53.02, 52.45, 52.15, 50.53.


NOE: Irradiated at 5.97 ppm (H₄b), aromatic hydrogen signals around 7.65 ppm were enhanced. Irradiated at 5.27 ppm (H₈d), no aromatic signal was enhanced.
Tetramethyl-4b,8b,8c,8d-tetrahydro-dibenzo[a,f]cyclopropa[cd]pentalene-1,5,8c,8d-tetracarboxylate (111B)

mp: 165-166 °C.

IR (KBr) \( \nu_{\text{max}} \): 2952, 1742 (C=O), 1717 (C=O), 1590, 1434, 1340, 1280, 1236 cm\(^{-1}\).

MS \( m/e \) (rel. intensity): 437 (M\(^+\) + 1, 12), 436 (M\(^+\), 48), 408 (11), 405 (22), 404 (18), 378 (11), 377 (50), 376 (100), 374 (10), 372 (28), 349 (47), 348 (37), 346 (20), 345 (47), 318 (20), 317 (24), 289 (17), 287 (17), 260 (11), 259 (13), 200 (27), 187 (24).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 7.14-7.80 (m, 6 H), 5.99 (s, 1 H, H4b), 4.75 (s, 3 H), 4.02 (s, 3 H), 3.84 (s, 3 H), 3.77 (s, 3 H), 3.73 (s, 3 H).

\(^13\)C NMR (CDCl\(_3\), 50 MHz) \( \delta \) ppm: 204.04, 168.97, 167.44, 166.56, 152.36, 151.74, 136.98, 130.11, 129.29, 129.10, 127.95, 127.46, 126.16, 123.45, 67.50, 58.92, 54.61, 52.44, 52.10, 51.83, 48.91.


NOE: Irradiated at 5.99 ppm (H4b) and 4.75 ppm (H8b) respectively, aromatic hydrogen signals were enhanced in both cases.
The Photolysis of Dimethyl 1,5-Dicyano-9,10-dihydro-9,10-ethenoanthracene-11,12-dicarboxylate (110)

The large scale photolysis of dibenzobarrelene 110 was conducted in acetone. The two photoproducts, 110A and 110B, could not be separated by column chromatography. 1H NMR spectra of the photoreaction mixture were analysed, and the structures of photoproducts 110A and 110B were assigned based on the 1H NMR spectra of the other three pairs of photoproducts isolated (109A and 109B; 111A and 111B; 112A and 112B). See text.

\[
\begin{align*}
110A & \quad (E = \text{CO}_2\text{Me}) \\
\delta H8d & \quad 4.81 \text{ ppm} \\
\delta H4b & \quad 5.40 \text{ ppm}
\end{align*}
\]

110B

\[
\begin{align*}
\delta H8b & \quad 4.70 \text{ ppm} \\
\delta H4b & \quad 5.45 \text{ ppm}
\end{align*}
\]

The Photolysis of Dimethyl 1,5-Dimethoxy-9,10-dihydro-9,10-ethenoanthracene-11,12-dicarboxylate (112)

Preparative scale irradiation of dibenzobarrelene 112 (648 mg, 1.7 mmol) was conducted in 200 ml of acetone for 20 h with the complete consumption of substrate 112. The two photoproducts were partially separated by column chromatography. Products 112A (106 mg) and 112B (307 mg) were eluted with diethyl ether in petroleum ether.
with a gradual increase of the diethyl ether content from 8% to 30% (v/v); their spectral characteristics are as follows:

**Dimethyl 1,5-Dimethoxy-4b,8b,8c,8d-tetrahydro-dibenzo[a,f]cyclopropa[cd]-pentalene-8c,8d-dicarboxylate (112B)**

![Chemical Structure](image)

mp: 150-152 °C.

IR (KBr) \( \nu_{\text{max}} \): 2949, 1746 (C=O), 1726 (C=O), 1588, 1485, 1437, 1290, 1276, 1225 (O-CH₃), 1205, 1171 cm⁻¹.

MS \( m/e \) (rel. intensity): 381 (M+ + 1, 14), 380 (M+, 64), 322 (21), 321 (100), 320 (88), 293 (35), 289 (39).

\(^1\)H NMR (CDCl₃, 400 MHz) \( \delta \text{ ppm} \): 6.60-7.10 (m, 6 H), 5.23 (s, 1 H, H₄b), 4.40 (s, 1 H, H₈b), 3.84 (s, 3 H), 3.82 (s, 3 H), 3.72 (s, 3 H), 3.70 (s, 3 H).

\(^{13}\)C NMR (CDCl₃, 50 MHz) \( \delta \text{ ppm} \): 169.65, 168.69, 156.35, 153.39, 151.83, 137.03, 136.62, 129.30, 128.47, 121.62, 117.90, 114.41, 109.52, 109.32, 65.78, 56.12, 55.57, 55.29, 52.57, 52.17, 52.08, 49.39.


NOE: Aromatic proton signals were enhanced upon irradiating at 5.23 ppm (H₄b) and 4.40 ppm (H₈b) respectively.
Dimethyl 1,5-Dimethoxy-4b,8b,8c,8d-tetrahydro-dibenzo[a,f]cyclopropa[cd]-pentalene-8b,8c-dicarboxylate (112A)

IR (KBr) νmax: 3020, 2954, 1734 (C=O), 1606, 1589, 1484, 1466, 1439, 1313, 1269 (broad, O-CH₃), 1217 (broad, O-CH₃) cm⁻¹.

MS m/e (rel. intensity): 380 (M⁺, 28), 321 (75), 320 (77), 293 (21), 263 (33), 247 (27), 189 (24), 176 (30).

¹H NMR (CDCl₃, 400 MHz) δ ppm: 6.58-7.10 (m, 6 H), 5.18 (s, 1 H, H₄b), 4.61 (s, 1 H, H₈d), 3.87 (s, 3 H), 3.85 (s, 3 H), 3.78 (s, 3 H), 3.69 (s, 3 H).

¹³C NMR (CDCl₃, 50 MHz) δ ppm: 169.41, 168.54, 156.85, 153.26, 151.66, 137.05, 135.12, 128.84, 128.49, 122.29, 118.26, 114.26, 109.46, 109.13, 66.87, 61.87, 57.44, 55.34, 52.84, 52.69, 52.24, 46.50.

High Resolution MS calcd for C₂₂H₂₀O₆ 380.1260, found 380.1264. (This product was isolated as an oil).

The Photolysis of Dimethyl 1,8-Dichloro-9,10-dihydro-9,10-ethenoanthracene-11,12-dicarboxylate (130)

Preparative scale irradiation of dibenzobarrelene 130 (1.173 g, 3.0 mmol) was conducted in 200 ml of acetone for 10 h with the complete consumption of substrate 130. The two photoproducts were partially separated by column chromatography.
Photoproduts 141 (100 mg) and 142 (210 mg) were eluted with 5% diethyl ether in hexanes (v/v); their spectral characteristics are as follows:

**Dimethyl 1,8-Dichloro-4b,8b,8c,8d-tetrahydro-dibenzo[a,f]cyclopropa[cd]-pentalene-8b,8c-dicarboxylate (141)**

![Structure of 141](image)

mp: 247-249 °C.

**IR (KBr)** $\nu_{\text{max}}$: 2955, 1744 (C=O), 1736 (C=O), 1726, 1439, 1259, 1234, 1210 cm$^{-1}$.

**MS** m/e (rel. intensity): 390 (M$^+$ + 2, 62), 388 (M$^+$, 97), 330 (80), 328 (100), 301 (49), 270 (62), 246 (44), 200 (68).

$^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ ppm: 7.00-7.10 (m, 6 H), 5.14 (s, 1 H, H$_{4b}$), 4.66 (s, 1 H, H$_{8d}$), 3.88 (s, 3 H), 3.73 (s, 3 H).

$^{13}$C NMR (CDCl$_3$, 50 MHz) $\delta$ ppm: 168.75, 167.01, 152.01, 151.29, 133.41, 131.82, 131.64, 129.65, 129.27, 128.28, 127.49, 124.30, 119.89, 119.85, 64.98, 57.36, 55.99, 53.01, 52.51, 47.81.

Anal. Calcd for C$_{20}$H$_{14}$Cl$_2$O$_4$: C, 61.72; H, 3.63; Cl, 18.22. Found: C, 61.47; H, 3.76; Cl, 17.95.

NOE: Irradiated at 5.14 ppm (H$_{4b}$), aromatic proton signals were enhanced. Irradiation at 4.66 ppm (H$_{8d}$), aromatic proton signals were not enhanced.
Dimethyl 4,5-Dichloro-4b,8b,8c,8d-tetrahydro-dibenzo[a,f]cyclopropa[cd]-pentalene-8b,8c-dicarboxylate (142)

mp: 190-192.5 °C.

IR (KBr) νmax: 2952, 1751 (C=O), 1728 (C=O), 1523, 1437, 1275, 1226, 1169 cm⁻¹.

MS m/e (rel. intensity): 390 (M⁺ + 2, 56), 388 (M⁺, 88), 330 (79), 328 (100), 301 (51), 270 (62), 251 (35), 200 (80).

¹H NMR (CDCl₃, 400 MHz) δ ppm: 7.00-7.30 (m, 6 H), 5.45 (s, 1 H, H₄b), 4.44 (s, 1 H, H₈d), 3.87 (s, 3 H), 3.75 (s, 3 H).

¹³C NMR (CDCl₃, 50 MHz) δ ppm: 168.55, 167.71, 147.22, 138.00, 136.80, 129.66, 128.94, 128.89, 128.69, 128.48, 128.28, 127.49, 124.30, 124.01, 68.72, 58.25, 53.50, 52.99, 52.57, 49.88.

Anal. Calcd for C₂₀H₁₄C₂O₄: C, 61.72; H, 3.63; Cl, 18.22. Found: C, 61.77; H, 3.60; Cl, 18.34.

NOE: Irradiated at 5.45 ppm (H₄b), aromatic proton signals were not enhanced. Irradiation at 4.44 ppm (H₈d), aromatic proton signals were enhanced.
The Photolysis of Dimethyl 1-Chloro-9,10-dihydro-9,10-ethenoanthracene-11,12-dicarboxylate (131)

Preparative scale irradiation of dibenzobarrelene 131 (1.53 g, 4.3 mmol) was conducted in 200 ml of acetone for 1 h with the complete consumption of substrate 131. There are four possible regioisomeric photoproducts, among which only one was isolated by column chromatography, and the other products could not be separated. Products 143 (150 mg) was eluted with 4% diethyl ether in hexanes (v/v) as the eluent; its spectral characteristics are as follows:

Dimethyl 1-Chloro-4b,8b,8c,8d-tetrahydro-dibenzo[a,f]cyclopropa[cd]-pentalene-8c,8d-dicarboxylate (143)

mp: 191-192 °C.
IR (KBr) v_max: 3062, 2945, 1743 (C=O), 1732 (C=O), 1571, 1434, 1289, 1251, 1224, 1167 cm⁻¹.
MS m/e (rel. intensity): 356 (M⁺ + 2, 15), 354 (M⁺, 42), 294 (100), 267 (44), 236 (45), 200 (39).

¹H NMR (CDCl₃, 400 MHz) δ ppm: 7.00-7.40 (m, 7 H), 5.10 (s, 1H, H₄b), 4.49 (s, 1 H, H₈b), 3.86 (s, 3 H), 3.72 (s, 3 H).
$^{13}$C NMR (CDCl$_3$, 50 MHz) $\delta$ ppm: 169.18, 167.61, 152.58, 149.62, 134.73, 131.81, 131.43, 129.48, 127.94, 127.75, 127.20, 125.70, 121.56, 119.87, 65.83, 57.59, 55.35, 52.93, 52.38, 49.16.


NOE: Aromatic proton signals were enhanced with the irradiation of protons at 4.49 ppm (H8b) and 5.10 ppm (H4b) respectively.

The structure of this compound was solved by an X-ray diffraction analysis. The crystal data are as follows: C$_{20}$H$_{15}$ClO$_4$ crystallized in space group P$\bar{1}$, $a = 9.7557$ (8) Å, $b = 10.5561$ (6) Å, $c = 8.8302$ (8) Å, $\alpha = 107.219$ (6)$^\circ$, $\beta = 105.310$ (7)$^\circ$, $\gamma = 95.404$ (6)$^\circ$, $V = 823.0$ (1) Å$^3$, $Z = 2$, $D_{calcd} = 1.432$ g/cm$^3$, $R = 0.035$.

5.4. Quantum Yield Studies

Apparatus

Irradiations were conducted in a merry-go-round apparatus$^{128}$ with a 450 W Hanovia medium pressure mercury lamp housed in a quartz immersion well. The 313 nm mercury line was isolated by a filter combination of 7-54 Corning glass plates and an aqueous solution of 0.002 M K$_2$CrO$_4$ containing 5% K$_2$CO$_3$ (wt/wt) circulated through a Pyrex cooling jacket.$^{128}$ The whole merry-go-round apparatus was immersed in a water bath whose temperature was maintained at 20 $\pm$ 3°C by passing cold water through a large copper coil inside the water bath. The temperature of the filter solution was also maintained at 20 $\pm$ 3°C by another copper coil with cold water running through it.
Purification of Solvents and Reagents

Thiophene-free benzene was used as the solvent and was prepared by successive washes with concentrated sulfuric acid, drying and distillation over sodium metal.\textsuperscript{122} Acetophenone (Aldrich) was distilled under reduced pressure before use. Valerophenone, tricosane and tetradecane (all from Aldrich) were used without further purification.

Internal Standards and GC Detector (FID) Responses

The internal standards were chosen so that their peaks would not overlap with any other peaks expected and yet have a retention time close to that of the photoproducts to be studied. Tetradecane was used as an internal standard for acetophenone, and tricosane was used as an internal standard for the photoproducts of ketone 150. Detector responses were measured from several injections (≥4) of accurately prepared solutions containing the starting material, photoproduct and the internal standard.

Actinometry

Valerophenone was used as the actinometer. The quantum yield of acetophenone formation is known to be $\Phi = 0.3$ with an opaque concentration (0.1 M) of valerophenone in benzene.\textsuperscript{106} Thus two 3 ml benzene solutions of 0.1 M valerophenone and 1.000 g/ml of tetradecane were degassed in Pyrex phototubes and were photolysed along with the test samples. The formation of acetophenone was monitored by GC (carbowax column, 20 m).
Irradiation of Samples

Solutions containing known concentrations of substrate and internal standard (3 ml aliquots) were pipetted into Pyrex phototubes (100 x 13 mm) and were then degassed by four freeze-thaw-pump cycles. These sample tubes were capped with B14 stoppers, sealed with polyethylene films and photolysed in the merry-go-round apparatus together with the actinometer solutions. The product formation was monitored by GC (DB-1, 15 m). The reaction conversion was limited to ≤ 7%.

Quantum Yield Calculation

The quantum yield was calculated from the following equation:

\[ \Phi = \frac{\text{Moles of photoproduct formed}}{\text{Moles of photons absorbed}} \]

The quantum yield of each photoproduct was calculated at different conversions, and the quantum yields were plotted against the conversions. The reported quantum yield values were determined by a zero conversion extrapolation.
5.5. The Synthesis and Photolysis of α-Cycloalkyl Acetophenones

1-(4-Fluorophenyl)-2-tricyclo[3.3.1.1^{3,7}]dec-1-yl Ethanone (148)

The procedure for making α-cycloalkylacetophenone was followed.\(^9\)

(a) The Preparation of Tricyclo[3.3.1.1^{3,7}]dec-1-yl-acetyl Chloride

Tricyclo[3.3.1.1^{3,7}]dec-1-yl-acetic acid (1-adamantaneacetic acid, 10.0 g, 51 mmol, Aldrich) was dissolved in 20 ml of thionyl chloride and the resulting solution was refluxed for 1 h. The excess of thionyl chloride was removed in vacuo. The oily residue was distilled under reduced pressure, and tricyclo[3.3.1.1^{3,7}]dec-1-yl-acetyl chloride (10.2 g, yield 94%, bp 100-103 °C, 0.3 mm Hg) was obtained, which was used immediately without further purification.

(b) The Friedel-Crafts Reaction

Freshly prepared tricyclo[3.3.1.1^{3,7}]dec-1-yl-acetyl chloride (10.2 g, 48 mmol) was added over 30 min. from an addition funnel to a mixture of anhydrous aluminum chloride (7.9 g, 59 mmol, Aldrich) and excess of fluorobenzene (30 ml, Aldrich). The reaction mixture was refluxed for 4 h and was cautiously poured into 80 ml of cold water with stirring. The yellow organic layer was separated and the aqueous layer was further extracted with 3 × 30 ml of diethyl ether. The combined organic extracts were washed with 2 × 30 ml of 10% NaOH solution, 2 × 30 ml of water and dried over magnesium sulfate. The organic solvents were removed in vacuo. The resulting yellow oil was
chromatographed on silica gel with 2% diethyl ether in petroleum ether (v/v) to afford ketone 148 (12.0 g, yield 92%) as colorless prisms, mp 64.5-65.5 °C (recrystallized from acetone).

IR (KBr) \( \nu_{\text{max}} \): 2909, 2847, 1664 (C=O), 1594, 1504, 1447, 1265, 1225, 1149, 856 cm\(^{-1}\).

MS \( m/e \) (rel. intensity): 272 (M\(^+\), 57), 271 (48), 255 (22), 254 (65), 197 (16), 135 (73), 123 (100), 95 (64).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 7.96 (m, 2 H), 7.11 (m, 2 H), 2.70 (s, 2 H, H2), 1.98 (m, 3 H, H3", H5", and H7"), 1.75-1.55 (m, 12 H).

\(^{13}\)C NMR (CDCl\(_3\), 50 MHz) \( \delta \) ppm: 198.53 (C=O), 168.09 and 163.04 (d, \( \text{J}_{\text{C-F}} = 252.5 \text{ Hz, C4'} \)), 135.26 (C1'), 131.07 and 130.89 (d, \( \text{J}_{\text{C-F}} = 9.2 \text{ Hz, C2'} \)), 115.66 and 115.23 (d, \( \text{J}_{\text{C-F}} = 21.6 \text{ Hz, C3'} \)), 51.16 (C2), 42.98, 36.71, 33.96(C1"), 28.69 (C3", C5" and C7").


The structure of this compound was further supported by an X-ray diffraction analysis. The crystal data are as follows: C\(_{18}\)H\(_{21}\)F crystallized in space group \( Pca2_1 \), \( a = 12.802 (3) \text{ Å, } b = 11.181 (3) \text{ Å, } c = 20.281 (2) \text{ Å, } V = 2903 (2) \text{ Å}^3, Z = 8, D_{\text{calcld}} = 1.246 \text{ g/cm}^3, R = 0.035.

1-(4-Cyanophenyl)-2-tricyclo[3.3.1.1\(^3,7\)]deca-1-yl Ethanone (149)
Potassium cyanide (2.8 g, 43 mmol) and 1-(4-fluorophenyl)-2-tricyclo[3.3.1.1^{3,7}]dec-1-yl ethanone (6.12 g, 22.5 mmol) were added to 35 ml of dimethyl sulfoxide and heated at 110-130 °C for 24 h. The reaction mixture was poured into 100 ml of water and extracted with diethyl ether (3 x 30 ml). The combined organic extracts were washed with water (30 ml), 5% sodium bicarbonate (30 ml) and dried over magnesium sulfate. The solvent was removed in vacuo to afford a light yellow solid, which was recrystallized from diethyl ether to give colorless needles of ketone 149 (5.2 g, yield 85%), mp 116.5-117.5 °C.

IR (KBr) vmax: 2900, 2849, 2234, 2223 (ON), 1692 (C=O), 1675, 1402, 1346, 1327, 1263 cm\(^{-1}\).

MS m/e (rel. intensity): 279 (M\(^+\), 80), 261 (M\(^+\)−H\(_2\)O, 40), 149 (11), 135 (100), 130 (61), 102 (55).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \(\delta\) ppm: 8.02 (d, 2 H, J = 8.8 Hz), 7.75 (d, 2 H, J = 8.8 Hz), 2.72 (s, 2 H, H2), 1.96 (m, 3 H, H3\(^"\), H5\(^"\) and H7\(^"\)), 1.72-1.58 (m, 12 H).

\(^13\)C NMR (CDCl\(_3\), 50 MHz) \(\delta\) ppm: 198.88 (C=O), 141.69, 132.41, 128.70, 118.02, 116.00, 51.43, 42.92, 36.63, 34.18, 28.62.

Anal. Calcd for C\(_{19}\)H\(_{21}\)NO: C, 81.68; H, 7.58; N, 5.01. Found: C, 81.44; H, 7.45; N, 4.97.

The structure of this compound was also supported by an X-ray diffraction analysis. The crystal data are as follows: C\(_{19}\)H\(_{21}\)NO crystallized in space group P2\(_1\)/a, \(a = 11.617 \ (2) \ \text{Å}, \ b = 6.643 \ (6) \ \text{Å}, \ c = 20.868 \ (2) \ \text{Å}, \ \beta = 103.27 \ (1)^{\circ}, \ V = 1567 \ (1) \ \text{Å}^3, \ Z = 4, \ D_{\text{calcd}} = 1.184 \ \text{g/cm}^3, \ R = 0.049.\)
1-(4-Carboxyphenyl)-2-tricyclo[3.3.1.13,7]dec-1-yl Ethanone (119)

A mixture of ketone 149 (5.20 g, 18.6 mmol), 30% potassium hydroxide (40 ml) and 8 ml of ethanol was refluxed for 24 h. This was then acidified with hydrochloric acid and the resulting white precipitate was filtered and recrystallized from 10% ethanol/water solution to give carboxylic acid 119 (5.20 g, yield 94%), mp 235-237 °C.

IR (KBr) \( \nu_{\text{max}} \): 2898, 2846, 2672, 2549, 1686 (broad, C=O), 1571, 1504, 1426, 1405, 1291, 1262 cm\(^{-1}\).

MS \( m/e \) (rel. intensity): 298 (M\(^+\), 11), 254 (34), 253 (100), 149 (74), 135 (56), 121 (26), 107 (19), 93 (43).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 13.25 (s, broad, 1 H, COOH), 8.10 (m, 4 H), 2.80 (s, 2 H, H2), 1.92 (m, 3 H, H3\(^\prime\), H5\(^\prime\) and H7\(^\prime\)), 1.70-1.50 (m, 12 H).

\(^13\)C NMR (CDCl\(_3\), 50 MHz) \( \delta \) ppm: 201 (C=O, ketone), 167 (C=O, acid), 141.62, 134.17, 129.65, 128.37, 50.87, 42.29, 36.33, 33.56, 28.13.

Anal. Calcd for C\(_{19}\)H\(_{22}\)O\(_3\): C, 76.48; H, 7.43. Found: C, 76.33; H, 7.40.
1-(4-Carbomethoxyphenyl)-2-tricyclo[3.3.1.13,7]dec-1-yl Ethanone (150)

A solution of carboxylic acid 119 (1.75 g, 5.9 mmol), 0.3 g of concentrated sulfuric acid and 20 ml of methanol was refluxed for 12 h. The excess solvent was evaporated in vacuo. Water (20 ml) containing the calculated amount of sodium carbonate was added to neutralize the sulfuric acid. This mixture was then extracted with diethyl ether (3 × 15 ml) and the ether extracts were dried over magnesium sulfate. The solvent evaporation in vacuo gave ester 150 (1.65 g, yield 90%), mp 108-109 °C (recrystallized from acetone).

IR (KBr) \( \nu_{\text{max}} \): 2902, 2849, 1722 (C=O, ester), 1670 (C=O, ketone), 1504, 1435, 1346, 1325, 1276, 1228, 1192, 1108 cm\(^{-1}\).

UV (CH\(_3\)CN) \( \lambda_{\text{max}} \): 249 nm (\( \varepsilon \) 14600), 313 nm (\( \varepsilon \) 146).

MS \( m/e \) (rel. intensity): 312 (M\(^+\), 3), 297 (9), 253 (100), 163 (72), 135 (44).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 8.12 (d, J = 8.5 Hz, 2 H), 7.98 (d, J = 8.5 Hz, 2 H), 3.95 (s, 3 H, COOCH\(_3\)), 2.75 (s, 2 H, H2), 1.95 (m, 3 H, H3\(^\prime\), H5\(^\prime\) and H7\(^\prime\)), 1.75-1.60 (m, 12 H).

\(^{13}\)C NMR (CDCl\(_3\), 50 MHz) \( \delta \) ppm: 199.88 (C=O, ketone), 166.31 (C=O, ester), 142.08, 133.51, 129.73, 128.22, 52.42, 51.59, 42.95, 36.69, 34.08, 28.66.

Anal. Calcd for C\(_{20}\)H\(_{24}\)O\(_3\): C, 76.88; H, 7.75. Found: C, 76.80; H, 7.72.
The Preparation of 1-(4-Carboxyphenyl)-2-tricyclo[3.3.1.1^{3,7}]dec-1-yl Ethanone-S- (+)-2-Pyrrolidinemethanol Salts 169p and 169n

The crystalline carboxylic acid-amine salts were prepared by dissolving a 1:1 mixture of S-(+)-2-pyrrolidinemethanol (135.7 mg, 1.34 mmol, Aldrich) and the carboxylic acid 119 (400 mg, 1.34 mmol) in 30 ml of refluxing acetone, this solution was cooled to room temperature and left overnight. Colorless plates (Salt 169p, 250 mg, yield 47%) were collected on filtration; after a few hours, colorless needle-shaped crystals (Salt 169n, 200 mg, yield 37%) were formed from the mother liquor. Their spectral characteristics are as follows:

1-(4-Carboxyphenyl)-2-tricyclo[3.3.1.1^{3,7}]dec-1-yl Ethanone-S-(+)-2-Pyrrolidinemethanol Salt 169p

mp: 116-118 °C.
IR (KBr) \( \nu_{\text{max}} \): 3188 (NH), 2909, 2847, 1673, 1631, 1586, 1547, 1387, 1287, 806, 757 cm\(^{-1}\).
UV (CHCl\(_3\)) \( \lambda_{\text{max}} \): 253 nm (\( \varepsilon \) 19700).
FAB MS \( m/e \): 400 (M\(^+\) + 1), 299, 281, 255, 165. [Matrix: 3-nitrobenzyl alcohol].
\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 8.04 (d, \( J = 8.4 \) Hz, 2 H), 7.93 (d, \( J = 8.4 \) Hz, 2 H), 3.95 (d, \( J = 9.9, 1 \) H), 3.78 (m, 2 H), 3.30 (m, 2 H), 2.73 (s, 2 H), 2.32-1.53 (m, 22 H).
\(^13\)C NMR (CDCl\(_3\), 100 MHz) \( \delta \) ppm: 200.53 (C=O, ketone), 173.54 (C=O, carboxylate), 140.79, 140.49, 129.58, 128.31, 61.91, 61.75, 51.83, 45.55, 43.25, 37.00, 34.26, 28.97, 26.72, 24.91.

The structure of this salt was supported by an X-ray diffraction analysis. The crystal data are as follows: C₂₄H₃₃NΟ₄ crystallized in space group P2₁2₁2₁, \( a = 11.798(1) \) Å, \( b = 43.563(3) \) Å, \( c = 8.4434(8) \) Å, \( V = 4340(1) \) Å³, \( Z = 8 \), \( D_{calcd} = 1.223 \) g/cm³, \( R = 0.056 \).

1-(4-Carboxyphenyl)-2-tricyclo[3.3.1.1³,7]dec-1-yl Ethanone-S-(+)-2-Pyrrolidine-methanol Salt 169n

mp: 128-130 °C.
IR (KBr) \( \nu_{max} \): 3183 (NH), 2902, 2845, 1675, 1638, 1586, 1546, 1385, 1260, 803, 754 cm⁻¹.
UV (CHCl₃) \( \lambda_{max} \): 253 nm (ε 19700).
FAB MS \( m/e \): 400 (M+ + 1), 299, 281, 255, 186, 165. [Matrix: 3-nitrobenzyl alcohol].

\(^1\)H NMR (CDCl₃, 400 MHz) δ ppm: the same as salt 169p.
\(^1\)³C NMR (CDCl₃, 100 MHz) δ ppm: the same as salt 169p.

The structure of this salt was also supported by an X-ray diffraction analysis. The crystal data are as follows: C₂₄H₃₃NΟ₄ crystallized in space group P2₁2₁2₁, \( a = 17.266(2) \) Å, \( b = 19.292(3) \) Å, \( c = 6.3739(9) \) Å, \( V = 2123.2(9) \) Å³, \( Z = 4 \), \( D_{calcd} = 1.250 \) g/cm³, \( R = 0.041 \).
The Preparation of 1-(4-Carboxyphenyl)-2-tricyclo[3.3.1.13,7]dec-1-yl Ethanone-R-(+)-α-phenylethylamine Salt 170

Salt 170 was prepared by dissolving a 1:1 mixture of R-(+)-α-phenylethylamine (122 mg, 1.0 mmol, Aldrich) and carboxylic acid 119 (300 mg, 1.0 mmol) in 50 ml of hot ethyl acetate and allowing the solution to stand overnight. Very fine needles (salt 170, 200 mg, yield 47%) were obtained on filtration, mp 235-236 °C.

IR (KBr) v_max: 2901, 2848, 1666 (C=O, ketone), 1622, 1581, 1529, 1454, 1388, 1316, 1263, 1206 cm⁻¹.

FAB MS m/z: 420 (M+ + 1), 371, 341, 299, 275, 253, 235, 220, 205. [Matrix: 3-nitrobenzyl alcohol].

¹H NMR (CDCl₃, 400 MHz) δ ppm: 7.81 (d, J = 8.4 Hz, 2 H), 7.76 (d, J = 8.4 Hz, 2 H), 7.35-7.10 (m, 5 H), 4.25 (m, 1 H), 2.73 (s, 2 H), 1.96 (m, 3 H), 1.75-1.48 (m, 15 H).

¹³C NMR (CDCl₃, 50 MHz) δ ppm: 200.28 (C=O, ketone), 140.42 (C=O, carboxylate), 129.40, 128.85, 128.26, 127.86, 126.36, 126.36, 51.57, 51.13, 43.02, 36.75, 34.01, 28.72, 21.67.


The Photolysis of 1-(4-Carbomethoxyphenyl)-2-tricyclo[3.3.1.13,7]dec-1-yl Ethanone (150)

Ketone 150 (1.67 g, 5.3 mmol) was dissolved in 200 ml of acetone, degassed for 30 min. and irradiated (Pyrex filter) for 1 h with the complete consumption of substrate 150. Four products were isolated by column chromatography. Products 161 (51 mg, 3%)
and 162 (61 mg, 3.7%) were eluted with 1% diethyl ether in petroleum ether (v/v); product 159 (1.29 g, 77.5%) was eluted with 10% diethyl ether in petroleum ether (v/v); product 160 (236 mg, 14%) was eluted with 40% diethyl ether (v/v). Their spectral characteristics are as follows:

3-(4-Carbomethoxyphenyl)-tetracyclo[5.3.1.15.9.01.4]dodec-3-ene (161)

\[
\begin{align*}
\text{mp: } & 124-126 \, ^{\circ}\text{C (recrystallized from acetone).} \\
\text{IR } & (\text{KBr}) \quad \nu_{\text{max}}: 2921, 2846, 1716 \, (\text{C} = \text{O}), 1669, 1606, 1433, 1410, 1311, 1279 \\
\quad & (\text{O-CH}_3) \quad 1182, 1110 \, \text{cm}^{-1}. \\
\text{MS } & m/e \quad (\text{rel. intensity}): 294 (M^+, 74), 279 (21), 251 (26), 235 (100), 193 (15), 177 (39), 135 (47). \\
\text{^1H NMR } & (\text{CDCl}_3, 400 \, \text{MHz}) \quad \delta \, \text{ppm}: 7.93 \, (\text{d, } J = 8.4 \, \text{Hz}, 2 \, \text{H}), \quad 7.29 \, (\text{d, } J = 8.4 \\
\quad & \text{Hz, } 2 \, \text{H}), \quad 3.91 \, (\text{s}, 3 \, \text{H, COOCH}_3), \quad 3.09 \, (\text{m, } 1 \, \text{H}), \quad 2.49 \, (\text{m, } 1 \, \text{H}), \quad 2.15-1.55 \, (\text{m, } 13 \, \text{H}). \\
\text{^13C NMR } & (\text{CDCl}_3, 50 \, \text{MHz}) \quad \delta \, \text{ppm}: 167.10 \, (\text{C} = \text{O, ester}), \quad 159.15, \quad 141.43, \quad 129.72, \\
\quad & 127.11, \quad 125.00, \quad 122.62, \quad 51.93, \quad 42.74, \quad 41.21, \quad 39.10, \quad 37.38, \quad 36.67, \quad 32.51, \quad 29.75. \\
\text{Anal. Calcd for } & \text{C}_{20}\text{H}_{22}\text{O}_2: \quad \text{C, } 81.60; \quad \text{H, } 7.53. \quad \text{Found: } \text{C, } 81.61; \quad \text{H, } 7.56.
\end{align*}
\]
(4-Carbomethoxy)-Benzo[4,5]tetracyclo[5.3.1.1^7,11,0^1,6]tetradecan-3-one (162)

mp: 114-116 °C (recrystallized from acetone).

IR (KBr) \( \nu_{\text{max}} \): 2915, 2852, 1722 (C=O, ester), 1693 (C=O, ketone), 1607, 1572, 1438, 1412, 1290, 1193, 1107 cm\(^{-1}\).

MS \( m/e \) (rel. intensity): 310 (M\(^+\), 100), 295 (5), 279 (19), 278 (23), 251 (75).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 8.09 (d, \( J = 8.1 \) Hz, 1 H, Hb), 8.07 (s, 1 H, Hc), 7.87 (d, \( J = 8.1 \) Hz, 1 H, Ha), 3.94 (s, 3 H, COOCH\(_3\)), 3.15 (m, 1 H), 2.85 (m, 1 H), 2.45 (m, 1 H), 2.20-1.20 (m, 15 H).

\(^13\)C NMR (CDCl\(_3\), 50 MHz) \( \delta \) ppm: 197.59 (C=O, ketone), 166.63 (C=O, ester), 145.01, 136.03, 134.50, 127.49, 127.13, 127.02, 53.22, 52.41, 48.05, 45.34, 38.05, 36.91, 36.34, 35.83, 30.52, 29.34, 28.10, 27.82.

High Resolution MS Calcd for C\(_{20}\)H\(_{22}\)O\(_3\): 310.1569. Found: 310.1566.
3-(4-Carbomethoxyphenyl)-(1α,3β,4α,5β,7α,9β)-tetracyclo[5.3.1.1\(^5\).9.0\(^1\).4]dodecan-3-ol (159)

mp: 160-161.5 °C (recrystallized from acetone).

IR (KBr) \( \nu_{\text{max}} \): 3477 (OH), 2897, 2849, 1704 (C=O, ester), 1610, 1440, 1405, 1351, 1316, 1284, 1201, 1102 cm\(^{-1}\).

UV (CH\(_3\)CN) \( \lambda_{\text{max}} \): 238 nm (\( \epsilon \) 14000).

MS \( m/e \) (rel. intensity): 312 (M\(^+\), 4), 311 (22), 310 (88), 294 (18), 253 (100), 163 (84), 149 (64).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 8.02 (d, \( J = 8.5 \) Hz, 2 H, H3'), 7.41 (d, \( J = 8.5 \) Hz, 2 H, H2'), 3.91 (s, 3 H, COOCH\(_3\)), 2.91 (m, 1 H, H10a), 2.40-1.54 (m, 16 H).

\(^{13}\)C NMR (CDCl\(_3\), 50 MHz) \( \delta \) ppm: 166.90 (C=O, ester), 153.45 (C4'), 129.93 (C3'), 128.80 (C1'), 125.04 (C2'), 83.98 (C3), 55.30 (C4), 52.09 (OCH\(_3\)), 48.30 (C2), 45.42, 41.00, 39.85 (C10), 38.07, 34.11 (C1), 32.22, 30.94, 29.77, 28.44.

Anal. Calcd for C\(_{20}\)H\(_{24}\)O\(_3\): C, 76.88; H, 7.75. Found: C, 76.94; H, 7.74.

Carbon and hydrogen assignments were based on HETCOR, APT, \(^{13}\)C NMR and \(^1\)H NMR spectra. See text.

The structure of product 159 was further supported by an X-ray crystal structure analysis on the corresponding salt form 159s. See text.
3-(4-Carbomethoxyphenyl)-(1α,3α,4α,5β,7α,9β)-tetracyclo[5.3.1.15,9.01,4]dodecan-3-ol (160)

mp: 118-120 °C (recrystallized from acetone).
IR (KBr) ν max: 3400-3000 (broad, OH), 2906, 2853, 1727 (C=O, ester), 1609, 1438, 1407, 1276, 1177, 1116, 1056, 1014 cm⁻¹.
UV (CH₃CN) λ max: 242 nm (ε 13000).
MS m/e (rel. intensity): 312 (M⁺, 1), 311 (6), 310 (29), 294 (74), 279 (25), 251 (57), 235 (100), 193 (22), 179 (26), 91 (33).
¹H NMR (CDCl₃, 400 MHz) δ ppm: 8.04 (d, J = 8.4 Hz, 2 H), 7.52 (d, J = 8.4 Hz, 2 H), 3.93 (s, 3 H, COOCH₃), 2.78 (d, J = 11.4 Hz, 1 H), 2.68 (s, 1 H), 2.40 (s, 1 H), 2.18-1.20 (m, 14 H).
¹³C NMR (CDCl₃, 50 MHz) δ ppm: 167.2 (C=O), 148.64, 129.80, 129.34, 127.90, 81.68, 60.47, 52.14, 47.34, 45.56, 40.97, 37.83, 37.76, 30.71, 30.61, 29.68, 28.98, 27.99.

The Photolysis of Salt 169n

Crystals of salt 169n (115 mg, 0.29 mmol) were placed between two Pyrex microscope plates, and by sliding the top and bottom plates back and forth, the sample
was distributed over the surface in a thin, even layer. The sample plates were then Scotch-taped together at the top and bottom ends, placed in a polyethylene bag and thoroughly degassed with nitrogen; this bag was then sealed under a positive pressure of nitrogen with a heat-sealing device. This sample bag was immersed in a cooling bath maintained at $-40 \, ^\circ\text{C}$ by means of a cryomat (Cryocool CC-100 II) and irradiated with the output from a 450 W Hanovia medium pressure mercury lamp for 20 h. After photolysis, the solid mixture was treated with dilute hydrochloric acid and extracted with diethyl ether. The diethyl ether solution was then washed with water and dried over magnesium sulfate. This diethyl ether solution was subsequently treated with an excess of etheral diazomethane to convert the acids to methyl esters, and these ester products were isolated by column chromatography on silica gel. Ketone 150 (22 mg, 24%) was eluted with 5% diethyl ether in petroleum ether (v/v); product 159 (56 mg, 62%) was eluted with 10% diethyl ether in petroleum ether (v/v); and product 160 (10 mg, 11%) was eluted with 20% diethyl ether in petroleum ether (v/v).

A small amount of unusual product 200 was also isolated occasionally from the solid state photolysis of salt 169n, and it is not clear how it was formed. The characterization of product 200 is given below.

3-[4-Vinyl Benzoate]-Tetracyclo[5.3.1.15,9.01,4]dodecan-3-ol (200)
mp: 129-132 °C (recrystallized from acetone).

IR (KBr) \( \nu_{\text{max}} \): 3508 (OH), 2901, 2849, 1710 (C=O), 1651, 1610, 1449, 1407, 1307, 1267, 1201, 1130, 1102 \text{ cm}^{-1}.

MS (DCI, NH\(_3\)) \( m/e \) (rel. intensity): 324 (M\(^+\), 5), 309 (10), 308 (51), 307 (100), 282 (37), 281 (69), 264 (22), 263 (45), 254 (17), 253 (21).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 8.06 (d, J = 8.4 Hz, 2 H, H\(_3^*\)), 7.49 (dd, J = 14, 6.2 Hz, 1 H, Hc), 7.42 (d, J = 8.4 Hz, 2 H, H\(_2^*\)), 5.06 (dd, J = 14, 1.7 Hz, 1 H, He), 4.69 (dd, J = 6.2, 1.7 Hz, 1 H, Hd), 2.91 (m, 1 H, H10a), 2.40-0.85 (m, 17 H).

\(^13\)C NMR (CDCl\(_3\), 75 MHz) \( \delta \) ppm: 163.44 (C=O), 141.40 (C\(_5^*\)), 130.38 (C\(_3^*\)), 130.00, 127.53, 125.23 (C\(_2^*\)), 98.21 (C\(_6^*\)), 83.95 (C3), 55.32 (C4), 48.32, 45.40, 40.99, 39.85 (C10), 38.03, 34.12, 32.21, 30.90, 29.74, 28.40.

Anal. Calcd for C\(_{21}\)H\(_{24}\)O\(_3\): C, 77.75; H, 7.46. Found: C, 77.32; H, 7.61.

HETCOR and APT spectra were also used to assign this structure.

**X-ray Crystallographic Data for Solid State Photoproduct 159s**

The absolute configuration of this salt was solved by an X-ray diffraction analysis. The crystal data are as follows: C\(_{48}\)H\(_{68}\)N\(_2\)O\(_9\) crystallized in space group \( P2_12_12_1 \), \( a = 11.021 \) (2) Å, \( b = 56.481 \) (8) Å, \( c = 6.840 \) (1) Å, \( V = 4258 \) (2) Å\(^3\), \( Z = 4 \), \( D_{\text{calcd}} = 1.275 \) g/cm\(^3\), \( R = 0.100 \).

**Synthesis of 1-(4-Fluorophenyl)-2-cyclohexyl Ethanone (182)**

The procedure for making \( \alpha \)-cycloalkylacetophenone was followed\(^{93,94}\).

(a) The Preparation of Cyclohexylacetyl Chloride
Cyclohexylacetic acid (10.0 g, 70.4 mmol, Aldrich) was dissolved in 30 ml of thionyl chloride and the resulting solution was refluxed for 1 h. The excess of thionyl chloride was evaporated in vacuo, and the remaining cyclohexylacetyl chloride was distilled under reduced pressure (9.9 g, yield 88%, bp 62-63 °C, 0.5 mm Hg). This material was used immediately without further purification.

(b) The Friedel-Crafts Reaction

Freshly prepared cyclohexylacetyl chloride (9.9 g, 62 mmol) was added over 30 min. from an addition funnel to a mixture of anhydrous aluminum chloride (9.0 g, 67 mmol, Aldrich) and excess fluorobenzene (50 ml, Aldrich) in a three-neck round-bottom flask fitted with a condenser and a calcium chloride drying tube. The reaction mixture was refluxed for 5 h and was cautiously poured into 100 ml of cold water with stirring. The yellow organic layer was separated and the aqueous layer was further extracted with 3 x 30 ml of diethyl ether. The combined organic extracts were washed with 2 x 30 ml of 10% NaOH solution, 2 x 30 ml of water and dried over magnesium sulfate. The organic solvents were evaporated in vacuo. The resulting yellow oil was chromatographed with 2% diethyl ether in petroleum ether (v/v) to afford ketone 182 (13.5 g, yield 97%) as a colorless oil.

IR (KBr) \( \nu_{\text{max}} \): 2924, 2851, 1686 (C=O), 1598, 1506, 1449, 1410, 1356, 1288, 1229, 1194, 1157 cm\(^{-1}\).

MS \( m/e \) (rel. intensity): 220 (M\(^+\), 11), 177 (1), 138 (100), 123 (71).

\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 7.95 (m, 2 H), 7.10 (m, 2 H), 2.75 (d, 2 H), 1.95 (m, 1 H), 1.70 (m, 6 H), 1.32-0.92 (m, 4 H).
1-(4-Cyanophenyl)-2-cyclohexyl Ethanone (183)

Ketone 183 was synthesized by following a known procedure.94 Thus, sodium cyanide (5.0 g, 100 mmol) and 1-(4-fluorophenyl)-2-cyclohexyl ethanol (13.5 g, 60 mmol) were added to 75 ml of dimethyl sulfoxide and heated to 110-130 °C for 20 h. The reaction mixture was then poured into 150 ml of water and extracted with diethyl ether (3 × 40 ml). The combined organic extracts were washed with water, 5% sodium bicarbonate solution, and dried over magnesium sulfate. The solvent was evaporated in vacuo, and the resulting 12.4 g of light yellow solid was chromatographed with 10% diethyl ether in petroleum ether (v/v) to afford ketone 183 (8.6 g, yield 62%) as colorless needles, mp 47-48 °C (lit.95 mp 47-48 °C).

IR (KBr) $\nu_{\text{max}}$: 2928, 2846, 2229 (C=N), 1683 (C=O), 1605, 1449, 1403, 1353, 1291, 1250, 1219, 1192, 1002 cm$^{-1}$.

MS $m/e$ (rel. intensity): 227 (M+, 9), 145 (100), 130 (65), 102 (52).

$^1$H NMR (CDCl$_3$, 400 MHz) δ ppm: 8.01 (d, 2 H), 7.75 (d, 2 H), 2.82 (d, 2 H), 2.00-0.90 (m, 11 H).

1-(4-Carboxyphenyl)-2-cyclohexyl Ethanone (184)

A mixture of ketone 183 (4.0 g, 18 mmol), 4 ml of ethanol and 20 ml of 30% aqueous potassium hydroxide solution was refluxed for 18 h. The reaction mixture was acidified with dilute hydrochloric acid to afford 4.4 g yellow solid, which was recrystallized from 10% aqueous ethanol to give colorless needles of ketone 184 (3.72 g, yield 84%), mp 184-185 °C (lit.95 185-186 °C).

IR (KBr) $\nu_{\text{max}}$: 2917, 2850, 2667, 2551, 2361, 1685 (broad, C=O), 1571, 1505, 1428, 1406, 1375, 1359, 1288, 1250, 1219, 1193, 1170, 1125, 1004 cm$^{-1}$.
MS \( m/e \) (rel. intensity): 246 (M\(^+\), 1), 164 (100), 149 (61), 121 (17).

1-(4-Carbomethoxyphenyl)-2-cyclohexyl Ethanone (185)

A solution of ketone 184 (1.5 g, 6.0 mmol), 0.2 g of concentrated sulfuric acid and 30 ml of methanol was refluxed for 12 h. Solvent methanol was distilled out. Water (20 ml) containing the calculated amount of sodium carbonate was added to neutralize the sulfuric acid. This mixture was extracted with diethyl ether (3 \( \times \) 15 ml); the ether extracts were dried over magnesium sulfate and evaporated \textit{in vacuo} to give ketone 185 (1.5 g, yield 96%), which was further recrystallized from acetone. mp 67-68 °C (lit. 95 67-68 °C).

IR (KBr) \( \nu_{\text{max}} \): 2927, 2851, 1722 (C=O, ester), 1683 (C=O, ketone), 1573, 1504, 1439, 1405, 1375, 1358, 1278 (O-CH\(_3\)), 1220, 1187, 1111, 1004 cm\(^{-1}\).

MS \( m/e \) (rel. intensity): 260 (M\(^+\), 0.4), 229 (5), 201 (19), 178 (100), 163 (60), 147 (37), 135 (18).

\( ^1\)H NMR (\text{CDCl}\(_3\), 300 MHz) \( \delta \) ppm: 8.10 (d, 2 H), 7.97 (d, 2 H), 3.93 (s, 3 H, COOCH\(_3\)), 2.84 (d, 2 H), 2.00-0.90 (m, 11 H).

The Photolysis of 1-(4-Carbomethoxyphenyl)-2-cyclohexyl Ethanone (185)

Ketone 185 (1.2 g, 4.6 mmol) was dissolved in 200 ml of acetonitrile, degassed for 30 min. and irradiated (Pyrex filter) for 1 h with the complete consumption of substrate 185. Three products were isolated by column chromatography on silica gel with 10% diethyl ether in petroleum ether (v/v). Photoproducts 186 (300 mg, 37%), 187 (450 mg, 38%) and 188 (150 mg, 13%) were eluted consecutively. Their spectral characteristics are as follows:
Methyl 4-Acetyl-Benzolate (186)

mp: 92-93 °C (recrystallized from acetone).
IR (KBr) \( \nu_{\text{max}} \): 2960, 1723 (C=O, ester), 1678 (C=O, ketone), 1572, 1502, 1438, 1409, 1380, 1357, 1284, 1195, 1113, 1079, 1016 cm\(^{-1}\).
MS \( m/e \) (rel. intensity): 178 (M\(^+\), 17), 163 (100), 147 (33), 135 (33), 103 (22).
\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 8.11 (d, \( J = 8.6 \) Hz, 2 H), 7.98 (d, \( J = 8.6 \) Hz, 2 H), 3.92 (s, 3 H), 2.62 (s, 3 H).

7-(4-Carbomethoxy)-(1\(\alpha\),6\(\alpha\),7\(\beta\))-bicyclo[4.2.0]octan-7-ol (187)

mp: 65-66 °C (recrystallized from acetone).
IR (KBr) \( \nu_{\text{max}} \): 3485 (broad, OH), 2927, 2854, 1723 (C=O), 1611, 1572, 1509, 1438, 1408, 1363, 1279, 1241, 1214 cm\(^{-1}\).
MS \( m/e \) (rel. intensity): 260 (M\(^+\), 1), 258 (30), 256 (22), 242 (18), 228 (20), 183 (50), 163 (100).
\(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) ppm: 7.99 (d, \( J = 8.4 \) Hz, 2 H), 7.40 (d, \( J = 8.4 \) Hz, 2 H), 3.90 (s, 3 H, COOCH\(_3\)), 2.30-1.20 (m, 13 H).
\(^{13}\)C NMR (CDCl\(_3\), 100 MHz) \( \delta \) ppm: 166.94 (C=O), 151.40, 129.77, 128.86, 125.18, 81.58, 53.36, 52.06, 42.09, 38.25, 31.56, 26.65, 26.02, 25.98..
MS $m/e$ (rel. intensity): 260 (M+, 0.7), 258 (15), 256 (10), 242 (22), 228 (12), 183 (64), 163 (100).

$^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ ppm: 8.02 (d, $J = 8.4$ Hz, 2 H), 7.51 (d, $J = 8.4$ Hz, 2 H), 3.90 (s, 3 H, COOCH$_3$), 2.89 (m, 1 H), 2.20-0.70 (m, 12 H).

$^{13}$C NMR (CDCl$_3$, 100 MHz) $\delta$ ppm: 166.95 (C=O), 146.72, 129.53, 129.23, 127.20, 79.58, 57.31, 52.09, 41.67, 33.02, 31.78, 28.33, 26.56, 25.87.

The Preparation of Crystalline Carboxylic Acid-Amine Salt (189)

The crystalline carboxylic acid-amine salt 189 was prepared by dissolving a 1:1 mixture of S-(+)-2-pyrrolidinemethanol (320 mg, 3.17 mmol, Aldrich) and the carboxylic acid 184 (780 mg, 3.17 mmol) in 50 ml of refluxing acetone. This solution was cooled to room temperature and left for 2 h. Colorless needles of salt 189 (600 mg, yield 55%) were collected on filtration. The spectral characteristics of salt 189 are as follows:

mp: 125.5-127.5 °C.

IR (KBr) $v_{max}$: 3282, 2915, 2847, 1683 (C=O), 1587, 1543, 1449, 1374, 1287, 1250, 1193, 1099, 1050 cm$^{-1}$.

FAB MS $m/e$: 348 (M$^+$ + 1), 289, 255, 247, 229, 203, 165. [Matrix: 3-nitrobenzyl alcohol].

$^1$H NMR (CDCl$_3$, 200 MHz) $\delta$ ppm: 8.60 (s, broad, 2 H, NH$_2$), 8.00 (d, $J = 8.4$ Hz, 2 H), 7.86 (d, $J = 8.4$ Hz, 2 H), 3.95-3.70 (m, 3 H), 3.22 (m, 2 H), 2.80 (m, 2 H), 2.15-0.85 (m, 16 H).
\[ ^{13}\text{C NMR (CDCl}_3, 50 \text{ MHz}) \delta \text{ ppm: 200.18 (C=O, ketone), 173.20 (C=O, carboxylate), 140.50, 139.05, 129.37, 127.79, 61.62, 61.45, 46.45, 45.27, 34.50, 33.41, 26.44, 26.23, 26.13, 24.60.} \]

Anal. Calcd for C\(_{20}\)H\(_{29}\)N\(_{04}\): C, 69.14; H, 8.41; N, 4.03. Found: C, 68.93; H, 8.28; N, 3.90.

The Preparation of Crystalline Carboxylic Acid-Amine Salt (190)

The crystalline carboxylic acid-amine salt 190 was prepared by dissolving a 1:1 mixture of S-(−)-\(\alpha\)-phenylethylamine (200 mg, 1.65 mmol, Aldrich) and the carboxylic acid 184 (400 mg, 1.63 mmol) in 20 ml of refluxing acetone. This solution was cooled to room temperature and left for 2 h. Colorless needles of salt 190 (400 mg, yield 67%) were collected on filtration. The spectral characteristics of salt 190 are as follows:

mp: 160-162 °C.

IR (KBr) \(\nu_{\text{max}}\): 2923, 1682, 1623, 1584, 1525, 1449, 1386, 1290, 1222, 1193, 1092, 1004 cm\(^{-1}\).

FAB MS \(m/e\): 368 (M\(^{+} + 1\)), 275, 247, 229, 220, 205, 186, 165, 122. [Matrix: 3-nitrobenzyl alcohol].

\(^{1}\text{H NMR (CDCl}_3, 200 \text{ MHz}) \delta \text{ ppm: 8.90 (s, broad, 3 H, NH), 7.70 (m, 4 H), 7.36-7.10 (m, 4 H), 4.28 (m, 1 H), 2.80 (m, 2 H), 2.05-0.95 (m, 15 H).} \]

\(^{13}\text{C NMR (CDCl}_3, 50 \text{ MHz}) \delta \text{ ppm: 200.18 (C=O, ketone), 172.48 (C=O, carboxylate), 140.18, 139.18, 138.91, 129.43, 128.86, 128.34, 127.57, 126.38, 51.16, 46.47, 34.58, 33.45, 26.25, 26.18, 21.43.} \]

Anal. Calcd for C\(_{23}\)H\(_{29}\)NO\(_3\): C, 75.17; H, 7.95; N, 3.81. Found: C, 74.92; H, 7.80; N, 3.61.
The procedure for making α-cycloalkylacetophenone was followed.\textsuperscript{93}

(a) The Preparation of 5-Methyltricyclo[3.3.1.1\textsuperscript{3,7}]dec-1-yl Acetyl Chloride

5-Methyltricyclo[3.3.1.1\textsuperscript{3,7}]dec-1-yl acetic acid (3-methyl-1-adamantaneacetic acid, 15.0 g, 72 mmol, Aldrich) was dissolved in 30 ml of thionyl chloride and the resulting solution was refluxed for 1 h. The excess of thionyl chloride was evaporated \textit{in vacuo}. The oily residue was distilled under reduced pressure, and 5-methyltricyclo[3.3.1.1\textsuperscript{3,7}]dec-1-yl acetyl chloride (15.0 g, yield 92%, bp 120-125 °C, 0.3 mm Hg) was obtained, which was used immediately without further purification.

(b) The Friedel-Crafts Reaction

Freshly prepared 5-methyltricyclo[3.3.1.1\textsuperscript{3,7}]dec-1-yl acetyl chloride (15.0 g, 66 mmol) was added over 30 min. from an addition funnel to a mixture of anhydrous aluminum chloride (14 g, 105 mmol, Aldrich) and excess of fluorobenzene (60 ml, Aldrich). The reaction mixture was refluxed for 5 h and was cautiously poured into 120 ml of cold water with stirring. The yellow organic layer was separated and the aqueous layer was further extracted with 3 x 40 ml of diethyl ether. The combined organic extracts were then washed with 2 x 40 ml of 10% NaOH solution, 2 x 40 ml of water and dried over magnesium sulfate. The organic solvents were evaporated \textit{in vacuo}. The resulting yellow oil was chromatographed with 2% diethyl ether in petroleum ether (v/v) to afford ketone 152 (15.0 g, yield 79%) as a colorless liquid.
IR (thin film, NaCl) \( v_{\text{max}} \): 2899, 2843, 1673 (C=O), 1597, 1506, 1455, 1254, 1236, 1201, 1157 cm\(^{-1}\).

MS \( m/e \) (rel. intensity): 286 (M\(^+\), 41), 268 (43), 149 (59), 123 (100).

\(^1\)H NMR (CDCl\(_3\), 200 MHz) \( \delta \) ppm: 8.00 (m, 2 H), 7.10 (m, 2 H), 2.70 (s, 2 H), 2.18 (s, 1 H), 1.98 (m, 2 H), 1.60 (m, 5 H), 1.38 (m, 6 H), 0.78 (s, 3 H, CH\(_3\)).

\(^13\)C NMR (CDCl\(_3\), 50 MHz) \( \delta \) ppm: 198.47 (C=O), 168.10 and 163.04 (d, \( ^1\)J\(_{\text{C}-\text{F}} = 254 \text{ Hz, C4'}\)), 135.27 and 135.21 (d, \( ^4\)J\(_{\text{C}-\text{F}} = 3 \text{ Hz, C1'}\)), 131.06 and 130.88 (d, \( ^3\)J\(_{\text{C}-\text{F}} = 9 \text{ Hz, C2'}\)), 115.68 and 115.24 (d, \( ^2\)J\(_{\text{C}-\text{F}} = 22 \text{ Hz, C3'}\)), 50.77, 49.82, 43.69, 42.23, 35.91, 34.70, 30.90, 30.62, 29.18.

High Resolution MS calcd for C\(_{19}\)H\(_{23}\)F\(_0\): 286.1732. Found: 286.1726.

1-(4-Cyanophenyl)-2-(5-methyltricyclo[3.3.1.1\(^3,7\)]dec-1-yl) Ethanone (153)

![Diagram of 1-(4-Cyanophenyl)-2-(5-methyltricyclo[3.3.1.1\(^3,7\)]dec-1-yl) Ethanone](image)

Potassium cyanide (2.0 g, 31 mmol) and 1-(4-fluorophenyl)-2-(5-methyltricyclo[3.3.1.1\(^3,7\)]dec-1-yl) ethanone (3.80 g, 13 mmol) were added to 35 ml of dimethyl sulfoxide and heated at 110-130 °C for 24 h.\(^94\) The reaction mixture was poured into 100 ml of water and extracted with diethyl ether (3 \( \times \) 30 ml). The combined organic extracts were washed with water (30 ml), 5% sodium bicarbonate (30 ml) and dried over magnesium sulfate. The solvent was evaporated in vacuo to afford a light
yellow solid, which was recrystallized from acetone to give colorless needles of ketone 153 (3.12 g, yield 82%), mp 96-97 °C.

IR (KBr) \( \nu_{\text{max}} \): 2926, 2895, 2841, 2226 (C=O), 1674 (C=O), 1460, 1445, 1312, 1274, 1254, 856 cm\(^{-1}\).

MS \( m/e \) (rel. intensity): 293 (M\(^+\), 52), 275 (26), 149 (100), 130 (42).

\(^1\)H NMR (CDCl\(_3\), 200 MHz) \( \delta \) ppm: 8.02 (d, \( J = 8.7 \) Hz, 2 H), 7.72 (d, \( J = 8.7 \) Hz, 2 H), 3.78 (s, 2 H), 2.00 (s, 2 H, H2), 1.74-1.30 (m, 12 H), 0.80 (s, 3 H, CH\(_3\)).

\(^{13}\)C NMR (CDCl\(_3\), 50 MHz) \( \delta \) ppm: 198.79 (C=O), 141.64, 132.41, 128.68, 118.00, 116.03, 51.04, 49.78, 43.60, 42.17, 35.83, 34.91, 30.86, 30.63, 29.12.

Anal. Calcd for C\(_{20}\)H\(_{23}\)NO: C, 81.87; H, 7.90; N, 4.77. Found: C, 81.56; H, 7.95; N, 4.43.

The structure of this compound was further supported by an X-ray diffraction analysis. The crystal data are as follows: C\(_{20}\)H\(_{23}\)NO crystallized in space group \( P2_12_12_1 \), \( a = 12.021 \) (3) \( \AA \), \( b = 20.149 \) (3) \( \AA \), \( c = 6.656 \) (2) \( \AA \), \( V = 1612.1 \) (5) \( \AA^3 \), \( Z = 4 \), \( D_{\text{calcd}} = 1.209 \) g/cm\(^3\), \( R = 0.046 \).

1-(4-Carboxyphenyl)-2-(5-methyltricyclo[3.3.1.1\(^3,7\)]dec-1-y1) Ethanone (120)

\[
\begin{array}{c}
\text{CH}_3 \\
\text{CH}_3 \\
\text{CH}_3 \\
\text{CH}_3 \\
\text{CH}_3 \\
\text{CH}_3 \\
\end{array}
\]

A mixture of ketone 153 (3.80 g, 13 mmol), 30% potassium hydroxide (40 ml) and 8 ml of ethanol was refluxed for 24 h. This mixture was then acidified with
hydrochloric acid, and the resulting white precipitate was filtered and recrystallized from 10% ethanol/water solution to give carboxylic acid 120 (3.60 g, yield 89%), mp 200-202 °C.

IR (KBr) v_max: 2902, 2843, 1683 (C=O), 1571, 1504, 1426, 1404, 1296, 1201, 1128 cm⁻¹.

MS m/e (rel. intensity): 312 (M⁺, 6), 268 (15), 267 (71), 149 (100), 93 (42).

¹H NMR (CDCl₃, 200 MHz) δ ppm: 7.80-7.58 (m, 4 H), 2.72 (s, 2 H, H2), 1.60 (m, 3 H), 1.30-0.90 (m, 11 H), 0.38 (s, 3 H, CH₃).

¹³C NMR (CDCl₃ + DMSO-d₆, 50 MHz) δ ppm: 199.52 (C=O, ketone), 167.20 (C=O, carboxylate), 141.44, 134.36, 129.57, 127.83, 50.81, 49.43, 43.37, 41.82, 35.59, 34.45, 30.70, 30.32, 28.81.


The structure of this compound was also supported by an X-ray diffraction analysis. The crystal data are as follows: C₂₀H₂₄O₃ crystallized in space group P1₁, a = 12.987 (3) Å, b = 18.439 (5) Å, c = 7.281 (2) Å, α = 101.23 (2)°, β = 98.32 (2)°, γ = 91.12 (2)°, V = 1690.3 (7) Å³, Z = 4, D_calcd = 1.228 g/cm³, R = 0.069.

1-(4-Carbomethoxyphenyl)-2-(5-methyltricyclo[3.3.1.1³,7]dec-1-yl) Ethanone (154)
A solution of ketone 120 (2.0 g, 6.4 mmol), 0.3 g of concentrated sulfuric acid and 20 ml of methanol was refluxed for 12 h. The excess solvent was removed in vacuo. Water (20 ml) containing the calculated amount of sodium carbonate was added to neutralize the sulfuric acid. This mixture was then extracted with diethyl ether (3 × 15 ml); the combined extracts were dried over magnesium sulfate and evaporated in vacuo to give product 154 (1.80 g, yield 86%), mp 60-61 °C (recrystallized from acetone).

IR (NaCl) ν_max: 3021, 2905, 1724 (C=O), 1677, 1438, 1283, 1218, 1111 cm⁻¹.

MS m/e (rel. intensity): 326 (M⁺, 3), 311 (10), 267 (100), 163 (49), 149 (29).

¹H NMR (CDCl₃, 200 MHz) δ ppm: 8.05 (d, J = 8.3 Hz, 2 H), 7.94 (d, J = 8.3 Hz, 2 H), 3.90 (s, 3 H, COOCH₃), 2.72 (s, 2 H, H₂), 2.18-1.25 (m, 14 H), 0.72 (s, 3 H, CH₃).

¹³C NMR (CDCl₃, 50 MHz) δ ppm: 199.74 (C=O, ketone), 166.26 (C=O, ester), 141.99, 133.51, 129.71, 128.19, 52.38, 51.16, 49.76, 43.65, 42.17, 35.87, 34.80, 30.88, 30.61, 29.15.


The Photolysis of 1-(4-Carbomethoxyphenyl)-2-(5-methyltricyclo[3.3.1.1³,7]dec-1-yl) Ethanone (154)

The preparative scale photolysis of ketone 154 was conducted in acetone. Eight photoproducts were detected but only three were successfully isolated by column chromatography with 5% diethyl ether in petroleum ether (v/v) as the eluent. The spectral characteristics of the isolated products, 168, 176 and 180, are given below.
3-(4-carbomethoxyphenyl)-7-Methyltetracyclo[5.3.1.1^5.9.0^1.4]-dodec-3-ene (180)

mp: 70-72 °C (recrystallized from acetone).

IR (KBr) ν_max: 2914, 2833, 1713 (C=O), 1663, 1606, 1435, 1410, 1309, 1274, 1193, 1172, 1102 cm⁻¹.

MS m/e (rel. intensity): 308 (M⁺, 100), 293 (34), 277 (13), 265 (22), 249 (81), 193 (41), 178 (24), 165 (19), 115 (30), 91 (37).

¹H NMR (CDCl₃, 200 MHz) δ ppm: 7.90 (d, J = 8.5 Hz, 2 H), 7.24 (d, J = 8.5 Hz, 2 H), 3.82 (s, 3 H, COOCH₃), 3.02 (m, 1 H), 2.40 (m, 2 H), 2.10-1.12 (m, 11 H), 0.80 (s, 3 H, CH₃).

¹³C NMR (CDCl₃, 50 MHz) δ ppm: 167.08 (C=O), 158.44, 141.35, 129.72, 127.18, 125.00, 122.95, 51.93, 49.40, 44.19, 43.67, 41.85, 40.65, 39.18, 36.60, 32.73, 32.15, 30.32, 29.96.

High Resolution MS Calcd for C₂₁H₂₄O₂: 308.1776. Found: 308.1777.
3-(4-Carbomethoxyphenyl)-7-methyl-(1α,3β,4α,5β,7α,9β)-
tetracyclo[5.3.1.15,9.01,4]dodecan-3-ol (168)

mp: 123-124 °C (recrystallized from acetone).

IR (KBr) νmax: 3484 (sharp, OH, non-hydrogen bonded), 2900, 2846, 1709
(C=O), 1609, 1454, 1440, 1403, 1366, 1351, 1287, 1194, 1154, 1112, 1016 cm⁻¹.

MS m/e (rel. intensity): 326 (M⁺, 2), 311 (11), 267 (100), 178 (6), 163 (83), 149
(49), 135 (16).

¹H NMR (CDCl₃, 500 MHz) δ ppm: 7.99 (d, J = 8.4 Hz, 2 H, H3'), 7.38 (d, J =
8.4 Hz, 2 H, H2'), 3.88 (s, 3 H, COOCH₃), 2.87 (m, 1 H, H10a), 2.33-1.23 (m, 15 H),
0.78 (s, 3 H, CH₃).

¹³C NMR (CDCl₃, 50 MHz) δ ppm: 166.90 (C=O), 153.46 (C4'), 129.91 (C3'),
128.78 (C1'), 125.05 (C2'), 83.17 (C3), 54.77 (C4), 52.07 (2 C, OCH₃ & CH₂), 48.01,
47.73, 45.08, 38.92, 33.96, 33.29, 31.38, 31.02 (CH₃), 29.60, 28.53.

Anal. Calcd for C₂₁H₂₆O₃: C, 77.27; H, 8.03. Found: C, 77.10; H, 7.92.

NOE and HETCOR spectra were used to assign this structure. See text.
3-(4-Carbomethoxyphenyl)-5-methyl-(1α,3α,4α,5β,7α,9β)tetrahydro[5.3.1.15,9.01.4]-dodecan-3-ol (176)

IR (NaCl, thin film) νmax: 3020, 2911, 1717, 1611, 1438, 1283, 1216 cm⁻¹.

MS m/e (rel. intensity): 326 (M⁺, 1.4), 311 (11), 308 (15), 267 (100), 249 (22), 178 (8), 163 (72), 149 (25), 135 (13), 105 (23), 93 (31), 91 (31).

¹H NMR (CDCl₃, 500 MHz) δ ppm: 8.00 (d, J = 8.6 Hz, 2 H, H₃'), 7.60 (d, J = 8.6 Hz, 2 H, H₂'), 3.88 (s, 3 H, COOCH₃), 2.80 (d, J = 11.4 Hz, 1 H, H₂a), 2.37 (s, 1 H, H₄), 2.28 (broad, 1 H, OH), 2.13 (s, 1 H), 2.00 (d, J = 11.4 Hz, 1 H, H₂b), 1.70-1.20 (m, 10 H), 1.13 (s, 3 H, CH₃), 1.08 (m, 1 H).

¹³C NMR (CDCl₃, 50 MHz) δ ppm: 166.85 (C=O), 148.91 (C₄'), 129.48 (C₃'), 129.10 (C₁'), 128.60 (C₂'), 83.84 (C₃), 66.31 (C₄), 52.11 (OCH₃), 49.58, 47.22, 44.54, 37.58, 37.08, 33.30, 31.23, 29.68, 29.03, 27.58 (CH₃).


NOE and HETCOR spectra were used to assign this structure. See text.
The Solid State Photolysis of 1-(4-Cyanophenyl)-2-(5-methyltricyclo[3.3.1.13,7]dec-1-yl) Ethanone (153)

Crystals of ketone 153 were placed in a Pyrex test tube and were photolysed with a medium pressure mercury lamp through a Pyrex filter for 96 h. (The conversion was limited to 20%). After photolysis, the solid sample was dissolved in chloroform and the major photoproduct 181 was isolated by column chromatography with 10% diethyl ether in petroleum ether (v/v). The assigned structure and spectral data of photoproduct 181 are given below.

3-(4-Cyanophenyl)-7-methyl-(1α,3α,4α,5β,7α,9β)-tetracyclo[5.3.1.15,9.01,4]-dodecan-3-ol (181)

\[
\begin{align*}
\text{Me} & \\
& \\
& \\
& \\
& \\
& \text{Me} \\
& \text{6} \\
& \text{5} \\
& \text{4} \\
& \text{3} \\
& \text{2} \\
& \text{1} \\
& \text{8} \\
& \text{9} \\
& \text{10} \\
& \text{CN} \\
& \text{Ha} \\
& \text{H} \\
& \text{OH} \\
& \text{Hb}
\end{align*}
\]

mp: 138-141 °C (recrystallized from acetone).
IR (KBr) \( \nu_{\text{max}} \): 3472 (OH), 2898, 2234 (C≡N), 1608, 1455, 1195 cm\(^{-1}\).
MS \( m/e \) (rel. intensity): 293 (M\(^+\), 20), 291 (31), 275 (53), 218 (39), 163 (38), 149 (90), 130 (63), 107 (47), 93 (100).

\(^1\)H NMR (CDCl\(_3\), 500 MHz) \( \delta \) ppm: 7.63 (d, \( J = 8.5 \) Hz, 2 H, H3'), 7.54 (d, \( J = 8.5 \) Hz, 2 H, H2'), 2.72 (d, \( J = 12.5 \) Hz, 1 H, H2a), 2.52 (s, 1 H, H4), 2.39 (m, 1 H, H9),
2.06 (d, J = 11.4 Hz, 1 H, H2b), 1.65 (m, 1 H, H5), 1.64-1.20 (m, 11 H), 0.78 (s, 3 H, CH3).

13C NMR (CDCl3, 50 MHz) δ ppm: 148.84 (C≡N), 132.28 (C3'), 128.74 (C2'), 118.70 (C4'), 111.33 (C1'), 80.81 (C3), 60.14 (C4), 52.11, 47.93 (C2), 46.92, 45.17, 37.06, 33.01, 30.76 (CH3), 30.56, 29.39 (C9), 29.21, 28.09 (C5).

High Resolution MS Calcd for C20H23N0: 293.1780. Found: 293.1777.

NOE and HETCOR spectra were used to assign this structure. See text.

5.6. The Synthesis of Tricyclo[22.2.2.11914]triaconta-11,13,24,26,27,29-hexaene-6,19-dione (108b)

Diketone 108b was synthesized according to the published procedures described below.110,111,114,115

4-Benzoylbutyric Acid (191)

In a 500 ml three-neck, round-bottom flask fitted with a mechanical stirrer and two reflux condensers were placed powdered, anhydrous aluminum chloride (54 g, 0.40 mol) and dry, thiophene-free benzene (250 ml). The stirrer was started, and glutaric anhydride (30 g, 0.26 mol, Aldrich) in 150 ml of benzene was added in 15 min. The temperature was kept under 15 °C for 4 h. With the flask surrounded by cold water, 100 ml of water was slowly added from a dropping funnel inserted in the top of one of the condensers. The excess benzene was removed by distillation, and the hot solution was at once poured into a 2000 ml beaker. After the mixture was cooled, the liquid was decanted from the precipitated solid and acidified with concentrated hydrochloric acid; 6.8 g of acid 191 was filtered out. The residual suspension in the beaker was boiled for 5
h with 1000 ml of water containing 120 g of sodium bicarbonate. The resulting solution was filtered and the filtrate was acidified with concentrated hydrochloric acid. The precipitated acid 191 was filtered and washed with hot water. White solid acid 191 (21.0 g, total yield 56%) was obtained, mp: 125-126 °C (lit.114 125-126 °C).

IR (KBr) νmax: 3300-2400 (broad, OH), 1695 (C=O, carboxylic acid), 1675 (C=O, ketone), 1596, 1579, 1450, 1412, 1378, 1321, 1298, 1232, 1194 cm⁻¹.

MS m/e (rel. intensity): 192 (M⁺, 6), 174 (2), 120 (17), 105 (100), 77 (40).

¹H NMR (CDCl₃, 300 MHz) δ ppm: 7.97 (m, 2 H), 7.60-7.43 (m, 3 H), 3.10 (m, 2 H), 2.53 (m, 2 H), 2.10 (m, 2 H).

5-Phenylvaleric acid (192)

A solution of hydrazine hydrate (3 ml), 4-benzoylbutyric acid (1.0 g, 5.2 mmol), sodium hydroxide (0.70 g, 17.5 mmol) and 15 ml of diethylene glycol was refluxed for 3 h at 150-160 °C, and the temperature was raised to 200 °C to distill the excess of hydrazine hydrate and water. The temperature was maintained at 200 °C for 3 h. After cooling to room temperature, the reaction mixture was poured into 75 ml of water and acidified with 20 ml of concentrated HCl. The white precipitate of product 192 (0.821 g, yield 89%) was collected after filtration, mp 58-59 °C (lit.115 58-59.5 °C).

IR (KBr) νmax: 3200-3000 (broad, OH), 1708 (C=O), 1494, 1464, 1454, 1410, 1320, 1256, 1202 cm⁻¹.

MS m/e (rel. intensity): 178 (M⁺, 16), 160 (20), 132 (11), 117 (11), 104 (26), 91 (100), 77 (9).

¹H NMR (CDCl₃, 300 MHz) δ ppm: 7.32-7.15 (m, 5 H), 2.65 (m, 2 H), 2.39 (m, 2 H), 1.68 (m, 4 H).
Methyl 5-Phenylvalerate (193)

A solution of 5-phenylvaleric acid (5.71 g, 32 mmol), methanol (20 ml), concentrated sulfuric acid (0.5 g) and 20 ml of 1,2-dichloroethane was refluxed for 8 h, after which the excess solvent was distilled off. Water (50 ml) containing the calculated amount of sodium carbonate was added to neutralize the sulfuric acid. This mixture was then extracted with diethyl ether (3 × 15 ml); the combined extracts were dried over magnesium sulfate and evaporated in vacuo to give methyl 5-phenylvalerate (yellow oil, 6.0 g, yield 97%).

MS m/e (rel. intensity): 192 (M+, 3), 160 (60), 132 (15), 117 (22), 104 (42), 91 (100).

$^1$H NMR (CDCl$_3$, 300 MHz) δ ppm: 7.30-7.14 (m, 5 H), 3.65 (s, 3 H, OCH$_3$), 2.62 (m, 2 H), 2.33 (m, 2 H), 1.66 (m, 4 H).

4-[4-(5-Phenylvaleric acid)-benzoyl]-butyric acid (194)

To a stirred solution of methyl 5-phenylvalerate (6.16 g, 32 mmol) and glutaric anhydride (5 g, 44 mmol) dissolved in 70 ml of 1,1,2,2-tetrachloroethane held at −5 °C in a salt-ice bath was added portionwise (two hours) anhydrous aluminum chloride. The resulting yellow solution was stirred for another 4 h below 0 °C and then at room temperature for 36 h. Ice (12 g) and 4 ml of concentrated hydrochloric acid were then added, the layers were separated, and the aqueous layer was washed with diethyl ether. The combined organic extracts were then washed with water, dried over magnesium sulfate and evaporated in vacuo to give acid 194 (6.83 g, yield 73%), mp 177-179 °C (lit.115 173-177 °C).
IR (KBr) \( \nu_{\text{max}} \): 3400-2500 (broad, OH), 1709 (broad, C=O), 1605, 1412, 1289, 1074, 984 cm\(^{-1}\).

\textbf{MS} \( m/e \) (rel. intensity): 292 (\( M^+ \), 15), 274 (13), 205 (100).

\(^1\text{H NMR (DMSO-}\text{d}_6, 300 \text{ MHz}) \delta \text{ ppm: 7.88 (d, 2 H), 7.33 (d, 2 H), 3.07 (m, 2 H), 2.66 (m, 2 H), 2.27 (m, 4 H), 1.83 (m, 2 H), 1.55 (m, 4 H).} \)

\textit{p-Phenylene-bis-(5-valeric acid) (195)}

A solution of acid 194 (6.83 g, 23.4 mmol), 3 g of potassium hydroxide and 3 ml of hydrazine hydrate in 15 ml of diethylene glycol was refluxed at 150-160 °C for 2 h. Water and the excess hydrazine hydrate were distilled out and the temperature was raised to 190 °C where it was held for 6 h. The solution was then cooled, diluted with 30 ml of water, and neutralized with concentrated hydrochloric acid. The resulting mixture was cooled to 0 °C and filtered; the acid 195 (6.21 g, yield 96%) was collected after washing with water, and was dried under reduced pressure, mp 177-180 °C (lit.\(^{115}\) 176-180 °C).

IR (KBr) \( \nu_{\text{max}} \): 3200-2600 (broad, OH), 1703 (broad, C=O), 1517, 1426, 1210 cm\(^{-1}\).

\textbf{MS} \( m/e \) (rel. intensity): 278 (\( M^+ \), 8), 174 (2), 260 (26), 242 (100), 214 (16), 204 (15), 191 (32), 186 (29), 173 (28), 145 (68), 131 (95), 117 (71), 105 (37), 91 (84), 77 (15).

\(^1\text{H NMR (DMSO-}\text{d}_6, 300 \text{ MHz}) \delta \text{ ppm: 7.25 (m, 4 H), 2.75 (m, 4 H), 2.47 (m, 4 H), 1.80 (m, 8 H).} \)
Dimethyl p-Phenylene-bis-(5-valerate) (196)

A solution of p-phenylene-bis-(5-valeric acid) (6.21 g, 22.3 mmol), 30 ml of absolute methanol and 0.5 g of concentrated sulfuric acid was refluxed for 8 h. The excess of methanol was distilled out and 60 ml of diethyl ether was added to the mixture. The mixture was washed with water, 5% aqueous sodium bicarbonate solution and twice again with water. The organic layer was dried, and the solvent was evaporated in vacuo. The oily residue was distilled (bp 182-184 °C, 0.4 mm Hg) to afford dimethyl p-phenylene-bis-(5-valerate) (6.29 g, yield 92%).

IR (KBr) νmax: 2948, 2861, 1741 (C=O), 1514, 1436, 1364, 1174, 1062 cm⁻¹.

MS m/e (rel. intensity): 306 (M⁺, 14), 274 (39), 242 (100), 214 (54), 186 (56), 173 (45), 145 (67), 131 (81), 117 (82), 91 (61).

¹H NMR (CDCl₃, 300 MHz) δ ppm: 7.08 (m, 4 H), 3.68 (s, 6 H), 2.60 (m, 4 H), 2.33 (m, 4 H), 1.67 (m, 8 H).

Tricyclo[22.2.2.2₁₁₄]triaconta-11,13,24,26,27,29-hexaene-6,19-dione (108b)

The literature method was followed in preparing diketone 108b.¹¹⁰,¹¹¹ To a 3-neck, 250 ml round bottom flask was added 50 ml of dry xylene (mixed, Aldrich) and 4.0
g of potassium t-butoxide (Aldrich). While this mixture was refluxing under nitrogen, dimethyl p-phenylene-bis-(5-valerate) (1.0 g, 3.3 mmol) in 45 ml of dry xylene was added through a syringe pump over 24 h. The reaction mixture was made acidic by adding 7 ml of glacial acetic acid. This mixture was then washed with water (3 x 30 ml). The xylene solution was filtered to remove insoluble polymeric ketones, and the filtrate was concentrated to a small volume by distillation at reduced pressure. To the residue was added hydrochloric acid (15 ml, 3 M) and the resulting mixture was refluxed for 10 h. The reaction mixture was extracted with ether (3 x 15 ml), and the combined organic extracts were then washed with 10% sodium bicarbonate (30 ml), water (30 ml), dried over magnesium sulfate, and evaporated under reduced pressure. The residue was chromatographed with 8% ethyl acetate in petroleum ether (v/v), and the eluate was recrystallized from ethanol to afford diketone 108b (0.13 g, yield 18%) in colorless plates, mp 125-127 °C (lit.110 124.5-126 °C).

IR (KBr) ν max: 3019, 2937, 2864, 1704 (C=O), 1610, 1516, 1459, 1438, 1399, 1369, 1327, 1285, 1252, 1213, 1150, 1128, 1021 cm⁻¹.

MS m/e (rel. intensity): 432 (M⁺, 7), 414 (72), 396 (14), 372 (8), 344 (11), 278 (13), 260 (19), 242 (87), 214 (22), 191 (22), 186 (32), 173 (35), 145 (74), 131 (100), 117 (92), 105 (45), 91 (83).

1H NMR (CDCl₃, 200 MHz) δ ppm: 6.95 (s, 8 H), 2.50 (m, 8 H), 2.23 (m, 8 H), 1.43 (m, 16 H).

13C NMR (CDCl₃, 50 MHz) δ ppm: 211.50 (C=O), 139.40, 128.36, 42.25, 35.12, 30.74, 23.19.

UV (CH₃CN) λ max: 273 nm (ε 702), 265 nm(ε 802), 259 nm (ε 682).

DSC analysis: ΔH = 102.94 J/G. Peak Temp. 124.2 °C

The structure of this compound was further supported by an X-ray diffraction analysis. The crystal data are as follows: C₃₀H₄₀O₂ crystallized in space group P2₁/c, a =
9.9200 (6) Å, \( b = 11.2088 \) (8) Å, \( c = 11.7547 \) (6) Å, \( \beta = 96.931 \) (5)°, \( V = 1297.5 \) (1) Å\(^3\), \( Z = 2, D_{\text{calcd}} = 1.107 \) g/cm\(^3\), \( R = 0.040 \).

5.7. The Synthesis and Photolysis of Pyrazinone 197 and Pyrazinethione 199

Literature procedures were followed to synthesize substrates 197 and 199.\(^{119,129,130}\)

2-Hydroxy-5,6-diphenylpyrazine (201)\(^{129}\)

To a refluxing mixture of glycine amide hydrochloride (2.2 g, 20 mmol, Aldrich), benzil (4.2 g, 20 mmol, Eastman) and 50 ml of methanol was added 3.2 ml (40 mmol) of 12.5 M sodium hydroxide over 30 min. After refluxing for another 30 min., the mixture was treated with 2.5 ml of 12 M hydrochloric acid, followed by 2 g of solid potassium bicarbonate. The yellow solid formed was filtered off, washed well with water, and recrystallized from \( t \)-butanol. Yellow needles of compound 201 were obtained after filtration (3.0 g, yield 60%), mp 248-250 °C (lit.\(^{129} 243-244 \) °C).

IR (KBr) \( \nu_{\text{max}}: 3050-2500 \) (broad), 1657, 1588, 1562, 1496, 1438, 1376, 1228, 1163, 1026 cm\(^{-1}\).

MS \( m/e \) (rel. intensity): 248 (M\(^+\), 100), 229 (5), 219 (62), 165 (28).

\(^1\)H NMR (DMSO-d\(_6\), 200 MHz) \( \delta \) ppm: 12.25 (s, broad, 1 H, OH), 8.18 (s, 1 H, 3-H), 7.30 (m, 5 H), 7.22 (m, 5 H).
1-Methyl-5,6-diphenylpyrazin-2(1H)-one (197)\(^{130}\)

To a stirred solution of compound 201 (0.5 g, 2 mmol) and sodium methoxide (from 64 mg, 2 mmol of sodium and 40 ml of methanol) was added dimethyl sulfate (0.252 g, 2 mmol, Aldrich) dropwise at room temperature and the reaction mixture was refluxed for 1 h. The solution was then concentrated under reduced pressure, poured into 10% HCl solution, and extracted with dichloromethane. The extract was washed in turn with 10% NaHCO\(_3\) solution and water and dried over anhydrous magnesium sulfate. After removal of the solvent, the residue was chromatographed with diethyl ether and petroleum ether (50/50, v/v) to give pyrazinone 197 (0.4 g, yield 76%), which was recrystallized from ethanol to afford yellow plates, mp 165-167 °C (lit.\(^{130}\) 165-167°C).

IR (KBr) \(\nu_{\text{max}}\): 3027, 1646 (C=O), 1578, 1556, 1483, 1442, 1414, 1319, 1241, 1185, 1155 cm\(^{-1}\).

MS \(m/e\) (rel. intensity): 262 (M\(^+\), 74), 233 (100), 218 (11), 165 (66), 118 (32), 89 (42), 77 (45).

\(^1\)H NMR (CDCl\(_3\), 200 MHz) \(\delta\) ppm: 8.30 (s, 1 H, H3), 7.42-7.12 (m, 10 H), 3.32 (s, 3 H, CH\(_3\)).

\(^{13}\)C NMR (CDCl\(_3\), 50 MHz) \(\delta\) ppm: 156.09 (C=O), 146.54 (C3), 138.59, 137.40, 133.85, 132.11, 129.90, 129.67, 129.17, 129.12, 127.81, 127.12, 33.80 (CH\(_3\)).

1-Methyl-5,6-diphenyl-2(1H)-pyrazinethione (199)

Compound 197 (0.5 g, 1.9 mmol) and excess of Lawesson's reagent (1.2 g, 3 mmol, Aldrich) in 40 ml of dry toluene was refluxed for 4 h. Toluene was then distilled out under reduced pressure and the residue was chromatographed with 10% of diethyl ether in petroleum ether (v/v) to give pyrazinethione 199 (0.3 g, yield 57%). Yellow
needles of 199 were obtained after recrystallization from acetone, mp 168-170 °C (lit.119 163-164.6 °C).

IR (KBr) νmax: 3051, 1508, 1475, 1390, 1272, 1163, 1120, 1092, 1030, 768, 704 cm⁻¹.

UV (CH₃CN) λmax : 309 nm (ε 13560), 394 nm (ε 8382).

MS m/e (rel. intensity): 278 (M⁺, 71), 277 (100), 234 (11), 233 (23), 165 (21), 118 (19), 77 (44).

¹H NMR (CDCl₃, 200 MHz) δ ppm: 8.95 (s, 1 H, H₃), 7.45-7.10 (m, 10 H), 3.73 (s, 3 H, CH₃).

¹³C NMR (CDCl₃, 100 MHz) δ ppm: 174.37 (C=S), 156.62, 141.20, 140.80, 136.87, 132.16, 129.95, 129.77, 129.31, 129.01, 127.85, 127.71, 42.54 (CH₃).

Anal. Calcd for C₁₇H₁₄N₂S: C, 73.35; H, 5.07; N, 10.06; S, 11.52. Found: C, 73.19; H, 5.09; N, 10.00; S, 11.52.

The X-ray crystallographic analysis on pyrazinethione 199 was done by Dr. M. Kaftory. The X-ray structural data are as follows: C₁₇H₁₄N₂S crystallized in space group P1, a = 15.246 (7) Å, b = 10.724 (5) Å, c = 9.602 (5) Å, α = 104.11 (5)°, β = 90.66 (5)°, γ = 106.77 (5)°, V = 1452.11 Å³, Z = 4, Dcalcd = 1.273 g/cm³, R = 0.0446.

3,7-Dimethyl-2,6,10,12-(1α,2α,5α,6α)-3,7,9,11-Tetraazatricyclo[4.2.2.2²,5]dodeca-9,11-diene-4,8-dione (198)

Photodimer 198 was isolated after the solid state photolysis of pyrazinone 197. A typical photolysis is given below: a single crystal of 197 (23 mg, 0.09 mmol) was photolysed for 20 h with a medium pressure mercury lamp equipped with a Pyrex filter. The resulting solid was dissolved in a small amount of ethyl acetate, and the photodimer 198 was isolated by column chromatography with 20% diethyl ether in petroleum ether.
Recrystallization from ethyl acetate gave colorless needles (17 mg, yield 74%), mp 148-150 °C (lit.\textsuperscript{117} 148-150 °C).

IR (KBr) $v_{\text{max}}$: 3058, 2967, 1675 (C=O), 1494, 1446, 1423, 1387, 1266, 1098, 1039, 1001 cm$^{-1}$.

MS $m/e$ (rel. intensity): 262 (100), 233 (82), 165 (83), 118 (90), 89 (79), 77(90).

$^1$H NMR (CDCl$_3$, 200 MHz) δ ppm: 7.35-6.85 (m, 20 H), 6.30 (s, 2 H), 2.52 (s, 6 H, CH$_3$).
REFERENCES

1. According to the article by Roth, H. D. *Angew. Chem., Int. Ed. Engl.* 1989, 28, 1193, the first investigation of organic photoreaction in the solid state was due to Trommsdorff, H. who reported that crystals of santonin turn yellow and cleave when exposed to sunlight (*Ann. Chem. Phar.* 1834, 11, 190.).


84. Compound 123 was first reported in 1931 (Ref. 79). The NMR spectral data are available on page 286, Ref. 85.

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APPENDIX

The Stereodiagram of Ketone 120