PROPOSED STUDY OF THE REACTION, $^7\text{Li}(^3\text{He},\alpha)^4\text{He}$, WITH A TIME-OF-FLIGHT SCATTERING CHAMBER

by

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B.Sc., The University of British Columbia, 1967

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE in the Department of PHYSICS

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Date June 9, 1970.
ABSTRACT

The reaction, $^7\text{Li}(^3\text{He}, \alpha)^4\text{He}$, is proposed to search for an asymmetry about the direction of motion of $^6\text{Li}$ in the breakup of the 4.57 MeV excited state of this nucleus as an intermediate state. This follows after the discovery in 1967 by Reimann et. al. of such an asymmetry about the direction of motion of $^5\text{Li}$ in the breakup of the ground state of this nucleus, as an intermediate state in the reaction, $^6\text{Li}(^3\text{He}, \alpha)^4\text{He}$. The purpose of these experiments is to attempt some understanding of the three-body reaction mechanisms involved, and the manner in which the various particles are correlated in the intermediate state.

The three-body kinematics of the reaction, $^7\text{Li}(^3\text{He}, \alpha)^4\text{He}$ were thoroughly investigated, and because of particle identification problems, a charged particle time-of-flight technique was proposed to distinguish the emitted deuterons from alpha particles. A 23 inch scattering chamber was designed and constructed for this and other work, and subsequently tested using the reaction $^7\text{Li}(p, \alpha)^4\text{He}$. 
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ACKNOWLEDGEMENTS

I am most grateful for the patient supervision of Dr. P. Stephas during my course of study, and to Dr. P. W. Martin for his valuable comments and suggestions on the writing of this thesis. Dr. G. M. Griffiths is also thanked for his comments during the writing of this thesis.

The assistance of the students, faculty and technical staff of the Van de Graaff group is most appreciated, especially during the design and construction of the experimental apparatus.
CHAPTER 1

INTRODUCTION

1. Three-Body Sequential Processes

Nuclear reactions which lead to final states consisting of several heavy particles have been of interest for some time. With the increasing availability of $^3$He particles and tritons as projectiles in the study of nuclear reactions, a new means of achieving these many-body final states has been found, particularly because of the large Q-values involved. These studies are especially interesting when the target particle is a light nucleus, where generally only the first few levels are bound for heavy particle emission, and the level spacing is such that many sharp, discrete levels often exist well above the threshold for heavy particle emission.

One problem of nuclear physics is to understand the reaction mechanism, or the means by which the multiparticle final state is formed, in the hope that this can provide information regarding the nuclear forces involved. With the reaction mechanism, we must attempt to determine whether the reaction proceeds via a single stage, by instantaneous breakup, by a series of two-body decays, or by some combination of these. However, when three or more particles are involved, the intractable many-body problem is encountered. Fortunately, there is a tendency for nucleons to group together into clusters of particles, such as alpha particles, or into closed shells, which often reduces the problem to a two-body system.
Phillips, (1964), introduces the cluster model which suggests that some three-body final state processes can be treated as a time sequence of two-body interactions. Moreover, these processes were termed "sequential", (Gatlinberg, 1965), implying that the distribution of events within the available phase space is not random, but is modulated by the interactions among the final state components. This is a useful definition in the cases of many of the states of light nuclei which have extremely short lifetimes, and may be more meaningfully described as resonances in the interaction between two of the final state components (e.g. the $\frac{1}{2}^-$ first excited state of $^5$Li).

Consider the reaction,
\[ a + b \rightarrow C^* \rightarrow d + e + f \]
which may be thought of as a time sequence of the following two reactions:
\[ C^* \rightarrow D^* + d \]
\[ D^* \rightarrow e + f \]

For this treatment by Phillips, we require that the system D$^*$ stays together in such a manner that its constituents, e + f, remain together as an excited localized system at least long enough for the emission of particle d beyond the short range nuclear force field of particle d.

An earlier treatment of final state interactions was given by Watson, (1952), where he separated the reaction into two mechanisms, a primary mechanism and then a final state mechanism. The primary reaction occurs within a certain interaction volume and the final
state interaction over a slightly larger volume of configuration space. By considering the time reversed reaction, in which the particles are sent backward into the compound nucleus interaction volume, the effect of the final state interaction can usually be determined.

The energy spectrum function, \( \frac{d^3\sigma}{dE d\Omega} \), for one final particle, and the triple-correlation distribution, \( \frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} \), for two final state particles, are found to be proportional to the corresponding transition probabilities. The transition probabilities are proportional to the square of a compound matrix element involving the summation over intermediate states. For direct break-up into three particles the matrix element is assumed to be a constant, so that the decay probability is uniform over the available phase space. For sequential decay processes, however, this compound matrix element is no longer constant, and must be evaluated.

These two distinct approaches by Watson and by Phillips provide a tool for obtaining spectroscopic information about the states of relatively long-lived intermediate systems and about the nuclear reaction mechanism. The detailed study of the decay of short-lived intermediate systems is also of interest, since it helps in the understanding of the effects of the third particle on the decay processes.

2. Review of Experimental Techniques

Early experiments attempted to study multiparticle final state reactions by detailed analysis of the single particle spectra for such reactions. These studies often led to ambiguous results, because some peaks in the single particle spectra can be misinterpreted, particularly in the situation where identical particles (say two alpha
particles) are emitted, and when there are several competing reaction channels. The primary difficulty in obtaining quantitative information from experimental results is the unambiguous identification of the three final state particles. In order to determine the final state exactly nine measurable variables are involved, but conservation of energy and momentum considerations reduces these to five quantities. Usually the energies and the momenta of two of the three particles are measured, which, with the total center-of-mass energy of the system, are sufficient to completely determine the kinematics. Consequently, it is usually necessary to measure simultaneously the energies of two or more of the particles emitted at specified angles in order to obtain information concerning the nature of the interaction.

The advent of dual parameter multichannel analysis has provided a powerful tool for such coincidence studies. When the directions of motion of two of three final state particles are determined, conservation of energy and momentum restricts all events to a kinematic contour on the two-dimensional energy plane, $T_i$ vs. $T_j$. The distribution of events along the contour is determined by the interactions taking place between the particles during the breakup, showing an increase in the coincidence yield at points along the contour at which the relative energy of one of the two-particle systems corresponds to a state of that system. For example, a sequential process, which uniquely determines the energy, appears as a dense point, while sequential processes going through short-lived intermediate states appear as distinct line segments on the contour, if these states have a natural width. If the three particles in the three-body breakup are of a different mass, there will be six distinct
curves of $T_i$ vs. $T_j$ corresponding to the six permutations of three particles with two detectors. Hence, the problem of associating each event with the appropriate contour is simplified by using two-dimensional energy analysis. If contours appreciably overlap, then particle identification may be required as well. Another solution is to perform a triple coincidence measurement in conjunction with two-dimensional analysis. A detailed description of these techniques requires a complete set of kinematic calculations in order to determine where two or all three of these particles are to be found, and what energies they would have. An explanation of complete three-body kinematics will be found in Chapter II and in the Appendix.

From an experimental point of view the fact that a coincidence experiment is being performed is useful in reducing background events from contaminant reactions. In the past few years a considerable volume of experimental work has been done on multiparticle final state interactions using two-dimensional analysis. The proceedings of the Gatlinburg Conference on Correlations of Particles Emitted in Nuclear Reactions (1965), contains an excellent summary of this work from both experimental and theoretical points of view.
CHAPTER II

THE PROPOSED EXPERIMENT $^7\text{Li}(^3\text{He},\alpha)^4\text{He}$

1. Symmetry Aspects in Sequential Processes

Consider the reaction $a + b \rightarrow D^* + d \rightarrow e + f + d$, which is illustrated in Figure 1. The two-body nature of the first stage of the reaction completely determines the direction of motion of the recoil system $D^*$, which subsequently breaks up into particles $e$ and $f$. If $D^*$ decays isotropically in its own rest frame (i.e. the recoil system center-of-mass frame, RSCM), it can be seen from the figure that cylindrical symmetry will be obtained about the recoil direction of $D^*$ in the lab frame.

An effect related to the lifetime of the intermediate state, and a possible new tool which could be used to examine the ground state wave function of the target nucleus and the wave functions of the intermediate states, was discovered in 1968 by Reimann et. al. during the investigation of the three-body reactions, $^6\text{Li}(^3\text{He},\alpha)p,\alpha$. A cylindrical asymmetry about the direction of motion of $^5\text{Li}$ was found in the breakup of the ground state, which is an intermediate state in this reaction. It was found that at an incident $^3\text{He}$ energy of 1.25 MeV and at an angle of $30^\circ$ on opposite sides of the $^5\text{Li}$ recoil axis, the proton yield in the forward direction exceeded that in the backward direction by a factor of about two. The asymmetry was defined as the ratio of the normalized proton yields observed at the two alternative positions in the reaction plane at equal angles to and on opposite sides of the $^5\text{Li}$ recoil axis.
Figure 1. The two possible directions for the emission of particles $e$ and $f$ in the lab frame. In case (a) particle $e$ is emitted at an angle $\phi$ in the recoil system center-of-mass frame (RSCM) relative to the direction of the recoiling $D^*$ in the laboratory. In (b) $e$ is emitted at $\phi + 180^\circ$ relative to the direction of $D^*$. $V_{\text{rscm}}$ is the velocity of $D^*$ in the lab.
To explain this phenomenon a semiclassical model was proposed in which the origin of this asymmetry is associated with the short lifetime of the $^5$Li intermediate state, and with the memory retained by the proton during this short life of its localization at the time of formation of $^5$Li. Besides this pronounced asymmetry, any suitable model must also explain two other observed features. Namely, the dependence of this asymmetry on proton energy, and the relatively large cross section for the process. The model that was used considered the reaction as a direct-delayed sequential process, in which a neutron is transferred very rapidly from $^6$Li to $^3$He. The neutron transfer was considered the direct part of the reaction, and the time taken for the reaction products, two alpha particles with a proton loosely attached to one of them, to sort themselves out, was called the delayed part. The reaction is sequential, since an alpha particle is emitted first, followed by the breakup of $^5$Li after a mean time of about $10^{-21}$ seconds. The $^5$Li lasts for a long time compared with the time taken for the transfer of the neutron to $^3$He, but the $^5$Li lifetime is not long compared with the time it takes for the loosely bound proton to move around the $^5$Li system. Hence the proton may retain some memory of where it was located during the neutron transfer. If this is true, the geometry of this reaction could yield an asymmetry in the proton yields at the two alternative positions. The proton velocity in the $^5$Li system governs the extent to which the initial localization of the proton in the alpha-proton system persists. Consequently, protons in the spectra with higher energies should tend to represent
shorter lived intermediate systems, and the asymmetry should increase with increasing proton energy, as the experimental results indicated. The large cross section found for this process implies a direct process is involved in which clusters are interacting much like the compound-cluster model of Phillips, (1964).

A schematic diagram was used to illustrate the model. This is shown in Figure 2. The transfer of a neutron is assumed to take place at the point of closest approach of the $^3$He to $^6$Li. The proton is assumed to be localized in one of the three possible positions shown by the black dot on the shaded hemisphere. The arrows indicate the direction (in the centre-of-mass frame of the reaction) in which the proton will tend to be emitted. Case A corresponds to the proton localized in the opposite hemisphere to that from the neutron picked up. Two particle pickup is represented by B and single particle pickup by C. Cases B and C are alternatives when the proton is localized on the same side of the $^6$Li as the neutron at the moment of transfer. It is assumed that the loosely bound proton has equal probability of transferring with the neutron (case B) or staying with the original alpha from $^6$Li (case C). A is assumed to occur 50% of the time, while B and C are each assumed to occur 25% of the time. The geometry shown would then favor the forward proton detector by 7 to 1.

In the proposed reaction, $^7$Li($^3$He,da)$^4$He, one may illustrate the possible asymmetry by the same model. Using the Cluster Model, one must first consider what clusters of particles can form $^7$Li. This nucleus can be thought of as an alpha core surrounded by
Figure 2. Diagram of primary reaction in the center-of-mass frame showing neutron pickup (solid curves) and two-particle pickup (dashed curves) for fixed $^5\text{Li}$ recoil direction.
a deuteron and a neutron. There is, however, evidence suggesting that $^7\text{Li}$ consists of an alpha core and a triton (Forsyth and Perry, 1965). First consider the former case, with $^7\text{Li}$ surrounded by a neutron and a deuteron, uncorrelated. Using the same arguments as those above, the reaction can proceed by single or three particle transfer. Case A (figure 3) corresponds to the deuteron being localized in the opposite hemisphere to that from which the neutron is picked up, and is assumed to occur 50% of the time. In cases B and C the deuteron is assumed localized on the same side of the $^7\text{Li}$ as the neutron at the time of transfer. The loosely bound deuteron has equal probability of transferring with a neutron (case B) or staying with the original alpha from $^7\text{Li}$. Cases B and C are each assumed to occur 25% of the time. This would give an asymmetry ratio 7 to 1, for the forward deuteron detector position yield to that of the backward position, as in the model used by Reimann et al.

This analysis has tacitly assumed that following the rapid transfer of the neutron from the $^7\text{Li}$ system, the remaining two p-shell nucleons can be regarded as a single entity, that is, effectively a "deuteron". The extent to which this is true would of course modify the picture, consequently affecting the asymmetry ratio.

One may now consider the arguments for $^7\text{Li}$ transferring a triton in a single stage process (see Figure 4). A triton can be transferred to $^3\text{He}$ to form $^6\text{Li}$. Forsyth and Perry, (1965), however, also point out that the structure of $^6\text{Li}$ is of the form
Figure 3. Diagram of primary reaction in the center-of-mass frame showing neutron pickup (solid curves) and three-particle pickup (dashed curves) for fixed $^6\text{Li}$ recoil direction.
Figure 4. Diagram of primary reaction in the center-of-mass frame showing neutron pickup (solid curves) and three-particle pickup (dashed curves) for fixed $^6\text{Li}$ recoil direction.
$^4\text{He} + d$ rather than $^3\text{He} + t$, so that this would suggest that such a transfer may be inhibited, and if it did occur, there would be no preferred direction for the emission of the deuteron from the mass six system. Contributions from this process would then tend to lower one maximum asymmetry ratio predicted by the simple model.

Thus, among other things, the predicted asymmetry will depend on the reaction mechanism and on the relative probability of single and three particle transfer. Experimental measurements would therefore be of interest in determining these aspects.

2. Kinematics of the Reaction $^7\text{Li}(^3\text{He},d\alpha)^4\text{He}$

The bombardment of $^7\text{Li}$ by $^3\text{He}$ leads to a three particle final state consisting of two alpha particles and a deuteron. We may consider the reaction proceeding via a sequence of the following two reactions:

$$^3\text{He} + ^7\text{Li} \rightarrow ^6\text{Li} + \alpha_1$$
$$^6\text{Li} \rightarrow \alpha_2 + d$$

Expressions for three-body final state kinematics proceeding through an intermediate excited state can easily be found. The incident energy, the internal state of excitation of the intermediate state, and the internal state of excitation (if any) of the components of the final system, must be known. In this reaction it is convenient to label the detectors $\alpha_1$, $\alpha_2$, and $d$. Thus the first alpha particle which leaves the $^6\text{Li}$ as a recoiling system, is recorded by detector $\alpha_1$, and the other by detector $\alpha_2$. The energies of the first alpha particle and of the
$^6$Li can be easily determined from simple two-body kinematic calculations. Since the Q-value of the secondary breakup is known, the energies and laboratory angles of the second alpha and of the deuteron can then be calculated. In these calculations we assume that the distance traveled by the intermediate $^6$Li system is negligible, and that it does not lose energy to any collision before it decays. A computer program, "Kinem", was written to perform these calculations. A description and a complete listing of Kinem is given in the Appendix.

Figure 5 displays a kinematic phase diagram showing the laboratory energies as a function of laboratory angle for the final alpha and the deuteron, at fixed energy and laboratory angle of the first emitted alpha. The curves represent the states at 3.56, 4.57 (FWHM = 0.35), 5.36 (FWHM = 0.32), and 6.0 MeV excitation in $^6$Li. These are plotted directly using a modification of the Kinem program and a Calcomp plotter. For excited states which are given a width, the program broadens the curve on the phase diagram into a set of three lines whose outer edges represent the full-width at half-maximum (FWHM) of the state. Figure 6 shows the energy levels of $^6$Li.

Since the Q-value of this reaction is more than 13 MeV, the effect of bombarding energy is small on the three-body final state kinematics. The position of $\alpha_1$ was chosen to geometrically optimize the $\alpha_2$ and d detector positions. The result was for example, 75° for $\alpha_1$ and -82.2° for the $^6$Li recoil. (Figure 7 shows the convention used to indicate the laboratory angles). The $^6$Li recoil direction defines an axis of symmetry which also
Figure 5. Kinematic phase diagram for the second alpha particle and the deuteron for fixed angle of the first alpha.

$^6\text{Li}$ EXCITED STATES (MeV) $\alpha_1=75^\circ$

A. 3.56
B. 4.57 (FWHM=0.35)
C. 5.36 (FWHM=0.32)
D. 6.0

NOTE: Primed letters refer to deuteron contours and un-primed letters to alpha contours.
Figure 6. Energy levels of $^6\text{Li}$.

(From T. Lauritsen and F. Ajzenberg-Selove, Nuclear Physics 78, (1966)1.)
Figure 7. The two alternative positions for the d and $\alpha_2$ detectors on opposite sides of the $^6$Li recoil direction for $\alpha_1=75^\circ$. 

Figure: The two alternative positions for the d and $\alpha_2$ detectors on opposite sides of the $^6$Li recoil direction for $\alpha_1=75^\circ$. 

Diagram: The diagram shows two alternative positions for the d and $\alpha_2$ detectors on opposite sides of the $^6$Li recoil direction for $\alpha_1=75^\circ$. The measurements are specified as $144^\circ$, $75^\circ$, $45^\circ$, $-44.3^\circ$, $-44.4^\circ$, $-119.9^\circ$, $-82^\circ$, $-120^\circ$. The beam axis is indicated by a horizontal line, with the target orientation and elastic scattering monitor labeled. The $^6$Li recoil direction is shown with arrows pointing in the forward and backward directions.
corresponds to the maximum deuteron energy. The deuteron energy drops as a function of laboratory angle, which limits the useful range of energy (because of timing and minimum energy considerations) in which the deuteron can be observed to about $70^\circ$ on either side of the $^6\text{Li}$ recoil. If we chose $38^\circ$ on either side of the $^6\text{Li}$ recoil to observe the alpha associated with the breakup of $^6\text{Li}$, then the deuteron will be observed $75^\circ$ away from the $\alpha_2$ detector. This means that the angle between the deuteron detector and the $\alpha_1$ detector is always greater than $120^\circ$. Consequently, provided that the deuteron detector can distinguish between deuterons and alpha particles, there is no possibility of observing the wrong particle for a particular $^6\text{Li}$ excited state. The experimental problem of identifying the deuterons in the presence of other particles is discussed in the next section.

3. The Experiment

An alpha particle spectrum from the reaction, $^7\text{Li}(^{3}\text{He},\alpha)^6\text{Li}$, was published by Allen et. al. (1960), which showed energy levels at 2.19, 3.56, 4.5, 5.3, 6.6, 7.4, 8.4, and 9.3 MeV in $^6\text{Li}$. The 4.5 and 5.4 MeV levels had also been found by Galonsky et. al. (1955), and the $\gamma$-emitting 3.56 MeV state had also been reported by Day and Walker (1952). Then in 1963 Linck et. al. published a study of this reaction which was in general agreement with Allen et. al., except that no levels above 6 MeV excitation were seen. In 1968 Cocke also reported finding no levels above 6 MeV excitation, nor did he find conclusive evidence for the 4.57 MeV excited state.

The proposed experiment involves a search for an
asymmetric breakup proceeding through the 4.57 MeV $^6\text{Li}$ excited state. There are however, some experimental problems. One of these is the possibility of contributions from competing modes. This reaction may also proceed via excited states of $^8\text{Be}$ (see Figure 8), $^7\text{Be}$ or $^9\text{Be}$, thus:

$$^3\text{He} + ^7\text{Li} \rightarrow ^9\text{Be} + d$$

$$\downarrow \alpha + \alpha$$

$$\rightarrow ^7\text{Be} + T$$

$$\rightarrow ^9\text{Be} + p$$

$$\downarrow \alpha + \alpha + n$$

The reaction proceeding through $^7\text{Be}$ (and then $^7\text{Li}$) has a threshold of 1.5 MeV and can be avoided at a bombarding energy of about 1 MeV. The four particle final state proceeding through $^9\text{Be}$ is experimentally avoided using triple coincidence techniques and suitable particle identification. The only other possible contribution to events of interest arises from the wide (6.7 MeV) 11.4 MeV excited state of $^8\text{Be}$. However, because of energy considerations, only the outer edge of this state can contribute. Furthermore, by choosing the detector positions appropriately this can also be avoided.

Contaminant reactions induced from target materials (see Chapter IV) can also be a problem. These are,

$$^3\text{He} + ^{12}\text{C} \rightarrow \alpha + ^{11}\text{C}$$

$$\rightarrow d + ^{13}\text{N}$$

$$^3\text{He} + ^{19}\text{F} \rightarrow d + ^{20}\text{Ne}$$

$$\rightarrow ^{16}\text{O} + \alpha$$
Figure 8. Energy levels of $^8$Be.

(See ref. on Figure 6)
However, these alpha particles and deuteron groups are of sufficiently low energy, are easily identifiable (see Chapter IV), and are removed by coincidence techniques.

Another experimental problem occurs because of other close (within 1 MeV) excited states in $^6$Li. These are the 3.56 MeV and and 5.36 MeV states. Figure 5 shows the second alpha particle and the deuteron energies as a function of laboratory angle, for these and other states. The 3.56 MeV excited state is narrow, while the 5.36 MeV state is 0.32 MeV (FWHM) wide. The excited state of interest, 4.57 MeV, is 0.35 MeV wide. However, these are separated by more than 0.4 MeV taking the difference in energy from the half-width points. A solid state detector with reasonable resolution (15 keV), can easily resolve these states.

The most difficult experimental problem arises because both alpha particles and deuterons are received by the detectors. Some means of distinguishing these is required. One method uses a totally depleted detector in front of one of the detectors and distinguishes particles by $dE/dx$ vs. $E$ analysis. For a totally depleted transmission detector, $\Delta E$,

$$T/a = (E + \Delta E)^{1.73} - E^{1.73},$$

where $T$ is the thickness of the $\Delta E$ detector, and $a$ depends on the
particle type (Ortec, 1966). Separation of various particles is based on the rate of energy less, \( \frac{dE}{dx} \), and for a particle of energy, \( E \), is given by,

\[
\frac{dE}{dx} = kmZ^2E
\]

The product, \( E \frac{dE}{dx} \), is independent of \( E \) and is proportional to the mass of the particle. This allows identification of particles when \( E \) and \( \frac{dE}{dx} \) are recorded. In the proposed experiment it is necessary to distinguish alpha particles and deuterons whose response to this system would require a totally depleted AE detector of between 5.5\( \mu \)m and 7\( \mu \)m. Although such detectors are commercially available, they are very delicate and expensive, and it was then decided to pursue the problem from another standpoint.

Another well known technique employs time-of-flight. However, the usual method uses time-of-flight with neutrons to find the energy of these particles. Here it is proposed to use time-of-flight to identify the particles, knowing what energies the particles should have from the kinematics. In other words, to investigate the breakup mode corresponding to excitation of the 4.57 MeV state of \( ^6\text{Li} \), it was decided to employ a charged particle time-of-flight technique to label the emitted deuterons.

Figure 9 shows the times-of-flight of the second alpha as a function of laboratory angle, and Figure 10 shows the differences in times-of-flight of the second
Figure 9. Times-of-flight of second alpha particle as a function of laboratory angle for the \( ^6\text{Li} \) excited states at 3.56, 4.57, and 5.36 MeV, with the first alpha emitted at 75°.
Figure 10. Differences in times-of-flight for the second alpha and the deuteron as a function of laboratory angle of the second alpha. The 3.56, 4.57, and 5.36 MeV excited states are shown. The first alpha is emitted at 75 deg.
alpha and the deuteron as a function of laboratory angle for the second alpha. Coincidence events can be stored, with the energies of these final two particles, along with their differences in times-of-flight. Knowing the energy of a particle, its time-of-flight can be found easily from the relation,

$$ t_1 = 71.92 \sqrt{\frac{M_i}{E_i}} \text{ nanoseconds/meter.} $$

Furthermore,

$$ E_i t_1^2 = (71.92)^2 M_i = k_i. $$

The quantity, $E_i t_1^2$, is a constant for a particular type of particle. In the cases of alpha particles and deuterons $K \alpha = 2K \alpha$. Therefore, if the data $\{E_\alpha, E_d, (t_\alpha - t_d)\}$ is stored, computing techniques can transform this to $\{E_\alpha, E_d, E_i t_1^2\}$.

If one considers flight paths of about 10 inches, the difference in times-of-flight is about 10 nsec. for the 4.57 MeV state. And, by plotting the data as $E_i t_1^2$ vs. $E_i$ the deuterons can be easily distinguished from the alpha particles, as shown in Figure 11. Moreover, all data points can be used, and experimentally undesirable groups, such as low energy particles, can be readily discarded. One would require, however, a sufficiently large scattering chamber; adequate moveable detector holders, would also be needed.
Figure II. $E_i + ^2$ as a function of $E_i$ for alpha particles and deuterons. The width of the band is due to the natural width of the 4.57 MeV state.
CHAPTER III

DESIGN OF THE 23 INCH SCATTERING CHAMBER

1. Introduction

This chapter describes the design and construction features of the scattering chamber referred to in Chapter II. A versatile aluminum scattering chamber with inside diameter of 23 inches and height 17 inches, was constructed. The chamber has around its center 20 standard 2 inch ports (18° apart). This cylindrical ring with the port flanges and "0"-rings was purchased from and especially manufactured by Norton International Inc., with all critical surfaces and ports machined to within ±0.003 inch.

Aluminum top and bottom plates of thickness \(\frac{1}{2}\) inches were made, and then fitted to the chamber. The entire chamber is mounted directly on its own vacuum system, complete with a steel carriage. The chamber is bolted in place on an 8 inch standard flange via the bottom plate, allowing a 6 inch diameter pumping port through the bottom plate of the chamber, permitting a close, concentric placement for a fast pump-out.

The vacuum system is a complete 200 liter/sec. unit with a liquid nitrogen baffled 4 inch oil diffusion pump and associated roughing pump and valves, and is mounted on the wheelable steel carriage. This vacuum system was also purchased from Norton International Inc., including
ionization gauge and controls. A liquid nitrogen automatic feed device was added to maintain the chamber under high vacuum for as long as required.

A long collimation system was added to the entrance port and a Faraday cup to the exit port. The latter was electrically insulated from the chamber to allow monitoring of the beam with a current integrator. Arrangements in the Faraday cup provided electron supression, and the inside of the Faraday cup was lined with tantalum to reduce background arising from charged particle induced reactions.

Some chamber ports were covered with Lucite viewing ports, equipped with light tight covers. A small light bulb was also installed inside the chamber for viewing purposes, and is electrically connected by means of two Covar seals, mounted in one of the blank port flanges.

2. Beam Collimation System

Beam collimation is accomplished by means of four tantalum discs placed inside a \( \frac{5}{8} \) inch thick wall brass tube. Figure 12 shows the arrangement used in the experimental run, and the method by which the spacing of these discs can be changed to suit the experiment. Screw caps on each end hold the parts in place. The entire system is 16 inches long and all critical surfaces are machined to within ±0.002 inch. The long collimator was necessary, since the beam was required to travel about 11 inches, and still be within 1 mm.
Figure 12. Layout showing the arrangement of tantalum collimating discs, with variable spacing (not to scale).
of the exact center of the scattering chamber, regardless of beam instabilities and focussing conditions.

Tantalum discs were chosen because of the relatively high melting temperature (2000°C) of this metal, and its large atomic number (Z = 73), which ensures little contribution to background counts if the bombarding beam is deuterium. The collimator tube fits inside an outer vacuum tight jacket, which is fastened to the outside wall of the scattering chamber. Evacuation of the beam line and collimation system was accomplished by mounting the collimator tube on a three-pronged web arrangement at each end, with semicircular baffles near the center to prevent stray parts of the beam from entering the scattering chamber.

3. Detector Holder Assemblies

The scattering chamber has three 360° rotatable detector holders, two of which can be rotated externally, while the chamber is under high vacuum. These two detector holders are positioned by two "rotary feed-through" devices, with a gear assembly inside. These detector holders are fastened on two aluminum plates, 44cm and 48cm in diameter, each with a bicycle chan fitted to its edge, and geared to the rotary feed-through on the bottom cover. The two plates are held in place via Nylatron dry bearings, and are positioned concentrically around the pumping port. The third detector holder is not movable from the outside, but can be positioned on a ring engraved in intervals of \( \frac{10}{2} \) from
0° to 360°. This is mounted inside another ring suspended from the inside wall of the chamber by three supports. Each detector holder consists of a movable carriage which allows positioning of the detector at 5cm. to 25cm. from the center of the chamber. Detectors are mounted on Microdot detector mounts fastened to the movable carriage and provisions are made for vertical adjustment.

A penta-prism is mounted near one of the lucite covers on one of the ports, and allows the experimenter to view the markings on the movable plates. The plates are engraved in intervals of $\frac{10}{2}$ from 0° to 360°, which allows external positioning of these two detectors to within $\pm \frac{10}{2}$. This is facilitated by a pointer system directly above the engraved plates.

Other detectors can be mounted directly on the remaining ports (18° intervals), allowing for example a Rutherford elastic scattering monitor to be placed at such backward angles as $\pm 162°$ or $\pm 144°$, etc. Other 360° movable detectors can also be mounted inside the chamber by mounting these on different diameter rings, as the third detector holder mentioned above. It is possible to make these externally movable by adding suitable feed-through devices and gears to the top lid.

Microdot detector mounts are connected to ports with Microdot 100 ohm, low capacitance (12pf./ft.)
coaxial cable. Electrical connection to the outside is made using special Microdot vacuum feed-through connectors. Special precautions were made to allow rotation of the two detectors through 360° without these cables becoming caught in the apparatus.

4. Target Holders and Assembly

Targets are inserted into the center of the scattering chamber from the top plate using a "rotary push-pull" vacuum feed-through. The target holders are attached to the feed-through and consist of four to six holes drilled in a \( \frac{1}{16} \) inch thick copper strip. Provisions are made on the target holder for a piece of quartz to facilitate beam focussing, or a small mirror to assist in chamber alignment. Targets can be selected externally and guided into position by an assembly attached to the top lid. The shaft of the rotary feed-through is connected to a disc with a pointer, which fits inside a brass plate graduated from 0° to 360°.

Figures 13 and 14 depict the parts of the scattering chamber, with important parts being marked as shown.
A Scattering Chamber  
B Faraday Cup  
C Collimation System  
D Pumping Unit  
E Target Holder Assembly

Figure 13
(Center Detector Holder and Top Lid Removed)

A Externally Movable Detector Holder
B Pointer and Gear Arrangement
C Pumping Port

Figure 14
CHAPTER IV

THE REACTION $^7\text{Li}(p,\alpha)^4\text{He}$ TO INDICATE CHAMBER SYMMETRY

1. Introduction

As a means of checking the scattering chamber for performance under actual experimental conditions, the reaction $^7\text{Li}(p,\alpha)^4\text{He}$ was chosen primarily because two alpha particles are emitted $180^\circ$ apart in the center-of-mass system. These would show the experimenter the degree to which the chamber collimation system, target holders, and detector holders are geometrically aligned and machined. Very slight deviations in workmanship would be multiplied over large distances. In this case some deviations multiplied over 23 inches could be extremely significant, and experimentally undesirable.

By rotating the two movable detectors one could determine even more precisely how symmetrical the chamber is, when the two alpha particles are observed in coincidence. The proton beam from the U.B.C. Van de Graaff accelerator is also one of the easiest of its various beams with which to work.

This reaction, $^7\text{Li}(p,\alpha)^4\text{He}$, which has been studied extensively (see for example, Freeman et. al. 1958; or more recently Duggan, 1968; and Lerner and Marion, 1969), could also test, at various beam intensities, the thin targets made by evaporating lithium fluoride onto a thin carbon backing. These targets will also be used
in the investigation of the reaction, $^7\text{Li}(^3\text{He},d^3\text{He})^4\text{He}$, as outlined in Chapter II.

2. Detector Positions

In the investigation of $^7\text{Li}(p,\alpha)^4\text{He}$ it is convenient to call one detector $\alpha_1$ and the other, $\alpha_2$, as it is shown in Figure 15.

The two alpha particles share the Q-value of the reaction and the bombarding energy in a manner shown in the kinematic diagram of Figure 16, where the two-body kinematics were calculated from the computer program, Kinem, which is equally useful for three-body kinematics. The large positive Q-value of 17.35 MeV makes measurements particularly convenient, especially at a bombarding energy of 1.5 MeV, which was chosen because the cross section varies smoothly with energy in this region.

To measure accurately and eliminate background, it was decided to perform a coincidence measurement using the two-dimensional analysis technique mentioned in Chapter I, with detectors placed at $45^\circ$ and $-126.1^\circ$ in the reaction plane. Since this reaction is a two-body process, the alpha particle energies are well defined, being 10.67 MeV and 8.17 MeV respectively. The coincidence spectrum will then appear as an intense point on the two-dimensional energy plane. Deviations in symmetry of the chamber can be checked by comparing the experimentally obtained energies with those predicted by the kinematics.
Figure 15. Detector positions and target orientations for two of the experimental runs.
Figure 16. Theoretical energies plotted as a function of lab angle for the first alpha, with bombarding energy of 1.5 MeV.
(allowing for energy loss corrections), and a more sensitive test, by looking for shifts in the energy spectra when the two detectors are interchanged.

It is also necessary to place foils in front of both detectors to stop elastically scattered protons from the reactions $^7\text{Li}(p,p)^7\text{Li}$, $^{19}\text{F}(p,p)^{19}\text{F}$, $^{12}\text{C}(p,p)^{12}\text{C}$, and $^{13}\text{C}(p,p)^{13}\text{C}$. For this purpose 40μinch foils were chosen.

3. Targets

Since thin targets (of order, 10μgm/cm² thickness) will be required for the investigation of the reaction, $^7\text{Li}(^3\text{He},d\alpha)^4\text{He}$, it was decided to use them for the scattering chamber investigation experiment. These targets give a reasonable yield, are self supporting (with a strong backing material), yet are thin enough so that the reaction products can be observed through the target with less than 10 keV energy loss. Since lithium metal has a great affinity for both water and oxygen, targets made from free lithium deteriorate very rapidly. For this reason a lithium salt was decided upon. The most useful of these is LiF, which is perhaps one of the easiest solids to evaporate. However, these targets require a strong backing material, since they are not self-supporting. Some experimenters use very thin metal foils, such as nickel (Cocke, 1968) and others use carbon (Dearnaley, 1960). Owing to the smaller energy losses involved, carbon foils
were used. They are relatively easy to prepare, and are adequately thermally and electrically conductive, and can withstand temperatures of almost 900° before melting.

Although a target of natural LiF prepared on a carbon backing will produce background nuclear reactions with $^{12}$C, $^{13}$C, and $^{19}$F, several advantages are obtained. The one-to-one ratio of lithium to fluorine nuclei permits the use of a monitor detector by observing the yield of elastically scattered beam particles from fluorine nuclei. If the coulomb barrier is sufficiently high so that nuclear effects can be neglected, the absolute cross section for the process under study can be evaluated by normalizing to the well known Rutherford scattering cross section for the yield in the monitor. This has the additional advantage that non-uniformities in the target composition are automatically accounted for.

The preparation of these thin targets is essentially a two stage process, consisting of the evaporation of carbon, and then the evaporation of lithium fluoride onto the carbon backings. Carbon foils were prepared in a vacuum of about $10^{-6}$ Torr in a standard bell-jar evaporator. Precleaned standard microscope glass slides were placed about 10 cm above two carbon rods, one of which was placed horizontally with the end
cut to a $45^\circ$ angle, and the other rod was sharpened to a point and placed at an angle of $30^\circ$ to the horizontal, much like the arrangement used by Makosky (1969). The two rods were held in contact by light springs fastened to water cooled brass mounts. A current of 200 amps was passed through the rods in 8 to 10 bursts, each burst lasting about 2 seconds, with the apparatus being allowed to cool for about one minute between bursts.

The edges of the glass slides were then scraped and the carbon layer was cut into squares large enough to cover the target holder holes. The slides were placed in a tray at an angle of $30^\circ$ to the horizontal, and warm water was used to float the films off by allowing the water to rise slowly in the tray. Two types of glass slides were used, the precleaned slides giving the best results. Slides coated with Tepol, a very highly soluble detergent, produced excellent foils as well, although some tended to break while being floated off.

The target holders consisting of six $\frac{5}{16}$ inch holes drilled in a copper strip, were placed into the water bath, and the foils were floated over the holes of the target holder consecutively, beginning at one end. The target holders with the carbon foils were next placed in a vertical position and allowed to dry for a day. Each target holder was placed horizontally in an evaporator, and held 15cm. above a tantalum boat containing
about one gram of the LiF salt. The LiF was evaporated onto the carbon backings in about 5 minutes by allowing 50 amps of current to pass through the boat, under a vacuum of almost $10^{-6}$ Torr.

This procedure gave 4 or 5 excellent targets per target holder of 10 to 15 µg/cm² thickness of LiF on a backing of 15 to 30 µg/cm² of carbon. Such targets typically have energy losses of only a few keV for a 10 MeV alpha.

4. Detectors

Two silicon surface barrier solid state detectors were chosen as the two alpha particle detectors. These are large-area p-n diodes comprised of an extremely thin p-type layer on the sensitive face of a high purity n-type silicon wafer. Electrical contact is made to the p-type surface by a thin gold film, typically 40 µg/cm² thick, and to the n-type silicon by means of a non-rectifying metal contact on the back surface. Upon application of an externally applied reverse bias voltage, a region known as the depletion region is obtained, which varies in depth as the square root of the applied voltage. The depletion region is the portion of the n-type silicon which contains the electric field (resulting from the reverse bias). Free charge carriers are created in this region by the ionizing radiation, and these are separated
by the influence of the electric field, and the resulting net current represents the basic source of information about the number of charge carriers created by the incident charged particle radiation. These diodes are then mounted in metal cylinders on which connection can be made with B.N.C. or Microdot connectors. The two detectors used were supplied by Oak Ridge Technical Enterprises Corporation (ORTEC), and typically have an alpha particle energy resolution of less than 60 keV for an $^{241}\text{Am}(5.477 \text{ MeV})$ alpha source and a very low noise amplifying system. Range-energy curves for silicon (Ortec, 1967) show that 12 MeV alpha particles typically travel 100 microns in silicon before being stopped. Consequently, the two detectors were operated at depletion depths of 110 microns, to ensure all alpha particles of interest were completely stopped within the depleted region.

Nickel foils of 40µinch thickness were placed in front of the detectors to stop the elastically scattered protons, and these were left on during the energy calibration procedure. These foils were placed inside the detector collimators, which consisted of cylinders which fit over the detectors, and are held in place by small locking screws. The collimator faces had holes drilled in them which were $\frac{1}{8}$ inch and $\frac{3}{16}$ inch in diameter.
Each detector was placed at 20cm ±0.1cm from the target axis (the center of the chamber), with the $\frac{1}{8}$ inch diameter collimator on the 45° detector and the $\frac{3}{16}$ inch collimator on the -126.1° detector (Figure 15). Thus the angles subtended by the two alpha detectors were 0.9° and 1.4° respectively. Alpha particles are detected by the 45° detector, within its solid angle. One must be certain that the corresponding alpha particles which share the energy with those recorded by the 45° detector, and which are in the vicinity of the -126.1° detector, are all recorded by this second detector. For an angle subtended by the 45° detector of 0.9° kinematic calculations show that the -126.1° detector must subtend an angle of 1.1°, due to kinematic spreading. Hence in double coincidence, if the -126.1° detector subtends an angle of 1.4°, we can be certain that all corresponding alpha particles are detected, provided of course, that the chamber and detectors etc. are all in reasonable alignment.

5. **Scattering Chamber Alignment**

Alignment of the scattering chamber, including beam collimator, target assembly, and detectors, was done optically. A continuous helium-neon gas laser was placed in the beam position, approximately 10 feet from the chamber entrance port. The Faraday cup was removed
and a special alignment flange, with a $\frac{1}{64}$ inch hole drilled through its center and which fits the port within 0.003 inch, was installed. The chamber was then carefully leveled and aligned by observing the laser beam on a wall after it had passed through the beam collimator system and the alignment flange. To check the target holder assembly with respect to the chamber, masking tape was placed over the six holes of the target holder, through the center of which pin holes were pierced. The target feed-through device was moved vertically and the laser beam spot was again observed on the wall after it had passed through each of the pin holes and the alignment flange, showing the precision by which the top plate of the scattering chamber and the target holder assembly had been constructed.

A small mirror was installed on the upper portion of the target holder, where care was taken to ensure that the reflecting surface of the mirror was on the central chamber axis. The detectors were aligned by reflecting the laser spot into the detector collimator holes in several backward angles, where both detectors were rotated. The target assembly was retracted and the two detectors were in turn rotated to the $0^\circ$ position where the laser spot was seen inside the detector collimator holes. As a final check, the target was inserted
and the laser beam was reflected backward upon itself, as a last test of optical alignment.

6. **Electronics**

The electronic arrangement consisted of standard commercially available units (see Table 1), with the exception of the preamplifiers whose operation is described by Whalen (1965). These are well suited for use with the delay-line clipped main amplifiers, since these charge sensitive nuvistor preamplifiers have a fast risetime (<15 nsec.), are low noise (resolution <10 keV), and have a slow decay time (~100 μsec.).

A block diagram of the amplification and coincidence system is shown in Figure 17. Pulses from the nuvistor preamplifier, which correspond to the detection of a charged particle, are double delay-line clipped by the main amplifier, whose prompt output triggers the single channel analyzer at the zero-crossover point, provided the pulse falls within the desired voltage range. The outputs from the two single channel analyzers are presented to the inputs of the Canberra fast coincidence unit. Negative output pulses from the coincidence unit are recorded by a scaler to count coincidence events, while positive pulses are delayed and then stretched to produce the correct gating pulses for the ND-160 analyzer, operated in coincidence mode. A
<table>
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<th>Table 1</th>
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<tr>
<td>Commercial Electronic Units Referred to by the Numbers in the block Diagram of Figure 17.</td>
</tr>
</tbody>
</table>

1) CI Model 1410 Linear Amplifier  
   (Canberra Industries Inc., Middletown, Conn.)

2) CI Model 1435 Timing Single Channel Analyzer

3) CI Model 1470 Scaler

4) CI Model 1441 Coincidence Unit

5) ORTEC Model 427 Delay Amplifier  
   (Oak Ridge Technical Enterprises Corp., Oakridge, Tenn.)

6) ORTEC Model 416 Gate and Delay Generator

7) ORTEC Model 411 Pulse Stretcher

8) NUCLEAR DATA Model ND-160 Dual Parameter Analyzer  
   (Nuclear Data Inc., Palatine Illinois)
Figure 17. Block Diagram of Electronic Arrangement
(numbers refer to units given in Table 1.)
scaler and a single channel analyzer were also added to one of the linear amplifiers in order to compare coincidence counts from various experimental runs.

The primary purpose of the electronic arrangement was to count coincidence events from the two detectors which satisfy the energy requirements, and which fall within the coincidence resolving time of 50nsec. Dual parameter analysis was provided by taking prompt outputs from the linear amplifiers, delaying them, and feeding to the X and Y inputs of the ND-160 dual parameter analyzer, where they were accumulated in a 64 X 64 array. (This display was used only to show the region in which the particles of this energy would lie, as well as to indicate to some degree what random coincidences might have occurred.) All of the analyzing equipment could be started and stopped by remote control. Not shown in Figure 17 are the Ortec detector bias supply, and the test pulse generator.

7. **Electronics Calibration**

The electronic system was calibrated using an $^{241}$Am alpha source, of which the major alpha particle group has an energy of 5.477 MeV. By applying various test pulses it is possible to determine the pulse height necessary to simulate particles of any desired energy in the experiment.
The $^{241}$Am source was attached to the target holder assembly and both detector-amplifier systems were calibrated by turning the source to face the desired detector. The calibration was carried out with the 40 μinch foils, used to stop elastically scattered protons, placed in front of the detectors, as these would be in place during the experiment. As a check, calibration was compared with the absence of foils, 75 μinch of foil, and 175 μinch of foil, using the $^{241}$Am source.

The amplifier gains were adjusted so that peaks corresponding to 5.477 MeV alpha particles were in a convenient position in the pulse height analyzer. The baselines and window widths of the single channel analyzers were adjusted so as not to allow events other than those corresponding to the energy regions of interest. This was accomplished by applying test pulses corresponding to the required energies using the calibration curves, and then checking these by observing single particle energy spectra from each of the two detectors, at the desired laboratory angles.

The coincidence resolving time was determined by varying the delay in the $\alpha_2$ channel, using the timing portion of the timing single channel analyzers, then plotting the number of coincidence events vs. delay time in the $\alpha_2$ channel. A plateau-like curve resulted, where
the resolving time was found from the width of this
curve, and the optimum delay in the \( \alpha_2 \) channel was
taken at the center of this plateau. Thus, the co-
incidence unit generated an output logic pulse when the
simultaneous energy and time requirements were met.

8. Experimental Results

Data was accumulated using the 3 MeV U.B.C.
Van de Graaff accelerator, and a 1.5 MeV proton beam
from the accelerator was analyzed by a \( 90^\circ \) deflecting
magnet, then focussed to a spot about 2mm. in diameter
on a LiF target in the 23 inch scattering chamber. The
beam current was monitored in the Faraday cup using a
current integrator, and was typically 0.3\( \mu \)amp.

Single particle energy spectra were accumulated
at several laboratory angles for both surface barrier
detectors. This was accomplished by operating the
electronics in single coincidence mode. Elastically
scattered protons were found to be completely absorbed
by the nickel foils in front of the detectors. Shown
in Figures 18 and 19 are single particle energy spectra
for the laboratory angles of \( 45^\circ \) and \(-126.1^\circ \) respectively,
with the chamber geometry as indicated in Figure 15.
The most striking feature of these two single particle
spectra is the presence of the two lower energy alpha
groups. These are attributed to the alpha decay of \(^{20}\text{Ne} \to \)
Figure 18. Single Particle Energy Spectrum, $\alpha_1 = 45^\circ$

$^{19}$F(p, $\alpha_1^16$O

$^7$Li(p, $\alpha_1^4$He)

Particle Energy (MeV)
Figure 19. Single Particle Energy Spectrum, $\alpha_2 = -126.1^\circ$

- $^7\text{Li}(p,\alpha_2)^4\text{He}$
- $^{19}\text{F}(p,\alpha_0)^{16}\text{O}$
- $^{19}\text{F}(p,\alpha_n)^{16}\text{O}$

Particle Energy (MeV)
the ground and first excited states of $^{16}O$, since they satisfy all physical and energy requirements.

The bombardment of $^{19}F$ by protons forms $^{20}Ne$ in excited states, which show a very high probability of decaying by alpha emission to states of $^{16}O$ (Ask, 1960). This decay can give five groups of alpha particles in the transitions to the ground state and four excited states of $^{16}O$. The two most energetic of these are denoted $\alpha_0$ and $\alpha_\pi$, which leave $^{16}O$ in the ground state and first excited nuclear-pair-emitting state respectively. (The presence of $^{19}F$ is of course due to the LiF used to make the targets).

These reactions, $^{19}F(p,\alpha_0)^{16}O$ and $^{19}F(p,\alpha_\pi)^{16}O$ have been observed by Lerner and Marion (1969), Telepov et. al. (1961), and many others. The relative instenities observed were also in agreement with these authors. The Q-values for these two reactions are 8.12 MeV and 2.06 MeV respectively. Ranken et. al. (1958), showed that in this energy region the main reaction mechanism is a process associated with the formation of an intermediate compound nucleus, in this case $^{20}Ne$.

To eliminate these two unwanted lower energy alpha groups it was necessary to set the $\alpha_1$ and $\alpha_2$ single channel analyzers to allow only pulses corresponding to alpha particles from the primary reaction, $^7Li(p,\alpha_1)\alpha_2$, to be analyzed. This was accomplished by using the test pulse generator and applying various
test pulses, then adjusting the baselines of the single channel analyzers until the unwanted pulses were eliminated.

Once the electronics were properly adjusted, \( \alpha_1 - \alpha_2 \) coincidences were counted using the \( \pm 45^\circ \) side of the electronics as a monitor (Figure 17). The detector positions were first, \( \alpha_1 \) at \( 45^\circ \) and \( \alpha_2 \) at \( -126.1^\circ \), where 500 coincidences were accumulated, with appropriate output cables being reversed. Measurements were repeated, this time by rotating the two detectors to opposite sides of the beam axis, \( \alpha_1 \) being placed at \( -45^\circ \) and \( \alpha_2 \) at \( 126.1^\circ \). Finally, \( \alpha_1 \) was placed at \( -126.1^\circ \) and \( \alpha_2 \) at \( 45^\circ \), and the procedure repeated. The larger detector collimator was in each case attached to the detector at the backward angle, and the monitor count was recorded for each of the four runs.

Results are summarized in Table 2. The coincidence yield per monitor counts were compared for each of the four cases. Cases A' and B' can be added to cases A and B, since no detector difference effects were seen. Dual parameter analysis displayed the two-dimensional energy region in each case (as well as a few random coincidences), where this region consisted of a few points around a dense central point. Theoretically, this "contour" would consist of only a single point. But, because of the finite target
Table 2. Coincidence and monitor counts for the four detector configurations.

<table>
<thead>
<tr>
<th>Case</th>
<th>$\alpha_1$ Lab Angle</th>
<th>$\alpha_2$ Lab Angle</th>
<th>$\alpha_1-\alpha_2$ Coincidences</th>
<th>Monitor Counts</th>
<th>Coincidences per Monitor with Statistical Error $\times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$45^0$</td>
<td>$-126.1^0$</td>
<td>500</td>
<td>967083</td>
<td>$5.238 \pm 0.236$</td>
</tr>
<tr>
<td>B</td>
<td>$-45^0$</td>
<td>$126.1^0$</td>
<td>500</td>
<td>964005</td>
<td>$5.189 \pm 0.237$</td>
</tr>
<tr>
<td>A'</td>
<td>$-126.1^0$</td>
<td>$45^0$</td>
<td>500</td>
<td>961718</td>
<td>$5.200 \pm 0.237$</td>
</tr>
<tr>
<td>B'</td>
<td>$126.1^0$</td>
<td>$-45^0$</td>
<td>500</td>
<td>954552</td>
<td>$5.237 \pm 0.238$</td>
</tr>
<tr>
<td>A''</td>
<td></td>
<td></td>
<td>1000</td>
<td>1928801</td>
<td>$5.185 \pm 0.168$</td>
</tr>
<tr>
<td>B''</td>
<td></td>
<td></td>
<td>1000</td>
<td>1918557</td>
<td>$5.212 \pm 0.169$</td>
</tr>
</tbody>
</table>
thickness, resolution of the detectors, and kinematic spreading due to a solid angle subtended at the target by the detectors, this contour can appear as a cluster of a few points around the primary point corresponding to the alpha particles of energies 10.7 MeV and 8.17 MeV. The peak positions of single particle spectra did not appear to shift more than $\frac{1}{4}$ of a channel, on the alternative sides of the beam axis.

9. Conclusions

In view of the experimental conditions imposed on the alignment and construction of the 23 inch scattering chamber, it is safe to say that it is well suited for multiparticle experiments, well machined and aligned, and extremely versatile. The long 16 inch collimation system proved to be highly successful in keeping the beam spot on the target, regardless of beam instabilities. In fact it was estimated to have moved less than $\frac{1}{2}$ mm over a period of several hours. The thin targets which will be used in the investigation of the reaction, $^7\text{Li}(^3\text{He},d)^4\text{He}$, proved to be able to withstand beam currents of more than 0.4 µamp over periods of a half hour, without appreciable damage. The excellent vacuum system permitted the experimenter to pump the scattering chamber down to pressures of $10^{-6}$ Torr in a few minutes. The only disadvantage found in using this large scattering chamber and its systems, was its great size and
weight, making assembly and moving difficult, but this appeared to be outweighed by the fact that the initial installation and alignment would likely not require adjustment for some time.
CHAPTER V
OTHER WORK

1. Other Experiments

Two other sequential processes in which mass five nuclei are formed are presently under investigation by Heggie et al. (1969). These are:

\[ d + ^7\text{Li} \rightarrow ^5\text{He} + \alpha + (\alpha + n) + \alpha \]

\[ ^3\text{He} + T \rightarrow ^5\text{Li} + n + (\alpha + p) + n \]

These two reactions are of current interest because of the possibility of finding asymmetries about the recoil directions of the mass five intermediate states, and to further study the mechanisms involved in these sequential processes.

2. Future Work With the 23 Inch Scattering Chamber

As was mentioned in Chapter II, Allen et al. (1960) and Cocke (1968) found no evidence for levels above 6.0 MeV excitation in \(^6\text{Li}\). Consequently, besides the proposed search for an asymmetry in the deuteron yield about the \(^6\text{Li}\) recoil direction in the reaction \(^7\text{Li}(^3\text{He}, \alpha)^4\text{He}\), some work may be useful to establish some of the dubious excited states of \(^6\text{Li}\).

In the investigation of the asymmetry found by Reimann et al. a plot of cross section as a function of center-of-mass angle showed a distinct discontinuity in the cross section curve for the forward and aft positions of the proton detector,
on opposite sides of the $^5\text{Li}$ recoil direction. This curve drops as a function of center-of-mass angle for the forward proton detector positions, except for the last point which suggests that the cross-section actually rises. Because of their small scattering chamber, the geometry forced the use of the aft detector positions, and this is where the asymmetry was discovered. A Distorted Wave Born Approximation calculation by Deutchman (1969) suggests that the cross section drops as a function of center-of-mass angle. Since the large size of this scattering chamber allows further investigation of forward detector positions, with the use of annular detectors, several more forward positions may be used. This might enable one to ascertain if the calculation by Deutchman is compatible with the experiment data.

To help explain the asymmetry observed in the breakup of $^5\text{Li}$ ground state, an experiment involving the first excited state of this system is also proposed. Since the first excited state is wider, and hence shorter lived, this possible asymmetry should be larger.
A computer program, "Kinem", was written to carry out the relevant calculations involving three-body sequential kinematics. The program was written as general as possible to allow the kinematics of almost any such reaction to be calculated (non-relativistic), and has as input variables, the masses of the six (or fewer) particles, the laboratory angles of interest, the bombarding energy of the projectile, the Q-values of the two sequential processes, and the excitation energies and natural widths (FWHM) of the intermediate state. A modification of this program will plot directly the kinematic phase diagrams showing particle energy as a function of laboratory angle, for the final two particles, for a fixed laboratory angle and energy of the first emitted particle. (See Figure 20)

The program calculates the following: for a specific angle of emission of the first particle (which can be automatically varied), it will calculate its energy and the angle and energy of the fourth particle (intermediate state in most cases). If this fourth particle decays into two more particles, it will calculate the energies as a function of angle for the center-of-mass and repeat the calculations. The program
will also calculate the times-of-flight of all three emitted particles, in nanoseconds per meter.

Table 3 gives a definition of the input and output symbols. For simplicity data is read with one number per card in F 10.6 format, in the following order:
DELTA1, DELTA2, LIM1, LIM2, LIM3, LIM4, M1, M2, M3, M4, M5, M6, E1, Q1, Q20.
This is followed by pairs of cards for each of the excited states of interest. The first of the pair is the excited state, and the second is the width of that state. (For the ground state and for very sharp states, the cards must be zero or blank). The last card after the data cards can be $ENDFILE.

A listing of Kinem follows Table 3, and is written in Fortran IV (and was rewritten for the I.B.M. 360/67). Figure 20 shows the various particles and the names of their respective laboratory angles.
Figure 20. Schematic diagram showing the three final state particles $M_3$, $M_5$, and $M_6$ and their lab angles $\psi_1$, $\theta_5$, and $\theta_6$ respectively.
Table 3

Definition of Output Symbols From "Kinem"

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M₁</td>
<td>mass of the bombarding particle</td>
</tr>
<tr>
<td>M₂</td>
<td>mass of target nucleus</td>
</tr>
<tr>
<td>M₃</td>
<td>mass of the first emitted particle</td>
</tr>
<tr>
<td>M₄</td>
<td>mass of recoil nucleus (intermediate state)</td>
</tr>
<tr>
<td>M₅</td>
<td>mass of second emitted particle</td>
</tr>
<tr>
<td>M₆</td>
<td>mass of third emitted particle</td>
</tr>
<tr>
<td>E₁</td>
<td>bombarding energy</td>
</tr>
<tr>
<td>Q₁</td>
<td>Q of first reaction</td>
</tr>
<tr>
<td>Q₂₀</td>
<td>Q of breakup of recoil nucleus</td>
</tr>
<tr>
<td>LIM₁</td>
<td>the smallest angle of interest for the first emitted particle, M₃. This is incremented by DELTA₁ until the largest angle at which M₃ is observed, is reached, which is LIM₂.</td>
</tr>
<tr>
<td>LIM₃</td>
<td>the smallest angle of interest for the second emitted particle, M₅. This is incremented by DELTA₂ until the largest angle at which M₅ is observed, is reached, which is LIM₄.</td>
</tr>
</tbody>
</table>

The natural width (FWHM) of the excited states of the recoil is incorporated into the calculation and is denoted by \( I \). Where \( I = 1, 0, +1 \), representing the upper middle and lower middle and lower line contours respectively, of the fifth emitted particle, M₅. If the state has no width, \( I = 0 \). 

PSI: the laboratory angle of M₃ 
ZETA₄: the laboratory angle of M₄
E3: the energy of M3
E4: the energy of M4
T3: the time-of-flight of M3
T4: The time-of-flight of Mr
THETA5, E5, T5: The laboratory angle, energy, and time-of-flight of M5, respectively.
THETA6, E6, T6: the laboratory angle, energy, and time-of-flight of M6, respectively.
THETAR5, THETAR6, ER5, ER6, TR5, TR6: the laboratory angles, energies, and times-of-flight of the fifth and sixth particles reversed in identity in the centre-of-mass frame.
$LIS KINEM

> 1 C   ** *** LAB SYSTEM ** ***

> 2 C

> 3 REAL M1,M2,M3,M4,M5,M6,LIM1,LIM2,LIM3,LIM4,MZET4,MZMAX

> 4 LOGICAL ROOT2,ROOT3,NOMAX,NOMAX6

> 5 ROOT2 =.FALSE.

> 6 XXX =360.

> 7 XX =0.

> 8 C READ IN AND WRITE DATA

> 9 READ(5,10)DELTA1,DELTA2,LIM1,LIM2,LIM3,LIM4

> 10 WRITE(6,12)DELTA1,DELTA2,LIM1,LIM2,LIM3,LIM4

> 11 READ(5,10)M1,M2,M3,M4,M5,M6,E1,Q1,Q20

> 12 WRITE(6,13)M1,M2,M3,M4,M5,M6,E1,Q1,Q20

> 13 IF(M3.LE.0.)M3=1.E-15

> 14 7 READ(5,10)EX,W

> 15 WRITE(6,305)

> 16 305 FORMAT(1H1)

> 17 WRITE(6,14)EX,W
18 10 FORMAT(F10.6)
19 12 FORMAT( 1X,8HDELTA1 =,F8.3,2X,8HDELTA2 =,F8.3,2X,6HLIM1 =,F8.3,2X,
       1,6HLIM2 =,F8.3,2X,6HLIM3 =,F8.3,2X,6HLIM4 =,F8.3,/)
20 13 FORMAT(1X,4HM1 =,F10.6,2X,4HM2 =,F10.6,2X,4HM3 =,F10.6,2X,4HM4 =,
       1F10.6,2X,4HM5 =,F10.6,2X,4HM6 =,F10.6,2X,/,1X,4HE1 =,F9.5,2X
       23 24H01 =,F9.3,2X,5H020 =,F9.3,/ )
24 14 FORMAT(10X,29HEXCITATION ENERGY OF RECOIL =,F9.3,2X,13HMEV ,FWHM
       25 1 =,F9.3,2X,3HMEV )
26  C ***************************************************************
27       LL=0
28       LM=2
29 1F(W,EQ.0.0)GO TO 9
30       GO TO 8
31 9    LL=1
32       LM=1
33 8    DO 5 J=LL,LM
34       J=J-1
35       Q =Q1-EX+FLOAT(I)*W/2. 

Q2 = Q20 + EX - FLOAT(I) \times W/2.

WRITE(6, 15) Q, Q2

FORMAT(\\\\\\\\\, 2X, 3HQ =, F9.3, 2X, 4HQ2 =, F9.3, 2X, 10H########## , /)

IF(I) 17, 18, 19

WRITE(6, 171)

FORMAT(1X, 3HI =, 13, 2X, 11HUPPER)

GO TO 16

WRITE(6, 181)

FORMAT(1X, 3HI =, 13, 2X, 6HMIDDLE)

GO TO 16

WRITE(6, 191)

FORMAT(1X, 3HI =, 13, 2X, 11HLOWER)

C

C1 = M4 \times (M2 \times E1 + Q \times M2 + Q \times M1)/ (M1 \times M3 \times E1)

PSIMAX = 360.

IF(C1.LT.-0.0) GO TO 5

B = M1 \times M3 \times E1/((M1+M2) \times (M3+M4))
C = M2 * M3 * (1 + M1 * Q / M2 / ET) / (M1 + M2) / (M3 + M4)
A = M1 * M4 * E1 / ET / (M1 + M2) / (M3 + M4)

C TEST FOR PSI MAXIMUM
C TEST FOR TWO VALUES OF E3
IF(C1 - 1.) 20, 20, 39
RPSIMX = ARSIN(SQRT(C1))
PSIMAX = RPSIMX * 57.2957
ROOT2 = .TRUE.
WRITE(6, 22) PSIMAX
FORMAT(/, 10X, 27H THERE IS A MAXIMUM ANGLE OF F9.4, 2X, 51H DEGREES FOR
1 PSI AND TWO VALUES FOR THE ENERGIES )
C
C
LIM2 = PSIMAX
PSI = LIM1
INCREMENT PSI
PSI = DELTA1 + PSI
IF(PSI.GT.LIM2)GO TO 5

RPS1 = PSI/57.2957

C MAX. ASYMMETRY ENERGY OF M 3

E3SYMM = ET*(1.-A-C)

WRITE(6,24)E3SYMM

FORMAT(/,2X,32HMAXIMUM ASYMMETRY ENERGY OF M3 = ,F9.3,/) 

ZMAX = 180.

ZMAX6 = 360.

ROOT3 = .FALSE.

NOMAX6 = .FALSE.

C3 = COS(RPS1)

AE3 = C3 + SQRT(C1-1. + C3*C3)

E3 = B*AE3*AE3

E4 = E1+Q-E3

IF(E4.LT.0.0)GO TO 5

XM = SQRT(M3*E3/(M4*E4))*SIN(RPS1)

IF(ABS(XM).GE.1.)GO TO 40

RZETA4 = ARSIN(XM)
ZETA4 = RZETA4 * 57.2957

C TEST ARCSIN OF ZETA4

P1 = SQRT(2. * M1 * E1)
P3 = SQRT(2. * M3 * E3)
DEL = P1 - P3 * COS(RPSI)

IF (DEL .LT. 0.) ZETA4 = 180. - ZETA4

LR05 = ZETA4

RO5 = ZETA4 - FLOAT(LR05)

T3 = 71.92 * SQRT(M3 / E3)

T4 = 71.92 * SQRT(M4 / E4)

IF (ROOT2) GO TO 42

MZET4 = - ZETA4

WRITE (6, 41) PSI, MZET4, E3, E4, T3, T4

FORMAT (/, 1X, 10HFOR PSI = , F10.4, 2X, 13HDEG. ZETA4 = , F9.4, 2X, 4HE3 =

1F9.4, 2X, 7HAND E4 = , F9.4, 2X, 4HT3 = , G9.4, 2X, 4HT4 = , G9.4, /)

GO TO 49

C
AE32 = C3 - SQRT(C1 - 1. + C3*C3)
E32 = B*AE32*AE32
E42 = E1 + Q - E32
IF(E42.LT.0.0)GO TO 5
XN = SQRT(M3*E32/(M4*E42))*SIN(RPSI)
IF(ABS(XN).GE.1.)GO TO 40
RZETA2 = ARSIN(XN)
ZETA42 = RZETA2*57.2957
P32 = SQRT(2.*M3*E32)
DEL2 = P1 - P32*COS(RPSI)
IF(DEL2.LT.0.)ZETA42 = 180. - ZETA42
T32 = 71.92*SQRT(M3/E32)
T42 = 71.92*SQRT(M4/E42)
WRITE(6,43) PSI, ZETA4, ZETA42, E3, E32, T3, T32, E4, E42, T4, T42
FORMAT(9X,9F4.1,T,5X,36HDEGREES, THE TWO VALUES OF ZETA4 ARE, 2(F9.3, 3X), /, 9X,
THE TWO VALUES OF E3 ARE, 2(F9.3, 3X), /, 9X,
THE TWO VALUES OF T3 ARE, 2(G9.3, 2X), /, 9X,
THE TWO VALUES OF E4 ARE, 2(F9.3, 2X), /, 9X,
THE TWO VALUES OF T4 ARE,2(G9.3,2X),/

IF((M5.EQ.0.0).OR.(M6.EQ.0.0))GO TO 40

WRITE(6,44)E3

FORMAT(10X,19HF0R THE LARGER E3 -,E9.3 ,/)

IF((M5.EQ.0.0).OR.(M6.EQ.0.0))GO TO 40

***********************************************************************

TEST FOR ZETA6 MAXIMUM

IF((M5*Q2/M6/E4)-1.)600,600,62

RZMAX6=ARSIN(SQRT(M5*Q2/M6/E4))

ZMAX6 =-RZMAX6*57.29578

NOMAX6=.TRUE.

WRITE(6,61)ZMAX6

FORMAT(/,10X,28HTHERE IS A MAXIMUM ANGLE OF ,F9.3,2X,9HFOR ZETA6)

TEST =M6*Q2/M5/E4

NOMAX =.TRUE.

TEST FOR ZETA5 MAXIMUM

IF(TEST-1.)70,70,54

RZMAX =ARSIN(SQRT(TEST))
NOMAX = .FALSE.

ZMAX = RZMAX * 57.29578

ROOT3 = .TRUE.

MZMAX = -ZMAX

WRITE(6, 72) MZMAX

72 FORMAT(/, 10X, 28H THERE IS A MAXIMUM ANGLE OF , F9.3, 2X, 9H FOR ZETA5)

LIM4 = ZMAX

***********************************

ZETA5 = -LIM3 + R05

WRITE(6, 50)

50 FORMAT(5X, 120H* THETA5 ***** E5 *** THETA6 ***** E6 ******** T5 ***

*I T6 *** THETR5 ***** ER5 ** THETR6 ***** ER6 ***** TR5 ******** TR6

2 *)

W1 = ZETA4 - 90.

W2 = ZETA4 + 90.

CARDS FOR THETA5, E5, ETC.
RZETA5 = ZETA5 / 57.2957

IF (LIM4 .EQ. ZMAX) ROOT3 = .TRUE.

IF (ZETA5 .LT. 0.0) AND (ABS(ZETA5) .GE. ZMAX) GO TO 60

IF (ZETA5 .GT. ZMAX) GO TO 40

C5 = COS(RZETA5)

AE5 = C5 + SQRT(TEST - 1. + C5 * C5)

E5 = E4 * AE5 * AE5 * M5 / M4

E6 = Q2 + E4 - E5

IF (E6 .LE. 0.0) GO TO 90

XL = SQRT(M5 * E5 / (M6 * E6)) * SIN(RZETA5)

IF (ABS(XL) .GT. 1.) GO TO 94

RZETA6 = 1.5707963 - ARCOS(XL)

ZETA6 = RZETA6 * 57.2957

THETA5 = ZETA4 - ZETA5

IF (THETA5 .GE. 360.) GO TO 60

IF (ROOT3 .OR. NOMAX) XX = XXX

THETA6 = ZETA4 + ZETA6

C ZETA6 ARCSIN CORRECTION
180 IF((NOMAX6).AND.(THETA6.LT.(ZETA4+ZMAX6)))GO TO 94
181 IF((NOMAX6).AND.(THETA6.GT.(ZETA4-ZMAX6)))GO TO 94
182 I = 0
183 IF(NOMAX6)GO TO 575
184 IF(NOMAX)ROOT3 = .TRUE.
185 IF(ROOT3)XXX = THETA6
186 IF((THETA5.GT.ZETA4).AND.(ROOT3).AND.(THETA6.GT.W1).AND.(XX.GT.
187 I.THETA6))I = -10
188 IF((THETA5.LT.ZETA4).AND.(ROOT3).AND.(THETA6.LT.W2).AND.(XX.LT.
189 I.THETA6))I = 10
191 I.THETA6))I = 10
193 I.THETA6))I = -10
194 IF(I.LT.0)THETA6 = 2.*W1-THETA6
195 IF(I.GT.0)THETA6 = 2.*W2-THETA6
196 575 IF(NOMAX)ROOT3 = .FALSE.
197 IF(THETA5.LE.LIM3)GO TO 40
GO BACK FOR ANOTHER PSI

THETA5, THETA6, ZETA5, ZETA6, ARE ALL MEASURED BELOW THE AXIS AND ARE ALL NEGATIVE WITH RESPECT TO PSI

XLR1 = SQRT(M4*E5/M6/Q2)*SIN(RZETA5)

IF(ABS(XLR1).GT.1.)GO TO 94

RTHE5 = ARSIN(XLR1)

ER5 = M6*E4/M4 + 2.*SQRT(M5*M6*E4*Q2/M4/M4)*COS(RTHE5) + M5*Q2/M4

ER6 = E4 + Q2 - ER5

IF(ER6.LT.0.0)GO TO 94

XLR2 = SQRT(M5*Q2/M4/ER5)*SIN(RTHE5)

IF(ABS(XLR2).GT.1.)GO TO 94

RZETR5 = ARSIN(XLR2)

XLR3 = SQRT(M6*Q2/M4/ER6)*SIN(RTHE5)

IF(ABS(XLR3).GT.1.)GO TO 94

RZETR6 = ARSIN(XLR3)

ZETR5 = RZETR5*57.29578

ZETR6 = RZETR6*57.29578

THETR5 = ZETA4 - ZETR5
\[ \theta_6 = \zeta_4 + \zeta_6 \]

If \( I \lt 0 \)
\[ \theta_6 = 2 \cdot w_1 - \theta_6 \]

If \( I \gt 0 \)
\[ \theta_6 = 2 \cdot w_2 - \theta_6 \]

\[ A_3 = -\theta_5 \]

\[ A_4 = -\theta_6 \]

\[ A_5 = -\theta_5 \]

\[ A_6 = -\theta_6 \]

\[ T_5 = 71.92 \cdot \sqrt{\frac{m_5}{e_5}} \]

\[ T_6 = 71.92 \cdot \sqrt{\frac{m_6}{e_6}} \]

\[ T_5 = 71.92 \cdot \sqrt{\frac{m_5}{e_5}} \]

\[ T_6 = 71.92 \cdot \sqrt{\frac{m_6}{e_6}} \]

\[ C \]

If \( \theta_5 \gt 190 \)
Go to 93

Write

\[ A_3, e_5, A_4, e_6, T_5, T_6, A_5, e_5, A_6, e_6, T_5, T_6 \]

Format

If \( \text{Root3} \)
Go to 90

If \( \zeta_5 \) is positive increment with a positive value, \( \Delta_2 \)

If \( \zeta_5 \) is negative, subtract \( \Delta_2 \) each time until \( \zeta_5 \) is
C LESS THAN OR EQUAL TO LIM3

IF(ZETA5.GE.0.0)GO TO 65

ZETA5=ZETA5-DELTA2

C TEST FOR THE CHANGE OF INCREMENT

GO TO 55

IF(ZETA5.GT.0.0)GO TO 40

ZETA5 =LIM3+R05

THETA6=0.

GO TO 55

ZETA5 =ZETA5 + DELTA2

GO TO 55

C**********************************************

IF (.NOT.ROOT2)  GO TO 40

E4 =E42

ZETA4 =ZETA42

WRITE(6,45)E32

FORMAT(10X,20HFOR THE SMALLER E3 -,E9.3)

ROOT2 =.FALSE.
GO TO 49
C
************
IF(.NOT.ROOT3)GO TO 94
AE5 =C5-SQRT(TEST-1.+C5*C5)
E5 =E4*AE5*AE5*M5/M4
E6 =Q2+E4-E5
IF(E6.LE.0.0)GO TO 94
ROOT3=.FALSE.
GO TO 57
CONTINUE
GO TO 7
STOP
END
# END OF FILE


