RICE UNIVERSITY

The Be$^9 + p \rightarrow d + 2\alpha$ Reaction

by

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Abstract

The reaction $\text{Be}^9 + p \rightarrow d + 2\alpha$ has been studied at bombarding energies of 7 and 9 Mev, using the proton beam from the Rice University Tandem Van de Graaff accelerator. Several two-parameter spectra have been taken, recording the kinetic energies of two of the three particles in the final state. In addition, three-parameter data have been taken using a time-of-flight particle identification technique. This affords separation of the various kinematic loci, corresponding to $d-\alpha$, $\alpha-d$, and $\alpha-\alpha$ coincidences. The technique has the added advantage of greatly reducing the background of random coincidences. Strong sequential decay is observed through the ground state and first excited states of $\text{Be}^8$, and through the 2.184 Mev and 4.52 Mev states in $\text{Li}^6$. There is evidence of interference effects similar to those noted by Bronson, et al. $^{3,4}$ in the three alpha decay of $\text{C}^{12}$. 
I. INTRODUCTION

In recent years, the development of solid state particle detectors with high energy resolution, coupled with multi-parameter pulse height analyzers with fast coincidence gating circuits has made possible a wide variety of experiments in nuclear physics. Studies of nuclear reactions involving three particles in the final state are particularly adaptable to these techniques. An experimental determination of the mechanism of these three-body reactions is of fundamental importance when various nuclear models are considered. In particular, were these reactions to proceed sequentially via a pair of two-body disintegrations, then a two-body cluster model of the nucleus would seem appropriate. If however, the reactions proceed via a simultaneous three-body disintegration, then a successful nuclear model would necessarily include three-body and possibly higher order interactions.

In the present work, the reaction $\text{Be}^9 + p \rightarrow d + 2\alpha$ has been studied at bombarding energies of 7.0 Mev and 9.0 Mev using the proton beam from the Rice University 12 Mev Tandem Van de Graaff accelerator. The Rice multiparameter computer-analyzer system\(^1\) was used in the two parameter (1,000 x 1,000 channel) mode to observe the energy spectrum of deuteron-alpha and alpha-alpha coincidences. In addition, three-parameter data have been taken recording the time-of-flight of one of the two coincident particles as well as both energies to afford
the particle identification necessary for a complete
determination of the final state over an entire kinematic
locus.

The object of the work has been three-fold: 1) to
study the mechanism of the three body decay in the case of
three, non-identical charged particles in the final state,
2) to investigate possible states of the intermediate meta-
stable nuclei, particularly the low energy anomaly in Be$_8$
discussed by Beckner, Jones, and Phillips$^2$, and 3) to de-
velop experimental techniques necessary for a workable par-
ticle identification system useful for a wide variety of
charged particles over a large energy range.

The complete specification of a three-particle final
state requires nine scalar variables, i.e., three components
of momentum for each particle. However the conservation of
energy and the conservation of the three components of
momentum can be used to eliminate four scalar variables. Thus
a measurement of the directions of the momentum vectors for
two of the particles (four scalar variables) plus the kinetic
energy of one of them should be sufficient. However, due to
the quadratic dependence of the energy equation, it is neces-
sary to measure both kinetic energies in order to make a com-
pletely unambiguous measurement.

In the case of three identical particles in the final
state, the conservation laws restrict the region where
coincidences may be observed to a calculable locus in the $T_1-T_2$ plane. (See Appendix A.) The distribution of coincidences along this locus provides a sensitive indication of the mechanism of the reaction. If the reaction proceeds via a simultaneous three-particle disintegration, then one would expect the intensity of coincident events to be proportional to the phase space available to the three particles $^6,$ $^7,$ $^8$). If however, the reaction proceeds sequentially via a pair of two-body disintegrations, one would expect to observe peaking in the distribution, corresponding to the formation of metastable states of the intermediate nuclei.

In the case in which the three particles of the final state are not identical, several kinematic loci are observed if the detector cannot distinguish the particle type. In the current study, there are two alpha particles and a deuteron in the final state. Thus three kinematic loci are observed, one corresponding to an alpha particle in detector 1 and a deuteron in detector 2 (referred to as the alpha-D locus), one corresponding to a deuteron in detector 1 and an alpha in detector 2 (D-alpha locus), and one corresponding to detecting the two alpha particles (alpha-alpha locus). These three curves are not always well separated in energy, and thus cannot always be clearly resolved. A complete experiment therefore requires a particle identification system sensitive to quite a wide range of incident particle energies in order to separate the
kinematic loci in the regions of overlap. This separation has been accomplished by utilizing a time-of-flight technique. One solid state detector is placed very near the target, while the other is placed some distance away. The near and far counters then provide start and stop signals for a time to amplitude converter. Three parameter data are then stored on magnetic tape, recording the two energies and the time-of-flight difference. Elementary physics dictates that for non-relativistic particles, the product of a particle's kinetic energy and the square of its time-of-flight is proportional to the particle mass. The three-parameter data \((E_1, E_2, T_1 - T_2)\) are then edited by a digital computer into the form \((E_1, E_2, E_1 T_1^2)\), where the time measured \((T_1 - T_2)\) is corrected to allow for the approximate time-of-flight of the start particle, and for the rise time of the start and stop pulses in the solid state detectors. Energy-energy spectra are then obtained, requiring that particle 1 be a deuteron (or alternatively, an alpha particle). In the case of the D-alpha locus, this provides a complete separation of the kinematic locus. The alpha-D and alpha-alpha loci cannot be separated over the entire kinematic range. However, in general these loci do not exhibit large regions of overlap.

The particle identification technique has one other advantage. Since the accidental coincidences are random in time, they are random in \(ET^2\). Thus the requirement that \(ET^2\)
fall within small limits accomplishes a dramatic reduction in the accidental background. This allows the use of much more intense beams than could otherwise be used.
II. EXPERIMENTAL PROCEDURE—TWO-PARAMETER STUDIES

A. The Scattering Chamber--Two-Parameter Studies

The two parameter experiments utilized a scattering chamber specially constructed at Rice University for investigating reactions with three-body final states\(^3,4\). As shown in figure 1, the chamber employed two counter arms, one which could be moved 360° about a vertical axis keeping the counter in the plane of the beam, and the other which could be moved anywhere on the surface of a sphere centered on the target foil. These counter arms housed commercial, solid-state surface-barrier detectors, together with their respective slit telescope systems. The beam entered the chamber through a telescope consisting of two .0995 inch circular apertures in tantalum discs, one at the entrance port of the chamber, and the other inside the beam tube one foot in front of the first disc. A set of anti-scattering slits completed the slit telescope. The target, positioned in the geometric center of the chamber, could be rotated about a vertical axis.

The beam was collected in a Faraday cup at the back of the chamber, which was used to monitor and integrate the beam current.

The Nuclear Diode solid-state detectors used in the early experiments were 11 Mev thick to protons. The detectors were rated at 20,000 ohm-cm resistivity, 200 volts bias, and had gold, dead layers of 0.3 mg/cm\(^2\) thickness. A slit telescope system
Figure 1. A simplified drawing of the charged-particle angular correlation chamber showing the beam-defining telescope, counter arms 1 and 2, the target holder, and the Faraday cup system with target for determination of energy calibration points using known neutron thresholds.

Legend:
A  Tantalum discs with 0.095" aperture
B  Quartz disc with 3/16" aperture
C  Ledex Rotary Solenoid
D  Counter Holder and telescope
E  Target holder
F  Counter arm 2
G  Faraday cup and neutron threshold system
H  Threshold target positioning rod
I  Neutron threshold target
J  Cold trap
K  Viewing port (covered when not used to read scales)
L  Graduated angular scale
M  Counter arm 1
N  Beam-defining telescope
O  Beam tube of Van de Graaff accelerator
P  Diffusion pump port for Faraday cup system
was used in front of each detector. This consisted of a tantalum slit with a .120 inch circular aperture placed immediately in front of each detector, and another with a .149 inch circular aperture placed one-half inch in front of the first slit. Detector 1 was positioned so that the .120 inch defining slit was three inches from the target center, while the defining slit for detector 2 was two inches from the target center. Thus the detectors subtended solid angles of $1.257 \times 10^{-3}$ str. ($\pm 4\%$) and $2.827 \times 10^{-3}$ str. ($\pm 4\%$) respectively.

The self-supporting $\text{Be}^9$ foil targets were prepared by evaporating beryllium metal under high vacuum onto clean glass slides coated with a commercial detergent (tepol). A tungsten boat was used to heat the beryllium for the evaporation. The foils were then floated off the glass in a warm water bath and deposited on the target holders. Great care was taken to avoid personal contact with the beryllium metal or inhalation of the vapor, due to the poisonous properties of the element. The targets used in the experiments were approximately 100 kev thick to the incident protons. Principal impurities were carbon and oxygen.

B. Electronics—Two-Parameter Studies

Figure 2 is a block diagram of the electronic system used in the two-parameter experiments. The signals from the two solid-state detectors were fed into charge-sensitive
Figure 2. A block diagram of the circuitry used with the Bonner Nuclear Laboratory's 2-parameter computer analyzer system.
preamplifiers (Tennelec model 100), and then were each branched to two separate linear amplifiers (Cosmic 900 and Hamner N-302). The signals from the Cosmic (double delay line clipped) amplifiers were used to drive the Cosmic coincidence circuitry. Two fast coincidence circuits were used, each with a time resolution of approximately 40 nanoseconds. The first produced gating signals corresponding to both "true" coincident events plus random coincident events. For the second coincidence circuit, the signal from one Cosmic amplifier was delayed by 400 nanoseconds. The same discriminator served both coincidence circuits for this signal. The 400 nanosecond delay was sufficient to insure that only random coincident events could trigger this "slave" circuit. These two coincidence circuits were then used to gate the Rice University 1,000 x 1,000 channel computer-analyzer system. In this computer-analyzer system, the delayed outputs of the Hamner amplifiers, gated by either the "true" coincidence signal or the "accidental" coincidence signal, were fed to two analog-to-digital converters. The outputs of these converters, together with a tag bit indicating which gating circuit had triggered the recorded event, were collected in the core storage of the IBM 1401 computer. After 400 such events had been recorded, the data was dumped onto magnetic tape, and the core storage used for the next 400 events, etc.
Each event recorded by the computer thus represented a pair of numbers proportional to the pulse height from each detector at the time a gating pulse was received. By recording both a "true" spectrum (which included both true and random coincident events) and an "accidental" spectrum (which included only random coincidences), the effect of these random events could be subtracted out.

The full resolution of the 1,000 x 1,000 channel analyzer was not needed in these experiments. The advantage of using the device lay in the virtually unlimited flexibility afforded by sorting the data in different ways. For example, the 1,000 x 1,000 channels could be integrated to give a 50 x 50 channel presentation of the spectrum, or a 100 x 100 channel presentation. If desired, any segment of the spectrum could be examined up to the full resolution of the device. The accidental spectrum could be subtracted automatically, or could itself be separately analyzed.

A second advantage of the computer-analyzer system lay in an auxiliary scaler incorporated into its circuitry which was automatically deactivated during analyzer dead-time. The output of this scaler was also recorded on magnetic tape at the end of each spectrum, and was found most convenient in making cross-section measurements. This was accomplished by the following method: The scaler was used to scale the output of a single-channel analyzer on the linear amplifier associated
with detector 2 (detector 2 was at the greater angle to the incident beam in all spectra taken). This single-channel analyzer was set around the peak corresponding to protons elastically scattered from Be\(^9\). Cross sections could then be determined by comparison to the well known elastic scattering cross sections\(^5\).

A two-dimensional storage oscilloscope was used to monitor the incoming spectra, and scalers recorded the number of true and accidental gating signals. In addition, the computer was programmed to give a 25 x 25 coarse sort of the true spectrum with each dump of 400 coincident events. The Faraday cup on the chamber was used to monitor beam current, and the beam current could be integrated if desired.

C. Calibration and Normalization—Two-Parameter Studies

Since small resolving time in the coincidence circuitry was desired, it was necessary to be most careful in the coincidence calibration. Both the true and accidental coincidence circuits were carefully synchronized using the output signals of a 60 c.p.s. pulser which had been adjusted to give pulses of the same height, rise time, and decay time as those expected from the detectors. After this rough calibration, the final synchronization was accomplished by scattering 7 Mev protons from a thin hydrogenous target (polyethylene), placing the detectors at 90° to one another, and varying the delay electronically so as to maximize the number of observed p-p
coincidences for a constant amount of beam current integrated. A series of these delay curves were taken, moving the detectors about the vertical axis, but maintaining their $90^\circ$ separation, so that the efficiency of coincidence detection could be maximized over the entire range of particle energy expected in the experiment. Using this technique, coincidence detection efficiency of essentially 100% was obtained for particles in the energy range of interest.

The overall circuit linearity was checked using the 60 c.p.s. pulser mentioned above. The system was found to be linear to better than 1% for all pulses which registered below channel 750 in the computer-analyzer. The analyzer was observed to have a slight "roll-off" above channel 750, which caused it to be about 2.5% off at full scale. For this reason, the amplifier gains were adjusted such that no counts fell above channel 750 in the computer-analyzer system. This insured an overall circuit linearity of better than 1%.

The pulse height to energy relationships were obtained by taking angular distributions of the free spectra from each detector. To avoid any unwanted gain shifts, the same arrangement of electronic components was used, and the computer-analyzer was programmed for a dual 1,000 channel configuration, rather than the two parameter configuration. Only the coincidence requirement was relaxed.
The detector dead layers, though only about 0.3 mg/cm², were found to contribute noticeable energy shifts for the low-energy deuterons and alpha particles. These energy shifts were therefore taken into account in calculating the three-body loci. (See Appendix B for details of this correction.)
III. EXPERIMENTAL PROCEDURE--THREE-PARAMETER STUDIES

A. Scattering Chamber--Three Parameter Studies

The scattering chamber used in the three-parameter studies is shown schematically in figures 3 and 4. The chamber consisted of a brass cylinder of seven inches inside diameter and 3-1/4 inches in height. Ports were provided for the beam entrance and for fixed detectors at 90° and 30° to the incident beam. The beam was collected in a Faraday cup at the rear of the chamber. A quartz which could be inserted in the Faraday cup facilitated chamber alignment. The lid of the chamber housed two movable counter arms. A small pin in the chamber wall fitted into a hole drilled in the lid, assuring proper orientation of the lid. The beam collimating system consisted of two tantalum slits with 1.6 mm diameter circular apertures placed 18.4 cm apart. Gold anti-scattering slits with 6.4 mm circular apertures were placed between these beam defining slits to complete the collimating system.

One of the movable counter arms was used to hold a solid state surface barrier detector whose sensitive surface was 5.7 cm from the target center. This detector, which had resistivity of 3,000 ohm-cm and was operated at 900 volts bias, provided the start pulse for the time-to-amplitude converter. The stop pulse was provided by a second counter mounted in a one-inch diameter brass tube which could be attached to either the 30° or the 90° port. The active surface of this detector was
Figure 3. Schematic view of the chamber used in the three-parameter studies.

A. Beam collimator.
B. Insulated base supporting target.
C1 and C2. Detector mounts.
D and E. Scales for setting the angular orientation of the detectors.
K, F, and Q. Faraday cup and quartz assembly.
L. Beam tube fitting.
Figure 4. Schematic drawing of chamber arrangement (three-parameter studies), showing near and far counters.
a distance of 64 cm from the target center. The stop detector (subsequently referred to as detector 1) was a silicone surface barrier detector of 6,300 ohm-cm resistivity, and was operated at 400 volts bias. Each detector was provided with an appropriate tantalum slit telescope system. For detector 2 (near detector), this consisted of a defining slit of 3/32 inch circular aperture, placed 2 inches from the target center, and a 7/64 inch circular aperture anti-scattering slit placed 1 inch in front of the defining slit. For detector 1 (far detector), the slit telescope consisted of a 3/8 inch circular aperture placed immediately in front of the detector surface, and an antiscattering slit of 1/8 inch circular aperture placed 3-1/2 inches from the target center.

The target was insulated from ground, and was held at 500 volts positive bias in order to keep electrons knocked out of the target from reaching the detectors.

Self-supporting Be$^9$ targets of approximately 100 kev thickness were prepared in the same manner as for the earlier experiments.

B. Electronics—Three-Parameter Studies

Figure 5 is a block diagram of the electronic configuration used in the three-parameter studies. The chief difficulty in this type of experiment is obtaining fast timing signals from the solid state detectors. The current pulses from the solid state detectors are too small to trigger a fast time
Figure 5. Block diagram of the electronic circuits—three-parameter studies.
pickoff unit directly for incident particle energies below about 3 Mev. An attempt was made to use a double delay line clipped amplifier following the charge-sensitive preamplifier, using a transition trigger for the timing signal, but this proved to have inadequate time resolution. This difficulty was overcome by inserting the time pickoff pulse transformer in series with the cathode of the third cascode amplifier stage in the Tennelec Model 100 charge sensitive preamplifier. In this position the signals are of sufficient amplitude to trigger the time pickoff units for incident particles of a few hundred kev energy. Further, the timing signal is obtained before the stretching and pulse shaping circuits in the preamplifier, and between (rather than inside) the feedback loops. The inductance of the time pickoff transformer is sufficiently small to have no measurable effect on the output pulses of the preamplifier.

Careful attention was also paid to the choice of detectors for the experiment. These were high field detectors, in order to minimize the charge collection time of the detector. In addition, the RC constant of the detectors were as small as possible, to minimize the pulse rise time. (See Appendix C.)

The time pickoff units used were Ortec Model 260. These provided timing pulses of -0.5 volts with a rise time of less than 2 nanoseconds and a width of 10 nanoseconds. These signals were fed into EGG Model TR 104 fast trigger
modules in order to present the time-to-amplitude converter with essentially square-wave inputs of -0.7 volts, 40 nano-
seconds width. The EGG Model TH200 time-to-amplitude con-
verter was used in these experiments, and was operated on
the 0 to 300 nanosecond scale. The stop pulse was delayed by
100 nanoseconds so that all pulses of interest from the con-
verter would lie in the upper two-thirds of its range. This
constant delay was subtracted from each measured time-of-flight
by the ET\textsuperscript{2} edit program. This program is described in detail
in the next section.

The signals from the two Tennelec Model 100 preamplifiers
and from the time-to-amplitude converter were fed to three
Cosmic Model 900 linear amplifiers. Appropriate delays were
inserted to guarantee that these signals arrived in coinci-
dence. The prompt outputs of these amplifiers were then placed
in slow coincidence (1 microsecond) in a Cosmic Model 900
coincidence circuit. This served several purposes. First it
provided a gating signal for the computer-analyzer system.
In addition it enabled free spectra from each detector to be
taken merely by changing the analyzer program from the multi-
parameter capture program to a 2 x 1,000 channel program, and
relaxing the gating coincidence requirements. In addition, it
served to greatly reduce accidental events which might
result from noise in the fast time pickoff circuits. Last,
a single channel analyzer on the E\textsubscript{2} coincidence circuit was
set about the peak corresponding to protons elastically scattered from Be$^9$, and was used to drive a scaler, facilitating cross-section calculations.

The delayed outputs of the three Cosmic amplifiers were then used to drive the three-parameter analyzer.

C. Calibration and Data Reduction

Since the data were stored in a three dimensional form with $10^9$ possible storage locations, extreme care in measuring all calibrations, particularly with regard to the timing axis, was essential. Free spectra from each detector were taken, relaxing only the coincidence requirement and changing the analyzer program, to provide accurate energy calibration. Detector dead layer corrections were made to the calculated kinematics curves as in the two-parameter experiments. (See Appendix B.) The slope of the time channel was obtained by feeding the same pulse to both the start and stop inputs to the time-to-amplitude converter through known delays. This also provided an accurate linearity check. In addition, the linearity of the two energy axes was checked using a 60 c.p.s. pulser. All these circuits were found to be linear to better than 1% over the full range of the experiment.

An absolute calibration of the time channel was obtained by scattering protons from a thin deuterated polyethylene target. This reaction produces knocked out deuterons at 30° which are coincident with elastically scattered protons at
90°. Since 30° and 90° are the positions of the ports available for detector 1 (far detector), it was possible to obtain both d-p and p-d coincidences. A series of calibration curves were then made, varying the proton bombarding energy in 1 Mev steps from 2 Mev to 10 Mev. The two counters were then physically reversed (the 30° counter placed at 90° and vice versa), and the measurements repeated, with the same electronic configuration. The calculated time-of-flight difference was then plotted against the measured time-of-flight difference. A typical result is shown in figure 6a. The result is not one straight line, but two, with slightly different slopes. The cause of this phenomenon is the non-zero rise time of the pulse in the detector. This is to a very good approximation, just the RC time constant of the detector itself. (See Appendix C.) Since a fixed voltage discrimination level is set to obtain a timing trigger pulse, a time displacement will be observed which is, to a very good approximation, inversely proportional to the energy of the incident particle. This effect is illustrated in figure 7. Figure 6b shows the same data as figure 6a after this correction has been made for each detector. The result is a single straight line of the proper slope. If these corrected data are then represented in a graph of calculated time-of-flight difference vs. measured channel number for the coincidences and the result extrapolated to the T = 0 axis, the intercept gives a
Figure 6. Two-body calibration data for time-of-flight measurements. Figure 6A (upper graph) shows calculated time-of-flight vs. measured time-of-flight for p-d and d-p coincidences, without correcting for the pulse rise time in the detectors. Figure 6B (lower graph) shows the same data with the rise time correction.
Calculated T.O.F. (nanosec)

no rise time correction

1 nanosec = 0.88 channel

○ p

● d

Calculated T.O.F. (nanosec)

with rise time correction

○ p

● d

\[ \tau_{c_1} = 24 \text{ ns} \]

\[ \tau_{c_2} = 14 \text{ ns} \]

discriminators:

\[ E_1 = 300 \text{ keV} \]

\[ E_2 = 300 \text{ keV} \]
Figure 7. Schematic drawing showing three-parameter detector arrangement and pulse rise time corrections.
Detector Rise Time Correction

\[ E_d = \left( \frac{E}{\tau_c} \right) \tau \]
\[ \tau = \frac{\tau_c E_d}{E} \]

\( \tau \) = Time to Rise to \( E_d \)
\( \tau_c \) = Rise Time of Detector

\[ T_1 = \text{TOF}_1 + \frac{\tau_c E_{d1}}{E_1} \quad T_2 = \text{TOF}_2 + \frac{\tau_c E_{d2}}{E_2} \]

\( T_{\text{measured}} = T_1 - T_2 \)

\[ \text{TOF}_1 = T_{\text{measured}} + 4.1 \left( \frac{m_2}{E_2} \right)^{1/2} + \frac{\tau_c E_{d2}}{E_2} - \frac{\tau_c E_{d1}}{E_1} \]
very accurate measurement of the total electronic delay in the circuit. This delay (specified as a channel number) is then subtracted from each measured $T$ in the experiment.

The quantity that must be measured in the particle identification scheme is the product of the particle's energy and the square of its time of flight ($E_T^2$). However, the time measured is not $T_1$, but $T_1 - T_2$, where $T_2$ is the time of flight of the start particle. Since we do not know the mass of the start particle, its time of flight cannot be calculated.

For a fast particle in detector 2 and a slow particle in detector 1, one may, to a very good approximation, neglect $T_2$ in comparison to $T_1$. However, for a low energy start particle, this is not a good approximation. It is possible to make a much better approximation, however, since the energy of the start particle has been measured, and since the time-of-flight varies inversely as the square-root of kinetic energy. Further, for the reaction under study, it is known that the start particle is either a deuteron or an alpha particle. If the start particle is assumed to be an alpha particle, this assumption should be right approximately $2/3$ of the time, since two of the three particles in the final state are alpha particles. If, however, the start particle were not an alpha, but a deuteron, then the time of flight calculated for the start particle would be too large by a factor of $(4/2)^{1/2} = 1.414$. If this time were added to the measured
time \((T_1 - T_2)\) this value would also be larger than the actual time-of-flight, and thus the calculated value of \(E_{1T1}^2\) would be too large. However, if the start particle were a deuteron, then the stop particle was of necessity an alpha particle. Thus the calculated value of \(E_{1T1}^2\) for this alpha was incorrect in the direction of a greater separation of alphas from deuterons, and the wrong mass assumption has actually helped, rather than hindered the separation.

The three-parameter data were taken in the form 
\((E_1, E_2, T)\), where 
\[ T = TOF_1 - TOF_2 + 1^2 + T_0 \]
where 1 and 2 are the times for the pulses to rise to the time pickoff discrimination level, and \(T_0\) is the inserted electronic delay. These pulses were converted to three-digit numbers by analog-to-digital converters in the computer-analyzer system, and then stored in the computer core storage. After 200 such events had been recorded, the data were dumped onto magnetic tape, and the core storage cleared for the next 200 events.

A program was then written which converted the three-parameter data in this form to three-parameter data in the form:
\[
\frac{E_1\left[T - T_0 + C_1/\sqrt{E_2} - C_2/E_1 + C_3/E_2\right]^2}{N}
\]
where \(C_1\) corrects for the time-of-flight of the start particle, \(C_2\) and \(C_3\) correct for detector rise times, and \(N\) is a normalization constant. This function is then a very close
approximation to the mass invariant quantity $E_1 T_1^2$.

A second program was then used to edit these data into a two-parameter format with limits on the third parameter. The general data reduction technique was as follows: First the raw three-parameter data were edited into three-parameter data in the above format. Second, a two dimensional print out of $E_1 T_1^2$ vs. $E_1$ was obtained, using the three-parameter to two-parameter edit program, with no limits on $E_2$. A typical such print out is shown in figure 8, and the projection of this along the $E_1 T_1^2$ axis is shown in figure 9. Here it is clearly seen that bands of counts occur corresponding to deuterons and alphas from the three-body reaction. In addition, low energy protons are observed from the four-body reaction $^{9}$Be + p → p + n + 2α. The appropriate limits on the $ET^2$ parameter to extract the deuteron and alpha spectra could then be easily chosen. The three to two-parameter edit program was then used again to extract the energy-energy spectra, requiring first that particle 1 be a deuteron, and then that particle 1 be an alpha particle. The calculated kinematics curves were then plotted on the spectra, and the intensities examined.
Figure 8. A typical spectrum of $E_{1T_1}^2$ vs. $E_1$.

Note bands of intensity corresponding to protons, deuterons, and alpha particles.
Figure 9. Projection of the data of figure 8 along the $E_{1T_{1}}^{2}$ axis.
IV. RESULTS AND CONCLUSIONS

Figures 10 and 11 are a representative sampling of the two-parameter data obtained in the early experiments. The figures show a rough contour map of the reaction yield in the $T_1$-$T_2$ plane, with the different plotting symbols representing different intensities of events. These yields are proportional to a product of the differential cross section of the form $\frac{d^4\sigma}{dT_1dT_2d\Omega_1d\Omega_2}$ times a "volume" element $\Delta T_1 \Delta T_2 \Delta \Omega_1 \Delta \Omega_2$.

Unfortunately, the kinematic loci for the 20°-100° spectrum (figure 10) are so completely intertwined that very little information can be obtained with regard to the reaction mechanism. The situation is much better in the 20°-74° spectrum so far as separating the kinematic loci is concerned. However, the internal energies available to the particles at this pair of angles does not include the ground state of Be$^8$, which we expect to be one of the principal channels for the reaction. (This expectation was substantiated by the later, three parameter experiments.)

Thus it is evident that a particle identification system is essential to a thorough study of the reaction mechanism. Figures 12 through 17 present data obtained using the ET$^2$ particle identification system. In addition to the contour map of the yield, the integrated yield is plotted as a histogram below each figure. Peaking due to the various sequential reaction channels is indicated on each histogram.
Figure 10. Two parameter data, $\theta_1 = 20^\circ$, $\theta_2 = 100^\circ$, $E_p = 7$ Mev.
$E_p = 7 \text{ MeV}$

$\theta_1 = 20^\circ$  $\theta_2 = 100^\circ$
Figure 11. Two parameter data, $\theta_1 = 20^\circ$, $\theta_2 = 74^\circ$, $E_p = 7$ Mev.
\[ \theta_1 = 20^\circ \quad \theta_2 = 74^\circ \]

\[ E_p = 7 \text{ MeV} \]
Figure 12. Three parameter data, $\theta_1 = 30^\circ$, $\theta_2 = 120^\circ$, $E_p = 9$ Mev, using ET technique requiring that particle 1 be a deuteron.
$\theta_1 = 30^\circ \quad \theta_2 = 120^\circ$

$E_p = 9.0 \text{ MeV}$

$D - \alpha$ projection

$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE}$ (arb. units)

- $\times \quad 2 - 5$
- $\circ \quad 6 - 9$
- $\bullet \quad \geq 10$

$E_1$ (MeV)

$E_2$ (MeV)

$\text{Li}^6 \quad 2.184 \text{ MeV}$  
$\text{Be}^8 \quad 2.9 \text{ MeV}$  
$\text{Li}^6 \quad 4.52 \text{ MeV}$
Figure 13. Same spectrum as figure 12, but requiring that particle 1 be an alpha particle.
\[ \theta_1 = 30^\circ \quad \theta_2 = 120^\circ \]

\[ E_p = 9.0 \text{ MeV} \]

Shading indicates region in which \(\alpha\)-D and \(\alpha\)-\(\alpha\) loci cannot be resolved.
Figure 14. Three-parameter data, particle 1 a deuteron, $\theta_1 = 30^\circ$, $\theta_2 = 90^\circ$, $E_p = 9$ Mev.
$d^3 \sigma / d\Omega_1 d\Omega_2 dE_1$

$E_2$ (MeV)

$E_1$ (MeV)

$\theta_1 = 30^\circ$  $\theta_2 = 90^\circ$

$E_p = 9$ MeV

$X$ 3 - 5
$O$ 6 - 14
$\bullet$ $> 15$

$D-\alpha$ projection

$Li^6$ 2.184 MeV
$Be^8$ 2.9 MeV

$D-\alpha$
Figure 15. Same spectrum as figure 14, but requiring that particle 1 be an alpha particle.
$\theta_1 = 30^\circ$, $\theta_2 = 90^\circ$

$E_p = 9$ MeV

$E_1$ (MeV)

$E_1$ (MeV)

$\alpha - \alpha$ projection

$\alpha - D$ projection

$\alpha - D$ projection

$\alpha - D$ projection
Figure 16. Three-parameter data, particle 1 a deuteron, $\theta_1 = 30^\circ$, $\theta_2 = 100^\circ$, $E_p = 9$ Mev.
$D - \alpha$ projection

$E_1$ (MeV)

$E_2$ (MeV)

$\theta_1 = 30^\circ$, $\theta_2 = 100^\circ$

$E_p = 9$ MeV
Figure 17. Same spectrum as figure 16, but requiring that particle 1 be an alpha particle.
\[ \theta_1 = 30^\circ, \theta_2 = 100^\circ \]
\[ E_p = 9 \text{ MeV} \]

Shading indicates region in which Q-D and Q-\( \alpha \) lid cannot be resolved.
Figure 12 shows the energy-energy spectrum using the ET^2 parameter to require that particle 1 (the particle in detector 1) be a deuteron, for \( \theta_1 = 30^\circ, \theta_2 = 90^\circ, E_p = 9 \text{ MeV} \). The spectrum is remarkably clean, and exhibits strong peaking due to the Li^6 \( 2.184 \text{ MeV} \) state. Weaker peaking is observed due to the \( 2.9 \text{ MeV} \) broad state in Be^8, and to the Li^6 \( 4.52 \text{ MeV} \) state.

Figure 13 is the same data, but edited requiring that particle 1 be an alpha particle. Here two kinematic loci are seen, one corresponding to the \( \alpha-d \) curve, the other the \( \alpha-\alpha \) curve. On the \( \alpha-d \) locus it is kinematically possible to reach the ground state of Be^8 in two different locations, and intense peaking is observed for both. In addition, the broad peaking due to the \( 2.9 \text{ MeV} \) first excited state in Be^8 is observed. There is also an intense peak in the spectrum just at the point at which the \( \alpha-d \) and \( \alpha-\alpha \) loci cross. The area where the curves cannot be individually resolved is indicated by cross-hatching in the figure. This peaking can be unambiguously identified as due to the \( 2.184 \text{ MeV} \) state in Li^6 however, since it corresponds to this excitation energy on both loci. This is expected, since one locus corresponds to detecting the first emitted alpha in detector 1, while the other corresponds to detecting the second emitted alpha. On the \( \alpha-\alpha \) loci, the only strong peaking corresponds to the Li^6 \( 2.184 \text{ MeV} \) state, which occurs in three
different locations.

Figure 14 shows the deuteron spectrum for $\theta_1 = 30^\circ$, $\theta_2 = 90^\circ$ and $E_p = 9$ Mev. Again, strong peaking is seen due to the Be\textsuperscript{8} 2\textsuperscript{+} state at 2.9 Mev. Also strong sharp peaking is evident from the 2.184 Mev state in Li\textsuperscript{6}. The alpha spectrum from this same data point is shown in figure 15. In this case, the two alpha loci do not cross, so that all three kinematics curves can be separately resolved. The $\alpha$-d spectrum exhibits essentially the same peaking as the d-$\alpha$ spectrum of figure 14. The $\alpha$-$\alpha$ spectrum shows additional peaking due to the Li\textsuperscript{6} 4.52 Mev state.

Figures 16 and 17 show the data obtained at $\theta_1 = 30^\circ$, $\theta_2 = 100^\circ$, $E_p = 9$ Mev. This is the most interesting spectrum for several reasons, and it is thus unfortunate that it has the poorest statistics. However this measurement will soon be repeated for a longer time and with greater beam intensity in order to obtain better statistics. The $\alpha$-$\alpha$ curve yields the most interesting data. Here it is kinematically possible to reach high excitation states in Li\textsuperscript{6}. A broad but weak peaking is observed which can be attributed to the broad state at 5.5 Mev in Li\textsuperscript{6}. In addition, the 4.52 Mev state in Li\textsuperscript{6} should occur in two different places separated by less than 1 Mev. Instead of a peak being observed at these positions, we see a valley, with a small peak in between. This small peak corresponds to no known state in either Be\textsuperscript{8}.
or Li$^6$. The statistics are too poor to justify a really firm conclusion about this effect, but it appears similar to the interference effects observed by Bronson, et al.\textsuperscript{3,4} in the three-alpha decay of C$^{12}$. In these experiments Bronson and group observed both constructive and destructive interference effects in the observed yield.

As an added point of interest, the deuteron spectrum (figure 16) exhibits two expected reaction channels which lie at very nearly the same point on the kinematic locus. These are the Be$^8$ 2.90 Mev state and the Li$^6$ 4.52 Mev state. Both these states are $2^+$, $T = 0$ states. It would then seem appropriate to make a series of measurements at this combination of angles, varying the bombarding energy, to observe any change in these interference effects.

The results to date with the three-parameter method are encouraging. The time-of-flight particle identification system seems effective both in identifying the particles under study, and in eliminating accidental background. The technique will probably have many applications for studying weak effects in the presence of intense background over a wide range of energies. In addition, it will be applicable to many problems in which three or more charged particles in the final state are observed. Already the technique has been used at Rice to study the Li$^6 + d$ reaction, in which no less than eleven three-body loci are observed corresponding to
the various coincidence permutations of the three different three-body final states. \((\text{He}^3-n)(\text{p-t})(\text{d-d})\)

Additional work on the \(\text{Be}^9 + \text{p}\) reaction is desirable, particularly to gain more information on the observed interference effects. No evidence has so far been found to explain the low energy anomaly noted by Beckner, Jones, and Phillips in \(\text{Be}^8\). However this is expected to be a weak effect, and the statistics of our measurements so far have not been sufficiently good to reach any definite conclusion on this point. In addition it may be interesting to use these (or similar) techniques to study the four-body reaction \(\text{Be}^9 + \text{p} \rightarrow \text{p} + \text{n} + 2\alpha\).

It has been shown that the \(\text{Be}^9 + \text{p} \rightarrow \text{d} + 2\alpha\) reaction is predominantly a sequential two-body reaction through states in \(\text{Be}^8\) and \(\text{Li}^6\). There is also evidence of interference effects which may contribute in an unknown fashion to the reaction yield and to the observed widths of states. In addition, a new time-of-flight particle identification system has been developed and tested, adding to the available technology for studying reactions of this type.
APPENDIX A

Three-Body Kinematics*

A. General Kinematic Relations.

It is desired to calculate the loci of all possible values of $T_2$ (the kinetic energy of the particle in detector 2 at angles $\theta_2, \phi_2$ to the incident beam) as a function of $T_1$ (the kinetic energy of the particle in detector 1 at angles $\theta_1, \phi_1$). The momentum and energy conservation requirements may be written as follows:

\[ P_e^0 = \sum_{i=1}^{3} P_i^0 \cos \theta_i \cos \phi_i \]  
\[ 0 = \sum_{i=1}^{3} P_i^0 \sin \theta_i \sin \phi_i \]  
\[ 0 = \sum_{i=1}^{3} P_i^0 \sin \theta_i \cos \phi_i \]  
\[ \frac{P_e^2}{2m_0^2} + Q = \frac{1}{2} \sum_{i=1}^{3} \frac{P_i^2}{m_i^2} \]  

where the $i$ subscripts refer to the three particles in the final state, and the zero subscripts refer to the bombarding

*The author is grateful to Dr. W. Dwain Simpson for this concise derivation of the kinematic relations.
particle. $\phi_3$ can be eliminated using equations (2) and (3) yielding:

$$P_3^2 \sin^2 \theta_3 = \left[ P_1 \sin \theta_1 \sin \phi_1 + P_2 \sin \theta_2 \sin \phi_2 \right]^2$$

$$+ \left[ P_1 \sin \theta_1 \cos \phi_1 + P_2 \sin \theta_2 \cos \phi_2 \right]^2 .$$

Combining equations (5) and (1) and substituting the result into (4) yields the result:

$$P_2^2 \left[ \frac{1}{2m_2} + \frac{1}{2m_3} \right]$$

$$+ \frac{P_2}{m_3} \left[ P_1 \cos \theta_1 \cos \theta_2 + P_1 \sin \theta_1 \sin \theta_2 \cos (\phi_1 - \phi_2) \right]$$

$$+ \frac{P_2}{m_3} \left[ -P_0 \cos \theta_2 \right]$$

$$+ \left[ P_1^2 \left( \frac{1}{2m_1} + \frac{1}{2m_3} \right) + P_0^2 \left( \frac{1}{2m_3} - \frac{1}{2m_0} \right) - \frac{1}{m_3} P_0 P_1 \cos \theta_1 \right] = Q$$

We may now calculate $P_2$ as a function of $P_1$ for fixed angles $\theta_1, \theta_2, \phi_1, \phi_2$:

$$P_2 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$
where

\[ A = \left[ \frac{1}{2m_3} + \frac{1}{2m_2} \right] \]

\[ B = \frac{1}{m_3} \left[ p_1 \cos \theta_1 \cos \theta_2 + p_1 \sin \theta_1 \sin \theta_2 \cos (\phi_1 - \phi_2) - p_2 \cos \theta_2 \right] \]

\[ C = \left[ p_o^2 \left( \frac{1}{2m_3} - \frac{1}{2m_0} \right) + p_1^2 \left( \frac{1}{2m_1} + \frac{1}{2m_3} \right) \right. \]

\[ \left. - \frac{1}{m_3} p_0 p_1 \cos \theta_1 - Q \right] \]

Thus the solution is double valued, and solutions will be referred to as \( P^+ \) and \( P^- \), corresponding to the two branches of the quadratic.

B. Kinematics for Sequential Decay.

The general kinematic relations above are, of course, valid irrespective of the mechanism of the reaction. However, it is possible to derive the internal energies of the various 2-particle systems in the case the reaction proceeds via a pair of two-body disintegrations.

Consider the reaction proceeding in two steps:
a) \[ A + B \rightarrow i + (j,k) \]

b) \[ i + (j,k) \rightarrow i + j + k \]

where we may allow any possible permutation of the indices \( i, j, \) and \( k \). Applying the conservation of momentum and the conservation of energy we obtain:

\[
T_0 + Q = T_i + T_{jk} + E_{jk} \tag{1}
\]

\[
P_0 = P_i \cos \Theta_i + P_{jk} \cos \Theta_{jk} \tag{2}
\]

\[
0 = P_i \sin \Theta_i \sin \Theta_i + P_{jk} \sin \Theta_{jk} \sin \Theta_{jk} \tag{3}
\]

\[
0 = P_i \sin \Theta_i \cos \Theta_i + P_{jk} \sin \Theta_{jk} \cos \Theta_{jk} \tag{4}
\]

where \( T_{jk} \) is the kinetic energy of the cluster \((jk)\) and \( E_{jk} \) is its internal energy. Since the 2-body kinematics restricts the first breakup to a plane,

\[
\Phi_i = \Phi_{jk} + \pi
\]

Using this relation, both \( \Phi_i \) and \( \Phi_{jk} \) may be eliminated between equations (3) and (4):

\[
P_{jk}^2 \sin^2 \Theta_{jk} = P_i^2 \sin^2 \Theta_i
\]
We may also eliminate \( \Theta \) using (2) and (3):

\[
P_{jk}^2 = P_j^2 \sin^2 \Theta_j + (P_0^2 - P_j \cos \Theta_j)^2
\]

\[
E_{jk}^2 = P_j^2 + P_i^2 - 2 P_0 P_i \cos \Theta_i
\]

Thus

\[
T_{jk} = \frac{1}{2 m_{jk}} \left( P_j^2 + P_i^2 - 2 P_0 P_i \cos \Theta_i \right)
\]

and, using equation (1) we obtain the result:

\[
E_{jk} = T_0 + Q - T_j - \frac{1}{2 m_{jk}} \left( P_j^2 + P_i^2 - 2 P_0 P_i \cos \Theta_i \right)
\]

If particle 1 (the particle in detector 1) is the first emitted particle, then the internal energy in the recoil (23) system is:

\[
E_{23} = T_0 + Q - T_1 - \frac{1}{2 m_{23}} \left( P_0^2 + P_i^2 - 2 P_0 P_i \cos \Theta_i \right)
\]

Thus \( E_{23} \) is a single-valued function of \( T_1 \).

If particle 2 is the first emitted particle, then the energy in the recoil system is:

\[
E_{13} = T_0 + Q - T_2 - \frac{1}{2 m_{13}} \left( P_0^2 + P_i^2 - 2 P_0 P_i \cos \Theta_i \right)
\]
This is a single-valued function of $T_2$, but since $T_2$ is a double-valued function of $T_1$, $E_{13}$ is also a double-valued function. The two solutions for $E_{13}$ as a function of $T_1$ are given by

$$E_{13}^\pm = T_0 + Q + T_2^\pm - \frac{1}{2m_3} \left( p_0^2 + (p_2^\pm)^2 - 2p_0p_2^\pm \cos \theta_2 \right)$$

Similarly, if particle 3 is the first emitted particle, the internal energy in the recoil system ($E_{12}$) is a double-valued function of $T_1$, and is given by:

$$E_{12}^\pm = T_0 + Q + \frac{p_0^2}{2m_3} + \frac{p_0}{m_3} \left( p_1 \cos \theta_1 + p_2^\pm \cos \theta_2 \right)$$

$$- \frac{1}{2} \left( \frac{1}{m_1} + \frac{1}{m_2} \right) \left\{ p_1^2 + (p_2^\pm)^2 + 2p_1p_2^\pm [\cos \theta_1 \cos \theta_2 + \sin \theta_1 \sin \theta_2 \cos (\theta_1 - \theta_2)] \right\}$$
APPENDIX B

Detector Dead Layer Corrections

Each of the detectors used in these experiments was a silicone surface-barrier detector with a front surface of gold approximately 0.3 mg/cm$^2$ thick. For protons in the energy range of a few Mev, the energy loss in this dead layer is quite small. However for deuterons and alpha particles, the energy loss is clearly observable, and it was necessary to correct the calculated kinematic loci for this energy loss in order to obtain good fits to the data. These corrections were made, using a recently published table of the energy loss for protons in gold$^9)$. The corrections for deuterons and alpha particles were then made, using the relations:

$$\frac{dE}{dx} \left(\text{deuteron}\right) \bigg|_E = \frac{dE}{dx} \left(\text{proton}\right) \bigg|_{E/2}$$

$$\frac{dE}{dx} \left(\text{alpha}\right) \bigg|_E = 4 \frac{dE}{dx} \left(\text{proton}\right) \bigg|_{E/4}$$

A program to calculate the kinematic loci, taking these corrections into account was then written for the IBM 1401 computer.
APPENDIX C

Detector Rise Time Corrections

The detector rise time corrections which were used in the experiment are shown graphically in figure 7 of the text. The success of the corrections in fitting the elastic p-d and d-p data (figure 6), as well as the three-body data (figures 8 and 9) is quite convincing evidence that the first order correction is adequate for the experiment. A simple argument will be given here to justify the use of the RC constant of the detector as the basis for this correction.

Consider the simplified circuit shown below:

Let \( C_D \) and \( R_D \) be the capacitance and resistance of the detector, and \( C_P \) be the input capacitance of the preamplifier. At time \( t = 0 \), we allow a charge \( Q_{D_0} \) to be deposited on the capacitor \( C_D \). Writing the loop equation we obtain:

\[
\frac{Q_D}{C_D} = \frac{Q_P}{C_P} + R_D \frac{\dot{Q}_P}{C_P}
\]  

(1)
We require that

\[ dQ_D = -dQ_P \]  \hspace{1cm} (2)

Inserting (2) into (1) we obtain:

\[ \frac{dQ_P}{dx} + \frac{Q_P}{R_D} \left( \frac{1}{C_P} + \frac{1}{C_D} \right) = \frac{Q_{D_0}}{R_D C_D} \]  \hspace{1cm} (3)

Since \( C_P \gg C_D \), we may write (3) approximately as

\[ \frac{dQ_P}{dx} + \frac{Q_P}{R_D C_D} \approx \frac{Q_{D_0}}{R_D C_D} \]

which has the simple solution:

\[ Q_P = Q_{D_0} \left[ 1 - e^{-x/R_D C_D} \right] \]

For \( t \ll R_D C_D \)

\[ Q_P \approx \frac{Q_{D_0} \chi}{R_D C_D} \ll \frac{E \chi}{R_D C_D} \]
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