RICE UNIVERSITY

3-Body Breakup of He

by

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The $d(p,2p)n$ reaction has been studied using the recently constructed angular correlation chamber at Rice University. The two protons from the reaction have been observed for incident proton energies of 5.0, 9.0, and 10.5 MeV using the two Rice University Van de Graaff accelerators. Kinematic calculations were made to determine the shape of the curve describing allowed solutions in terms of the energy of one of the detected protons versus that of the other. Observed experimental curves of the same form have been presented along with the calculated excitation energies of the 3 possible intermediate configurations if the reaction were to proceed via sequential 2-body decay. Evidence of sequential 2-body decay to a low excited state of the n-p system is observed at particular angles for 9.0 and 10.5 MeV bombarding energies. Similar decay is not observed at 5.0 MeV, but this effect is likely due to experimental difficulties in observing the appropriate region of the energy curves at this energy. The data at all three bombarding energies and for many angles show evenly populated distributions, indicating for these cases either simultaneous 3-body decay of the $\text{He}^3$ configuration or sequential 2-body decay through quite broad intermediate states.
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I. INTRODUCTION

The forces acting between 3-nucleons are of interest because of their fundamental importance in the investigation of the properties of nuclear interactions. Although these interactions represent one of the simpler cases of the many-body problem, there is no method of exact solution to describe them. In the laboratory, the simplest method of studying these forces is to observe the breakup of a 3-nucleon system, which involves only these 3-nucleon interactions. Of the two 3-nucleon configurations available in nuclear reactions, He$^3$ and H$^3$, the He$^3$ configuration is the easier to study since two of the breakup particles are protons whose energies may be determined more accurately and easily than those of neutrons.

With reactions involving the breakup of a many-particle system, the question arises as to whether the reaction is a simultaneous, many-body breakup or a succession of 2-body breakups. The answer is not always evident since it depends on the time scale as well as the theoretical description of the process.

The breakup of the deuteron by a nucleon is an important method of studying the nuclear three-body forces. The recent development of commercially available multi-parameter analyzers has made it possible to investigate, by coincidence techniques, the energy and angular distributions of two of the particles from the breakup of the
3-nucleon system.

The reaction \( d(p, 2p)n \) has been used in the present investigation of the problem, using proton beams of 5.0, 9.0, and 10.5 MeV from the 2 Rice University Van de Graaff accelerators. The targets used in the study were deuterated polyethylene self-supporting foils of approximately 100 \( \mu g/cm^2 \).

Calculations based simply on the kinematics of the interaction were used to determine the shape of the curve of allowed solutions in terms of the energy of one of the detected particles versus that of the other. The population of the calculated curve will be dependent on the mode of decay, with a continuum distribution to be expected for simultaneous 3-body breakup and some structure if the breakup is by sequential 2-body breakups. However, the distribution may be such that there is little difference to be expected between the simultaneous breakup mode and that of a sequential decay proceeding through broad intermediate states. Differences due to the two different modes of breakup will be discussed primarily from the standpoint of simple kinematics for the reaction as viewed from each mode.
As mentioned in the previous section, we must consider two possible modes of decay for the break-up of the He\(^3\) configuration when this configuration is formed in an excited continuum state by the bombardment of deuterons with protons. The first mode is that of simultaneous 3-body breakup, i.e., the He\(^3\) configuration spontaneously decays into two protons and a neutron. The only kinematic conditions that need be satisfied then are the conservation of energy and momentum between the initial and final states. The initial state is taken to be that of the proton having energy \(T_0\) and momentum \(P_0\) while the deuteron is taken to be at rest. The final state is described by two protons having energies \(T_1\) and \(T_2\) with momenta \(P_1\) and \(P_2\) and a neutron having an energy of \(T_3\) and momentum \(P_3\). If, for the present, we restrict the breakup to a plane, then we may solve for the energies of the two protons in the case of detecting them with two counters in the same plane as the beam. The calculation of the energy of one of the protons as a function of the other has been carried out in Appendix I. The result of these considerations is that there is a closed curve in momentum space of allowed solutions for \(P_1\) and \(P_2\) for a given value of \(P_0\), provided that \(T_0\) is greater than the threshold energy of the \(d(p,2p)n\) reaction. This threshold value, for a \(Q\) value of \(-2.22471\pm0.00040\) MeV, \(^1\) is
3.3371 \pm 0.0006 \text{ MeV.}

Figure 1 shows the result of calculations for bombarding energies of 4.0 to 9.0 MeV for simultaneous emission of protons at angles of 20° and 35°, with the angles measured from the opposite sides of the incident beam direction as discussed in Appendix I. Kinematically, then, all possible combinations of energies which describe these loci are allowable in simultaneous 3-body decay.

The second mode of decay, sequential 2-body decay, has quite different kinematical properties. For this mode we may think of 3 combinations that are possible in the two-stage process. These three cases are discussed in detail in Appendix I and are as follows:

(I) Particle 1 is the "free" nucleon, leaving the short-lived (23) deuteron configuration.

(II) Particle 2 is the "free" nucleon, leaving the short-lived (13) deuteron configuration.

(III) Particle 3 is the "free" nucleon, leaving the (12) di-proton configuration.

In each of these cases, the 2-particle configuration may be left in an excited discrete (or continuum) state which decays very rapidly. The excitation energies corresponding to a given combination of values for T_1 and T_2 are easily calculated as done in Appendix I. It is thus possible to calculate a set of excitation curves E_{23}, E_{13}, and E_{12} corresponding to these three configurations and to plot them, along with T_2, as a function of T_1. Thus if the
Figure 1. Loci of possible combinations of the energies of the two emitted protons, $T_1$ and $T_2$, emitted at angles $\theta_1$ and $\theta_2$, respectively, to the direction of the incident proton. The loci are shown for 1.0 MeV steps of bombarding energy from 4.0 MeV to 9.0 MeV. It will be noted that at 4.0 MeV the entire locus is within the "positive" energy quadrant while for greater energies portions of the curves are cut by the energy axes. The solutions thus eliminated correspond to particles moving away from the detectors along the detector direction and are thus not detected.
breakup proceeds via sequential 2-body decay through particular excitation energies in the intermediate configuration, the population of the 3-body loci similar to those in Figure 1 will be peaked at points corresponding to these excitation energies. Thus the use of such plots could be of great assistance in the determination of the mode of decay of the He\(^3\) configuration, and the excitation energies of the intermediate states may be obtained if the decay occurs via the sequential 2-body mode.

Previous studies of the breakup of a three nucleon system, either H\(^3\) or He\(^3\), have been made using the reactions d(p,np)p and d(n,np)n. The analysis that has been applied is that the reactions occur by inelastic scattering of the incident particle, leaving the deuteron in an excited continuum state which then decays into a free neutron and proton.\(^2\text{-}^8\) The neutron spectra from these reactions have been studied over a range of energies and angles.\(^9\text{-}^{14}\) The proton and neutron spectra from the reaction p(d,np)p have also been investigated.\(^14\text{-}^{16}\)

Theoretical calculations of the neutron spectra have been carried out by several authors.\(^4\text{,}^5\text{,}^6\) The spectra may be described fairly well by including the effect of final state interactions.\(^17\) Frank and Gammel\(^5\) considered the problem from elementary views, using zero-range potentials and the Born approximation. Their results agreed quite well with the neutron data they had at hand, but their theory does not explain the upper peak in
the forward direction of the neutron spectra later seen by experiment. Heckrotte and MacGregor have attributed this peak to the final state interaction of the two protons, which was not considered by Frank and Gammel. The calculations of Heckrotte and MacGregor, however, proved to agree with experimental data at 0° only in the region of this peak in the upper part of the neutron spectrum. Komarov and Popova have extended the consideration of the final state interactions to include the interaction of the two protons with the neutron. Using the results of calculations on the final state interactions between all combinations of the particles in the system, they were able to make quite good fits to the neutron spectra taken at 0° and 180°.

The advantages of using the two parameter method of analysis in the form described in this paper is that for each particle observed in one counter there is a second particle observed in the other counter at the same time, so that both the energy and direction of these particles are known. This uniquely describes the energy and direction of the third particle so that there is no uncertainty about which kinematical process took place to produce the observed peaks, since the excitation energies corresponding to the possible cases are easily calculated and the peak may be traced through several angular settings to determine which is the correct interpretation.
III. EXPERIMENTAL PROCEDURE

The scattering chamber used in this investigation is the recently constructed charged-particle angular correlation chamber built at Rice expressly for the study of reactions involving 3 particles in the final state. Solid state diffused-junction detectors (RCA Victor Co. (Canada), Ltd.) are mounted in the chamber on 2 independent counter arms, which in the rest of this discussion will be referred to as the "F" and "M" counter arms, with counter No. 1 being in the "M" arm and counter No. 2 being in the "F" arm.

The M counter arm is pivoted about a vertical axis and thus can move in a complete 360° arc in the horizontal plane containing the incident proton beam. The F counter is mounted such that, in addition to similar motion in the horizontal plane, it can move out of the plane about an axis normal to the projected counter direction in the horizontal plane and passing through the target spot. Thus the F counter can move to any position on the surface of a sphere.

The proton beam is defined upon entering the chamber by a telescope of two .0995" circular apertures in tantalum discs placed one at the beam entrance port of the chamber and another 1 foot in front of the chamber within the beam tube. The telescope is rigidly fastened to the chamber and thus defines a circular beam spot on a target placed in the center of the chamber and normal to the beam. After
passing through the target, the beam is collected in a Faraday cup at the rear of the chamber and integrated.

The back of the chamber was modified slightly while this investigation was being conducted to allow the insertion of energy calibration targets within the Faraday cup system. With this arrangement, a target could be inserted in the cup system while there was not a target in the chamber to determine a beam energy calibration using neutron thresholds as calibration points. The target could then be placed in the chamber and the neutron thresholds re-run to determine the energy thickness of the target.

Figure 2 shows a simplified drawing of the chamber, telescope, counter arms, and neutron threshold set-up. The solid state detectors are encased in holders provided with a telescope system of tantalum discs with circular apertures to define the solid angle of the detector and eliminate detection of particles scattered from points other than the target spot. A more detailed description of the chamber is given by J. D. Bronson.\textsuperscript{18}

The targets used in this study are thin deuterated polyethylene foils of about 100 $\mu$g/cm$^2$ thickness, with the hydrogen content of the polyethylene ($\text{H}_2\text{C}_2\text{H}_4$) being 98.3% $\text{H}^2$ and 1.7% $\text{H}^1$. The preparation of these foils is described in Appendix II. The use of these foils prevented the use of proton beam currents of more than about 150 nano-amps. The presence of the small percentage of $\text{H}^1$ in the target proved to be very useful in the
Figure 2. A simplified drawing of the charged-particle angular correlation chamber showing the beam-defining telescope, the "F" and "M" counter arms, the target holder, and the Faraday cup system as modified for determining neutron thresholds.

Legend:

A  Tantalum disc with .0995" aperture
B  Quartz disc with 3/16" aperture
C  Ledex Rotary Solenoid
D  Counter holder and telescope
E  Target holder
F ,M "F" and "M" counter arms
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
N  Beam-defining telescope
O  Beam tube of Van de Graaff accelerator
P  Diffusion pump port for Faraday cup system
alignment of the electronic circuitry in that the delay lines of the two counter circuits could be aligned by using the coincident protons resulting from p on p scattering. This alignment procedure is discussed below.

The electronic circuitry is shown in block form in Figure 3. The signals from the detectors are first amplified by charge sensitive, low-noise preamplifiers (Tennelec Model 100A) connected directly to the counter terminals on the chamber. The signal from the second counter goes through a delay box which contains a .4 μsec delay cable in one branch and an attenuator circuit in the other. The attenuator line is matched to the impedance of the delay line so that switching either branch into the circuit does not alter the shape or size of the signal pulse. The preamplifier of the second counter amplifies 8 times that of the first in order to overcome the effect of this attenuation.

The signals are then fed into linear amplifiers (Cosmic Radiation Laboratories Model 901) which double-delay-line clip the signal. The signals from the amplifiers are then fed both to a multiple coincidence circuit (Cosmic Radiation Laboratories Model 801) and to the inputs of a 32 X 32 channel 2-parameter analyzer (Nuclear Data Model ND-150FM), with the analyzer inputs delayed by circuitry in the linear amplifiers to allow the coincidence pulse, which gates the analyzer, to arrive at the analyzer at least as soon as the coincidence pulses arrived.
Figure 3. A block diagram of the electronic circuitry used in taking 2-parameter spectra of the protons from the d(p,2p)n reaction. The flow of information as described in the text is indicated by the arrows.
PROTON BEAM

TARGET

$\theta_1$, $\theta_2$

DET. 1

PREAMP

DELAY BOX

AMP

FAST COINCIDENCE

SLOW COINCIDENCE

32 x 32

2-DIMENSIONAL ANALYZER

DET. 2

PREAMP

AMP
Because of slight incompatibility between the coincidence circuits and the analyzer in timing it was also necessary to include additional delay in the coincidence circuitry to enable the coincidence signal to arrive at the analyzer just before the signal pulses.

The adjustable delays in the coincidence circuit are matched using proton signals from the detectors when placed at an angular separation of 90° in the laboratory, corresponding to the emission angles of the scattered and recoil protons from the p(p,p)p scattering. Delay spectra are taken with this arrangement to set the resolving time as low as possible and still have a plateau of constant counting rate when counting rate is plotted versus one adjustable delay setting while the other is held fixed. Having determined this plateau, the center is chosen as the operating point. A delay curve of this type is shown in Figure 4. The delay curve is checked several times during an experimental run to insure that the delay settings do not drift enough to lose coincident counts.

In addition to the fast coincidence requirements above, the signals also are required to satisfy the slow coincidence requirements of the coincidence circuitry in order to use the window feature to provide an upper-level cut-off on the pulse sizes. This cuts down on wasted analyzer time used to analyze the elastically scattered proton pulses which occur above the pulse-height region of interest, and which may at some angles be detected in
Figure 4. A typical delay curve as described in the text. Coincidence counts are plotted versus the delay setting $D_1$ in circuit 1 (M) for a constant delay setting of $D_2$ in circuit 2 (F). Full scale for $D_1$ or $D_2$ is 100 divisions corresponding to 0.3 microseconds.
$P(P,P)P$

COINCIDENCE COUNTS

$\theta_1 = \theta_2 = 45^\circ$

$D_2$ SETTING = 0

$T_0 = 9.0$ MEV

TARGET NO. 4
Coincidence with the recoil nuclei.

Coincidence spectra were taken in the 2-parameter mode of the analyzer which provides a $32 \times 32$ array of 1024 "boxes" of energy widths $dT_1$ and $dT_2$ where $dT_1$ and $dT_2$ correspond to the pulse widths accepted by the corresponding channels of the two analog-to-digital (ADC) converters employed in the analyzer. Thus a pulse corresponding to an energy of between $T_1$ and $T_1 + dT_1$ in the M counter will fall in channel $N_1$ of the M ADC while a pulse of energy between $T_2$ and $T_2 + dT_2$ will fall in channel $N_2$ of the F ADC. If these two pulses satisfy the coincidence requirements of the coincidence circuitry, then the event will be recorded by storing a count in the "box" of the array having coordinates $(N_1, N_2)$ with $N_2$ being the ordinate. Counts may be stored in all of the 1024 positions of the array except for the position $(1,1)$ which is reserved for the recording of the live-time of the analyzer for the spectrum taken.

It will be noted that even while employing the coincidence techniques in the 2-parameter mode as described above, it is possible for "accidental" counts to be recorded, corresponding to any of the reaction products of any of the reactions observed in Figure 5 being detected in one detector with a similar event occurring in the other detector within the resolving time of the coincidence circuitry. These accidental counts will be of a statistical nature and thus dependent on the intensity and
stability of the beam. There should thus be no difference, outside of statistical fluctuations, in the number of distribution of accidental counts obtained when the pulses from the two detectors are analyzed in coincidence or when one of the signals is delayed by an arbitrary length of time, as long as other conditions remain the same. This then provides a method of determining which of the observed counts on the 2-parameter map correspond to true coincidences and which correspond to accidental counts. Thus to insure that true coincidence spectra were obtained, an accidental spectrum was taken in the 2-parameter mode with the .4 μsec delay line in the F circuit for each coincidence spectrum taken. The pulses in an accidental spectrum are treated exactly the same as are the pulses in a coincidence spectrum, requiring a coincidence pulse from the coincidence circuitry before pulses in the two detectors are analyzed. For analysis, each accidental spectrum was subtracted from the corresponding coincidence spectrum to yield the distribution of the true coincidence events. Spectra of this type will be displayed in the next section.

Single parameter spectra of both F and M detectors were also taken before and after each 2-parameter spectrum so that the condition of the target could be monitored and the pulse heights of the elastic and inelastic peaks used for energy calibration. These single parameter spectra also allowed the monitoring of any gain shifts which might
occur. In these spectra a single ADC is employed, the M ADC for the M circuit, and the F ADC for the F circuit. However, the ADC is gated by the coincidence circuit which is used only to supply a coincidence pulse for every pulse occurring in either the F or M detector. Thus the conditions for taking the single parameter spectra are very much like those for the 2-parameter analysis, enabling the use of the single parameter spectra for energy calibration. A typical single parameter spectrum, with energy scale assigned, is shown in Figure 5.

Only two targets were used in collecting the data presented here. Target No. 3 (thickness = 120 $\mu$g/cm$^2$) was used for the runs L, M, and N through N6. For the rest of experimental run N, N7-N15, target No. 4 (thickness = 130 $\mu$g/cm$^2$) was used. The targets were prepared as described in Appendix II, with the thicknesses being determined by the shift in neutron threshold as described above.
Figure 5. A single parameter spectrum taken with target No. 3 at 9.0 MeV and an angle of 25°. The elastic and inelastic peaks observed serve to determine energy calibrations for the d(p,2p)n breakup.
IV. RESULTS

The data are here presented in a form similar to that taken directly from the 2-parameter analyzer as discussed earlier. In Figures 6 through 17 the upper right hand portion of the figure contains a "contour" plot of the data showing the general shape of the locus of allowed solutions, with the excitation curves discussed below superimposed on the same plot. As an indication of the spectrum of the breakup as seen by each detector, the distribution is projected onto the two energy axes. The resulting histograms of projected channel populations show the distribution of protons detected in one of the detectors for events where a coincident proton is detected in the other detector. It will be recognized that these spectra are of the type that would be obtained if two multi-channel analyzers, one associated with each detector, were used to determine the energy distribution of the protons in each detector for events in which both analyzers receive pulses in coincidence. The 2-parameter plot is used to advantage here, for not only is the distribution along the allowed locus given almost at a glance, but also the accidental coincidence counts due to the high rate of elastic scattering events may be largely eliminated simply by projecting only that part of the 2-parameter map immediately around the locus line, particularly when the accidental peaks fall off of the line. In addition, an
accidental 2-parameter spectrum, as described in the previous section, is taken for each coincidence spectrum and the accidental counts subtracted from the coincidence spectrum before the projection is made. Thus, within statistics, the projected histograms show the distribution curve of the particle energy distributions in the two counters.

The calculated loci shown on the plots are determined from the kinematical relations described in Appendix I, using the energy calibrations obtained from the single parameter spectra, and are seen to fit the observed distributions quite well.

The data enclosed were taken on three separate occasions, experimental set run "M" on the 5.5 MeV Van de Graaff and experimental set runs "L" and "N" on the Tandem Van de Graaff. The spectrum number indicates the experimental run in which the spectrum was taken.

The first three figures (Figures 6, 7, 8) show typical data taken at a bombarding energy of 5.0 MeV. In Figure 6 the entire calculated locus of the values of the energy of the proton detected in counter 2 ($T_2$) versus the value of the energy of the proton detected in counter 1 ($T_1$) is seen to fall in the observable energy quadrant. This curve has two branches, labeled $T_{2+}$ and $T_{2-}$ corresponding to the two solutions for $T_2$ as described in Appendix I.

The three excitation energy curves for the sequential 2-body decay modes are also given on the same plot, with
Figures 6, 7, and 8. 2-parameter spectra M2, M3, and M4 of the d(p,2p)n reaction at $T_0 = 5.0$ MeV with target No. 3.
D(P,2Pn)
SPECTRUM M=2
\[ \theta_1 = 25^\circ \]
\[ \theta_2 = 25^\circ \]
\[ T_0 = 5.0 \text{ MEV} \]
\[ Q = 560 \mu \text{Coulomb} \]
DIP, SPIN
SPECTRUM M=3
θ₁ = 28°
θ₂ = 30°
T₀ = 5.0 MEV
Q = 550 µCULOMB
DIP, RPJN
SPECTRUM M=4
θ₁ = 25°
θ₂ = 35°
T₀ = 5.0 MEV
Q = 560 microcoulomb
the two possible solutions for \( E_{13} \) and \( E_{12} \) given as \( E_{13}^+ \), \( E_{13}^- \), \( E_{12}^+ \), and \( E_{12}^- \). As shown in the calculations in Appendix I, the \( E_{23} \) curve has only one branch when plotted against \( T_1 \). All branches of the excitations energy curves are shown in Figure 6, even though only the (+) curves could apply to the portion of the curve that has been observed. In some of the later figures, where the \( T_2 \) locus is not entirely contained in the observable energy quadrant, the inapplicable portions of the excitation curves have been omitted.

No strong peaking is indicated in the 5.0 MeV data, with the observable portions of the locus being quite evenly and continuously populated. It will be noted in Figure 6 that the excitation energy \( E_{13}^+ \) curve has a minimum value at a value of about 0.3 MeV for \( T_1 \). This portion of the \( T_2 \) curve was not observed due to the lower cut-off of the pulses by the coincidence circuitry, so that no conclusions may be drawn as to whether decay could proceed through the deuteron singlet unbound state whose excitation energy is within the range of values at the minimum of this curve. For the other two spectra shown at 5.0 MeV, Figures 7 and 8, the curve is again quite continuous and no indication of decay through sharp states is observed.

Figures 9, 10, 11, 12 show similar behaviour at 9.0 MeV with the observed portions of the loci being fairly smoothly populated, and no definite peaks observed.
Figures 9, 10, and 11. 2-parameter spectra L9, L14 and N4 of the d(p,2p)n reaction at $T_0 = 9.0$ MeV with target No. 3.
D(P,2P)n
SPECTRUM L-9
θ₁ = 30°
θ₂ = 30°
γ₀ = 9.0 MEV
Q = 200 μGOULOMB
D/P, 58Pm
Spectrum L-14
$\theta_1 = 50^\circ$
$\theta_2 = 25^\circ$
$T_0 = 9.0$ MeV
Q = 200 $\mu$ Coulomb
DIP, 2PIN
SPECTRUM N=4
$\theta_1 = 35^\circ$
$\theta_2 = 35^\circ$
$T_0 = 9.0$ MEV
$Q = 200$ $\mu$Coulomb
Figure 13, at $\theta_1 = \theta_2 = 50^\circ$ and $T_0 = 9.0$ MeV, shows definite structure in the histograms, with a broad peak at low energies and a fairly sharp peak at the high end of the energy spectrum. Investigating the projection on the $T_1$ axis we see that the upper peak corresponds to a range of excitation energies from $\sim 44$ kev up to $\sim 220$ kev on the $E_{23}$ excitation curve. Now looking at the lower, broad peak we find the range of excitation energies on the $E_{13}^+$ curve to be about the same. The interpretation is that the two peaks correspond to the same state in the deuteron of excitation energy between $\sim 44$ kev and $\sim 220$ kev. Two peaks are observed since, as described in Appendix I, the first "free" proton can go into either counter. In fact, if the intermediate state were quite sharp, we would expect to see two peaks at the lower energy, corresponding to the two values of $T_1$ which occur for the same value of $E_{13}^+$. Because of the symmetry of the plot ($\theta_1 = \theta_2$) it is noted that the projection along the $T_2$ axis should be of the same form, except that the upper peak observed along the $T_1$ axis would project back on the $T_2$ axis as two peaks (or a single broad peak), while the lower broad peak (or two peaks) will project onto the $T_2$ axis as only one peak. This is obvious from the kinematics since the roles of $E_{13}$ and $E_{23}$ are interchanged when the curves are plotted versus the $T_2$ axis. Thus all of the peaks correspond to sequential decay through a state in the deuteron of excitation between 44 and 220 kev. This range covers the values often quoted
Figures 12 and 13. 2-parameter spectra N7 and N8 of the reaction d(p,2p)n taken at 9.0 MeV with target No. 4.
DIP,2PIN
SPECTRUM N-7
θ₁ = 30°
θ₂ = 30°
T₀ = 9.0 MEV
Q = 200 μ COULOMB
D(P,2P)N
SPECTRUM N=8
\( \theta_1 = 50^\circ \)
\( \theta_2 = 50^\circ \)
\( T_0 = 9.0 \text{ MEV} \)
\( Q = 200 \text{ \mu\text{C}} \text{OULOMB} \)
for the energy of the level of the unbound singlet state of the deuteron.

Again in Figures 14, 15 and 16 with $T_0 = 10.5$ MeV, the distribution along the $T_2$ locus is apparently continuous and no sharp peaking effects occur. It will be noticed in these figures that the excitation curves $E_{13}$ and $E_{23}$ never extend below 135 kev, but these points may be below the observable coincidence region so that this value should not be considered an upper limit to the value of the excitation energy of this unbound state.

In Figure 17, we again see definite peaking, again at $\theta_1 = \theta_2 = 50^\circ$, but now at 10.5 MeV. The explanation of the peaks is the same as for those in Figure 13, with the lowest value of $E_{13}$ and $E_{23}$ being $\sim 31$ kev while the maximum is $\sim 185$ kev. On the two lower sets of peaks, as suggested before, the appearance of double peaks seems to be occurring. If a line is projected back from the center of each of these "peaks" onto the $E_{13+}$ curve and the center line of the upper peak is projected back onto the $E_{23}$ curve, a consistent value of $\sim 35$ kev is found for the excitation energy of the unbound singlet state of the deuteron.
Figures 14, 15, 16 and 17. 2-parameter spectra N10, N11, N13, and N15 of the d(p,2p)n reaction taken at \( T_0 = 10.5 \text{ MeV} \) with target No. 4.
DIP, 2PIN
SPECTRUM N = 10
$\theta_1 = 28^\circ$
$\theta_2 = 25^\circ$
$T_0 = 10.5$ MEV
$Q = 200$ $\mu$Coulomb
DNP, PPN
SPECTRUM N=111
$\theta_1 = 30^\circ$
$\theta_2 = 30^\circ$
$T_0 = 10.5$ MEV
$Q = 200$ $\mu$COULOMB
DP(2P)IN
SPECTRUM N=13
\( \theta_1 = 35^\circ \)
\( \theta_2 = 35^\circ \)
\( T_0 = 10.5 \text{ MEV} \)
\( Q = 200 \mu \text{Coulomb} \)
DIP, 2PIN
SPECTRUM N=15
$\theta_1 = 50^\circ$
$\theta_2 = 50^\circ$
$T_0 = 10.5$ MEV
$Q = 200 \mu$COULOMB
V. CONCLUSIONS

At counter angles of $\theta_1 = \theta_2 = 50^\circ$ and for bombarding energies of 9.0 and 10.5 MeV, evidence of sequential 2-body breakup of the $\text{He}_3$ configuration has been observed using 2-parameter analysis and simple kinematics. At other angles and at energies of 5.0, 9.0, and 10.5 MeV no evidence of sequential decay through discrete, sharp states has been observed. The population along the loci described in the text for these angles and energies are such that the decay either proceeds via simultaneous 3-body breakup or sequential 2-body breakup via very broad (and hence short-lived) states in either a deuteron or di-proton configuration. For these angles and energy values, the decay through the singlet deuteron state is kinematically forbidden.

These experiments will be continued in a systematic effort to determine if evidence of sequential 2-body breakup also occurs via the di-proton intermediate state. Cross-section measurements of the different observable modes of decay are planned, with particular attention to be given to angular distributions about the recoil direction of the intermediate deuteron or di-proton configuration.
APPENDIX I: KINEMATICS

All of the data taken in this investigation were taken with both counters in the same plane, thus restricting the third particle (the neutron) to this same plane. Thus in considering the kinematics of the reaction the discussion will be restricted at the present to the planar 3-body kinematics. Only the conservation of energy and momentum need be applied in order to find the locus of all possible combinations of energy distribution between the two detected protons, so that the intermediate state is not considered. As mentioned before, the distribution along this curve will be strongly dependent on the mode of the breakup, but there are no possible solutions that do not fall on the locus of values determined from purely kinematical considerations.

The breakup is described in the lab system by Fig. A1 in which the incident proton has an energy of $T_Q$ and momentum along the beam axis of $P_0$. In the final state the two protons and neutron resulting from the $p(d,2p)n$ reaction will be described by energies $T_1, T_2$ and $T_3$ and momenta $P_1, P_2$ and $P_3$, with $T_3$ and $P_3$ describing the neutron. The problem at hand is to find the relation of $T_2$ to $T_1$ as a function of $T_Q$, the $Q$ of the reaction, and the angles $\theta_1$ and $\theta_2$. For a particular combination of these angles and the energy of the incident proton, the solutions for $P_2$ as a function of $P_1$ will form a closed curve in the
Figure Al. A momentum diagram of the $^3$-body breakup of the $^3\text{He}$ configuration via the $^3\text{d}(p,2p)n$ reaction. The vectors represent the momenta in the initial and final states and define the angles $\theta_1$, $\theta_2$, and $\theta_3$ as used in the kinematic solutions.
coordinate system of $\vec{P}_1$ and $\vec{P}_2$. Since only particles of positive momentum along the counter directions may be detected, the solutions for negative momenta along these directions must be omitted. Thus when converting to a plot of $T_2$ versus $T_1$ the locus of solutions will not necessarily be a closed curve, since for many of the angles and energies considered here, only a portion of the complete, mathematically possible, curve will correspond to particles moving in the direction of the counters and thus detectable.

Starting first with the conservation of momentum, we have first the equation:

$$\vec{P}_0 = \vec{P}_1 + \vec{P}_2 + \vec{P}_3. \quad (1)$$

Writing this equation in terms of the components along the beam axis and normal to the beam axis:

$$P_0 = P_1 \cos \theta_1 + P_2 \cos \theta_2 + P_3 \cos \theta_3, \quad (2)$$

$$0 = P_1 \sin \theta_1 - P_2 \sin \theta_2 - P_3 \sin \theta_3. \quad (3)$$

Now considering the energy equation:

$$T_0 + Q = T_1 + T_2 + T_3,$$

where $Q$ is the energy required to break up the deuteron and has the value of $-2.22471 \pm 0.00040$ MeV. Writing the energy equation in terms of the momenta:
\[
\frac{P_0^2}{2M_0} + Q = \frac{P_1^2}{2M_1} + \frac{P_2^2}{2M_2} + \frac{P_3^2}{2M_3}.
\]

From (2 and (3):

\[
P_3 \cos^2 \theta_3 = (P_0 - P_1 \cos \theta_1 - P_2 \cos \theta_2)^2,
\]

\[
P_3 \sin^2 \theta_3 = (P_1 \sin \theta_1 - P_2 \sin \theta_2)^2.
\]

Adding these two equations then gives:

\[
P_3^2 = (P_0 - P_1 \cos \theta_1 - P_2 \cos \theta_2)^2 + (P_1 \sin \theta_1 - P_2 \sin \theta_2)^2.
\]

Substituting this value into equation (5:

\[
T_0 + Q = T_1 + T_2 + \frac{1}{2M_3} \left[ P_0^2 + P_1^2 + P_2^2 + 2P_1 P_2 (\cos \theta_1 \cos \theta_2 - \sin \theta_1 \sin \theta_2) - 2P_0 P_1 \cos \theta_1 - 2P_0 P_2 \cos \theta_2 \right].
\]

Thus:

\[
T_0 + Q = T_1 + \frac{P_2^2}{2M_2} + \frac{1}{2M_3} (P_0^2 + P_1^2 - 2P_0 P_1 \cos \theta_1) + \frac{P_2^2}{2M_3} + \frac{P_2}{M_3} \left[ P_1 \cos (\theta_1 + \theta_2) - P_0 \cos \theta_2 \right].
\]
The equation is thus a quadratic equation in $P_2$:

$$P_2^2 \left[ \frac{1}{2M_3} + \frac{1}{2M_2} \right] + P_2 \left( \frac{1}{M_3} \right) \left[ P_1 \cos(\theta_1 + \theta_2) - P_o \cos \theta_2 \right]$$

$$+ \left[ T_1 - T_0 - Q + \frac{1}{2M_3} \left( P_o^2 + P_1^2 - 2P_o P_1 \cos \theta_1 \right) \right] = 0.$$ 

Or:

$$A P_2^2 + B P_2 + C = 0$$

where:

$$A = \left[ \frac{1}{2M_3} + \frac{1}{2M_2} \right],$$

$$B = \frac{1}{M_3} \left[ P_1 \cos(\theta_1 + \theta_2) - P_o \cos \theta_2 \right],$$

$$C = T_1 - T_0 - Q + \frac{1}{2M_3} \left[ P_o^2 + P_1^2 - 2P_o P_1 \cos \theta_1 \right].$$

Thus the solution for $P_2$ is given by

$$P_2 = \frac{-B \pm \left[ B^2 - 4AC \right]^{\frac{1}{2}}}{2A}.$$ 

There are thus two possible solutions for $P_2$ when $(B^2 - 4AC)$ is positive. These will be labeled as $P_{2+}$ and $P_{2-}$:

$$P_{2+} = \frac{-B + \left[ B^2 - 4AC \right]^{\frac{1}{2}}}{2A},$$

$$P_{2-} = \frac{-B - \left[ B^2 - 4AC \right]^{\frac{1}{2}}}{2A}.$$
The energies corresponding to these values of momenta are thus:

\[
T_{2+} = \frac{P_{2+}^2}{2M_2},
\]

\[
T_{2-} = \frac{P_{2-}^2}{2M_2}.
\]

We may thus get a plot of \(T_2\) (including both solutions above) versus \(T_1\) by choosing particular values of \(\theta_1\) and \(\theta_2\) at a given bombarding energy \(T_0\), and calculating values for \(T_2\) as we step the values of \(T_1\). These calculations for a number of different values of energy and angles have been carried out, with some representative results shown already in Figure 1.

The calculations above yield the loci of possible values of \(T_2\) as a function of \(T_1\) for a given bombarding energy and angular setting of the two detectors, considering only the initial and final state energy and momenta. If the breakup can occur by sequential 2-body decay, there will be an intermediate state involving one free nucleon with the other two nucleons forming either a deuteron or di-proton configuration in an excited state, with an excitation energy which may be determined from the kinematics. For the purpose of this discussion we may label the proton entering detector 1 as particle 1, the proton entering detector 2 as particle 2, and the
undetected neutron as particle 3. There are thus the three following cases to be considered:

(I) Particle 1 is the "free" nucleon, leaving 2 and 3 in the short-lived deuteron configuration (23).

(II) Particle 2 is the "free" nucleon, leaving 1 and 3 in the short-lived deuteron configuration (13).

(III) Particle 3 is the "free" nucleon, leaving 1 and 2 in the di-proton configuration (12).

These three cases are indicated in the figures labeled (I), (II), and (III) in Figure A2. The convention of measuring the angles of (1) and (2) with respect to the beam axis is indicated, with positive angles for both indicating that both detectors are in the configuration illustrated while one negative angle will indicate that both detectors are on the same side of the beam axis.

In case (I) proton (1) is detected in detector 1 and proton (2) in detector 2, with (2) resulting from the breakup of the deuteron configuration (23) with the excitation energy of the intermediate (23) state being $E_{23}$. From 2-body kinematics then, the initial breakup into (1) and (23) will be described by the energy and momentum equations:

Energy equation: $T_0 + Q = E_T = T_1 + T_{23} + E_{23}$.
Figure A2. Momentum diagrams of the 3 cases in which the d(p,2p)n reaction may proceed if decay occurs via sequential 2-body break-up. The solid arrows indicate the momenta of the free nucleons while the dotted arrows indicate the momenta of the intermediate deuteron or di-proton configuration.
momentum equations:  

\[ P_0 = P_1 \cos \theta_1 + P_{23} \cos \theta_{23}, \]

\[ 0 = P_1 \sin \theta_1 - P_{23} \sin \theta_{23}, \]

thus:

\[ P_{23}^2 = P_0^2 + P_1^2 - 2P_0P_1 \cos \theta_1, \]

\[ T_{23} = \frac{1}{2M_{23}} (P_0^2 + P_1^2 - 2P_0P_1 \cos \theta_1). \]

Therefore:

\[ E_{23} = T_0 + Q - T_1 - \frac{1}{2M_{23}} (P_0^2 + P_1^2 - 2P_0P_1 \cos \theta_1). \]

Thus there is only one solution for \( E_{23} \) at a given value of \( T_0, Q, \theta_1, \) and \( T_1 \), and this solution is a function only of these parameters, as is \( T_{23} \).

In case (II) the proton detected in counter 1 is taken to be the one that follows from the breakup of the deuteron configuration (13) which exists in the intermediate state.

The kinematics for the initial breakup yield:

momentum equations:  

\[ P_0 = P_{13} \cos \theta_{13} + P_2 \cos \theta_2, \]

\[ 0 = P_{13} \sin \theta_{13} - P_2 \sin \theta_2, \]

thus:

\[ P_{13}^2 = (P_0^2 + P_2^2 - 2P_0P_2 \cos \theta_2), \]

\[ T_{13} = \frac{1}{2M_{13}} (P_0^2 + P_2^2 - 2P_0P_2 \cos \theta_2). \]

Therefore:

\[ E_{13} = T_0 + Q - T_2 - \frac{1}{2M_{13}} (P_0^2 + P_2^2 - 2P_2P_2 \cos \theta_2). \]
Thus $E_{13}$ is a function of $T_0$, $Q$, $P_2$, and $\theta_2$. For a given counter arrangement, $\theta_1$ and $\theta_2$, we have seen above that for a proton entering counter 1 with momentum of $P_1$, there are two solutions for the value of the momentum $P_2$ in counter 2. Thus we must consider both solutions in calculating $E_{13}$ as a function of $T_1$. Thus for a particular value of $T_1$, particle 2 will have energy $T_2+$ or $T_2-$ with corresponding momentum of $P_{2+}$ or $P_{2-}$. The two solutions for $E_{13}$ will then be:

$$E_{13+} = T_0 + Q - T_{2+} - \frac{1}{2M_{13}}(P_o^2 + P_{2+}^2 - 2P_oP_{2+}\cos\theta_2),$$

$$E_{13-} = T_0 + Q - T_{2-} - \frac{1}{2M_{13}}(P_o^2 + P_{2-}^2 - 2P_oP_{2-}\cos\theta_2).$$

For case (III) the intermediate state has the configuration (12), or a di-proton configuration. Again applying the kinematics for the initial breakup:

Energy equation: $T_0 + Q = E_T = T_{12} + E_{12} + T_3$,

momentum equations: $P_o = P_{12}\cos\theta_{12} + P_3\cos\theta_3$,

$$0 = P_{12}\sin\theta_{12} - P_3\sin\theta_3.$$

But from the general 3-body equations:

$$P_o = P_1\cos\theta_1 + P_2\cos\theta_2 + P_3\cos\theta_3,$$

$$0 = P_1\sin\theta_1 - P_2\sin\theta_2 - P_3\sin\theta_3.$$
and \( E_T = T_1 + T_2 + T_3 \).

Thus: \( P_3^2 = \left[ P_0 - (P_1 \cos \theta_1 + P_2 \cos \theta_2) \right]^2 + (P_1 \sin \theta_1 - P_2 \sin \theta_2)^2 \).

Now if \( \gamma = (P_1 \cos \theta_1 + P_2 \cos \theta_2) \),
\( \beta = (P_1 \sin \theta_1 - P_2 \sin \theta_2) \),
then: \( P_3^2 = (P_0 - \gamma)^2 + \beta^2 \).

And: \( T_3 = \frac{1}{2M_3} \left[ \left( P_0 - \gamma \right)^2 + \beta^2 \right] \).

Also: \( P_{12} \cos \theta_{12} = \gamma \),
\( P_{12} \sin \theta_{12} = \beta \),
so that \( P_{12}^2 = \gamma^2 + \beta^2 \),
\( T_{12} = \frac{1}{2M_{12}} (\gamma^2 + \beta^2) \).

Thus \( E_{12} = T_0 + Q - \frac{1}{2M_{12}} (\gamma^2 + \beta^2) - \frac{1}{2M_3} \left[ (P_0 - \gamma)^2 + \beta^2 \right] \).

But for a given value of \( T_1 \), \( \gamma \) and \( \beta \) have two values, corresponding to the two solutions \( P_{2+} \) and \( P_{2-} \) for \( P_2 \). Thus the two solutions for \( E_{12} \) will be:
\[ E_{12^+} = T_0 + Q - \frac{1}{2M_{12}} (\gamma_+^2 + \beta_+^2) - \frac{1}{2M_3} [ (P_0 - \gamma_+)^2 + \beta_+^2 ] \]

\[ E_{12^-} = T_0 + Q - \frac{1}{2M_{12}} (\gamma_-^2 + \beta_-^2) - \frac{1}{2M_3} [ (P_0 - \gamma_-)^2 + \beta_-^2 ] \]

where \( \gamma_+ = P_1 \cos \Theta_1 + P_2 \cos \Theta_2 \), etc.

In order to facilitate the plotting of the excitation energies and the kinetic energies of the two detected particles, \( T_1 \) and \( T_2 \), the energy to channel conversion relations were taken from the single parameter spectra, with two points along the energy to channel conversion line given for both sides (F and M) in terms of both energy and channel number. These values were then used by the Rice Nuclear Laboratory 1401 computer, while calculating \( T_2 \), \( E_{13^+} \), etc., to determine also the equivalent channel so that all the curves could be plotted directly on the data curves.
APPENDIX II: TARGET PREPARATION

Preliminary studies of the \(d(p,2p)n\) reaction were made using deuterated paraffin \((\text{C}_n\text{D}_{2n+2})\) as targets, with the paraffin deposited on thin carbon foils for support. This target system proved undesirable for two reasons. First the percentage of carbon in the resulting compound target is much greater than the percentage of deuterium, which causes an undesirable thickness of target for the amount of deuterium contained and also produces such high counting rates of elastically scattered protons from the carbon that the dead-time of the analyzer was significant and the number of accidental coincidence counts prohibitively high except for very low beam currents. Second, the deuterated targets prepared in this manner deteriorated rapidly under bombardment by the proton beam so that again only very low beam currents could be used, even then with significant target deterioration.

At present the targets used are prepared from deuterated polyethylene in the form of thin foils. The advantages to this method are twofold. First the polyethylene is self-supporting so that the only carbon in the target, other than that caused by the buildup due to the beam, is the carbon in the polyethylene, whose chemical formula is \((\text{C}_2\text{D}_4)_X\). Thus there will be less elastically scattered protons from carbon and higher beam currents may be used. Secondly, higher beam currents may be used because the
polyethylene targets do not deteriorate nearly as rapidly as do the paraffin targets, although some deterioration does occur which must be considered in the data analysis.

The targets are prepared from polyethylene shavings (supplied by Union Carbide Nuclear Company, Oak Ridge, Tennessee) by first dissolving the shavings in boiling carbon tetrachloride (CCl₄). Slight agitation and addition of more CCl₄ as it boils off is usually necessary to completely dissolve the polyethylene. (Usual precautions are taken to prevent excessive breathing of CCl₄ fumes.) While this solution is still hot, a few drops are poured onto the surface of hot water (kept at about the same temperature as the solution) and the film that is formed may be picked up onto a target support directly. After drying, the foils usually require a drop or two of coil dope or glyptal around the edges to prevent the foil from falling off of the target holder.
REFERENCES


7. V. V. Komarov and A. M. Popova, Soviet Physics JETP 11 (1960) 1123.

8. V. V. Komarov and A. M. Popova, Nuc. Phys. 18 (1960) 296.


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