ground-state angular distribution can be obtained by assuming contributions from both knock-on and heavy-particle stripping. The possibility that the backward peaking may result from distortion effects rather than heavy-particle stripping can not be excluded, but a check of this hypothesis must await further theoretical developments.

The $C^{12}(p,\alpha)B^9$ angular distribution roughly resembles that expected for a triton pickup or knock-on process, but the plane-wave theories predict far too much forward peaking of the over-all distribution, and also fail to match an observed decrease of the cross section at small angles. The oscillations in the angular distribution can be fitted at both 15.6 and 18.6 MeV only by assuming a smaller interaction radius at the higher bombarding energy.

The (p,α) reactions on Li^7, Be^9, and C^{12} all exhibit angular distributions which are not strongly dependent on the bombarding energy, and all of the cross sections decrease with increasing proton energy.

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Neutrons from Deuteron Breakup on D, T, and He^4†

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The continuous neutron spectra produced by deuteron bombardment of D, T, and He^4 have been studied at deuteron energies near 9 MeV with a time-of-flight spectrometer. Angular distributions of the continuous spectra from $D+d$ and He^4+d were obtained for deuteron energies of 9 and 10 MeV. The center-of-mass angular distributions are peaked forward for neutrons of all energies. Two maxima present in the 0° spectrum from He^4+d at $E_d=10$ MeV are consistent with the interpretation that He^5 and Li^5 are produced in their ground states as alternative intermediate steps in the reaction. Two maxima are also present in the continuous neutron spectrum from $T+d$. The higher energy maximum occurs near the maximum possible neutron energy from the $T(d,np)T$ reaction and cannot be caused by the $T(d,2n)He^3$ reaction. If this peak is caused by an excited state in He^4, it would correspond to an excitation in He^4 of 20.0 ± 0.2 MeV, and be unbound.

INTRODUCTION

THIS paper reports on the investigation of deuteron breakup on isotopes of hydrogen and helium. The occurrence of deuteron breakup in the $D+p$, He^3+d, $T+d$, and He^4+d reactions was first demonstrated by Henkel *et al.*[1] Deuteron breakup in the $D+d$ reaction was first observed far above threshold by Bogdanov *et al.*[2] and was studied near threshold by Cranberg *et al.*[3] The $T+d$ reaction has also been studied by Vlasov *et al.*[4] and an anomalous peak was observed in the neutron spectrum.

The energy spectrum of neutrons or protons from deuteron breakup has been shown to provide information about the interactions between the final state nuclei. Heckrotte and MacGregor,[5] and Komarov and Popova[6] have been able to explain the presence of an anomalous peak in the continuous neutron spectrum from $D+p$ breakup[7] by considering the final state n-p and p-p interactions as S-wave scattering interac-

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[1] R. L. Henkel, J. E. Perry, Jr., and R. K. Smith, Phys. Rev. **99**, 1050 (1955).
[2] G. F. Bogdanov, N. A. Vlasov, S. P. Kalinin, B. V. Rybakov and V. A. Sidorov, Soviet Phys.—JETP **3**, 113 (1956).
[3] L. Cranberg, A. H. Armstrong and R. L. Henkel, Phys. Rev. **104**, 1639 (1956).
[4] N. A. Vlasov, G. F. Bogdanov, S. P. Kalinin, B. V. Rybakov, and V. A. Sidorov, Proceedings of the International Conference on the Neutron Interactions with the Nucleus, Columbia University, New York, September, 1957 (unpublished).
[5] W. Heckrotte and M. H. MacGregor, Phys. Rev. **111**, 593 (1958).
[6] V. V. Komarov and A. M. Popova, Nuclear Phys. **18**, 296 (1960).
[7] M. P. Nakada, J. D. Anderson, C. C. Gardner, J. W. McClure, and C. Wong, Phys. Rev. **110**, 594 (1958); **116**, 164 (1959).

tions. Ilakovac *et al.*[8] have used the experimental proton spectra from D+n breakup to infer a value of the n-n scattering length by considering the final state n-n and n-p interactions. Vlasov *et al.* have suggested that the peak in the T+d neutron spectrum was caused by a level in He^4 at 22 MeV.

Since measurements of deuteron-breakup spectra yield interesting information regarding few nucleon systems, it appeared desirable to extend earlier measurements of neutron spectra from deuteron breakup to other energies and angles.

A practical reason for studying the breakup neutron spectra from the T+d and D+d reactions is that the D(d,n)He^3 and T(d,n)He^4 reactions are widely used as sources of monoenergetic neutrons. Above the breakup threshold, the neutron spectrum is contaminated by breakup neutrons. In many experiments, the low-energy breakup neutrons may be biased out if an energy-sensitive neutron detector is used. This is not possible, for example, in activation cross-section measurements so that differential neutron energy spectra must be used to correct measurements of this type for the presence of breakup neutrons.

EXPERIMENTAL

Neutron Spectrometry

Deuterons were accelerated with a tandem electrostatic accelerator. Neutron energies were measured with a pulsed-beam time-of-flight spectrometer.[9,10] Figure 1 shows a block diagram of the accelerator and components of the spectrometer. An rf deflection system and a pair of slits were used to chop the charged-particle beam into short bunches after acceleration. The deflection plates, 50 cm long, 5 cm wide, and separated by 1.9 cm, were adjacent to the magnetic lens. They were capacitively coupled to the output tank coil of an rf power amplifier and could be driven in push pull to 14 kV peak-to-peak at 4 Mc/sec. Deflection plate charging was minimized by grounding the plates through 10 MΩ deposited carbon resistors. The flight path between deflection plate centers and the chopping slits was about 4 m. Vertical deflection of the beam allowed the energy control slits to function in their normal manner. Slit separation was normally 1.3 mm and nearly all of the steady beam could be focused through the slits. The deflection system was capable of producing bursts of charged particles less than 2 nsec in duration for the maximum beam energies that could be obtained.

To reduce the component of random background which was associated with the accelerated beam, a second rf amplifier and deflection plate set was used to chop out unwanted beam before acceleration. Proper phasing of the two rf systems was accomplished with a variable delay line. Random background reduction achieved by not accelerating unwanted beam was a factor of 3 for a deuteron energy of 8 MeV and an unchopped beam of 1 μA.

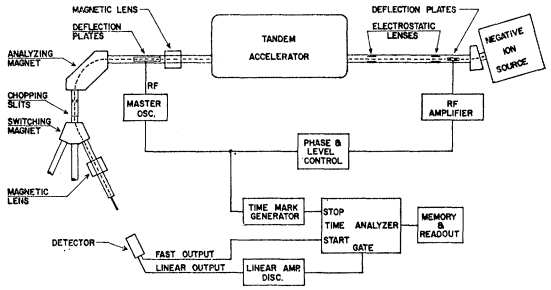

FIG. 1. Block diagram of the tandem accelerator and the components of the time-of-flight neutron spectrometer.

A one-turn pickup coil with variable coupling to the output tank coil field was used to obtain an rf signal at low impedance for time mark generation. The pickup coil delivered 4V peak-to-peak of rf to three cascaded Hewlett-Packard wide band amplifiers. When driven in this way, the amplifiers saturate and deliver a square-wave output. The square wave was differentiated with a 25-cm shorted stub of RG 63/U transmission line. Alternate positive and negative fast pulses were thus produced. The timing system, however, was sensitive only to positive pulses so that only one time mark per rf cycle was effective. Because two charged particle bursts are produced per rf cycle, two spectra were accumulated simultaneously.

Neutrons were detected with a recoil-proton scintillation counter. The scintillator was a disk of Pilot B type plastic,[11] 7.8 cm in diameter and 2.5 cm thick. The plastic was shielded in front and on the sides by 1.3 cm of lead to reduce sensitivity to low-energy gamma rays from radiocativity in the target assembly. The scintillator was coupled to an RCA 7046 photomultiplier tube which was shielded with mu metal. With the shield, gain changes caused by changes in position and orientation of the tube in the stray magnetic fields in the target room were less than 2%. High voltage for the multiplier was supplied by two power supplies. The anode was held at +2600 V, dynode 9 was at ground potential, and the photocathode was at −1600 V. Intermediate dynodes were supplied, respectively, by high- and low-current voltage dividers.

A linear signal was taken from dynode 9, integrated with a long RC time constant, and delivered to a linear amplifier. Since dynode 9 was not attached to a voltage divider, the high-pulse currents near the tube output could not feed back through the voltage divider and affect the linearity. Good shielding was necessary to minimize capacitive coupling between the large non-

[8] K. Ilakovac, L. G. Kuo, M. Petravić, and I. Šlaus, Phys. Rev. 124, 1923 (1961).

[9] J. H. Neiler and W. M. Good, *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers, Inc., New York, 1960), Vol. 1, Chap. IVA.

[10] B. V. Rybakov and V. A. Sidorov, *Spectrometry of Fast Neutrons* (Consultants Bureau, Inc., New York, 1960).

[11] Pilot Chemical Company, Waltham, Massachusetts.

linear anode signal and the linear signal from dynode 9. A pulse-height discriminator at the output of the linear amplifier was used to obtain a stable and reproducible bias point. The bias was set by observing the pulse-height distribution from a Na^{22} gamma-ray source with a gated multichannel pulse-height analyzer. Bias for the measurements to be reported here was set at a pulse height equal to one-third of that from 340-keV electrons, the maximum electron energy deposited in the scintillator by Compton scattering of a 511-keV positron annihilation gamma ray. This bias was found to correspond in pulse height to recoil protons of 850 keV. The bias settings were reproduced to 3%.

Fast pulses for timing were obtained from the multiplier anode. The severe shift in position of the leading edge of the pulse with pulse height which has been reported previously[12,13] was partially overcome by using a shorted transmission line of proper length and a zero-crossing detector.[12] The zero-crossing signal was obtained with a two-stage amplifier using EFP60 secondary emission pentodes. The photomultiplier focus voltages were set by observing the response of the multiplier to light flashes from a mercury relay.[14] Focus voltages were adjusted to obtain minimum shift in the zero-crossing signal as the input light pulse amplitude was varied.

The time intervals between the neutron detector pulse and the next following oscillator time mark were measured by a vernier chronotron.[15] The chronotron bias was substantially lower than the side-channel linear bias. Time interval measurements were begun for detector pulses above the chronotron threshold but were allowed to continue to completion only if the side-channel system indicated that the pulses were above the linear threshold.

The time-scale calibration for use in converting the time spectra to energy spectra was derived from the data in the following manner: For the D+d and T+d reactions the interval between the prompt gamma-ray peak and the monoenergetic neutron peak was used as a calibration. For the He^4+d reaction, calibration was obtained from the spacing of the successive gamma-ray peaks in the two recorded spectra and the known repetition frequency. Systematic errors in calibration using a neutron group may be produced by differences in the pulse-height distributions from the gamma-ray burst and the neutron group. Errors in calibration using successive gamma-ray bursts can be caused by deflection plate charging.

The time resolution of the system varied between 2.5 and 3 nsec as determined from the full width at half maximum of the gamma-ray peak. The channel width used was 1 nsec. The difference in counting rate for spectra taken with and without gas in the target caused channel width changes of 2.5% or less. These channel width changes were corrected in the analysis before subtracting the backgrounds.

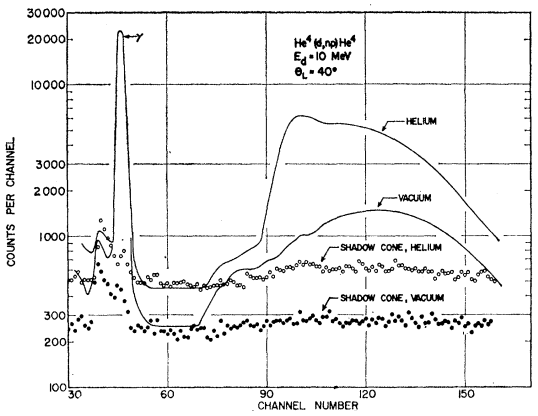

FIG. 2. Time-of-flight spectra at 40° with the gas target filled with helium and evacuated. The solid curves were obtained with the detector unshielded; the experimental points were obtained with a brass shadow cone between the target and detector. The region of the spectra to the right of the gamma-ray peak gives a measure of the random background from all sources. The difference in random background with and without gas in the target is caused by scattering and capture of neutrons in the target room.

Data for the D+d and He^4+d reactions were obtained with a flight path of 1.5 m. Data from the T+d reaction were taken with flight paths from 1.5 to 4 m. For 3-nsec time resolution, the energy resolution of the spectrometer is given nonrelativistically by

$$\Delta E/E \cong 0.083 E^{1/2}/l$$

for E in MeV and l in m.

Detector Efficiency

The detector efficiency, defined as the number of neutrons detected per neutron incident, was measured as a function of energy using the $T(p,n)He^3$ reaction for neutrons between 1 and 5 MeV and the $D(d,n)He^3$ reaction for higher neutron energies. Uncertainty in the isotopic purity of the tritium required normalization of the T+p data to the D+d data at a neutron energy of 5 MeV. The reaction cross sections used were those given by Brolley and Fowler.[16]

Targets

The target gases were contained in a small cell with a gold beam stop, and were separated from the accelerator vacuum system by a nickel or tantalum foil. For measurements at laboratory angles from 0° to 30°, the target gas pressure was 62 cm Hg absolute. At this pressure a nickel foil of 1μ thickness was sufficient to contain

[12] H. W. Lefevre and J. T. Russell, Proc. Inst. Radio Engrs. **NS5**, 146 (1958).
[13] C. Cernigoi, I. Gabrilli, and G. Iernetti, Nuclear Instr. and Methods **9**, 303 (1960).
[14] Q. A. Kerns, F. A. Kirsten, and G. C. Cox, Rev. Sci. Instr. **30**, 31 (1959).
[15] H. W. Lefevre and J. T. Russell, Rev. Sci. Instr. **30**, 159 (1959).
[16] J. E. Brolley and J. L. Fowler, *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers, Inc., New York, 1960), Vol. 1, Chap. I.C.

the gas. For measurements at observation angles greater than 30°, the target pressure was raised to 370 cm Hg absolute, and a 12-μ-thick tantalum foil was used. The nickel and tantalum foils were 55 and 620 keV thick, respectively, at a deuteron energy of 9 MeV. Energy spreads in the gas targets at 9 MeV caused by the combined effects of target thickness and straggling in the foil and gas were about 60 and 270 keV, respectively, for the low and high pressures.

The gas target was separated from the beam tube by an insulated section of tubing which was biased at −300 V with respect to the beam tube and target cell. Secondary electrons were thus prevented from reaching the cell from elsewhere or leaving the cell if produced there. A tantalum diaphragm defined the beam to an area smaller than the foil entrance into the gas target. Diaphragm current was monitored and was minimized by focusing with the magnetic lens near the target (Fig. 1). Beam currents of about 15 nA were used. The running time per spectrum was about 10 min.

CORRECTIONS AND CONVERSIONS

An IBM 704 computer was programmed to convert time spectra to both laboratory and center-of-mass neutron energy spectra. The computer was also used to perform the background subtractions.

As previously described, two time spectra were accumulated during each run but only one of these was complete. One charged-particle bunch was usually more intense when the preacceleration beam pulsing system was adjusted. The fraction of the integrated current which produced the complete spectrum was obtained from the ratio of the areas of the two gamma-ray peaks.

Several sources of background were present during the measurements. A major portion of the neutron background was caused by neutrons which were produced in the target backing and foil. This background was measured by taking a spectrum with the target evacuated. The spectra, obtained with the target filled and evacuated, also contained a component of background caused

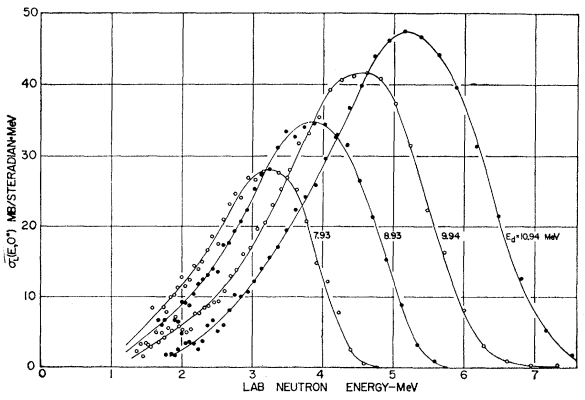

FIG. 3. Zero-degree yield of neutrons from the D(d,np)D reaction in the laboratory system.

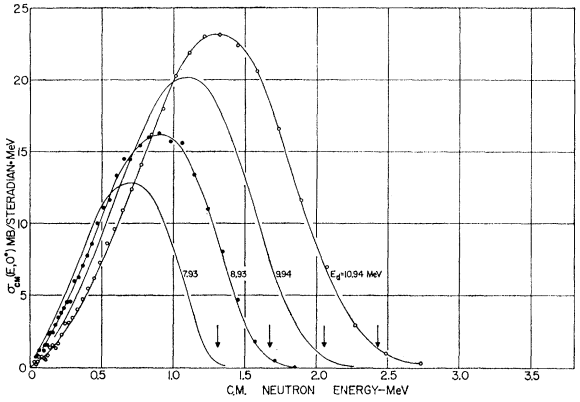

FIG. 4. Zero-degree yield of neutrons from the D(d,np)D reaction in the center-of-mass system. The arrows indicate the calculated maximum possible neutron energy for this reaction at each bombarding energy.

by radiation not coming directly from the target. This component was measured by inserting a brass shadow cone of negligible transmission between the target and the detector. Figure 2 shows four time spectra to illustrate these various components of background.

Accuracy of the Measurements

The statistical uncertainty of the data is indicated by the scatter in the data points. Statistical uncertainties were small compared with other uncertainties in the measurements. The uncertainty in areal density of target gas atoms caused by errors in calibration, reproducibility of the gauge setting, and cell length uncertainty was 7%. The uncertainty of the absolute detector efficiency owing to uncertainties in the reaction cross sections, normalization of the T(p,n)He^3 and D(d,n)He^3 data, and background corrections was ±15%. Uncertainty in the detector efficiency caused by uncertainty in the bias setting of the detector is considerably larger than 15% for laboratory neutron energies below 2 MeV. This conclusion was reached by comparing the measured cross sections for the D(d,np)D reaction at different laboratory neutron energies and angles, which had the same center-of-mass energy, and were symmetrically located about 90° in the center-of-mass system. The neutron spectrum from the D+d breakup reaction must be symmetric about 90° in the center-of-mass system. The compounded probable error in the cross sections for neutrons of laboratory energy above 2 MeV is ±20%, except for the T+d reactions for which a hydrogen contaminant in the tritium gas introduces additional uncertainty.

The energy scales for the D+d neutron spectra were reproducible to about 2% but systematic errors larger than this may have been present. In spectra which were taken with photomultiplier focus voltages improperly set, the flight-time calibration obtained from the spacing of the γ ray and neutron peaks could be in error by 5%. To determine the accuracy of the calibrations with the

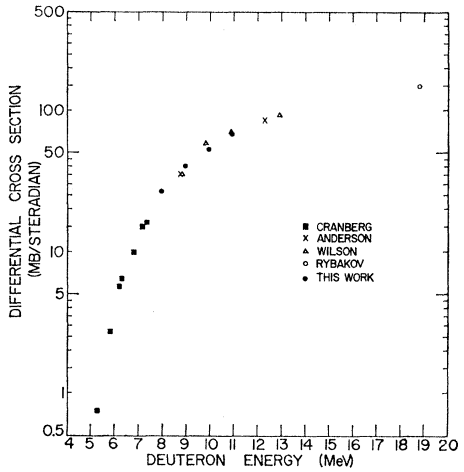

FIG. 5. Laboratory differential cross section for the D(d,np)D reaction with neutron emission at 0°.

voltages properly set, the gamma-ray-neutron calibration was compared with that obtained from the spacing of the gamma-ray peaks. For this measurement the spacing of successive pairs of gamma-ray peaks was found to be equal to within 1%. Time scale calibration by the two methods agreed to within 1%. For the D+d data, systematic errors in the energy calibrations are less than 5% for the laboratory spectra.

For the He^4+d measurements, time-scale calibration was obtained from the gamma-ray peaks. Changes in the spacing of these peaks caused by changes in deflection plate charging by the ion beam were found to be at most 3%. The energy scales for the laboratory spectra are in error by less than ±6%. The presence of a systematic error in the calibrations for the T+d spectra will be discussed later.

RESULTS AND DISCUSSION

D(d,np)D

Figures 3 and 4 show the variation with bombarding energy of the 0° neutron spectrum from the D(d,np)D reaction in the laboratory and center-of-mass systems. The calculated maximum possible neutron energies are indicated by arrows in Fig. 4. The spectra of Fig. 3 were integrated over energy to obtain the differential cross sections shown in Fig. 5. For comparison, Fig. 5 also shows results obtained by others.[3,16,17,18]

Figure 6 shows the variation of the laboratory neutron spectrum with observation angle for a bombarding energy of about 10 MeV. The variation with angle is typical of what is observed at 8 and 9 MeV. Since the transformation of angles from the laboratory to center-of-mass system involves the neutron energy, neutrons of different energies which are emitted at the same laboratory angle other than zero degrees, are not emitted at the same center-of-mass angle. For this reason, it is not possible to plot neutron spectra in the center-of-mass system at angles other than zero degrees. However, the data of Fig. 7 show that the shape of the center-of-mass spectrum changes with center-of-mass angle. High-energy neutrons are more strongly peaked about zero degrees than are low-energy neutrons. At zero degrees the most probable neutron energy is slightly higher than half the maximum possible neutron energy. At a center-of-mass angle of 90° the most probable energy is less than half of the maximum possible energy.

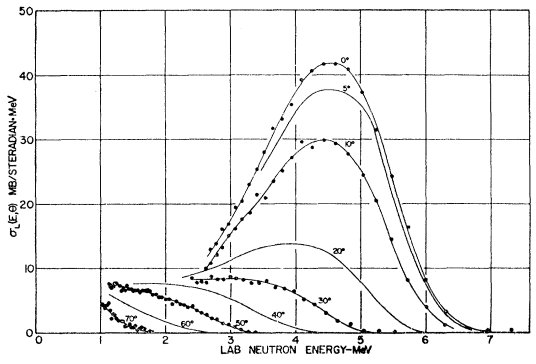

FIG. 6. Angular distribution of the D(d,np)D neutron spectrum in the laboratory system. For $\theta \leq 30°$, $E_d = 9.94$ MeV. For $\theta > 30°$, $E_d = 9.75$ MeV.

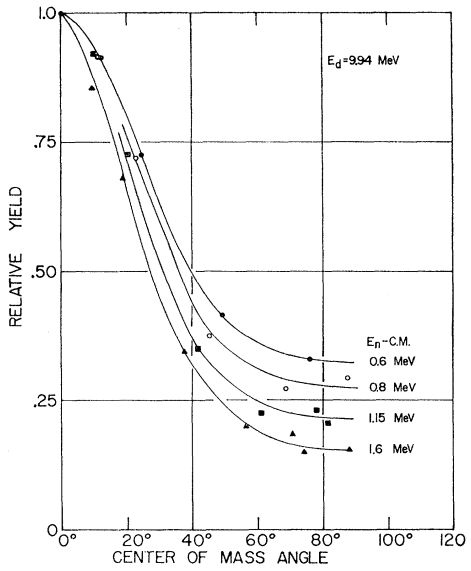

FIG. 7. The relative center-of-mass cross section as a function of center-of-mass angle for four neutron energies at a deuteron energy of about 10 MeV. The normalization for these curves may be obtained from Fig. 4.

Rybakov *et al.*[18] have suggested that the shape of the neutron spectrum from the D(d,np)D reaction can be explained by the production of particle pairs in states of nonzero angular momentum. They obtain a good fit to

[17] W. E. Wilson, Ph.D. thesis, University of Wisconsin, 1961 (unpublished).

[18] B. V. Rybakov, V. A. Sidorov, and N. A. Vlasov, Nuclear Phys. **23**, 491 (1961).

the zero-degree neutron spectrum for 18.4-MeV deuterons by assuming a mixture of final states but they do not discuss the question of interference between these states. As Delves[19] points out, cross terms between differing states will usually be present. Perhaps the formalism developed by Delves will be able to explain the variation in the shape of the neutron spectrum with center-of-mass angle which is reported here.

$He^4(d,np)He^4$

Figures 8 and 9 show the variation with bombarding energy of the zero-degree neutron spectrum from the $He^4(d,np)He^4$ reaction in the laboratory and center-of-mass systems. The calculated maximum possible center-of-mass neutron energies are indicated by arrows in Fig. 9. In contrast to the $D+d$ breakup neutron spectrum (Fig. 4) where the number of neutrons is high near the maximum possible energy, the He^4+d spectra have few neutrons near the maximum. The spectra of Fig. 8 were integrated over energy to obtain the differential cross sections shown in Fig. 10. Figure 10 also contains

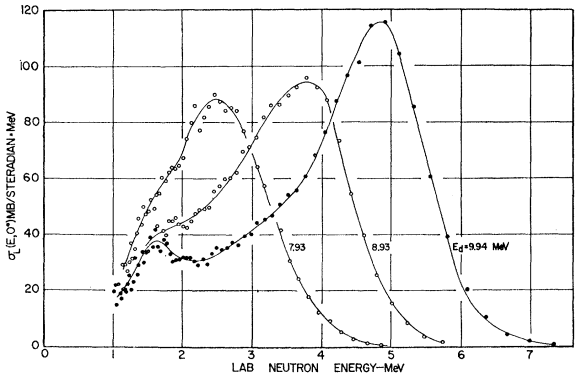

FIG. 8. Zero-degree yield of neutrons from the $He^4(d,np)He^4$ reaction in the laboratory system.

the results of Henkel *et al.*[1] and Rybakov *et al.*[18] for this reaction. Figure 11 shows the variation with angle of the neutron spectra for a deuteron energy of about 10 MeV.

As in the $D(d,np)D$ reaction, neutrons of all energies from $He^4(d,np)He^4$ are peaked forward suggesting a stripping mechanism for the reactions. The $He^4(d,np)He^4$ reaction can proceed in three ways:

$$He^4+d \rightarrow He^5+p \rightarrow He^4+p+n, \quad (1)$$

$$He^4+d \rightarrow Li^5+n \rightarrow He^4+p+n, \quad (2)$$

$$He^4+d \rightarrow He^4+p+n. \quad (3)$$

If a stripping mechanism predominates in reaction (1), the protons would tend to be concentrated in the forward direction as has been observed.[20,21] Neutrons in the forward direction would then originate from neutron emission by the backward recoiling He^5. For 10-MeV deuterons the center-of-mass energy of a neutron emitted at 0° from a He^5 nucleus recoiling at 180° is 0.280 MeV. This probably accounts for the peak at 0.3 MeV in the spectrum for 10-MeV deuterons (Fig. 9).

Stripping in reaction (2) would tend to concentrate the neutrons in the forward direction. Table I shows the observed energy of the highest energy maximum in the neutron spectrum (Fig. 9) and the energy calculated assuming that neutrons are produced via reaction (2). Rybakov *et al.*[18] have observed the neutron spectrum at

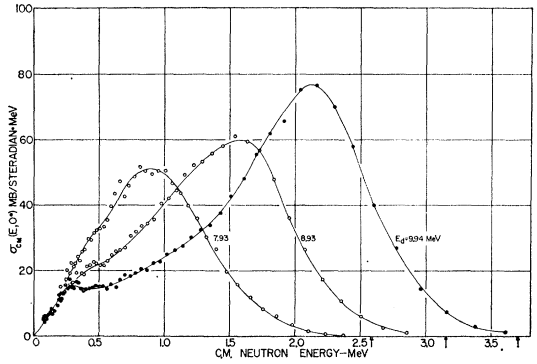

FIG. 9. Zero-degree yield of neutrons from the $He^4(d,np)He^4$ reaction in the center-of-mass system. Maximum possible neutron energies for each bombarding energy are indicated by arrows.

TABLE I. Comparison of the observed energy of the higher energy maximum in the center-of-mass neutron spectrum from $He^4(d,np)He^4$ with that calculated[a] from $He^4(d,n)Li^5$.

E_d (MeV)	7.93	8.93	9.94
Observed E_n(MeV)	0.9	1.6	2.2
Calculated E_n(MeV)	1.05	1.61	2.16

[a] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

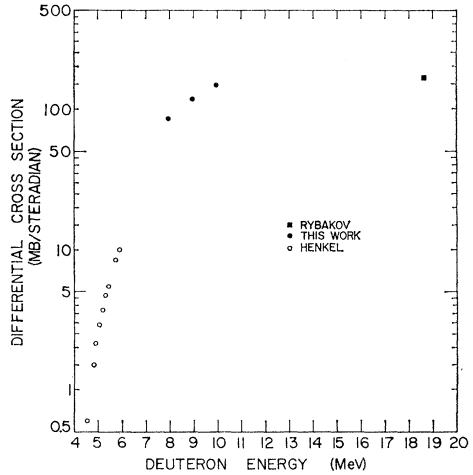

FIG. 10. Laboratory differential cross section for the $He^4(d,np)He^4$ reaction with neutron emission at 0°.

[19] L. M. Delves, Nuclear Phys. **20**, 275 (1960).
[20] E. K. Warburton and J. M. McGruer, Phys. Rev. **105**, 639 (1956).
[21] H. P. Artemov and N. A. Vlasov, Soviet Phys.—JETP **12**, 1124 (1961).

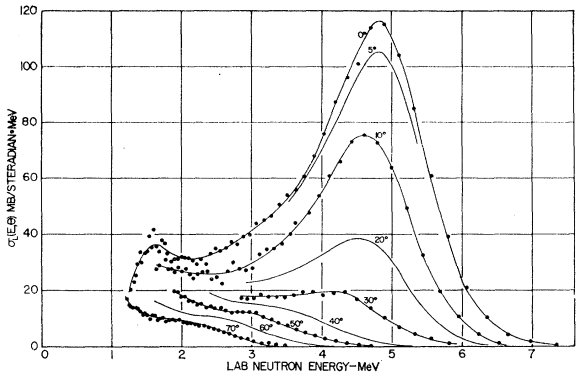

FIG. 11. Angular distribution of the $He^4(d,np)He^4$ neutron spectrum. For $\theta \leq 30°$, $E_d = 9.94$ MeV. For $\theta > 30°$, $E_d = 9.75$ MeV.

a deuteron energy of 18.4 MeV from $He^4(d,np)He^4$. They find good agreement between the position of the peak in the neutron spectrum and the position expected from formation of Li^5 in its ground state.

$T(d,np)T$ and $T(d,2n)He^3$

At the bombarding energies used for these measurements both the $T(d,np)T$ and the $T(d,2n)He^3$ reactions can take place. The Q values of the two reactions differ by 767 keV, the $(d,2n)$ reaction being more endoergic. The neutrons from the breakup reaction may thus be observed without interference from the $(d,2n)$ reaction for a center-of-mass neutron energy extending down $\sim$600 keV from the maximum neutron energy for the breakup reaction.

Figure 12 is a time spectrum at 0° from the T+d reactions with a 2.5-m flight path for a deuteron energy of 8.23 MeV. For this bombarding energy and observation angle, the maximum possible laboratory neutron energy from the (d,np) reaction is 5.2 MeV, while that from the $(d,2n)$ reaction is 4.2 MeV. The peak at about 5.2 MeV in Fig. 12 is therefore due to the breakup reaction. Below 4.2 MeV, neutrons from both reactions can contribute to the neutron spectrum. The occurrence of the $(d,2n)$ reaction was demonstrated by Brolley *et al.*[22] who observed He^3 emission from the T+d reactions.

The peak at or near the maximum possible neutron energy from breakup is interesting for the following reason: A neutron can be produced with the maximum possible energy only if the proton and triton recoil together with the same velocity and remain together until the neutron moves out of the range of nuclear forces. The peak in the neutron spectrum shows that this occurs with high probability and suggests that the proton and triton tend to remain together because of attractive forces. This is equivalent to an excited state of He^4. The position of the level can be determined from the energy of the neutrons which leave the residual nucleus in the excited state. If such a state occurs, its energy above the He^4 ground state is of interest.

To improve the accuracy and resolution of the neutron energy measurements, a spectrum was taken with a 4-m flight path. Bombarding energy was 7.93 MeV, and the detector was at 10°. The slope of the high-energy cutoff of the neutron spectrum was limited by the resolution of the spectrometer and occurred in less than 210 keV. The measured midpoint of the high energy edge was 4.8±0.2 MeV while the calculated maximum energy from $T(d,np)T$ was 4.85 MeV. The position of the maximum in the spectrum was 4.6±0.2 MeV and the slope of the spectrum at flight times longer than that of the maximum was smaller by a factor of five than the slope for smaller flight times. Within the accuracy and resolution of the measurement, the neutron yield from $T(d,np)T$ cuts off sharply at the maximum possible neutron energy.

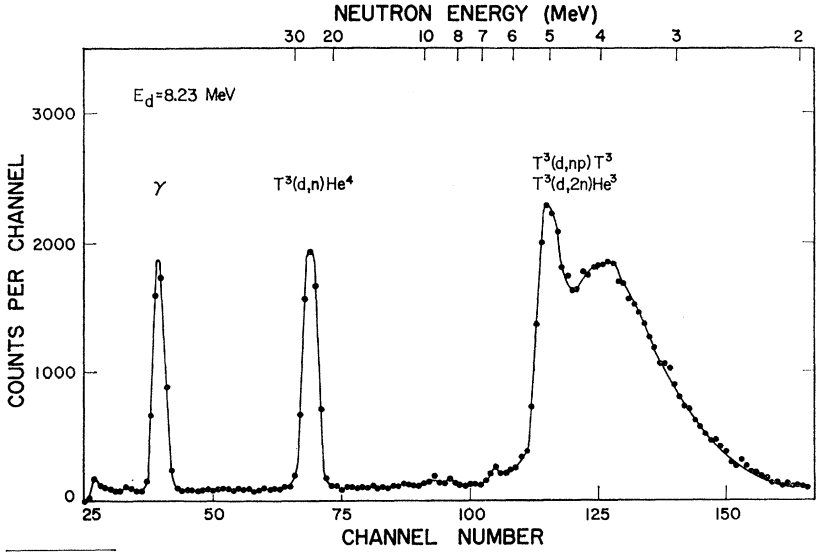

FIG. 12. Time spectrum from T+d reactions at 0° for $E_d = 8.32$ MeV. For this spectrum the flight path was 2.5 m and the detector bias was 2.4 MeV.

[22] J. E. Brolley, Jr., W. S. Hall, L. Rosen, and L. Stewart, Phys. Rev. **109**, 1277 (1958).

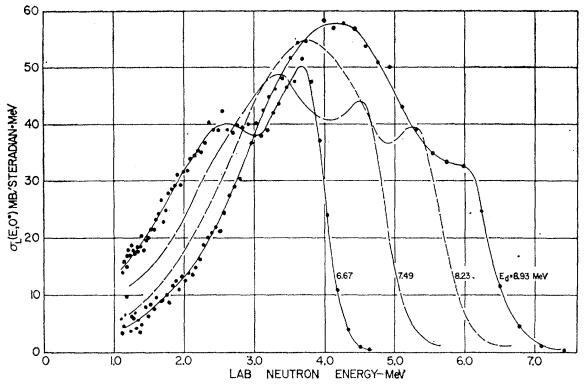

FIG. 13. Zero-degree yield of neutrons from T(d,np)T and T$(d,2n)$He^3 in the laboratory system.

Figures 13 and 14 show the variation of the neutron energy spectrum with bombarding energy in the laboratory and center-of-mass system. These spectra were obtained with a 1.5 m flight path. The energy scale is correspondingly less accurate than that for the spectra with longer flight paths. The midpoints of the high-energy edge of the spectra are higher than the calculated end points (arrows in Fig. 14) by about 7%. On the basis of the data taken with a 4-m flight path, the energy scale in Figs. 13 and 14 should probably be changed to place the midpoint of the high-energy edge of the neutron spectrum at the maximum possible neutron energy from breakup. If the peak near the breakup maximum energy is caused by an excited state of He^4, the data obtained at 4 m would place it at 20.0±0.2 MeV above the ground state. The energy above the ground state at which He^4 becomes unstable against proton emission is 19.81 MeV. Below this energy, a level in He^4 would be bound.

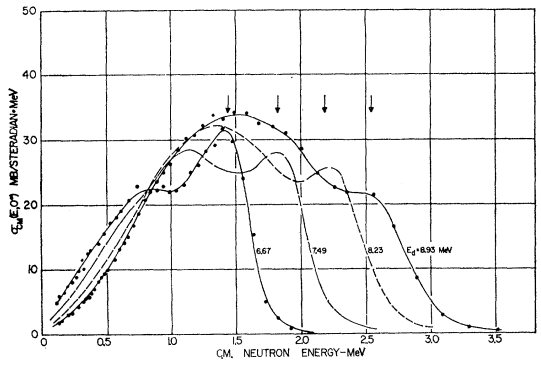

FIG. 14. Zero-degree yield of neutrons from T+d reactions in the center-of-mass system. Maximum possible neutron energies from T(d,np)T are indicated by arrows. As mentioned in the text, the energy calibration for these spectra has a large uncertainty.

Vlasov *et al.*[4] have also observed two maxima in the continuous neutron spectrum from T+d reactions for deuteron energies of 18 and 19 MeV. They ascribe the higher energy maximum to a level in He^4 at 22 MeV and suggest that this level is responsible for the observed broad maximum in the T(p,n)He^3 cross section at $E_p=3$ MeV. As described above, however, the data reported here are not consistent with a level in He^4 at 22 MeV.

Bergman *et al.*[23] have suggested a level in He^4 at about 20 MeV above the ground state. The evidence for this level is the behavior of the n+He^3 capture cross section at low energy. The ratio of the He$^3(n,p)$T cross section to the Li$^6(n,\alpha)$T cross section increases with decreasing neutron energy. Bergman's measurements of the Li$^6(n,\alpha)$T cross section as a function of energy indicated that this cross section varied as $1/v$. Their results thus indicate that the He$^3(n,p)$T cross section increases with decreasing neutron energy faster than $1/v$. Bame and Cubitt,[24] however, find that the Li$^6(n,\alpha)$T cross section does not vary as $1/v$. Using Bergman's cross-section ratios and their own Li$^6(n,\alpha)$T cross section, Bame and Cubitt find a $1/v$ dependence for the He$^3(n,p)$T cross section.

Bergman *et al.* explain their observed energy dependence of the He$^3(n,p)$T cross section by assuming a resonance at negative energy in the n+He^3 system. For an S-wave resonance, the position of the level was −750 keV; for a P-wave resonance, a level at −250 keV was required. In either case the He^4 level would be unstable against proton emission.

Several other experiments have been reported which are pertinent to the question of the existence of an excited state in He^4.[25–28] The results of these experiments are either negative or inconclusive. An analysis of the data of Fig. 14 in terms of an excited state of the α particle is presented in the following paper.[29]

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