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Neutrons from D+T and D+H*

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Continuous neutron spectra produced by bombarding T and H with deuterons have been measured using time-of-flight spectrometry for a wide range of deuteron bombarding energies and neutron emission angles. The observed spectra for the D+T interaction exhibit two maxima, one occurring at a neutron energy slightly below the maximum possible energy of neutrons from deuteron breakup and the other occurring several MeV lower. The high energy peak is interpreted as arising from monoenergetic neutrons which leave He^4 in an excited state at 20 MeV. For the D+H interaction the observed spectra exhibit no structure.

INTRODUCTION

This paper reports an investigation of the continuous neutron spectra produced when T and H are bombarded with deuterons. These continuous spectra arise from reactions in which three particles occur in the final state. The existence of neutrons from deuteron breakup on H and T, as well as on He^3 and He^4, was first reported by Henkel *et al.*,[1] although energy spectra were not obtained. For the D+T interaction neutrons with a continuous energy distribution may also be produced by the $T(d,2n)He^3$ reaction[2] when the deuteron bombarding energy exceeds 4.99 MeV.

Neutron spectra from the D+T interaction were first observed using time-of-flight spectrometry by Vlasov *et al.*[3] In addition to the monoenergetic group of neutrons from the $T(d,n)He^4$ reaction, a continuum of low energy neutrons was observed. At deuteron bombarding energies of 18 and 19 MeV a slight peak observed on the high-energy end of the continuous spectrum was interpreted as a group of neutrons which leave He^4 in an excited state at 22 MeV.[4]

The possibility of excited states in the alpha particle has been suggested in connection with other experiments. The broad maximum in the total cross section for the $T(p,n)He^3$ reaction has been interpreted as arising from a 2^- level at an excitation energy of 22 MeV.[5] The electric dipole nature of the angular distribution of gamma rays from the $T(p,\gamma)He^4$ reaction has led to the suggestion of a 1^- level.[6] Evidence for a level near 22 MeV has also arisen from an observation[7] of protons inelastically scattered from He^4. Various authors[8–10] have pointed out, however, that the results of these experiments can be explained without assuming an excited state in the alpha particle.

Continuous neutron spectra similar to those observed by Vlasov *et al.* have been obtained in previous work at this laboratory.[11] These spectra also exhibited a peak near the high-energy end. The measurements indicated that if the peak is caused by an excited state in the alpha particle the excitation energy would be 20 MeV, but a systematic error in the energy calibration for the D+T neutron spectra was reported. Furthermore, the D+T data had not been corrected for the presence of a hydrogen contaminant in the tritium target gas. These problems have been overcome in the present experiment and the measurements have been extended in order to examine more thoroughly the dependence of the neutron spectra on deuteron energy and neutron emission angle.

Although the D+H interaction has been examined in some detail both experimentally[12–15] and theoretically,[16,17] it was necessary to obtain additional data in order to correct the D+T neutron spectra for the presence of neutrons from deuteron breakup on the hydrogen contaminant. The data reported here extend earlier measurements of D+H neutron spectra to lower center-of-mass energies.

EXPERIMENTAL

Deuterons were accelerated with a tandem electrostatic accelerator and neutron spectra were obtained using pulsed-beam time-of-flight spectrometry. The various components of the spectrometer have been

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described in detail[18] and the experimental procedure was similar to that used earlier.[11]

The efficiency of the detector was obtained as a function of neutron energy by measuring neutrons emitted at zero degrees from neutron producing reactions with known cross sections. The $T(p,n)He^3$ reaction was the source of neutrons of energies from the detector bias of 850 keV to about 6 MeV. The yield was measured with the time-of-flight spectrometer, and the zero-degree $T(p,n)$ cross section used to compute the efficiency was that of Perry *et al.*[19] For neutrons of energies between 5 and 15 MeV the $D(d,n)He^3$ reaction was used and the reaction cross section was that given by Fowler and Brolley.[20] Because the purity of the tritium target gas was not known, the efficiency measured with the $T(p,n)$ reaction was normalized to that measured with the $D(d,n)$ reaction.

The target gas was contained in a cylindrical gas cell about 2 cm long. A 2.5-μ Ni foil separated the target gas from the vacuum in the accelerator beam tube. The charged particle beam was stopped in a 0.5 mm thick pure Au backstop at the end of the cell. Gas pressure was usually maintained at about 0.8 atm.

Before converting the time-of-flight data to energy spectra, background corrections were made. Background neutrons produced in the foil and target backing were measured by taking a time spectrum with the target cell evacuated. Background caused by radiation not coming directly from the target was measured by placing a brass shadow bar between the target and the detector and was found to be uncorrelated in time with the beam bursts. In a spectrum taken without the shadow bar, the region of the spectrum between the target gamma peak and the highest energy neutrons was found to be a good measure of this flat background.

Another source of background is the presence of neutron-producing contaminants in the target gas. From the measured yield of neutrons from deuteron breakup on hydrogen it was possible to correct the D+T data for the presence of a hydrogen contaminant. The relative amount of tritium in the target gas was determined from the normalization of the efficiency measured with p+T neutrons to that measured with D+D neutrons. The impurity in the target gas was attributed entirely to hydrogen. Gaseous impurities such as D_2, N_2, O_2, CO_2, and water vapor appeared to be unimportant because no peaks in any time spectrum (with background subtracted) corresponding to neutrons from the $D(d,n)$, $N^{14}(d,n)$, $O^{16}(d,n)$, and $C^{12}(d,n)$ reactions were observed. Unlike the tritium, the hydrogen used in the D+H measurements and the deuterium used in the efficiency measurement had a purity greater than 99.5%.

RESULTS

The D+T Interaction

Figures 1, 2, and 3 show the continuous energy spectra of neutrons emitted at zero degrees from the D+T interaction for incident deuteron energies from about 5 to 12 MeV. A smooth curve is drawn through the data points to indicate the trend of the data. The data points are cut off at a lower limit of 1 MeV. Below this limit the uncertainty in the detector efficiency and the poor statistics because of the small value of the efficiency make the data unreliable.

Because of the nonlinear nature of the conversion of time to energy, the data points get closer and closer together as the neutron energy decreases. Below 2 MeV the points shown are averages of three adjacent points. This averaging was done for every spectrum except the one obtained for a deuteron energy of 4.80 MeV where the averaging was done only on the low-energy side of the peak.

The maximum possible energy of neutrons emitted at 0° from the reactions $T(d,np)T$ and $T(d,2n)He^3$ is indicated by the arrows shown on each spectrum; the

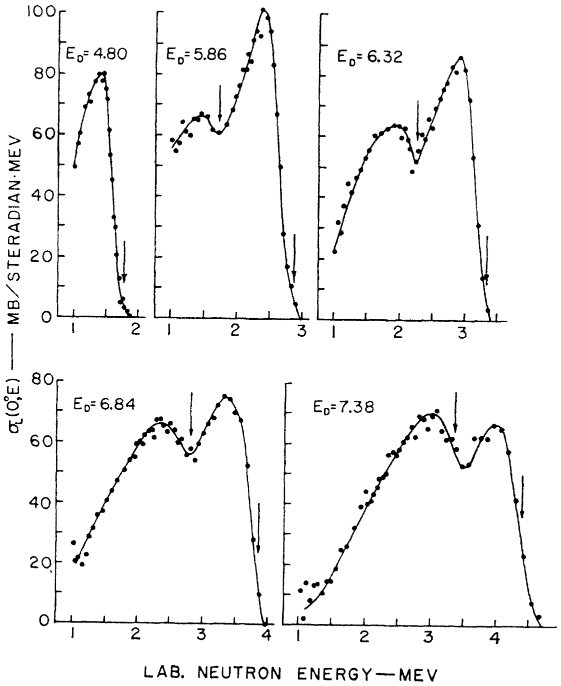

FIG. 1. Energy spectra of neutrons emitted at zero degrees from the D+T interaction for various deuteron bombarding energies, E_D(MeV). The arrow appearing at the higher neutron energy indicates the maximum possible energy of neutrons from the $T(d,np)T$ reaction; the other arrow indicates the maximum possible energy of neutrons from the $T(d,2n)He^3$ reaction.

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arrow appearing at the higher neutron energy is always for the T(d,np)T reaction. Only one arrow is shown for the spectrum obtained for a deuteron energy of 4.80 MeV, because the threshold (4.99 MeV) for the T($d,2n$)He^3 reaction has not yet been reached.

For deuteron bombarding energies greater than 10.44 MeV, neutrons with a continuous energy distribution can also be produced from the T(d,nd)D reaction. The maximum possible energy of such neutrons would be 1.99 and 3.28 MeV, respectively, for deuteron bombarding energies of 10.89 and 11.89 MeV. Nothing that indicates the presence of such neutrons can be seen in the relevant spectra in Fig. 3.

The spectra shown in Figs. 1, 2, and 3 exhibit two prominent features. First, there is the peak near the high-energy end of the spectrum. This peak, which is narrow and well defined at the lower deuteron energies, reaches a maximum height at a deuteron energy of about 6 MeV. The peak then gradually decreases and becomes less distinct as the deuteron energy increases. For deuteron energies near 11 and 12 MeV the peak has become only a slight shoulder on the high-energy side of the spectra.

The second prominent feature of these spectra is the broad maximum appearing at lower neutron energies. This maximum is first observed in the spectrum obtained for a deuteron bombarding energy of about 6 MeV. It increases to a maximum height at a deuteron energy of about 8 MeV. From 9 MeV on, the height of this maximum remains approximately constant, while its width steadily increases.

Angular distributions of the neutron spectra are shown in Figs. 4–8. The smooth curves indicate the trend of the data points, which, for clarity, are shown only on every other curve. Again, below 2 MeV the points shown are averages of three adjacent data points. The maxima observed at 0° are also seen at other angles, although the high-energy peak becomes less

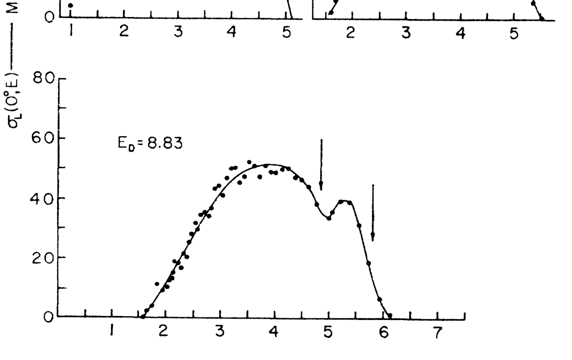

FIG. 2. Energy spectra of neutrons emitted at zero degrees from the D+T interaction for various deuteron bombarding energies, E_D(MeV). The arrow appearing at the higher neutron energy indicates the maximum possible energy of neutrons from the T(d,np)T reaction; the other arrow indicates the maximum possible energy of neutrons from the T($d,2n$)He^3 reaction.

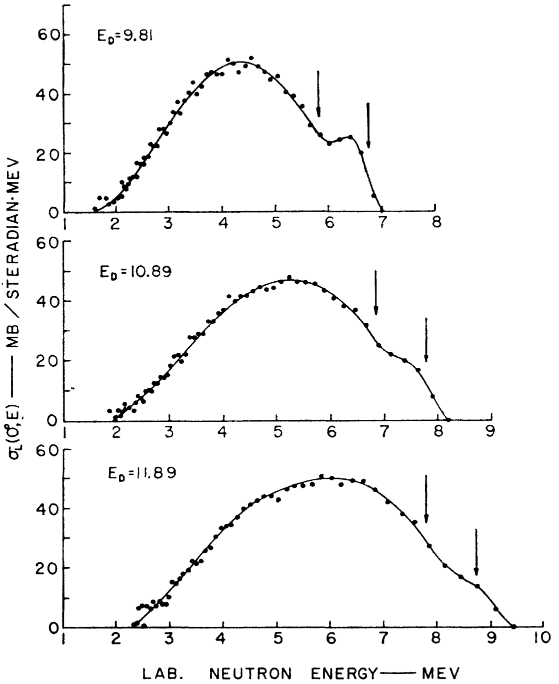

FIG. 3. Energy spectra of neutrons emitted at zero degrees from the D+T interaction for various deuteron bombarding energies, E_D(MeV). The arrow appearing at the higher neutron energy indicates the maximum possible energy of neutrons from the T(d,np)T reaction; the other arrow incidates the maximum possible energy of neutrons from the T($d,2n$)He^3 reaction.

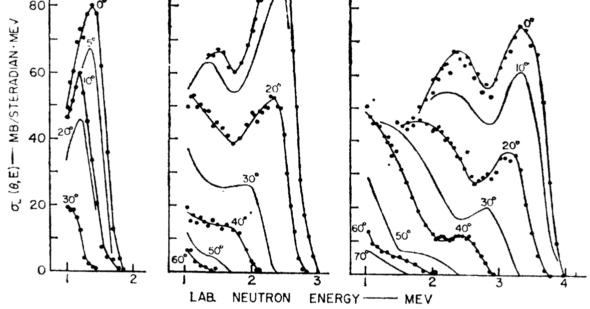

FIG. 4. Angular distributions of the neutron spectra for the D+T interaction at E_D=4.80, 5.86, and 6.84 MeV.

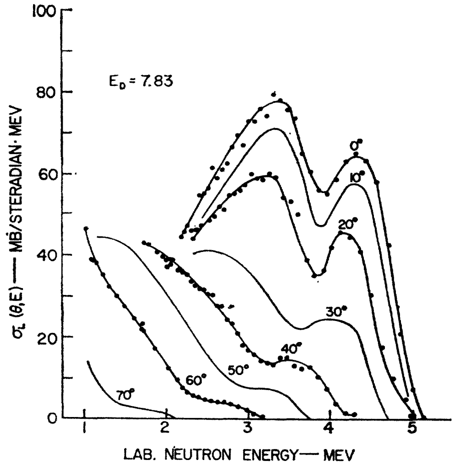

FIG. 5. Angular distribution of the neutron spectrum for the D+T interaction at E_D=7.83 MeV.

distinct as the angle increases. The height of this peak decreases more rapidly with angle than the maximum appearing at the lower neutron energy.

The D+H Interaction

The energy spectra of neutrons emitted at zero degrees from the D+H interaction are shown in Fig. 9 for deuteron bombarding energies from about 7.5 to 12 MeV. The smooth curves show the trend of the experimental points, and as before points below about 2-MeV neutron energy are averages of three adjacent data points. These spectra show no marked structure, the only prominent feature is the peaking of the spectra at high neutron energies as the deuteron energy is increased. The arrows indicate for each spectrum the maximum possible energy of neutrons from deuteron breakup on hydrogen, $H(d,np)H$. The appearance of points at energies greater than the maximum possible neutron energy is caused by the resolution of the spectrometer.

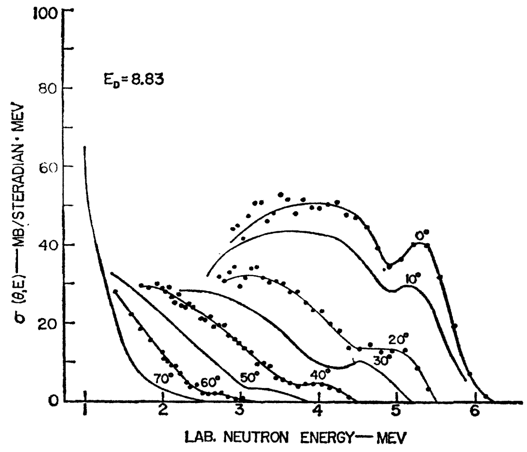

FIG. 6. Angular distribution of the neutron spectrum for the D+T interaction at E_D=8.83 MeV.

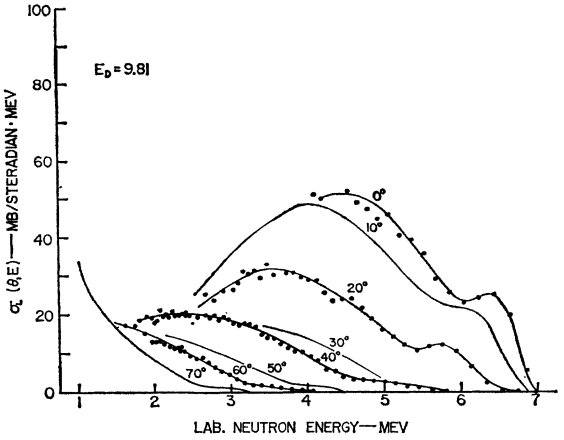

FIG. 7. Angular distribution of the neutron spectrum for the D+T interaction at E_D=9.81 MeV.

Neutrons from the $H(d,np)H$ reaction lie within a cone centered about zero degrees. In the range of deuteron energies covered, the half-angle of the cone varies from about 20° to 40°. At this angle the maximum possible neutron energy is 1.48 MeV, independent of the incident deuteron energy. This maximum energy is only about 0.5 MeV greater than the energy below which the data have been considered unreliable. Consequently, angular distributions were taken only to an angle of 20°. Angular distributions of the neutron spectra are shown in Fig. 10.

Accuracy of the Measurements

The scatter of the data points is a measure of the statistical uncertainty. Because of the smaller yield the statistical uncertainty of the D+H data is generally greater than that of the D+T data. For both reactions other uncertainties are considerably larger than the statistical uncertainty.

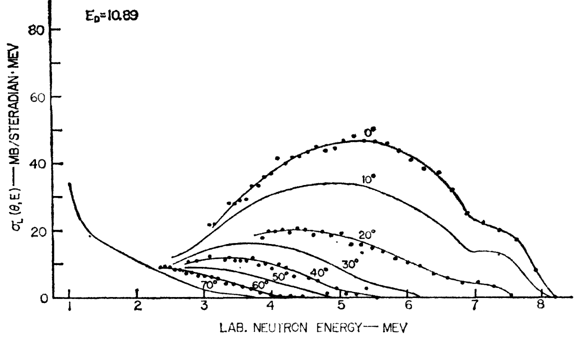

FIG. 8. Angular distribution of the neutron spectrum for the D+T interaction at E_D=10.89 MeV.

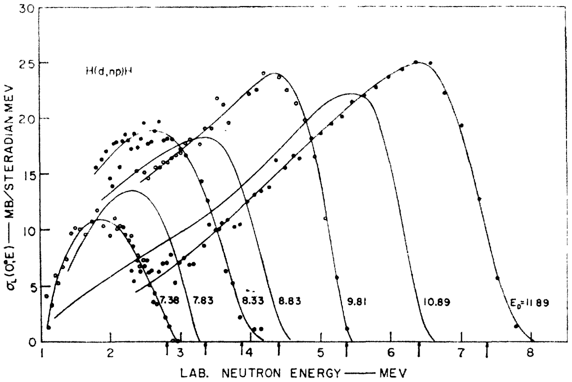

FIG. 9. Energy spectra of neutrons emitted at zero degrees from the D+H interaction for various deuteron bombarding energies, E_D(MeV). The arrows indicate for each spectrum the maximum possible energy of neutrons from the H(d,np)H reaction.

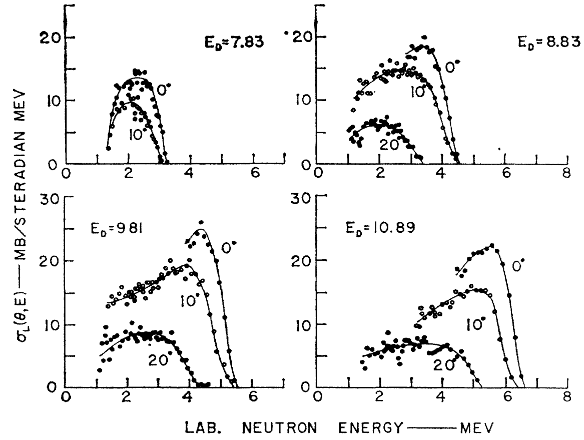

FIG. 10. Angular distributions of the neutron spectra for the D+H interaction for various deuteron bombarding energies, E_D(MeV).

A major source of uncertainty is the measurement of the detector efficiency. The uncertainty in the absolute detector efficiency owing to uncertainties in the reaction cross sections, areal density of target nuclei, charge integration of the incident beam, background subtraction, and normalization of the T(p,n) data to the D(d,n) data is ±15% for neutron energies greater than 2 MeV. For neutron energies less than 2 MeV shifts in the detector bias can cause the uncertainty to be larger than ±15%.

In the D+T data additional uncertainty is introduced because of the uncertainty in the relative amount of tritium in the target gas. This affects both the absolute value of the cross section and the shape of the spectra. The shape is affected through the contribution of neutrons from D+H.

The maximum uncertainty caused by the combined uncertainties in the statistics, efficiency measurement, background subtraction, target thickness, and charge integration is difficult to evaluate exactly. A value of ±20% probably represents an upper limit for the uncertainty assigned to the cross section for the D+H reaction, while, because of the uncertainty in the purity of the tritium, ±25% is probably an upper limit for the D+T reaction.

On the basis of comparisons between measured and calculated energies of monoenergetic neutron groups from reactions with known Q values, it is felt that the error in the absolute energy calibration is less than ±2% for all the data. Energies of peaks on a particular spectrum taken on widely separated dates were reproducible to within ±1.5%.

DISCUSSION

D+T

If, as suggested by Vlasov *et al.*,[4] the peak observed near the high-energy end of the continuous spectrum is caused by a group of monoenergetic neutrons which leave He^4 in an excited state, it should be possible to calculate a unique Q value for the reaction from the position of the peak. To determine the position of the peak, a smooth curve from the region of the spectrum corresponding to the maximum possible energy of neutrons from the T$(d,2n)$He^3 reaction was extrapolated to zero at the maximum possible energy of neutrons from the breakup reaction. The smooth curve was subtracted from the curve drawn through the data points. It should be noted, however, that there is no *a priori* reason to assume that the only contribution of the breakup neutrons to the shape of the spectrum in this region is represented by the smooth curve. The position of the resulting peak then falls at a neutron energy E_n somewhat greater than the energy corresponding to the highest point of the peak as it appears in the spectrum. Q values calculated from E_n are listed in Table I for all spectra in which the position of the peak could be reliably determined. These values are symmetrically and randomly distributed about a mean of −2.50 MeV with a standard deviation of 0.06 MeV. 70% of the values lie within one standard deviation from the mean. A Q value of −2.50 MeV for the T(d,n)He^{4*} reaction corresponds to an excitation energy in the alpha particle of 20.1 MeV.

An attempt was made to determine the width of the state. The resolution function of the spectrometer and the peak that results from the subtraction of the smooth curve from the data were treated as Gaussian functions so that a simple correction could be made for the effect of finite resolution. The width was then determined for all spectra corresponding to the deuteron energies and neutron emission angles given in Table I, with the exception of the 4.80-MeV data. The resulting values (full width at half-maximum) in the center-of-mass system lie between 300 and 400 keV and no systematic variation with energy is evident. Because of the uncertainty in the method of accounting for the breakup

TABLE I. Q values for the reaction $T(d,n)He^{4*}$ calculated at various deuteron bombarding energies E_D, and neutron emission angles θ. E_n' is the energy of the highest point of the peak as it appears in the spectrum; E_n is the energy of the peak after subtraction of the smooth background.

E_D(MeV)	θ(deg)	E_n'(MeV)	E_n(MeV)	$-Q$(MeV)
4.80	0	1.41	a	2.48
	5	1.39	a	2.48
	10	1.20	a	2.57
	20	1.23	a	2.48
	30	1.11	a	2.43
5.86	0	2.39	2.45	2.55
	5	2.43	2.45	2.54
	10	2.40	2.49	2.48
	20	2.27	2.36	2.45
	30	1.93	1.96	2.56
	40	b	1.75	2.48
6.32	0	2.92	2.96	2.48
6.84	0	3.31	3.50	2.50
	5	3.43	3.52	2.48
	10	3.35	3.43	2.50
	20	3.17	3.36	2.41
	30	2.18	2.89	2.53
	40	2.39	2.53	2.51
7.38	0	3.95	4.09	2.46
7.83	0	4.31	4.55	2.45
	5	4.26	4.38	2.57
	10	4.12	4.29	2.59
	20	4.09	4.23	2.45
	30	3.55	3.67	2.61
	40	b	3.36	2.49
8.33	0	4.59	4.93	2.53
8.83	0	5.21	5.43	2.52
	5	5.01	5.45	2.49
	10	5.06	5.40	2.48
	20	4.80	4.98	2.60
	30	4.56	4.63	2.54
	40	3.92	4.11	2.54
9.33	0	5.81	6.11	2.36
9.81	0	6.42	6.52	2.41
	5	6.17	6.43	2.46
	10	6.02	6.29	2.52
	20	5.75	5.89	2.59

[a] Not enough of a spectrum to determine smooth background. It is not expected that E_n will differ very much from E_n' at this low energy, so that the values of Q shown are calculated from E_n'.

[b] Peak becomes distinct only after smooth background is subtracted.

neutrons and the simplification regarding the spectrometer resolution, the values obtained for the width are dubious.

The data taken earlier at this laboratory[11] have been analyzed by Werntz[21] in terms of a stripping reaction in which the proton and triton remain unbound and interact strongly in the final state. Werntz was able to fit the data by assuming that the $p-T$ interaction in the singlet state is an s-wave resonant scattering with a resonance energy of about 0.4 MeV in the $p-T$ system.

Other evidence for an excited state in the alpha particle near 20 MeV has been reported. Bergman *et al.*[22,23] have suggested that an observed deviation of the low-energy $n+He^3$ capture cross section from a $1/v$ law may be explained by the presence of a 0^+ level in the alpha particle at an excitation energy near 20 MeV. This spin and parity assignment is in agreement with Werntz' assumptions. However, Gemmell *et al.*[24] report that Lane has interpreted the $T(p,\gamma)$ cross section in terms of a 1^- state near the $T(p,n)$ threshold (19.8-MeV excitation energy).

The difference in excitation energies calculated in the present work and the work of Vlasov *et al.*[4] appears to be well outside any errors in energy calibration. It is believed, therefore, that the peak observed here is not the same as the one observed at 18 and 19 MeV deuteron bombarding energy.

D+H

The D+H interaction has been studied in terms of final-state nuclear interactions with varying degrees of success. Frank and Gammel[25] considered only final state n-p interactions, while Heckrotte and MacGregor[16] considered only final-state p-p interactions. These authors were only partially successful in fitting experimental data. By considering both types of interactions, Komarov and Popova[17] were able to explain successfully the presence of two peaks in a spectrum obtained by Rybakov *et al.*[14]

Because the data reported here do not exhibit the structure observed by others at higher center-of-mass energies, it is possible that final-state nuclear interactions need not be considered here. In the absence of such interactions the shape of the spectrum would be largely determined by the density of the neutron energy states. When the final state is composed of three

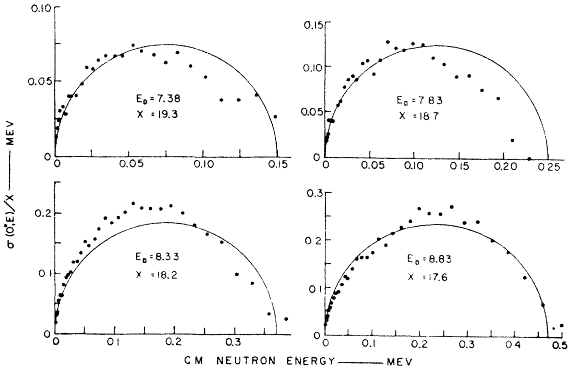

FIG. 11. Plot of the experimental values of $\sigma(0°,E)/X$ vs center-of-mass neutron energy, E, for various deuteron bombarding energies, E_D(MeV). $\sigma(0°,E)$ is the zero-degree differential cross section in the center-of-mass system for the emission of neutrons of energy between E and $E+dE$ from the $H(d,np)H$ reaction. For each spectrum the value of X in mb/sr. MeV^2 is indicated. The semicircle is a plot of the function $\sigma(0°,E)/X=[E(E_M-E)]^{\frac{1}{2}}$, where E_M is the maximum possible energy of neutrons from the $H(d,np)H$ reaction.

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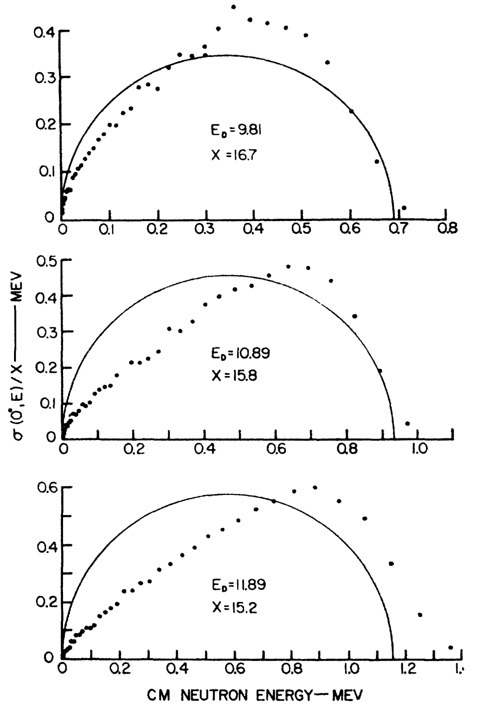

FIG. 12. Plot of the experimental values of $\sigma(0°,E)/X$ vs center-of-mass neutron energy, E, for various deuteron bombarding energies, E_D(MeV). $\sigma(0°,E)$ is the zero-degree differential cross section in the center-of-mass system for the emission of neutrons of energy between E and $E+dE$ from the H(d,np)H reaction. For each spectrum the value of X in mb/sr. MeV^2 is indicated. The semicircle is a plot of the function $\sigma(0°,E)/X=[E(E_M-E)]^{\frac{1}{2}}$, where E_M is the maximum possible energy of neutrons from the H(d,np)H reaction.

particles, the density of final states, or phase-space factor, $\rho_f(E)$, is given by [26]

$$\rho_f(E) \propto [E(E_M-E)]^{1/2} \tag{1}$$

where E and E_M are, respectively, the energy and the maximum possible energy of the detected particle in the center-of-mass system.

The zero-degree spectrum obtained at a deuteron bombarding energy of about 9 MeV was transformed to the center-of-mass system and fitted to

$$\sigma(0°,E)=C[E(E_M-E)]^{1/2}/v_D \tag{2}$$

where v_D is the velocity of the incident deuteron, and C is a constant determined from the fit. Because the energy of the incident deuteron is at least several times the energy of the Coulomb barrier, it is expected that the variation of the cross section with bombarding energy will be contained entirely in the phase-space factor, i.e., C is not a function of v_D. Using the value of C obtained from the 9-MeV data, experimental values of $\sigma(0°,E)/X$, where $X=C/v_D$, are plotted as a function of E in Fig. 11 for values of the deuteron bombarding energy from about 7.5 to about 9 MeV. The semicircle is σ/X, where σ is given by Eq. (2) and E_M is calculated from the kinematics.

Figure 12 shows data obtained at deuteron energies near 9, 10, and 11 MeV. The deviation of the experimental points from the semicircle becomes quite marked as the deuteron energy increases. On the basis of the analysis of Komarov and Popova[17] it is possible that the peaking in the data reported here indicates the onset of a final state nuclear p-p interaction.

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[26] See, for example, E. Fermi, *Elementary Particles* (Yale University Press, New Haven, Connecticut, 1951), p. 55.