able. With this value the scale for the abscissa in Fig. 2 is, as shown, of the order of millibarns, and we see that the cross section for this case is very small. On the other hand, a similar calculation by Margolis and Pollack[13] for a zero to zero transition, with the excited level 1 Mev above ground, gives a cross section of several tens of millibarns, very close to the maximum of 100 mb.

[13] B. Margolis (private communication).

ACKNOWLEDGMENTS

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Neutrons from the D-D Reactions*

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An investigation has been made of the neutron spectra resulting from D-D reactions for a range of incident deuteron energies of 4.75 to 7.33 Mev, using a pulsed-beam time-of-flight method. In addition to monoenergetic neutrons from the reaction $D(d,n)He^3$, a continuum of neutrons is observed corresponding to $D(d,np)D$. The yield of the latter reaction has been measured at about 0.5-Mev intervals at zero degrees, and at an energy of 6.3 Mev an angular distribution has been obtained for both reactions. At 6.3-Mev deuteron energy and at zero degrees the yield of the continuum for neutron energies above 0.95 Mev is 17% of the yield of monoenergetic neutrons. The yield from both reactions is strongly forward in the laboratory reference frame, and for the breakup process increases rapidly with increase in energy above threshold.

INTRODUCTION

THE exothermic reaction $D(d,n)He^3$ is commonly used as a source of monoenergetic neutrons for energies above 2.5 Mev. The neutrons from this reaction are the only ones produced in a D-D process up to the bombarding energy for which breakup of one of the deuterons becomes energetically possible. Above that energy a continuum of neutrons is to be expected due to the three-body process $D(d,np)D$ in addition to the monoenergetic group due to $D(d,n)He^3$. Such a continuum has indeed been observed for 14-Mev deuterons,[1] although at that energy breakup of both deuterons is energetically possible. It seemed worthwhile, therefore, to make a detailed examination of the neutron spectra from the D-D reaction at energies above the threshold for breakup, that is, above a laboratory energy of 4.45 Mev. Such data should be useful as input data for other experiments which use energetic D-D neutrons, and are pertinent to the physics of the reactions of light nuclei.

METHOD AND APPARATUS

Neutron spectra were obtained by a straightforward application of the pulsed-beam time-of-flight techniques previously described,[2] using the pulsed deuteron beam output of the large Los Alamos electrostatic accelerator. The gas target was 6 cm long, filled with D_2 gas at a pressure of 60 cm of Hg, and was sealed off from the vacuum system by a nickel foil 1.5 μ thick. Design of the target was such as to minimize the amount of material in the immediate vicinity of the gas which might scatter neutrons. Although this was the first time a pulsed deuteron beam was used no special problems were encountered. A high neutron background filled the target area even when there was no beam on target, due presumably to the deflected beam striking low-Z material, but the shielding around the detector was very effective against this background. The detector used was the same as the one previously described[2] and was mounted at a distance of 1.5 meters from the target. The average target current was about 0.05 μa and the running time for a spectrum was about ten minutes.

RESULTS

Spectra have been obtained as a function of angle at the primary deuteron energy of 6.3 Mev at ten degree intervals up to 40 degrees, and at zero degrees data have been taken in approximately 0.5-Mev intervals from 4.75 Mev to 7.33 Mev.

Figure 1 shows the time spectra obtained at zero degrees with and without deuterium in the target for a deuteron energy of 6.3 Mev. These spectra were recorded in the same way as those described previously.[2] Although the raw data are in the form of a 100-channel

* This work performed under the auspices of the U. S. Atomic Energy Commission.
[1] Bogdanov, Vlasov, Kalinin, Rybakov, and Sidorov (private communication); J. Exptl. Theoret. Phys. (U.S.S.R.) (to be published).
[2] L. Cranberg and J. S. Levin, Phys. Rev. 103, 343 (1956).

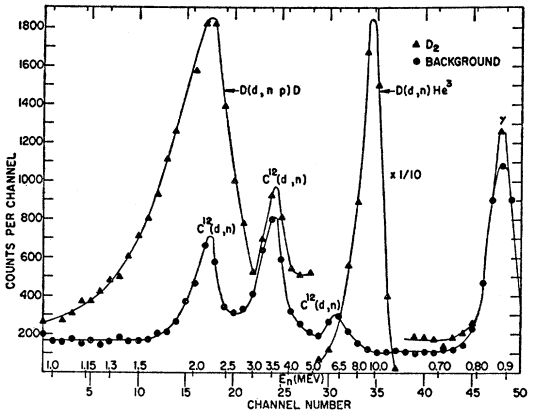

FIG. 1. The time spectrum of neutrons from the D-D reactions for an incident deuteron energy of 6.3 Mev as seen at zero degrees to the deuteron direction. The corresponding spectrum for an evacuated target is also shown.

presentation of two cycles of the data, only a single cycle is shown in Fig. 1.

The vacuum background was unexpectedly structured, and since one of the peaks appeared to coincide with a peak in the "gas-in" run, it seemed advisable to identify the source of the structure. A run with hydrogen in the target gave a result identical to the vacuum run, thereby eliminating the possibility that the gas might be scattering deuterons into the steel walls of the target, making neutrons there. A spectrum was then run with a filling of methane. This gave almost precisely the same three peaks with the same relative intensities as those which are identified in Fig. 1 as due to the reaction $C^{12}(d,n)$. The small differences in the positions of the peaks for the vacuum and methane runs could be accounted for if it were assumed that in the vacuum case the carbon was on the entrance side of the nickel window. For the methane filling, it was assumed that the effective source was at the center of the target. The chief difference between the carbon and methane spectra should then be due to a 200-kev difference in the effective deuteron energy. This difference was clearly evident in its effect on the energy of the least energetic neutron group. From the energies of the groups, the Q values calculated for the ground state and first two excited states of N^{13} agreed with those given in the literature within the experimental uncertainty of about 5%. The second and third levels of N^{13}, being only 50 kev apart, could not be resolved. Thus the main features of the background are clearly understood.

The energy scale for all this work was established by assuming a linear time-to-voltage conversion and taking the positions of the γ ray and the energy of the neutrons from the reaction $D(d,n)He^3$ to be known.

It might be expected that the background due to carbon would be sensitive to the focus and to the precise position of the deuteron beam. If this were so, one would expect difficulty in reproducing results and particularly in getting the carbon peaks to subtract out. In fact the subtraction always seemed reasonable in the region which should exhibit this difficulty most sensitively—namely, in the region of the strong carbon peak which was of intermediate energy. The gamma-ray line subtraction was not a sensitive indicator because the methane run showed that carbon was not an important contributor to the strength of the gamma-ray line. It is surmised that most of the gamma rays originate in reactions in the nickel window and gold end-cap of the target. Neutrons from (d,n) or $(d,n\gamma)$ processes in the nickel or the (d,np) process in gold are evidently not numerous at the energies of these measurements.

As is clear from Fig. 1, the difference between "gas-in" and "gas-out" consists essentially of a strong group of monoenergetic neutrons due to $D(d,n)He^3$ and a continuum of lower energy neutrons which extends from about 3 Mev to at least as low as 0.67 Mev. Since the

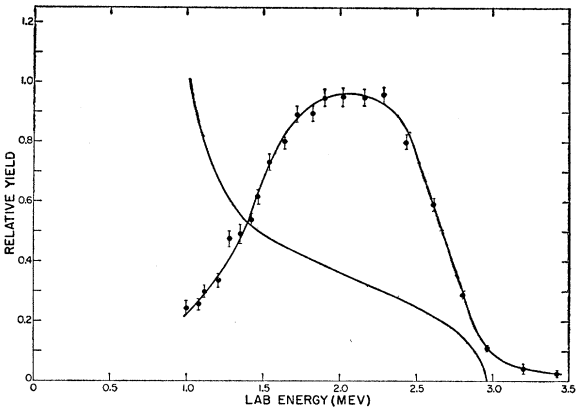

FIG. 2. The energy spectrum in the laboratory system of neutrons from the reaction $D(d,np)D$ at zero degrees for an incident deuteron energy of 6.3 Mev. Also shown is the neutron energy spectrum calculated for a statistical three-body breakup.

gas sample was specified to be better than 99.5% pure deuterium and the same result was obtained for several samples, the neutron continuum could be plausibly assumed to be due to deuteron breakup. As a check on the possible role of air contamination of the sample, a spectrum was also obtained for air. This spectrum showed clearly that the neutron continuum of Fig. 1 could not be due to air contamination.

The difference between the two curves of Fig. 1 is shown plotted in Fig. 2, after multiplication of the data at each point by the factor t^3, where t is the corresponding flight time. This factor converts the data from number per unit time interval to number per unit energy interval. For comparison Fig. 2 also shows an unnormalized spectrum calculated[3] on the simplest assumption—namely, that the three-body process occurs with random probability in all elements of phase

[3] E. Fermi, *Elementary Particles* (Oxford University Press, London, 1951).

space which are accessible, if one takes account of energy and momentum conservation and assumes that the detector subtends negligible solid angle at the target. Under the conditions of the measurements, correction for finite detector solid angle was negligible. The upper limit of this spectrum, which is derived from conservation considerations alone, agrees quite well with any reasonable extrapolation of the experimental data. The small experimental yield above this limit is plausibly explained as the effect of finite time resolution in combination with two other effects: low-energy neutrons from the preceding cycle and the tail from the very strong D(d,n)He^3 group.

It is clear from Fig. 2 that the neutron spectrum ascribed to D(d,np)D has the proper upper energy limit and that it departs quite markedly from the shape calculated on the basis of a purely statistical model. The low-energy divergence of the statistical spectrum of Fig. 2 is due to the combination of a center-of-mass dependence at low energy which goes as $E^{\frac{1}{2}}$, where E

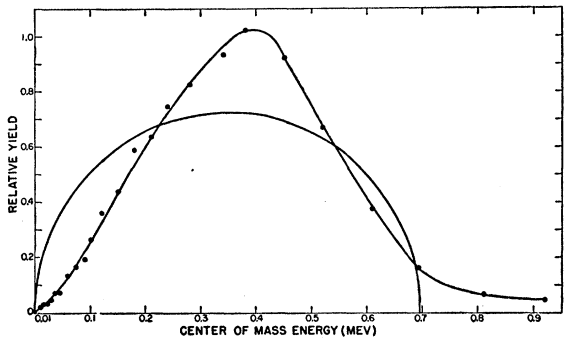

FIG. 3. The energy spectrum in the center-of-mass system of neutrons from the reaction D(d,np). Also shown is the energy distribution calculated for a statistical three-body breakup.

is the center-of-mass energy of the neutron, and a conversion factor proportional to $1/E$ in going from the center-of-mass system to the laboratory system.

The data of Fig. 2 are shown transformed into the center-of-mass coordinate system in Fig. 3. Here the theoretical curve is an ellipse whose area has been normalized to that of the experimental data. It is clear that the experimental data differ from the random distribution chiefly in being more peaked at the average energy, with fewer low- and high-energy neutrons. The effect of finite resolution is to cause this effect to be underestimated.

The lower curve in Fig. 4 shows the yield obtained at zero degrees as a function of neutron energy for the integral over the spectrum of the breakup neutrons. Because of problems associated with overlap of spectra from successive cycles, this integral extends from the kinematical limit down to 0.95 Mev except for the two lowest energy points. For the two lowest points, the lower end of the spectrum was pushed to 0.75 Mev. The errors shown on the figure are statistical. The upper

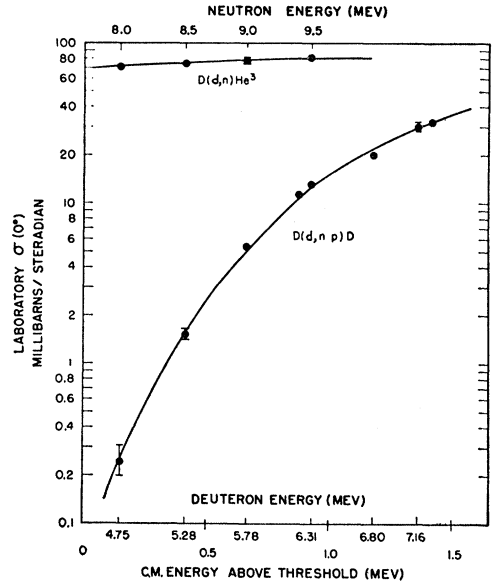

FIG. 4. The yield at zero degrees of the D(d,np)D reaction and the yield of the D(d,n)He^3 reaction according to reference 4. The upper scale gives the energy of the neutrons from the latter reaction.

curve in Fig. 4 for the yield at the corresponding deuteron energy of the reaction D(d,n)He^3 has been measured at this laboratory with a counter telescope.[4] It is shown on the same scale as the yield of breakup neutrons to indicate the trend of the branching ratio for the two reactions. The data of the lower curve of Fig. 4 are given in Table I.

The excellent agreement shown in Table I between the calculated and observed values of the upper energy limit for the continuum neutrons must be regarded as conclusive proof that these have been correctly identified. At the lowest deuteron energy the signal-background ratio was too poor to allow an accurate measurement of the maximum energy.

The cross-section values given in the table for the breakup neutrons were obtained in the following way. The curve for the relative sensitivity of the detector as a function of neutron energy has been extended upward from the result given previously[2] to a neutron energy of 10.5 Mev by using the T(p,n)He^3 and

TABLE I. Data on the zero-degree yield of the reaction D(d,np)D.

Deuteron energy (Mev)	Neutron energy upper limit (Mev) calculated	observed	σ (mb/sterad)
4.75	1.20	...	0.24±0.06
5.28	1.88	1.88±0.03	1.5 ±0.2
5.78	2.43	2.38±0.05	5.4 ±0.3
6.21	2.87	2.90±0.05	11.4 ±0.6
6.31	2.98	2.95±0.05	12.9 ±0.6
6.80	3.47	3.35±0.1	19.8 ±1.0
7.16	3.80	3.83±0.1	30.2 ±2.0
7.33	4.00	4.02±0.1	32.0 ±2.0

[4] R. K. Smith and J. E. Perry (private communication).

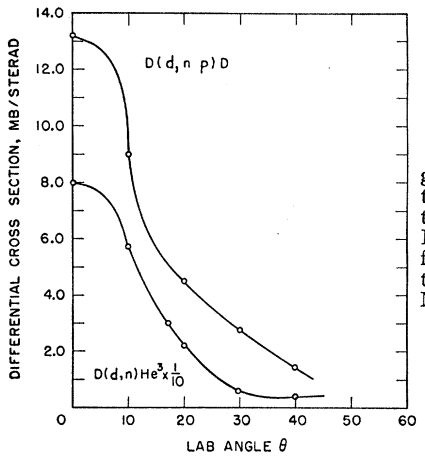

FIG. 5. The angular distribution of the neutrons from the D(d,np)D and D(d,n)He^3 reactions for a primary deuteron energy of 6.3 Mev.

D(d,n)He^3 reactions at zero degrees. The two parts of the curve given by the two reactions were normalized to each other in the region several Mev wide in which they overlap. By means of the sensitivity curve obtained in this way, it is then possible to compare directly the yields obtained for the breakup neutrons and the neutrons from the reaction D(d,n)He^3 in terms of the known cross section of the latter reaction.

The uncertainty in the absolute value of the cross-section scale is due to the uncertainty of the normalizing procedure just referred to, and to the uncertainty in the cross section of the D(d,n)He^3 reaction, which amount in sum to an estimated uncertainty of plus or minus 5%. The errors given in Table I are the sum of this 5% and the statistical uncertainty. The cross-section values given in Table I contain an additional error, which is hard to estimate, due to inaccuracy of the background subtraction discussed above. From the scatter of the points from a smooth curve and from the reproducibility of the data, this error probably does not exceed 10% at any point.

The results of the measurements of the angular distribution of the D-D neutrons are given in Fig. 5 and Table II. The continuum yields represent the integral down to 0.65 Mev at all angles. The angular data which have been obtained incidentally on the neutrons from the reaction D(d,n)He^3 are also given since they have not been reported previously for this energy. The same remarks made above with regard to the accuracy of the results apply to the angular data.

CONCLUSIONS

The fact that the observed spectral distributions for the breakup neutrons depart from the statistical one in the ways indicated is hardly surprising. Maximum-energy neutrons correspond to the proton and deuteron recoiling collinearly at the same velocity in the center-of-mass system. Coulomb repulsion and the possibility of proton and deuteron being bound under these conditions should diminish the probability of this situation. A similar remark applies to low-energy neutrons.

The success of a stripping model[5] in describing the reactions D(d,n)He^3 and D(d,p)T above 5 Mev suggests that this model may also be applicable to the breakup process. No calculations on this or any other model appear to have been carried through for the breakup process, however.

For the present the chief interest of these data is that they call attention to the fact that D-D neutrons cease to be monoenergetic at the appropriate threshold. In this respect the D-D reaction is not qualitatively different from reactions[6] in which the deuteron is incident on other light nuclei.

TABLE II. Angular dependence of the yield of D(d,np)D and D(d,n)He^3 at E_D=6.31 Mev.

Lab angle (degrees)	D(d,np)D (mb/sterad)	D(d,n)He^3 (mb/sterad)
0	13.5±0.7	80.0±4.0
10	9.0±0.5	56.9±3.0
20	4.5±0.3	22.2±1.0
30	2.8±0.2	5.5±0.4
40	1.5±0.2	4.6±0.3

The practical implication of these results is that there is no satisfactory source of monoenergetic neutrons in the energy range from approximately 8 Mev to about 12 Mev, where monoenergetic neutrons are available from the T(d,n)He^4 reaction at back angles. In many situations, however, the techniques used in taking these data can be used effectively to separate the monoenergetic D-D neutron group from the lower energy continuum. Where such techniques are not applicable, these data should be useful for making appropriate corrections.

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[5] W. M. Fairbairn, Proc. Phys. Soc. (London) **A67**, 990 (1954).
[6] Henkel, Perry, and Smith, Phys. Rev. **99**, 1050 (1955).