Breakup of Deuterons by Protons*

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Results are given for the neutron spectra at zero degrees from the reaction $p+d\rightarrow 2p+n$ for a range of incident proton energies from $E_p=4.0$ to $E_p=7.0$ Mev. Also given are the spectra as a function of angle for $E_p=6.5$ Mev. The observed shapes show systematic discrepancies from those given by the theory of Frank and Gammel; these discrepancies increase with increasing proton energy although the reaction yield is accurately given by the theory.

THE breakup of deuterons by protons is of interest because it represents the simplest possible reaction involving nucleons. Theoretical discussions of this reaction have been given by Frank and Gammel[1] and of the similar *n-d* reaction by Bransden and Burhop.[2] A refinement of the theory of Frank and Gammel which emphasizes the role of the final state *p-p* interaction is due to Heckrotte and MacGregor.[3]

The Q of the reaction is 2.225 Mev and the threshold, when protons are accelerated, is 3.338 Mev. Studies of the proton yield of this reaction for 9.66- and 14.1-Mev incident protons are reviewed by Frank and Gammel.[1] More recently measurements of total neutron yield up to 5.5-Mev incident protons have been made by Gibbons and Macklin,[4] and of the zero-degree yield up to 5.4-Mev proton energy by Henkel *et al.*[5] Neutron spectra for incident protons up to 3.92 Mev have been given by Ferguson and Morrison,[6] for protons of 8.9 Mev by Nakada *et al.*,[7] and results of Nakada *et al.* up to 13.5 Mev have been given by Heckrotte and MacGregor.[3]

The purpose of this paper is to supply fairly detailed information on this reaction in the region from threshold to 7.0-Mev proton energy by observing the spectrum of neutrons obtained as a function of excitation energy and angle of observation. An early investigation[8] at 7.0 Mev indicated that this is a region in which the neutron spectrum acquires a structured character, as reported by Nakada *et al.* at 8.9 Mev, which is quite different from that which had been predicted.[1]

The apparatus and procedures used in this study are identical with those in the previously reported study[9] on D(d,np)D, and represent a straightforward application of the pulsed-beam time-of-flight technique, using the large Los Alamos electrostatic generator.

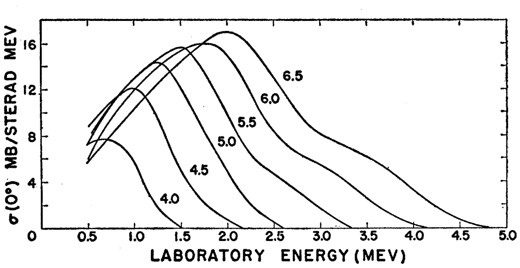

FIG. 1. Zero-degree neutron yield as a function of laboratory neutron energy for various incident proton energies.

RESULTS

Figure 1 illustrates the neutron spectra obtained at zero degrees at various incident proton energies, and Fig. 2 gives the spectra as a function of angle for $E_p=6.5$ Mev. Figure 3 gives a detailed zero-degree spectrum for $E_p=7.0$ Mev with a first-order correction for instrumental resolution indicated by the dashed lines, and the form of the spectrum as converted to the center-of-mass system. Also shown in Fig. 3 is the zero-degree spectrum in the laboratory reference frame, designated "F and G," as calculated by Gammel according to the theory of Frank and Gammel.[1] The experimental curve of Fig. 3 was taken with higher bias and somewhat better resolution than the curves of Figs. 1 and 2.

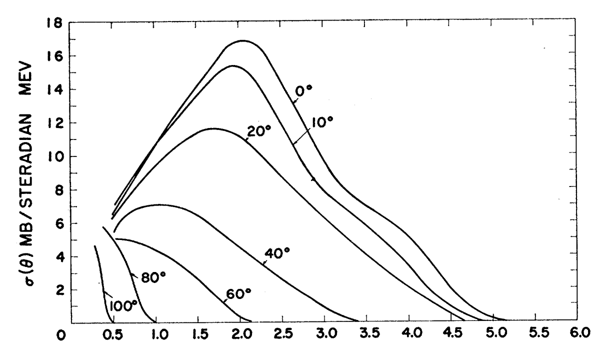

FIG. 2. Angular dependence of the neutron spectrum for $E_p=6.5$ Mev.

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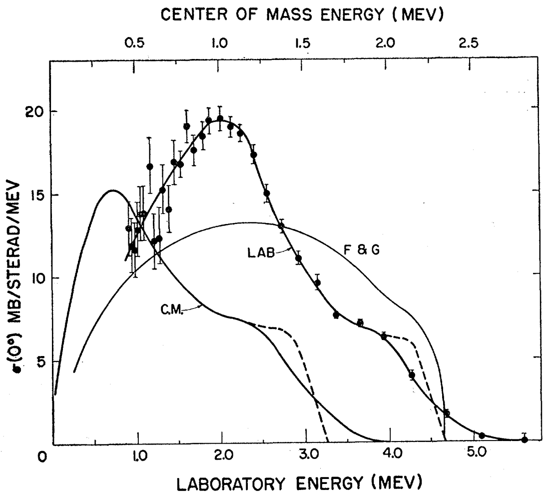

FIG. 3. Detailed spectrum of the zero-degree neutron yield for $E_p=7.0$ Mev *versus* laboratory neutron energy. Errors shown are statistical. The curve marked "C.M." is the experimental curve transformed to the center-of-mass coordinate system and shown to arbitrary ordinate scale. Dashed portions of the curves represent a crude correction for resolution effect. The curve marked "F and G" is the theoretical curve of Frank and Gammel (reference 1).

In all cases the maximum neutron energy observed is consistent with that to be expected from the energetics of the reaction $p+d\rightarrow 2p+n$, so that the neutron yield can be confidently ascribed to this reaction in all cases.

Figure 4 gives the integral of the zero-degree neutron yield as a function of incident proton energy, considering only neutrons whose energy is in excess of 500 kev. In this figure and in Figs. 1 and 2 the uncertainty in the magnitude of the cross-section scale is estimated to be $\pm 10\%$. The chief source of uncertainty in the shapes of the curves is due to uncertainty in the shape of the detector sensitivity curve, which is presumed to be known to about $\pm 7\%$ for the ratio at any pair of energies above 500 kev. The data of Fig. 4 are consistently lower than those of Ferguson and Morrison and of Henkel *et al.*, as is to be expected, considering the fact that our low-energy neutron cutoff of 500 kev is higher than that of the previous work shown on the curve. Extrapolating the curves of Fig. 1 to zero energy indicates that our cross-section results are in agreement with those of Ferguson and Morrison and of Henkel *et al.* within the experimental uncertainties and the uncertainty of the extrapolation.

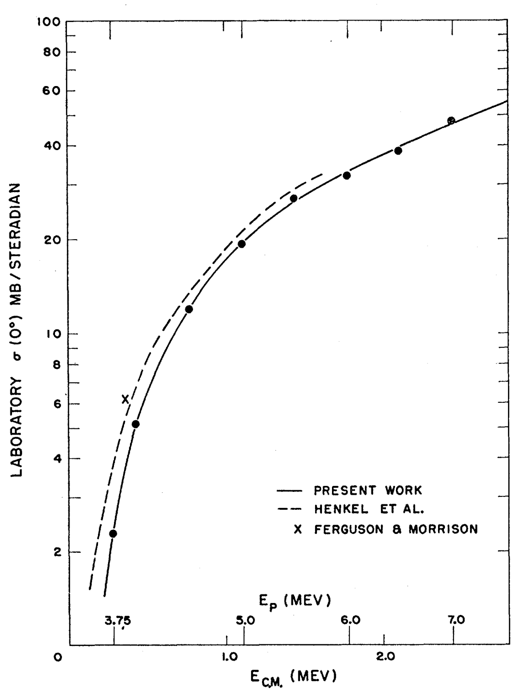

FIG. 4. The integral zero-degree yield of neutrons in excess of 500-kev energy *versus* proton energy and *versus* energy available in the center-of-mass system in excess of the threshold energy for the reaction. Also shown are previous results of Ferguson and Morrison (reference 5) and Henkel *et al.* (reference 4).

Figure 5 gives the angular distribution for $E_p=6.5$ Mev as obtained by integrating under the curves of

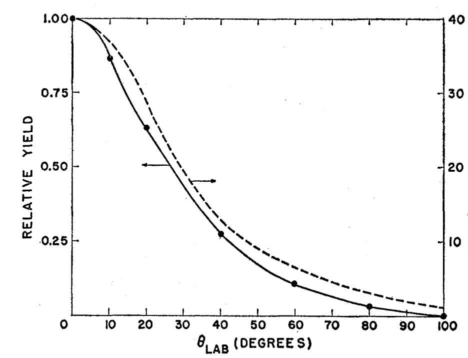

FIG. 5. The relative integral yield of neutrons in excess of 500-kev energy as a function of laboratory angle for $E_p=6.5$ Mev (solid curve). The dashed curve represents the distribution obtained after extrapolation to zero neutron energy, and refers to the cross-section scale to the right.

Fig. 2 for a 500-kev bias (solid curve) and as extrapolated to zero neutron energy (dashed curve). The yield at 6.5 Mev integrated over angle and energy is 65 mb with an uncertainty of about $\pm 15\%$. This result is in good agreement with an extrapolation of the results of Gibbons and Macklin.[4]

DISCUSSION

The spectrum for $E_p=4.0$ Mev at zero degrees in Fig. 1 is in excellent agreement both as to shape and magnitude of yield with the result of Ferguson and Morrison[6] at $E_p=3.92$. It has already been noted by Ferguson and Morrison that their curves differ from the predictions of Frank and Gammel by exhibiting a larger yield at lower neutron energies and a lower yield at higher neutron energies. It is clear from Fig. 3 that at 7.0 Mev proton energy the shape of the predicted spectrum exhibits a very marked disagreement of the same character. Indeed, starting at $E_p=6$ Mev one might say that the theoretical and experimental curves are quite different, since the experimental data start to exhibit a double-humped structure which is much more pronounced than in the results given by the theory of Frank and Gammel. This double-humped feature is even more apparent in the work of Nakada *et al.* at 8.9 Mev. Despite the shape discrepancy the agreement in yield is excellent at 3.92 Mev as already noted by Ferguson and Morrison and corroborated by our work at 4.0 Mev. At $E_p=7.0$ Mev, for the integral above 1 Mev neutron energy, the yield is 44 ± 4 mb/sterad while the result of Frank and Gammel is 41.5 mb/sterad. Despite the accuracy of the yield predictions it is clear, however, that a revision or refinement of the theory of this reaction is required to give spectral shapes correctly. It has recently been shown[3] that a refinement of the theory of Frank and Gammel which takes account of the final state *p-p* interaction improves the agreement of the theoretical with the experimental spectra, in particular in giving the double-maximum which is particularly conspicious at high energies.[7] Agreement is still poor, however, in the energy range of these measurements.

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Nitrogen-Induced Nuclear Reactions in Potassium

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Excitation functions have been measured for the production of Fe^{53}, Fe^{52}, Mn^{52}, Mn^{52m}, Mn^{51}, Cr^{49}, V^{48}, V^{47}, and Ti^{45} from the nitrogen bombardment of potassium in its normal isotopic mixture. The method used was activation of thick targets of KBr followed by chemical separations and absolute beta-counting. The cross sections at 27.5 Mev range from 0.14 mb for Fe^{52} to 8.3 mb for Mn^{51}. The relation of the Mn^{52}:Cr^{49}:Fe^{52} ratio to the odd-even effect in the nuclear level density is discussed. The total cross section for formation of the compound nucleus was estimated at several energies. The fraction of this total accounted for by one-particle emissions from the compound nucleus is surprisingly large.

INTRODUCTION

As part of a continuing systematic survey of nuclear reactions produced by energetic N^{14} ions,[1–7] thick targets containing potassium were bombarded in the Oak Ridge National Laboratory 63-inch cyclotron, and cross sections measured for the formation of the nuclei Fe^{53}, Fe^{52}, Mn^{52}, Mn^{52m}, Mn^{51}, Cr^{49}, V^{48}, V^{47}, and Ti^{45}. Potassium was selected as the target nucleus for the activation studies because so many of the possible reactions lead to observable radioactive nuclei. Low yields were expected since at the maximum bombarding energy of 28 Mev, the center-of-mass energy (20.6 Mev) is less than the entrance Coulomb barrier (22.0 Mev for $r_0=1.50\times10^{-13}$ cm).

The large mass numbers of the observed nuclei indicate that they are formed by fusion of most of the nucleons in the projectile and the target. It is not known by what mechanism this occurs. Many models are possible, ranging from the "buckshot" hypothesis[8] to the compound nucleus picture. The former regards the N^{14} projectile as a loose assembly of nucleons and nucleon groups; some of these are captured by the target and the rest pass on undisturbed. The compound nucleus point of view assumes complete fusion and sharing of energy, followed by statistical evaporation of particles. The consequences of the latter picture are described by Blatt and Weisskopf.[9]

The compound nucleus point of view will be taken in this paper since experimental data on the energy distributions of charged particles from other nitrogen-induced reactions[10–12] fit the statistical theory. Where deviations from statistical theory are observed in the angular distributions,[10] they represent only a small fraction of the total reaction cross section. The cross section

* Operated for U. S. Atomic Energy Commission by Union Carbide Corporation.
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