Neutron Spectra from the $p+d$ Reaction*

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The energy and angular distributions of neutrons from the $p+d \rightarrow n+p+p$ reaction have been measured for incident protons of energy 6.06, 7.15, 8.90, and 13.5 Mev. The peak in the neutron spectra near the maximum neutron energy is in qualitative agreement with the calculations of Heckrotte and MacGregor.

INTRODUCTION

THE simplest reaction involving three nucleons is the breakup of the deuteron by a proton or a neutron. Theoretical discussions of these reactions have been given by Frank and Gammel[1] and Bransden and Burhop.[2] As reported previously[3] the zero-degree neutron spectrum resulting from the disintegration of the deuteron by 8.9-Mev protons shows a peak near the maximum allowed neutron energy which is not predicted by Frank and Gammel. Heckrotte and MacGregor[4] have investigated the possibility that this peak can be accounted for by direct nucleon-nucleon scattering processes, including the final state interaction of the two residual protons. Calculations for the n-d reaction have been made by Gluckstern and Bethe,[5] and by Migdal.[6] Using time-of-flight techniques in conjunction with the natural phase bunching of the Livermore variable-energy cyclotron, we have extended these measurements to other proton energies and angles. Neutron spectra measurements were made for incident proton energies of 6.06, 7.15, 8.90, and 13.5 Mev, with particular emphasis on the highest energy neutrons. The neutron spectra were also measured as a function of angle out to a laboratory angle of 30°. A summary of previous measurements may be found in a paper by Cranberg and Smith[7] in which they present the zero-degree spectra of neutrons for an incident proton energy of 4 to 7 Mev as well as giving the angular distribution of the emitted neutrons at 6.5-Mev proton energy.

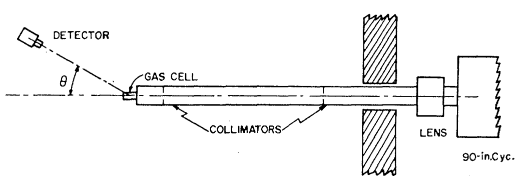

Fig. 1. Schematic drawing of the experimental geometry.

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[5] R. L. Gluckstern and H. A. Bethe, Phys. Rev. **81**, 761 (1951).
[6] A. B. Migdal, J. Exptl. Theoret. Phys. U.S.S.R. **28**, 3 (1955) [translation: Soviet Phys. JETP **1**, 2 (1955)].
[7] L. Cranberg and R. K. Smith, Phys. Rev. **113**, 587 (1959).

EXPERIMENTAL DETAILS

Geometry

The experimental geometry is shown in Fig. 1. The external proton beam from the Livermore variable-energy cyclotron is focused with a quadrupole lens and collimated before entering the deuterium gas target. The neutron detector is mounted on a remotely controlled angle-changer centered on the gas target. The detector was mounted 4 feet above the light aluminum flooring of the cyclotron pit and away from any massive structures.

Electronics

A schematic diagram of the electronics is shown in Fig. 2. The pulses in the plastic scintillator were viewed by a RCA-6342 photomultiplier. The anode signal of the photomultiplier passes through a cathode follower, linear amplifier, and into a discriminator gate unit. This relatively slow and stable channel sets the bias level. The fast channel consists of the output of the last dynode of the photomultiplier amplified by Hewlett Packard wide-band amplifiers and fed directly into the start channel of the "time-to-pulse height converter." An rf signal is picked up on a loop in the cyclotron tank, amplified, shaped and further amplified by wide-band amplifiers before entering the stop channel of the converter. The output of the converter is amplified and fed into an Argonne-type 256-channel pulse-height analyzer, which is gated by the output of the discriminator gate.

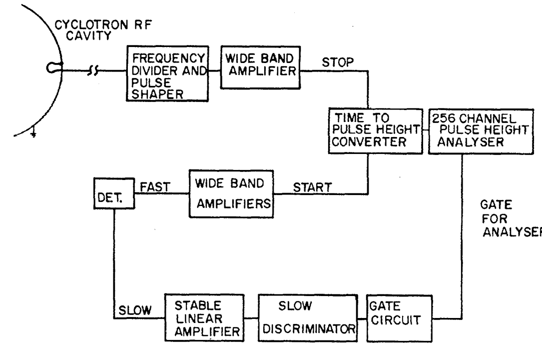

Fig. 2. Schematic diagram of the electronics.

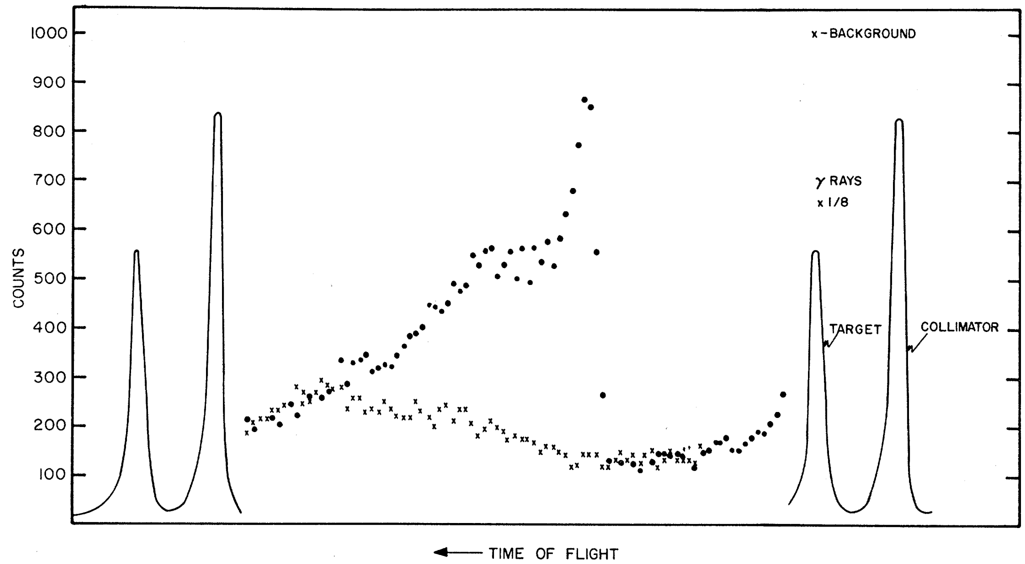

FIG. 3. Typical time-of-flight neutron spectrum for $p+d \rightarrow p+p+n$ reaction at 0° for an incident proton energy of 13.5 Mev. The time scale is 1.01 mμsec per channel. The gamma rays are produced by protons striking the collimator and the deuterium gas cell. The background run is taken on an evacuated target and also shows the gamma peaks.

Detector Calibration

The detector was a plastic scintillator 1 in. in diameter by 1 in. thick. The detector biases were set with reference to the Compton edge of the 0.511-Mev gamma ray (annihilation radiation) from a Na^{22} source. Three biases were used: half, twice, and equal to the Compton edge. The detector efficiencies were measured absolutely using the $D(d,n)He^3$ reaction[8] and the $T(p,n)He^3$ reaction.[9] The efficiencies were calculated and found to agree with the measurements to within 5% to 10%.

The same gas cell and current integrator used in the $D(d,n)He^3$ efficiency measurement were also used during the $D(p,n)2p$ experiment. A BF_3 counter was used as an auxiliary monitor.

RESULTS

Typical time spectra for the signal and background are shown in Fig. 3. Background runs were taken by evacuating the D_2 gas cell. To check that neutrons were not scattered in by walls, floors, etc. (such a contribution is not measured by a gas-out run), a copper slug was placed between target and detector. This "true" background was the same as the gas-out background corrected for capture gamma rays; this showed no appreciable inscattering of neutrons. The differential cross section (millibarns/sterad Mev) for neutron production was obtained by the following formula:

$$\sigma(\theta E)=\frac{1.92\times 10^{-4}\eta_E(\Delta t/\Delta C)^2(C_0-C_E)^3}{N_d q A \epsilon(E)}, \quad (1)$$

where η_E = counts in the channel corresponding to the neutron energy E, $(\Delta t/\Delta C)$ is the time calibration of the system in millimicroseconds/channel, C_E is the channel number corresponding to neutron of energy E, and C_0 is the channel number corresponding to zero time. $C_0=C_\gamma+(R/k)(\Delta C/\Delta t)$ (C_γ corresponds to the channel number for target gamma rays, k is the velocity of light, and R is distance from target to detector), N_d is the number of deuterons per cm^2 in target, q is the number of protons striking the target, $\epsilon(E)$ is the efficiency of the detector for neutrons of energy E, and A is the area of the detector. Figures 4–7 display the cross sections for various proton energies and angles.

The zero-degree spectra at 6.06 and 7.15 Mev are in good agreement with the measurements of Cranberg and Smith.[7]

Errors

Inspection of Eq. (1) indicates several sources of error. The statistical uncertainty in η_E was less than

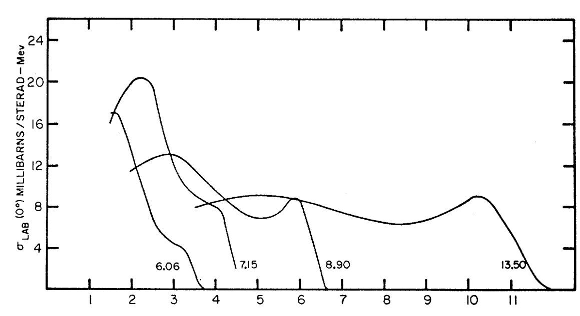

FIG. 4. 0° experimental neutron spectra at several bombarding energies, in the laboratory system and uncorrected for time resolution.

[8] L. Rosen (private communication).

[9] J. L. Fowler and J. E. Brolley, Revs. Modern Phys. 28, 103 (1956).

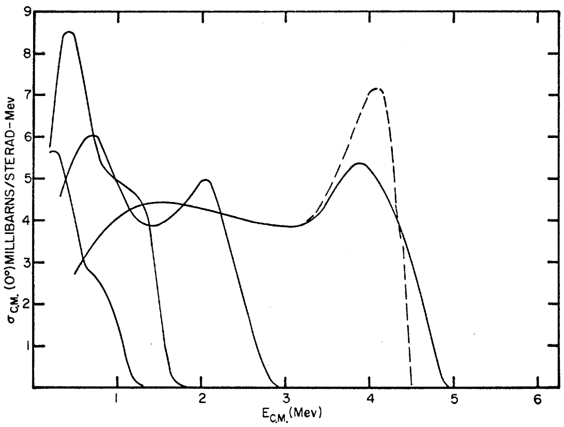

FIG. 5. 0° experimental neutron spectra plotted in c.m. system. The effect of a time unfold is shown as a dashed curve.

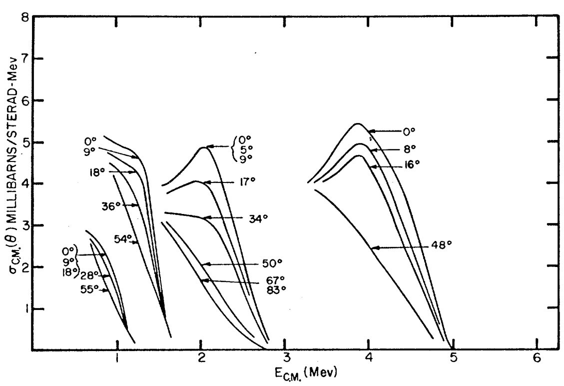

FIG. 6. The experimental neutron spectra plotted in c.m. system as a function of bombarding energy and c.m. angle. The variation of c.m. angle over the neutron energies plotted is less than ±5°.

10% and in general was only a few percent. The average value of $\Delta t/\Delta C$ over the channels occupied by the neutron spectra was determined by using a double display, that is, one stop pulse for every two rf cycles. In this way the spectra appeared doubly (Fig. 3) and the time between succeeding gamma peaks corresponded to the period of the cyclotron—an accurately known time. The variation of $\Delta t/\Delta C$ with channel was measured by feeding the start channel of the converter with a source and using the cyclotron rf to generate stop pulses, thus producing a random time spectrum. For a constant $\Delta t/\Delta C$ this spectrum should be flat, and it was measured to be flat within a few percent. (This operation was repeated during the experiment from time to time and indicated no reproducible structure.) The remaining errors in number of deuterons per cm² in target, charge collection efficiencies,

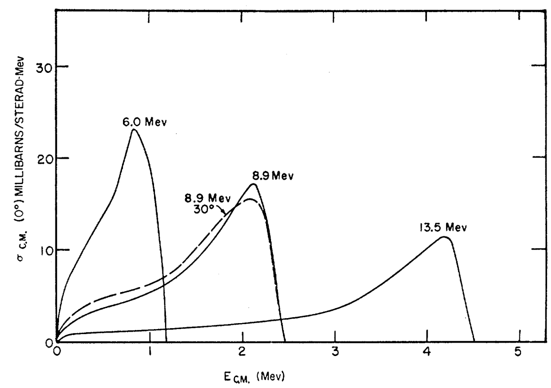

FIG. 7. 0° neutron peaks calculated in Born approximation, which are to be compared with the experimental results shown in Figs. 5 and 6.

and efficiency of detector may all be lumped together since the detector was calibrated using a $D(d,n)He^3$ source, i.e., the same gas, gas cell, current integrator, and associated gear were used in calibration as in the *p-d* runs. Therefore, the only error is in the cross section measurement for the $D(d,n)He^3$ reaction. This is estimated to be about 5%. Secondary electron emission from the gas target and local beam heating effects in the D_2 gas introduced less than 5% errors. The absolute errors on the cross sections are thus of the order of 10%.

DISCUSSION

From Fig. 5 it can be seen that the calculations of Heckrotte and MacGregor[4] give the correct shape and position for the high energy peak. If the Coulomb interaction of the two protons is neglected then the peak occurs at the maximum available energy. This is in agreement with the calculations for the *nd* reaction.[5,6] Heckrotte's and MacGregor's calculations indicate that at 8.9 Mev the angular distribution of this peak should be relatively constant from 0° to 30° in the c.m. system and then decrease rapidly for larger angles. This prediction is in qualitative agreement with the data (Fig. 6). It is not surprising that the absolute cross section and the variation of cross section with energy are incorrectly given since Heckrotte and MacGregor have assumed that the incident proton collides with a "free" neutron.

ACKNOWLEDGMENTS

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