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Yield and Angular Distribution of the D-D Neutrons*

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The differential and total cross sections for neutron emission from the d−d reaction have been measured for deuteron energies between 0.5 and 3.7 Mev. A "thin" deuterium gas target and an energy insensitive neutron detector were used in the measurements. The yield in the center of mass coordinates was of the form $N(\theta)=K(1+A\cos^2\theta+B\cos^4\theta+C\cos^6\theta)$; the total cross section was essentially constant (0.1 barn) for deuteron energies above 1 Mev. The coefficient A was found to be negative above 1.4 Mev and appreciable $\cos^4\theta$ was needed at all energies. Above 2.5 Mev, a $\cos^6\theta$ term was also appreciable. The angular distribution results can be understood qualitatively in terms of penetration of Coulomb and centrifugal barriers plus spin-orbit coupling.

INTRODUCTION

ACCURATE information concerning the neutrons from the

$$D+D\rightarrow He^3+n+3.27\text{ Mev}$$

reaction is of both experimental and theoretical importance since (a) for most laboratories the reaction is the only practical source of monochromatic neutrons of energy between 1.8 and 7 Mev, and (b) it is a simple enough reaction that detailed theoretical considerations about yield and angular distribution become feasible.[1]

Both the neutron and proton emission from this reaction have been investigated extensively for deuteron energies below 500 kev.[2–4†] However, most of the low energy data are "thick" target data and are difficult to translate with any certainty to differential and total cross-section measurements.

At higher deuteron energies data of Bennett, Mandeville, and Richards[5] and the recent work of Blair, Freir, Lampi, Sleator, and Williams[6] are available. The former data give only relative neutron yields and are limited to but two angles of observation to the deuteron beam. The Minnesota data[6] includes differential cross sections for both disintegration protons and He^3 particles for deuteron energies of 1 to 3.5 Mev. The angular range (~15° to 85° in c.m.s. coordinates) investigated in that work was limited in the forward direction by the geometry of the charge measuring system and at large angles by the low energy of the He^3 particle. The counting of charged particles in a known geometry did, however, permit the Minnesota group to obtain quite accurate differential cross-section values for the above angular range.

There are also recent differential neutron and pro-

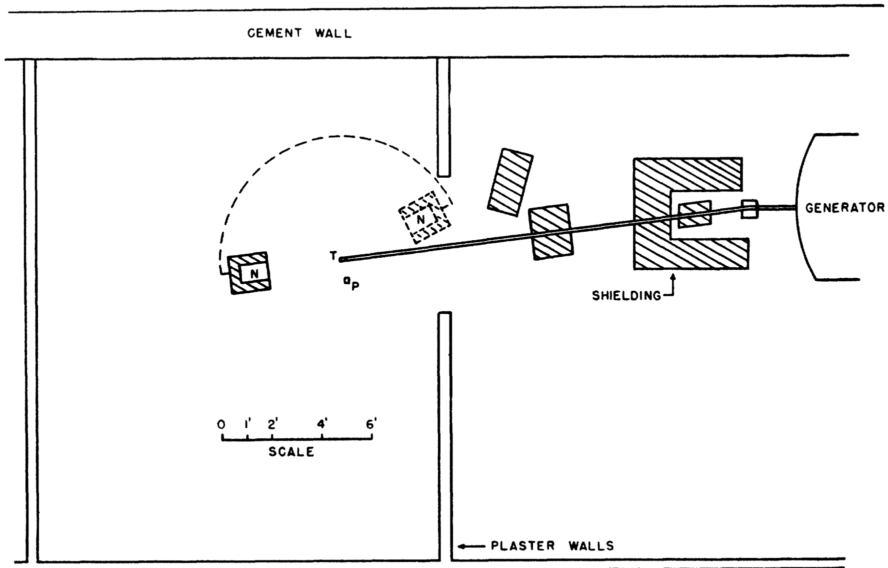

FIG. 1. Schematic experimental arrangement. T is the gas target and P is the proton monitor counter. N is the shielded neutron detector.

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[1] E. J. Konopinski and E. Teller, Phys. Rev. **73**, 822 (1948).
[2] Bretscher, French, and Seidl, Phys. Rev. **73**, 815 (1948).
[3] Manley, Coon, and Graves, Phys. Rev. **70**, 101A (1946).
[4] Graves, Graves, Coon, and Manley, Phys. Rev. **70**, 101A (1946).
† References to earlier work may be found in references 1, 2, and 5.
[5] Bennett, Mandeville, and Richards, Phys. Rev. **69**, 418 (1946).
[6] Blair, Freier, Lampi, Sleator, and Williams, Phys. Rev. **74**, 1599 (1948).

ton cross-section measurements for 10-Mev deuterons.[7,8]

EXPERIMENTAL ARRANGEMENTS

In the present investigation it was decided to observe the neutrons rather than the charged He^3 so that measurements could include all angles in the c.m.s.

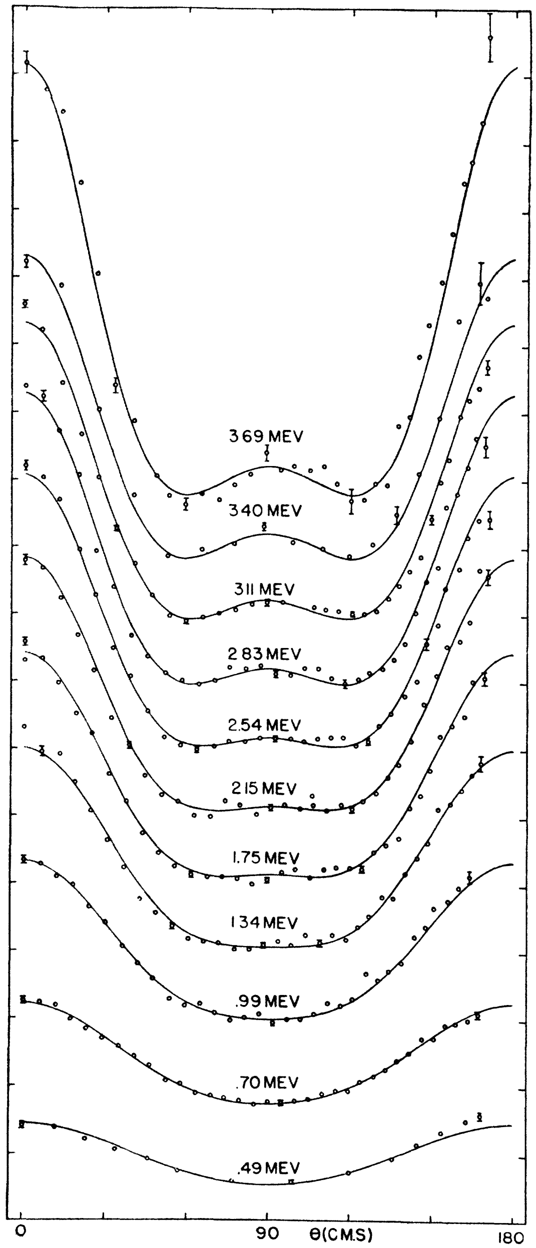

FIG. 2. Observed angular distribution plotted in c.m.s. coordinates after correction for background and for neutron counter efficiency. The ordinate scale for each successive energy has been displaced one unit to prevent overlapping of data. The curves drawn through the experimental points are of the form $N(\theta) = K(1+A\cos^2\theta+B\cos^4\theta+C\cos^6\theta+\cdots)$.

from 0° to nearly 180°. At 180° (laboratory coordinates) the neutron energy varies only between 1.9 and 1.6 Mev for deuteron energies between 0.5 and 4 Mev, but in the forward direction the corresponding variation of neutron energies is from 3.5 to 7.0 Mev. Hence an energy insensitive neutron detector is desirable for measurement of the angular distribution. A shielded long counter[9] was used for this purpose. From the measurements of reference 9, the efficiency of such a counter is almost independent of neutron energy in the range from 1.5 to 3 Mev and is down about 5 percent at 5 Mev (average energy of Ra—Be neutrons). Extrapolation of Hanson and McKibben's data would indicate a relative efficiency of almost 90 percent even for 7 Mev neutrons.

Because of the identity of the two particles initiating the d-d reaction, the differential cross section must be symmetrical about the equatorial plane in the c.m.s. One might, therefore, use any experimentally observed asymmetry about this equatorial plane as a measure of the variation of the detection efficiency with energy. Our data, Fig. 2, after correction for counter efficiency according to the data of reference 9, was always symmetric about 90° in the c.m.s. This efficiency correction was small for most angles and energies and never exceeded 11 percent. The observed symmetry may then be taken as verification of Hanson and McKibben's efficiency curve, or if their efficiency curve is accepted, be taken to indicate the absence of large systematic error in our angular distributions.

Figure 1 shows the schematic experimental arrangement. A magnetically analyzed deuteron beam was brought to a deuterium gas target through a 20-foot long brass tube. The high resolution electrostatic analyzer[10] was not used since targets of 50–150 kev in thickness were desirable for satisfactory counting rates and for minimizing background neutrons.

The gas target (2 cm in length) was separated from the vacuum system by a 0.00005-inch (1 micron) nickel foil[11] which when unsupported over a 6-mm aperture could withstand a pressure differential of almost two atmospheres. The effective thickness of the foil[12] corresponded to an energy loss of 150 kev for the lowest energy deuterons, but only about 75-kev loss for the higher energies.

After passing through the gas target the beam was stopped by a 0.1-mm gold foil. The target chamber could be evacuated and filled with either hydrogen (for background runs) or deuterium gas which was purified by passing through a palladium tube. Appropriate gauges permitted the gas density in the target to be measured to within a few percent. Beam current was integrated by observing with a string electrometer the potential difference across a known capacitance.

A small end window proportional counter fixed at

[7] Erickson, Fowler, and Stovall, Jr., Phys. Rev. 75, 894 (1949).
[8] Leiter, Meagher, Rodgers, and Kruger, Phys. Rev. 76, 167 (1949).

[9] A. O. Hanson and J. L. McKibben, Phys. Rev. 72, 673 (1947).
[10] Warren, Powell, and Herb, Rev. Sci. Inst. 18, 559 (1947).
[11] Available from the Chromium Corporation of America, Waterbury 90, Connecticut.
[12] As measured by observing the shift in the $Li^7(p, n)Be^7$ threshold resulting from the foil being inserted ahead of the target.

90° to the beam was used to count disintegration protons from $D(d, p)H^3$. This reaction was used to monitor conditions while the angular distribution of neutrons was being investigated.

Background neutrons (from the foil, defining apertures, etc.) were troublesome only at high deuteron energies. Thus at 0.7-Mev deuteron energy, background neutrons amounted to only 2 percent of the d-d yield and at 3.1-Mev background was 7 percent of the total yield in the forward direction but 22 percent at 110°. At 3.7-Mev background was 20 percent of the forward yield and 68 percent of the 110° yield. This large and somewhat fluctuating background makes our highest energy data somewhat unreliable.

RESULTS

Angular distribution results after conversion to c.m.s. coordinates and correction for counter efficiency are shown in Fig. 2. The deuteron energy associated with each curve is the average energy of the deuteron beam in the gas target. Because of non-uniformities in the foil and voltage fluctuations, this average bombarding energy is probably not known better than ±10 kev. The ordinates (yield in arbitrary units) of each curve have been displaced one unit to display more clearly the experimental data associated with each curve. The indicated error is statistical only.

The curves drawn through the experimental points of Fig. 2 are expressions of the form

$$N(\theta)=K(1+A\cos^2\theta+B\cos^4\theta+C\cos^6\theta+\cdots).$$

This is the conventional representation. The experimental data can also be represented as a linear expansion in Legendre polynomials of the first kind:

$$F(\mu)=A_0P_0+A_2P_2+A_4P_4+A_6P_6+\cdots$$

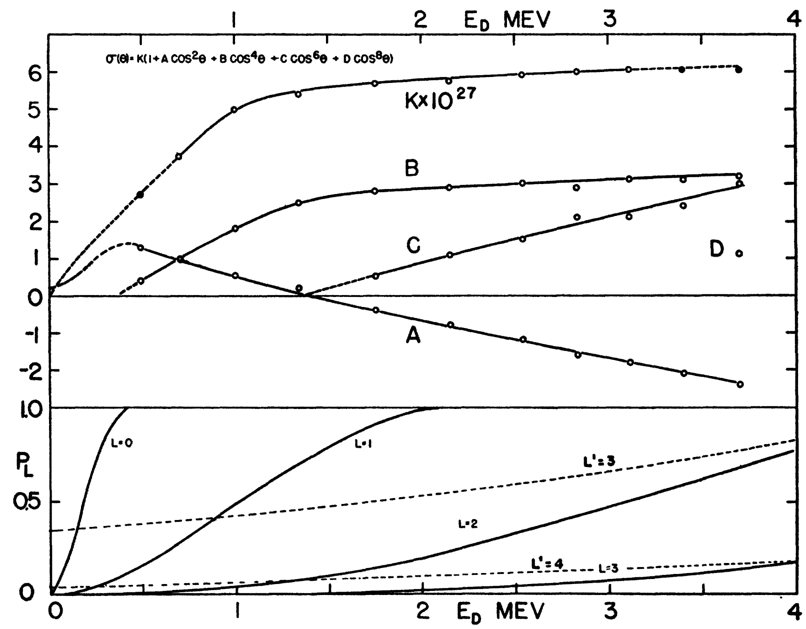

FIG. 3. Variation with deuteron energy (E_d) of the coefficients K, A, B, etc. of the $\cos^n\theta$ representation of the data. The extrapolation to zero energy is based on the low energy data of reference 2. Solid circles indicate that the normalization of these points was not checked because of generator difficulty. Also is included a plot of the penetrabilities P_L for the incoming deuterons (solid curve) and outgoing neutrons (dashed curve).

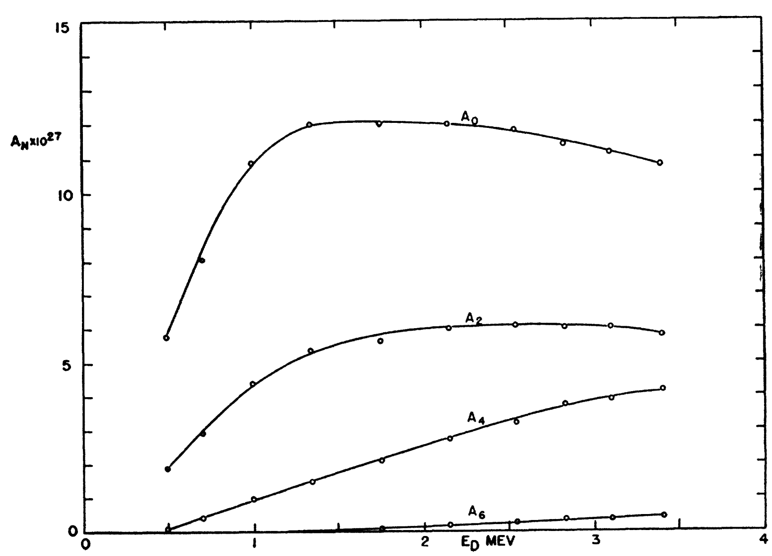

FIG. 3a. Variation with deuteron energy E_d of the coefficients of the Legendre polynomial fit to the outgoing neutron intensity in c.m.s. coordinates.

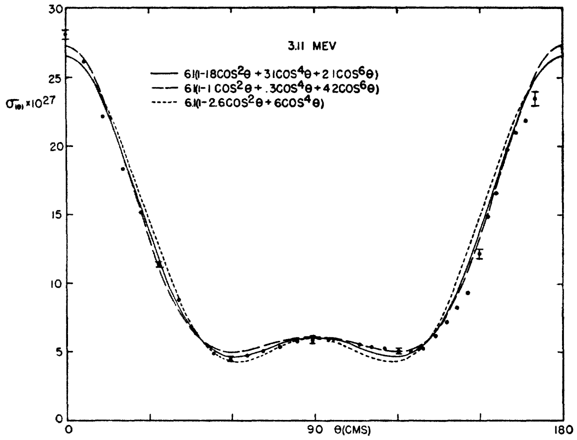

FIG. 4. Illustration of the latitude in choice of parameters which can be used to fit a given experimental curve. The dashed curve is from a Legendre polynomial analysis. The solid curve has coefficients consistent with those of neighboring deuteron energies and the dotted curve shows the best fit possible if only terms up to $\cos^4\theta$ are included. The assumption that the coefficients should be a slowly varying function of the deuteron energy considerably reduces the ambiguity in choice of parameters.

where $\mu=\cos\theta$ and $P_n(\mu)$ is the Legendre polynomial of order n. This representation may be preferred for theoretical discussions since it better displays the partial waves of which the outgoing neutron intensity is formed. The coefficients A, B, C, etc., and A_0, A_2, A_4, etc., for the two representations are given as a function of energy in Fig. 3 and in Fig. 3a. In either case the coefficients were obtained from the experimental data by a Legendre polynomial analysis similar to that developed by F. Reines[13] except that in some instances the coefficients were modified to give a smoother variation of the coefficients as a function of deuteron energy.

When only two parameters are used to describe the angular distribution, their values are quite closely fixed by the experimental data. However, for higher deuteron energy, three parameters are needed and in this case considerably more leeway is available in the choice of coefficients. This is best illustrated by the 3.11-Mev data, where in Fig. 4 it is seen that reasonable fit of the data is possible for significantly different expressions. The dashed curve is that obtained by the straight Legendre polynomial analysis. The solid curve has had the coefficients modified to be consistent with values at neighboring energies, and the dotted curve shows the best fit possible if no terms higher than $\cos^4\theta$ are included. Data at other energies required considerably less modification of the Legendre polynomial analysis.

The absolute value of the reaction cross section was determined by placing a calibrated[14] Ra-Be source at the gas target and by use of Hanson and McKibben's data[9] on the long counter detection efficiency for Ra-Be neutrons.

Figure 5 gives the resulting absolute differential

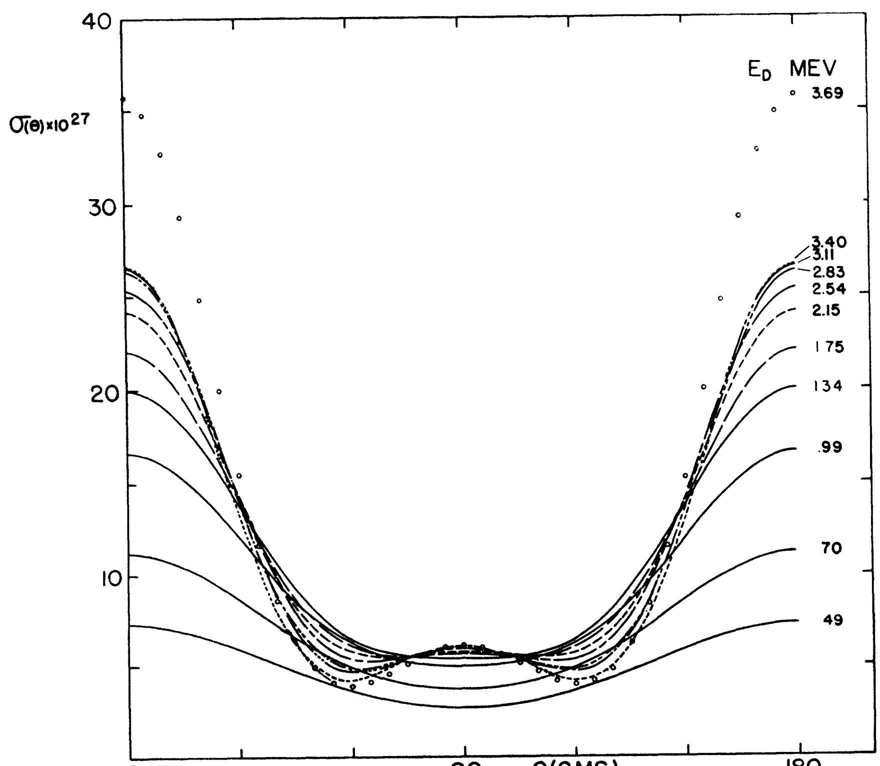

FIG. 5. Differential cross section for $D(d,n)He^3$ in c.m.s. coordinates. The 3.69 and 3.4-Mev data are somewhat unreliable because of large and fluctuating backgrounds.

[13] See Appendix IV, R. Taschek and A. Hemmendinger, Phys. Rev. 74, 373 (1948).

[14] The source was calibrated by the Argonne National Laboratory. The absolute calibration of this source may be uncertain by as much as 10 percent.

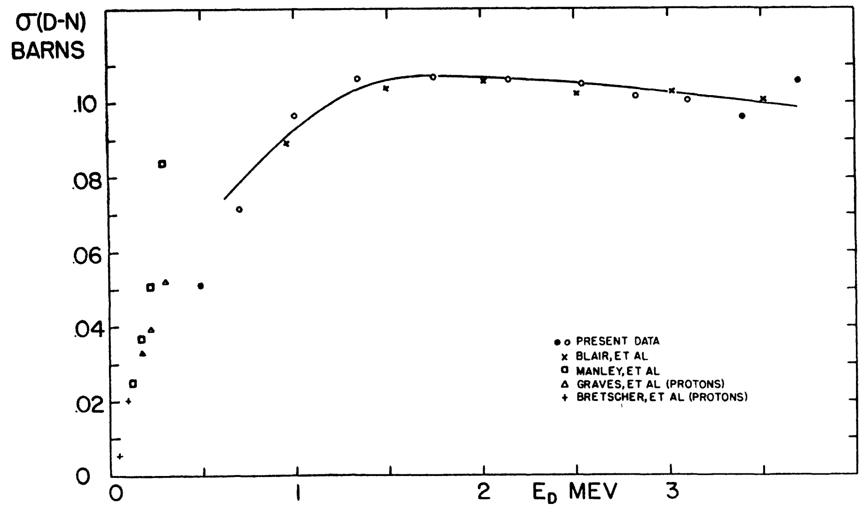

FIG. 6. Total cross section for $D(d, n)He^3$.

cross sections for the analytic expressions which have been fitted to the data of Fig. 2. The ordinates of the 3.4 and 3.69-Mev curves have considerable uncertainty because generator and background difficulties at the time prevented a careful normalization of this data to that at lower energies.

The total cross section (obtained by integrating the differential cross sections) is displayed in Fig. 6 along with comparison values from other experimenters. There is remarkably good agreement with the results of Blair *et al.*,[6] but the present data does not extrapolate to the very low energy data of Manley *et al.*[3]

The laboratory differential cross-section curves, Fig. 7, are included for the convenience of the experimentalist who uses this reaction as a source of neutrons.

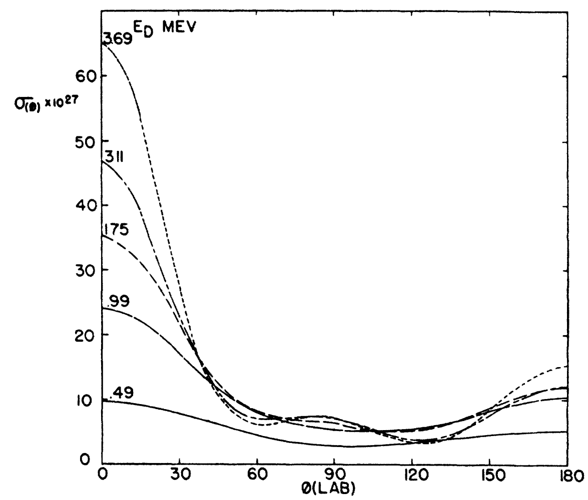

FIG. 7. Laboratory differential cross section for $D(d, n)He^3$.

DISCUSSION

Since the present data show no evidence of sharp resonances, we may attempt to explain qualitatively the behavior of the differential cross section solely on the basis of Coulomb and centrifugal barrier penetrabilities. These penetrabilities (with $R = 7\times10^{-13}$ cm as assumed in reference 1) are plotted in Fig. 3 for both the incident deuterons and the outgoing neutrons of various orbital angular momentum.

These penetrabilities indicate that for low deuteron energies the outgoing angular neutron distribution will be influenced chiefly by the penetrabilities of the incoming deuterons[15] and therefore the angular distribution will change rapidly with deuteron energy. However, at higher deuteron energies it will be the outgoing penetrabilities which limit the complexity of the angular distribution. Under these circumstances one expects the angular distribution to be a much less sensitive function of the deuteron energy. Experimentally this result is evidenced in the plot of Legendre polynomial coefficients (Fig. 3a) and would indicate that even for much higher deuteron energies than those here investigated, the angular distribution would not change drastically. The 10-Mev deuteron data of references 7 and 8 support this contention.

It will be noted that spin and orbital angular momentum do not appear to be conserved independently. For example, outgoing D neutron waves are of quite appreciable intensities even for very low penetrabilities of incoming D deuterons. This result is consistent with the large spin-orbit coupling advocated by Konopinski and Teller.[1]

ACKNOWLEDGMENTS

Valuable assistance in recording data and in operation of the electrostatic generator was provided by Messrs. Stanley Bashkin, Gerson Goldhaber, James Hamilton, Virgil Johnson, and Raymond Smith.

[15] According to a theorem of Eisner and Sachs, Phys. Rev. **72**, 680 (1947), the outgoing wave intensities cannot contain spherical harmonics of order greater than $2L$ where L is the order of the incoming wave.