apparatus has since been modified considerably. One possible explanation may arise from the fact that the original runs on Th^{233} were sandwiched between runs on a 5-Mev beta spectrum. The operation of the lens spectrometer at such very high fields may have induced residual dipoles in neighboring iron (such as the reenforcing in the concrete floor). The superposed dipole field might have resulted in the observed reduced transmission at low energies.

The half-life of Th^{233} was remeasured by following the decay of a variety of sources with either a side-window or end-window methane-flow beta proportional counter. The sources consisted of ThO_2, Th metal, or ThF_4 (evaporated on 0.25-mil Al) irradiated with neutrons for 5 to 7 minutes. The decay curves, starting about 15 min after the end of the irradiation, showed two components (Th^{233} and 27-day Pa^{233}), except for a small contribution from Na^{24} from the Al-backed source. A least-squares analysis of the data, covering about 8 half-lives, gave a value of 22.4 ± 0.1 minutes for the half-life of Th^{233}. This is somewhat shorter than the previously reported values.[4]

The gamma radiations from Th^{233} were investigated with a NaI(Tl) scintillation spectrometer and 100-channel analyzer. A search for internal conversion lines down to about 5 kev was made with the solenoid spectrometer employing a thin Zapon-window counter. These surveys indicate the presence of only very weak ($\lesssim 1\%$) transitions. It is therefore concluded that Th^{233} decays predominantly by the 1.23-Mev beta transition directly to the ground state of Pa^{233}.

We are indebted to M. Allan Johnsrud for preparing the ThF_4 films.

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Angular Distribution of the $D(d,n)He^3$ Reaction below 1 Mev*†

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Angular distributions of the $D(d,n)He^3$ reaction have been measured at 9 deuteron energies ranging from 0.1 Mev. to 0.9 Mev. Neutrons were detected by two plastic scintillators mounted on photomultiplier tubes, one of which could be rotated to make angles of 0° to 165° with the beam direction. The other scintillator, placed on the rotational axis, was used as a reference counter. Data were fitted to the expression $d\sigma(\theta')=d\sigma(90°)(1+A\cos^2\theta'+B\cos^4\theta')$ in the center-of-mass system by the method of least squares. The asymmetry coefficients are compared with those obtained by other workers.

INTRODUCTION

DATA on the $D(d,n)He^3$ reaction in the energy range below 1.0 Mev as reported from several laboratories[1–4] are in considerable disagreement regarding the angular distribution. The angular distribution may be expressed in the form $d\sigma(\theta')=d\sigma(90°)\ (1+A\times\cos^2\theta'+B\cos^4\theta')$ at these energies, but the experiments are at variance as to the values of the energy-dependent asymmetry coefficients. It seems important to determine more closely the values of the asymmetry coefficients and their variation with bombarding energy. The present work was undertaken to measure the relative angular distribution as a function of energy between 0.100 and 0.900 Mev.

EXPERIMENTAL ARRANGEMENT

The deuterons were accelerated in a Van de Graaff machine and were allowed to strike a deuterium-zirconium target 300 $\mu g/cm^2$ thick on a 0.25-mm platinum backing. Targets were mounted on the end of a 10-mil wall brass tube with a vinyl cement. Insulation from the beam tube was achieved with a thin mica ring placed between the tube and the target. Target cooling consisted of air blasts directed on the platinum backing and on the beam tube directly above the target. This method of cooling was adequate at an energy of 0.900 Mev, an ion current of about 0.5 μa, and a beam 5 mm in diameter.

The desired ion beam energy was determined by adjusting the field of a shunted permanent-magnet analyzer. The generating voltmeter used to measure the accelerating potential was calibrated before and during the series of runs by using the gamma-ray

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[1] I. Bartholdson, Arkiv Fysik 2, 271 (1950–51).

[2] P. R. Chagnon and G. E. Owen, Phys. Rev. **101**, 1798 (1956).

[3] G. T. Hunter and H. T. Richards, Phys. Rev. **76**, 1445 (1949).

[4] Preston, Shaw, and Young, Proc. Roy. Soc. (London) **226**, 206 (1954).

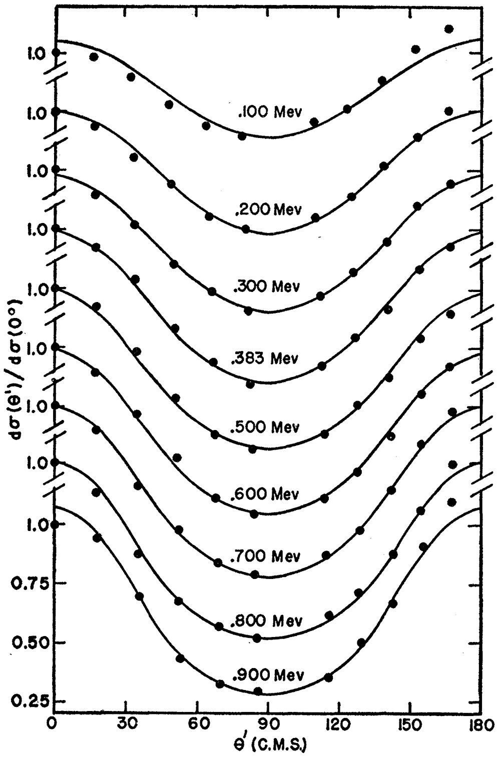

FIG. 1. Center-of-mass angular distributions of the $D(d,n)He^3$ reaction. The curves are least-squares fits of the experimental points. Successive ordinates have been displaced to prevent overlapping of the data.

resonances of the $F^{19}(p,\alpha\gamma)O^{16}$ reaction. Calculated target thicknesses[5] ranged from 44 to 52 kev with an uncertainty of about ±20%. The uncertainty in average deuteron energy in the target varied from 1.5% at 0.900 Mev to 6% at 0.100 Mev.

Neutrons were detected with two plastic scintillators[6] mounted on Du Mont 6292 photomultipliers, one of which could be rotated to make angles of 0° to 165° with the incident beam direction. The other scintillator, placed on the rotational axis, was used as a reference counter. Data were recorded at 15° intervals in the laboratory coordinate system. To minimize changes in counting distance due to variation in the beam position, counts taken successively on opposite sides of the beam were added. The angular resolution of the rotatable counter was ±3° for the counting distance used at energies below 0.700 Mev, and ±4° at 0.700 Mev and higher energies. Angles were measured to ±1°. Statistical errors in counting were ±1% or less at all bombarding energies except 0.100 Mev, where the maximum error was ±1.5%.

The output of the movable photomultiplier was fed into a single-channel analyzer whose integral bias was set to accept only pulses whose heights were greater than half the height of those from recoil protons with the full neutron energy. The ratio of these counts to those in the reference counter was obtained at each angle. To include all proton recoils produced, the ratios were multiplied by a factor obtained from the pulse height response of the scintillator, assuming that the *n-p* scattering is isotropic so that equal recoil-energy intervals contain equal numbers of protons. The pulse-height response of the scintillator for protons above 1.75-Mev energy was determined from the end points of proton recoil distributions of neutrons with energies of 1.75 to 4.0 Mev. It was found that this measured response was in very good agreement with that published for stilbene by Fowler and Roos[7] after the two curves were normalized at 3.9 Mev. The stilbene curve was used as the extrapolation below 1.75 Mev. In obtaining the multipliers for the ratios mentioned above, the only part of the extrapolation used was the segment between 1.12 and 1.75 Mev. Small deliberate alterations of the shape of the lower energy region of the response curve resulted, for proton recoils from the *d-d* neutrons,

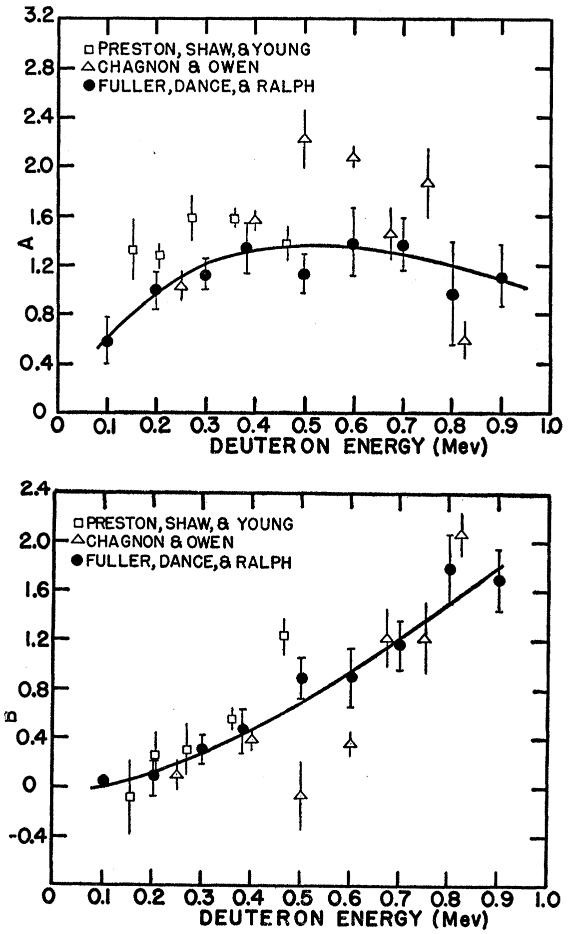

FIG. 2. Energy variation of the asymmetry coefficients *A* and *B* of the reaction $D(d,n)He^3$.

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[5] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. 25, 779 (1953).

[6] National Radiac Corporation, "Sintilon."

[7] J. M. Fowler and C. E. Roos, Phys. Rev. 98, 996 (1956).

in very noticeable apparent asymmetries about 90° in the center-of-mass system, while the identity of the reacting particles requires symmetry about 90°. Achievement of this symmetry with the unaltered curve therefore gave confidence in the stilbene extrapolation for the lower recoil energies. The data were adjusted for the effect of the variation in efficiency of the scintillator with neutron-proton scattering cross section.

Investigation of general neutron background consisted, in part, of determining the angular distribution at two widely different counting distances. This investigation revealed no significant reduction in the measured total asymmetry. No neutron background corrections were applied to the data. Carbon contamination of the target surface gave rise to gamma-ray and neutron background from the $C^{12}(d,p)C^{13*}$ and $C^{12}(d,n)N^{13}$ reactions above about 0.600-Mev bombarding energy. The pulse discrimination level was always adequately high to eliminate these low-energy neutrons. Corrections for the 3.1-Mev gamma rays from C^{13*} were determined at each angle by detecting a known fraction of them with the integral bias set high enough to eliminate all pulses from recoil protons. The fraction counted was obtained from a previously determined differential bias curve of the gammas. The extent of annihilation radiation from the positron decay of N^{13} was determined by counting these gamma rays at the end of each run. The maximum total background correction obtained by these two methods was less than 8%.

RESULTS

After transformation to center-of-mass coordinates,[8] the data were fitted to the expression

$$d\sigma(\theta')=d\sigma(90°)(1+A\cos^2\theta'+B\cos^4\theta'),$$

by using a three-constant least-squares treatment from which $d\sigma(90°)$, A and B were obtained. The differential cross sections appearing in the expression are relative, since the yields are normalized to unity at 0 degrees.

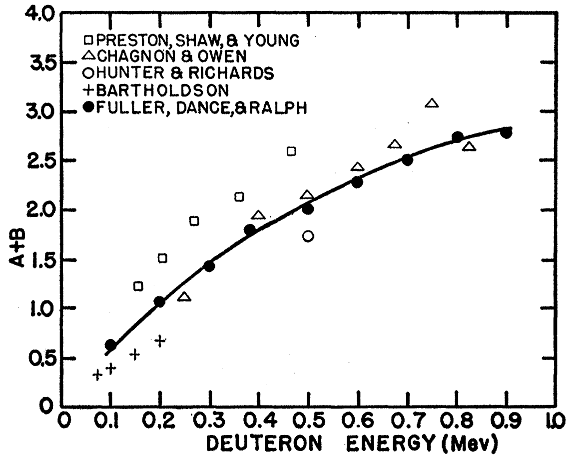

FIG. 3. Energy variation of the sum $(A+B)$ of the asymmetry coefficients of the reaction D(d,n)He^3.

In Fig. 1 the angular distributions in the center-of-mass system are shown with their least-squares fits at each average deuteron energy in the target. The ordinates for each distribution have been displaced to prevent overlapping. No terms higher than $\cos^4\theta'$ were required, as was expected from previous work.[3]

Variation of A and B with incident deuteron energy is shown in Fig. 2, along with the values reported in references 2 and 4. The errors indicated are standard deviations obtained in the formal way from the least-squares analysis; the curves are arbitrary fits to the present data. It is observed that the range of values of A and B reported from different laboratories is large at several energies. The present data show smooth energy variation of the coefficients below 1 Mev. $(A+B)$ as a function of bombarding energy is represented in Fig. 3; A is plotted at lower energies,[1] where a $(1+A\cos^2\theta')$ analysis was employed. Again the curve is an arbitrary fit to the present data. In regard to total asymmetry, this presentation indicates reasonable agreement of the present results with those of Chagnon and Owen[2] and varying extent of agreement with other authors. It is noted that the charged-particle work[4] tends to give greater asymmetries at energies below 0.500 Mev.

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[8] J. B. Marion and A. S. Ginzbarg, *Tables for the Transformation of Angular Distribution Data from the Laboratory System to the Center-of-Mass System* (Shell Development Company, Houston).