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Polarization of Neutrons from the $Be^9(d, n)B^{10}$ Reaction with 0.9- to 2.48-MeV Deuterons

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Three polarization distributions over the angular range from 15° to 135° (lab) have been obtained for neutrons produced in the $Be^9(d, n)B^{10}$ reaction. Polarization distributions were obtained for deuteron bombarding energies of 1.56, 2.064, and 2.48 MeV. Polarization measurements were made for up to five neutron groups corresponding to transitions to the ground- and the 0.72-, 1.74-, 2.15-, and 3.58-MeV states of B^{10}. A liquid-helium time-of-flight coincidence neutron polarimeter was used to make the measurements. In general, the polarization of the neutrons from the ground state is negative at forward angles and positive at back angles for deuteron bombarding energies from 1.56 to 2.48 MeV, whereas the polarization of the neutrons from the excited states is positive for forward angles and negative for back angles, the exception being neutrons from the 1.74-MeV level in B^{10}. The maximum polarization observed is about 35%.

I. INTRODUCTION

DURING the past few years, several measurements of neutron polarization from (d, n) reactions on light nuclei have been performed for deuteron energies below 10 MeV.[1–15] The distorted-wave Born approximation (DWBA) has been very successful in calculating angular distributions of heavy and medium weight nuclei.[16] In a few cases, DWBA also has been used successfully to calculate polarization effects on heavy and medium weight nuclei.[17,18] Attempts to calculate polarization effects in (d, n) reactions on light nuclei have proved at best only qualitatively successful.[19–21] The application of DWBA theory to these nuclei is complicated by the following circumstances: (1) The optical model, which requires averaging over an energy interval containing a number of compound nuclear resonances, is of limited applicability[22] for light nuclei whose resonances are fewer and more separated. Also for very light nuclei, exchange reactions may occur with sufficient frequency to render the optical model invalid.[22] (2) The validity[23] of the perturbation treatment applied in the DWBA theory has to be investigated for low bombarding energies where the perturbation is no longer small compared with the incident energy. (3) The effect of the D-state component of the deuteron[24,25] internal wave function, which is usually omitted, may be important. (4) Inclusion of tensor potentials in the calculation of the deuteron scattering wave function could be significant.[26] (5) There is insufficient evidence to justify an assumption that the direct reaction model should describe polarization effects for relative low bombarding energies where compound nucleus formation is known to be a competitive reaction mechanism. In fact, recent comparisons of angular distribution and polarization data from (d, n) reactions with the results of DWBA calculations

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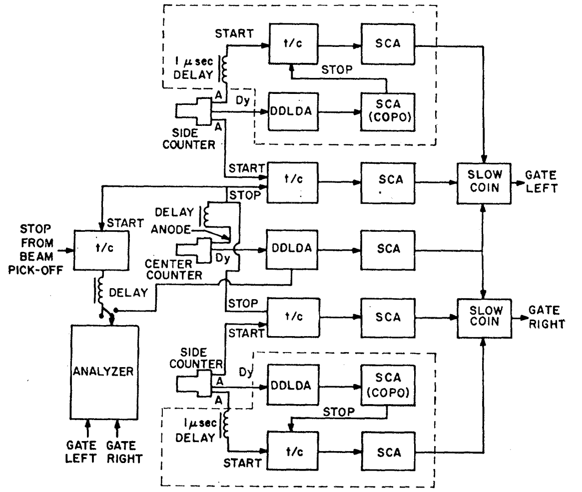

FIG. 1. Block diagram of electronics used in neutron polarization experiment. The γ discrimination circuitry is enclosed by dashed lines. SCA stands for single channel analyzer, DDLDA stands for double delay line differentiated analyzer. COPO stands for crossover pickoff and *t/c* stands for time-to-pulse height converter.

which also include compound nucleus contributions have been encouraging.[27,28]

Siemssen *et al.*[29] have found that for stripping reactions on light nuclei the angular distributions often do not change significantly even near compound resonances, although the differential cross sections fluctuate strongly. They find that in some cases the angular distributions on the resonances are even more characteristic of a direct process than are those measured off the resonance. Elwyn *et al.*[30] find for the reaction $C^{12}(d, n)N^{13}$ that the shape of the angular distributions averaged over bombarding energy is probably given by the direct amplitude alone with the compound amplitude contributing a more or less isotropic background.

Researchers at Duke University have studied neutron polarization for several (d, n) reactions on light nuclei[1,2] and report a characteristic trend for their results. They note that for several (d, n) reactions which proceed with an orbital angular momentum transfer of one unit, polarization functions similar to that which persists in the $C^{12}+d$ reaction are obtained. They have also noted the similarity of the polarization produced in the $C^{12}(d, n)$ and $C^{12}(d, p)$ reactions at certain energies. The $B^{10}(d, n)C^{11}$ and $B^{11}(d, n)C^{12}$ reactions are special cases which do not follow this pattern.[1,15]

These results suggest that direct reactions play a large part in (d, n) reaction on light nuclei. In order to study these trends further, the $Be^9(d, n)B^{10}$ reaction was chosen. This (d, n) reaction is suitable for studying these trends for the following reasons: (1) The $Be^9(d, p)Be^{10}$ reaction has been studied in some detail at energies of interest to this experiment. (2) The $Be^9(d, n)B^{10}$ reaction is relatively free of resonance structure, although Siemssen *et al.*[29] report indications of resonance structure in the $Be^9(d, n)B^{10}$ reaction at 2.1 MeV. A strong resonance was found at 1.0 MeV in the $Be^9(d, n)B^{10}$ reaction by Shpetnyi,[31] but this resonance has not been seen by others.[32] It was hoped that polarization excitation curves would shed light on these resonant structures. (3) The $Be^9(d, n)B^{10}$ reaction is amenable for study by the methods to be used here, i.e., pulsed-beam time of flight. The cross section for neutron production is fairly large, and the neutron groups are well separated in time for the deuteron energies used here.

II. APPARATUS AND PROCEDURE

The polarization measurements were made at the Oak Ridge National Laboratory. A deuteron beam produced by the ORNL 3 MV Van de Graaff accelerator, operated in the pulsed mode, was allowed to strike a beryllium target of 250-μg/cm^2 thickness. The polarization of the emitted neutrons was determined by observing the asymmetry in elastic scattering from liquid helium. Two counters were used simultaneously and then interchanged to cancel counter efficiency differences. By the use of this technique, it was possible to determine the asymmetry for up to five groups of neutrons simultaneously. The angle θ_2 was set equal to 123° (lab) for this experiment. The polarimeter used is the same as previously described[33,34] except that liquid scintillators of NE 213 were used as side counters in the present work. These scintillators were cylinders 2 in. long by 2 in. diam, positioned with their axes of symmetry normal to the scattering plane at a distance of 7 in. from the liquid helium. The NE-213 scintillators were mounted on XP-1020 photomultiplier tubes. Pulses produced by gamma rays and noise in the side counters were eliminated by using zero crossover pulse-shape discrimination techniques.[35–37]

A block diagram of the electronics is shown in Fig. 1. Energy selection was accomplished by conventional time-of-flight techniques between a beam pickoff

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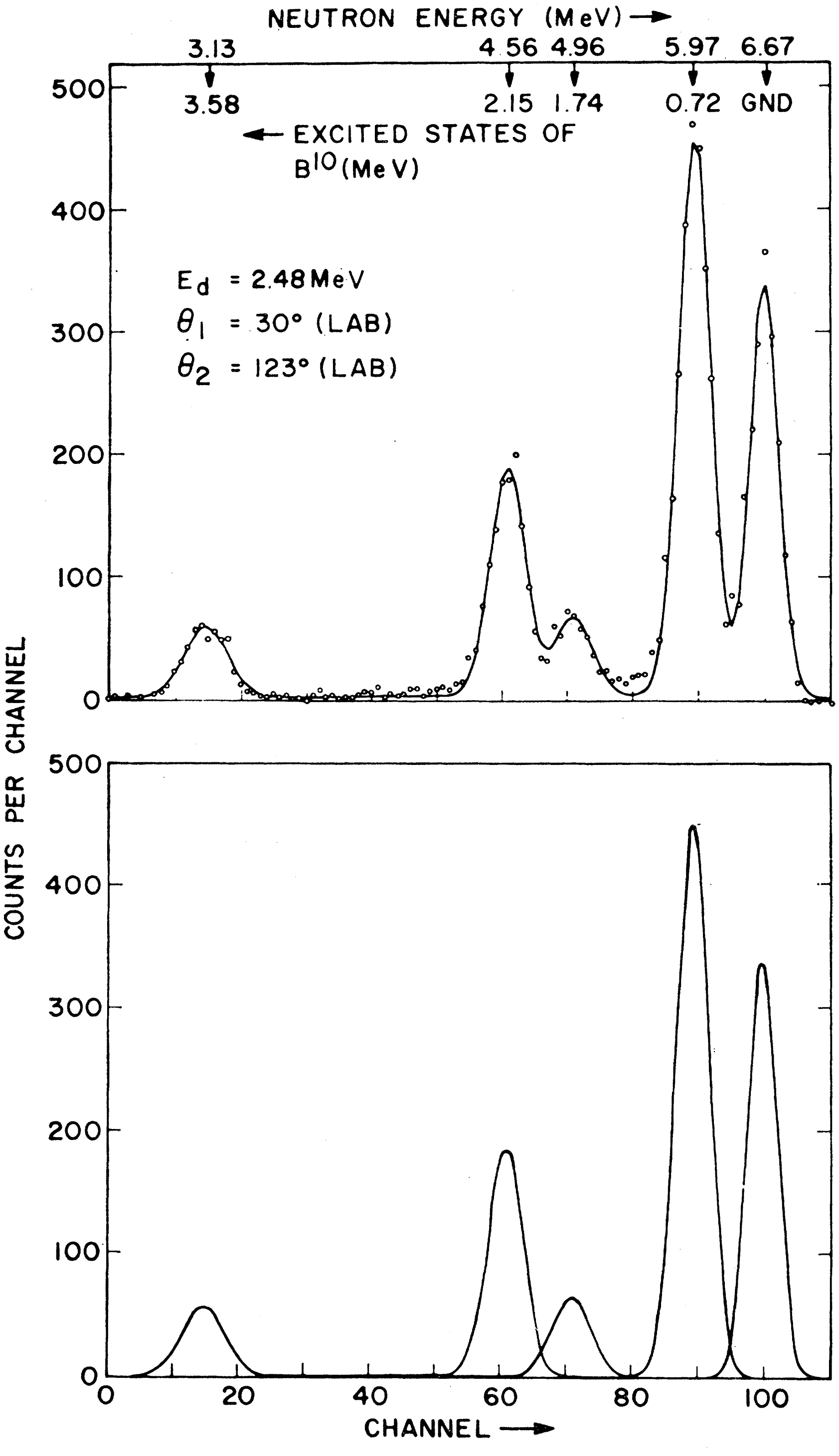

FIG. 2. Top: A neutron time-of-flight spectrum of the $Be^9(d, n)B^{10}$ reaction with $E_d=2.48$ MeV, $\theta_1=30°$ (lab), $\theta_2=123°$ (lab), and flight path of 3 m. The small circles represent the experimental points, and the solid line shows the computer fit to the data, assuming the peaks are Gaussian. Bottom: A plot of the individual Gaussian curves from above computer fit.

placed just before the beryllium target and the liquid-helium polarizer-analyzer. Additional energy selection and background reduction was achieved by using a fast-slow coincidence system between the scatter and the side counters. Fast coincidences between pulses from the helium scintillator and the side counters were detected with time-to-pulse height converters fed by the anodes of the center and side counters. The slow portion of the "fast-slow" system consisted of signals from the pulse shape discrimination circuit (shown by dashed lines in Fig. 1) with the single-channel analyzer set to pass neutrons. It was also possible to do energy

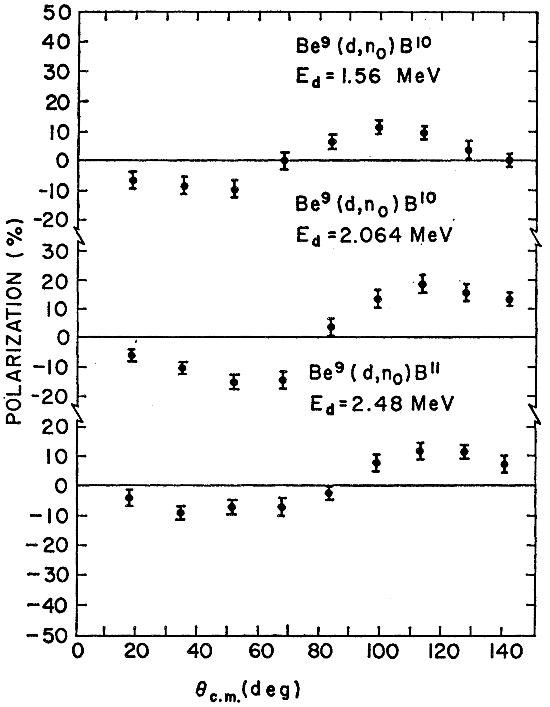

FIG. 3. Angular dependence of neutron polarization from the reaction $Be^9(d, n_0)B^{10}$ for three deuteron bombarding energies.

discrimination on the dynode signal from the liquid-helium scintillator. Output pulses from the coincidence network were used to gate a 4096-channel analyzer. Time-of-flight spectra for neutrons which scatter to the right and to the left were routed to separate sections of the analyzer memory. At deuteron bombarding energies used in this experiment, up to five neutron groups are emitted corresponding to the ground and 0.72-, 1.74-, 2.15-, and 3.58-MeV states of B^{10}. A typical time-of-flight spectrum is shown in Fig. 2 (top: small circles) where the different peaks represent the different neutron groups. Under typical operating conditions, the accelerator produced about 10-μA average current at less than 2-nsec pulse width. The over-all system resolution was about 2.5 nsec (FWHM) for the neutron peaks.

In order to obtain the counts under each peak, it was assumed that the peaks can be approximated as Gaussian, and hence the complete curve could be fitted by a summation of the form

$$y=\sum_{k=1}^{n} y_k \exp\left[-\frac{(x-\bar{x}_k)^2}{2\sigma_k^2}\right], \qquad (1)$$

where $\bar{x}_k$, σ_k, and y_k represent the position, half-width, and height of the kth peak, and n is equal to the number of Gaussian peaks in the data to be fitted. A computer code was written that fits the data by the method of differential corrections.[38] From the experimental data, initial estimates are made of the position, half-width, and height of each peak. Figure 2 (top: solid line) shows the fit for a set of experimental data. Note in Fig. 2 (top) that a small constant background was subtracted from the initial data before the data were fitted. The counts under the kth Gaussian is then found by integrating the function

$$y=\int_{-\infty}^{\infty} y_k \exp\left[-\frac{(x-\bar{x}_k)^2}{2\sigma_k^2}\right]=(2\pi)^{1/2}y_k\sigma_k. \qquad (2)$$

Figure 2 (bottom) shows each Gaussian with the background subtracted. From four such sets of experimental data, the asymmetry could be determined for a given deuteron bombarding energy at a particular angle.

The statistical uncertainty ΔP_n in P_n was determined in accordance with the assumption that the contributions from each of the separate factors considered were uncorrelated.

$$(\Delta P_n)^2=\sum (\partial P_n/\partial f_i)^2(\Delta f_i)^2, \qquad (3)$$

where

$$\partial P_n/\partial f_i$$

measures the sensitivity of P_n to the parameter f_i and $\pm\Delta f_i$ is the assumed uncertainty in that parameter. In calculating the statistical uncertainty, the number of counts N in a particular peak was assumed to be given by

$$N=N_T-N_B, \qquad (4)$$

where N_T represents the total counts and N_B represents the background counts under the peak.

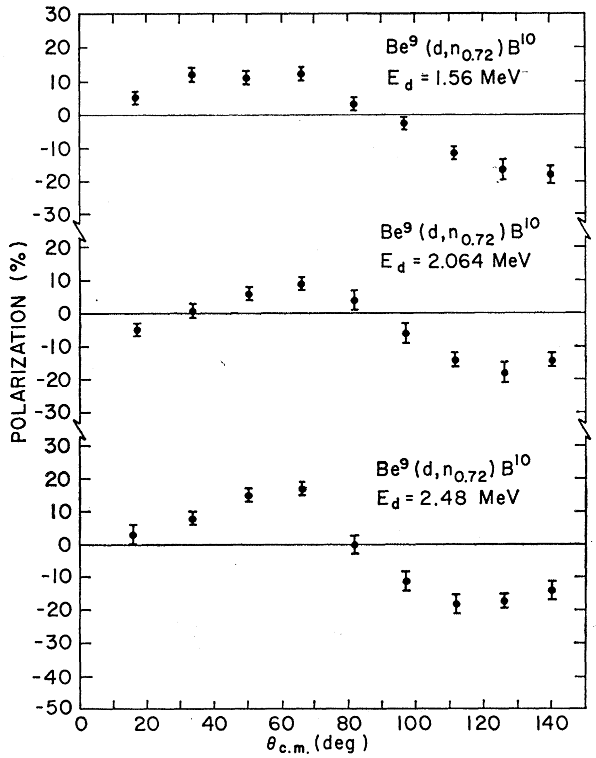

FIG. 4. Angular dependence of neutron polarization from the reaction $Be^9(d, n_{0.72})B^{10}$ for three bombarding energies.

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A Monte Carlo code similar to a code by Aspelund and Gustafsson[39] was written which derives the polarization of the neutron beam from the measured asymmetry.[40,41] The code uses the phase shifts of Hoop and Barschall[42] to derive the necessary parameters, the angular distribution $d\sigma/d\Omega$, the polarization P, and the spin rotation parameter β needed for consistent tracking of polarization effects in successive neutron scatterings from the spin-zero nuclei helium. The code adjusts the initial input polarization needed to reproduce the measured asymmetry. Since the code uses the actual geometry of the experiment, the data are automatically corrected for finite geometry and multiple scattering. The code calculates polarization effects for up to four scatterings and assumes zero polarization for higher-order scatterings. The measurements reported here are in agreement with the Basle sign convention.[43]

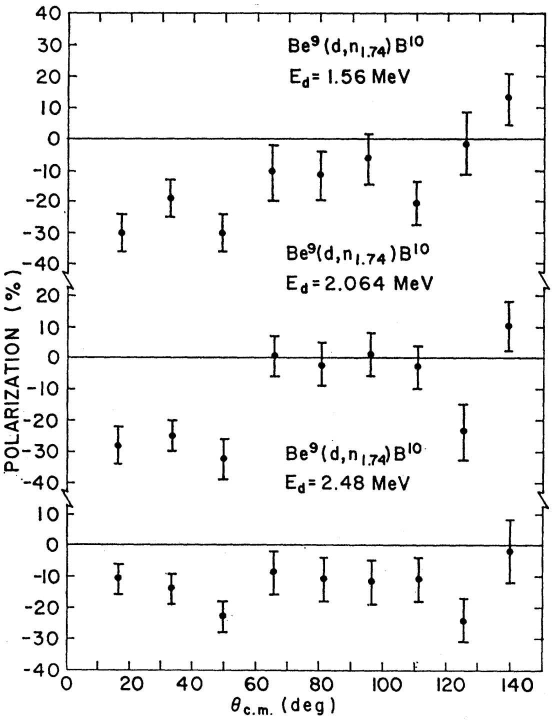

FIG. 5. Angular dependence of neutron polarization from the reaction $Be^9(d, n_{1.74})B^{10}$ for three deuteron bombarding energies.

III. RESULTS AND DISCUSSIONS

The results of the polarization distribution measurements are presented in Figs. 3–8. In general, the polarization of the neutrons from the ground state is negative at forward angles and positive at back angles for deuteron bombarding energies from 1.56–2.48 MeV, whereas the polarization of the neutrons from the excited states is positive for forward angles and negative for back angles. The exception is the neutrons from the 1.74-MeV level in B^{10} at 1.56 and 2.48 MeV. The polarization of the neutrons from this level tend to be negative for all angles less than about 120° for deuteron bombarding energies of 1.56 and 2.48 MeV. The shape

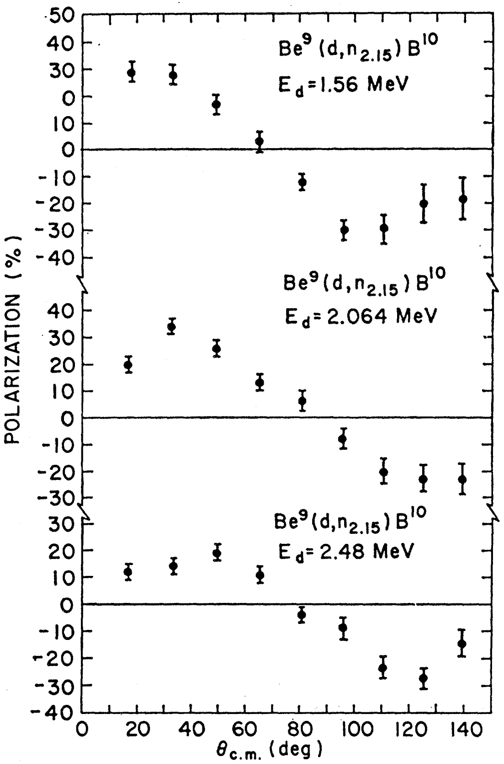

FIG. 6. Angular dependence of neutron polarization from the reaction $Be^9(d, n_{2.15})B^{10}$ for three deuteron bombarding energies.

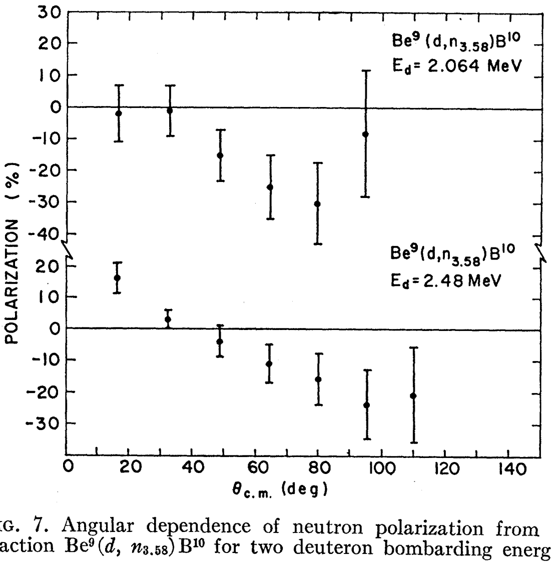

FIG. 7. Angular dependence of neutron polarization from the reaction $Be^9(d, n_{3.58})B^{10}$ for two deuteron bombarding energies.

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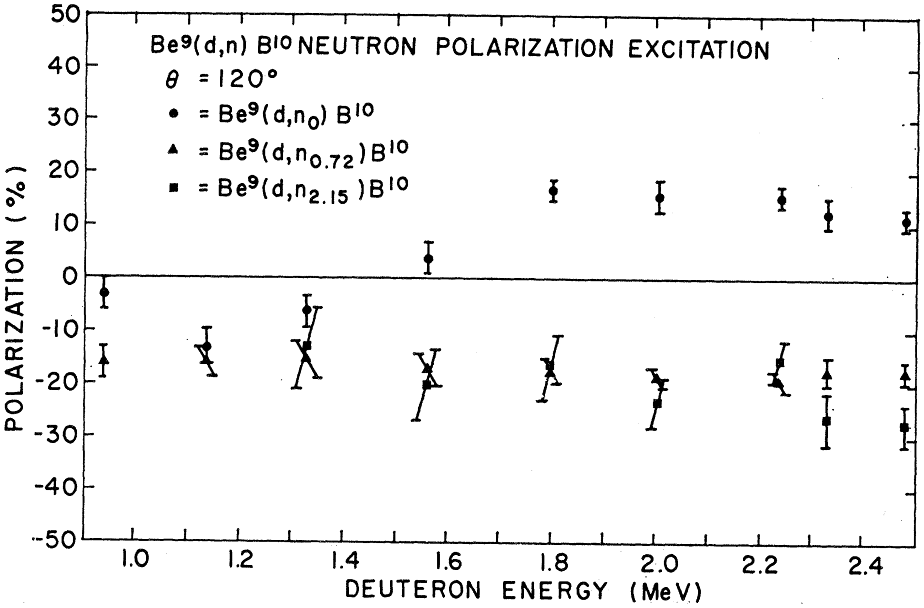

FIG. 8. $Be^9(d, n)B^{10}$ neutron polarization for E_d equal 0.9–2.48 MeV for θ_1 equal to 120° for neutrons from the ground and 0.72- and 2.15-MeV levels in B^{10}.

of the distributions for each level do not change appreciably, except for the neutrons from the 1.74-MeV level in B^{10}, as the deuteron bombarding energy is changed from 1.56 to 2.48 MeV. The sign of the polarization tends to change in the interval of 60° to 90° (c.m.) for neutrons from all levels except neutrons from the 3.58-MeV level in B^{10}. These distributions tend to be positive for angles less than 40° (c.m.) and negative for angles larger than 40° (c.m.).

The results of the neutron polarization for the $Be^9(d, n_0)B^{10}$, $Be^9(d, n_{0.72})B^{10}$, and the $Be^9(d, n_{2.15})B^{10}$ reactions are presented in Fig. 8 for θ_1 equal to 120° for E_d equal 0.9 to 2.48 MeV. The neutron polarization for the ground-state group is negative for energies between 0.9 and 1.5 MeV and positive for energies between 1.5 and 2.48 MeV. The neutron polarization for neutrons from the 0.72- and 2.15-MeV levels in B^{10} is negative and shows little structure between 0.9 and 2.48 MeV. These results do not rule out the possibility of a resonance at 1 MeV, as found by Shpetnyi,[31] as the polarization of the ground-state group does show some structure around 1 MeV. Additional data below 1 MeV and at other angles would be helpful.

It is interesting that the $Be^9(d, n_0)B^{10}$ neutron polarization is similar to the $Be^9(d, p_0)Be^{10}$ proton polarization.[44] One would not necessarily expect a similarity since B^{10} and Be^{10} are not mirror nuclei. Neglecting Coulomb effects, one would expect the neutron polarization from the lowest $T=1$ state in B^{10} (1.74 MeV) to resemble the proton polarization from the $Be^9(d, n_0)Be^{10}$ reaction. At 2.50 MeV, Blue *et al.*[44] measure a proton polarization that is negative for angles less than 50° (c.m.) and positive above 50° (c.m.) except at about 138° (c.m.) where the polarization is again negative. The polarization reported here for neutrons from the 1.74-MeV level in B^{10} is negative for all angles measured between 0° and 140° (c.m.).

Attempts to fit both the cross section and the polarization data using the DWBA code JULIE[45] have been unsuccessful, although it has been possible to obtain qualitative fits to either the cross-section data or the polarization data individually.

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