Deuteron Polarization from the $^9Be(p,d)^8Be$ Reaction at 3–5 MeV*

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The polarization of deuterons produced in the $^9Be(p,d)^8Be$ ground-state reaction was measured at several deuteron emission angles in the region of the stripping peak for proton energies of 3, 4, and 5 MeV. A carbon analyzer via the $^{12}C(d,p)^{13}C$ ground-state reaction was used, along with the relationship ϵ (the asymmetry) $=3\,\mathbf{P}_p.\mathbf{P}_d$, to determine the magnitude and sign of the deuteron polarization. At 3 and 4 MeV the sign near the stripping peak was found to be positive, which is in agreement with earlier experimental findings and with distorted-wave Born-approximation calculations for which deuteron-wave distortion is assumed to predominate. At 5 MeV, however, the sign was measured to be negative, which may be due to a relatively greater proton-wave distortion at this energy.

INTRODUCTION

It has been suggested by several investigators[1–5] that polarization measurements for stripping and pickup reactions should be directly applicable to nuclear spectroscopy if the relative directions of the angular momentum l and the intrinsic spin s of the exchanged nucleon can be determined from the measured sign of the polarization of the reaction product. In this respect it has been predicted that in stripping reactions in which only one value of l contributes to the neutron capture and the total spin j is $l-\frac{1}{2}$, the maximum value of the proton polarization $|\mathbf{P}_p|$ in the stripping peak is $\frac{1}{3}$ and its sign is negative[1]; correspondingly, for pickup reactions $|\mathbf{P}_d|_{\max}$ is $\frac{2}{3}$ and the sign negative.[2,3] If $j=l+\frac{1}{2}$, then for stripping reactions $|\mathbf{P}_p|_{\max}$ is $\frac{1}{3}l/(l+1)$ and positive,[1] and for pickup reactions $|\mathbf{P}_d|_{\max}$ is $\frac{2}{3}l/(l+1)$ and positive.[2,3] These maximum values can be increased if spin-orbit interaction is not negligible.

In all the above predictions, it was assumed that the proton and deuteron waves are distorted by the nucleus. It was pointed out by Tobocman,[4] and later verified by the calculations of Newns and Refai,[5] that to obtain signs of polarization that agree with the experiments of Hilman[6] and of Juveland and Jentschke,[7] the deuteron distortion had to be greater than the proton distortion.

This communication compares the predictions discussed above with some recent deuteron polarization measurements for the $^9Be(p,d)^8Be$ reaction. The measurements were for proton energies of 3, 4, and 5 MeV and deuteron emission angles in the region of the stripping peak. All the results have been made to conform to the Basel convention,[8,9] i.e., the polarization is taken as positive along the direction of $\mathbf{k}_{\text{in}}\times\mathbf{k}_{\text{out}}$, where $\mathbf{k}_{\text{in}}$ is the propagation vector of the incoming particle and $\mathbf{k}_{\text{out}}$ that of the outgoing particle.

EXPERIMENTAL APPARATUS AND METHOD

The experimental arrangement consisted of the double-scattering chamber shown in Fig. 1. Protons penetrating the ^9Be target were position-monitored by two beam-pickoff electrodes. The emitted deuterons, corresponding to ground-state transitions ($Q=+0.56$ MeV), passed through collimator slits at an angle θ_1 and struck a carbon analyzer. The resulting $^{12}C(d,p)^{13}C$ ground-state reaction ($Q=+2.7$ MeV) produced protons well separated in energy from the primary protons and from deuterons scattered from the carbon. The left-right asymmetry of these reaction protons was measured with two surface-barrier diodes which were located in the plane of the double reaction, 10 cm from the carbon analyzer and 45° to the deuteron beam. Each measurement was repeated with the analyzer chamber rotated 180°. An averaging of the two measurements corrected for differences in the active area of the detectors and for detector misalignment but not for axial misalignment of the initial proton beam. Axial alignment was achieved by removing the carbon target, reducing the aperture of the collimator that preceded the carbon target, and moving the proton beam across the ^9Be foil to maximize the count rate of the pinhole-collimated monitor located axially at the far end of the second scattering chamber. The two beam-pickoff electrodes were then centered, and they were subsequently used to maintain this alignment during the measurement.

In order to obtain the polarization from the observed left-right asymmetry, corrections must be made for the finite target size. To evaluate the reliability of the

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[9] *Proceedings of the International Symposium on Polarization Phenomena of Nucleons* (Birkhauser Verlag, Basel and Stuttgart, 1961).

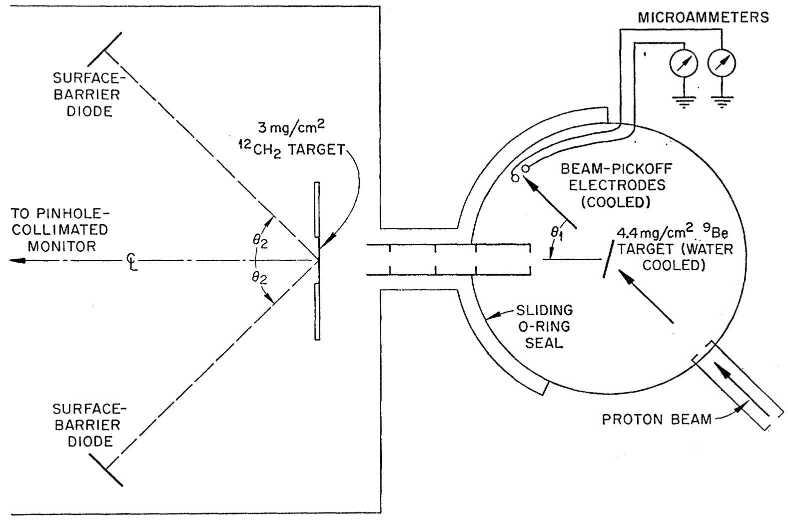

FIG. 1. Double-scattering chamber. The beam-pickoff electrodes can be moved laterally to the proton beam, the angle θ_1 can be varied by virtue of the sliding O-ring seal, and the second scattering chamber can be rotated about the center line along which the pinhole-collimated monitor is located.

method for calculating this effect, a measurement of left-right asymmetry was made with a 5-mg/cm^2 gold-foil scatterer replacing the carbon analyzer foil. The gold scatterer should yield only the finite-target-size asymmetry, since the Coulomb barrier of gold is several times the proton energy and no distortion of the proton wave by the nuclear potential would be expected. Protons scattered doubly from the beryllium and gold were measured, along with a negligible fraction of deuterons produced in the beryllium and scattered by the gold. The measured asymmetry is caused by a higher flux of protons at the right side of the gold scatterer, as shown in Fig. 1, because of the negative slope of $\sigma(\theta_1)$, the differential scattering cross section of beryllium for protons. When the Rutherford scattering cross sections for $\sigma(\theta)$ were used, the calculated asymmetries were about 1–4%, depending on θ_1. These were equal to the gold-scatterer results within 1%.

As a further check on the accuracy of the experimental method, both the ^{9}Be target and the second scatterer (i.e., the gold) were replaced with 0.4-mg/cm^2-thick carbon targets and the polarization of carbon elastic scattering was measured by a double 45° scattering of protons. The average energy of the protons incident on the first and second carbon scatterers was 5.2 and 4.7 MeV, respectively, and the experimental results agreed within statistical error with results reported elsewhere.[10]

The additional features of the experimental arrangement that were important to the reliability of the data included the following: (i) the collimator following the beryllium target had an opening of about two beam-spot diameters to eliminate pinhole camera effects which amplify the beam-spot asymmetry and axial misalignment; (ii) the final aperture of the post-beryllium collimator was moved out of the line of sight of the counters, thereby eliminating practically all the troublesome background counts as measured with the carbon analyzer foil removed; and (iii) the diodes were collimated so as to cover the edges where the potting compound was in contact with the gold surface layer. This reduced the effective area from 300 to 240 mm^2 and produced a large improvement in overall resolution.

Typical pulse-height distributions are shown in Fig. 2 for a running time of about 3 h. The high peaks representing protons from ground-state transitions to ^{13}C in the ^{12}C$(d,p)^{13}$C reaction are well separated from other events, such as proton double scattering.

The proton beam current during the deuteron-polarization measurements could be kept at nearly 10 μA without buckling the beryllium target, because of conductive heat removal to a water-cooled brass target holder and a small 1-cm-diam opening in the brass plates. The total running time for each polarization value was in the vicinity of 10 h.

DATA ANALYSIS

First, the left-right asymmetry

$$\epsilon_1=(L_A-R_B)/(L_A+R_B)$$

was calculated for counter A in the left position and counter B in the right position. Then $\epsilon_2=(L_B-R_A)/(L_B+R_A)$ was calculated for the positions of the counters reversed by rotating the second scattering chamber 180°. The net value of $\epsilon=(\epsilon_1\epsilon_2)^{1/2}$ was calculated and then corrected for that part of the asymmetry due to finite target size. Some of the runs were repeated many days later to check reproducibility and to improve counting statistics, and the polarization values and statistical uncertainties of the separate runs were appropriately weighted.

[10] R. E. Warner and W. P. Alford, Phys. Rev. **114**, 1338 (1959), and *Nuclear Data Tables*, edited by J. B. Marion (U. S. Government Printing and Publishing Office, Washington D. C., 1960), Part 3.

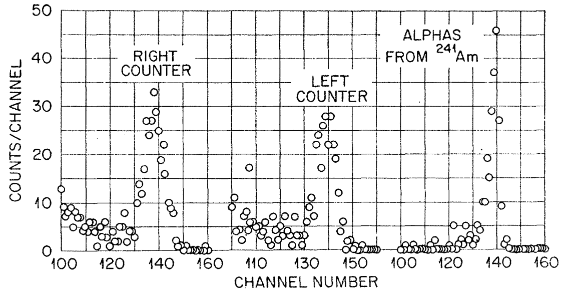

FIG. 2. Pulse-height distributions of protons from the $^{9}Be(p,d)^{8}Be$ and $^{12}C(d,p)^{13}C$ double reactions. The resolution of the center is indicated by the pulse-height distribution shown for ^{241}Am alphas.

The magnitude of the finite-target-size correction increases both with the size of the beam spot irradiating the ^{9}Be target and the area of the carbon analyzer irradiated by the deuterons. During the experiment, the intense portion of the beam spot was kept to a diameter of 2–3 mm. The halo was kept dim by careful focusing, and was kept small by precollimation. The ^{9}Be-to-^{12}C distance was 100 mm, and about a 14-mm diam of the carbon analyzer was irradiated. With this geometry, the beam spot can be taken as a point source to a good approximation. The calculation of the finite size of the carbon analyzer was done numerically by breaking up the carbon target into eight vertical strips. Since the finite-target-size correction turned out to be only a few percent, the above simplifications appear to be well justified.

In calculating the deuteron polarization from the measured asymmetry produced by the carbon analyzer, use was made of the simple relation[1] between proton polarization $\mathbf{P}_p$ produced when unpolarized deuterons are used and the differential cross section $(d\sigma/d\Omega)_{\text{pol}}$ when the incident deuterons have a polarization $\mathbf{P}_d$:

$$(d\sigma/d\Omega)_{\text{pol}}=(d\sigma/d\Omega)_{\text{unpol}}(1+3\mathbf{P}_p\cdot\mathbf{P}_d). \tag{1}$$

Equation (1) is valid if there is negligible spin dependence of the distorting optical potential, including spin-orbit coupling. The resulting asymmetry ϵ is then

$$\epsilon=3\mathbf{P}_p\cdot\mathbf{P}_d, \tag{2}$$

and the maximum value of polarization is parallel to $\mathbf{k}_{\text{in}}\times\mathbf{k}_{\text{out}}$. The deuteron polarization was calculated with Eq. (2), taking the proton polarization to be 0.40 ± 0.10 at all energies. All uncertainties assigned to the polarization values represent the statistical uncertainty combined with the rather large value of the uncertainty in $\mathbf{P}_p$.

RESULTS

Table I gives our values of $\mathbf{P}_d$ at proton-bombarding energies of 3, 4, and 5 MeV, along with two values measured by Lambert *et al.*[2] at 3 MeV. For ^{9}Be, the picked-up neutron has a total angular momentum $j=l+s$, with $l=1$. Therefore, the sign should be positive

TABLE I. Polarization of deuterons from the $^{9}Be(p,d)^{8}Be$ reaction.

	$\mathbf{P}_d$ 3 MeV	4 MeV	5 MeV
30°	$+0.11\pm0.05$[a]		
30°	$+0.17\pm0.05$		-0.065 ± 0.02
45°	$+0.18\pm0.06$	$+0.06\pm0.03$	-0.045 ± 0.02
60°	$+0.056\pm0.03$		$+0.01\pm0.025$
90°	$+0.06\pm0.03$[a]		

[a] J. M. Lambert *et al.*, Phys. Rev. 124, 1959 (1961).

in the angular region of the stripping peak, and the maximum value should be $\frac{2}{3}l/(l+1)=\frac{1}{3}$. While the measured values of $\mathbf{P}_d$ are well below $\frac{1}{3}$ at all energies, assuming Eq. (2) is valid, there is a rather definite change of sign at a proton energy of 5 MeV.

An attempt was made to check the validity of Eq. (2) by first polarizing the protons by means of elastic scattering from carbon, then using a ^{9}Be target as the second target. The asymmetry in this case[3] should be

$$\epsilon=\tfrac{1}{2}\mathbf{P}_p\cdot\mathbf{P}_d, \tag{3}$$

and this would provide an independent check of the relations derived on the assumption of negligible spin interaction discussed above. However, the Q value of $+0.56$ MeV for the $^{9}Be(p,d)^{8}Be$ reaction was inadequate to provide good separation of the deuterons from doubly scattered protons, and dE/dx counters with the required shallow thickness were not available at this time.

Also, an effort was made to measure $\mathbf{P}_p$ independently at the deuteron energies encountered in the seven measurements of Table I by using a deuteron beam and carbon target as the first target, and elastically scattering the protons from a second carbon target. In this case, the protons could not be separated from a rather large background that was especially prominent in the right counter of Fig. 1, a background that was probably produced by stripping neutrons in the carbon target. Since there was no opportunity to redesign the equipment to provide adequate shielding, the arbitrary value of $\mathbf{P}_p=0.4\pm0.1$ was assumed for the $^{12}C(d,p)^{13}C$ reaction at 45°. The compilation of Goldfarb[8] was used as a basis, noting from it that $\mathbf{P}_p$ is very nearly constant for $4<E_d<15$ MeV at 45°. Both the value of $\mathbf{P}_d$ and the assigned uncertainty should be recomputed with Eq. (2) when better values of $\mathbf{P}_p$ become available in the 3–5-MeV energy region.

DISCUSSION

While the maximum value of $\mathbf{P}_d$ is well below the theoretical limit of $\frac{1}{3}$ that assumes spin-dependent forces are negligible, the sign of $\mathbf{P}_d$ becomes negative at 5 MeV. This change of sign is not consistent with the prediction of a positive sign by Tobocman[4] and by Newns and Refai[5] who invoked a predominance of deuteron interaction with the nucleus over proton interaction to get the sign to agree with earlier experi-

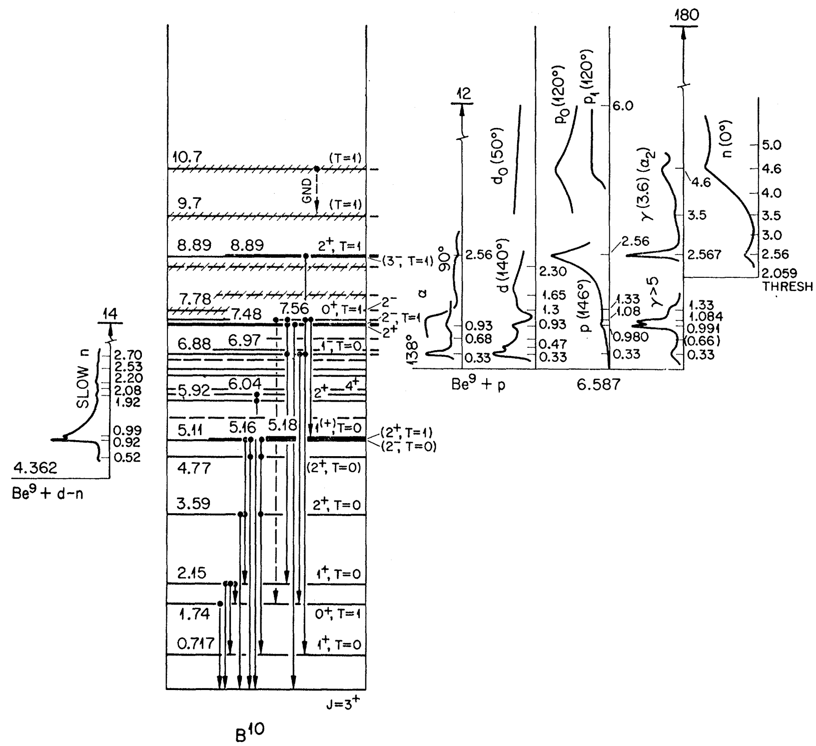

FIG. 3. Excerpt from Nuclear Data Sheet NRC 61–5, 6–91 showing some relative reaction probabilities for deuterons and protons on beryllium as a function of bombarding energy.

ments. But rather, at 5 MeV, the earlier prediction by Newns[11] seems to hold out. Newns first postulated that the sign would be negative for ^{9}Be because of a predominance of proton-wave distortion.

The answer may lie in the data given in Fig. 3, which has been taken from NRC 61–5, 6–91 [*Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C.)]. To the left of the sheet can be seen a ^{9}Be(d,n) excitation function for slow neutron production, a function that decreases with energy above 1 MeV and becomes flat at a 3-MeV deuteron bombarding energy. On the other hand, the proton elastic and inelastic cross sections at 120° are lowest at 3 MeV, higher at 4 MeV, and highest at 5 MeV. Between 4 and 5 MeV, the inelastic scattering cross section becomes important. Thus, the proton interaction with the nucleus at 5 MeV may well become greater than the deuteron interaction and this in itself could account for the change of sign in $\mathbf{P}_d$ at 5 MeV.

The observed change of sign at 5 MeV indicates that the use of polarization in determining the relative direction of l and s of a picked-up or captured nucleon is not reliable as a technique in nuclear spectroscopy. In support of this, the calculations of Robson[12] showed that the inclusion of spin dependence of nuclear forces led to a violation of the limits given in the introduction of this paper. This violation has been observed experimentally[7,13] for proton polarization in the ^{12}C$(d,p)^{13}$C reaction. Here, $|\mathbf{P}_p|$ is greater than $\frac{1}{3}$ in the region of the stripping peak.

In summary, it appears that the predictions of sign and magnitude of polarization outlined in the Introduction of this paper are generally unreliable; that is, the spin dependence of the distorting optical potential is at times significant, in which case it increases the limits of the magnitude of the polarization. Also, the proton-wave distortion may, in certain circumstances, become greater than deuteron-wave distortion, leading to a violation of the sign prediction.

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