Deuteron Polarization in the $Be^9(p,d)Be^8$ Reaction*

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The polarization of the deuterons from the $Be^9(p,d)Be^8$ reaction was investigated at two angles, 30° and 90°, at an incident proton energy of 3 Mev. The deuteron polarization was measured by utilizing the asymmetry of the protons from the $D(d,p)H^3$ reaction. The asymmetries were corrected for the finite geometry of the experiment. The analysis of the polarization from this data was performed employing a restricted set of interactions, and in this specific case the deuteron polarization was found to be $+(11\pm5)\%$ at 30°, and $+(6+3)\%$ at 90°. The sign of the polarization is in agreement with the semiclassical model, and the magnitude is less than the theoretical upper limit of 33%.

I. INTRODUCTION

POLARIZATION in stripping and pickup reactions has become an increasingly useful method for studying the properties of nuclei. Angular distributions can be used, for example, to obtain orbital angular momenta from direct-interaction theory. In a similar manner, polarization measurements determine the total angular momentum of the states involved in these reactions. Equally as important, the polarization of the reaction products proves to be an extremely sensitive parameter for testing the range of applicability for various phenomenological theories. In this respect, relatively simple models of direct interactions can be used to fit angular distribution and correlations, but the models must be more comprehensive in order to predict the results of polarization experiments.[1,2]

The $Be^9(p,d)Be^8$ reaction was investigated to determine the polarization of the outgoing deuterons at two laboratory angles, 30° and 90°; and further to determine the feasibility of using the $D(d,p)H^3$ reaction as a polarization analyzer.

In this double scattering experiment, deuterons from $Be^9(p,d)Be^8$ were incident upon a gas deuterium target, and the azimuthal asymmetry of the protons from the $D(d,p)H^3$ reaction was measured. These protons were detected in the plane formed by the proton and scattered-deuteron beams, and the experimental asymmetry is defined by

$$\epsilon_x = (LL-LR)/(LL+LR),$$

where LL refers to the number of protons from the beam that were scattered twice to the left, etc.

II. EXPERIMENTAL ARRANGEMENT

A Be target (5×10^{-4} in. thick) was bombarded with a 10-μ amp proton beam having an energy of 3 Mev, and collimated to $\frac{3}{16}$-in. diameter. The scattered deuterons entered the polarimeter, which was 3.8 cm. from the Be target, through a $\frac{3}{16}$-in. aperture. The polarimeter consisted of a sealed chamber containing 3 atm (absolute) of deuterium gas with CsI(Tl) crystal detectors at 40° to the right and left of the direction of the deuteron beam.

In order to measure the polarization at different angles, a vacuum chamber large enough to hold the polarimeter was constructed. This chamber was a cylinder 3 ft across and 10 in. high. The cylindrical section was made of $\frac{1}{2}$-in. Al, and the top and bottom were 1-in. Al having an O-ring groove 3 ft in diameter and $\frac{1}{8}$ in. deep milled into each. A turntable 30 in. in diameter and made of $\frac{1}{2}$-in. Al was placed in the bottom of the chamber and rotated by a shaft extending through the bottom of the chamber. To keep the height of the turntable constant in spite of deflection of the bottom plate under vacuum, the turntable was supported at the periphery by 1-in. ball bearings running in a race machined in the bottom plate. The shaft to rotate the turntable was vacuum sealed to the bottom plate by an O-ring, but was free to slide vertically with respect to the bottom plate of the vacuum chamber.

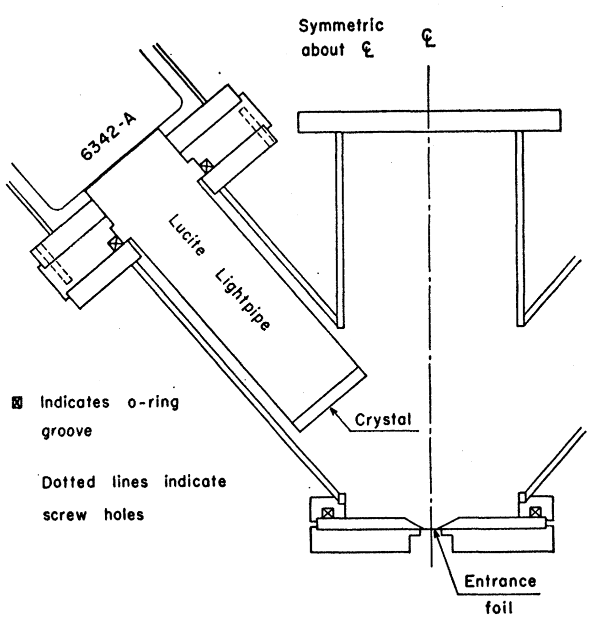

FIG. 1. Deuteron polarimeter. The light pipe and crystal are in three atmospheres of deuterium gas, and the entire polarimeter is in a vacuum chamber.

* Supported in part by the Atomic Energy Commission.
[1] H. C. Newns and M. Y. Refai, Proc. Phys. Soc. (London) 71, 627 (1958).
[2] W. Tobocman, Phys. Rev. 115, 98 (1959).

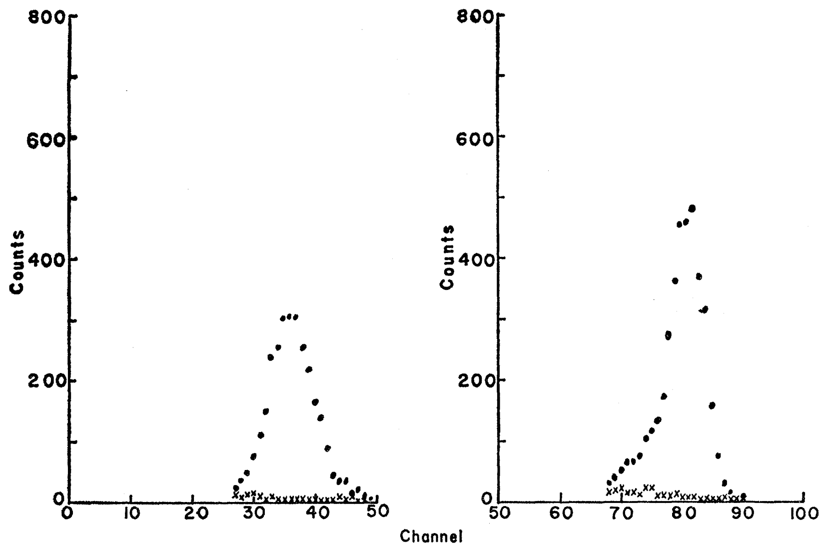

FIG. 2. Proton spectra from the two photomultipliers as recorded on the two halves of a 100-channel pulse height analyzer. The lower curves show the background when the deuterium gas is replaced by nitrogen gas. The low-energy background is not shown.

Inside of the rotating shaft a second shaft was inserted. This shaft supported the Be target, and could be rotated independently of the chamber or turntable. Copper tubing for water cooling the target was introduced along the center of this support. The polarimeter (Fig. 1) had a Ni foil (approx. 2×10^{-4} in. thick) sealed to the entrance aperture, and additional foils could be inserted in front of this aperture in order that the scattered deuterons entering the deuterium gas have a constant energy of 1 Mev, independent of the angular setting of the polarimeter. To obtain the foil thickness, the foils (and the Be target) were weighed on a microbalance and measured on a traveling microscope. From these data the energy loss of the particles in the foils was calculated from range-energy tables.[3,4] Although the range of 1-Mev deuterons in three atmospheres of deuterium gas is 2.02 cm, the distance from the foil at which the average number of protons is produced is 0.67 cm. This number was obtained by a numerical convolution using the range-energy curve and the $D(d,p)H^3$ differential cross section as a function of energy. Taking the center point of the *d-d* reaction region at 0.67 cm from the entrance foil, the angle from this point to the center of the crystals is approximately 45° in the center-of-mass system of the *d-d* reaction.

The detector crystals were CsI(Tl) (5×10^{-3} in. thick) on a glass backing that was $\frac{1}{8}$ in. thick and 1 in. in diameter. To provide a light seal, very thin Ni foils were placed in front of the crystals. The detectors subtended a solid angle of approximately 0.21 s. The photomultipliers were RCA 6342-A with conventionally wired tube bases which worked very satisfactorily in a vacuum of 2×10^{-4} mm Hg with a cathode voltage of -1200 v.

Because of the relatively high deuterium gas pressure in the polarimeter, no charged particles except protons from the *d-d* reaction ($Q=4.038$ Mev) were energetically capable of reaching the detectors. The use of thin crystals made the gamma-ray background negligible in the region of the proton peak. As a result the proton spectra were very sharp. To insure that the peak observed was associated with the *d-d* protons, the deuterium gas in the polarimeter was replaced with nitrogen gas, and the peak disappeared entirely, leaving a negligible background as shown in Fig. 2.

Since the direct proton beam struck the face of the polarimeter for angles less than about 75°, the polarimeter had to be water cooled. Also, it was necessary to electrically insulate the entire vacuum chamber from ground. This allowed the beam striking the target to be measured and used as a monitor, because the geometry did not allow space for a Faraday cup.

III. EXPERIMENTAL PROCEDURE

In order to avoid errors caused by fluctuations in beam current, data were taken from the two detectors simultaneously, and recorded in two 50-channel sections of a RIDL 100-channel pulse height analyzer.

To obtain useful counting rates, the large solid angles were required. As a result special efforts were made to compensate for geometrical misalignments. For this reason, the asymmetry was measured with the polarimeter first on one side of the proton beam, and then on the other, these runs being about 45 min each. As a second check, the polarimeter was designed to be completely symmetric when inverted. Therefore, an equal number of runs were taken in the inverted position. Special alignment holes and dowel pins were used so that the geometry could be exactly reproduced. Since the spectra had so little background, the number of counts in the peaks were counted directly from the readout tapes of the pulse height analyzer, and all of the LL and LR counts were added to calculate the experimental asymmetry ϵ_x.

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

[4] Ward Whaling, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 34, p. 193.

IV. ANALYSIS

A. Finite-Geometry Correction

Before the experimental asymmetry can be used to calculate the polarization of the deuterons, a correction must be made for the finite experimental geometry. In fact, the experiment should show an experimental asymmetry even if no polarization were present. This can be described with reference to Fig. 3(a), which exaggerates the geometry, and for the purposes of illustration shows only the two-dimensional asymmetry in a plane parallel to the plane formed by the first and second scattered beams. In this approximation it is assumed that both targets are thin lines. For convenience, assume that the differential cross sections for both targets decrease monotonically with angle. (This is true for this experiment up to about 90°.) For a proton beam striking the first target at an angle θ_0, there will be more deuterons impinging on the right side of the second target than on the left. Not only will more particles enter the counter on the right due to solid-angle considerations, but also because more than half of the particles strike the second target with their momentum vector to the right of the center line, so the forward peaking of the differential cross section of target two contributes to the higher counting rate in the right detector. Under these conditions, there should be a negative asymmetry when no polarization is present, (i.e., LR is greater than LL).

The number of particles entering one of the detectors is given by [see Fig. 3(b)]

$$N=C_0\int_{-x_0}^{x_0}dx\int_{\Theta_1}^{\Theta_2}\left(\frac{d\sigma}{d\Omega}\right)_1\left(\frac{d\sigma}{d\Omega}\right)_2 d\theta\Delta\Omega, \qquad (2)$$

where the constant C_0 contains the properties of the two targets. The variable x is the distance along target two measured from the center, and θ is the angle from the point x on target two to a point on target one, measured with respect to the center line between the targets. $\Delta\Omega$ is the solid angle subtended by the detector from the point x. The integral is expanded in a Taylor's series about the mean scattering angles and the integration over θ is performed. The limits of integration, θ_1 and θ_2, and the resulting integrand are then expanded as a function of x and the second integration is performed. Since this is an integration between symmetric limits, the result will be of the form

$$N=Ax_0+Bx_0^3+\cdots, \qquad (3)$$

where all expansion coefficients contributing to A and B have been included. In terms of these expansion coefficients, and dropping terms that contribute less than $\frac{1}{2}\%$ to N, the beam asymmetry ϵ_B can be written as

$$\epsilon_B=\frac{\alpha_1D(\beta_1\delta_1+\eta_1)-2\alpha_1\beta_1}{[(3D^2/x_0^2)+2(\alpha_2+\beta_2)-1]}, \qquad (4)$$

with α_1 and β_1 being the slopes of the cross sections for targets one and two, respectively, and α_2 and β_2 their curvatures. If $\phi(x)$ is the angle from the point x to the center of the detector, measured from the line joining the center of target two to the center of the detector, then δ_1 is the coefficient of the first power of x in the expansion, and similarly, η_1 is the coefficient of the first power of x in the expansion of $\Delta\Omega(x)$. D is the distance between the targets, and $2x_0$ is the length of the line target. (The two targets are of the same width in this experiment.) Since both of the targets are actually circular, a better approximation to the three-dimensional case is to use the average diameter rather than $2x_0$. Thus

$$2x_0=\pi d/4,$$

where d is the diameter of the targets.

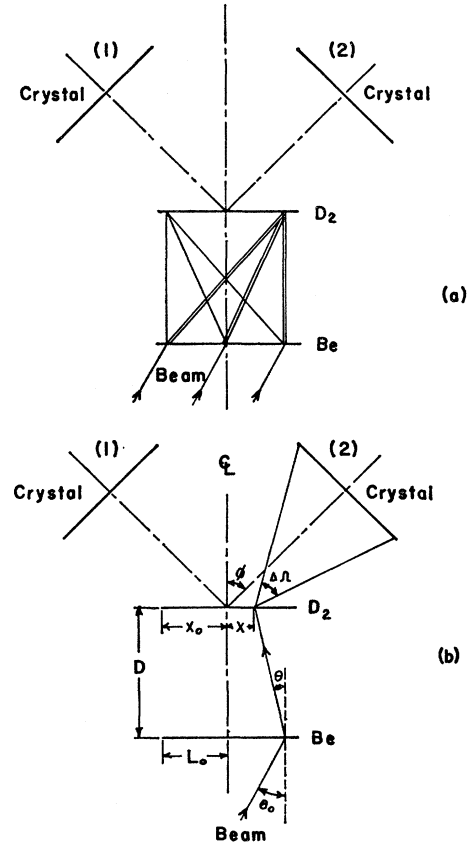

FIG. 3. (a) Schematic indication of the asymmetry caused by variation of the differential cross section of the Be target. (b) The variables used in the beam asymmetry correction.

B. Polarization

In 1953, Newns[5] developed a very simple, pictorial model to describe the gross aspects of polarization in the stripping and pickup interactions. Introduction of the distortion of the wave functions of the constituents indicates a polarization of the reaction products, and this distortion was interpreted to imply

[5] H. C. Newns, Proc. Phys. Soc. (London) **A66**, 477 (1953).

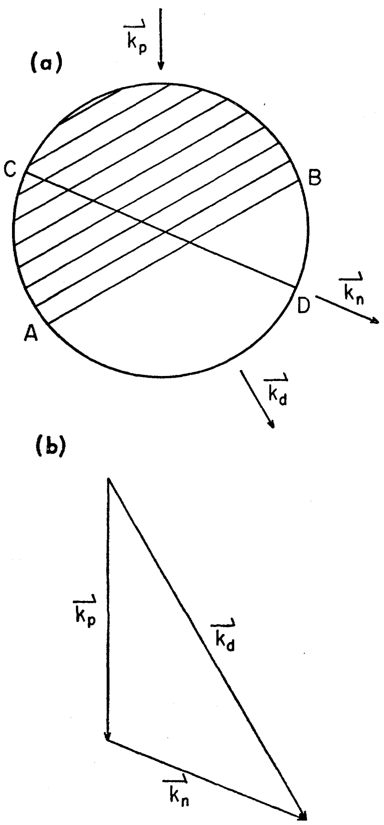

FIG. 4. (a) Illustration of the semi-classical (p,d) polarization model as discussed in the text. (b) The relation of the vectors in the pickup approximation.

that the region of interaction acts as a scattering or absorbing region for protons or deuterons that have to traverse this region. Although Newns originally assumed that the proton distortion was the greater of the two, suggestions by Tobocman[6] and later calculations by Newns and Rafai indicated that the deuteron distortion had to be greater to agree with experiments. This model is illustrated in Fig. 4(a) for the pickup reaction. The circle represents the region of interaction, and the proton approaches from the top with a wave vector $\mathbf{k}_p$. The deuteron is detected in the direction of its wave vector $\mathbf{k}_d$, which makes an angle θ with $\mathbf{k}_p$. The shaded area is perpendicular to $\mathbf{k}_d$, and the assumption is made that if the deuteron is formed in the shaded region it is not detected at the angle θ due to scattering or absorption. Thus only deuterons coming from the unshaded region will be detected. The direct-interaction assumption is now invoked that at the moment of interaction the wave vectors of the proton and picked-up neutron combine to form the wave vector of the deuteron (i.e., $\mathbf{k}_p+\mathbf{k}_n=\mathbf{k}_d$). Therefore, $\mathbf{k}_n$ will be in the direction shown in Fig. 4(b). If the positive direction is defined as being a long $\mathbf{k}_p\times\mathbf{k}_d$, the orbital angular momentum $\mathbf{l}$ of the neutron with respect to the target nucleus will be positive if the neutron is picked up below the line CD, and negative if it is above CD. The total angular momentum of the neutron will be $j_n=l\pm\frac{1}{2}$, and since the deuteron must be formed in the triplet state, the deuterons from region I will have spin ±1 when $j_n=l\pm\frac{1}{2}$, and those from region II will have spin ∓1 under the same conditions.

An unpolarized proton beam will therefore produce polarized deuterons since region I is larger than region II. Be^9 has $j_n=l+\frac{1}{2}$, so the deuterons should have positive polarization (i.e., more deuterons will have their spin parallel to $\mathbf{k}_p\times\mathbf{k}_d$ than antiparallel).

Several authors[7–9] have developed the formalism of polarization for particles of spin greater than $\frac{1}{2}$ which indicate that there can be tensor as well as vector polarization. However, Satchler showed that under the assumptions of stripping theory, only vector polarization should be expected. Vysotskii and Sitenko[10] summarized polarization and angular distributions for stripping and pickup reactions for both polarized and unpolarized beams. Their development was based on the S-matrix formalism neglecting Coulomb and spin-orbit interactions. (The latter interaction was calculated by Newns and Refai[1] and its contribution was quite small.) Vysotskii and Sitenko give an expression for the vector polarization of the pickup reaction in the $l-s$ representation, and when this is transformed to $j-j$ coupling scheme (as expected by the shell model), the z component of the deuteron polarization is given by

$$P_d=\frac{2}{3}\left\{\sum_{l,j(n)}\frac{\gamma_{lj(n)}}{(2l+1)}\frac{[j_n(j_n+1)-l(l+1)-\frac{3}{4}]}{l(l+1)}\times\sum_m m|J_l{}^m|^2\right\}\left\{\sum_{l,j(n)}\frac{\gamma_{lj(n)}}{(2l+1)}\sum_m|J_l{}^m|^2\right\}^{-1}, \quad (5)$$

where $\gamma_{lj(n)}$ is the reduced width, and $J_l{}^m$ is an integral appearing in the S matrix. No attempt was made to evaluate this integral, but Eq. (5) will give the maximum value by assuming that only one value of j_n and l occur, and by taking m equal to its maximum value, l. Under these conditions, the maximum value of the polarization is

$$P_d=\frac{2}{3}\frac{[j_n(j_n+1)-l(l+1)-\frac{3}{4}]}{(l+1)}=\begin{cases}\frac{2}{3}l/(l+1); & j_n=l+\frac{1}{2}\\ -\frac{2}{3}; & j_n=l-\frac{1}{2}.\end{cases} \quad (6)$$

For the Be^9, $j_n=l+\frac{1}{2}$ and $l=1$, so the maximum polarization is $\frac{1}{3}$. It should be noted that the maximum can be greater than $\frac{1}{3}$ if a spin-orbit interaction is included.

Now consider the analyzer reaction, $D(d,p)H^3$. According to Vysotskii and Sitenko, the differential

[6] W. Tobocman, Technical Report No. 29, Case Institute of Technology (unpublished).

[7] W. Lakin, Phys. Rev. 98, 139 (1955).

[8] L. J. B. Goldfarb, Nuclear Phys. 1, 622 (1958).

[9] L. J. B. Goldfarb and J. R. Rook, Nuclear Phys. 12, 494 (1959).

[10] G. L. Vysotskii and A. G. Sitenko, J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 812 (1959).

cross section for a (dp) reaction is given by

$$d\sigma/d\Omega = (d\sigma/d\Omega)_0[1+3\mathbf{P}_p\cdot\mathbf{P}_d], \tag{7}$$

where $(d\sigma/d\Omega)_0$ is the cross section when the incoming deuterons are unpolarized, and $\mathbf{P}_p$ is the polarization of the outgoing protons when unpolarized deuterons are incident. It should be noted that although $\mathbf{P}_p$ is not zero experimentally, this theory predicts that it should be because $l=0$. In general, one would expect to have an asymmetry term proportional to $\mathbf{P}_p\cdot\mathbf{P}_d$, but the coefficient of this term may depend on the interaction model that is used. However, in order to discuss the predictions of the deuteron polarization in the primary reaction, it will be assumed that Eq. (7) correctly predicts the analyzer cross section. In this case, Eq. (7) gives the magnitude of the asymmetry as

$$\epsilon = (\mathrm{LL}-\mathrm{LR})/(\mathrm{LL}+\mathrm{LR}) = 3\mathbf{P}_p\cdot\mathbf{P}_d \tag{8}$$

when the detectors are in the plane of the two scatterings.

V. RESULTS AND DISCUSSION

The beam asymmetry parameter ϵ_B was calculated using the experimental cross sections to evaluate Eq. (4). At 90°, $\alpha_1 \simeq 0$ so no correction was made, but at 30°, with $D=4.48$ cm and $x_0=0.294$ cm, the value

$$\epsilon_B = 2.0\%, \quad \theta = 30° \tag{9}$$

was obtained.

The uncorrected experimental results are given in Table I where "Normal" and "Inverted" refer to the polarimeter in the upright and inverted positions as discussed in Sec. III. From these data,

$$\frac{\mathrm{LL}-\mathrm{LR}}{\mathrm{LL}+\mathrm{LR}} = \begin{cases} -(8.3\pm0.3)\%, & \theta=30° \\ -(3.6\pm0.3)\%, & \theta=90°, \end{cases} \tag{10}$$

where the errors are only statistical.

These corrected asymmetries are

$$\epsilon = \begin{cases} -6.3\%, & \theta=30° \\ -3.6\%, & \theta=90°. \end{cases} \tag{11}$$

The deuteron polarization is then calculated from

$$P_d = \epsilon/3P_p.$$

Segel and Hanna[22] found the proton polarization to be $P_p = -(17\pm7)\%$ where the positive direction is defined by $\mathbf{k}_d\times\mathbf{k}_p$. The deuteron energy was 0.64 Mev, and this was done at 45° in the c.m. system. This paper also lists a value of P_p [by B. Maglic (private communication)] for an energy of 1.2 Mev on a thick deuterium target at 135° in the laboratory system. This corresponds to an average c.m. angle of about 140° (since it is a thick target). The value at this angle is $P_p = +(24\pm10)\%$, and by the symmetry of the $d-d$ reaction in the c.m. system, this corresponds to a value of $P_p = -(24\pm10)\%$ at a c.m. angle of 40°. The present experiment was done at 45° in the c.m. system, but the solid angle included 40°. The energy was 1.0 Mev, and the detector was a thick target, so it is probably reasonable to assume that the proton polarization was approximately an average of these values which would be $P_p = -(20\pm8)\%$, where all three have about the same percentage error (i.e., 40%).

[22] R. E. Segel and S. S. Hanna, Phys. Rev. **106**, 536 (1957).

TABLE I. The number of experimental counts of scattered protons used in the calculation of the beam asymmetry.

	30°		90°	
	Normal	Inverted	Normal	Inverted
LR	27 700	26 690	13 685	14 027
LR	33 151	31 176	14 865	14 887

The errors other than statistical errors are rather difficult to estimate. For example, the beam asymmetry correction at 30° amounts to 25% of the observed asymmetry. However, the correction was made assuming a thin detector target placed at the average reaction center. Further, this was a two-dimensional calculation which neglects a possible three-dimensional effect (although it is expected that this effect would be small). It should also be noted that in spite of the fact that the asymmetry at each angle was averaged over four geometrical configurations to eliminate effects of geometrical misalignment, this might not have been completely successful. In this regard, an attempt was made to elastically scatter deuterons from a gold primary target into the polarimeter to check the symmetry; this effort was unsuccessful because of the high background encountered. However, it is expected that these errors should be less than the beam asymmetry correction, so if the error in the measured asymmetry is assumed to be 20%, the main source of error is in the value of the detector polarization, giving an over-all error of 45% in the value of the deuteron polarization. That is,

$$P_d = \begin{cases} +(11\pm5)\%, & \theta=30° \\ +(\ 6\pm3)\%, & \theta=90°. \end{cases}$$

Again it should be remarked that the analysis which gives these numbers utilizes the interaction of reference 10.

Finally, a word should be said about the polarization between 30° and 90°. Some data were collected at each 15° interval in this region, but the statistics did not warrant making beam asymmetry corrections. The general trend, however, was for a monotonic decrease in polarization from 30° to 90°, with no anomalous points.

Thus the results of this experiment indicate that the deuterons from the $Be^9(p,d)Be^8$ reaction are polarized, and the sign of the polarization agrees with the semiclassical model. It also suggests that the $D(d,p)H^3$ reaction can be used as a polarization analyzer for deuterons, even in the presence of high background radiation.