Polarization of Protons in $Be^9(d,p)Be^{10}$

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Measurements of the angular dependence of the polarization of protons in the $Be^9(d,p)Be^{10}$ reaction are described. The results, together with the $(d,p\gamma)$ angular correlation measurements at the same energy, indicate that spin-dependent calculations are required to fit the data.

INTRODUCTION

MEASUREMENTS of the proton polarization produced in a (d,p) reaction are valuable both as a spectroscopic tool for the determination of nuclear spins and as a sensitive means of investigating the reaction mechanism. Models for the reaction which differ only slightly in form predict nearly identical differential cross sections, but radically different polarizations. It is this sensitivity of the angular dependence of the polarization to the choice of parameters that make polarization measurements so useful in obtaining a better understanding of the mechanism. In the last few years calculations, using modern computors, have been made[1] of the differential cross section and the polarization of the outgoing protons using the distorted wave Born approximation (DWBA) assuming spin-independent forces. These calculations, together with available measurements of the polarization, indicate that spin-independent theories are not adequate and that the spin-orbit forces must play an important part in the reaction mechanism. As a result the more difficult problem of including the spin-orbit term is now being attacked,[2] although theoretical results applicable to the Be^{10} problem are not yet available.

The objective of the work described in this paper was the measurement of the proton polarization as a function of angle, the absolute differential (d,p) scattering cross section for the ground state in the reaction $Be^9(d,p)Be^{10}$, and the (d,d) differential elastic scattering cross section for Be^9. These results, together with the $Be^9(d,p\gamma)Be^{10}$ data already available[3] at the same deuteron energy, form essentially the complete experimental picture necessary for analysis.

EXPERIMENTAL METHOD

The apparatus was essentially the same as that previously described.[4] The polarization was measured using a helium polarimeter, the protons being elastically scattered at an energy near the $p_{\frac{3}{2}}$ resonance of Li^5. A set of quadrupole magnets placed between the first and second scattering chambers allowed the use of considerable shielding without loss of solid angle, and a low resolution analyzer magnet just ahead of the polarimeter permitted selection of protons corresponding to the ground or first excited state of Be^{10}.

The targets were self-supporting beryllium foils 1-in. square mounted on a copper frame. The target thickness was varied with scattering angle to give an adequate flux of protons through the polarimeter, a 0.001-in.-thick target being used at 10°; 0.002-in. at 20°, 40°, and 60°; and 0.003-in. at 80°.

The protons scattered by the helium were detected in eight Ilford K-2 nuclear emulsions arranged each 45° in azimuth around the proton beam. The background count averaged 20% of the true count and was determined by exposing a second set of plates with the helium chamber in the polarimeter evacuated; otherwise conditions for the two exposures were identical. The total number of tracks on each plate was counted and each track was analyzed according to criteria designed to ensure that it corresponded to a proton which originated in the polarimeter and had the proper energy. The data were analyzed by fitting a curve of the form $N=A+B\sin\phi$, to the azimuthal distribution of true counts (number of tracks minus the normalized background), ϕ being the azimuthal angle of the nuclear emulsion with respect to the proton beam as measured from the axis of quantization $\mathbf{n}=[\mathbf{k}_d\times\mathbf{k}_p]$. The proton polarization is then given simply by $P=B/(AP_\alpha)$ where the quantity P_α is the polarization in p-α scattering and was obtained from the known p-α phase shifts[5] by the method of Lepore.[6]

TABLE I. Measured proton polarization in $Be^9(d,p)Be^{10}$ using 7.8-MeV deuterons.

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)	Level (MeV)	Polarization
10	11.1	0	$+0.24\pm0.05$
20	22.3	0	$+0.10\pm0.03$
40	44.2	0	$+0.16\pm0.09$
60	65.7	0	$+0.15\pm0.06$
80	86.5	0	-0.42 ± 0.11
20	22.4	3.37	-0.14 ± 0.04
40	44.6	3.37	-0.49 ± 0.09

[1] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955); J. L. Richter and E. V. Ivash, *ibid.* **111**, 245 (1958); W. Tobocman, *ibid.* **115**, 98 (1959).
[2] L. J. B. Goldfarb and R. C. Johnson, Nuclear Phys. **18**, 353 (1960); G. R. Satchler, *ibid.* **18**, 110 (1960); D. Robson, Nuclear Phys. **22**, 34 (1961). L. J. B. Goldfarb, *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961* (Academic Press Inc., New York, 1961); R. C. Johnson, ibid., papers C5/58, 59.
[3] R. T. Taylor, Phys. Rev. **113**, 1293 (1959).
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[6] J. V. Lepore, Phys. Rev. **79**, 137 (1950).

The absolute differential cross-section measurements were made using a self-supporting beryllium foil 0.0006 in. thick in the charged-particle analysis system associated with the Michigan 42-in. cyclotron.[7]

RESULTS

The results of the polarization measurements are summarized in Table I. The axis of quantization is that adopted at the Basel Symposium,[8] namely, $\mathbf{n}=(\mathbf{k}_d\times\mathbf{k}_p)$. The uncertainty quoted in the results represents only the statistical factors inherent in the counting process and does not take into account any systematic or other possible errors. These errors, as discussed before,[4] are expected to be small. The measurements on the proton group from the first excited state were limited by kinematics to the angular range 20° to 40°; thus, while the angle at which sign reversal occurs could not be determined, the data do permit comparison with the $(d,p\gamma)$ results.

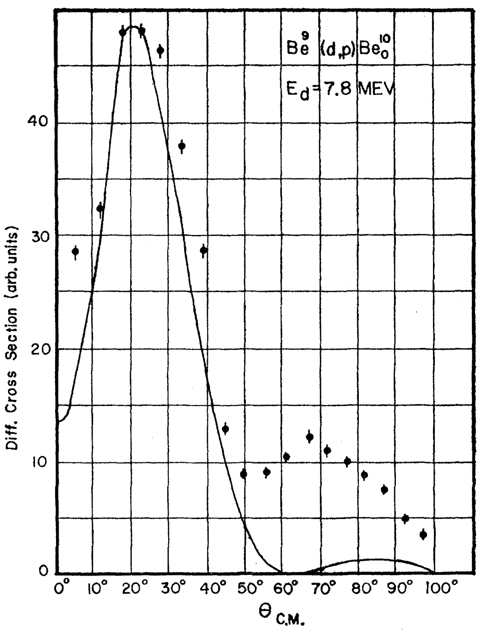

FIG. 1. The relative differential cross section for the $Be^9(d,p)Be^{10}$ reaction leading to the ground state of Be^{10}. The solid curve is the Butler curve calculated for $l_n=1$, using $r_0=5.2$F.

The differential cross section obtained for the $Be^9(d,p)Be^{10}$ reaction is plotted in Fig. 1. The Butler curve was computed using the parameters $l_n=1$, $r_0=5.2\times10^{-13}$ cm. This large stripping radius required to fit the data is characteristic of the Butler theory[9] and is in good agreement with other measurements. The

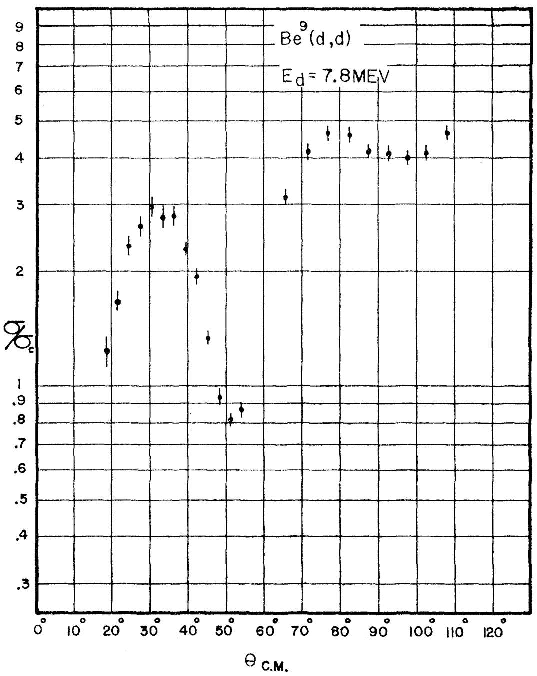

FIG. 2. The ratio of the absolute differential cross section to the Rutherford cross section for 7.8-MeV deuterons elastically scattered from Be.

$Be^9(d,d)Be^9$ differential cross section is plotted in Fig. 2 as a ratio of the measured cross section to the Rutherford cross section normalized at $\theta_{\text{c.m.}}=36°$. Because of the thick target and the low Z of beryllium, the limiting Rutherford cross section was not reached at the smallest scattering angle of 20°. The uncertainty in the absolute cross section (approximately 20%) arises almost entirely from the nonuniform thickness of the target. The uncertainty associated with each point in Figs. 1 and 2 represents only the statistical uncertainty due to the counting process.

DISCUSSION

In the approximation that the distorted wave contribution for the protons and deuterons is small in comparison to the plane-wave contribution, the radial cutoff form of the DWBA theory predicts that the polarization will change sign where the plane-wave differential cross section has its first minimum. The measured minimum in the cross section occurs at $\theta_{\text{c.m.}}=55°$ while the minimum in the Butler cross section for $l=1$, $r_0=5.2$ F occurs at $\theta_{\text{c.m.}}=60°$. The polarization however changes sign at $\theta_{\text{c.m.}}=71°$ (by linear extrapolation) which indicates that the scattering or distortion of the incoming deuteron wave and the outgoing proton wave contributes significantly to the total stripping amplitude. A similar situation exists in the $C^{12}(d,p)C^{13}{}_0$ reaction.

The relation between the proton polarization in a (d,p) reaction and the $(d,p\gamma)$ angular correlation for the decay of an excited state of the final nucleus has so far

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[9] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).

TABLE II. Values of the distorted-wave parameter λ for $Be^9(d,p)Be^{10*}$.

E_d (MeV)	$\theta_{c.m.}$	λ	Method	Reference
4.82	26°	1.50±0.70	$(d,p\gamma)$	Read *et al.*[a]
5.0	26°	1.70±0.80	$(d,p\gamma)$	Read *et al.*
5.0	26°	1.40±0.50	$(d,p\gamma)$	Read *et al.*
5.0	45°	0.50±0.20	$(d,p\gamma)$	Read *et al.*
7.8	22°	0.86±0.12	Polarization	Present work
7.8	45°	Imaginary	Polarization	Present work
7.8	22°	1.10±0.40	$(d,p\gamma)$	Taylor[b]

[a] Read, Calvert, and Schork, Nuclear Phys. **23**, 386 (1961).
[b] See reference 3.

been explicitly computed in DWBA only for spin-independent distortions of the deuteron and the proton waves.[10] The relation is characterized by a real parameter λ ($0\leq\lambda\leq1$), where the value $\lambda=1$ represents the plane-wave limit of the distorted wave theory. The first excited state of Be^{10}, known to decay by a pure E-2 transition, is not formed in the (d,p) reaction by the capture of a neutron having a single value of total angular momentum, but rather with a combination of $j_n=\frac{1}{2}$ and $\frac{3}{2}$. The unknown mixing ratio of these two j values appears in the relation between the polarization and the $(d,p\gamma)$ correlation. Its value can be estimated, however, by using the plane-wave mixing ratio[11] and the empirical rule of the sign of the polarization [$P=(\pm)$ when $j_n=l_n\pm\frac{1}{2}$]. On this basis an analysis of the $(d,p\gamma)$ measurements[3] at 7.8 MeV indicates that the ratio of the number of neutrons captured with $j_n=\frac{3}{2}$ to the number captured with $j_n=\frac{1}{2}$ is 0.14±0.24. Using this value of the ratio, the parameter λ can be computed independently from the results of the $(d,p\gamma)$ and the polarization measurements. A summary of such computations is given in Table II.

At 22° the value inferred from the present work compares favorably with the value of Taylor taken at the same energy and suggests that $\lambda\simeq1$. Thus, near the stripping peak, the plane-wave limit appears to be a good approximation. The imaginary value of λ at 45° is a statement of the fact that the measured polarization is larger than the maximum value ($P_{max}=-0.27$) allowed by the spin-independent theory. [The fact that the first three values of λ listed in Table II have a good probability of being greater than unity is not consistent with DWBA theory and requires further investigation. It might be noted that the values of λ found in the $Be^9(d,n)B^{10}$ reaction are all less than unity.[12]]

In the absence of spin-dependent forces, the DWBA theory[4] predicts that the maximum polarization for $j=l+\frac{1}{2}$ is $1/[3(l+1)]$ and for $j=l-\frac{1}{2}$ is $-1/3l$ which implies $P_{max}{}^0=+0.167$ for the pure $j=\frac{3}{2}$ ground-state group and $P_{max}{}^1=-0.27$ for the predominantly $j=\frac{1}{2}$ first excited state. These limits are violated (Table I), and in fact at $\theta_{lab}=80°$ the polarization of the ground-state group is $2.5P_{max}$. Thus, it is clear that spin-dependent calculations are required to fit the polarization data.

As a final remark, the sign of the polarization for the ground-state group supports the empirical "rule" that $P=(\pm)$ when $j_n=l_n\pm\frac{1}{2}$. From the point of view of the DWBA theories, however, there is no basis in fact for such a general rule since the sign depends only on the relative balance between the strengths of the proton and deuteron interactions. The "rule," therefore, implies that the deuteron distortion overweighs the proton distortion. An exception to the "rule" occurs in the $Ca^{40}(d,p)Ca^{41}$ reaction[13] and there is recent evidence[14] that the 3.40-MeV level of Mg^{25} may also be an exception.

ACKNOWLEDGMENT

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