Dividing (B2) by (B3) one has

$$\frac{A_{\mathrm{I}}^{\mathrm{eff}}(0)}{A_m^{\mathrm{eff}}(0)}\equiv\frac{1}{R}=\left(\frac{\lambda_1-\lambda_2}{\lambda_1-\lambda_{\mathrm{I}}}\right)\frac{B_2}{B_1}\left[1+\frac{(1-F_1)\lambda_g(\lambda_2-\lambda_{\mathrm{I}})}{F_1B_2\lambda_2(\lambda_g-\lambda_{\mathrm{I}})}\right], \tag{B4}$$

where

$$B_1=1+\frac{\lambda_2}{\lambda_g-\lambda_2}F_2 \quad\text{and}\quad B_2=1+\frac{\lambda_{\mathrm{I}}}{\lambda_g-\lambda_{\mathrm{I}}}F_2.$$

Thus, $1/R$ is insensitive to λ_1, F_2, λ_g and depends linearly on $1/F_1$. Using the above half-lives and solving for F_1, one finds $F_1=0.835R/(1-0.152R)$.

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Proton Polarization in the $Sr^{88}(d,p)Sr^{89*}$(1.05-MeV) Reaction*

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The polarization of protons from the $Sr^{88}(d,p)Sr^{89*}$ reaction exciting the 1.05-MeV state in Sr^{89} has been measured at 14 laboratory angles from 12 to 131° using a deuteron bombarding energy of 11 MeV. In this reaction, which involves no orbital-angular-momentum transfer by the captured neutron, spin-orbit terms in the optical-model potentials describing the interactions of the incident and exit particles are considered to be responsible for the polarization. The measurements were made using a heavy-particle magnetic spectrometer to select the desired proton group and focus it on the carbon second scatterer. This scatterer was viewed to the "right" and the "left" by a pair of scintillation counters set at a mean laboratory angle of 40°. The sign of the polarization seems to correspond to the sign of the slope of the angular distribution, being negative at the forward angles with apparent sign changes at the subsequent minima and maxima. This behavior is in approximate agreement with the "derivative rule" for stripping reactions with $l_n=0$ orbital-angular-momentum transfer. The polarization changes most rapidly near the stripping minima and becomes largest at the backward angles (−28% at 95°).

I. INTRODUCTION

Angular distributions of protons emitted in deuteron stripping reactions have been successfully fitted by the distorted-wave Born approximation,[1] in which the waves describing the incoming deuterons and outgoing protons are distorted by an optical-model potential. While theoretical fits to the angular distributions yield useful information with regard to the reaction process, a more sensitive test of the theoretical formulation is obtained when the polarization of the outgoing nucleons is considered. Since polarized particles do not result if plane waves are assumed in the formulation, measurements showing nonzero proton polarizations from stripping reactions clearly emphasize the necessity for using a distorted-wave-Born-approximation (DWBA) treatment.

Newns[2] was the first to suggest a measurement of the proton polarization resulting from a deuteron stripping reaction. He postulated that the nucleus receives a net oriented pulse of orbital angular momentum (l_n) due to unequal absorption of the incoming and outgoing beams of particles. Hence, for a given angular-momentum transfer to the nucleus (j_n), the emitted particle is expected to be polarized since the neutron and proton spins are coupled in the deuteron. These absorptive distortion effects alone are not sufficient to account for the polarizations observed experimentally, however. Neglecting spin-dependent interactions, distorted-wave calculations[3,4] predict polarizations restricted in magnitude to $\leq 33\%$. The sign of the polarization is expected to conform to the rule that $P=\pm$ for $j_n=l_n\pm\frac{1}{2}$, assuming deuterons are more strongly absorbed than protons in nuclear matter. (The direction of positive polarization is taken to be $\mathbf{n}=\mathbf{k}_d\times\mathbf{k}_p$ in accordance with the Basel convention.) A further consequence of these calculations is the absence of polarization for $l_n=0$ neutron transfers. Previousp olarization measurements have

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[1] Examples of these fits and references to others are given in W. Tobocman and W. R. Gibbs, Phys. Rev. **126**, 1076 (1962); R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory, Physics Division Annual Progress Report, ORNL-3085, 1961 (unpublished); B. Buck and P. E. Hodgson, Nucl. Phys. **29**, 496 (1962); W. R. Smith and E. V. Ivash, Phys. Rev. **131**, 304 (1963).

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yielded polarizations larger than the 33% limit,[5–9] and nonzero polarizations for $l_n=0$ transfers.[9–12]

One means of accounting for the above discrepancies is to include additional terms in the optical-model potentials which affect the spins of the incident and outgoing particles directly. The effects of a spin-orbit term in the optical-model potential seen by the proton, for example, may be visualized by considering outgoing protons with opposite spin projections, which therefore see potential wells of different depths. If the spin-orbit potential is considered attractive as in the shell model, the addition of this term should shift the angular distribution of protons with spin and orbital angular momentum parallel toward more forward angles, and the angular distribution of protons with spin and orbital angular momentum antiparallel to more backward angles.

Oscillations occur in the resultant polarization pattern which are related to the oscillations in the angular distribution, as observed in many cases of nucleon-nucleus elastic scattering.[13,14] Rodberg,[15] in considering the effects of the spin-orbit force in the elastic scattering of spin-$\frac{1}{2}$ particles, has obtained a simple approximate mathematical expression relating the angular dependence of the polarization and the differential cross section, usually referred to as the "derivative relation." This relation can be written

$$\mathbf{P}\propto\frac{1}{(d\sigma/d\Omega)}\frac{d}{d\theta}\frac{d\sigma}{d\Omega}\langle\beta\rangle\mathbf{n}\,, \tag{1}$$

where $\langle\beta\rangle$ is related to the magnitude of the spin-orbit potential and $\mathbf{n}=\mathbf{k}_d\times\mathbf{k}_p$. Biedenharn and Satchler[4] have extended this relation to the deuteron stripping reaction for $l_n=0$ transfers. If it can be verified experimentally, the derivative relation would present a simple approximate method for anticipating the qualitative features of the polarization from a knowledge of the angular dependence of the differential cross section. For example, this relation would predict that the polarization should pass through zero at the stationary points of the angular distribution and become large at angles where the differential cross section is small (usually the backward angles).

Measurements of the polarization of protons emitted from deuteron stripping reactions in which the neutron is transferred with zero-orbital angular momentum are particularly significant, since, in this case, the spin-orbit potential is solely responsible for the polarization. However, most of the experiments involving such transfers have been performed on very light elements at the more forward angles. Isoya and Marrone[11] have studied the $Al^{27}(d,p)\,Al^{28}{}_{\text{g.s. and }0.03\text{ MeV}}$ and $Si^{28}(d,p)\,Si^{29}{}_{\text{g.s.}}$ reactions with 15-MeV deuterons for laboratory angles less than 75°. The polarization patterns for these two elements were found to be similar but showed only limited agreement with the derivative rule; the polarization changed sign at the minima of the angular distributions but retained the same sign in the vicinity of the stripping peaks. Reber and Saladin[16] investigated the $Mg^{24}(d,p)\,Mg^{25*}{}_{0.58\text{ MeV}}$ reaction with 15-MeV deuterons and found essentially the same polarization pattern at forward angles as for Al and Si targets. The $Si^{28}(d,p)\,Si^{29}{}_{\text{g.s.}}$ reaction has also been studied with 10-MeV deuterons,[10] and the similarity of these data to the data of Isoya *et al.* suggests that the polarization is insensitive to the deuteron energy for this reaction.

The present experiment also represents an attempt to investigate the effects of the spin-orbit potential by measurement of the proton polarization for a stripping reaction in which the neutron is transferred to the nucleus with zero orbital angular momentum. However, the $Sr^{88}(d,p)\,Sr^{89*}{}_{1.05\text{ MeV}}$ reaction was chosen since it represents an $l_n=0$ capture by a fairly heavy target nucleus, leading to a residual nucleus with well-separated levels. Particle interactions with heavy nuclei are expected to be represented more closely by an optical-model potential than those with the lighter nuclei where the previous measurements have been made. The present measurements were also extended to the backward angles in hopes of finding sizable polarizations.

II. EXPERIMENTAL PROCEDURE

The polarization (P_1) of the protons produced in the first target (d,p) reaction was determined by means of elastic scattering from a second carbon target of measured analyzing power (P_2). Measurement of the left-right scattering asymmetry then determines P_1 from the relation

$$P_1P_2=R-L/R+L\,, \tag{2}$$

where R and L are the number of counts in the right and left counters, respectively. In the present experiment, P_2 was first determined by measuring the left-right asymmetry for incident protons of known initial polarization. Such protons were obtained by using recoils from the elastic process $H^1(\alpha,\alpha)H^1$, for which the polarization is known from phase-shift analyses[17] of differential cross-section measurements.

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[16] L. H. Reber and J. X. Saladin, Phys. Rev. **133**, B1155 (1964).
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A. Experimental Apparatus

Several features of the experimental arrangement and procedures are similar to those used by Johnson *et al.*[18] and others,[19,20] and will not be discussed in detail. The 11.1-MeV deuteron beam from the Indiana University cyclotron was incident on a strontium target centered in a 16-in. scattering chamber. Rigidly attached to the bottom half of the target chamber is a 180° double-focusing magnetic spectrometer, which was used to select and focus the protons corresponding to the level under study. This spectrometer may be rotated about the axis of the scattering chamber to obtain laboratory scattering angles from 12.2 to 140°.

The polarimeter was mounted near the image focus of the spectrometer, and consisted of a 44-mg/cm^2 carbon scatterer which was viewed by a pair of scintillation counters set to the "right" and "left" at a mean laboratory angle of 40°. A total angular variation of $\pm 10°$ with a half-maximum angular variation of $\pm 5°$ was defined by a series of collimating vanes.

The side counters of the polarimeter were often subjected to large amounts of fast-neutron background resulting from the heavy-deuteron beam, which tended to obscure the proton peaks. In order to lessen background effects, a 0.005-in.-thick diffused-junction solid-state counter[21] (referred to below as the "dE/dx counter") was inserted before the polarimeter. Proton pulses from the side counters were registered in the multichannel analyzers only when in coincidence with proton pulses from the dE/dx counter. A typical spectrum of the dE/dx counter is shown in Fig. 1.

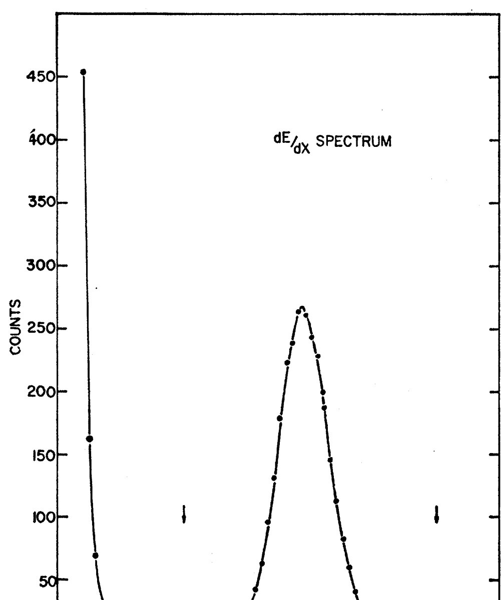

FIG. 1. A typical spectrum of the dE/dx counter, which was used to provide a coincidence requirement for background reduction. The arrows indicate the settings of the upper and lower discriminators.

Located between the dE/dx counter and the polarimeter was a series of aluminum foils used to degrade the magnetically analyzed protons from the reaction to an energy of about 7.6 MeV. It was necessary to adjust the energy of the protons entering the polarimeter to the same value at each scattering angle to avoid variations in the analyzing power of the polarimeter. The uncertainty in energy degradation introduced an uncertainty of 3% in the analyzing power of the polarimeter, in addition to the uncertainties discussed in Sec. IIIA. A 44-mg/cm^2 carbon foil could also be inserted in the foil holder to yield the same proton energy when the second scatterer was removed during background runs. A diagram of the dE/dx system, the foils, and the polarimeter is shown in Fig. 2.

B. Experimental Techniques

The rolled-strontium targets used during the experiment were 20, 26, and 30 mg/cm^2, corresponding to energy losses for 11-MeV deuterons of 760, 990, and 1150 keV, respectively. These relatively thick targets were chosen to provide maximum counting rate without overlap of the proton groups corresponding to different levels of the residual nucleus.

A typical momentum spectrum of the proton group under study, obtained by varying the spectrometer field and counting protons passing undeflected through the polarimeter into the "center counter," is shown in Fig. 3. During the data and background runs, the spectrometer field was kept adjusted to correspond to the peak of the spectrum. Beam lineup and momentum spectrum procedures were repeated after every sequence of two data runs and a background run, or whenever the cyclotron conditions had been altered significantly.

The spectrometer is mounted in such a way that it always accepts reaction particles 12.2° below the horizontal plane. Therefore, at all but the most forward spectrometer angles, the direction of polarization and the spectrometer field are not aligned. This causes a precession of the proton spin about the spectrometer field, and results in conversion of part of the transverse polarization into longitudinal polarization. Owing to this precession, it was necessary at each new spectrometer angle to rotate the polarimeter so as to align the transverse component of the polarization of protons leaving the spectrometer with the normal to the plane of second scattering.

[18] W. P. Johnson and D. W. Miller, Phys. Rev. **124**, 1190 (1961).
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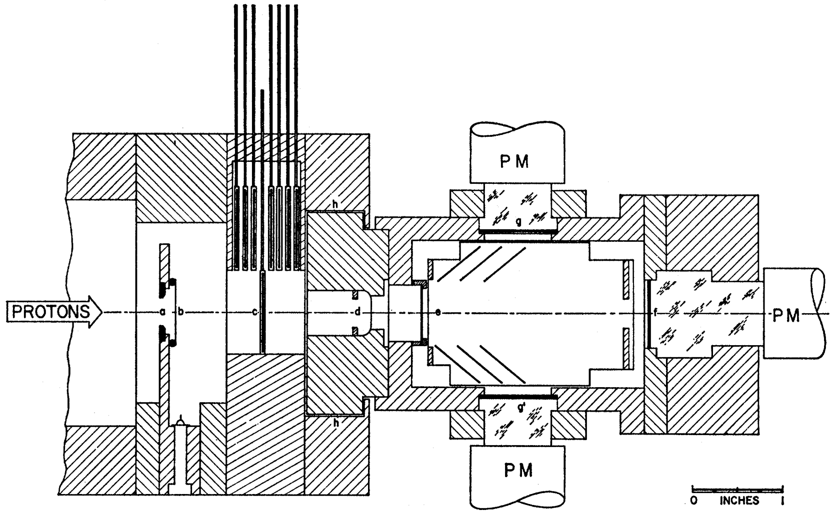
[21] This detector was fabricated by C. N. Inskeep, using his technique described in I. R. E. Trans. Nucl. Sci. **NS-9**, 167 (1962).

FIG. 2. After magnetic analysis in the spectrometer, the protons pass through the solid-state dE/dx counter (b), the degrading foils (c), collimators (a) and (d), and then strike the carbon second scatterer at (e). Stainless-steel vanes determine the acceptance angles for particles scattered into the side counters at (g) and (g′). The center counter (used to monitor unscattered protons) is located at (f). The polarimeter is rotated within a fixed flange by means of a rotating O-ring seal at (h).



C. Data Analysis and Corrections

In order to obtain counting rates sufficient to allow polarization angular distributions to be taken to large angles, it was necessary to employ rather thick second scatterers. This advantage was obtained only by sacrificing clean separation of the proton groups from the background. The thickness of the second target was therefore a compromise between counting-rate and background considerations.

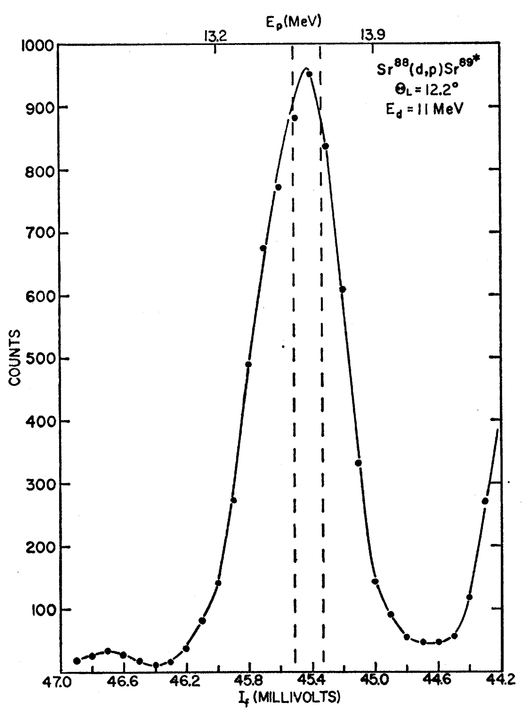
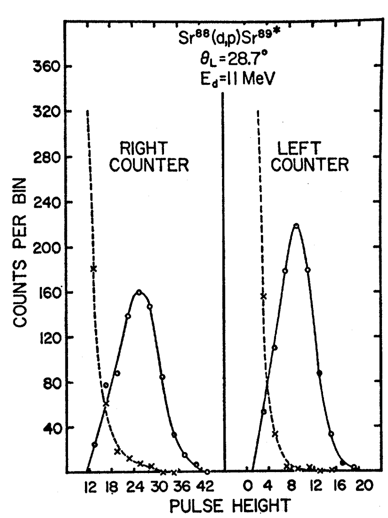


FIG. 3. A typical momentum spectrum of the proton group corresponding to the first excited state of Sr^{89}(1.05 MeV). The dashed lines represent the maximum momentum interval accepted by the polarimeter apertures during the measurements.

The data consisted of from 4 to 18 individual spectra taken in the right and left counters at every scattering angle studied. These spectra were combined by summing the counts in the individual channels. The background spectra were similarly combined, normalized, and then subtracted from the data runs. Because the background resulted mainly from chance coincidences, the background normalizations were made by comparing both the total-deuteron-beam charge collected and the beam intensities during the data and background runs. Figure 4 gives an example of a side-counter proton peak obtained *after* background subtraction, shown along with the normalized background spectrum for comparison.

A sizable uncertainty sometimes existed in determining the total number of counts in the proton peaks of the side counters caused by the difficulty in establishing the shape and cutoff point of the low-energy side of the peaks. The uncertainty due to background

FIG. 4. A good example of the spectra in the side counters. The dashed lines show the normalized background spectra which were subtracted from the raw data to yield the proton peaks (solid lines).



was accounted for by including the number of background counts in the statistical-error calculation for P_1P_2 and by considering other possible interpretations of the curves in calculating the total error of P_1P_2. The number of normalized background counts amounted to as much as 30% of the proton-peak counts at the extreme backward angles. At other angles, however, the background was generally much less serious.

Counting statistics proved to be the largest source of uncertainty in the determination of the product polarization at most angles. At all but one scattering angle, a total of 500 or more counts remained in the proton peaks after background subtraction.

Two different types of corrections were applied to the data during the course of the data analysis. The first type resulted from the finite size of the counter apertures and the spatial spread of the focused protons, which could permit one counter to receive more scattered protons even if they were not initially polarized. A second type of correction resulted from the spin precession of the protons about the magnetic field of the spectrometer. By calculating the magnitude of the component of longitudinal polarization introduced by this precession as a function of spectrometer angle, a plot of the ratio of the (observable) transverse component of polarization (P_t) to the total polarization (P) was obtained, as shown in Fig. 5.

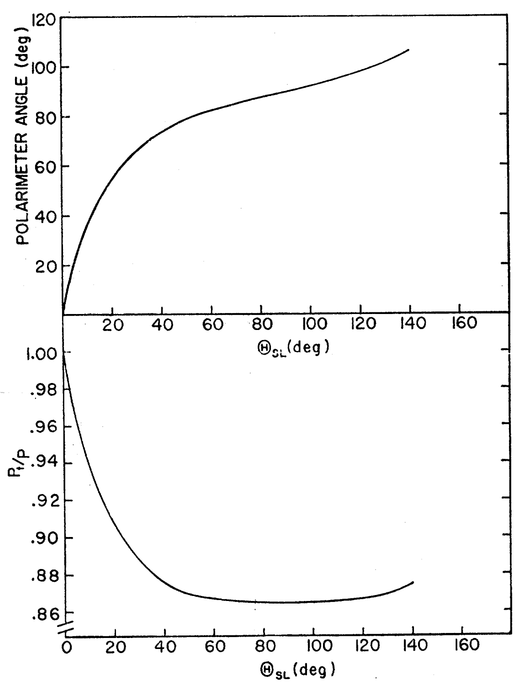


FIG. 5. Plots of the rotation angle of the polarimeter and the ratio of the transverse polarization (P_t) of protons entering the polarimeter to their total polarization (P) as a function of the angle (Θ_{SL}) between the beam direction and the plane of the spectrometer. Note the break in the ordinate scale on the lower plot. Because the magnetic spectrometer was mounted to accept reaction particles below the horizontal plane, the direction of polarization and the spectrometer field were aligned only when Θ_{SL} was 0°.

In order to correct for inherent differences in the counter solid angles and electronics, several polarization measurements were repeated with the polarimeter rotated about the axis of the proton beam by 180° to interchange the roles of the right and left counters. The correction was found to be small, indicating that both sides of the electronic system counted properly and that the polarimeter was constructed symmetrically. Corrections were also applied to the data for effects which shifted the "mean proton" off the symmetry axis of the polarimeter. A shift of this nature alters the solid angles effectively subtended by the two counters and thereby introduces an asymmetry into the measurements. The only significant corrections applied to the data of this type arose from the variation of the proton angular distribution from the first target over the acceptance angle of the spectrometer, and from the shape of the spectrometer acceptance aperture.

Several other sources of error were considered and estimated to be substantially smaller than statistical uncertainties. These sources included possible motion of the deuteron beam across the first target, drifts in the spectrometer field, the inclusion of protons corresponding to different energy levels of Sr^{87} and Sr^{88} in the proton flux entering the polarimeter, and the inclusion of protons *inelastically* scattered from carbon in the spectra of the side counters. Only the last two of the above-mentioned sources are mentioned below since the others have been discussed in an earlier paper.[18] An examination of the close-lying groups evident in the spectra from the natural strontium target indicated that unwanted groups contributed less than 3% of the protons entering the polarimeter. The absolute error in the polarization due to these weak proton groups was estimated to be ± 0.01 for an unfavorable case. It was also possible for proton inelastic scattering to occur in the second scatterer, exciting C^{12} to its 4.43-MeV level, since the protons were only degraded to about 7.6 MeV before scattering. However, protons inelastically scattered toward the side counters had energies of about 0.5 MeV, well below the energy (2.5 MeV) of the slowest elastically scattered protons.

An attempt was made to check the estimates of the corrections by measuring the asymmetry of the entire first target-spectrometer-polarimeter system. A measurement of this type may be obtained in principle by measuring the left-right asymmetry using a second scatterer with an analyzing power $P_2=0$. The second scatterer used was a 0.001-in. lead foil inserted to scatter 12.5-MeV recoil protons from the $H^1(\alpha,\alpha)H^1$ reaction. Although polarization data for protons elastically scattered from lead were not available, this polarization would be expected to be very small, judging from meas-

TABLE I. Experimental results obtained for the calibration of the analyzing power P_2 of the carbon polarimeter, using recoil-polarized protons from α-p elastic scattering with assumed polarization P_1 from Ref. 17.

$\theta_{c.m.}$	E_p (MeV)	P_1P_2 (uncorrected)	Geometric correction	P_1P_2 (corrected)	P_2	Estimated total error
24.4°	7.2	+0.361±0.021	+0.006±0.012	+0.367±0.025	−0.676±0.045	±0.051
24.4°	7.65	+0.348±0.014	+0.006±0.012	+0.355±0.019	−0.654±0.034	±0.041
24.4°	7.8	+0.321±0.022	+0.006±0.012	+0.326±0.025	−0.601±0.047	±0.051
24.4°	8.0	+0.269±0.021	+0.006±0.012	+0.275±0.024	−0.507±0.045	±0.048
24.4°	8.4	+0.211±0.021	+0.006±0.012	+0.217±0.024	−0.401±0.044	±0.047

urements at 40° on other heavy elements.[13,22] The present check yielded a product polarization $P_1P_2 = +0.025\pm0.025$, which from the known value of P_1 implied $P_2 = -0.045\pm0.046$. Since this measurement of P_2 resulted both from the polarization in scattering from lead and any asymmetry of the equipment, no conclusion was possible except that there did not appear to be any unexpectedly large asymmetry inherent in the equipment.

D. (d,p) and Elastic-Deuteron Angular-Distribution Measurements

Two different detectors were used to obtain the elastic-deuteron scattering data; a lithium-drifted counter[23] was employed during the forward-angle measurements and an Ortec surface-barrier detector was used during measurements at the backward angles. The surface-barrier detector reverse bias was set to produce a depletion region just sufficient to stop 11-MeV deuterons in the elastic-scattering measurements. The (d,p) angular distributions were obtained with a 70-kΩ resistivity Ortec surface-barrier detector biased so that 14-MeV protons from this reaction stopped in the depletion region. All of these counters were positioned in cylindrical counter mounts equipped with a system of collimators to provide double collimation of the scattered particles.

III. RESULTS

A. Polarimeter Calibration

The calibration of the polarimeter consisted of a series of measurements of the polarimeter analyzing power P_2 as a function of E_p, the proton energy before the second scattering. The results obtained for P_2, as given in Table I, actually correspond to polarizations averaged over the energy lost by the protons (about 2.7 MeV) in traversing the second scatterer. All of these results depend upon the value $P_1 = -0.542\pm0.035$ for recoil protons from α-p elastic scattering at $\theta_{lab} = 12.2°$, obtained from the p-α scattering results of Barnard *et al.* [17] Figure 6 contains a plot of the experimental values of P_2 in Table I for comparison with values obtained by integrating the polarization measurements of Moss *et al.*[24] for protons scattered from carbon over the appropriate intervals of angle (40° ±5°) and energy (4.3–7.2, 4.9–7.65, 5.1–7.8, 5.4–8.0, and 5.9–8.4 MeV). In this integration, each value of the polarization at a given energy and angle was weighted by the magnitude of the elastic-scattering differential cross section at that energy. The errors shown in Fig. 6 are statistical errors only. Table I includes statistical errors as well as an estimate of the total error involved in the measurement.

It should be noted that the polarimeter was calibrated at these unusually low energies so that higher excited states of nuclei could be investigated without recalibrating the polarimeter. Lighter elements may also be investigated at large scattering angles with this calibration without the proton energy falling below the calibration energies.

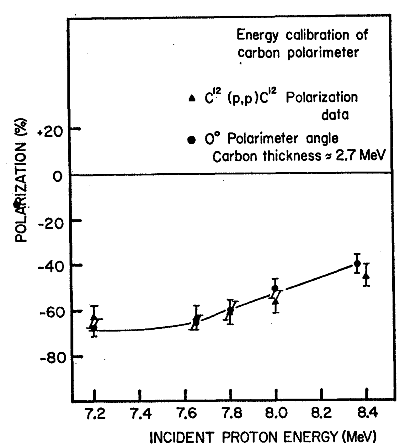


FIG. 6. Experimental calibration of the polarimeter analyzing power (circles) plotted as a function of *incident* proton energy for comparison with polarization values (triangles) determined by integrating the polarization measurements of Moss *et al.* (Ref. 24) over the range of proton energies before second scattering and the angular range utilized in the polarimeter. Note that the polarization plotted is the average over the energy thickness of the carbon scatterer, but is placed on the figure at the *incident* energy.

[22] S. Yambe, M. Kondo, S. Kato, T. Yamayaki, and J. Ruan, J. Phys. Soc. Japan **15**, 2154 (1960).

[23] The authors are indebted to Dr. James Mayer of Hughes Aircraft Company for the use of this counter.

[24] S. J. Moss, R. I. Brown, D. G. McDonald, and W. Haeberli, Bull. Am. Phys. Soc. **6**, 226 (1961).

B. Elastic Deuteron Scattering

In order to obtain a reasonable set of optical-model parameters to describe the interactions between the initial nucleus and the incident deuterons, the angular distribution of deuterons elastically scattered from strontium was measured. A 5% relative error and a 20% absolute error was assigned to the elastic cross sections. The relative error was primarily due to the uncertainty in background subtraction, while the absolute error resulted from uncertainties in target thickness, beam integration, solid angle, and background subtraction. A plot of the ratio of the elastic-scattering cross section to the Rutherford cross section is shown in Fig. 7.

C. (*d,p*) Polarization and Angular Distribution Measurements

The proton polarizations measured in the $Sr^{88}(d,p)$-$Sr^{89*}_{1.05\,\mathrm{MeV}}$ reaction are presented in Table II. Errors attached directly to the polarizations in the tables are statistical. The total errors tabulated separately in these tables include uncertainties from data interpretation (i.e., uncertainty in determining the low-energy cutoff point of the proton peaks), geometric corrections, depolarization corrections, proton energy degradation, and the determination of the polarimeter calibration from α-p scattering. The total uncertainty was computed by taking the rms sum of all sources of uncertainty except that due to data interpretation, which was added directly to the rms sum. It should be noted that statistical uncertainties and data-interpretation uncertainties contributed most heavily to the values of the total error.

The differential cross section for the $Sr^{88}(d,p)$-$Sr^{89*}_{1.05\,\mathrm{MeV}}$ reaction was also measured using 11.1-MeV deuterons. Relative and absolute errors of 10 and 30%, respectively, were assigned to the cross-section measurements at angles less than $90°_{\mathrm{lab}}$. The (*d,p*) angular distribution is plotted above the proton-polarization angular distribution in Fig. 8.

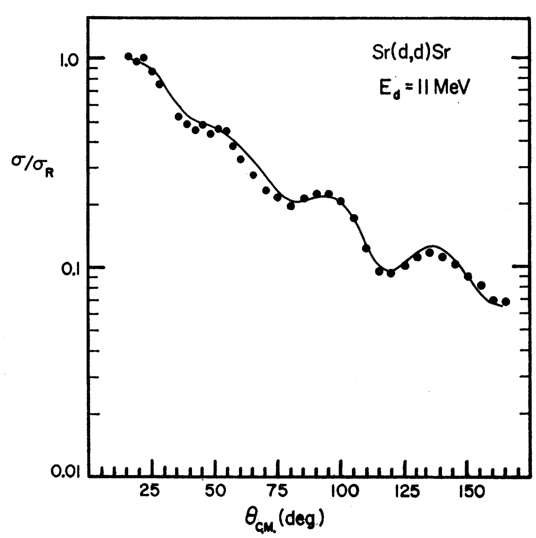


FIG. 7. Experimental results for the ratio of the elastic-scattering differential cross section to the Rutherford cross section for the Sr(*d,d*)Sr reaction. The solid line represents a sample fit obtained by Satchler, Bassel, and Drisko as discussed in the text.

IV. DISCUSSION

A. Calibration

The values of P_2 obtained for the polarimeter calibration as a function of incident proton energy are dependent upon the polarization predictions of Barnard *et al.*[17] based on phase-shift analyses of angular distributions obtained from experimental measurements of p-α scattering. The apparent agreement (see Fig. 6) of the polarimeter-calibration data of the present experiment with the expected values of P_2 obtained by integrating the polarization measurements[24] of the $C^{12}(p,p)$-C^{12} scattering process is good evidence for the over-all consistency between these two sets of measurements and the work of Barnard *et al.*

B. (*d,p*) Polarization Measurements

The observation of polarized protons from the $l_n=0$ reaction $Sr^{88}(d,p)Sr^{89*}_{1.05\,\mathrm{MeV}}$ indicates that simple distorted-wave theory is inadequate in predicting polarizations unless additional terms (e.g., spin-orbit terms) are included in the optical-model potentials. The proton-polarization angular distribution shown at the bottom

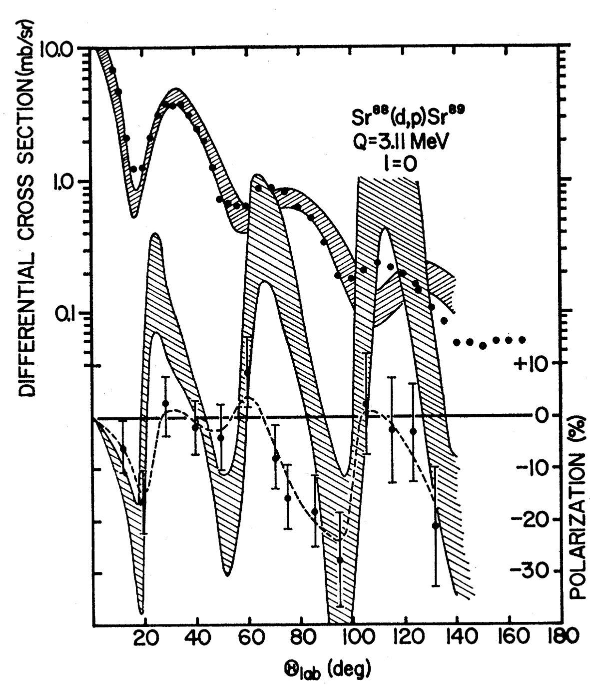


FIG. 8. A comparison of the (*d,p*) angular distribution with the proton-polarization angular distribution for the $Sr^{88}(d,p)Sr^{89*}$ reaction exciting the 1.05-MeV state of Sr^{89}. The shaded bands represent the range of variation of predictions obtained by Satchler, Bassel, and Drisko using reasonable parameters as discussed in the text.

TABLE II. Experimental results for the polarizations of protons (P_1) emitted in the $Sr^{88}(d,p)Sr^{89*}{}_{1.05\text{ MeV}}$ reaction at various laboratory angles (θ_{lab}) for a deuteron bombarding energy of 11.1 MeV. Errors directly attached to P_1 are statistical; the total errors include other uncertainties discussed in the text.

θ_{lab}	P_1P_2 (uncorrected)	P_1P_2 (corrected)	P_1 (transverse)	Depolarization factor	P_1	Total error
12.2°	+0.044±0.032	+0.037±0.034	−0.056±0.051	1.00	−0.056±0.051	±0.052
19.6°	+0.088±0.034	+0.096±0.037	−0.149±0.057	0.919	−0.162±0.062	±0.064
28.7°	−0.029±0.027	−0.016±0.029	+0.025±0.044	0.888	+0.028±0.050	±0.051
39.9°	+0.009±0.029	+0.011±0.031	−0.017±0.047	0.876	−0.020±0.054	±0.054
49.9°	+0.017±0.036	+0.022±0.037	−0.034±0.057	0.870	−0.039±0.065	+0.087 −0.085
60.0°	−0.059±0.037	−0.050±0.039	+0.076±0.060	0.868	+0.087±0.069	±0.069
70.4°	+0.039±0.033	+0.046±0.035	−0.069±0.053	0.867	−0.077±0.062	±0.080
75.2°	+0.083±0.033	+0.089±0.035	−0.135±0.054	0.866	−0.155±0.062	+0.092 −0.063
85.1°	+0.099±0.038	+0.106±0.040	−0.158±0.060	0.866	−0.182±0.069	+0.101 −0.074
95.1°	+0.139±0.046	+0.143±0.048	−0.239±0.080	0.866	−0.276±0.092	+0.142 −0.127
105.0°	−0.021±0.054	−0.013±0.055	+0.021±0.086	0.866	+0.024±0.099	+0.131 −0.104
115.0°	+0.006±0.058	+0.015±0.059	−0.023±0.090	0.867	−0.028±0.103	±0.139
123.0°	+0.014±0.053	+0.018±0.054	−0.028±0.083	0.868	−0.029±0.096	±0.150
131.5°	+0.112±0.064	+0.120±0.066	−0.184±0.100	0.870	−0.211±0.115	±0.135

of Fig. 8 appears to be correlated with the differential cross-section distribution plotted above. At the extreme forward scattering angles, where the slope of the angular distribution is negative, the measured polarizations are also negative. The possible change in sign of the polarization near 25° corresponds to the change in sign of the slope of the angular distribution near that angle. Sign changes in the slope of the angular distribution occur again near 35, 55, 70, 100, and 115°, which are close to the angles at which the polarization appears to change sign. The large statistical errors preclude any definite statement about cross-over points, but the signs of the observed polarizations appear to obey the "derivative rule" [given by Eq. (1)]. In addition, the observation of larger polarizations at the backward angles where the differential cross section is small agrees qualitatively with the prediction of the derivative rule that the polarization should be inversely proportional to the magnitude of the differential cross section.

Data taken with lighter elements, such as the aluminum and silicon data of Isoya *et al.*,[11] have shown only limited agreement with the derivative rule. Isoya *et al.* observed polarization sign changes at angles close to the stripping minima but not at the stripping peaks. The fact that the present results are not in disagreement with the derivative rule, which has failed for lighter elements, suggests that heavier elements may be more useful in examining the spin-orbit contribution to the optical-model potential.

Some attempts have been made at Oak Ridge by Satchler, Bassel, and Drisko[25] and by Smith[26] to fit the polarization angular distribution reported here with suitable spin-orbit potentials, using the deuteron optical-model parameters required to fit the elastic deuteron angular distributions, and reasonable proton parameters obtained from other work. These fits have generally exhibited larger oscillations than have been found experimentally, but do indicate that the sign of the required spin-orbit potentials are in agreement with those used in shell-model calculations and in theoretical analyses of elastic-proton scattering data.[13,14] The shaded bands in Fig. 8 show the range of variation of the predictions[27] of the differential cross section and the polarization obtained using six different deuteron potentials fitting the elastic-scattering data (a sample fit is shown in Fig. 7), a spectroscopic factor $S=0.3$, deuteron spin-orbit strengths from 0 to 10 MeV, a proton spin-orbit strength of 7.5 MeV,[28] cutoffs between 5 and 6 F, and employing both zero- and finite-range calculations. These predictions are preliminary in the sense that a continuing analysis is under way to determine better proton-optical-model parameters in this region.

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