Polarization of Photoneutrons Produced from Deuterium by 2.75-MeV Gamma Rays*

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An earlier experiment has been modified by the addition of a spin-precessing solenoid to permit an improved measurement of the polarization of the neutrons from photodisintegration of deuterium. Monoenergetic 2.75-MeV gamma rays were obtained from Na^{24} and the neutron polarization was analyzed by scattering from magnesium. The polarization normal to the reaction plane was measured for γ-n laboratory angles from 30 to 150°. Empirical corrections were derived for neutron scattering in the deuterium source as well as in the Mg analyzer. Within the errors the polarization is found to be symmetric about 90°, consistent with the absence of noncentral forces. The magnitude is, however, $(12\pm7)\%$ smaller than that calculated by Kramer from $E1$-$M1$ interference using effective-range theory. A major source of uncertainty in the experiment is the analyzing power of Mg. For a γ-n laboratory angle of 90°, the neutron polarization was also determined in the direction of the incident gamma ray. The result $P<0.01$ is consistent with the conservation of parity in the reaction.

I. INTRODUCTION

IN general the measurement of the polarization of photoneutrons can supply valuable information in addition to that obtained from the total cross section and angular distribution. Because interference terms give rise to the polarization, a small transition amplitude may become more prominent through interference with a larger amplitude. For the $D(\gamma,n)H$ reaction, the $M1$ transition, through interference with the normally dominant $E1$ transition, produces a relatively large polarization.

The first mention in the literature that the photoneutrons should be polarized was made by Rosentsveig[1] and by Czyž and Sawicki.[2] Since then a number of theoretical studies have been made.[3–11] The paper by Rustgi *et al.*[8] covering medium energies and that by Kramer and Müller[9] covering low energies give extensive discussions of the theoretical situation.

Until recently no polarization measurements had been made, mainly because of experimental difficulties. The first attempt to measure the polarization of the protons from the photodisintegration of deuterium was made by Feld *et al.*[12] using 240-MeV gamma rays. The experiment, performed with nuclear emulsions, was marginal because of poor statistics. A recent measurement[13] at 249 MeV appears to be in disagreement. These experiments were made above the meson threshold where no pertinent theoretical calculations have been made.

An early measurement of the polarization of photoneutrons was published by John and Martin.[14] They employed the 2.75-MeV gamma rays from the beta decay of Na^{24} to disintegrate deuterium. Polarizations were measured for five gamma-ray-neutron angles between 49.6° and 135.7°. The results were in good agreement with the calculations made by Kramer and Müller,[9] taking into account only the $E1$ and $M1$ transitions and using only central forces. Bösch *et al.*[15] repeated the experiment at 44.4° and 93.6°, obtaining excellent agreement with John and Martin.

At medium energy, Frederick[16] measured the polarization of the photoneutrons from deuterium at about 148° for photon energies between 11.0 and 22.9 MeV. For these conditions approximately half of the polarization is due to pure $E1$ transitions and half to the $E1$-$M1$ interference. Agreement was found with the calculations of Rustgi *et al.*[8] within the sizable statistical errors. More recently, Bertozzi *et al.*[17] have measured the photoneutron polarization from about 13 to 24 MeV at 90° to the photon beam so that the polarization was largely due to the $E1$-$M1$ interference. No large deviation from theory was detected. Later results by the same group give polarizations somewhat lower than the theoretical predictions.[18]

The present work represents an extension of the

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[3] L. N. Rosentsveig, Zh. Eksperim. i Teor. Fiz. **31**, 166 (1956) [English transl.: Soviet Phys.—JETP **4**, 280 (1957)].
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[18] W. Bertozzi, P. Demos, F. Hanser, S. Kowalski, C. Sargent, W. Turchinetz, R. Fullwood, and J. Russell, Office of Technical Services, Department of Commerce, Washington 25, D. C., CONF-502-3, 1964 (unpublished).

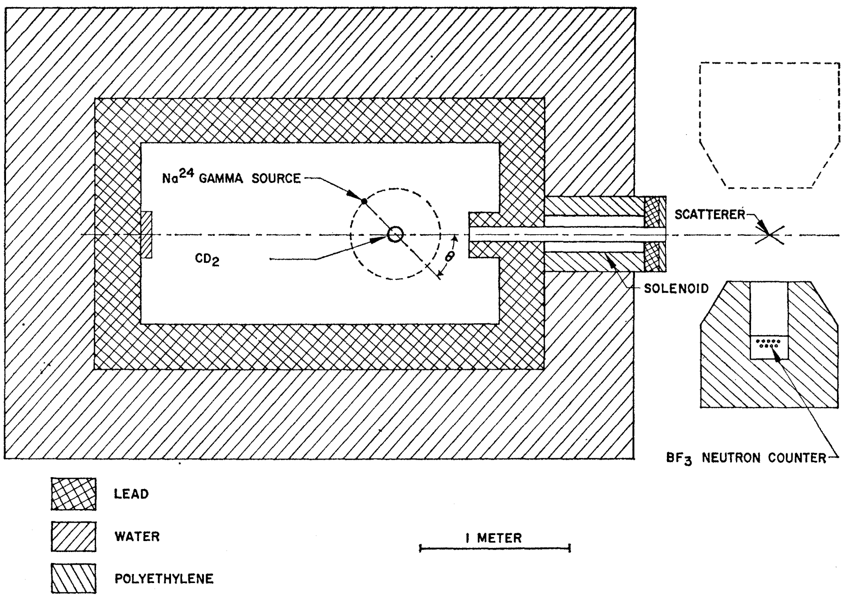

FIG. 1. Plan of experimental arrangement.

earlier Livermore experiment[14] with considerable improvement in the accuracy of the measurements. At low energy the electromagnetic interaction is particularly simple, involving only dipole transitions. Furthermore, the neutron-proton system can be treated with effective-range theory. Thus, the calculations give definite predictions which can be checked by polarization measurements. The magnitude of the polarization tests the computed $E1$ and $M1$ amplitudes, as well as the ${}^1S_0$ n-p phase shift. The angular dependence of the polarization is sensitive to the presence of noncentral forces which would produce a departure from symmetry about 90°.

In addition, in the present work an attempt has been made to detect the presence of neutron polarization in the direction of the incident gamma ray. It has been pointed out that this polarization would indicate parity nonconservation in the $D(\gamma,n)$ reaction.[19] Moreover, this reaction is particularly suitable for this test since the electromagnetic transitions produce effects linear in the parity nonconserving potential and since the two-nucleon system is especially amenable to calculation. Unfortunately for experimentation, the effects predicted from weak interactions are extremely small.

II. EXPERIMENTAL PROCEDURE

A. General

The general method was the same as in the earlier Livermore experiment. A 2-kCi Na^{24} source provided monochromatic 2.75-MeV gamma rays which were used to disintegrate deuterium in a CD_2 target. The photoneutrons emerging at a designated reaction angle were collimated and then the neutron polarization normal to the reaction plane was analyzed by observing the left-right asymmetry in the nuclear scattering from Mg. It has been shown by Elwyn and Lane,[20] that the broad neutron-scattering resonance in Mg at 270 keV has a high polarization analyzing ability.

Before presenting the experimental details, we will summarize here the principal changes made over the earlier Livermore experiment:

1. A solenoid was added to precess the neutron spins between the deuterium source and the Mg analyzer. Scattering asymmetries could then be determined by observing the ratio of the neutron counting rates with no magnetic field to that with a field sufficient to rotate the neutron spins by 180°. Since the neutron trajectories are virtually unaffected by the magnetic field, false asymmetries due to misalignments cancel out in first order.

2. The source shielding cave was enlarged to reduce the number of neutrons which could scatter from the shielding and then emerge from the collimator to contaminate the neutron beam. In addition, the room background was considerably reduced by extending the water shielding to completely envelope the source cave. The new cave is completely symmetric about the beam plane and allows the gamma-ray-neutron angle to be varied between $-170°$ and $+170°$ in the laboratory.

3. More detailed investigations were made to determine the correction necessary because of multiple scattering of the neutrons in the CD_2 source as well as in the Mg analyzer.

B. Experimental Setup

The layout of the experiment is shown in Fig. 1. The basic shielding seen from the source consisted of 30 cm

[19] R. J. Blin-Stoyle and H. Feshbach, Nucl. Phys. 27, 395 (1961).

[20] A. J. Elwyn and R. O. Lane, Nucl. Phys. 31, 78 (1962).

of lead followed by 60 cm of water. Lead was used as gamma-ray shielding not only for personnel protection but also to avoid making photoneutrons in the deuterium contained in the water. The necessary shielding-wall thickness determined the scale of the experiment. Inside the cave, the source was placed near the front wall. A short extension of the lead portion of the collimator into the cave was added to reduce streaming of gamma rays at small angles. Outside of the cave, the Mg analyzer was located 0.9 m downstream so that the shielding wall would not reflect an objectionable fraction of neutrons into the counter. About 10 m from the cave a thick concrete wall stopped the direct beam for personnel protection.

A motor-driven arm supported the gamma-ray source so that it could be swung around a pivot accurately located on the axis of the neutron collimator under the center of the deuterium target. From a remote control panel the arm angle (laboratory γ-n angle) could be set at 10° intervals to within 0.1°. For polarization measurements the Na-to-CD_2 distance was 32.7 cm. Both the Na and CD_2 samples were mounted on platforms which could be moved radially by means of remotely-controlled motors.

Gamma rays which are scattered through angles larger than 17° are degraded below the photoneutron threshold. The large dimensions of the cave prevented any appreciable photoneutron production from gamma rays scattered by the shielding.

C. Na^{24} Source

The Na source consisted of reagent grade NaF powder compressed isostatically at about 4900 kg/cm^2 to form a dense (2 g/cc) rod. This was then accurately machined, with due precaution taken for the toxicity of the compound, to 3.3 cm o.d. and 15.2 cm high. The diameter of the source was limited by the size that would fit into the reactor core. The length was made about 5 times greater than the diameter to gain source strength without unduly increasing the spread of the reaction angle. The NaF cylinder was placed in a cylindrical can of high-purity aluminum having a wall thickness of 3.1 mm. The lid was hermetically sealed by heliarc welding.

Possible impurities were investigated by activating the sample weakly and observing the gamma-ray spectrum with a NaI detector. No significant gamma rays were seen above the photoneutron threshold of 2.225 MeV.[21] In addition, during the experiment the photoneutrons were observed to decay over one or two half-lives by an amount in agreement to within 1% with that calculated from the accepted 15.0-h half-life. Stranded stainless-steel cable was used to handle the source. To avoid activating the Mn in the steel, the cable was coupled to the source after irradiation.

For activation the sample was suspended at the center of the core of the Livermore Pool Type Reactor in a flux of 5×10^{13} neutrons-cm^{-2}-sec^{-1} for periods from 3 to 5 days in order to nearly saturate the 15-h activity. The center of the reactor core afforded maximum flux and also a flux uniform to within about 15%. Furthermore, flux gradients are approximately symmetrical about the center of the core. Source strengths of about 2 kCi were used. Because of limited space in the reactor pool, a compact cask having 18-cm-thick walls was fabricated of U^{238} clad in stainless steel. The source was loaded into the cask under the pool water and then transferred to the experimental setup in a separate building. From reactor shutdown to the beginning of a run was a period of about 1.5 h.

D. Deuterium Targets

In order to maintain reasonable solid angles and also limit the scattering of neutrons in the deuterium targets, thin-walled cylinders were fabricated from deuterated polyethylene. These were stiffened and shaped by thin disks of Styrofoam. The cylinders were mounted on light Styrofoam supports 10 cm high. The CD_2 cylinders were all 10.0 cm o.d.$\times$15.2 cm high. A series of wall thicknesses were used to investigate the correction to be applied for neutron scattering as described below. There was no problem of sample purity since beryllium is the only other element which can be photodisintegrated at 2.75 MeV.

E. Solenoid

To turn 260-keV neutrons through 180° by Larmor precession requires about 100 000 ampere-turns. We used a solenoid whose bore was oval in cross section (10.2 cm wide and 15.2 cm high with rounded corners) and 66 cm long. Windings of hollow copper conductor were potted in epoxy resin and then surrounded by paraffin. Cooling water was circulated through the conductor. The magnet assembly served as the outer end of the collimator. Currents up to 600 A at 25 kW were available from a self-excited welder which proved surprisingly stable. A filter capacitor was connected across the terminals. A potentiometer connected across a low resistance in the current leads was used to monitor the current which was maintained within 1% of the desired value.

F. Magnesium Analyzers

Magnesium scatters were fabricated from flat slabs of 99.9% pure magnesium metal. Two slabs were fitted together to form a "cross," thus affording symmetry to the neutron beam and detector when positioned as shown in Fig. 1. The analyzers were placed on a light triangular platform of steel strips supported by wires. Total mass of the support in the neutron beam was about 3 g, compared to 374 g for the most frequently used Mg analyzer. The scatterers were aligned within about 0.3 mm of the collimator axis.

[21] J. W. Knowles, Can. J. Phys. **40**, 257 (1962).

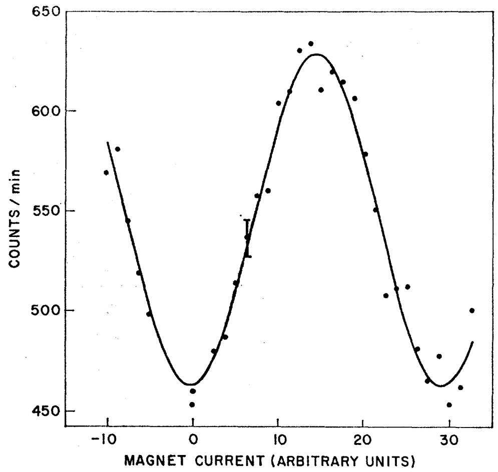

FIG. 2. Observed count rate versus magnet current from one of four runs used to calibrate the magnet with polarized neutrons from D(γ,n) at 90°. The curve is a least-squares fit to the function $C=A+B\cos\psi+D\sin\psi$. The coefficients A and D were used to search for a possible polarization in the direction of the incident gamma ray.

G. Neutron Counter

Because of the requirements of high efficiency and low gamma-ray sensitivity, a counter was constructed of BF_3 tubes surrounded by a neutron moderator. Nine 1-in.-diam BF_3 tubes were imbedded in a block of polyethylene 20.3 cm wide, 40.6 cm high, and 15.3 cm thick. The arrangement of the tubes for optimum counting efficiency was determined empirically by tests with BF_3 tubes in water. The polyethylene block was surrounded by a thermal neutron shield of 0.076 cm of cadmium and 0.635 cm of Boral. Then the counter was placed within a massive laminated shield of polyethylene designed to shield against background neutrons diffusing in the room. A hole in the shield served as a collimator which helped to limit neutrons scattered from the Mg analyzer to direct paths to the counter, instead of via surrounding objects. The entire counter assembly was mounted on a cart pivoted about a point on the collimator axis directly below the Mg analyzer.

All of the BF_3 tubes were operated in parallel with a discrimination level high enough to essentially eliminate all gamma-ray counts. Checks were made to ensure that the gamma-ray background did not affect the neutron counting efficiency. Counts of several calibrated neutron sources were made to determine the dependence of the counter efficiency on neutron energy. Absolute efficiency at the present energy was about 12%. The variation of efficiency over the small energy range of the photoneutrons of the present experiment was negligible. It was determined that the stray field of the solenoid changed the neutron counting efficiency by less than 0.1%. Counts of a standard Pu-Be source showed that the counting system reproduced within 2% over many months.

III. EXPERIMENTAL MEASUREMENTS

A. Magnet Calibration and Parity Experiment

A direct calibration of the precession solenoid was made with the deuterium photoneutrons. This consisted of observing the counting rate of the neutron detector as a function of the current in the solenoid. For these measurements θ, the (γ,n) angle, was set at 90° (lab). It was possible to invert the neutron polarization by replacing θ by $-\theta$, or alternatively by rotating the detector from one side of the beam to the other. In order to average out any geometrical asymmetries, data were taken in all four possible combinations of source and detector positions. A CD_2 cylinder with a 0.096-g/cm^2-thick wall and a Mg analyzer 3.1 mm thick (normal to slab) were employed. The data from one of the runs are plotted in Fig. 2. The solid line is a plot of the function

$$C=A+B\cos\psi+D\sin\psi\,, \tag{1}$$

where C is the observed counting rate and A, B, and D are constants, and $\psi=2\pi I/I_0$ where I is the magnet current and I_0 the period. Equation (1) was fitted to the points by least squares. I_0 was chosen to minimize the sum of the squares of the residuals.

I_0 could be independently determined from the magnetic field. A Hall probe was used to obtain a plot of the field both inside and outside of the solenoid with relative values good to 2%. An accurate absolute calibration of the field at the center was made with a proton resonance probe. By a graphical integration the ampere-turns acting on the neutrons for a given magnet current was determined.

In order to find the current needed to precess neutron spins through 180°, it is necessary to know the neutron velocity. The energy of the photoneutrons in the laboratory is given by

$$E_n(\text{keV})=262.5+32.6\cos\theta+2.0\cos^2\theta\,,$$

where the equation given by Amaldi[22] has been evaluated for $E_\gamma=2.754$ MeV,[23] and $Q=2.2245$ MeV.[21] For $\theta=90°$, the necessary turning current derived from the magnetic-field plot agreed with that found directly from the photoneutrons to within 1%. This was regarded as an excellent over-all check of the system. Fringing fields can cause a depolarization of the neutron beam through precession about radial components of the magnetic field. This effect has been calculated by Atkinson and Sherwood.[24] For our solenoid, which is relatively long compared to its diameter, the depolarization is less than 1%.

The scattering asymmetries of the polarized neutrons may be evaluated from the coefficients in Eq. (1). We

[22] E. Amaldi, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1959), Vol. 38, Chap. 2, pp. 98.
[23] A. Hedgran and D. E. Lind, Arkiv Fysik **5**, 177 (1952).
[24] J. Atkinson and J. E. Sherwood, University of California Radiation Laboratory Report No. UCRL-12113 (unpublished); Nucl. Instr. Methods (to be published).

distinguish between the polarization $P_\perp$ perpendicular to the reaction plane (in the direction $\mathbf{k}_\gamma \times \mathbf{k}_n$) and the polarization $P_{\parallel}$ in the reaction plane (in the direction $\mathbf{k}_\gamma$). Then the left-right scattering ratios $\epsilon_\perp$ and $\epsilon_{\parallel}$ are given by

$$\epsilon_\perp = C(\psi=0)/C(\psi=\pi) = (A+B)/(A-B),$$
$$\epsilon_{\parallel} = C(\psi=\tfrac{1}{2}\pi)/C(\psi=-\tfrac{1}{2}\pi) = (A+D)/(A-D).$$

The corresponding polarizations are given by

$$P_i = (\epsilon_i - 1)/[(\epsilon_i+1)P_2], \tag{2}$$

where P_2 is the analyzing power of Mg. In evaluating the above expressions for ϵ_i and P_i, the signs must be chosen consistently. $P_\perp$ will not be discussed here since the measurements specifically taken for $P_\perp$ and the necessary corrections are discussed in detail below.

We find that $P_{\parallel} = -0.010 \pm 0.008$. Thus, there is no significant polarization in the direction of the incident gamma ray, and parity is conserved within the accuracy of the measurement.

B. Polarization Measurements

1. Data Runs

Data were taken for each γ-n angle in the four possible combinations of source position at $+\theta$ and $-\theta$ and detector on the right and left sides of the beam. Groups of several 10-min counts were made with the geometry held fixed and the magnet current set alternately to zero and at the value to produce 180° rotation of the neutron spin. The Mg analyzer was then removed and background counts were taken. From each raw count a small time-independent background was subtracted which was determined by counts in the absence of the source. The count was then corrected for the decay of the Na^{24}. After the no-analyzer background was subtracted, a left-right scattering ratio ϵ could be determined from each group of counts. The weighted average of all such groups for a given angle yielded the final ϵ.

Data runs were all made with a CD_2 cylinder having a wall thickness of 0.096 g/cm^2 and a Mg analyzer 3.1 mm thick (normal to slab). Counting rates ranged from 200 to 300 counts/min. The no-analyzer background was about 30 counts/min, while the no-source background was about 13 counts/min. In all, six source runs were made to accumulate the data.

A null check for false asymmetry was made using neutrons from the Be(γ,n) reaction and a graphite analyzer. From this it could be concluded that spurious asymmetry in the experiment was less than 0.005.

2. CD_2 Thickness Effect

A neutron photoproduced in the CD_2 cylinder may be scattered before escaping, resulting in a change of direction and possibly a change in polarization. In order to investigate the effect on the observed scattering asymmetry, measurements were taken at 30°, 90°, and 150° with four different thicknesses of CD_2. The observed ϵ are plotted as a function of the CD_2 thickness in Fig. 3. The curves were calculated by a Monte Carlo technique on a digital computer. The calculation took into account the angular distribution of the photoneutrons and the geometry accurately. All scattered neutrons were assumed to be completely unpolarized. The variation of the Mg scattering cross section with energy was taken into account approximately. Although the calculation could not be made exact, the fit to the points is generally satisfactory. The data runs were corrected to zero CD_2 thickness by means of the calculated corrections at each angle.

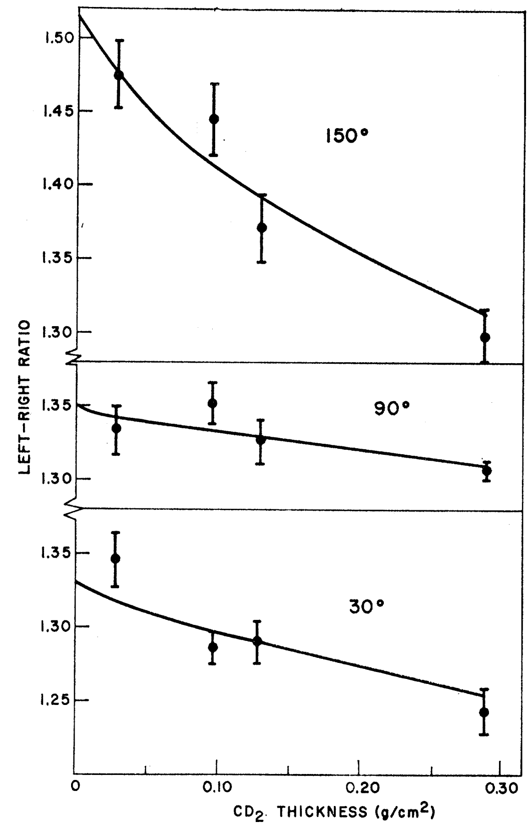

FIG. 3. Left-right scattering ratio observed for four CD_2 cylinder wall thicknesses at γ-n angles of 30°, 90°, and 150°. The curves are from the Monte Carlo calculation which was used to correct the data taken at 0.096 g/cm^2 to zero thickness.

3. Mg Analyzer Thickness

Multiple scattering of neutrons in the analyzer will also alter the observed ϵ. The experiment of Elwyn and Lane[20] from which the analyzing power of Mg was taken utilized a single Mg slab 3.1 mm thick at 45° to the beam. In order to increase the counting rate for data taking, we have used a slightly different geometry. The probability of single scattering of a neutron is proportional to the thickness of Mg in the beam direc-

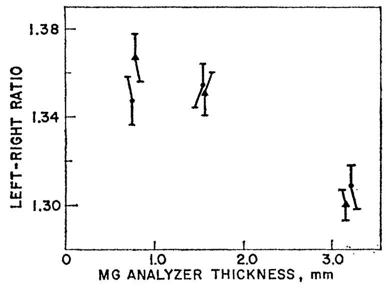

FIG. 4. Comparison of observed left-right scattering ratios for Mg-analyzer crosses with slabs at 26.5° to the neutron beam (triangles) and 45° (circles). The thicknesses are given normal to slab.

tion. On the other hand, the probability for multiple scattering in a slab of material is, to first-order, proportional to the thickness normal to the slab. Therefore, when the detector is at right angles to the beam, the desired single scattering can be increased without unduly increasing the multiple scattering by inclining the slab at a small angle to the beam. In the present experiment the angle was 26.5°. A practical limit on the angle is set by the acceptable increase in the angular spread from the analyzer to the detector. Fortunately, the measurements by Elwyn and Lane at 90° and 45° show that the polarization is relatively insensitive to the angle.

A comparison was made between observed asymmetries for a 45° "cross" and the 26.5° "cross" for three slab thicknesses. The results, plotted in Fig. 4, show that the observed ϵ is the same within errors as expected. Therefore, the data were taken with the 26.5° "cross" with a gain of a factor of about 1.4 in the counting rate.

To determine the correction for the slab thickness used, a series of ϵ measurements were taken for three thicknesses at γ-n angles of 30°, 90°, and 150°. The points are plotted in Fig. 5, with the straight lines fitted to the points by least squares. These lines were used to correct the observed ϵ to the thickness employed by Elwyn and Lane. Since they used no multiple scattering corrections, our corrected data can then be used with analyzing powers quoted in their experiment. These analyzing powers are plotted in Fig. 6 with the arbitrary curve we have used to interpolate to the appropriate neutron energies.

It should be pointed out that in making the thickness correction we have assumed that a "cross" is equivalent to a single slab having twice the thickness of the individual slabs of the "cross." This probably overestimates the effective thickness of the cross. The total correction to the left-right ratio is about 3%, and the overcorrection might be about 1%. A more serious uncertainty is introduced by the fact that Elwyn and Lane made no thickness correction. As discussed by them and illustrated in Fig. 5 of Ref. 20, Elwyn and Lane found that the left-right ratio tended to stay constant for slabs below 3.2 mm thickness, although the results seemed to depend on energy and angle. On the other hand our results (Fig. 5) indicate a linear increase of the left-right ratio with diminishing Mg thickness and would indicate the need for a further 3% correction to zero thickness. Unfortunately the uncertainty cannot be resolved at this time and so we accept the results of Ref. 20.

4. *Scattered Neutron Background*

Photoneutrons emitted from the CD_2 in a direction away from the collimator may be redirected into the collimator by scattering on the inner walls of the shielding cave. This process requires a final scattering from the back wall opposite the collimator. Two precautions were taken to reduce this effect. First, the back wall was placed as far away as possible by constructing a long cave. Secondly, a small water tank was placed at the back wall to cover the area seen through the collimator. Water should help by absorbing and also by degrading the neutrons. The Mg scattering resonance affords a cross section approximately twice as great for primary photoneutron energies as for degraded energies.

In order to derive an empirical correction for cave scattering, the CD_2 and Na source were displaced radially a distance of 15 cm so that the CD_2 could not be seen through the collimator. With the Mg analyzer in place, the counting rate was 2% of the normal rate. For this measurement the source arm was positioned at 90°. Previous tests showed that the "off-center" counting rate was insensitive to the arm angle, as expected. The off-center rate was subtracted from the data as a background. However, since the calculated left-right ratios were increased by less than 0.01 at most angles, the correction was relatively unimportant.

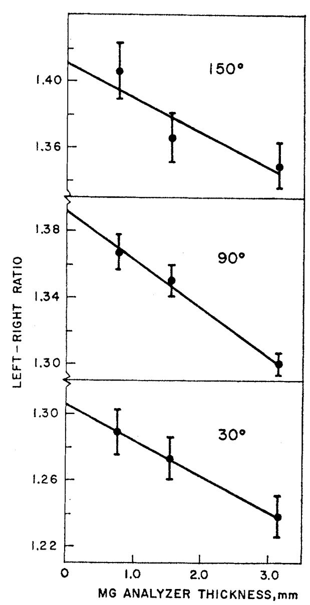

FIG. 5. Observed left-right scattering ratios versus Mg-analyzer thickness measured normal to one of the slabs of the 26.5° "cross" used. The straight lines were fitted to the points by least squares and used as the basis for the correction for analyzer thickness.

TABLE I. Measured left-right ratios ϵ, corrected ratios, and calculated photoneutron polarization. Positive polarization is taken in the direction $\mathbf{k}_\gamma \times \mathbf{k}_n$.

$\theta_{c.m.}$ (deg)	Measured ϵ with statistical error	ϵ corrected for Mg thickness	ϵ corrected for CD_2 thickness	P_2 for Mg	Photoneutron polarization P_1	Final P_1 corrected for geometry with total error
31.8	1.296±0.011	1.332	1.375	−0.605	−0.261	−0.287±0.024
52.7	1.317±0.011	1.359	1.388	−0.661	−0.246	−0.260±0.021
73.3	1.320±0.009	1.365	1.384	−0.730	−0.221	−0.231±0.018
93.5	1.348±0.004	1.395	1.414	−0.795	−0.216	−0.225±0.019
113.3	1.408±0.012	1.454	1.484	−0.842	−0.231	−0.242±0.020
132.7	1.426±0.013	1.469	1.514	−0.865	−0.236	−0.250±0.025
151.8	1.427±0.010	1.463	1.550	−0.865	−0.249	−0.275±0.029

Some neutrons were also scattered from the inner walls of the collimator. This effect is very difficult to assess. A rough estimate was made by calculating the contribution from single isotropic scattering, neglecting absorption and multiple scattering. On this basis 0.5% of the neutrons striking the Mg analyzer were scattered from the collimator. Since the effect is quite small, no correction was made for it. As a precaution the Mg analyzer was designed to cover only the umbra of the beam, since the penumbra probably contains a higher fraction of scattered neutrons.

Finally, after the neutrons have been scattered from the Mg analyzer there is a possibility that some of them will reach the counter by an indirect route, having scattered from surrounding materials. In order to determine that the counter shield and collimator functioned properly, some measurements were made with a small Na-D_2O neutron source. First the counting rate was measured as a function of the source-counter separation. The counting rate was found to follow the inverse-square law within 2% out to a distance of 140 cm from the face of the counter. The Mg analyzer was 57 cm from the counter face for the polarization measurements. In addition, counts were taken with and without a shadow shield of polyethylene interposed between the source and counter. From both of the tests described above, we conclude that less than 1% of the neutrons from the Mg analyzer are scattered by other objects before reaching the counter.

5. *Results and Corrections*

The results are summarized in Table I. The "measured" left-right ratio ϵ includes all background subtractions. Corrections for CD_2 and Mg thickness were discussed above in Secs. B.2 and 3. The analyzing power P_2 for Mg was taken from the curve in Fig. 6. The photoneutron polarization P_1 was calculated from Eq. (2). The result must be corrected for the finite extent of the Na and CD_2 sources, the Mg analyzer, and the neutron detector. The factor needed is essentially the mean cosine of the angle between the neutron production plane and the scattering-analyzing plane.

A Monte Carlo calculation was made which took into account the exact geometry of the Na and CD_2 sources, as well as the differential cross section of the $D(\gamma,n)$ reaction. Because of the large distance between the CD_2 and Mg, the problem separates into a calculation for the Na-CD_2 sources and one for the Mg-counter analyzer system. The correction derived from the Na-CD_2 sources requires multiplying the measured P_1 by a factor varying from 1.02 at 90° to 1.08 at the extreme angles. The correction from the Mg-counter system is a factor of 1.024 at all γ-n angles.

No correction was made for Compton scattering of the gamma rays in the Na source. This produces degraded photons and consequently lower energy neutrons as well. Approximately 14% of the photons are scattered in the source. However, of these, only about 16% have energies still above the photoneutron threshold. Thus, about 2% of the gamma rays produce lower energy neutrons. The effect on the polarization measurement is even less since (a) the photoneutron cross section decreases toward threshold, (b) the scattering cross section of the Mg analyzer decreases with energy (except for a narrow resonance at 83 keV), and (c) the photoneutron polarization is a slow monotonic function of gamma-ray energy according to theory.

6. *Errors*

The error analysis has been divided into three main parts: (a) statistical errors in the left-right ratio measurements, (b) systematic errors due to uncertainties in the various corrections applied to the data, and (c)

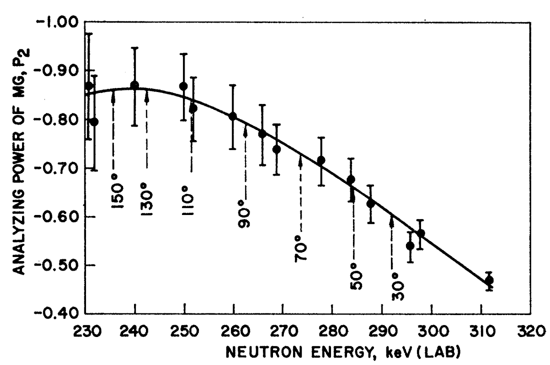

FIG. 6. Analyzing power of Mg versus neutron energy from Ref. 20. The arbitrary curve was used to interpolate to the neutron energies at the γ-n angles shown.

TABLE II. Errors in the photoneutron polarization P_1. The errors from this experiment include statistics and systematics; the uncertainty in P_2 is from Ref. 20.

$\theta_{c.m.}$ (deg)	Error from this experiment (%)	Uncertainty in P_2 for Mg (%)	Total error in P_1 (%)
31.8	6.1	5.4	8.2
52.7	4.3	7.0	8.2
73.3	3.3	6.8	7.6
93.5	2.4	8.3	8.6
113.3	3.3	7.7	8.4
132.7	3.7	9.4	10.1
151.8	4.4	9.4	10.4

the uncertainty in the analyzing power of Mg. The statistical errors in ϵ are listed in Table I. Systematic errors are comparable to, or larger than, the statistical errors, depending on the angle. Because of the peaking of the differential cross section at 90°, the corrections and the corresponding uncertainties are minimal there. For example, at 90° the absolute systematic uncertainties in ϵ were ± 0.002 from the off-center background subtraction, ± 0.005 from the Mg thickness correction, and ± 0.010 from the CD_2 thickness correction. At all angles the CD_2 thickness correction was the largest source of systematic error.

In Table II the errors are listed according to angle. The errors from this experiment are listed first and include the statistical and systematic errors. The uncertainty in P_2 taken from Ref. 20 is then listed. Finally, the errors are combined by square-root-of-sum-of-squares into a total error. In the event that P_2 for Mg should be remeasured with better accuracy, it would be possible to reduce the total error considerably, as can be seen from Table II.

It should be pointed out that the measured ϵ are asymmetric about 90° because of the energy dependence of P_2 (Fig. 6). It is thus important to consider the consequences of error in the neutron energy of the experiment[20] which "calibrated" the Mg analyzer. An error in the Van de Graaff energy of 5 keV would produce a change in P_2 such that the calculated P_1 at 30° is changed by about one-half of the quoted error. At larger angles the error would be less. On the other hand, the photoneutron energies are known to about ± 1 keV. Hence, we conclude that uncertainties in neutron energy do not affect the results appreciably.

IV. DISCUSSION

A. Photoneutron Polarization

The photodisintegration of the deuteron just above threshold proceeds predominantly by the dipole transitions:

$$^3S \to {}^3P \quad \text{electric dipole,}$$
$$^3S \to {}^1S \quad \text{magnetic dipole.}$$

Kramer and Müller[9] write the following expression for the polarization:

$$P(d\sigma/d\Omega) = (\gamma_0 + \gamma_1 \cos\theta + \gamma_2 \cos^2\theta)\sin\theta.$$

Near $E_\gamma = 2.75$ MeV; their calculation shows that γ_1 is approximately 2% of γ_0 while γ_2 is negligible. Thus, γ_0 accounts for essentially all of the polarization at low energy. Kawaguchi[5] has shown on general grounds that

$$\gamma_0 = (\tfrac{2}{3}ab)^{1/2} \sin[\delta(^1S) - \delta(^3P)],$$

where $\delta(^1S)$ and $\delta(^3P)$ are the phase shifts for neutron-proton scattering, and a and b are the coefficients in the usual expression for the differential cross section:

$$d\sigma/d\Omega = a + b\sin^2\theta.$$

The above formula for γ_0 exhibits the fact that the polarization arises from the interference between the $M1$ and $E1$ transitions since a is due almost entirely to the $M1$ transition and b to the $E1$ transition.

Kramer and Müller[9] have calculated a, b, γ_0, and γ_1. Since the $E1$ amplitude is extremely insensitive to the method of calculation, it will not be discussed further here. The $M1$ transition was treated using effective-range theory to calculate $\delta(^1S)$ from the known a_s and r_s. The radial wave function for the ^1S state was generated from a square well, while the ground state of the deuteron was taken from Hulthén and Sugawara. For $E_\gamma = 3$ MeV, a is found to vary by a maximum of 6% over trial variations of the parameters of the calculation, while γ_0 varied by a maximum of 4%. Moreover, a and γ_0 are correlated so that the calculated polarization varies by a maximum of 3%.

Kramer[25] has carried out a similar calculation at $E_\gamma = 2.759$ MeV for comparison to the present experiment. The results are displayed in Table III. Since the effective range for the singlet state is the most uncertain parameter involved, the calculation was made for three values. Recent data favor set 2, although it can be seen from Table III that the results are insensitive to r_s.

The polarization calculated from set 2 is drawn as the solid line in Fig. 7 for comparison to our experimental points. Since the points are systematically above the curve, a dashed curve has been drawn representing the theoretical curve multiplied by 0.879. The experimental points appear to fit the dashed curve satisfactorily. There is a slight tendency of the points at extreme angles to lie above the curve, but we do not regard it as significant. The observed symmetry about

TABLE III. Photoneutron polarization and cross sections calculated by Kramer[25] for the D(γ,n) reaction at $E_\gamma = 2.759$ MeV.

Set	r_s, F	γ_0, μb	a, μb	b, μb	a/b	σ_T, μb
1	2.0	−41.2	23.8	136.9	0.174	1446
2	2.4	−40.9	23.0	136.9	0.168	1436
3	2.8	−40.3	22.0	136.9	0.161	1423

[25] G. Kramer (private communication).

90° verifies the smallness of γ_1 and the unimportance of noncentral forces at this energy.

It is difficult to see why the magnitude of the polarization should be 12% smaller than the theory predicts. This can be emphasized by writing the polarization in the following form:

$$P=\frac{(\frac{2}{3})^{1/2}(a/b)^{1/2}\sin[\delta(^1S)-\delta(^3P)]}{(a/b)+\sin^2\theta}.$$

The polarization depends on a and b only through the ratio a/b. No experimentally reasonable value of this ratio can reduce P by 12%. Similarly, no reasonable effective-range parameters can reduce $\delta(^1S)$ sufficiently to produce agreement. $\delta(^3P)$ is negligible. Furthermore, the basis of the above equation was shown by Kawaguchi[5] to be dependent only on fundamental assumptions. On the other hand, the calculated σ_T is about 7% lower than the experimental values. And while the calculated a/b is in good agreement with experiment, at slightly lower energies there is apparently a discrepancy between theory and experiment.[26] Also, for n-p capture there is a necessity for introducing other effects into the theory, such as exchange currents.[27]

At medium gamma-ray energies, the photoneutron polarization at 90° also depends largely on the $E1$-$M1$ interference term. Recent measurements of P_n from 6 to 22 MeV by Bertozzi *et al.*[17,18] are smaller in magnitude than theory[7,8,10] by 0.02 ± 0.01; the theory predicting about -0.08.

Unfortunately, we cannot definitely exclude the possibility that the analyzing power of Mg upon which our result depends could be in error by an amount of the order of 10%. We have included the quoted error in the analyzing power in our error estimates. However, because of the fact that the scattering experiments on Mg used to "calibrate" it as an analyzer were done with ordinary Mg, there may be a systematic error arising from the minor isotopes present. The calibration is dependent on resonance parameters derived from total-cross-section data. It is thus important that all significant interactions be included. The fits neglecting the minor isotopes were actually quite good. Also where the data overlapped with Li^7-analyzer data the agreement was satisfactory, although the accuracy of the Li^7 data was not sufficient for our present purpose.

Elwyn and Lane[20] have pointed out the desirability of using separated Mg isotopes. Careful cross-section and polarization measurements would be necessary to calibrate Mg^{24}. Hopefully, at the same time ordinary Mg could be calibrated with sufficient accuracy, otherwise the photoneutron experiment would have to be repeated with Mg^{24} isotope. There is no other analyzer as suitable at this energy. Since the scattering experiment on Mg also calibrates the $Li(p,n)$ reaction as a source of polarized neutrons, the scattering experiment with separated isotopes would be quite valuable. Of course any other experiment which determined the polarization of the $Li^7(p,n)$ neutrons could be used to calibrate Mg by means of the data of Elwyn and Lane.

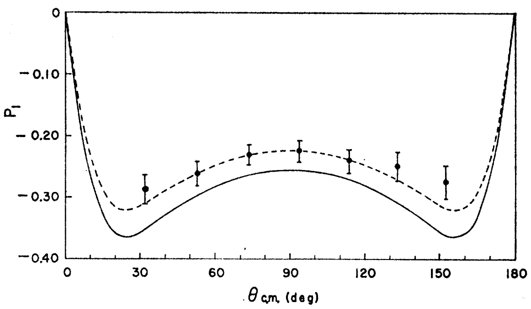

FIG. 7. Polarization of the neutrons from the $D(\gamma,n)$ reaction with $E_\gamma=2.754$ MeV. The solid curve is from a theoretical calculation by Kramer. The dashed curve is the theoretical curve multiplied by an arbitrary factor of 0.879 for comparison to the data points.

B. Parity Conservation

The measurement of the photoneutron polarization in the direction of the incident gamma ray described in Sec. IIIA is the experiment B discussed by Blin-Stoyle and Feshbach[19] concerning parity-nonconserving potentials between two nucleons. Using a parity-nonconserving potential from the theory of weak interactions, they estimate a polarization of the order of 10^{-10} at our energy. A similar result was obtained by Partovi.[28] Since our result is $P_{\parallel}<0.01$, the measurement is only a check against the possibility of parity nonconservation arising from other effects. Furthermore, since two very recent experiments[29,30] on complex nuclei have apparently detected parity-nonconservation effects in the order of 10^{-7}, the significance of the present measurement is correspondingly reduced.

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