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Measurements of the Polarization of Protons from Deuteron Photodisintegration*

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The polarization of the proton produced by the photodisintegration of the deuteron has been measured at several angles for photon energies between 170 and 450 MeV. The polarization is found to be around −0.20 (Basel convention) for 90° c.m. and photon energies between 200 and 300 MeV. This is in reasonable agreement with a calculation by D. George based upon the Austern model. However, the calculation fails to explain the strong increase in polarization with increasing photon energies. At a photon energy of 450 MeV and 90° c.m. the proton polarization is as large as −0.60.

I. INTRODUCTION

PHOTODISINTEGRATION of the deuteron is the simplest reaction involving the interaction of a photon with a complex nucleus, and is therefore of theoretical interest.

In the energy range from threshold to about 100 MeV the reaction cross sections can largely be explained by the interaction of the photon with the two nucleons as they move in a static potential.[1] For photon energies above 100 MeV, the interaction of the photon with the meson current becomes increasingly important[2] so that the above theory is no longer sufficient. In the energy region from 100 to 1000 MeV the total and differential cross sections fall off smoothly with increasing energy, except for a pronounced peak near 250 MeV.[3–7] This peak has been qualitatively explained by assuming that the reaction proceeds through an intermediate state in which one of the nucleons is excited to the N^* isobar.[8,9]

Polarization measurements on the ejected protons determine the imaginary parts of partial-wave interference amplitudes. Hence, such measurements near 250 MeV provide a sensitive test to the model. Further measurements at higher energies can determine how far the model is still valid. Until now the proton polarization has been measured at only one point.[10] In this experiment, we have made a systematic study of the proton polarization between 170- and 450- MeV photon energies.

II. APPARATUS

The experimental arrangement is shown in Fig. 1. The momentum analyzed electron beam from the

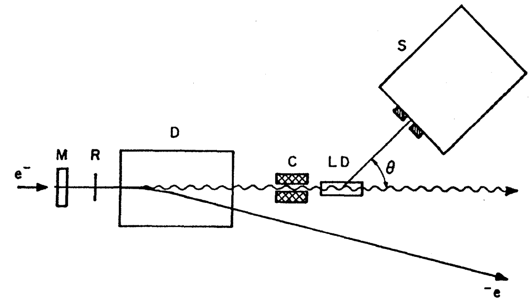

Fig. 1. The experimental layout. M, SEM beam monitor; R copper radiator; D, ditching magnet; C, lead collimator; LD liquid-deuterium target; S, 90° bend $n=0$ magnetic spectrometer.

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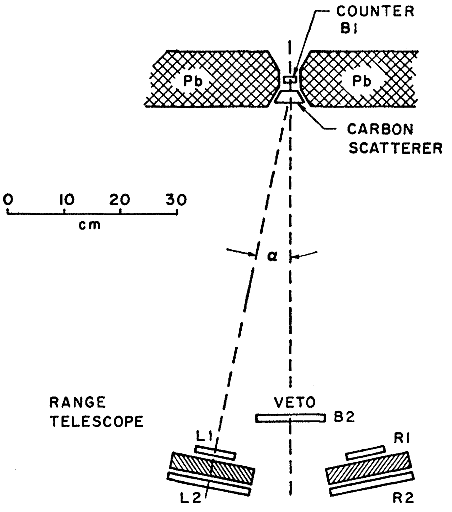

FIG. 2. The details of proton polarimeter at the exit of the magnetic spectrometer. B1 and B2 are plastic scintillation counters. Plastic scintillation counters L1 and L2 form a proton range telescope for the left arm of the polarimeter; R1 and R2 form the right arm.

Stanford Mark III linear accelerator was focused to a $\frac{1}{4}$-in. spot on a copper radiator. The beam was monitored by a thin secondary emission monitor (SEM). A deflecting magnet was placed after the radiator to separate the degraded electrons from the photon beam. The photon beam was then collimated 66 in. away from the radiator to 1-in.-diam. by a 2-in.-thick lead collimator placed directly in front of the liquid-deuterium target. The cylindrical target cell was made with 0.002-in. stainless-steel walls and was 1.875 in. in diameter and 12 in. long. The axis was oriented along the beam direction. By raising the target cell an identical dummy cell could be introduced into the photon beam for empty target runs.

Protons emitted about the horizontal plane were deflected in a vertical plane by a 90°, $n=0$ magnetic spectrometer.[11] The spectrometer aperture was defined by a rectangular collimator $2\frac{1}{2}$ in. wide and 4 in. high located 33 in. from the spectrometer pivot. This mask limits the acceptance in the bend plane to $\pm 3.5°$. The momentum acceptance was 3% and the angular acceptance was 1.2° full width.

TABLE I. Dimensions of the various plastic scintillation counters of the proton polarimeter. The counters L1 and R1 are trapezoidal with these two lengths, the shorter side being nearer the polarimeter axis.

Counter	Thickness (in.)	Width (in.)	Length (in.)
$B1$	0.25	1.0	3.0
$B2$	0.25	4.25	7.0
$L1$	0.25	2.9	5.0; 8.3
$L2$	0.25	6.0	12.0
$R1$	0.25	2.9	5.0; 8.3
$R2$	0.25	6.0	12.0

Figure 2 shows the polarization analyzer located in the shielded spectrometer cave. The protons were recorded in the momentum defining counter, B1, and then passed through 3.5 to 5.0 g/cm^2 of carbon. Protons scattered to the left and right were detected in identical range telescopes in coincidence with B1. Random coincidences between the range telescopes and counter B1 were less than 1% of the prompt rates. A veto counter B2 was placed in the unscattered beam of protons (Fig. 2). Coincidences between protons passing through counters B1 and B2 were used as veto signals to reduce the random coincidences to a completely negligible level.

Each range telescope consisted of two plastic scintillators with an appropriate thickness of copper absorber between them. The dimensions of the counters are given in Table I.

III. EXPERIMENTAL PROCEDURE AND ANALYSIS

The kinematics of the deuteron photodisintegration are shown in Fig. 3. The spectrometer selects the emitted protons in angle and momentum and thus uniquely determines the energy of the interacting photon. In this experiment, the shape of the bremsstrahlung spectrum is of no importance; however, the end point was chosen to be 80 to 100 MeV higher than the interacting photon energy, but always low enough to exclude protons which were associated with pion production.

Data were taken at four different momentum settings, as shown in Fig. 3. The proton momenta were chosen

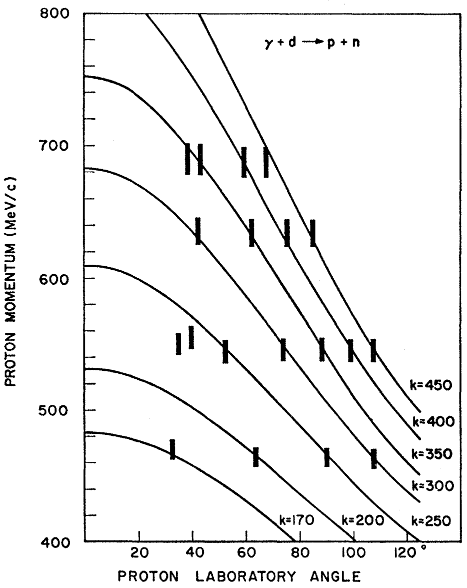

FIG. 3. Deuteron photodisintegration kinematics. The photon energies are given near each curve. The data points are indicated.

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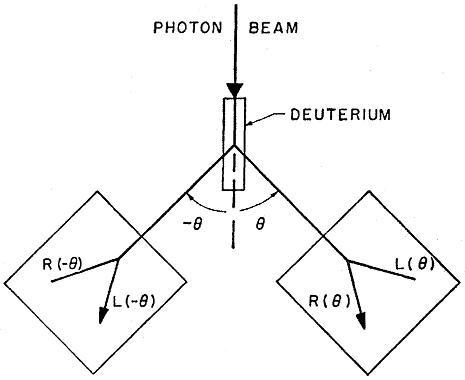

FIG. 4. Definition of the quantities used for defining the asymmetry.

to correspond to energies at which the analyzing power of carbon has been measured.[12–17] The angle and momentum acceptance of the spectrometer is shown for each point, after correction for small energy losses. Instrumental asymmetries in the system were cancelled by effectively reversing the sign of the polarization of the protons entering the apparatus. Since the spin must be normal to the production plane defined by the vector product of the incoming photon and outgoing proton momentum vectors (**k** and **q**, respectively), the proton spin can be reversed by rotating the spectrometer from angle θ on one side of the deuterium target to an angle $-\theta$ on the other side. However the instrumental asymmetry due to small geometrical misalignments or inefficiencies of the telescopes does not change. Hence measuring the asymmetry with the spectrometer at θ as well as with the spectrometer at $-\theta$ allows us to average over both arms of the polarimeter so that small differences between the two cancel out.

The geometry involved is shown in Fig. 4. Here L and R denote the number of counts registered in the two arms of the polarimeter with the spectrometer at θ or at $-\theta$, normalized to the same number of $B1B2$ coincidences. The asymmetry due to the polarization of the proton is then given by

$$\epsilon=([L(\theta)-R(\theta)]+[R(-\theta)-L(-\theta)])/([L(\theta)+R(\theta)]+[L(-\theta)+R(-\theta)]),$$

and the instrumental asymmetry is given by

$$\epsilon'=([L(\theta)-R(\theta)]-[R(-\theta)-L(-\theta)])/([L(\theta)+L(-\theta)]+[R(\theta)+R(-\theta)]).$$

This method of eliminating instrumental asymmetries was tested by measuring the polarization from elastic-electron scattering from hydrogen in a kinematical region where the polarization is expected to be

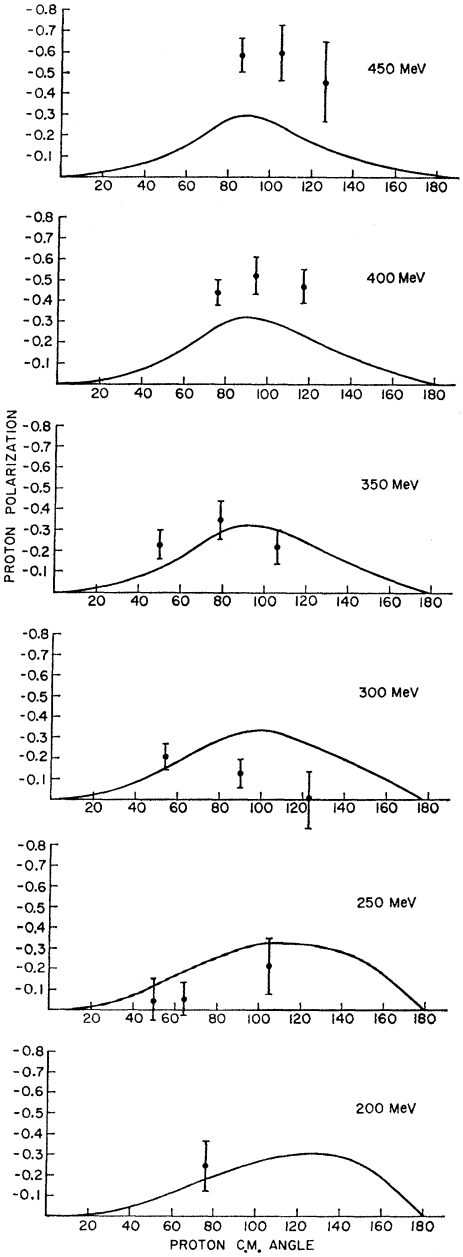

FIG. 5. The angular distribution of the polarization of the proton for different photon energies. The smooth curve is the predicted polarization from the isobar model.

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small. At 900 MeV and 10 F^{-2} an asymmetry of 0.007 ± 0.018 was measured.[18]

Empty-target runs were frequently made during the course of the experiment. The measured background was typically 2%. The asymmetry was corrected for the background assuming these protons were unpolarized.

With the apparatus set for protons the contaminations due to pions were measured. This was done by reversing the field in the spectrometer, thus accepting only negative pions. The negative pion background and hence π^+ backgrounds were found to be entirely negligible.

In Table II the measured asymmetry ϵ as well as the quantity ϵ' are listed after subtraction of the background. The small values of ϵ' indicate the system is working properly and no gross misalignment is present in the set-up.

The variation of proton illumination over the surface of the carbon scatterer due to the angular dependence of the photodisintegration cross section can give rise to an artificial asymmetry. This asymmetry does not cancel out by this method of data taking. However, folding the known[4] angular distribution with the spectrometer acceptance showed this effect to be negligible.

The statistical error in the asymmetry measurement can be written as

$$[\delta\epsilon]^2=[1-\epsilon^2]/[L(\theta)+R(\theta)+L(-\theta)+R(-\theta)].$$

A typical value of $\delta\epsilon$ is $\simeq 0.05$. Hence we believe that in this experiment the statistical errors are large compared with the systematic errors.

TABLE II. Measured asymmetry of the photoprotons.

Spectrometer momentum (MeV/c)	Electron energy (MeV)	θ_L (deg)	Measured asymmetry $\epsilon\pm\Delta\epsilon$	Artificial asymmetry $\epsilon'\pm\Delta\epsilon'$
455	240	32.5	$+0.099\pm0.034$	-0.162 ± 0.052
455	300	64.0	$+0.059\pm0.029$	-0.066 ± 0.029
455	350	90.0	$+0.041\pm0.028$	-0.002 ± 0.028
455	450	107.5	$+0.002\pm0.029$	-0.002 ± 0.029
540	340	35.0	$+0.004\pm0.029$	$+0.029\pm0.028$
546	325	40.0	$+0.016\pm0.052$	-0.016 ± 0.052
540	340	52.5	$+0.021\pm0.033$	-0.023 ± 0.033
540	425	74.0	$+0.054\pm0.031$	-0.012 ± 0.031
540	500	88.5	$+0.091\pm0.034$	-0.071 ± 0.034
540	580	99.0	$+0.172\pm0.034$	$+0.035\pm0.034$
540	600	107.5	$+0.191\pm0.079$	$+0.046\pm0.076$
630	370	42.5	$+0.116\pm0.034$	-0.063 ± 0.035
630	430	62.5	$+0.195\pm0.049$	$+0.013\pm0.051$
630	500	75.5	$+0.290\pm0.047$	-0.035 ± 0.048
630	550	85.0	$+0.328\pm0.072$	$+0.006\pm0.076$
684	410	38.5	$+0.154\pm0.046$	-0.111 ± 0.046
684	410	43.0	$+0.151\pm0.065$	-0.075 ± 0.065
684	500	59.5	$+0.292\pm0.040$	-0.116 ± 0.042
684	530	67.5	$+0.383\pm0.050$	$+0.003\pm0.053$

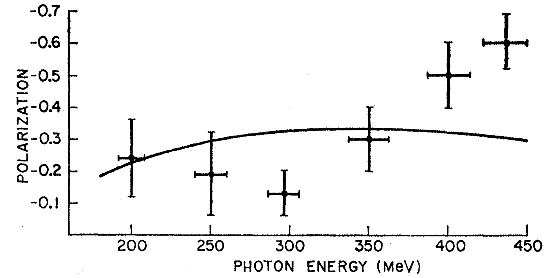

FIG. 6. Polarization of the proton at 90° c.m. as a function of photon energy. The smooth curve is the predicted polarization.

IV. EFFECTIVE ANALYZING POWER

To infer the polarization of the protons from the measured asymmetry the effective analyzing power of carbon A must be known. Since only the spin component normal to the scattering plane is being analyzed, the effective analyzing power A for a uniform flux of protons incident on the surface of the carbon analyzer can be written as

$$A=\sum_{i=1}^{9}\left[\int\int\int\frac{d\sigma(\delta,E)}{d\Omega}a(\delta,E)(\mathbf{S}\cdot\mathbf{n})d\Omega dE\right]_i\Bigg/\sum_{i=1}^{9}\left[\int\int\int\frac{d\sigma(\delta,E)}{d\Omega}d\Omega dE\right]_i. \quad (1)$$

In this expression, $d\sigma(\delta,E)/d\Omega$ is the differential scattering cross section for unpolarized protons by carbon, $a(\delta,E)$ is the carbon analyzing power for polarized protons as a function of angle δ and energy E. $\mathbf{S}$ is the proton unit spin vector upon leaving the spectrometer and $\mathbf{n}$ the unit vector normal to the plane defined by the incident and scattered directions of the proton. This definition of A together with the definition of ϵ corresponds to a positive polarization along the axis defined by $(\mathbf{k}\times\mathbf{q})$. To a good approximation $\mathbf{S}\cdot\mathbf{n}=\cos\rho$, where ρ is the total precession angle of the proton in the magnetic field of the spectrometer. This precession angle is given by $\rho=\theta_p(\frac{1}{2}g-1)\gamma$. Here θ_p is the total bend angle of the proton, $\frac{1}{2}g=2.79$, and γ the ratio of total energy to the rest energy of the proton. The summation in Eq. (1) extends over 9 typical rays. The experimental values[12–17] were used for $d\sigma(\delta,E)/d\Omega$ and $a(\delta,E)$. The range of integration of δ and Φ is given by the geometry of the counters; the range in E is determined by the energy loss of the protons in the carbon scatterer. This varied between 20 and 25.5 MeV. Since the range telescopes were set to include events up to about 10-MeV inelasticity, scattering from the first few excited states of carbon has to be included. Because of a lack of data this can only be done for the 4.4-MeV level; however, contributions from higher levels were estimated to be small for our conditions.

The computed values of A are listed in Table III together with the mean carbon thickness, the mean

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[18] R. Anderson, D. M. Ritson, and D. Lundquist (private communication).

TABLE III. Mean analyzing power of the proton polarimeter.

Spectrometer momentum (MeV/c)	Mean carbon thickness (g/cm^2)	Mean scattering angle α (deg)	Mean precession angle ρ (deg)	Mean analyzing power A
684	4.61	11	201	−0.659±0.020
630	4.61	11	196	−0.558±0.025
546	3.11	12	188	−0.461±0.017
540	3.11	11	188	−0.424±0.015
455	3.11	14	179	−0.220±0.013
		16		−0.245±0.015

TABLE IV. Results of present measurements.

Photon energy $K\pm\Delta K$ (MeV)	C.m. angle $\theta_{\mathrm{c.m.}}$ (deg)	Polarization $P\pm\Delta P$
172±13	39.2	−0.41±0.14
200± 7	76.0	−0.25±0.12
248± 8	104.9	−0.21±0.13
299±13	122.9	−0.01±0.13
228± 7	43.4	−0.01±0.07
237± 7	49.6	−0.04±0.11
249± 8	64.5	−0.05±0.08
296±10	89.8	−0.13±0.07
346±12	106.0	−0.22±0.08
401±15	117.4	−0.47±0.08
446±19	126.0	−0.45±0.19
305± 9	53.8	−0.21±0.06
355±11	78.5	−0.35±0.09
407±13	94.0	−0.52±0.09
460±16	105.0	−0.59±0.13
341±10	49.6	−0.23±0.07
352±10	55.4	−0.23±0.10
401±12	76.0	−0.44±0.06
436±14	86.0	−0.58±0.08

scattering angle as well as the angle of precession. The quoted error in A results mainly from the experimental error in $\sigma(\delta,E)$ and $a(\delta,E)$.

V. DISCUSSION

The results are presented in Table IV and plotted against the c.m. angle of the proton for different photon energies in Fig. 5. By interpolation in Fig. 5 the polarization at 90° c.m. as a function of photon energy can be inferred. This energy dependence is plotted in Fig. 6. The quoted error is the combined error of the asymmetry measurements and the error in the analyzing power. The previous measurement[10] gave a polarization of (−0.12±0.11) for a mean c.m. angle of the proton at 72° and an average photon energy of 290 MeV. This result agrees well with the present measurements.

The point at 172 MeV and 40° c.m. can be compared with computations of Breit *et al.*[1] The computed polarization is very small and positive as opposed to a measured polarization of (−0.40±0.14). Since all mesonic effects in this computation are neglected the disagreement is not surprising. Similar disagreements have been observed above 100 MeV in other experiments.[2,19]

A relativistic covariant computation of the deuteron photodisintegration including mesonic effects has been done by George.[20] The mesonic effects are taken into account by assuming that one of the nucleons gets excited to the N^* isobar and then decays by exchanging a pion with the nonresonating nucleon.[8] The parameters in the computation are taken from high energy pion disintegration experiments. His results are the solid lines in Figs. 5 and 6. There is reasonable agreement between the measured and computed values of the polarization up to a photon energy of about 350 MeV. However, above this energy the measured polarization increases with energy whereas the theoretical polarization decreases. This discrepancy may be due to the neglect of higher nucleon isobars as intermediate states.

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