Polarization of High-Energy Photoprotons from Light Elements*

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The polarizations of photoprotons from Li, Be, B, and C were measured by means of a counter polarimeter at proton production angles of 45°, 56°, and 90° in the laboratory system. The photon source was the bremsstrahlung from the Purdue synchrotron operating at a peak energy of 335 MeV. The observed protons had energies in the range 135 to 200 MeV. The left-right asymmetry of scattering of the photoprotons in a carbon analyzer was used to determine their polarization. The observed polarization was small and is consistent both with a zero value and with the theory. A qualitative discussion in terms of quasi-deuteron and isobar models is given.

I. INTRODUCTION

OBSERVATIONS of the photodisintegration of the deuteron can lead to an understanding of two important phenomena: the two-nucleon force and the interaction of electromagnetic quanta with nucleons. At low energies, theory and experiment are in good agreement, but for photon energies higher than about 20 MeV there has been considerable difficulty in constructing a theoretical description of the process which agrees well with measurements of total cross sections and angular distributions. In general, two approaches have been used to interpret the data. The first method involves a description in the angular momentum representation in terms of nucleon-nucleon phase shifts and matrix elements between angular momentum states. Below meson threshold this representation should be reasonably adequate except that it requires a knowledge of phase shifts that are not well determined at the higher energies in this range.

The second method involves the use of some specific nucleon-nucleon potential such as those proposed by Gammel and Thaler,[1] and Signell and Marshak.[2] Measurements of total cross sections, angular distributions, and outgoing nucleon polarizations can be used to test these potentials especially at higher energies where the reaction depends on the shape of the potential much more than at lower energies. As is pointed out by Rustgi *et al.*,[3] higher energies favor final states of higher angular momenta for the two outgoing nucleons making the tensor and spin-orbital parts of the potential more influential.

For the alternative phase-shift representation, high-energy photodisintegration data, particularly if it includes nucleon polarization measurements, can lead to information about high angular momenta phase shifts and matrix elements. In this region of interest (photon energies 50 to 175 MeV) there has been a fairly extensive investigation of angular distributions and total cross sections[3] but little work has been done experimentally to measure the polarizations of outgoing nucleons.[4]

It is for these reasons that an experimental program was started to measure the polarization of photoprotons from deuterium and other light elements. The experimental difficulties associated with such measurements are numerous. Most important is the fact that the most suitable polarization analyzing material is carbon which is only useful for protons with energies above 90 MeV. This limitation requires the use of photon energies above about 150 MeV which is above both π-meson threshold and the region in which recent theoretical studies have been made.[3,5] The prospects of a detailed meson theoretic interpretation being made soon are small but it was felt that if photon energies not too much above the meson threshold (perhaps up to 100 MeV) were used, meson effects could be ignored in terms of a qualitative comparison of theory and experiment.

Another practical difficulty in this kind of measurement is the low counting rates due to the need for double interaction processes; i.e., the proton has first to be produced by a photon and then has to be scattered into the detector by the carbon analyzer. The beam intensity of the Purdue electron synchrotron has recently been increased to the point where this kind of measurement is feasible with counter telescopes,[6] and a counter polarimeter was constructed to pursue a polarization measuring program.

Initially it was planned to measure photoprotons from deuterium and then do the same for some of the

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[1] J. Gammel and R. Thaler, Phys. Rev. **107**, 291 (1957).

[2] P. S. Signell and R. E. Marshak, Phys. Rev. **109**, 1229 (1958).

[3] M. L. Rustgi, W. Zernik, G. Breit, and D. J. Andrews, Phys. Rev. **120**, 1881 (1960). This paper also gives references to most of the recent experimental work on the photodisintegration of the deuteron.

[4] B. T. Feld, B. C. Maglić, and J. Parks, Suppl. Nuovo cimento **17**, No. 2, 241 (1960).

[5] W. Czyż and J. Sawicki, Phys. Rev. **110**, 900 (1958); M. Kawaguchi, *ibid.* **111**, 1314 (1958); J. J. de Swart and R. E. Marshak, *ibid.* **111**, 272 (1958); A. F. Nicholson, and G. E. Brown, Proc. Phys. Soc. (London) **73**, 221 (1959); J. J. de Swart, W. Czyż, and J. Sawicki, Phys. Rev. Letters **2**, 51 (1959); W. Zickendraht, D. J. Andrews, M. L. Rustgi, W. Zernik, A. J. Torruella, and G. Breit, Phys. Rev. **124**, 1538 (1961).

[6] Purdue Synchrotron Annual Progress Report, Atomic Energy Commission Contract AT(11-1)-123, June 30, 1961 (unpublished).

other light elements. The order of the measurements was reversed, however, when it became clear that (1) aligning a cryogenic target with the polarimeter axis with sufficient accuracy was quite difficult, and (2) the statistical and systematic accuracies of the deuterium measurement made with a carbon plate spark chamber would be much superior to those for a measurement with a counter polarimeter. Consequently, polarization measurements of photoprotons from lithium, beryllium, boron, and carbon were started and a spark chamber was built to carry out the deuterium measurements.

This paper reports the results of the first part of the program and the spark chamber measurement is currently under way. The measurements reported here are by no means definitive and their interpretation would be facilitated by having deuterium data for comparison. However, it is possible to make some qualitative comparisons with the theoretical predictions by leaning heavily on the quasi-deuteron model for photodisintegration which probably is legitimate.

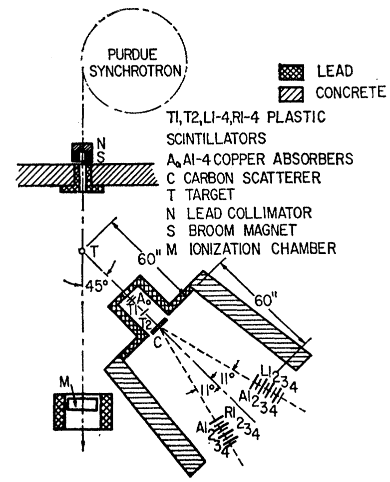

FIG. 1. The experimental layout.

II. EXPERIMENTAL ARRANGEMENT

The Purdue synchrotron was used to produce a gamma-ray beam with a peak bremsstrahlung energy of 335 MeV. All beam and collimation conditions were the same as those described in another paper.[7] The general experimental layout is shown in Fig. 1.

The polarimeter consisted of a defining counter telescope, two proton counter telescopes, and a carbon analyzer. The defining counter telescope employed two $\frac{1}{4}$-in.-thick plastic scintillators, subtending a solid angle of approximately 8.9×10^{-3} sr. The analyzer was a plate of carbon measuring 8 in.$\times$4 in.$\times\frac{1}{2}$ in. The proton counter telescopes were placed at a mean distance of 60 in. from the carbon plate. The axis of each of the proton counter telescopes made a mean angle of 11° with the axis of the defining counter telescope. Each of the proton counter telescopes consisted of four $\frac{1}{2}$-in.-thick plastic scintillators and four accompanying copper absorbers. The absorber thicknesses were chosen so that each of the energy intervals was approximately 20 MeV. The front counter in each telescope was 12 in. long and 3 in. wide and subsequent counters were larger to partially compensate for multiple scattering.

Conventional fast electronics was employed for the coincidence and anticoincidence circuits. The two counter telescopes had identical associated electronics. Attempts were made to match the corresponding left and right photomultipliers (DuMont 6292) in their gain and signal-to-noise ratio. Slight drifts in gain were compensated daily before each run by varying the high voltage to the photomultipliers. This compensation was usually very small. A ThC″ source placed at standard positions served as a calibrating standard for each channel.

[7] Y. S. Kim, F. F. Liu, F. J. Loeffler, and T. R. Palfrey, Phys. Rev. (to be published).

The method adopted in this experiment for proton identification involved a conventional, dE/dx-range measurement. Biases on all the counter discriminators were set by alternately moving the left and the right telescopes in line with the carbon scatterer and a carbon target. The front copper absorber eliminated all the low-energy electrons and deuterons and the main possibility for background came from π mesons. This absorber slowed down the protons but did not alter their polarization.

Optical alignment of the target with respect to the polarimeter axis was used. A sighting telescope was lined up with a plumb line hanging midway between the back counter telescopes and a fiducial line along the bottom edge of the carbon analyzer. A plumb line with bob was set up over the photon beam center, and adjusted so that the plumb line was lined up with the cross wire in the sighting telescope. The center of the target was then placed directly underneath the pointed bob. With this procedure, we felt that an uncertainty in the target position with respect to the axis of the polimeter was less than $\frac{1}{32}$ in. We also deliberately misplaced the target by as much as $\frac{1}{4}$ in. and measured the resultant asymmetries ϵ. Using these measured values the error introduced by the uncertainty in the target position was determined and combined with the other uncertainties.

The front transmission telescope was housed in a lead cave with an entrance for the protons. A 2-in. lead wall prevented any protons scattered in the front counter from reaching the back telescopes. The singles rates in the back counters were found to be essentially unchanged as expected when a 4-in.-thick lead block was placed behind the carbon analyzer thus stopping any protons from the target from reaching the back telescopes. We made use of this fact to measure the accidental rate between events in the front telescope and events in either one of the back telescopes. This rate was ordinarily less than 25% of the real rate. The rate for

counting scattered protons was typically 1 event per 3×10^{10} effective quanta or about $\frac{1}{3}$ event per minute.

III. ANALYSIS OF DATA

The different sources of error and uncertainty in this experiment are presented here. Corrections, where possible, were made in the final result. We may distinguish between two kinds of errors, the symmetric and the asymmetrical kind. Nuclear attenuation and multiple scattering in the target material would be expected to be symmetrical. No correction was made for these. The pion contamination was estimated to be less than 0.3%, so that it was neglected in the final result. The chance and the background events were subtracted out. This correction, which was a function of the photon beam intensity, was applied to each run. The chance rate came mainly from the high counting rates in the front defining counters.

The effects of the asymmetrical errors were more serious. These sources of error are discussed below in order of their relative importance to the final result. As mentioned earlier, the mechanical assembly of the polarimeter was done with sufficient care so that there was no important inherent physical asymmetry of the back telescopes with respect to the axis of the polarimeter. In calculating the effective analyzing power of the polarimeter, only the elastic scattering in carbon was taken into account. This was legitimate since in our energy range the inelastic scattering cross section is inappreciable for angles less than 20°. In the polarimeter the maximum angle of scattering was 17.5°.

The light collection in the front defining counters was checked and found to be symmetrical. Similarly, the counters in the back telescopes were checked. Errors due to electronics asymmetry were minimized by frequently interchanging the back telescopes. As in all polarization measurements of this kind, the alignment of the target with respect to the polarimeter must be done carefully in order to avoid false asymmetry in the measurement. Our alignment procedure was discussed earlier and our positional uncertainty introduced a false asymmetry of less than 2%.

The largest correction that we made was for the variation of the proton production differential cross section with angle. The photoprotons that came out of the target were peaked forward in the laboratory system, so that they did not illuminate all parts of the carbon analyzer with uniform intensity. This had the effect of increasing the number of protons scattered to the right side of the polarimeter axis. This effect was calculated in the mean production plane and was found to be approximately the same for all the four target materials in our angular range. The effect was to introduce a bias term of +4.5% in the polarization value for carbon, for example.

To compute the polarization of the photoprotons, we need to know the effective analyzing power of the polarimeter. It is well known that a beam of polarized protons will show an azimuthal scattering asymmetry in a suitable target, and this knowledge is often used to determine the degree of polarization of a beam of protons. The differential scattering cross section is given by[8]

$$I(\theta_s,T')=I_0(\theta_s,T')[1+P(\theta_p,T)A(\theta_s,T')\cos\phi],$$

where I_0 is the differential cross section for an unpolarized beam. The angles θ_s, θ_p, and ϕ are defined as follows:

$$\cos\theta_s=\hat{u}_2\cdot\hat{u}_1,\ \cos\theta_p=\hat{u}_1\cdot\hat{k},\ \cos\phi=(\hat{k}\times\hat{u}_1)\cdot(\hat{u}_1\times\hat{u}_2),$$

$\hat{k}$, $\hat{u}_1$, and $\hat{u}_2$ are the unit vectors along the directions of the photon, the outgoing proton, and the scattered proton, respectively. T' denotes the kinetic energy of the proton at the carbon analyzer and T the proton production energy. The number of protons per unit monitor response scattered into the left telescope by the carbon analyzer is given by

$$N_L=n_Tn_S\int_L dkd\Omega d\Omega' dT \times f(k)\frac{d^2\sigma}{d\Omega dT}(k,\theta_p,T)I_0(1+AP\cos\phi),$$

where the integral is over the appropriate energy interval of the protons, the geometric dimensions of the target, the analyzer and the detector. n_T is the number of target atoms per unit area, n_S is the number of atoms per unit area in the analyzer, $(d^2\sigma/d\Omega dT)(\theta_p,k,T)$ is the photoproduction cross section, and $f(k)dk$ is the number of photons with energy between k and $k+dk$ per unit monitor response. T and T' are related in that $T'=T-\Delta T_a$, where ΔT_a is the energy lost by the proton in traveling from the interior of the target to the center of the analyzer. A similar expression N_R gives the number of protons scattered to the right. The left-right asymmetry ϵ is given by

$$\epsilon=(N_L-N_R)/(N_L+N_R),$$

or

$$\epsilon=(d+PD)/(B+Pb).$$

The angular dependence of the photoproton production cross section $d\sigma/d\Omega$ does not factor from the above integration, and this term acts as a weighting factor favoring a negative value of ϵ. The term d is the difference term between the integration of the production term $(d\sigma/d\Omega)I_0$, on the left side and the right side of the polarimeter. Similarly, b denotes the difference term involving the azimuthal angle ϕ and the analyzing power P. These terms are a few percent of B and D, which involve a summation of the left and the right

[8] L. Wolfenstein, Ann. Rev. Nuclear Sci. 6, 43 (1956).

contributions. We may solve the expression for P

$$P=-\frac{d}{D}+\frac{\epsilon}{(D/B)}$$

Here we have neglected terms quadratic in $\epsilon(d/D)$. This leads to an error of about 0.045% in the polarization for the case of a carbon target. (D/B) was obtained by means of numerical integration with an IBM 7090 computer. Published data on the carbon analyzing power were used.[9] The value of the effective analyzing power (D/B) of the polarimeter for the conditions of this experiment varied between 20 and 30%.

IV. EXPERIMENTAL RESULTS

Although three proton energy bins were available with the counter telescopes, the number of events observed per bin was sufficiently small that it was fruitless to attempt to specify polarization as a function of energy. Also one suspects that the polarization is not strongly energy dependent. For these reasons the data from all bins were lumped together and a mean proton energy was specified. A concurrent measurement of the proton energy spectrum was made and so it was possible to determine this mean energy.[7]

Two values of energy had to be determined. First was the mean proton energy at production in the target material. This energy was degraded by the time the proton reached the center of the carbon analyzer and it was necessary also to determine the mean energy here in order that the correct value of the analyzing power of the polarimeter could be used.

The corrections mentioned in Sec. III were made to the data and the final results are shown in Table I. It is apparent, first of all, that most of the results are not inconsistent with a zero value for the polarization. Since the errors are large for all of the individual polarization values, it is interesting to see if the individual measurements can be combined in some suitable way to give a resultant polarization value with a smaller error than those for the individual values. This can be done if we postulate an identical photon absorption process for each kind of nucleus (namely, by a quasi-deuteron). If this is valid, we would expect the polarization results to be the same for each. With this in mind we combined

TABLE I. Polarization of high-energy photoprotons given in percent.

Element	Li^7	Be^9	B^{11}	C^{12}
Mean proton production energy	155 MeV	175 MeV	154 MeV	168 MeV
$\theta_p=45°$	$+7.3\pm15$	-12.9 ± 15	$+12.4\pm15$	$+24\pm15$
$\theta_p=56°$	-2.4 ± 15	-5.7 ± 15	$+7.5\pm15$	-11.8 ± 15
$\theta_p=90°$				-11.3 ± 15

[9] J. M. Dickson and D. C. Salter, Nuovo cimento **6**, 235 (1957).

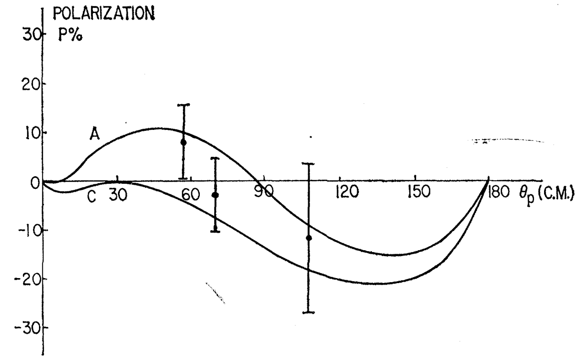

FIG. 2. Comparison of the experimental results with the predicted polarization.

the results for all four elements (by taking a weighted average) at the three angles of measurement and plotted them in Fig. 2. The point for 90° in the laboratory contains data from carbon only. The quoted errors include statistical uncertainties and the uncertainty in the target position. The sign convention is the same as that used by Rustgi *et al.*[3] A positive polarization corresponds to most of the proton spins oriented in the direction $\hat{k}\times\hat{u}_1$. Comparison with the theoretical curves will be made in the next section.

V. DISCUSSION OF RESULTS

The description of a photonuclear reaction is usually based on a model best suited to a particular photon energy range. A photon of energy 300 MeV has a wavelength of 4 F, so that in this energy range, nuclear subunits are of major importance in the description of the photoeffect. A quasi-deuteron subunit was first proposed by Levinger[10] in 1951, and by means of this model, he was able to explain several characteristic phenomena observed in the high-energy photoeffect.

Our data can probably be best interpreted in the light of this model. Inside a nucleus, the n-p pair differs from the free deuteron not only in having a positive energy but also in being able to be in a relative ${}^1S_0$ state. Therefore, we have to consider, in addition to the usual transitions from the ${}^3S_1$ deuteron state, the possible transitions ${}^1S_0\rightarrow{}^3S_1$ and ${}^1S_0\rightarrow{}^1P_1$. The contribution to the polarization due to the above two transitions was calculated in the manner of reference 3, using what we think are reasonable values of phase shifts, and the result is shown in Fig. 3. The solid curves shown in Fig. 2 are the results of the addition of the calculations of Rustgi *et al.*[3] on the proton polarization from the deuteron to the contribution from the ${}^1S_0$ quasi-deuteron state. The curves A and C are the same approximations indicated in reference 3. In approximation A, only $E1$ transitions are considered. We have not considered Rustgi's B approximation since tensor coupling of the final states, ${}^3P_2$ and ${}^3F_2$, does not affect the angular

[10] J. S. Levinger, Phys. Rev. **84**, 43 (1951).

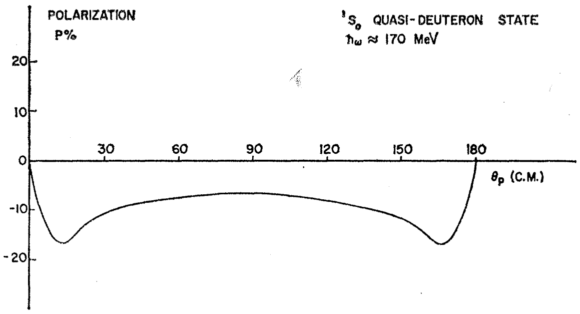

FIG. 3. The polarization from the $^1S_0$ state of the quasi-deuteron.

dependence to any great extent. In approximation C, the $M1$ transition from the $^3S_1$ state to the $^1S_0$ state is also taken into account, in addition to $E1$ transitions. They have considered $E2$ transitions too, but their effect is small.

In this experiment, the photon energy is high enough for pion production. Real pion production in processes like $\gamma+p\rightarrow\pi^0+p$; $\gamma+n\rightarrow\pi^-+p$ are excluded from observation by kinematics, the protons having too low an energy to be observed. Wilson[11] and Austern[12] attempted to take the virtual pion effect into account by assuming the formation of an isobaric nucleon as an intermediate process in the deuteron photodisintegration. This isobaric state is assumed to be a $J=\frac{3}{2}$, $T=\frac{3}{2}$ state, as suggested by π-p scattering experiments. If the isobaric nucleon and the other nucleon are in a relative S state, then as shown by Austern, the only final state of the two-nucleon system is $^1D_2$. Pure intermediate S state will, therefore, not give rise to any polarization phenomena in the mesonic processses. An admixture of P states will probably contribute negligibly to the polarization as they will favor real pion emission rather than photonucleon emission. At this energy, the isobaric nucleon state $J=\frac{3}{2}$, $T=\frac{1}{2}$ will be relatively unexcited. One possible contribution to the polarization could come from interference between this $^1D_2$ state, which arises from the virtual pion process, and other nonmesonic final states. We have not tried to estimate this contribution largely because of a lack of knowledge concerning the values of the appropriate phase shifts. It should be realized, however, that this interference could conceivably make an important contribution to the polarization.

In conclusion, we may say that our results are consistent both with a zero value for the polarization and also with the theory. Although the combined data from the four elements measured suggest a decrease in polarization with angle, as does the theory, it is not clear that such a decrease is statistically significant. Also more detailed comparison with the deuteron calculation is not warranted for reasons mentioned in the introduction. A comparison with the polarization values of protons from the deuteron will be more meaningful when those data become available.

ACKNOWLEDGMENT

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[11] R. R. Wilson, Phys. Rev. **86**, 125 (1952).
[12] N. Austern, Phys. Rev. **100**, 1522 (1955).