"width" for the extracted function of 450 MeV/c obtained by multiplying the usual width by the mass ratio $(E_k+M)/E_k$. On the other hand, the "width" of the wave-function part can be estimated by performing the $\mathbf{x}$ integrals for the special case of the asymptotic-deuteron wave function; the resulting function is

$$F(\mathbf{p}_B)=8\pi\alpha[\alpha^2+(\mathbf{p}_B+\tfrac{1}{2}\mathbf{m})^2]^{-1}[\alpha^2+(\mathbf{p}_B+\tfrac{1}{2}\mathbf{k})^2]^{-1} \quad (57)$$

whose "width" for backward scattering is 250 MeV/c, which is not very small compared to 450 MeV/c.

If this explanation of the backward-scattering discrepancy is valid it suggests that the pion-deuteron scattering amplitude depends critically on the pion-nucleon amplitudes for many values of the scattering parameters, most of which are off the energy shell. In that case a correct calculation of the pion-deuteron scattering amplitude awaits the development of methods adequate to handle the unphysical values of the pion-nucleon amplitudes.[26] Pion-deuteron scattering will then provide information about features of the pion-nucleon interaction not accessible to pion-nucleon scattering experiments as well as information about the deuteron wave function.

ACKNOWLEDGMENTS

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[26] Such methods are proposed by R. E. Cutkosky, in *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester*, edited by E. C. G. Sudershan, J. H. Tinlot, and A. C. Melissinos (Interscience Publishers, Inc., New York, 1960), pp. 236-243.

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Polarization of Protons from the High-Energy Photodisintegration of Deuterium*

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Photons with a mean energy of 294 MeV yielded photoprotons from a deuterium target at a mean angle of 58° in the laboratory. The protons were observed in a carbon-plate spark chamber and measurements of their elastic scattering in the carbon were used to determine the polarization components of the protons. The component parallel to the photodisintegration plane was found to be consistent with a value of zero within the statistical errors of the measurement as was expected. The component of polarization perpendicular to the photodisintegration plane was observed to be small and negative, and not inconsistent with a value of zero.

INTRODUCTION AND EXPERIMENTAL PROCEDURES

PROTONS from the photodisintegration of deuterium have been observed in a carbon-plate spark chamber. Measurements of elastic scattering in the carbon plates have been used to deduce their polarization in the direction perpendicular to the production plane defined by the photon propagation vector $\mathbf{K}_\gamma$ and the proton momentum $\mathbf{p}$. As is customary we define the polarization as positive if most of the protons have their spins in the direction $\mathbf{K}_\gamma\times\mathbf{p}$.

A 320-MeV bremsstrahlung beam from the Purdue synchrotron was used in conjunction with a 2-in.-diam liquid-deuterium target. The resultant protons from elastic photodisintegration processes were observed and identified at a mean-production angle of 58° in the lab (72° in the center-of-mass system) by a four scintillation counter telescope. This detector triggered the spark chamber when traversed by protons with production energies between 155 and 180 MeV in the lab. The mean proton energy at production was 165 MeV corresponding to a photon energy of 294 MeV. Protons from inelastic processes (i.e., pion production) were excluded by kinematic limits and the estimated pion contamination was less than 5%. The spark-chamber configuration as seen by a proton entering from the direction of the target was as follows: three thin aluminum plates, each $\frac{1}{16}$ in. thick; six carbon plates, each $\frac{1}{2}$ in. thick; three thin aluminum plates ($\frac{1}{16}$ in.); two carbon plates ($\frac{1}{2}$ in.); two thin aluminum plates ($\frac{1}{16}$ in.). The lateral dimensions of all plates were 8 in.×16 in. Figure 1 shows the experimental arrangement.

Approximately 75 000 photographs were taken using a 90° stereo, Fresnel mirror system, and at least 98% of these showed a single track coming from the target direction.

Scanning and measuring of these photographs were

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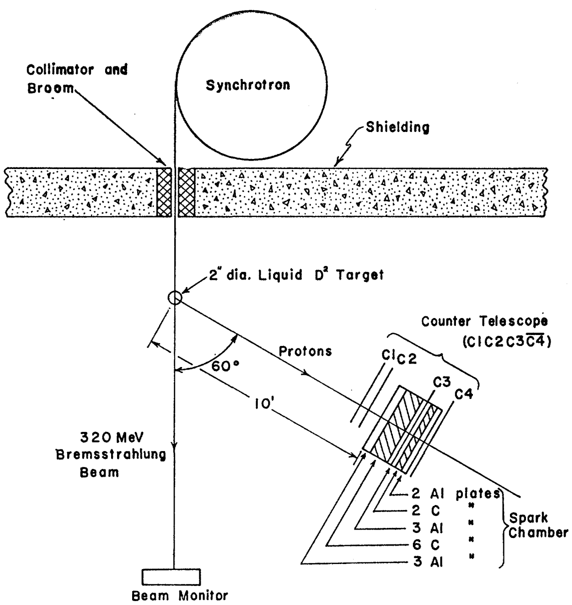

FIG. 1. Experimental arrangement.

done at the same time, the appropriate scattering coordinates being read from fiducial grids attached to two sides of the spark chamber. Tracks which showed a single scatter were measured by recording the four sets of coordinates in each of the two stereoscopic views which defined the two-track segments of the event. This information allowed the determination of the production energy (range measurement) and angle of the proton, extrapolation to insure that the proton originated in the target, calculation of the scattering angle θ_s of the proton and its energy at scattering, and the determination of the angle ϕ made by the normals to the scattering and production planes. The precision of the angular measurements was no worse than $\pm 0.5°$. Events that did not extrapolate to the target area were discarded. We accepted scattering angles between 7° and 20°. Angles smaller than about 7° correspond to small values of analyzing power for carbon and are also likely to originate from multiple scatters. At angles larger than 20° inelastic scattering becomes important. We required the proton energy at scattering to be larger than 50 MeV. A "fiducial volume" criterion was established by demanding that the mirror image of each accepted event (opposite but equal scattering angle) would also lie in a detectable region of the chamber.

The geometrical reconstruction of the events and the application of the above criteria were done using IBM-7090 computer programs. The events meeting the above conditions numbered 1481 and were used in the polarization analysis.

ANALYSIS OF DATA AND RESULTS

At this point two pieces of information were available concerning the orientation of each proton spin vector. One can define the quantities $p_{\perp i}$ and $p_{\parallel i}$ which for an event i, are the probabilities of the proton spin being oriented perpendicular to the photodisintegration plane and lying in this plane, respectively. These probabilities are related to the scattering quantities as follows:

$$p_{\perp i}=\frac{1+A_i\cos\phi_i}{2},\quad p_{\parallel i}=\frac{1+A_i\cos\phi_i'}{2},$$

where ϕ and ϕ' are the azimuthal angles of the scattering plane pertinent to the two components of polarization. A is the analyzing power of the carbon scatterer and depends on the scattering angle θ_s and the energy at scattering of the proton.[1] All these quantities were calculated for each event by the 7090 program.

In order to determine the average values of the two polarization components for N events a maximum likelihood calculation was done using the two likelihood functions,

$$L_\perp=\prod_{i=1}^{N}\left[\frac{1+P_\perp A_i\cos\phi_i}{2}\right],$$

$$L_\parallel=\prod_{i=1}^{N}\left[\frac{1+P_\parallel A_i\cos\phi_i'}{2}\right],$$

where $P_\perp$ and $P_\parallel$ are the maximum-likelihood estimators of the two polarization components.

A 7090 computer program was used to evaluate the logarithmic derivatives of these functions for various values of $P_\perp$ and $P_\parallel$. The results of these calculations are plotted in Fig. 2. The most probable values of $P_\perp$ and $P_\parallel$ correspond to maximum values of the likelihood functions which occur when the logarithmic derivatives become zero.

Several tests were applied to the data to determine their influence on the values of $P_\perp$ and $P_\parallel$. One might be concerned that what appeared to be small-angle single-scattering events were really due to multiple scattering. Since such a mistake would rapidly vanish

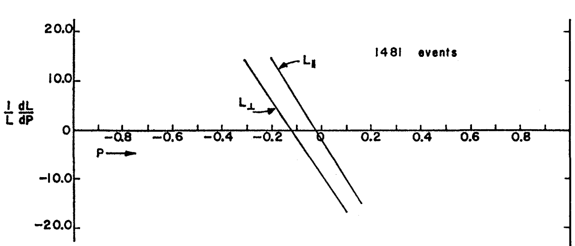

FIG. 2. Logarithmic derivative of the likelihood function versus polarization value for the two components of polarization of the proton spins, i.e. perpendicular and parallel to the plane of the photodisintegration.

[1] Values for the analyzing power of carbon were obtained from measurements reported in the following work: J. M. Dickson and D. C. Salter, Nuovo Cimento, **6**, 235 (1957); R. Alphonce, A. Johansson, and G. Tibell, Nucl. Phys., **3**, 185 (1957); W. G. Chestnut, E. M. Hafner, and A. Roberts, Phys. Rev. **104**, 449 (1956).

as the scattering angle became larger, we used several minimum angle cutoffs for θ_s up to 15° and found that $P_\perp$ and $P_{\parallel}$ were independent, within statistics, of the minimum scattering angle used. To test whether irregularities in sensitivity throughout the spark chamber might result in apparent scattering asymmetries, we divided the chamber into several regions and found that the events in each region led to the same values for $P_\perp$ and $P_{\parallel}$. Finally, the variations of the polarization values with minimum energy of the protons at scattering were investigated for several energy cutoffs above 50 MeV. No statistically significant variations were observed.

Pion contamination would influence the observed value of $P_\perp$ seriously if an appreciable fraction of the events were pion scatters. From energy-loss curves and discriminator-bias curves for our counter telescope we deduced that a conservative estimate for the pion contamination was 5% or less. Since the pion and proton scattering cross sections are roughly equal at the energies and angles pertinent to this measurement, the true polarization, $P_\perp'$ is related to the observed polarization, $P_\perp$ by: $P_\perp'=P_\perp(1+\delta)$, where δ is the ratio of the number of pions to the number of protons triggering the spark chamber. We have not made a correction for this effect because only an upper limit on δ is known ($\delta\leq 0.05$) and in any event the maximum correction would be smaller than our statistical uncertainty in $P_\perp$.

The results from the present measurement are given in Table I.[2] The error given for each polarization value is statistical in origin and in magnitude corresponds to one standard deviation.

[2] A measurement of the polarization of photoprotons from deuterium at angles and energies similar to the ones in this experiment has also been reported; Paul Gorenstein, David Luckey, and Louis Osborne, Bull. Am. Phys. Soc. **8**, 36 (1963). These results are in disagreement with the ones reported herein.

TABLE I. Polarization of protons from the photodisintegration of deuterons.

$\bar{E}_\gamma$ (lab) (MeV)	$\bar{\theta}_p$ (lab)	$\bar{\theta}_p$ (c.m.)	$P_{\parallel}$	$P_\perp$
294	58°	72°	−0.03±0.11	−0.12±0.11

DISCUSSION

Both components of the polarization are small and consistent with values of zero within the accuracy of the measurement. Since parity is conserved in the photodisintegration process, it can be shown that $P_{\parallel}$ must vanish and the small value we observe helps to reassure us that any biases leading to false asymmetries in our measurement technique are small. At the present time it is impossible to make a detailed comparison of our value of $P_\perp$ with any theoretical predictions. No complete meson-theoretic calculation for this process has been done up to this time. However the work of Rustgi *et al.*[3] for photon energies somewhat lower than the ones in this measurement indicates negative polarizations of about 0.15 at this center-of-mass angle for the proton. An estimate of the polarization based on a Wilson[4] type isobaric model suggests polarization magnitudes as high as 0.20.[5] Probably the most interesting region to explore next is the backward-production hemisphere where, unfortunately, the energy of the photo-protons falls off to inconveniently low values for polarization analysis in carbon scatterers.

[3] M. L. Rustgi, W. Zernik, G. Breit, and D. J. Andrews, Phys. Rev. **120**, 1881 (1960); W. Zickendraht, D. J. Andrews, M. L. Rustgi, W. Zernik, A. J. Torruella, and G. Breit, Phys. Rev. **124**, 1538 (1961).

[4] R. R. Wilson, Phys. Rev. **86**, 125 (1952).

[5] A. Tubis (private communication).