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Elastic Scattering of Protons by Polarized ^{3}He†

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Protons from 3.8 to 10.9 MeV have been elastically scattered from a ^{3}He target polarized by optical pumping. The left-right scattering asymmetries are reported, and construction of the target cell and optical pumping apparatus is discussed.

I. INTRODUCTION

STUDIES of the structure of mass-four nuclei have become increasingly numerous and detailed.[1] One aspect of these studies is the information regarding the ^{4}Li system which can be obtained by observations of the elastic scattering of protons by ^{3}He. The present experiment[2] was undertaken to determine whether existing phase-shift descriptions[3] of this process, which were based on differential cross section and proton polarization data in the 0- to 12-MeV energy range, would be adequate to describe asymmetries in the scattering of protons by polarized ^{3}He. The results of subsequent attempts[4,5] to obtain precise phase shifts incorporating more extensive proton polarization data[6] and, later, the data reported here, indicate that further experiments[7] employing polarized ^{3}He and polarized or unpolarized protons are needed to specify the phase shifts to within a few degrees.

The left-right asymmetry of the scattering of unpolarized protons by polarized ^{3}He was measured at laboratory angles of 45° and 90°. This gives the same information as a measurement of the ^{3}He polarization following the scattering of an unpolarized beam by an unpolarized target,[8] and hereafter we shall use the notation $\mathcal{P}_3$ to refer either to the polarization of the ^{3}He after the collision in an unpolarized beam-unpolarized target experiment or to the scattering asymmetry of initially unpolarized protons which would be observed if the ^{3}He target were completely polarized.

II. POLARIZED ^{3}He TARGET

A. Apparatus

The ^{3}He target nuclei were polarized by the technique of optical pumping.[9,10] In this process ^{3}He atoms in the metastable 2^3S_1 state are produced by a weak discharge in ^{3}He gas at a few Torr. Circularly polarized resonance radiation (2^3P-2^3S) polarizes the metastable atoms and they, in turn, polarize the much more numerous ground-state atoms through metastability exchange collisions.

The experimental arrangement is illustrated schematically in Fig. 1. The optical pumping apparatus was mounted on a beam collimation assembly at the end of one of the beam tubes of the Bonner Laboratory tandem accelerator. The orientation was such that scattering in the plane perpendicular to the direction of target polarization could be observed.

The optical pumping light was provided by a lamp of the design reported in Ref. 10. The lamp oscillator design is similar to that of Salomaa.[11] The ^{4}He gas excited by the lamp oscillator was contained in a quartz (or high-temperature glass) button-shaped cavity of approximate inside dimensions: 25 mm diameter and 4 mm thickness. This volume was connected to a reservoir volume so that the loss of pressure due to diffusion through the hot quartz was not too rapid. A jet of compressed air was used to cool the lamp envelope. A ^{4}He pressure of 10 to 20 Torr in the lamp was chosen because it produced the largest amount of 1.08-μ light for the optical pumping process. A single concave mirror was used to reflect the ^{4}He light toward the optical pumping cell since this arrangement appeared to be as satisfactory as more complicated optical systems using lenses. One difficulty encountered involved occasional variation in light level of the lamp produced by changes in the magnetic field applied to the region of the optical

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† Work supported by the U.S. Atomic Energy Commission.

[1] W. E. Meyerhof and T. A. Tombrello, Nucl. Phys. **A109**, 1 (1968).

[2] Preliminary reports of this work were made by S. D. Baker *et al.*, Bull. Am. Phys. Soc. **12**, 86 (1967), and by D. H. McSherry *et al.*, *ibid.* **12**, 189 (1967).

[3] T. A. Tombrello, Phys. Rev. **138**, B40 (1965).

[4] W. Haeberli and L. W. Morrow, in Symposium on Light Nuclei, Few Body Problems and Nuclear Forces, Brela, Yugoslavia, 1967 (to be published).

[5] L. Drigo and G. Pisent, Nuovo Cimento **51B**, 419 (1967).

[6] L. W. Morrow, Ph.D. thesis, University of Wisconsin, 1967 (unpublished); L. W. Morrow and W. Haeberli, Nucl. Phys. (to be published).

[7] D. H. McSherry, S. D. Baker, R. Plattner, T. B. Clegg, Nucl. Phys. (to be published).

[8] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).

[9] F. D. Colegrove, L. D. Schearer, and G. K. Walters, Phys. Rev. **132**, 2561 (1963). This and the following reference contain much practical information on how to produce polarized ^{3}He by optical pumping.

[10] R. L. Gamblin and T. R. Carver, Phys. Rev. **138**, A946 (1965).

[11] M. K. Salomaa, Nucl. Instr. Methods **15**, 113 (1962).

pumping cell. It was found, however, that minor adjustments of the geometry of the apparatus reduced this effect to tolerable levels.

The circular polarization of the light was produced by a linear polarizer and quarter wave plate[12] combination in which the linear polarizer could be rotated with respect to the quarter wave plate to change the sense of the circular polarization.[13] The linear polarizer was cooled by a jet of air to keep it below 80°C, above which it rapidly deteriorates. A second lamp and circular polarizer combination may be placed on the other side of the cell to double the pumping light.

The weak discharge in the ^{3}He cell was excited by placing electrodes outside the cell and driving them with a high-impedance rf oscillator at about 500 kHz.

The light transmitted through the optical pumping cell was detected by a PbS infrared detector[14] whose resistance was monitored by a simple dc bridge circuit feeding into a chart recorder.

A uniform magnetic field of several gauss was set up along the optical axis in the region of the cell by means of a Helmholtz pair, 66 cm in diameter. This coil eliminated excessive magnetic field gradients which shorten the spin relaxation time of the ^{3}He, and hence the attainable polarization.[15] It was also necessary to avoid using magnetic materials in the apparatus since these may cause field gradients large enough to reduce the polarization appreciably. The current through the coil, and hence the magnetic field, could be smoothly reversed to provide an adiabatic rotation of the ^{3}He spin direction.

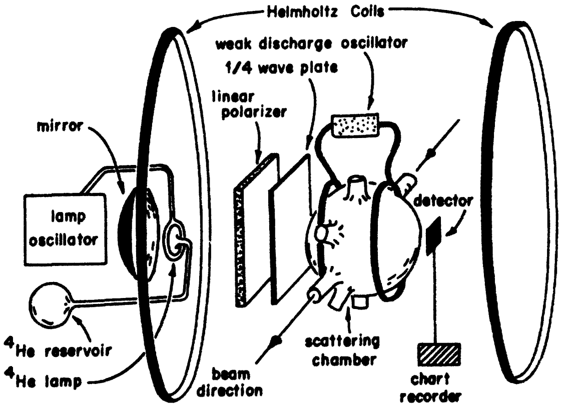

FIG. 1. Schematic view of optical pumping apparatus. Target polarization is perpendicular to beam direction.

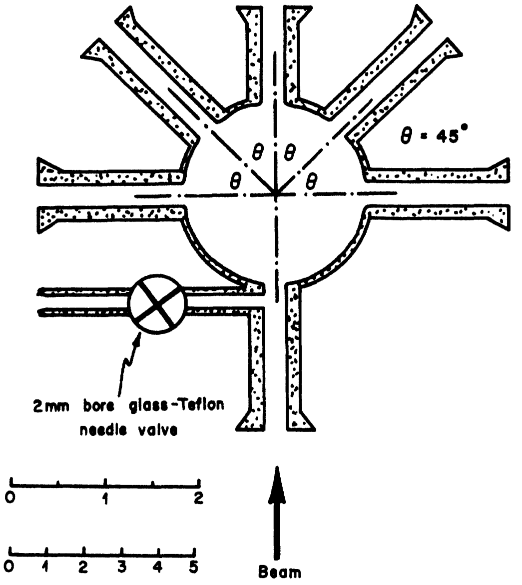

FIG. 2. Section through glass work of optical pumping cell.

The optical pumping cell consisted of a 5-cm-diam spherical glass bulb with flanged glass tubes.[16] Mounted on the ends of the tubes were foils to allow the entrance and exit of the beam and to allow observation of the scattered particles. Figure 2 shows a section through the glass work. Aluminum foils 9 μ thick were mounted by simply clamping them against a flat gasket made of indium wire pressed onto the end of the glass tube. Figure 3 shows such an arrangement which also allows for the mounting of a particle detector.[17] For the cell used in this study, a Teflon-glass needle valve was used to isolate the cell when it was removed from its filling system and allowed it to be conveniently refilled when that became necessary. Later cells have been constructed with ordinary high vacuum stopcocks lubricated with low vapor pressure silicone grease and give satisfactory results.

The procedure followed to clean the cells is essentially the same as that described in Ref. 9. A bright discharge in the center part of the cell was maintained using microwave power.[18] Discharges in the glass arms and at the surfaces of the foil windows were excited by means of a high-voltage Tesla coil of the kind used to find leaks in glass vacuum systems. The progress of the cleanup was monitored by observing the optical spectrum of the bright discharge with a low resolution spectroscope. After the cell was sufficiently clean, it was

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[12] Type HR linear polarizer, 280-mμ optical retarder, obtained from the Polaroid Corporation, Rochester, N.Y.

[13] A convenient way of determining the absolute sense of the circular polarization of the light is by comparing its sense with that of a reference beam of elliptically polarized light produced by the reflection of linearly polarized light at an oblique angle from a metal surface.

[14] Infrared Industries, Waltham, Mass.

[15] L. D. Schearer and G. K. Walters, Phys. Rev. 139, A1398 (1965).

[16] Sentinel brand glass pipe.

[17] An improved design for use with more fragile foils is reported by D. M. Hardy (private communication) and consists primarily of mounting the foils in aluminum frames which can be vacuum tested and then mounted, in the frame, on the glass pipe.

[18] Conveniently supplied with a Raytheon Model CMD5 diathermy generator.

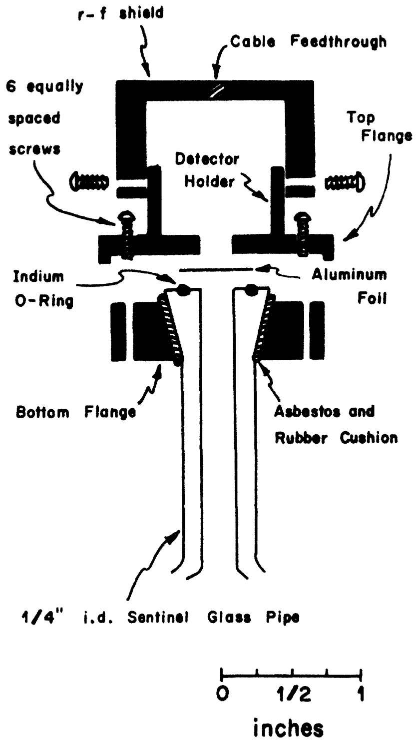

FIG. 3. Construction of foil windows on optical pumping cell.

filled with ^{3}He to about 4 Torr with ^{3}He gas which had just been passed through a trap cooled to liquid-helium temperatures. In spite of care in vacuum testing the foil windows and in cleaning up the cell, tiny leaks and/or continual outgassing ordinarily produce enough impurities within several days to a few weeks to substantially reduce the polarization.

B. Determination of Target Polarization

The target polarization was determined by optical measurements in the manner described by Colegrove *et al.*[9] It should be noted that the formulas of Colegrove *et al.* or of Greenhow[19] are idealized cases in which the transition probabilities are accurately known, the spectrum of the pumping light is accurately known, and the light is assumed to be completely circularly polarized and parallel to the z axis. One can examine the effects of all but the parallelism of the light by writing an equation for the light absorbed by the ^{3}He metastable atoms, similar to that of Colegrove *et al.* or that of Schearer.[20] Here ρ is equal to the ratio of the intensities in the pumping light of the circularly polarized component of the wrong sense to the total pumping light, and f is equal to the ratio of the intensity of the pumping light which induces $m_F=\frac{3}{2}$ to $m_F=\frac{1}{2}$ transitions to the total pumping light intensity $(2^3P_0-2^3S_1)$:

$$I(P)=\frac{n}{6+2P^2}\{af[(1-P)^3+\rho P(6+2P^2)]$$
$$+[bf+c(1-f)](1-P)(1+P)[1+P(2\rho-1)]\}, \quad (1)$$

where a, b, and c are transition probabilities, P is the polarization, and n is a constant of proportionality which depends on the density of metastable atoms.

The method of adiabatically rotating the magnetic field allows the optical measurement to be made without destroying the polarization. The optical signals from which the polarization may be determined are $\delta I(P)=I(P)-I(-P)$, observed during the field reversal, and $I(P)$, observed by switching off the discharge in the cell. For each value of the ratio $\delta I/I$ a value for the polarization P can then be found in terms of the quantities a, b, c, f, and ρ.

The transition probabilities a, b, and c have been calculated by Colegrove *et al.*[9] and Schearer.[20] The value of ρ is determined from measured characteristics of the circular polarizer. The value of f, however, can conceivably range from 0.5 to 1.0 depending on the width of the 1.08-μ ^{4}He optical pumping line and various references give values of 0.5, 0.6, 0.84, and 1.0.[21]

In obtaining the data reported here, measurements of $\delta I(P)$ and $I(P)$ were made prior to each change in polarization or magnetic field direction. Each determination consisted of switching on and off the weak discharge twice and reversing the magnetic field four times, giving four values of $I(P)$ and four values of $\delta I(P)$. The measurement process, which takes about 10 sec, destroys some of the polarization, and a correction is made for this loss. The effect of the magnetic field direction on the output of the lamp also had to be taken into account. The light from the weak discharge in the optical pumping cell was measured and provided a negligible correction to the measurement of $I(P)$. Within the accuracy of the optical determinations, the ratio $\delta I/I$ did not vary over the time during which the data were taken. We have, therefore, taken the value of this ratio to be the mean of the individual determinations and its error to be the standard deviation about the mean plus an estimate of the error in determining the correction for the polarization lost in the measurement process.

The ratio $\delta I/I$ thus obtained was 0.453 ± 0.025. Assuming the values of a, b, and c as given in Ref. 9 and $\rho=0.02\pm0.02$, for $f=1.0$ the polarization was 0.079 ± 0.004 and for $f=0.5$ the polarization was 0.1065 ± 0.005. We will quote the polarization as 0.093 ± 0.005, the mean value between these two limits,

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[19] R. C. Greenhow, Phys. Rev. **136**, A660 (1964).

[20] L. D. Schearer, Ph.D. thesis, Rice University, 1965 (unpublished).

[21] Colegrove *et al.* (Ref. 9) assumed $f=0.5$ in their treatment. Greenhow (Ref. 19) asserted, however, that $f=1.0$. Later Schearer (Ref. 20) found $f=0.6$ using an optical pumping technique at 77°K. More recently Rohrer *et al.*, Helv. Phys. Acta **41**, 436 (1968), report a value of $f=0.84$.

including in the error only the random error in $\delta I/I$ measurement, the error in ρ and the error in determining correction for polarization loss. It should be remembered, therefore, that the target polarization and therefore all the values of $\mathcal{P}_3$ may be multiplied by a single factor between 0.85 and 1.15.

III. PROTON ASYMMETRIES

Data were taken at nine energies between 3.8 and 10.9 MeV over a period of several days. Beam currents in the cell were typically 1 μA. A substantial part of this energy range was swept through twice and the reproducibility was satisfactory within the experimental errors discussed below. These data also agree with another data set, taken several weeks earlier, whose statistical errors were so large, however, as to have a negligible effect on the final results.

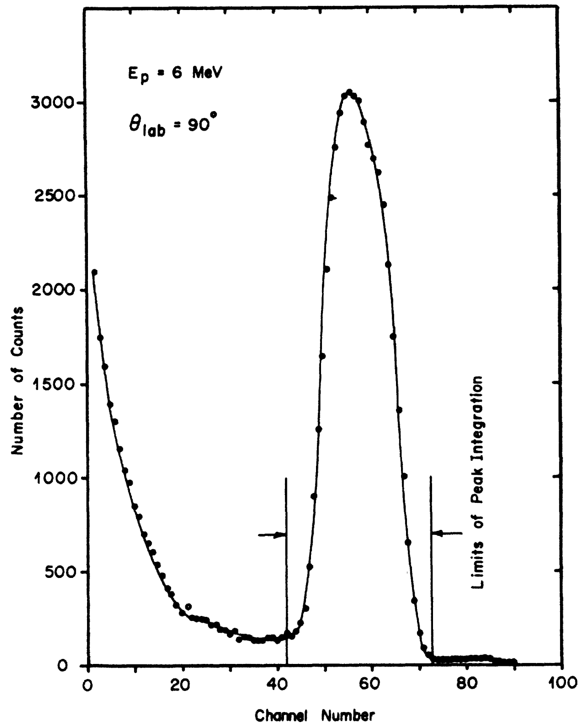

FIG. 4. Pulse height spectrum for scattering at 90° in the lab at incident proton energy of 6 MeV. Solid lines indicate the limits of peak integration.

Protons scattered by the ^{3}He target gas emerged from the optical pumping cell and were detected with silicon surface barrier detectors. Pulses from the pairs of detectors at 45° and 90° were fed into a multichannel analyzer which is set up so that the dead time is the same for all four spectra, insuring that the number of counts in each detector relative to the others is unaffected by dead time in the electronics. A typical pulse-height spectrum is shown in Fig. 4. Experiments with no gas in the target indicated that the "background" at channels immediately below the peak in the spectrum was due to scattering from ^{3}He and is presumably due to very small angle scattering from the walls of the glass exit tube. These experiments also indicated that background not due to scattering from ^{3}He was in all cases less than 0.1% of the elastic scattering events. Therefore, no background subtraction has been made and the spectrum is simply summed over the region of the peak between limits such as those shown in Fig. 4.

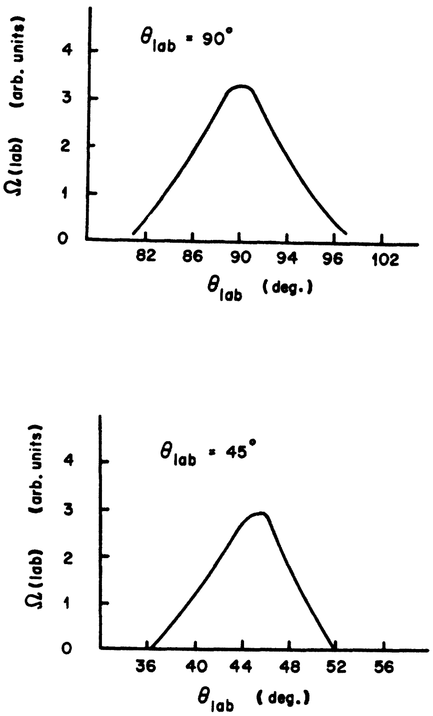

FIG 5. Solid angle versus laboratory scattering angle for the two angles of the scattering chamber.

TABLE I. Characteristics defining the data counts $N_1 \cdots N_8$ used in determining left-right scattering asymmetries (see text for explanation of symbols).

	Target polarization	Magnetic field
$N_1 = I_1\Omega_L M_{UL}\sigma_0(1+P_3^{(1)}\mathcal{P}_3^{(L)})$	Up	Up
$N_2 = I_1\Omega_R M_{UR}\sigma_0(1-P_3^{(1)}\mathcal{P}_3^{(R)})$		
$N_3 = I_2\Omega_L M_{DL}\sigma_0(1-P_3^{(2)}\mathcal{P}_3^{(L)})$	Down	Down
$N_4 = I_2\Omega_R M_{DR}\sigma_0(1+P_3^{(2)}\mathcal{P}_3^{(R)})$		
$N_5 = I_3\Omega_L M_{DL}\sigma_0(1+P_3^{(3)}\mathcal{P}_3^{(L)})$	Up	Down
$N_6 = I_3\Omega_R M_{DR}\sigma_0(1-P_3^{(3)}\mathcal{P}_3^{(R)})$		
$N_7 = I_4\Omega_L M_{UL}\sigma_0(1-P_3^{(4)}\mathcal{P}_3^{(L)})$	Down	Up
$N_8 = I_4\Omega_R M_{UR}\sigma_0(1+P_3^{(4)}\mathcal{P}_3^{(R)})$		

TABLE II. $\mathcal{P}_3$ data for center-of-mass scattering angles of 58° and 110° and incident proton energies listed. Errors do not include the possible systematic error in target polarization corresponding to different values of f which could cause the values of $\mathcal{P}_3$ and their errors to be multiplied by a single factor between 0.85 and 1.15 (see text).

Energy (MeV)	$\theta_{\mathrm{cm}}=58°$	$\theta_{\mathrm{cm}}=110°$
3.80±0.03	0.040±0.015	0.113±0.031
4.35±0.05	0.023±0.015	0.104±0.033
4.85±0.05	0.002±0.015	0.121±0.024
5.85±0.05	−0.008±0.015	0.144±0.020
6.90±0.05	−0.078±0.015	0.124±0.020
7.90±0.05	−0.056±0.015	0.112±0.020
8.90±0.05	−0.082±0.015	0.068±0.028
9.90±0.05	−0.078±0.015	0.082±0.030
10.90±0.05	−0.024±0.015	0.054±0.043

The glass exit tubes for the scattered protons were mounted at laboratory angles of (45.0±0.5)° and (90.0±0.5)° with respect to the axis of the target cell. The central ray of the beam made angles of no more than 1.5° with respect to the axis of the cell. The results of a rough calculation of the angular acceptance of the detectors at the two scattering angles are given in Fig. 5. The function $\Omega(\theta_{\mathrm{lab}})$ plotted there is proportional to the effective solid angle subtended by the detector as a function of the laboratory scattering angle. This angular acceptance is large enough so that it should be taken into account when making detailed comparisons of calculated values of proton asymmetries with those observed in this experiment. However, it is sufficient for rough comparisons to say that the angular acceptance functions in the center-of-mass system are approximately Gaussian with mean values of 58° and 109° and full widths at half maximum of 13° and 10°, corresponding, respectively, to the nominal laboratory angles of 45° and 90°.

To measure the left-right scattering asymmetries at a given energy, data were collected during four counting intervals, each one corresponding to a different combination of target polarization (up or down) and magnetic field direction (up or down).[22] During each counting interval, approximately the same amount of beam charge entered the cell. Neglecting statistical errors and instabilities in the apparatus, there are eight numbers of counts obtained[23] for each angle and energy (see Table I). The I's are the beam integrations for the four counting intervals; Ω_L and Ω_R are the effective solid angles for the left and right detectors, respectively; the M's allow for some unspecified effect on the counting rates in the left and right detectors due to the magnetic field direction, e.g., a small shift in particle trajectories; σ_0 is the unpolarized cross section; $P_3^{(i)}=P_3(1+\delta_i)$, $i=1$, 4, are the four values of target polarization during the four counting periods, where $(\delta_1+\delta_2+\delta_3+\delta_4)=0$; and $\mathcal{P}_3^{(L)}=\mathcal{P}_3(1+\gamma)$ and $\mathcal{P}_3^{(R)}=\mathcal{P}_3(1-\gamma)$ are the values of the analyzing power for left and right scattering, respectively, which allows for the possibility, for example, that the mean scattering angle is not quite the same for the left and right detectors. We now compute the quantity

$$R=N_1N_4N_5N_8/N_2N_3N_6N_7$$
$$=\left[\frac{1+P_3\mathcal{P}_3}{1-P_3\mathcal{P}_3}\right]^4\left[1+\text{second- and higher-order terms in } \mathcal{P}_3\gamma \text{ and } P_3\delta\right]. \tag{2}$$

In this experiment we can safely assume that the δ_i and γ are small enough to give a negligible error. In this case,

$$P_3\mathcal{P}_3=(R^{1/4}-1)/(R^{1/4}+1). \tag{3}$$

As an internal check on the data the quantity

$$R_0=N_1N_3N_6N_8/N_2N_4N_5N_7 \tag{4}$$

may also be computed, which, under the same conditions, should give a value of zero for

$$P_3\mathcal{P}_0=(R_0^{1/4}-1)/(R_0^{1/4}+1). \tag{5}$$

Values of $P_3\mathcal{P}_3$ and $P_3\mathcal{P}_0$ were calculated at each energy and angle. At 90° the values of $P_3\mathcal{P}_0$ were consistent with zero within counting statistics, and the errors assigned to $P_3\mathcal{P}_3$ at 90° are therefore taken simply as the standard deviations expected from counting statistics. At 45°, however, the fluctuation of $P_3\mathcal{P}_0$ about zero, although apparently random, was very much larger than could be expected from counting statistics alone. The possible explanation for this is that the errors due to counting statistics were much smaller than those at 90°, thus permitting the observation of the effects of beam wander, which might be expected to be more pronounced at 45°. The magnitude of the fluctuation of $P_3\mathcal{P}_0$, rather than counting statistics, appeared to be a better measure of the over-all stability of the measurements of $P_3\mathcal{P}_3$ at 45°, and the error used for these points is therefore the standard deviation of the values of $P_3\mathcal{P}_0$ about zero.

The values of $P_3\mathcal{P}_3$, obtained from the proton asymmetry data, were divided by the value of P_3, obtained from the optical measurement of the target polarization, and the resulting values of $\mathcal{P}_3$ are given in Table II. The errors quoted were obtained by folding the error in P_3, obtained in Sec. II B, with the error in $P_3\mathcal{P}_3$ discussed in the preceding paragraph. These errors are

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[22] In reality, the field and polarization were horizontal and the scattering took place in a vertical plane as shown in Fig. 1. However, we will here use the more familiar nomenclature of most polarization experiments in which the scattering is observed in a horizontal plane.

[23] This treatment is similar to that described by R. C. Hannah, in *Proceedings of the International Conference on Polarization Pheonomena of Nucleons, Karlsruhe, 1965*, edited by P. Huber and H. Schopper (W. Rosch and Co., Bern, 1966), p. 280.

meant to represent standard deviations in the measurement and do *not* include the possible systematic error in the optical measurement corresponding to different values of f which could cause the values of $\mathcal{P}_3$ and their errors to be multiplied by a single factor between 0.85 and 1.15 as discussed previously.

The errors quoted in the incident proton energies arise from an estimate of the accuracy of the accelerator calibration and the determination of the energy loss in the entrance foil of the target.

Phase-shift searches incorporating these data have been presented by Haeberli and Morrow[6] and need not be described here. It is sufficient to say that these authors have found that two different families of phase shifts, the one found by them and the one found by Tombrello,[3] can be adjusted to include these data.

A subsequent experiment[7] has allowed a more precise specification of the phase shifts in the neighborhood of 9-MeV proton energy and the results of further phase-shift analyses are presented with the report of that work.

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Proton-Proton Bremsstrahlung at $E_p = 10$ MeV[*]

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A measurement of the proton-proton bremsstrahlung cross section at $E_p = 10$ MeV has been made. Two silicon surface-barrier detectors were placed in a hydrogen gas target at 30° on opposite sides of the beam axis. The energies of the two final-state protons and their time-of-flight difference were measured. E_1-E_2 spectra corresponding to events in the true and accidental regions of the time spectrum were obtained in off-line analysis. An upper limit of 0.42 μb/sr^2 has been established for the proton-proton bremsstrahlung cross section at $E_p = 10$ MeV, $\theta = 30°$.

INTRODUCTION

CONSIDERABLE effort has been spent recently in the calculation[1–5] and measurement[6–11] of the nucleon-nucleon bremsstrahlung cross section over an energy range of 10–200 MeV. It was hoped, at the beginning of this period of activity, that the off-energy shell behavior of the nucleon-nucleon bremsstrahlung process might lead to the determination of an unambiguous model of the nucleon-nucleon potential. However, several potentials predict quite closely the bremsstrahlung cross section over the energy range. Probably the best fits to data have been obtained by Pearce *et al.*[3] using the Tabakin nonlocal, separable potential, and by Brown[4] using the Bryan-Scott one-boson-exchange potential. A comparably good fit has been obtained by Brown with the Hamada-Johnston potential. Finally, Signell[5] and Nyman[12] have shown that the potential model-dependent contribution to the proton-proton bremsstrahlung cross section is small compared to the model-independent part.

By far the largest amount of work has been done on the proton-proton bremsstrahlung (PPB hereafter), although the neutron-proton process has received some attention.[3,7] All of the PPB data, except for one case,[13] have been at an incident energy above 20 MeV. Complete calculations have not been extended below 20 MeV since some of the approximations used for the higher energy calculations are no longer valid. It is

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