Small-Angle Proton-Proton Polarization and Cross Section at 213 MeV*

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This experiment was a simultaneous measurement of the proton-proton cross section and polarization for the angular range 8.9°–38.7° c.m. at 213±6 MeV. An experimental normalization of the cross section of ±1.3% accuracy was obtained. The results agree with the predictions of the latest phase-shift analyses except for $\theta_{\mathrm{c.m.}} \lesssim 15°$.

INTRODUCTION

THIS experiment was performed to extend previous measurements of the proton-proton cross section[1] and polarization[2,3] at 213 MeV to the small-angle region. Accurate measurements of these quantities at this energy were confined to the angular region 30°–90° c.m. Another objective of this measurement was to improve the accuracy of the experimental normalization of the cross section.

The ensemble of proton-proton measurements at about 213 MeV has now served to determine a unique set of phase shifts at this energy.[4,5] The results indicate, however, that some attempts to improve the data would be justified.

In the modified phase-shift searches, the total nuclear part of the nucleon-nucleon interaction in all higher angular momentum states beyond a certain $L_{\max}$ is given in closed form by the one-pion-exchange potential, which is characterized by the pion-nucleon coupling constant g^2. The value of g^2 deduced from the modified phase-shift analysis at 213 MeV is somewhat lower than that obtained from pion-nucleon scattering ($g^2 \approx 15$).[5] MacGregor and Arndt attribute this result to destructive two-pion-exchange contributions in the higher angular momentum states which are therefore not correctly represented by the one-pion-exchange amplitude. Improvement of the data should make it possible to release more of the higher angular momentum phases and thus to determine the effects of two-pion exchange.

Another problem which appears to warrant investigation is that the exact relativistic form of the Coulomb interaction is not known. It seems likely that the measurement of the cross section and polarization in the Coulomb interference region will give an indication of the accuracy of the approximate amplitude which is used in the phase-shift analyses. Although the shapes in the Coulomb interference region of the cross-section and polarization curves which are predicted from a given set of phase shifts depend fairly sensitively upon the relativistic corrections, the results of the present experiment are not sufficiently accurate to determine them. It can be hoped that some usable information on this problem can be obtained from these results together with those at nearby energies. Rose[6] has recently summarized the experimental results on *p-p* scattering in the medium-energy range.

EXPERIMENTAL METHOD

Production of the external polarized proton beam at the Rochester 3.3-m synchrocyclotron has been described elsewhere.[7] By means of a carefully constructed collimator which consisted of a series of circular tantalum-lined apertures, a well-defined beam of mean energy 215±2 MeV was produced. The energy spread of the beam was about 10 MeV full width at half-maximum (FWHM) and the polarization was determined to be 90±2%. The beam was cylindrically symmetrical and less than 1 cm in diameter at the target. The divergence of the beam was less than $\pm\frac{1}{4}°$. The average energy of the beam was determined from the mean range in copper of 44.0±0.6 g cm^{-2}.[8] By means of a time-of-flight measurement it was established that the energy spectrum of the beam was nearly symmetrical about the mean energy and that less than 0.2% of the total intensity had an energy less than 190 MeV. Because of the energy loss in the target cup, the mean energy of scattering was 213±2 MeV.

The incident-beam polarization was measured by detecting the protons scattered from carbon in the horizontal plane to left and right of the beam axis (see Fig. 1). Copper absorbers were used to give thresholds of 150 and 185 MeV for measurements at 10° and 14° lab. It was assumed that *p*-C inelastic scattering could be neglected, and this was supported by agreement of the beam polarization deduced from the four combinations of angle and threshold. The incident-beam

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[4] P. Signell, N. R. Yoder, and J. E. Matos, Phys. Rev. **135**, B1128 (1964).

[5] M. H. MacGregor and R. A. Arndt, Phys. Rev. **139**, B362 (1965).

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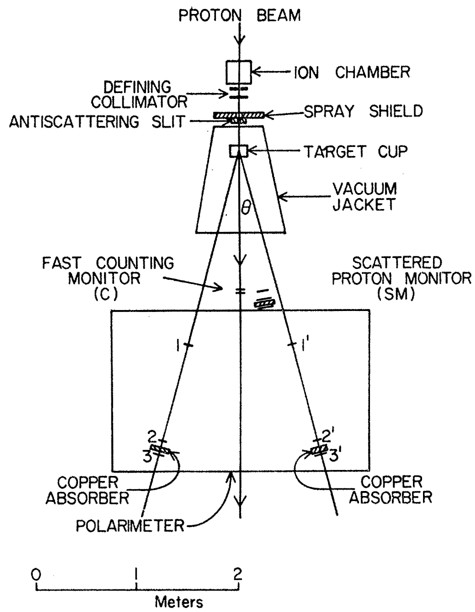

FIG. 1. Experimental layout for measurement of the proton-proton cross section and polarization. The scattering telescopes are 123 and 1′2′3′. The solid angle is defined by 2 and 2′, while 3 and 3′ are dE/dx counters.

polarization was then calculated using previous measurements of the p-C elastic polarization.[9]

For the proton-proton data, the protons scattered to left and right of the beam axis by the liquid-hydrogen target were detected by triple coincidence counters which were rigidly mounted on a rotating frame or polarimeter. The polarimeter was used to eliminate certain experimental asymmetries such as inaccuracy in setting the included angle between the counters and inhomogeneities in the target or counters, by exchanging the counters on one side of the beam axis with those on the other periodically. The uncertainty of the alignment of the polarimeter axis was less than 2 min relative to the mean beam direction with each point on the axis within 0.05 cm of the true beam centroid. The detectors were plastic scintillators viewed through Lucite light pipes by RCA 6810A photomultiplier tubes. The dimensions of the defining counters were 2.5 cm×8.9 cm×0.6 cm for the small-angle counters (for $\theta \leqslant 20°$ c.m.) and for the counters used at larger angles, 3.8 cm×12.7 cm ×0.6 cm. The solid angles subtended by the two counters were then 2.33 msr and 4.65 msr in the c.m. system at 30°. For setting the various angles, the defining counters were moved on radii of circles so that the laboratory solid angle was constant. The telescopes were designed with the first and third counters sufficiently larger than the second or defining counter that outscattering effects were minimized. Calculations for multiple scattering effects in the target cup, target vessel, counters, and air were made on the basis of cross-section data at 208 MeV.[10]

An experimental check was made for spurious scattering effects in the first counter by making it thicker with extra pieces of plastic. It was found experimentally that the scattering resulted in 0.6%±0.5% loss versus a calculated loss of 0.5% based on the assumption that only large-angle nuclear scattering was significant.

The coincidences were of the standard type, except that the third counter of each telescope was used as a dE/dx counter as shown in Fig. 1. The output of the third counter was fed into a 400-channel pulse-height analyzer after being gated by the 123 coincidence and stretched. The energy resolution obtained was sufficiently good to distinguish the hydrogen-scattered protons from the bulk of the background which was produced by scattering in the collimator. The efficiency of the counters was assured by frequently checking that the voltage settings of all counters were on 100-V plateaus.

A triple monitor system was used. First an ionization chamber (IC) was used as a relative monitor of the incident proton flux. The ion chamber was filled with an argon-CO_2 mixture and was placed before the target as shown in Fig. 1. An absolute measure of the beam intensity was obtained with a fast double coincidence scintillation counter (C) which intercepted all the protons which were not scattered beyond 2° lab. The third monitor (SM) was a large triple coincidence counter which was placed slightly below the median plane at an angle of about 10° lab. This scattered-proton monitor served to indicate whether the target was full or empty as well as to give a measure of the incident-beam intensity. The measurement of the C-monitor counting losses was performed by means of the ionization chamber. It was separately established that the proportionality of the integrated ion chamber response to the total proton flux was independent of the counting

TABLE I. The cross-section and polarization results and total errors. The normalization is experimental but the errors are relative only. The cross-section over-all normalization is 1.000±0.013 and for the polarization the over-all normalization is 1.000±0.025.

$\theta_{\text{c.m.}}$ (deg)	σ (mb/sr)	P
8.9	4.86±0.12	0.061±0.035
9.8	4.12±0.10	0.120±0.027
10.4	3.67±0.09	0.133±0.019
12.2	3.49±0.06	0.173±0.013
13.2	3.47±0.07	0.215±0.015
14.8	3.50±0.04	0.218±0.012
17.2	3.55±0.06	0.255±0.012
18.5	3.59±0.04	0.269±0.020
19.4	3.55±0.04	0.255±0.010
21.7	3.77±0.06	0.299±0.015
24.2	3.72±0.03	0.277±0.011
29.0	3.76±0.03	0.321±0.010
38.7	3.67±0.05	0.340±0.006

[9] W. G. Chesnut, E. M. Hafner, and A. Roberts, Phys. Rev. **104**, 449 (1956).

[10] H. G. de Carvalho, Phys. Rev. **96**, 398 (1954).

TABLE II. Typical corrections and their errors for the cross section and polarization at two angles. The cross-section corrections and errors are for the normalization factor as well as the relative cross section. The polarization errors are relative only.

	Multiplicative cross-section corrections		Additive polarization corrections	
	10.4° c.m.	29.0° c.m.	10.4° c.m.	29.0° c.m.
Statistics	1.000±0.020	1.000±0.008	0.000±0.021	0.000±0.015
Absorber	1.150±0.008	1.009±0.002	0.000±0.021	0.000±0.015
Helium background	1.036±0.002	1.018±0.001	0.000±0.000	0.000±0.000
Geometry	0.995±0.001	1.000±0.000	0.003±0.000	0.011±0.000
Monitor calibration	1.000±0.005	1.000±0.005	0.002±0.000	0.000±0.000
Misalignment	1.006±0.004	1.000±0.005	0.000±0.005	0.000±0.001
Multiple scattering	1.006±0.008	1.006±0.002	0.000±0.000	0.000±0.000
Target thickness	1.005±0.010	1.005±0.010	0.000±0.000	0.000±0.000
Target-detector distance	1.000±0.004	1.000±0.004	0.000±0.000	0.000±0.000
Short-term monitor	1.000±0.008	1.000±0.003	0.000±0.001	0.000±0.001
Background subtraction	1.000±0.003	1.000±0.000	0.000±0.000	0.000±0.000
Area of counter	1.000±0.004	1.000±0.004	0.000±0.000	0.000±0.000

rate. The actual dead time of the C monitor was estimated to be 10 nsec. The duty cycle of the cyclotron was about 1%. The counting-loss corrections were determined from the average measured intensity during the data runs.

The data were taken in two principal runs. Target thicknesses of 0.46 and 0.69 g cm^{-2} were used in the two runs. The target cup, as seen in Fig. 1, resembled a thick lens in cross section. The walls were of 50-μ Mylar. The volume of the target could be accurately determined for purposes of the normalization of the cross section. The target cup was filled and emptied remotely during the runs by expelling the liquid with helium gas. Corrections were made in the data to account for the presence of the helium gas at 20°K in the cup, using the measurements of Gotow[11] for the cross section and polarization of p-He scattering at this energy. This procedure was checked by taking background with the target cup filled with helium gas at room temperature. The scattered protons emerged from the target vacuum vessel through windows of 250-μ Mylar.

During the data runs, data were accumulated at two angles simultaneously. The monitor counts were recorded together with the data. The polarimeter was rotated from side to side and the target cup was filled and emptied frequently in systematic but independent cycles. The angular settings were shifted often so that data were taken at each angle in at least two discrete sets during each run.

In order to reduce the background of low-energy protons, it was found necessary to use copper absorbers in the counter telescopes between the second and third counters, as shown in Fig. 1. The amount of absorber used varied from 1.4 g cm^{-2} at the largest angle to 24.0 g cm^{-2} at the smallest one. The background-to-effect ratios varied from 0.1 at 29° to 1.0 at 9.8° c.m. Experimental correction factors to the cross-section data for nuclear interactions in the Cu absorber were determined by placing the counter telescopes in the direct beam which had been spread out by multiple Coulomb scattering in a 4 g cm^{-2} lead plate. At low beam, the ratio of 12 coincidence counts to those for the 123 coincidence gave the absorber correction directly. The results were checked by overlapping the angular ranges of different absorbers during the data runs and by calculations on the basis of published cross sections for nucleon-Cu scattering.

[11] K. Gotow, thesis, University of Rochester, 1958 (unpublished).

There was an appreciable neutron flux in the experimental area which was produced by protons which were stopped in the shielding and collimator. An experimental check was made for neutron conversion in the liquid-hydrogen target by blocking the beam at the last collimator with a lead brick. It was established that any neutron-associated effects contributed less than 0.1% to the cross section.

RESULTS

The results for the polarization and cross-section measurements are listed in Table I together with the total relative errors. The normalizations are experimental. The standard deviations of the absolute measurements are ±1.3% for the cross section and ±2.5% for the polarization.

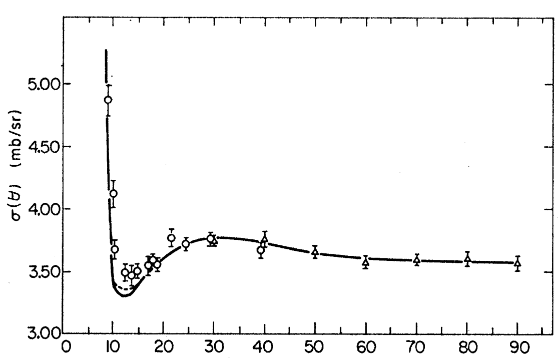

FIG. 2. p-p cross section at 213 MeV. The triangles represent the data of Ref. 1, which have been renormalized by a factor 0.986 from the tabulation of Ref. 4. The open circles are for the present measurement. The indicated errors are relative only and the overall normalization is experimental by 1.000±0.013. The smooth curve is the phase-shift prediction of Ref. 4 renormalized by a factor 1.008.

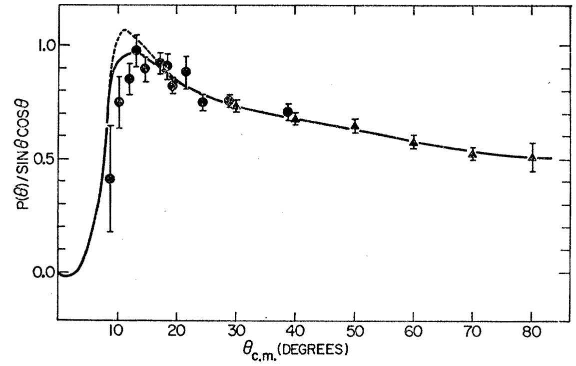

FIG. 3. p-p polarization at about 213 MeV. The results of the present experiment are represented by closed circles. The indicated errors are relative only. The normalization is experimental by 1.000±0.025. The results of Ref. 2, which are represented by triangles, have been renormalized by 1.02 to account for the difference in the energies of the measurements. The smooth curve is the phase-shift prediction of Ref. 4 and has been renormalized by a factor 1.035.

In Table II are listed the typical corrections and errors for the polarization and cross section. Both the relative and normalization errors and corrections have been included in the tabulation for the cross section. The polarization errors do not include the error of the determination of the incident-beam polarization.

Both the polarization and cross-section data were corrected for geometrical effects. (The total spread in scattering angle was about ±0.7° c.m.) This angle was obtained by summing quadratically the spread in incident angle, the rms multiple Coulomb scattering angle, and the divergence associated with the finite size of beam, target, and detectors. Because of the vertical extent of the defining counter, the polarization must be corrected by a factor $\langle\cos\phi\rangle^{-1}$, where $\langle\cos\phi\rangle$ is the average of $\cos\phi$ over the counter surface.

The error of the He background correction was the statistical error of the experimental measurement of the scattering by the "empty" cup. The most important part of the cross-section misalignment error was the inaccuracy of setting the distance from target to detector. The most significant nonstatistical error in the polarization was the uncertainty of the alignment of the axis of the polarimeter in the plane of scattering.

CONCLUSIONS

The p-p small-angle cross-section results of this experiment are shown in Fig. 2 and the polarization results are shown in Fig. 3. Also shown are the phase-shift predictions of Signell, Yoder, and Matos[4] and large-angle data from previous experiments.[1,2] (The phase shifts obtained by MacGregor and Ardnt[5] are essentially the same.) The polarization has been plotted as $P(\theta)/\sin\theta\cos\theta$ to emphasize the Coulomb interference effects. The dashed line was derived by Signell, Yoder, and Matos[4] by first obtaining the phase shifts using the ordinary form of the Coulomb amplitudes and then recalculating with the relativistic Garren amplitude.[12]

As they are shown in Figs. 2 and 3, the cross-section predictions of Ref. 4 have been renormalized by a factor 1.008 and the polarization predictions by a factor 1.035 to agree with the results of this experiment for the angles 20° c.m. and greater. Since the absolute cross-section normalization is quite sensitive to the $^3P_1$phase shift, this cross-section renormalization can be produced by a change of +0.35 in the $^3P_1$ phase shift. There is also a difference of 2% between the polarization normalization obtained in this experiment and that obtained by Tinlot and Warner.[2] However, the earlier measurement was performed at a nominal energy of 210 MeV, while the present one was at 213 MeV. An examination of the measurements of maximum polarization at different energies[13] leads to the expectation that the normalization of the 213-MeV polarization data would be about (2±1)% higher. Accordingly, the data of Ref. 2 have been renormalized by a factor 1.02 in Fig. 3.

As they are shown in Fig. 2, the cross-section data of Ref. 1 have been renormalized by a factor 0.986, to join them smoothly with the present data. The normalization of the earlier data was based upon an interpolation of $\sigma(90°)$ between results at nearby energies. This normalization is discussed by Signell *et al.*[4] Since this procedure is less accurate than our experimental normalization and depends on measurements done at other energies, the data of Ref. 1 are considered as being relative only.

It is clear that the inclusion of results in a phase-shift search will result in some changes of the phase shifts since somewhat weaker interference effects are indicated by the data at the smallest angles. A calculation of the polarization and cross section in which some of the phase shifts were varied by one standard deviation showed that the shape in the small-angle region of the relative cross section and polarization was rather sensitive to the H waves (among others) which have not been very well determined yet.

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[13] R. Wilson, *The Nucleon-Nucleon Interaction, Experimental and Phenomenological Aspects* (Interscience Publishers, Inc., New York, 1963), p. 82.