Measurement of the Triple Scattering Parameter R' at 213 MeV*

KAZUO GOTOW AND FREDERICK LOBKOWICZ
Department of Physics and Astronomy, University of Rochester, Rochester, New York
(Received 27 July 1964)

In a continuation of the study of the nucleon-nucleon interaction, a combination of the triple scattering parameters R and R' in proton-proton scattering at 213 MeV was measured in the angular range 30–90° c.m. By using an earlier measurement of R, values of R' have been obtained. The data are compared to predictions given by the Hamada-Johnston potential model and by a modified phase-shift analysis using all previously measured data.

I. INTRODUCTION

THE experiment reported here was performed as a continuation of an effort to determine to maximum precision the scattering matrix for p-p scattering at an energy of 213 MeV. Similar experiments have been performed at other energies.[1]

In this experiment we have measured the triple scattering parameter R'. If a proton beam with initial polarization P_1 is scattered off a hydrogen target T_2 in the plane defined by the incident proton momentum and the initial polarization vector (Fig. 1), then in the scattering plane the scattered beam will have a transversal polarization RP_1 and a longitudinal polarization $R'P_1$. After the scattered beam passes through a bending magnet, where the proton momentum is changed by an angle φ, the final transversal polarization in the scattering plane will be

$$P_f = P_1(R\cos\chi - R'\sin\chi), \quad (1)$$

where

$$\chi = (\mu_p - 1)(1-\beta^2)^{-1/2}\varphi. \quad (2)$$

Here $\mu_p = 2.793$ is the proton magnetic moment in nuclear magnetons, and β is the ratio of proton velocity to the light velocity.[2]

Ideally, one would like $\chi = 90°$ in order to measure R'. However, in this experiment a bending angle φ of 29° was chosen because of physical limitation. This corresponded to a precession angle χ of 57° for protons scattered at 90° c.m.

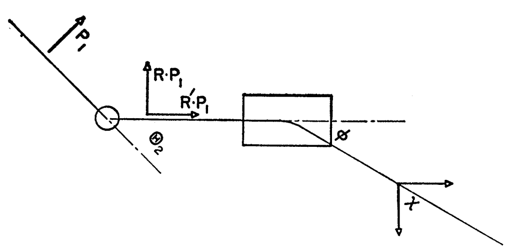

FIG. 1. Definition of measured parameters. The scattering and bending planes are identical.

* Supported by the U. S. Atomic Energy Commission.

[1] R. Wilson, *The Nucleon-Nucleon Interaction* (Interscience Publishers Inc., New York, 1963), especially pp. 73–93, where further references can be found.

[2] V. Bargmann, L. Michel, and V. L. Telegdi, Phys. Rev. Letters **2**, 435 (1959).

The transversal polarization of the twice-scattered beam was measured by scattering off a carbon target T_3. Two telescopes, each consisting of three counters, measured the left-right asymmetry. Their positions could be interchanged. The so-measured asymmetry was then related to the parameter R' by

$$P_f P_3 = P_1 P_3 (R\cos\chi - R'\sin\chi) = P_1 P_3 F. \quad (3)$$

Here P_3 is the analyzing power of the third scattering. The coefficient P_1P_3 was determined from a separate calibration experiment.

II. ALIGNMENT PROCEDURE

The polarized proton beam of the Rochester synchrocyclotron had a mean energy of 215 MeV with an energy spread of ±8 MeV rms. The mean proton energy at the center of the hydrogen target was 213 MeV. The beam was 91% polarized; however, the absolute value of the initial polarization did not enter the measurement, as seen from Eq. (3). Details of the beam density distribution as used in the measurements at 30–60° c.m. can be found in Ref. 3. For the larger angles, the energy-position correlation in the beam was eliminated by using two slits, one inside the cyclotron fringing field, and the other before the wedge magnet.

Protons scattered from hydrogen (Fig. 2) through a laboratory angle $\theta_2^{\rm lab}$ upward passed through a slit (21) into the spin-precession magnet. A counter (22) at the exit of the magnet and counter (23) defined the direction of the protons after bending. Protons scattered off a carbon target T_3 through an angle of 9–14° were registered by the two counter telescopes 3a and 3b.

The spin-precession magnet was equipped with crosshairs marking the desired entrance and exit of the scattered proton beam. At each angle, the magnet was aligned optically to within ½ mm horizontally and 1 mm vertically to the desired scattering angle. The polarimeter was first aligned optically so that protons bent by 29° would enter its center. After the magnet current was set to the desired value, horizontal and vertical profiles were swept at the exit of the spin-precession magnet and near the entrance to the polarimeter. These profiles were taken in coincidence with a counter situ-

[3] K. Gotow, F. Lobkowicz, and E. Heer, Phys. Rev. **127**, 2206 (1962).

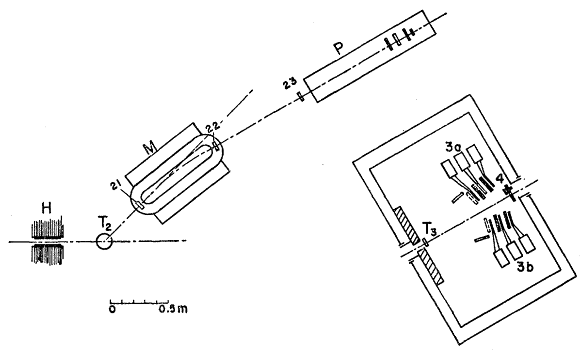

FIG. 2. Experimental arrangement. H, wedge magnet; T_2, hydrogen target; M, spin-precession magnet; P, polarimeter; T_3, carbon target; 21, 22, 23, defining counters for the twice-scattered beam; 3a, 3b, asymmetry-measuring telescopes; 4, profile-sweeping telescopes.

ated immediately behind the polarimeter entrance slit thus simulating the carbon target. Unless those profiles were well centered with respect to the magnet exit and the polarimeter entrance, the polarimeter front was slightly shifted, until the agreement was good to $\frac{1}{2}$ mm. The typical horizontal shift of the polarimeter front required to achieve this alignment was about 2–3 mm.

After the polarimeter front had been aligned, vertical and horizontal profiles were swept at the back of the polarimeter and the polarimeter back then aligned to the centroid of the proton beam to within 1 mm vertically and $\frac{1}{2}$ mm horizontally. The horizontal alignment defines the zero angle of the third scattering and is the most critical one due to the rapid variation of the differential scattering cross section for carbon with scattering angle. A more detailed evaluation of this effect and the accuracy required can be found in Ref. 3. Here we just mention that with the achieved accuracy of alignment the error due to this effect was typically $\frac{1}{5}$–$\frac{1}{3}$ of the statistical error.

In addition to this alignment procedure, which was repeated at all angles, at 30, 60, and 90° c.m. a vertical profile of all protons accepted by the polarimeter was taken at the entrance to the spin-precession magnet. This was done in order to check if the optical alignment of the magnet entrance was sufficient to determine the scattering angle (and thus also the bending angle) to the desired accuracy. The centroids of these vertical profiles always agreed with the optical center to within the measuring accuracy of $\frac{1}{2}$ mm. This corresponds to an error in the mean second scattering angle of ± 5 min of arc.

The angular acceptance of the polarimeter in the vertical plane corresponds to a second scattering angle opening of $\pm 2°$ in the laboratory system. The energy spread of the scattered beam due to this angular opening was checked by taking range curves at each scattering angle. The agreement was excellent.

For the asymmetry measurement, absorbers were placed between the counters of the a and b telescopes so that essentially all hydrogen-scattered protons could be counted if scattered elastically from the carbon target. Inelastic scattering from the carbon target was largely suppressed.

III. DETERMINATION OF P_1P_3

To determine this parameter, the polarimeter was set into the polarized proton beam. The proton beam was degraded to the desired energy by inserting lead degraders at the position usually occupied by the hydrogen target. The magnet was replaced by a "mock-magnet," an iron slit with its dimensions identical to the magnet pole pieces. During an early calibration measurement, it was noted that the asymmetry was very strongly dependent on the exact positioning of the iron slit. This was found to be due to small-angle scattering off the mock-magnet faces. To eliminate this effect, the mock-magnet opening was narrowed down by a brass slit. This slit was designed so that protons scattered off the pole faces had to scatter at least once more before reaching the polarimeter. After this slit was installed, the mock-magnet front or back could be misaligned by up to 3 mm without any measurable effect on the asymmetry in the carbon scattering. Any larger misalignment, however, again drastically changed the asymmetry. Since a misalignment of this amount was just sufficient for the polarimeter entrance to see part of the mock-magnet faces, it was felt that with the usually achieved accuracy of alignment of 0.5 mm any effect due to scattering off the magnet faces could be safely neglected. The so obtained values of P_1P_3,

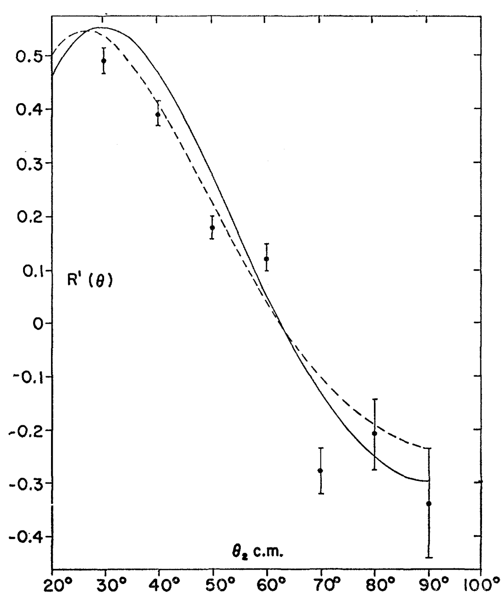

FIG. 3. Comparison of the results of $R'(\theta)$ at 210 MeV with predictions. The solid line is the prediction of the Hamada-Johnston potential model (Ref. 5); the dashed line gives the result of a modified phase shift analysis (Ref. 6) which uses all the previous Rochester data, but not the measurement of F.

agreed always within statistics with values obtained earlier with the same equipment.[3] As a result of this experience, a similar slit was installed in the spin-precession magnet used in the actual measurement.

IV. DATA AND EVALUATION

At each angle, after the equipment had been aligned, asymmetries were taken with hydrogen target full and empty and with carbon target in and out. The background subtraction was done in a conventional way. Random background was found to be negligible. The data at each angle were subdivided into several cycles and a statistical compatibility check was performed among all cycles at one angle. At all angles except 90° the variations between individual cycles were in good agreement with the counting statistics. At 90° c.m., where 5 cycles were taken, the root-mean-square deviation from the mean was twice the statistical error of each cycle. This was realized during the taking of the asymmetries and the electronic equipment checked frequently. While some random fluctuation may have been present, it was almost certainly not due to a faulty electronics system. 75% of the χ^2 contribution is due to two of the five cycles; omitting these two changes the value of F by less than 25% of its statistical error. It is therefore felt that the quoted purely statistical error is realistic. For P_1P_3 the calibration values were taken directly without any correction, since the carbon target and absorbers used in measurement and calibration were identical and the proton ranges were equal to within the experimental accuracy of 0.01 in. of copper.

V. RESULTS

The results are summarized in Table I. Since the values quoted for R' involve a contribution from the

TABLE I. Measured values of the parameter $F(\theta_2,\chi)=R\cos\chi-R'\sin\chi$.

θ_2 c.m.	χ	$F\pm\Delta F$	$R\pm\Delta R$ [a]	$R'\pm\Delta R'$
30°	−61° 13′	0.331±0.021	−0.203±0.012	0.491±0.025
40°	−61° 08′	0.277±0.019	−0.133±0.017	0.390±0.024
50°	−61° 04′	0.135±0.017	−0.041±0.018	0.177±0.022
60°	+60° 30′	−0.070±0.018	0.071±0.026	0.120±0.025
70°	+59° 12′	0.313±0.036	0.147±0.029	−0.277±0.045
80°	+58° 09′	0.307±0.053	0.248±0.042	−0.208±0.068
90°	+57° 11′	0.406±0.082	0.223±0.055	−0.340±0.104

[a] Reference 4.

parameter R measured previously,[4] they cannot be considered as statistically independent data for the purpose of a phase-shift analysis. Instead, the quoted values of the parameter F should be used.

Figure 2 shows the comparison of the measured values with predictions by the Hamada-Johnston potential model[5] and with the result of a modified phase-shift analysis, which uses all previous Rochester data, but not the measurement presented here.[6] Inclusion of the values of F into the phase-shift search changes the prediction very little. While the modified phase-shift analysis prediction agrees somewhat better with the measured values, the Hamada-Johnston potential gives a sufficiently similar behavior so that no distinction can be made.

[4] A. C. England, W. A. Gibson, K. Gotow, E. Heer, and J. Tinlot, Phys. Rev. **124**, 561 (1961).
[5] T. Hamada and I. D. Johnston, Nucl. Phys. **34**, 382 (1962).
[6] P. Signell (private communication); see also P. Signell, N. R. Yoder, and J. E. Matos, Phys. Rev. **135**, B1128 (1964).