Proton-Proton Scattering at 9.7 Mev

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(Received February 5, 1954)

The differential cross section for scattering of 9.7-Mev protons from hydrogen gas has been measured. Angles over the range from 27° to 112° in the center-of-mass system have been measured with a statistical error of less than ±1.0 percent and a probable error of ±1.1 percent has been assigned to the absolute values of differential cross section.

It is observed that within the accuracy of the measured cross section, the scattering can be described as pure S wave. The phase shift analysis is reported in a following paper.

I. INTRODUCTION

THE new 9.8-Mev Berkeley proton linear accelerator, which is to be used as an injector for the Bevatron, has been used to do proton-proton scattering. Although this energy range has been investigated by others,[1,2] the accuracy of the measurements is not sufficient to allow a critical analysis of the data.

The new proton linear accelerator[3] has a well-collimated monoenergetic beam of protons with low background radiation. It is a very stable and reliable accelerator, thus it is possible to make long runs while investigating any systematic errors that may be present in the scattering apparatus.

II. SCATTERING AND DETECTION APPARATUS

The proton beam from the linear accelerator was focused with a set of four magnetic quadruple strong-focusing magnets[4] and then deflected 24° by a double-focusing wedge magnet (Fig. 1). The beam was then collimated by a three-slit system having graphite slits of circular cross section and of 1.00 mm thickness (Fig. 2).

The beam entered the scattering chamber through two layers of 0.0002-inch thick rubber hydrochloride.

Since the protons are scattered only in the forward direction, it is reasonable to arrange a set of fixed counter telescopes to detect the scattered protons.

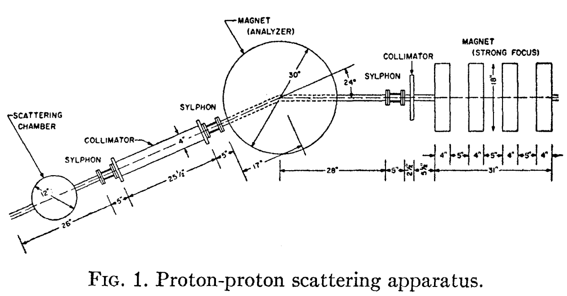

Fig. 1. Proton-proton scattering apparatus.

[1] R. R. Wilson, Phys. Rev. **71**, 384 (1947).

[2] Allred, Armstrong, Bondelid, and Rosen, Phys. Rev. **88**, 433 (1952).

[3] Bruce Cork, University of California Radiation Laboratory Report UCRL-2385 (in preparation).

[4] Bruce Cork and Emery Zajec, University of California Radiation Laboratory Report UCRL-2182, April 15, 1953 (unpublished).

This greatly simplifies the scattering chamber and the detection apparatus.

A drawing of the scattering chamber is shown in Fig. 3. Pure hydrogen is admitted to the scattering chamber through a hot palladium tube, until a pressure of approximately 5-cm Hg is reached. The scattered protons are then selected by each of the several telescopes, which define the solid angle for scattering. The scattered protons leave the telescopes through a 0.001-inch thick aluminum window and enter a NaI(Tl) crystal scintillator through another 0.001-inch thick aluminum window. For large angles, the windows were made of 0.0005 Mylar. An RCA 6199 photomultiplier, followed by a linear amplifier, supplies the signals to a pulse-height discriminator and scale of 16. Three angles were measured simultaneously.

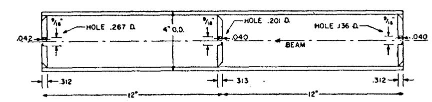

Fig. 2. Beam collimator geometry.

The beam current is monitored with an ionization chamber coaxial with the beam. The beam then leaves the scattering chamber through a 0.001-inch aluminum foil and enters the Faraday cup, which is used as a current integrator.

III. SOLID-ANGLE CALCULATIONS

Since the scattering volume is defined by the counter detector telescopes, the formula of Critchfield[5] can be applied. The product of the effective scattering length S and the solid angle Ω is given by the relation

$$\Omega S=\frac{HA^2}{lR_0\sin\theta}\left[1-\frac{A^2}{4l^2}+\frac{A^2}{12R_0^2}\cot^2\theta+\cdots\right],$$

where H is the height of the back slit, A is the width, l is the separation between the front and rear slits, and R_0 is the distance from the back slit to the center of the scattering chamber.

The front and rear slits in the counter telescopes (Fig. 3) were made of brass $\frac{1}{2}$-mm thick with 0.250-inch

[5] Jack Benveniste and Bruce Cork, Phys. Rev. **89**, 422 (1953).

square holes accurately broached and aligned. The baffles, located as indicated, were $\frac{3}{8}$-inch diameter apertures. The telescopes define an angle of ± 2.0 degrees.

IV. METHOD OF ALIGNMENT

The center of the scattering chamber was used as the reference point, and a simple alignment jig was used in order that each counter telescope could be inserted into the wall of the chamber with its axis passing through the center of the chamber. While the jig was in place, the telescopes were soldered into the wall of the scattering chamber. After all the telescopes were soldered into place, the chamber was centered on a calibrated dividing head, and the angles were accurately measured relative to the entrance and exit ports.

The beam collimator, scattering chamber, and Faraday cup were aligned by observing the position of a spot "burned" on a glass plate where the proton beam struck it. The 12-inch diameter chamber was centered to within $\pm\frac{1}{16}$ inch or ± 0.6 degree by this method.

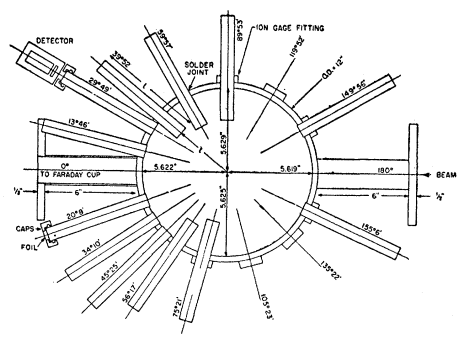

FIG. 3. Geometry of the proton-proton scattering chamber.

The differential cross section at 60° in the center-of-mass system was measured on both the left and right sides of the chamber, and the cross sections were observed to agree within the statistics of ± 1.0 percent.

V. COUNTING PROCEDURE

Since the background radiation was low and the crystal counters could easily be well shielded, the background counts were very low. This greatly simplified the procedure for obtaining counter thresholds. The RCA 6199 photomultipliers were operated at 800 volts and the linear amplifier gains were adjusted so that the proton pulses were 70 volts. Pulse-height discriminator runs were made first with protons entering the crystals and then with shutters inserted between the counter telescopes and the crystal detectors. The background was usually measured in this manner, but on occasions the hydrogen was pumped out of the scattering chamber so that if protons were scattered from the beam collimator and entered the detector telescope, they could be detected.

The discriminators were usually set to detect any

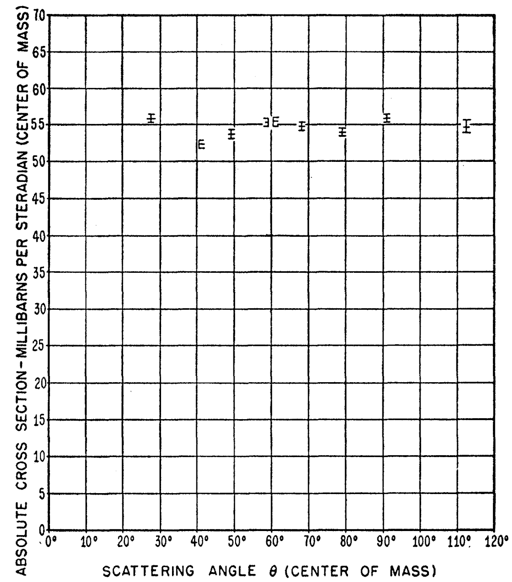

FIG. 4. Angular distribution of the absolute cross section for 9.7 Mev incident protons.

pulse height greater than 60 percent of the peak proton pulses.

However, runs were always made with discriminators adjusted over a range of 35 volts or 50 percent of the elastic proton pulse height. After the proper discriminator pulse-height settings were determined, the number of counts and background in each of three counters was measured until a total of over 10 000 counts per counter was observed. Two of the counters were then rearranged, the third left as a monitor. Seven angles could be measured to a statistical accuracy of ± 1.0 percent during a ten hour day.

VI. MEASUREMENT OF ENERGY

The scattering chamber was filled with He^4 to a pressure of 10-cm Hg, and a triple coincidence counter[5] was arranged to detect the protons elastically scattered from He^4 at an angle of 30°. The front two counters were arranged in coincidence, the third counter in anticoincidence. The elastic peak was measured by determining the amount of aluminum absorber required ahead of the counters such that protons would stop in the 1.9 mg/cm^2 foil separating the second and third counters. The energy was observed to be 9.73 ± 0.05 Mev, and the energy spread of the eleastic peak was observed to be less than ± 0.1 Mev. The measurement of the energy spread was limited by the energy straggling in the aluminum absorber that was used to determine the range of the protons. Thus the actual energy spread was probably less than ± 0.1 Mev.

The magnet current of the analyzing magnet was regulated and was kept constant to ± 0.2 percent. Care was taken to approach the proper current in the same manner for each run, and the stability of the

TABLE I. Experimental proton-proton differential cross section $\times 10^{-27}$ cm^2 *versus* $\theta_{c.m.}$ at 9.73 Mev.

Date	$\theta_{c.m.}$ 27°32′	40°16′	49°48′	59°38′	60°8′	68°20′	79°44′	90°50′	112°34′
9–15–53		52.20 ±0.48		54.82 ±0.62		53.26 ±0.66			
9–16–53		52.59 ±0.30		56.22 ±0.37		55.87 ±0.42			
	55.21 ±0.48	54.08 ±0.52						60.02 ±1.02	
9–17–53	56.41 ±0.52	55.10 ±0.63						55.60 ±1.06	
		53.04 ±0.28					54.72 ±0.40	57.16 ±0.49	
9–18–53		49.89 ±0.28					53.58 ±0.41	54.98 ±0.49	
9–23–53							55.83 ±0.44		54.52 ±0.58
10–13–53			53.89 ±0.31		55.38 ±0.40				
11–5–53		51.66 ±0.32		54.25 ±0.40				55.54 ±0.54	
11–6–53	56.06 ±0.30					53.81 ±0.47	52.31 ±0.48		
12–1–53		53.28 ±0.42						55.52 ±0.71	
12–3–53		52.61 ±0.35		54.05 ±0.48		55.20 ±0.49			
		52.61 ±0.36					51.62 ±0.51	55.49 ±0.61	
Average millibarns	55.95	52.46	53.89	55.06	55.38	54.84	53.91	56.11	54.52
Statistical error mb	±0.23	±0.10	±0.31	±0.22	±0.40	±0.24	±0.20	±0.23	±0.58
Absolute error in percent	±0.90	±0.83	±1.00	±0.90	±1.08	±0.89	±0.88	±0.91	±1.34
Absolute error millibarns	±0.50	±0.43	±0.54	±0.49	±0.60	±0.49	±0.47	±0.51	±0.73

magnet was checked by using a bismuth probe[6] cooled with liquid nitrogen.

VII. MEASUREMENT OF PRESSURE AND TEMPERATURE

The pressure of the hydrogen in the scattering chamber was measured by reading the difference in heights of a closed mercury manometer. The difference could be measured with a precision cathetometer to an accuracy of ±0.3 percent. Corrections were made for the change in density of the mercury with temperature. Since a slight amount of hydrogen leaked through the thin foil, the pressure and temperature were measured at frequent intervals. Comparison was made with another manometer and the two agreed within an accuracy of ±0.1 percent.

The temperature of the top of the scattering chamber was measured with a mercury thermometer to an accuracy of ±0.1 percent.

VIII. MEASUREMENT OF INTEGRATED CHARGE

The Faraday cup used for these measurements has been described.[7] The charge was collected on a low-leakage 0.1-microfarad polystyrene condenser and the potential measured by connecting the Faraday cup to the grid of a 5803 electrometer tube used as a null indicator. The feedback voltage was applied to a Leeds and Northrup recording voltmeter which was self-calibrating against a standard cell. The voltmeter was also calibrated against a Leeds and Northrup potentiometer and voltage could be measured to ±0.2 percent.

The capacitance of the 0.1-microfarad condenser was measured with a General Radio 1000-cycle bridge by comparing the capacitance with a General Radio mica condenser that was calibrated by the National Bureau of Standards. The capacitance could be measured to an accuracy of ±0.2 percent.*

During runs, the pressure in the Faraday cup was always less than 10^{-5} mm Hg; and a bias of -90 volts was applied to the guard cylindrical electrode. It was demonstrated, by using the scattered protons as a monitor, that a bias of greater than 20 volts was required to prevent secondary electrons from leaving

[6] H. B. Keller, University of California Radiation Laboratory Report UCRL-2249, June 9, 1953 (unpublished).

[7] Cork, Johnston, and Richman, Phys. Rev. **79**, 71–80 (1950).

* *Note added in proof.*—The capacitance of these condensers was compared with a polythene condenser recently measured by the National Bureau of Standards and observed to agree within 0.2 percent.

the Faraday cup. Over the range from -20 volts to -300 volts, the "plateau" was flat to ± 0.4 percent, limited by the statistical accuracy.

IX. MEASUREMENT OF CONTAMINATION

Care was taken to keep all the internal parts of the apparatus clean. The chamber was pumped with a well trapped pump to less than 10^{-4} mm Hg and the rate of rise was measured with the system sealed off. The contamination over a 5-hour period was estimated to be less than 2 parts in 10^5. Hydrogen was admitted through a directly heated palladium tube, which had been well outgassed.

Contamination was measured by inserting an aluminum foil ahead of the 40° counter. This foil was thick enough to stop protons elastically scattered from hydrogen, but protons elastically scattered from He^4 or heavier nuclei would be detected. Assuming the proton-proton cross section and the contamination cross section were the same in the laboratory system, the contamination background was less tha 0.3 percent at the 40° angle.

X. MULTIPLE SCATTERING AND SLIT SCATTERING

Estimates were made of the change in counting rate due to multiple scattering. The Williams formula[8] was used for small-angle scattering, and the largest correction was less than 0.2 percent. The differential cross section was measured over the region of 3.0 cm to 30 cm Hg, and no effect beyond the statistical fluctuation of ± 1.0 percent was observed. Thus, no correction was made.

To reduce slit scattering, care was taken to make the defining slits just sufficiently thick to stop the elastic protons. Also the slit widths were fairly large. The Williams formula was used to estimate the number of protons scattered from the front analyzer slit. The corrections for these scattered protons were estimated to be less than 0.2 percent for all except the 28° center-of-mass angle. Background runs were made with no gas in the scattering chamber, with the shutter ahead of the counter both in and out. The number of protons scattered from the collimator slits was less than 0.2 percent for all angles measured except 28° in the center-of-mass system. For this angle, a correction of 1.0 percent for slit scattering was made.

Table II. Summary of experimental uncertainties.

		Probable error (percent)
Proton current	a. Capacitance	± 0.3
	b. Voltage	± 0.2
	c. Leakage	$+0.0$
Proton energy		± 0.5
Gas contamination		± 0.1
Slit scattering		± 0.2
Solid angle calculations		± 0.2
Multiple scattering		± 0.2
Statistics		$< \pm 1.0$
Pressure		± 0.3
Temperature		± 0.1
Counting losses		± 0.2
Angular resolution		0.0

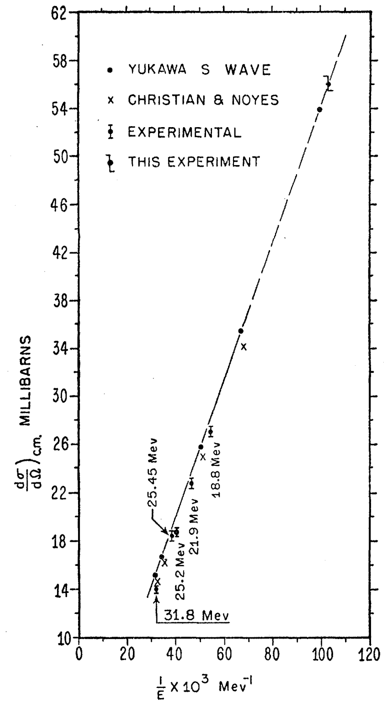

FIG. 5. Variation of the absolute differential cross section at 90° (center-of-mass system) as a function of the reciprocal of the energy of the incident protons.

XI. RESULTS

The differential cross section in the center-of-mass system and the probable errors are listed in Table I and plotted in Fig. 4.

The 60° center-of-mass cross section to the left and to the right of the beam are observed to agree within statistics, also the 68° and 112° center-of-mass cross sections—the symmetrical angles about 90°—are observed to have the same differential cross section within statistics.

Figure 5 is an extension of previous cross section data[9,10] for the 90° center-of-mass angle.

The phase shift analysis of these data has been made by Dr. Harold Hall, and it has been observed that within the experimental accuracy of these measurements, the scattering cross section can be described by pure S wave scattering.

The known errors are listed in Table II, expressed in percent.

[8] E. J. Williams, Proc. Roy. Soc. (London) **A169**, 531 (1939).

[9] Bruce Cork, Phys. Rev. **80**, 321 (1950).

[10] J. L. Yntema and M. G. White, Princeton University Technical Report NYO-3478 (unpublished).