Proton-Proton Scattering at 68 Mev*

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(Received February 4, 1960)

Differential cross sections have been measured for the scattering of 68.3-Mev protons by hydrogen gas at 26 laboratory angles from 5° to 50°. The angular resolution is $\pm\frac{1}{2}°$ at small angles, and the estimated absolute probable errors are ±0.9% except at the smallest angles. The interference minimum of 5.19 millibarns occurs at 16.3° c.m. The cross section then rises to a maximum of 6.33 mb at 34° and falls to 6.16 mb at 90°.

I. INTRODUCTION

MORE and more complete experimental data seem to be required before a satisfactory understanding of the nucleon-nucleon interaction can be had. For the *p-p* interaction below 100 Mev, angular distributions can be measured with considerable accuracy, but polarization measurements become quite difficult. It is hoped that accurate angular distributions will lead to precise, though perhaps ambiguous, phase shift information; and that polarization and correlation data of attainable accuracy can resolve the remaining ambiguities in the phase shifts.

The protons for this experiment have the highest energy obtainable from the Minnesota linear accelerator. The energy spectrum of the beam is shown in Fig. 1.

II. APPARATUS

Since the scattering chamber and most of the techniques used in this experiment are similar to those used for 40-Mev *p-p* scattering,[1] the reader is referred to the earlier report. The changes indicated below were required by the increased background and scattering from metal walls and slits at this higher energy. The layout of the experiment is shown in Fig. 1, reference 1. The proton beam from the accelerator is bent through an angle of 20° and collimated by a three-eighths inch diameter hole. The beam then travels sixteen feet to the input collimator and entrance foil of the scattering chamber. The input collimator is rectangular, 1.65 cm high by 1.02 cm wide.

The antiscattering baffle[1] used with the small-angle telescope was modified to move continuously in two dimensions. Precise setting of this baffle at each angular setting of the detector telescope resulted in a great reduction of the proton illumination of the front slits and walls of the telescope.

Because of the large neutron background arising from the stoppage of the 68-Mev beam in the collector cup, the cup was moved five feet downstream from the scattering chamber to allow two feet of shielding to be placed between the cup and the scintillation [NaI(Tl)] detectors. The collector cup of Fig. 5, reference 1 was enlarged to insure complete collection of the enlarged beam. Minus 1000 volts was applied to the repeller ring ahead of the cup, to repel secondary electrons from the cup and from the exit foil. No magnetic fields were used in the collector system.

In order to reach small scattering angles, the front section of the small-angle telescope was constructed with a flat side to allow clearance for the beam collector cup. (See Fig. 2, reference 1.) The illumination of this flat side by hydrogen-scattered protons at small angles results in rescattering from the wall into the detector, which amounted to a 2% spurious increase in counts at 12°. It was found possible to accurately evaluate this wall scattering by installing a shutter in each telescope at such a position that the valid scattered protons might be completely stopped without disturbing the wall illumination. Figure 2 shows the installation of the shutter "*S*" in the small-angle telescope. Background runs taken with the shutter "in" gave a measurement of the wall-scattered protons, added to the other sources of background counts. Wall scattering was negligible in the large-angle telescope due to its adequate wall clearances.

The target material was hydrogen gas at a pressure

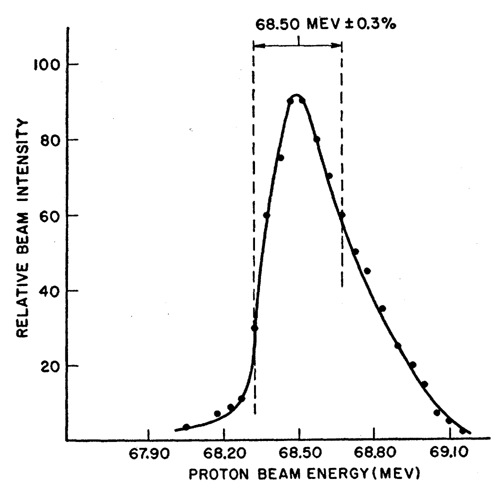

Fig. 1. Energy spectrum of incident proton beam. Energy is reduced from 68.50 to 68.30 by absorption in entrance foil and hydrogen gas.

* Supported in part by the U. S. Atomic Energy Commission.
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[1] L. H. Johnston and D. A. Swenson, Phys. Rev. **111**, 212 (1958).

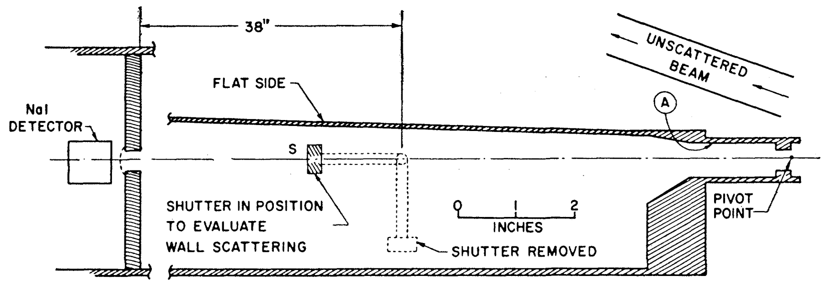

FIG. 2. Small-angle detector telescope, showing shutter "S" used for evaluating wall-scattered protons.

slightly above one atmosphere, obtained from a palladium filter. Based on experience at 10 Mev[2] where scattering from contaminants is more serious, the gas was changed at intervals of 24 hours or less, with small-angle runs having preference after each filling.

III. CORRECTIONS AND ERRORS

The formulae and methods used for calculating the cross sections in the laboratory system are given in reference 2. The conversion of angles and cross sections to the center-of-mass coordinate system was done relativistically, as in reference 1.

The significant sources of error are listed in Table I along with estimates of their contribution to the absolute and relative probable error in the cross section. The nature of these errors is discussed in reference 1. The largest correction to the data was that due to nuclear reactions in the sodium iodide detector, which amounts to 5.7%±0.4% at 68 Mev. This correction has been measured at several energies by Service.[3]

Slit-scattering corrections amounted to a maximum of 1.5%, the correction being experimentally determined as before.[1]

It is a feature of the scattering chamber that the small-angle telescope covering the angular range from 4° to 20° overlaps the angular range (10° to 60°) of the large-angle telescope. After calculating the cross sections obtained with both telescopes, a discrepancy of about 1% existed between them in the region of overlap. Beam pictures taken at the exit end of the scattering chamber showed that while the geometrical beam cylinder was well lined up with the chamber, the illumination of the beam was slightly heavier on the side of the chamber occupied by the small-angle telescope than on the other, in agreement with the sign of the discrepancy. Accordingly the discrepancy was resolved by assuming the center of the beam to be displaced 0.056 cm from the center of the chamber, and making this correction to the data of both telescopes at all angles.

TABLE I. Summary of experimental errors.

Source of error	Absolute error	Relative error
Beam current errors		
Capacity	±0.1%	±0.1%
Voltage	±0.1%	±0.1%
Electrometer drift	±0.1%	±0.1%
Collection of stray charges	±0.1%	0
Counting errors		
NaI inelastic nuclear reactions	±0.4%	±0.1%
Slit scattering	±0.3%	±0.2%
Counting statistics	±0.3%	±0.3%
Counting losses	±0.1%	±0.1%
Background and wall scattering	±0.2%	±0.1%
Geometry errors		
Geometry calculation	±0.2%	±0.1%
Angle calibration[a]	±0.2%	±0.1%
Beam displacement	±0.2%	0
Target errors		
Target temperature	±0.1%	±0.1%
Target pressure	±0.1%	±0.1%
Gas impurities	±0.1%	±0.1%
Beam energy errors		
Mean energy	±0.4%	±0.1%
Energy distribution	±0.2%	±0.1%
Total error	±0.9%	±0.5%

[a] This angle calibration error is exceeded at 5°, 6°, and 7°.

IV. RESULTS

Table II lists the resulting cross sections, along with our estimate of their absolute and relative probable errors. These are based on 75 experimental runs taken

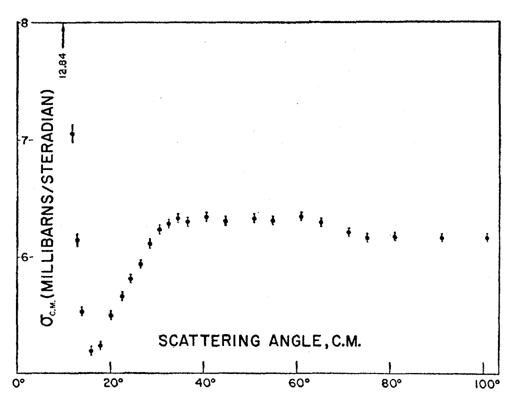

FIG. 3. Angular distribution of p-p cross sections at 68.30 Mev. The error bars indicate the relative probable error.

[2] L. H. Johnston and D. E. Young, Phys. Rev. **116**, 989 (1959).

[3] D. Service, Minnesota Linear Accelerator Annual Progress Report, November, 1958, (unpublished), p. 35.

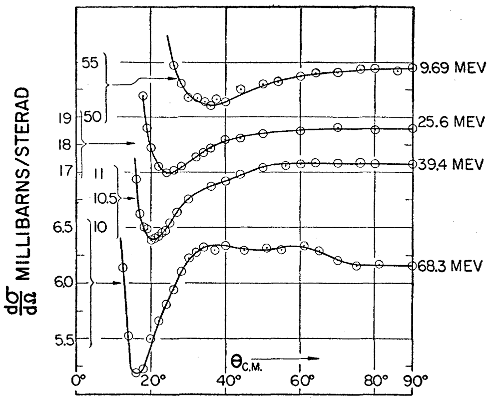

FIG. 4. Summary of p-p cross sections at the four energies shown. Each curve has a different scale of cross sections, as indicated.

over a period of six months following establishment of the final operating and beam energy criteria. The results are plotted in Fig. 3. Figure 4 shows in one plot a comparison of proton-proton angular distributions taken at energies of 10 Mev,[2] 25 Mev,[4] 40 Mev,[1] and 68 Mev (present work). Analysis shows the 10-Mev curve to represent nearly pure S-wave scattering.[5] The increasing complexity of the curves at successively higher energies may be taken as graphic evidence for the increasing importance of higher order phase shifts.

MacGregor has kindly supplied preliminary sets of phase shifts which fit the 68-Mev data, two of which are as follows:

$^1S_0$	$^3P_0$	$^3P_1$	$^3P_2$	$^1D_2$
30.6°	18.2°	−10.4°	6.8°	2.7°
38.0°	−14.5°	0.13°	8.3°	1.06°

These are obtained in a phase shift search in which all phase shifts of order higher than D are fixed at values calculated by the one-pion exchange interaction.[6] The

[4] T. H. Jeong, L. H. Johnston, C. N. Waddell, and D. E. Young, Phys. Rev. **118**, 1080 (1960).
[5] M. H. MacGregor, Phys. Rev. **113**, 1559 (1959).
[6] P. Cziffra, M. H. MacGregor, M. J. Moravcsik, and H. P. Stapp, Phys. Rev. **114**, 880 (1959).

TABLE II. Experimental cross sections for proton-proton scattering using 68.30-Mev protons.

θ_{lab}	$\theta_{\text{c.m.}}$	$d\sigma/d\Omega$ (c.m.) (mb/sr)	Absolute probable error (±)	Relative probable error (±)
5°	10.18°	12.84	1.8%	1.7%
6°	12.21°	7.05	1.2%	0.9%
6.5°	13.23°	6.14	1.1%	0.8%
7°	14.25°	5.53	1.0%	0.6%
8°	16.28°	5.19	0.9%	0.5%
9°	18.32°	5.23	0.9%	0.5%
10°	20.35°	5.50	0.9%	0.5%
11°	22.39°	5.66	0.9%	0.5%
12°	24.42°	5.81	0.9%	0.5%
13°	26.45°	5.94	0.9%	0.5%
14°	28.48°	6.11	0.9%	0.5%
15°	30.52°	6.23	0.9%	0.5%
16°	32.55°	6.28	0.9%	0.5%
17°	34.58°	6.33	0.9%	0.5%
18°	36.61°	6.30	0.9%	0.5%
20°	40.66°	6.34	0.9%	0.5%
22°	44.72°	6.30	0.9%	0.5%
25°	50.79°	6.32	0.9%	0.5%
27°	54.83°	6.30	0.9%	0.5%
30°	60.89°	6.34	0.9%	0.5%
32°	64.92°	6.29	0.9%	0.5%
35°	70.97°	6.21	0.9%	0.5%
37°	74.98°	6.16	0.9%	0.5%
40°	81.01°	6.17	0.9%	0.5%
45°	91.02°	6.16	0.9%	0.5%
50°	101.01°	6.16	0.9%	0.5%

F waves from this pole calculation are as follows:

$$^3F_2,\ 0.6°;\quad ^3F_3,\ -1.2°;\quad ^3F_4,\ 0.13°;\quad \epsilon_2,\ -2.5°.$$

The phase shifts are the nuclear bar phase shifts and ϵ_2 is the coupling parameter between $^3P_2$ and $^3F_2$ waves, as defined by Stapp et al.[7]

V. ACKNOWLEDGMENTS

This work has been helped by periodic discussions with Professor G. Breit, H. P. Noyes and M. H. MacGregor. We are indebted to T. H. Jeong for helping take the data and to the linear accelerator crew, working under the direction of R. P. Featherstone, for the rigorous accelerator operation which helped to make the precision of the experiment possible.

[7] H. P. Stapp, T. J. Ypsilantis, and N. Metropolis, Phys. Rev. **105**, 302 (1957).