Proton-Proton Scattering at 90° from 28 to 68 Mev*

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Proton-proton scattering cross sections are measured at 45° in the laboratory system, from 28 Mev to 68 Mev, with an accuracy of about ±1.2%. These measurements fill the energy gap between the work of Cork on the low-energy end, and that of Ramsey *et al.* at higher energies. In the region of overlap with these experiments there is reasonable agreement. The cross section falls monotonically with increasing energy.

I. INTRODUCTION

PERHAPS the most important single feature of a proton-proton scattering angular distribution is the cross section at 90° in the center-of-mass system. Since measurement techniques are relatively simple at this angle, it is an appropriate place to measure cross sections as a function of energy.

Cork[1] has made this measurement from 18.8 Mev to 31.8 Mev with roughly ±2.2% probable errors, and Kruse, Teem, and Ramsey[2] have done it from 40 Mev to 95 Mev with probable errors in the neighborhood of ±4%. This experiment is undertaken to reach greater precision and to fill the energy gap.

II. EXPERIMENTAL METHOD

Protons were scattered from hydrogen gas at one atmosphere pressure, into a detector telescope fixed at 45° in the laboratory system as shown in Fig. 1. The telescope takes in an angular interval of ±2.5°, lab.

The reader is referred to a previous report[3] for details of the proton detector, the electronics, the supply of pure hydrogen gas, and the measurement of the incident beam charge, all of which were similar to techniques used in taking angular distributions. A different scattering chamber is used here to make use of the smaller beam currents available at reduced energies.

The beam from the linear accelerator[4] is deflected 20° by a magnet, after which it passes through an absorber wheel which sometimes is used for reducing the energy. After this it is recollimated and passes into the gas of the scattering chamber through a one-mill Dural foil. An antiscattering baffle (Fig. 1) prevents the front slit of the detector telescope from being illuminated by protons scattered at angles smaller than 40°.

Methods for Obtaining Reduced Proton Energies

The linear accelerator normally produces proton beams at discrete energies of 10, 40, and 68 Mev from its three successive accelerating cavities. Two different methods were used in obtaining intermediate-energy beams.

Method A

Protons of energies between 28 Mev and 40 Mev were obtained by passing the 40-Mev beam through various aluminum absorbers in the absorber wheel. The energy was then calculated from the known initial energy and the range-energy data of Rich and Madey.[5]

Method B

Energies between 68 Mev and 40 Mev were obtained by operating the third accelerating cavity of the linear accelerator at reduced rf voltage. As detailed in reference 4, this produces a usable quantity of protons of reduced energy. Under these conditions the beam has an energy spread of ±5% or greater, so the 20° bending magnet is used as a monochromator to select the desired energy and reduce the energy spread to about ±2%. In spite of this energy spread, the mean energy is known to ±0.6% since the beam used is selected from a much wider spectrum, which may be regarded as uniformly populated in the region of the selected energy interval. The magnetic field was continuously monitored by means of a current balance,[3] and the absolute calibration of the monochromator in terms of mean energy *versus* magnetic field was made at several energies by the floating-wire technique.[3]

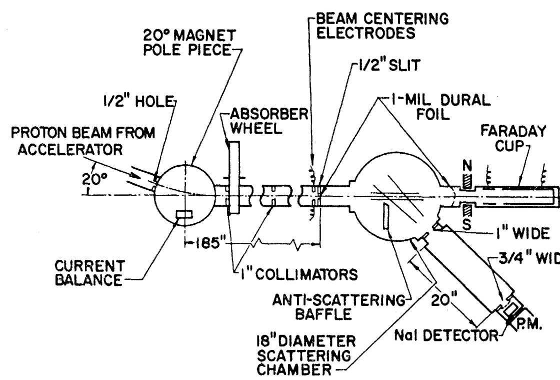

FIG. 1. Layout of p-p scattering apparatus, approximately to scale.

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[1] Bruce Cork, Phys. Rev. **80**, 321 (1950).
[2] Kruse, Teem, and Ramsey, Phys. Rev. **101**, 1079 (1956).
[3] L. H. Johnston and D. A. Swenson, Phys. Rev. **111**, 212 (1958).
[4] Day, Featherstone, Johnston, Lampi, Tucker, and Williams, Rev. Sci. Instr. **29**, 457 (1958).
[5] Marvin Rich and Richard Madey, "University of California Radiation Laboratory Report," UCRL-2301 (unpublished).

TABLE I. Proton-proton cross sections at 90° cm as a function of energy.

Mean beam energy Mev	Energy spread of beam	Probable error of mean energy	Method of reducing energy[a]	$d\sigma/d\Omega$ (mb/sterad) cm
68.42	±0.5%	±0.6%	*C*	6.13±1.1%
61.92	±2%	±0.6%	*B*	6.76±1.1%
56.15	±2%	±0.6%	*B*	7.45±1.1%
50.17	±2%	±0.6%	*B*	8.40±1.1%
44.66	±2%	±0.6%	*B*	9.51±1.1%
39.60	±0.5%	±0.3%	*C*	11.19±1.0%
36.90	±0.7%	±0.3%	*A*	12.14±1.0%
34.20	±1.1%	±0.3%	*A*	13.36±1.0%
31.15	±1.3%	±0.3%	*A*	14.68±1.0%
28.16	±2%	±0.6%	*B*	16.27±1.3%
9.68	±0.5%	±0.3%	*C*	54.6 ±0.8%

[a] *A* = aluminum absorption; *B* = reduced rf; *C* = standard accelerator energy.

At 68 Mev and 40 Mev the normal beams of the accelerator were used, having energy spreads of $\pm\frac{1}{2}\%$. The mean energies were measured absolutely by the calibrated 20° magnetic monochromator.

III. CORRECTIONS AND ERRORS

The probable errors in our values of the beam energy depend on the methods used to obtain the reduced energy. They are listed at each energy in Table I of Results. An error of ±0.5% is added at each angle due to a lack of knowledge of the details of the distribution of energies and intensities within the one-half inch wide incident beam in the scattering chamber.

The remaining errors are of the same nature as those discussed in reference 3, and hence will only be listed with their estimated magnitudes: Beam current measurement, ±0.25%; nuclear reactions in NaI detector, ±0.3%; slit scattering, ±0.2%; counting statistics, 0.3% (except 0.8% at 28.16 Mev); counting losses, ±0.1%; geometry, ±0.4%; angle calibration, ±0.1%; target gas density, ±0.2%. The resultant error for the cross section measurements is given in the last column of Table I.

Strictly speaking, these measurements are made at 45° in the laboratory system, so that the corresponding center-of-mass angle varies from 90°19′ at 28.16 Mev to 90°44′ at 68.42 Mev. However, due to the symmetry of scattering about 90°, negligible error is introduced by assuming all the measured cross sections to be at 90°.

IV. RESULTS

The cross sections are listed in Table I and are plotted in Fig. 2. For completeness we include an additional point taken in this laboratory[6] at 9.68 Mev as part of an angular distribution. Since the dominating behavior of the cross section in this energy region is a $1/E$ dependence, Fig. 2 plots E times cross section *versus* E. This emphasizes the degree to which variations from the $1/E$ dependence occur.

To give a broader view of the variation of σ with energy which may now be seen, we have included in Fig. 2 the work of Cork[1] from 18 to 32 Mev, the Harvard data[2] from 41 to 95 Mev, and seven single points from other authors[7–13] to extend the energy down to 3.5 Mev. Notice the striking maximum in $\sigma \times E$ which occurs at 10 Mev, and the broad minimum near 60 Mev. The maximum at 10 Mev is almost certainly associated with a maximum value of the ^1S phase shift here, while the rise beyond 60 Mev is to be expected as the high-energy region is approached where σ is nearly independent of E. No theoretical analysis of these results has been made.

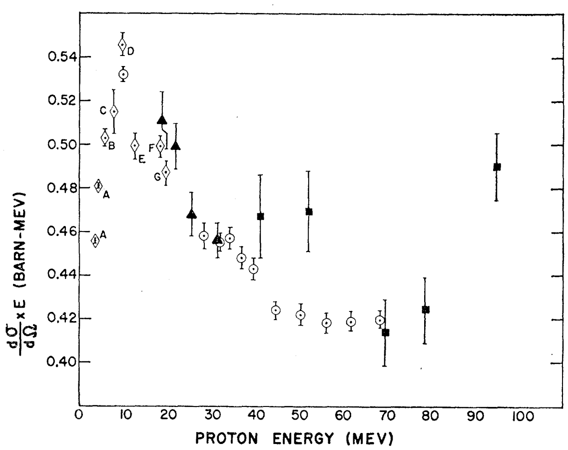

FIG. 2. Plot of differential cross section for *p*-*p* scattering at 90° cm, multiplied by laboratory proton energy; plotted against laboratory proton energy. Circles, present work. Triangles, Cork, reference 1. Squares, Kruse, reference 2. Diamonds: *A*, Worthington, reference 7; *B*, Zimmerman, reference 8; *C*, Rouvina, reference 9; *D*, Cork, reference 10; *E*, Faris, reference 11; *F*, Yntema, reference 12; *G*, Burkig, reference 13.

ACKNOWLEDGMENT

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[6] L. H. Johnston and D. E. Young (to be published).

[7] Worthington, McGruer, and Findley, Phys. Rev. **90**, 899 (1953), (4.203, 3.527 Mev).

[8] Zimmerman, Kerman, Singer, Kruger, and Jentschke, Phys. Rev. **96**, 1322 (1954), (5.77 Mev).

[9] J. Rouvina, Phys. Rev. **81**, 593 (1951), (7.51 Mev).

[10] Bruce Cork, Phys. Rev. **94**, 1300 (1954), (9.73 Mev).

[11] F. E. Faris and B. T. Wright, Phys. Rev. **79**, 577 (1950), (12.4 Mev).

[12] J. L. Yntema and M. G. White, Phys. Rev. **95**, 1226 (1954), (18.28 Mev).

[13] Burkig, Richardson and Schrank, Phys. Rev. **113**, 290 (1959), (19.84 Mev).