Proton-Proton Scattering from 40 to 95 Mev*

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Proton-proton scattering experiments between 40 and 95 Mev are described. Two methods for observing the proton-proton differential scattering cross section were employed; in the first, hydrocarbon scatterers were used to obtain the angular distribution at 95 Mev and to obtain the cross section at 90° as a function of energy. In the second, liquid hydrogen was used for the target and the angular distribution at 95 and 70 Mev was obtained to angles of 25°. Throughout, a Faraday cup was used to monitor the incident beam. The cross section rises smoothly from 4.65±0.25 mb at 95 Mev to 11.4±0.8 mb at 41 Mev. At 95 Mev the cross section shows a slight increase to smaller angles; the ratio between 40° and 90° is 1.06±0.03.

INTRODUCTION

THE proton-proton scattering experiments described in the present paper were performed with the external proton beam of the Harvard cyclotron. Both hydrocarbon scatterers and liquid hydrogen scatterers were used. Some of the results with hydrocarbon scatterers have already been briefly described in a preliminary communication,[1] but all the liquid hydrogen results are described here for the first time. The experimental arrangements will be given in detail, typical data will be presented, the principal sources of error will be discussed, and finally, our results will be compared to those obtained at other laboratories.

For a typical scattering event, the angle of scattering θ in the center-of-mass system is chosen to be smaller than 90°. The proton scattered into θ will be denoted as the "scattered" proton, its partner as the "recoil" proton. For angles of θ near 90° the protons have nearly equal energy. Both will emerge from a thin target without much energy loss or multiple scattering and they can be detected by counters in coincidence. This method, denoted as Method 2 by Chamberlain,[2] has the advantage that scatterings from materials other than hydrogen in the target are eliminated, except in the comparatively rare case of two charged particles appearing simultaneously 90° apart. Thus hydrocarbon targets may be used and the contribution from carbon and background is small. For small angles of scattering, however, the "scattered" proton carries away almost the full energy and it becomes difficult to detect the "recoil" proton. Therefore Method 1, which employs counters to detect the scattered proton only, is used. With this method, it is difficult to distinguish between scatterings by hydrogen and scatterings from other sources. Therefore all materials other than hydrogen in the beam must be reduced to a minimum and the collimation must attempt to eliminate extraneous scatterings.

The cross section for scattering in the center-of-mass system is given by

$$\sigma(\theta)=\frac{(2Mc^2+E_0\sin^2\Phi)}{2Mc^2(2Mc^2+E_0)}\frac{1}{4\cos\Phi}\frac{H}{nN\Omega},$$

where θ is the angle of scattering in the center-of-mass system, Φ is the corresponding laboratory angle, E_0 is the energy of the incident proton in the laboratory system, Mc^2 is the rest energy of the proton, H represents the number of protons scattered by hydrogen, n the number of protons incident, N the number of scatterers/cm^2, and Ω the solid angle of the defining detector. This experiment determined these quantities for the proton-proton cross section as a function of angle and energy in the range between 40 and 90 Mev.

EXPERIMENTAL EQUIPMENT

The external beam of protons was obtained by scattering into a magnetically shielded channel. Particles escaping the cyclotron were then led to the experimental area through a vacuum pipe. The protons passed through a magnet which bent the beam toward the experimental equipment just outside the main concrete shielding. The beam was defined by 3 sets of slits, the first just outside the main cyclotron chamber, the next in front of the bending magnet, and the third just outside the shielding. Behind the third slit, called the defining slit, a fourth antiscattering slit was mounted to eliminate protons scattered from the defining slit. With the third slit setting of $\frac{1}{2}$ inch by $\frac{3}{4}$ inch, a beam of 2×10^6 protons/sec with a mean energy of 95 Mev was usually obtained. To obtain lower energies lithium hydride absorbers were placed behind the third slit, the fourth slit was cut down in size to act as a defining slit, and additional shields comprising a fifth slit system were placed in front of the target to reduce the number of slit-scattered protons. The low-energy beams were much reduced in intensity because of scattering losses; in the extreme case of the 40-Mev beam, the resulting intensity was 5×10^4 protons per second.

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[1] Kruse, Teem, and Ramsey, Phys. Rev. 94, 1795 (1954).
[2] Chamberlain, Segrè, and Wiegand, Phys. Rev. 83, 923 (1951).

EXPERIMENTS WITN HYDROCARBON TARGETS

For this scattering experiment, the recoil method was used first, and the results have already been briefly reported. In this phase of the experiment, a circular scattering platform was used to support the counting equipment on two arms. The arms turned about a central post which also held the target changer mechanism. The plan view is shown in Fig. 1, which also includes a view of the beam current monitoring equipment to be described below. The scatterers used were thin sheets of polyethylene or polystyrene; to allow the subtraction of events due to the carbon in the targets, graphite scatterers of nearly equal stopping power were used. The targets were large enough to span the whole beam and they were held flat by a thin aluminum frame with three windows, used for the hydrocarbon, carbon, and background positions. By remote control, the scatterer could be changed without disturbing cyclotron operation.

The desired contribution from hydrogen is given by $H=(CH_\beta-E)-Z(C-E)$, where CH_β, C, and E represent the net coincidences from the hydrocarbon, carbon, and background positions, respectively. The factor Z is the ratio of the number of carbon scatterers per cm^2 in the hydrocarbon target to the number in the carbon target. The densities of the targets were obtained by weighing small samples. Commercial polyethylene sheet was used and the density was found to be uniform to one percent for 60-mil-thick samples. The composition for the thick polyethylene target was determined from an analysis by the National Bureau of Standards which agreed to one percent with the expected CH_2 for polyethylene. Since the carbon and background contributions C and E were usually small compared to the hydrocarbon contribution CH_β, the dependence of the net hydrogen rate on Z was not critical. Polystyrene (CH) targets allowed a good systematic check, here the carbon contribution is more important. The net hydrogen rate agreed within statistics with the rate measured from polyethylene.

The scattered particles in this experiment were detected with scintillation detectors. The "scattered" proton was counted in a defining scintillator counter 1, roughly 1 inch by 1 inch followed by another, counter 3, immediately behind whose size was $1\frac{1}{2}$ inches by 2 inches. The recoil proton in turn was detected in a similar scintillator, counter 2, 2 inches wide by 3 inches high. The 1-inch square scintillator served to define the solid angle and was either $\frac{1}{8}$-inch or $\frac{3}{16}$-inch thick. The distance to the center of the target was varied between 16 inches and 24 inches. The "recoil" detector was chosen sufficiently large to detect all the recoil protons associated with scattered protons in the defining counter. It was placed very close to the target, 3 inches or 4 inches. The counter was moved vertically and horizontally about the proper recoil position, at all times there was no net hydrogen coincidence contribution outside the area subtended by the recoil counter.

The counters were carefully centered above the arms and the angles of these in turn could be determined to within $\frac{1}{4}°$. To eliminate possible errors due to misalignment of the table, the cross section was measured for equal angles to the right and to the left, this also eliminated possible polarization effects.

The efficiency of the counters was checked in the main beam of reduced intensity by placing smaller counters in front and behind the detectors in question. A coincidence from the center counters was required whenever a proton was known to have penetrated both the smaller counters. This method cannot be used to detect efficiency near the edges, however the uniformity of pulse heights and the consistency between various defining scintillators give reasonable assurance of 100 percent efficiency across the whole face of the crystal. To assure continued 100 percent efficiency under scattered beam conditions the cables were readjusted in length to take account of the different times of flight.

Accidental coincidences were determined by putting in delay cable sufficient to delay one pulse a time equivalent to one or two revolutions with the cyclotron.

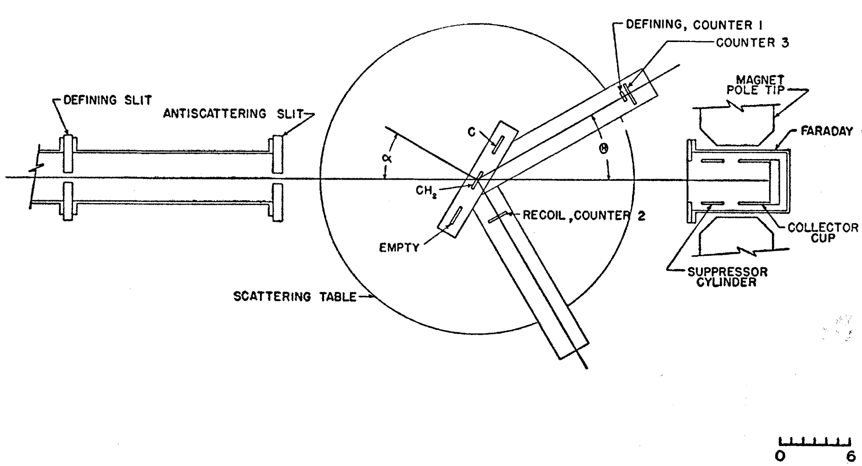

FIG. 1. Experimental arrangement, coincidence method.

TABLE I. Typical data with coincidence method (90° cm).

	Observed counts CH_2	Observed counts C	Observed counts E	Accidentals CH_2	Accidentals C	Accidentals C
2-fold coincidence	1232	115	4	9	16	3
3-fold coincidence	1143	44	2	5	7	0
Faraday cup (volts)	2.701	1.352	0.451	0.900	0.901	0.452

Normalized to 1 volt, accidentals subtracted	CH_2	$-0.675C$	$-0.325E$	H
2-fold coincidence	446.1	45.5	0.7	399.9
3-fold coincidence	417.6	16.7	1.4	399.5

At all times the delayed or accidental coincidence rate was very small compared to the prompt rate and in rough agreement with the rate estimated from the resolving times of the circuits. The prompt coincidence rate from carbon was well above the accidental rate from carbon, a weak correlation in angle for the net rate was found and the events were attributed to quasi-free proton-proton scattering in the carbon nucleus. The net coincidence rate from background was sufficiently small so that it was not investigated closely.

The beam current was monitored throughout the experiment by means of a Faraday cup shown in Fig. 2. The cup opening was 4 inches in diameter to assure that most of the multiple scattering of the beam would be caught. To eliminate the possible escape of protons, the back of the cup was made thick compared to the range of the highest energy protons. The collection of spurious charges from ionization was minimized by maintaining a vacuum better than 10^{-5} mm of mercury at all times of operation. Also, to prevent electrons from leaving or entering the cup, an electrostatic voltage was applied to a suppressor cylinder immediately in front of the cup. An electromagnet also maintained a magnetic field of roughly 700 gauss across the face and in the interior of the cup. The various parameters of pressure, suppressor voltage and magnetic field could be varied and at no time were any differences in charge collection larger than $\frac{1}{2}$ percent observed.

The electric charge of the protons stopped in the cup was collected on a condenser and the voltage across the condenser measured by means of a vibrating reed electrometer. To minimize the effects of leakage currents, the cup itself was held at a constant potential, therefore only the leakage currents across the standard condenser will vary with time. All insulators between the cup structure and other points were of fused quartz or lucite. The condenser itself was a modified air type condenser, the original ceramic insulator was replaced by fused quartz; its capacity at 1000 cycles per sec was 127 $\mu\mu$f as determined by a General Radio Type 716-C bridge.

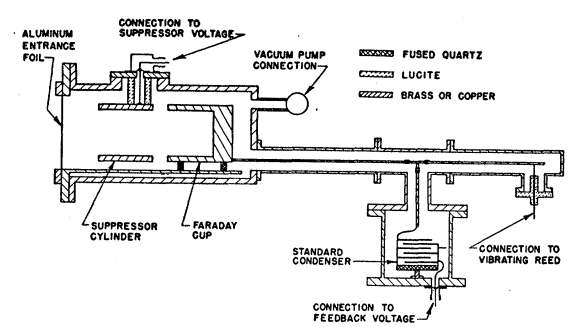

FIG. 2. Faraday cup construction.

The condenser was in the Faraday cup vacuum system itself and all connections were made with $\frac{1}{8}$-inch brass rods or large diameter wire. The system was found to have negligible drift currents in general, so that charge accumulated in twenty minute runs with beam currents as small as 10^{-14} ampere could still be determined to high accuracy.

Thin-walled ionization chambers were used as auxiliary monitors. These were argon filled, and employed an active volume roughly $1\frac{1}{2}$ inches long in the beam direction. The charge was usually integrated in a system very similar to the integrator of the Faraday cup, in this case however, polystyrene condensers were used. A simple switching circuit allowed the substitution of a resistor to measure the intensity of the beam current. The ionization chambers also made possible an intercomparison between the Faraday cup and nuclear track plates. The ionization chamber was first compared to the Faraday cup by letting several bursts of roughly 10^7 protons traverse the chamber and then stop in the cup. Then nuclear track plates were inserted directly behind the chamber, inclined at roughly 20° to the horizontal, and completely spanning the beam area. One burst of 10^7 protons was then allowed to fall on the plates. The number of tracks in the plates was determined by suitable scanning and the number compared with the number expected from the Faraday cup calibration of the ion chamber. The numbers so obtained agreed within the statistics of the track scanning which was about three percent.

The beam energy was determined with the ionization chamber and Faraday cup by measuring the range curve for aluminum. The ionization chamber served to monitor the beam incident on the aluminum while the Faraday cup measured the number of protons which penetrated the absorber stack. This method does not measure low-energy contamination in the beam reliably. For the lower-energy beams particularly, the energy spread of the beam together with uncertainty of nuclear absorption in aluminum made it difficult to assign a sharp lower limit to the energy of particles in the beam.

The results of the experiments with the recoil method are presented in Tables I–IV. Table I gives typical data obtained using the thick polyethylene and carbon

TABLE II. Estimated standard errors in the cross sections according to source (coincidence method).

Item[a]	41 Mev	51.5 Mev	69.5 Mev	78.5 Mev	95 Mev	Relative errors 95 Mev
N	1.6	1.6	1.6	1.6	1.6	1.6
H	3.1	3.1	3.1	3.1	3.1	3.1
Ω	1.9	1.9	1.9	1.9	1.9	0
n	3.5	3.5	3	3	2	0
Φ	0.6	0.6	0.6	0.6	0.6	0.6
E	4	4	3	3	2.2	0.5
Totals	7%	7%	6%	6%	5%	3.6%

[a] N—No. of hydrogen scatterers per square cm; H—No. of protons scattered by protons; Ω—solid angle of defining counter; n—No. of incident protons; Φ—laboratory scattered angle; E—laboratory energy.

targets, perpendicular to the beam. The defining counter had an area of 0.916 inch^2 and was placed at an angle of 45° in the laboratory and 15.88 inches from the target, which contained 1.085×10^{22} hydrogen atoms per cm^2. The value of Z for the carbon subtraction ratio for the thick targets was 0.675. Table II gives a summary of the possible errors in the cross section resulting from the uncertainties in the listed items. The values stated give our estimate of the standard deviation in the cross section. All items were assumed to have standard deviations which could be added quadratically to give an estimate of the overall error. To estimate the possible error in the cross section expected from uncertainty in the energy, the cross section was taken to vary as $1/E$. This is roughly true for the energy range here considered. The final results obtained are then given in Tables III and IV.

EXPERIMENTS WITH LIQUID HYDROGEN TARGETS

Method 1, with counters to detect the scattered protons only, was used to explore the cross section to smaller scattering angles. The scattered protons were detected at angles from $12\frac{1}{2}°$ to 45° in the laboratory. The angular distribution in this range was determined at 95 Mev and also at 70 Mev.

Liquid hydrogen targets with thin walls were used with a large steel scattering chamber constructed for experiments with low temperature targets. The plan view is shown in Fig. 3. The chamber had windows placed suitably to allow the detection of scattered particles in a wide range of angles. The window through which the beam emerged was removed sufficiently far from the target to permit the shielding of counters from particles scattered by the window. In order to reduce background to a minimum for small scattering angles, the target chamber was connected directly to the external beam vacuum pipe. Flexible bellows allowed the rotation of the chamber to an angle of $7\frac{1}{2}°$ on either side of the center position. The center exit window extended from $-15°$ to 15° and another window was at 45°. Therefore, with the bellows attached, only particles within the range of laboratory angles $-20°$ to $+20°$, and 40° to 50° could be detected. The seal between the high vacuum of the target chamber and the fore vacuum of the beam pipe was made just behind the third slit. This point was sufficiently far from the target that it did not materially contribute to the background. Initial attempts were made to use a 5-mil aluminum foil, as an entrance window on the chamber. This arrangement would have given greater freedom of rotation for the chamber. However at small scattering angle, there was appreciable background from this foil.

TABLE III. Angular distribution 95 Mev (coincidence method) first series.

Center-of-mass angle (degrees)	Center-of-mass cross section (mb/sterad) counting statistics
40	4.93±0.12
50	4.81±0.10
60	4.81±0.10
70	4.68±0.09
80	4.53±0.10
90	4.54±0.09

TABLE IV. Cross sections at 90° c.m. (coincidence method) estimated standard errors.

Incident proton energy Mev	Center-of-mass cross section millibarns/sterad
14	11.4 ±0.80
52	8.83±0.62
69.5	5.96±0.36
78.5	5.40±0.32
95	4.65±0.25

The target was a flat can of copper beryllium 3 inches in diameter and 1 inch long in the direction of the beam. The ends were made with 2-mil-thick copper beryllium foils. A flat target design was chosen to keep the length of liquid hydrogen as uniform as possible over the entire beam. The purpose was to minimize effects of shifts in beam intensity distribution.

The cryostat using liquid helium as a refrigerating agent for the hydrogen was constructed originally by Stahl[3] and has been described elsewhere. The hydrogen vapor pressure in the target was monitored throughout the run and suitable corrections for variations in density of liquid hydrogen were made.

The counters were similar to those used in the recoil experiment, here however two sets were used simultaneously. The "North" counters covered laboratory angles from $+12\frac{1}{2}°$ to 45°, the "South" counters from $-12\frac{1}{2}°$ to $-20°$. The counters were shielded from particles scattered by the exit window by means of brass shields. Also throughout the experiment brass blocks were placed periodically in front of the counters so on protons from the target could reach the counters. The background observed with the counters blocked was

[3] C. A. Swenson and R. H. Stahl, Rev. Sci. Instr. 25, 608 (1954).

TABLE V. Typical liquid hydrogen data normalized to 1 volt. Proton energy 95 Mev.

	Counter open	Counter blocked	Net
	Target full 12½°		
South 2[a]	7746± 98	226±24	7520±101
North 2	8075±100	634±40	7441±108
3	7361± 96	65±13	7296± 71
	Target empty 12½°		
South 2	4521± 75	168±21	4353± 78
North 2	4648± 75	687±42	3961± 85
3	3906± 70	60±12	3846± 70
	Target full 45°		
North 3	2410± 55	53±12	2357± 56
	Target empty 45°		
North 3	146± 14	48±11	96± 17

[a] 2 ≡2-fold coincidences; 3 ≡3-fold coincidences.

attributed to the general neutron background; the "blocked" counting rate was strongly reduced by placing thin absorbers between the counters and was unaffected by stopping the beam at the cyclotron end of the external beam pipe. To eliminate any possible contributions from n-p scattering in the hydrogen target the counting rate was observed with the proton beam stopped at the cyclotron and with counters blocked and unblocked from the target. No difference due to n-p scattering in the target was found within the statistical accuracy of the final p-p results. The rate observed with counters blocked was therefore subtracted at all times from the counting rate without the blocks, the net rate being associated with proton beam induced events.

The background associated with the evacuated target was measured before and after the run with hydrogen. This arrangement was not ideal since the interval of time involved was usually two days, the constancy of the background over this length period was however reasonably good. The use of targets allowing the displacement of the liquid by gas or the use of an empty "dummy" target is to be preferred. In our case, this would have involved excessive liquid hydrogen and therefore helium consumption or further complications in cryostat construction.

The number of counts from scattering by materials other than hydrogen is not necessarily the same with hydrogen in the target as with the target empty. Low-energy particles may contribute to this background after traversing the empty target, yet may have insufficient energy to be detected after traversing a full target. This effect was indeed observed; at 70 Mev the background changed appreciably when an absorber, equivalent to the hydrogen in stopping power, was placed in front of the counters. The background subtractions for 70 Mev is therefore difficult to determine and provides the principal source of uncertainty. For 95 Mev, the beam was better collimated and the background was found to be almost independent of compensating absorber. Only scattering in the hydrogen will then vary the background, it should not be appreciable for the thin target used. In both the 95- and 70-Mev runs the target empty rate measured with compensating absorber in front of the counter was subtracted from the target full rate to give the net rate associated with hydrogen.

The target window itself bowed somewhat, the exact amount of bowing at liquid hydrogen temperatures was difficult to determine, therefore no attempt was made to obtain an absolute cross section with liquid hydrogen. Absolute cross section may of course be obtained by normalizing the results to the polyethylene data in the region of overlap.

The same beam-current monitoring equipment was used in this phase of the experiments and the beam energy was determined as before.

In Table V the results of typical measurements for liquid hydrogen are given. The extreme cases of high

TABLE VI. Angular distribution 95-Mev liquid hydrogen data (relative rates corrected to center-of-mass system, counting statistics only).

Center-of-mass angle	North telescope	South telescope	Average
25°	850±13	852±12	851±10
30°	833± 8	870± 7	852± 5
35°	863±10	844±10	854± 7
40°	841±10	879± 9	860± 7
80°	809± 5		
90°	815±10		

TABLE VII. Angular distribution 70-Mev liquid hydrogen data (relative rates corrected to center of mass, counting statistics only).

Center-of-mass angle	North telescope Usual absorber	North telescope No absorber	South telescope Usual absorber
25°	1209±29		1266±32
30°	1224±29		1217±39
35°	1214±26		1234±26
40°	1165±23		1218±36
80°	1208±15	1170±39	
90°	1145±30	1227±38	

TABLE VIII. Angular distributions. Ratio of cross sections to that at 90°.

	10°	25°	30°	40°	60°	80°	90°	Errors
30 Mev[a]	1.69	0.86	0.87	0.98	0.97	1.03	1.00	
95 Mev, CH_2 first series				1.08	1.06	1.00	1.00	4%
95 Mev, CH_2 second series				1.06	1.03	1.02	1.00	4%
95 Mev, liquid H_2		1.045	1.045	1.055		0.995	1.00	5%
170 Mev[b]	1.62	1.10	1.13	1.07	1.03			

[a] Reference 4.
[b] Reference 5—assuming $\sigma(60°)/\sigma(90°)=1.03$.

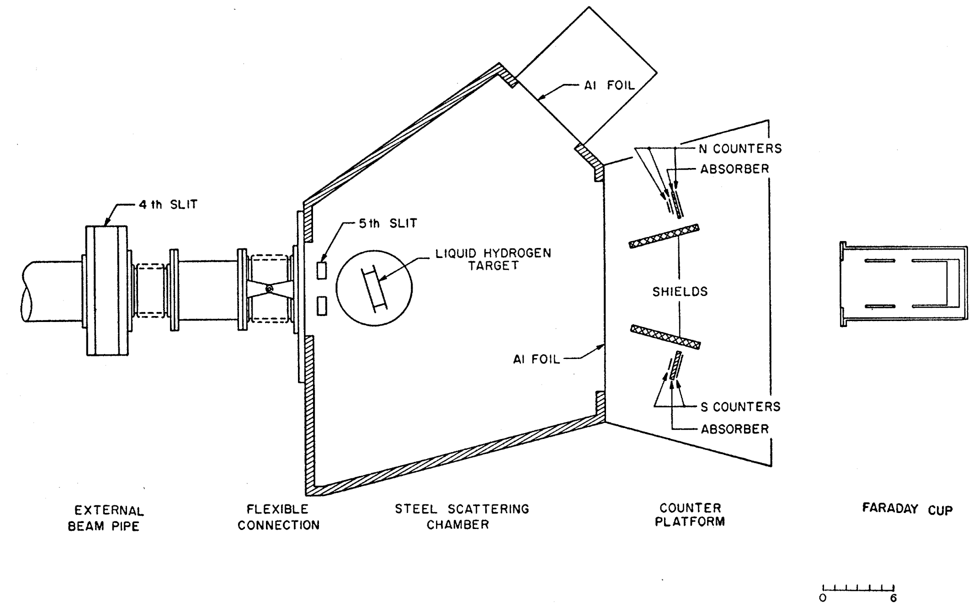

FIG. 3. Experimental arrangement, liquid hydrogen.

background at $12\frac{1}{2}°$ and low background at 45° are presented. Table VI gives the averages of all 95-Mev runs as converted to the center-of-mass system, relative rates alone are significant, only statistical fluctuations are given. In Table VII the results for 70 Mev appear, again only counting statistics are listed in the errors. For 80° and 90° two values are listed showing the effect of subtraction with and without absorber in the "North" telescope. The discrepancies illustrate the importance of possible systematic errors in the proper subtraction of background at this energy.

In Table VIII the ratios of the cross section at various angles to the cross section at 90° is given for both methods. The errors listed are those involved in the relative cross sections only. There seems to be a definite increase from 90° to 40° in our data at 95 Mev. The corresponding ratios for 30 Mev[4] and 170 Mev[5] are also given. Figure 4 shows the values of the differential cross section as a function of energy for the energy range from 30 to 270 Mev. We have changed the Rochester values[6] which were based on the determination of the $C^{12}(p,pn)C^{11}$ cross section to agree with more recent data on this cross section.[7] Previously

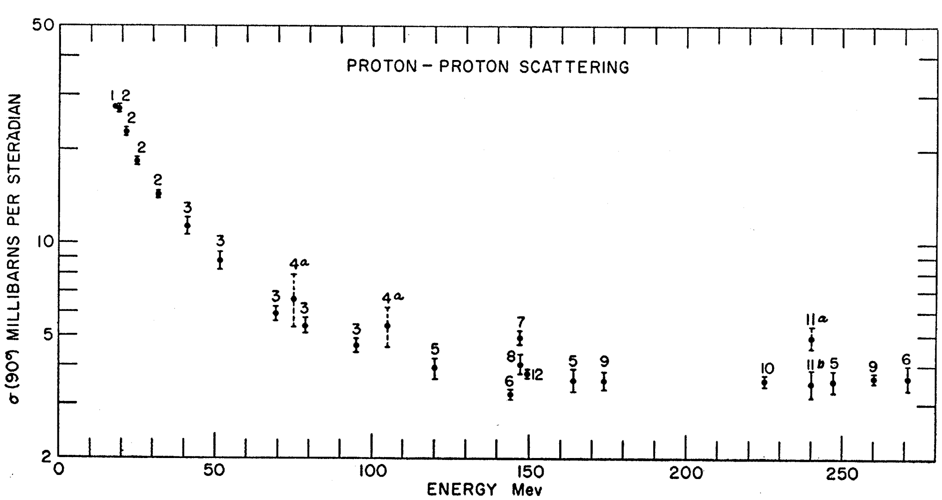

FIG. 4. Proton-proton scattering (center-of-mass cross section at 90°). *a*—Dashed points, as originally published, uncorrected for new carbon cross section; *b*—solid point corrected for new carbon cross section; 1—Princeton, reference 13; 2—Berkeley, reference 14; 3—Harvard, Present data; 4—Harvard (1951), reference 12 (uncorrected); 5—Berkeley, reference 2; 6—Chicago, reference 19; 7—Harwell, reference 9; 8—Harwell, reference 10; 9—Berkeley (60° cm), reference 5; 10—Berkeley, total σ, reference 16; 11—Rochester (*a*—uncorrected, reference 6; *b*—corrected, reference 7 and 8); 12—Harwell, total σ, reference 11.

[4] F. L. Fillmore, Phys. Rev. **83**, 1252 (1951).
[5] O. Chamberlain and J. D. Garrison, Phys. Rev.-**95**, 1349 (1954); J. D. Garrison, University of California Radiation Laboratory Report UCRL-2659 (unpublished).
[6] C. L. Oxley and R. D. Shamberger, Phys. Rev. **85**, 416 (1952); O. A. Towler, Phys. Rev. **85**, 1024 (1952).
[7] Birnbaum, Crandall, Millburn, and Pyle, University of California Radiation Laboratory Report UCRL-2756 (unpublished).

these appeared nearer 5 mb/sterad. The proper correction is not completely clear since two independent absolute calibrations of the β counters were made at Rochester.[8]

No correction has been made to the earlier Harwell data[9] since the beam was independently calibrated. More recent data give a somewhat lower differential cross section,[10] also an independent measurement of the total cross section would give a decreased differential cross section.[11]

A similar correction would also lower the earlier Harvard results,[12] to 4.3 mb at 105 Mev and 5.3 mb at 75 Mev. The extrapolation to these energies of the $C^{12}(p,pn)C^{11}$ cross section seems somewhat uncertain, however. We have therefore not made the correction at this time. The present measurements do not involve this uncertainty, and the absolute cross sections obtained in this experiment should be more reliable. A smooth connection can now be made between the data near 30 Mev[4,13–15] to the energy-independent behavior between 120 Mev and 400 Mev.[2,5,6,9–11,16–19]

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[8] C. L. Oxley (private communication).
[9] Cassels, Pickavance, and Stafford, Proc. Roy. Soc. (London) **214**, 262 (1952).
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[15] Cork, Johnston, and Richman, Phys. Rev. **79**, 71 (1950).
[16] Chamberlain, Pettengill, Segrè, and Wiegand, Phys. Rev. **93**, 1424 (1954).
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Characteristics of K^+-Particles*†

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A large nuclear emulsion stack was exposed in the magnetically analyzed beam of K^+ particles, at the Berkeley Bevatron. The secondaries of stopped K-mesons have been analyzed, and examples of all the known modes of decay: $K_{\mu2}$, $K_{\pi2}$, K_{e3}, $K_{\mu3}$, τ, and τ' have been identified. The decay processes of the $K_{\mu2}$, $K_{\pi2}$, and τ' mesons have been confirmed, and a possible decay scheme for the $K_{\mu3}$ has been considered. The masses of the particles decaying in the different ways have been determined from momentum-range measurements, and for $K_{\mu2}$ and $K_{\pi2}$ particles, from the Q of the decay as well. The masses of all the particles are consistent with a value of 965 m_e, within about 10 m_e. The relative frequencies of the various modes of decay have been estimated, and by comparison with other data, it is found that the apparent lifetimes of all the particles are $\sim 1\times10^{-8}$ sec.

INTRODUCTION

SINCE the discovery of heavy mesons, a considerable amount of information has been collected on their decay products, masses, and lifetimes. Among positive particles there have been phenomenologically identified six types of heavy mesons, and these have been named the τ, the $K_{\pi3}$ or τ', the $K_{\mu3}$, the K_{e3}, the $K_{\pi2}$, and the $K_{\mu2}$, each characterized by a particular decay mode. Experimental evidence thus far presented indicates a mass of $\sim 1000\ m_e$ for all particles, and lifetimes varying from 10^{-8} to 10^{-10} sec.[1]

These particles, together with all heavy unstable

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[1] For summaries of data, see *Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1955), and Dilworth, Occhialini, and Scarsi, Ann. Rev. of Nuc. Sci. **4**, (1955).