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Proton-Proton Scattering at 8 Mev

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A coincidence method of studying the scattering of protons by protons has been developed and applied to the 8-Mev protons obtained from the Princeton cyclotron. Relative measurements of the scattering cross section as a function of the angle of scattering are most consistent with theoretical cross sections calculated, assuming S wave scattering only. However, the accuracy of the experiment is not great enough definitely to exclude P wave scattering effects, positive or negative. An absolute measurement of the scattering cross section has been made and the experimental value $1.7\pm.1\times10^{-25}$ cm^2 agrees with the theoretical value 1.80×10^{-25} cm to within the experimental uncertainty.

1. INTRODUCTION

ONE of the immediate problems of nuclear physics is the determination of the nature of the short range forces between elementary particles of the nucleus. The study of the anomalous scattering of protons by protons has given much information on this subject. The first work was done by Wells,[1] and White.[2] Tuve, Heydenburg, and Hafstad[3] have examined proton-proton scattering in the energy range from 200 kev to 1.6 Mev, and Herb[4] and others have extended the measurements to proton energies of 2.4 Mev. Breit, Condon, and Present,[5] and Breit, Thaxton, and Eisenbud[6] have shown that all of the measurements can be adequately fitted by a theory which assumes only the effects of Mott type scattering, plus an anomaly obtained from the solution of the Schroedinger wave equation corresponding to the partial wave of zero angular momentum. The best fit of the data was obtained when a square potential hole 10.5 Mev deep and of electronic radius, (e^2/mc^2), was used. However, other shapes required by the various nuclear force theories fit nearly as well. The present experiment on proton-proton scattering was carried out with 8 Mev protons, since the differences in the scattering predicted by various theories at this energy are much larger than those which obtain in the region already investigated.

Unfortunately, this work was interrupted by the war at a time when consistent results were just beginning to be obtained. The data are presented, even though the accuracy is not high, because in arriving at this stage a number of difficulties were met and overcome, and it is thought worth while to point out some of these difficulties to future workers in this field.

2. METHOD

To eliminate to a large extent background counts, a coincident counting method first tried out by one of us at Berkeley was used. In the collision of like particles, one of which is initially at rest, the angle between the two velocity vectors after collision is 90°.[7] By use of a narrow proton beam and a thin cellophane foil as scatterer, the point of scattering was well defined so that two counters fixed on rotating arms at 90°, with the scattering foil at the center of rotation, could be used to count the scattered and the recoiling particle in coincidence. This prevented counting particles scattered from the oxygen and carbon of the foil or from gas in the vacuum chamber. The apparatus is shown schematically in Fig. 1.

3. COUNTERS

Although good results have been obtained by others in counting protons with an ionization chamber and linear high gain amplifier, and indeed this system was tried out in early work by

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[1] W. H. Wells, Phys. Rev. **47**, 591 (1935).
[2] M. G. White, Phys. Rev. **47**, 573 (1935).
[3] M. A. Tuve, N. P. Heydenburg, and L. R. Hafstad, Phys. Rev. **50**, 806 (1936).
[4] R. G. Herb, D. W. Kerst, D. B. Parkinson, and G. J. Plain, Phys. Rev. **55**, 998 (1939).
[5] G. Breit, E. U. Condon, and R. D. Present, Phys. Rev. **50**, 825 (1936).
[6] G. Breit, H. M. Thaxton, and L. Eisenbud, Phys. Rev. **55**, 1018 (1939).

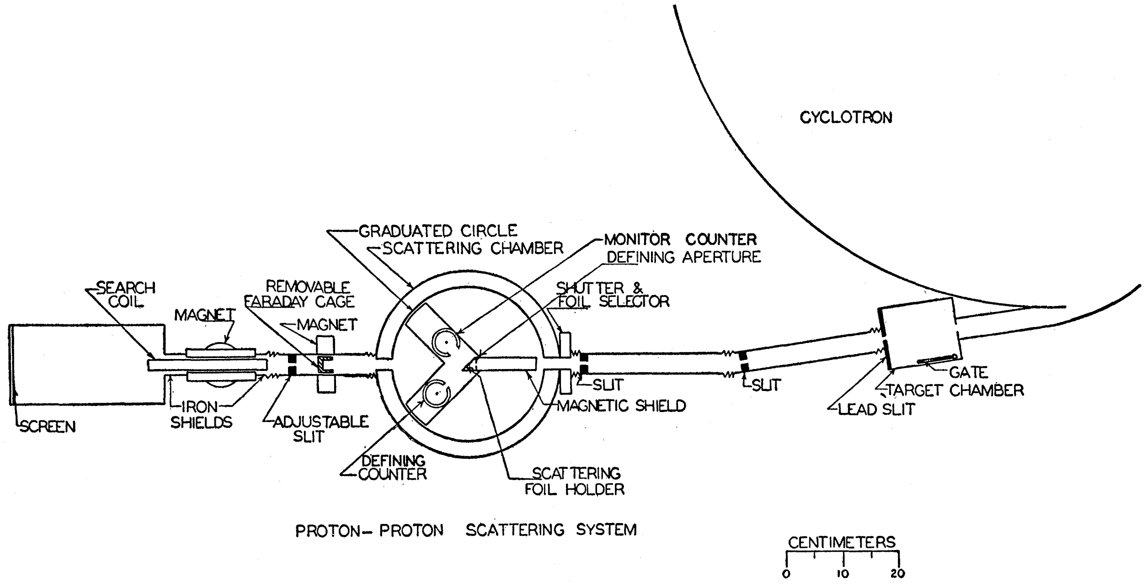

FIG. 1. Schematic drawing showing three slit energy-selecting system, scattering chamber, and the energy measuring device.

one of us at Berkeley, it was decided to use proportional counters for the following two reasons. First, owing to the small amount of ionization produced by several million volt protons passing through a few centimeters of low pressure gas, considerable amplification is required, so the large gas-amplification obtained in this type of counter is very desirable. Second, it is quite difficult completely to eliminate radio-frequency pick-up from the cyclotron oscillator in the a.c. lines and amplifier circuits, making the extremely high electrical amplification required with the non-multiplying chamber less convenient to use.

Because of the neutron field which always surrounds an operating cyclotron, it was necessary to design the counters so that no hydrogenous material was exposed to their sensitive regions, thus eliminating proton recoils. The counters used are illustrated in Fig. 2. It was necessary to use various sized apertures in the counters, as is explained in Section 9. Interchangeable diaphragms with circular openings could be placed over the elongated windows. This shape of window was chosen for the monitoring counter (and hence for both, to keep them internally identical) because the area determined by drawing all possible "conjugate" proton paths corresponding to protons being scattered from any part of the finite scattering area and into any part of the circular aperture of the defining counter, is oval in shape. Thus, considerable height to the maximum useful oval was obtained, without needlessly increasing the background count as would have been done by using a large circular opening..

In order to maintain a sufficiently uniform field (and hence to secure uniform pulses) the long axis of the hole had to be parallel to the axis of the counter, and not perpendicular to it, as was found by trial. The length was limited by the depth of the scattering chamber, and as the length must also be greater than a certain minimum to obtain a uniform field, a compact design of the counter ends was essential. The counters were completely assembled with neoprene gaskets. The wire used was 0.005″ steel. The windows were 0.0001″–0.0005″ Cellophane made gas tight with lead gaskets punched out of foil about 0.002″ thick by means of a simple concentric punch.

For scattering at small angles, it was found desirable to put about 0.006″ of aluminum over the defining counter window to slow the protons down somewhat and increase their specific ionization, thus improving the voltage plateau. The counter at large angles, which received lower

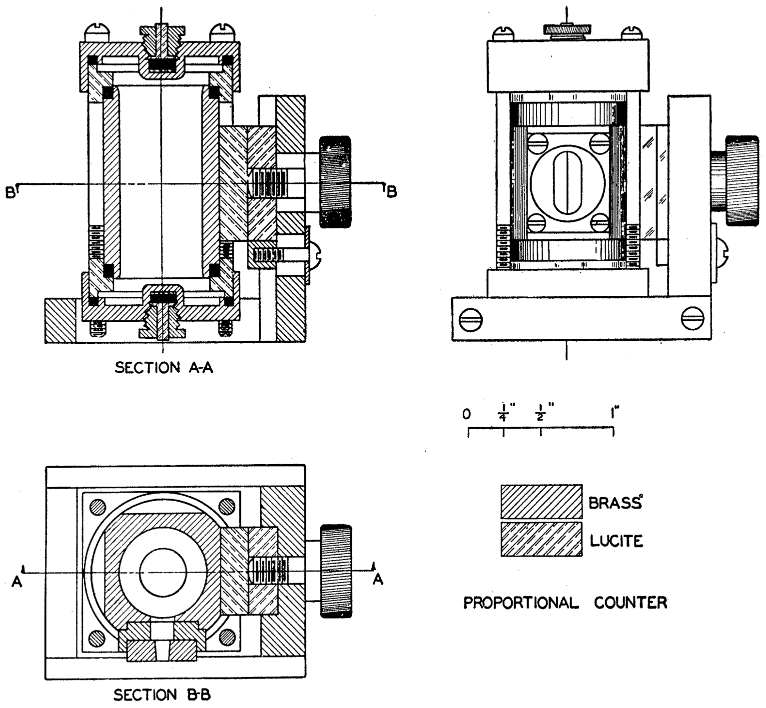

FIG. 2. The proportional counter.

energy protons, always had a 0.0001″ Cellophane window. The counters were filled with dry air at about 7 cm pressure, measured with a mercury manometer and kept constant to $\frac{1}{2}$ mm during a run.

The efficiency of this type of counter was measured by sending alpha-particles through two in series, the front one having a hole in back. First the pulses in the rear chamber were counted, and next the coincidences between the two. The efficiency was thus found to be better than 99 percent. The over-all resolving time of the counters and electrical circuits was measured by placing separate alpha-particle sources in front of two separate counters and counting, first the pulses in the individual counters, and then the accidental coincidences. The resolving time was 5×10^{-6} second computed from the usual formula

$$N=2n_1n_2\tau, \qquad (1)$$

where N = accidental coincidence counting rate; n_1, n_2 = counting rates in the two counters, respectively; and τ = resolving time. This fairly long resolving time arose from the slowness of the high gain amplifiers available at that time (1940).

4. ALIGNMENT

After having determined that the proton beam was horizontal, the scattering foil holder and iron magnetic shield (see Fig. 1) were leveled and the iron shield centered in the chamber. A rectangular block of brass was machined flat on one end, and a scratch made on its side, perpendicular to the flat end. This scratched face was then sprayed with fluorescent material. When the block was placed on the floor of the chamber with the scratch vertical and intersecting the center line of the chamber, the proton beam was turned on. The chamber was then rotated slightly about a vertical axis until the fluorescent spot caused by the beam was split by the scratch. Thus the beam was accurately parallel to the center line of the chamber. A steel mandril was made to fit snugly into the magnetic shield when the defining aperture was removed. With the other end of the mandril slipped into the window of the defining counter, the counter was fastened in place on the rotating arm, and the index was set on the zero of the graduated circle. The rotating arm was then turned until the index read $89\frac{1}{2}°$,[7] and the mandril pushed into the window of the monitoring counter, which was next fastened in place. To assure that the axis of rotation of the counter arms was perpendicular to the beam and to the floor of the chamber, the heights of the counter apertures above the floor were measured for several angular positions, and agreed to 0.001″.

Another method of checking the alignment of the counters was to replace the counter window with a brass disk on which cross lines had been scratched and fluorescent material sprayed. With the beam coming through the chamber the counter was turned into the beam, and the centering of the fluorescent spot on the cross lines was observed with the index of the angular scale set a 0° and $89\frac{1}{2}°$ for the defining and monitoring counters, respectively.

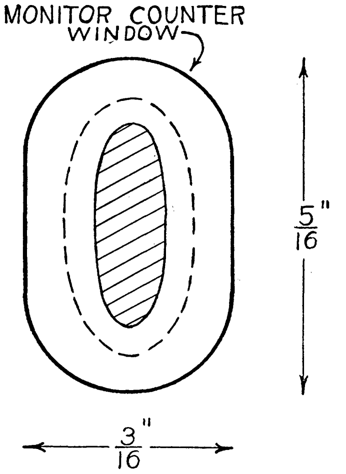

FIG. 3. The thick outside line indicates the area of the monitor counter aperture. The shaded area indicates where the recoils of protons scattered into the defining counter can enter the monitor counter when the defining counter is at 15°. The dotted curve indicates the magnitude of the effect of multiple scattering in diffusing the shaded area.

5. EFFECT OF MULTIPLE SCATTERING

In an early attempt to increase the ionization of the proton by slowing it down with foils placed in the scattered beam, the yield was found to decrease. This was found to be caused by the diffusion of the beam by small angle scattering and showed the necessity of using very thin scatterers. The multiple scattering of the protons can be calculated by the application of Williams'[8] formula. According to it, the mean square deflection[9] is given by:

$$\langle\theta^2\rangle = \frac{\pi}{2}\left(\frac{Ze^2}{E}\right)^2 Nt \log\frac{Z^{4/3}Nth^2}{2m^2v^2}, \qquad (2)$$

where Z is the atomic number of the scattering foil, e the electronic change, E the energy, N the number of nuclei per cm³, t the thickness of foil, h Planck's constant, m the electronic mass, and v the proton velocity.

Let us assume the Cellophane in the foil has the molecular formula $C_6H_{10}O_5$ and has a density of 1.15 g/cm³. Then the root mean square deflection becomes

$$\langle\theta^2\rangle^{\frac{1}{2}} = 0.5t^{\frac{1}{2}}/E_{\mathrm{Mev}} \text{ radian.} \qquad (3)$$

The log term was evaluated for a one Mev proton, then its variation with E neglected. A factor of $\frac{2}{3}$ has been included in Eq. (3) because the protons are as likely to be scattered near the back of the foil as near the front of the foil, and the average value of $(X)^{\frac{1}{2}} = \frac{2}{3}(X_{\max})^{\frac{1}{2}}$.

In Fig. 3 the heavy oval line represents the opening of the monitor counter which is 4 cm from the scatterer. Let us consider protons scattered at 15° from a parallel beam 2 mm in diameter into the monitor counter whose aperture is $\frac{1}{16}$″ in diameter and which is 7.6 cm from the

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[7] Actually this angle ϕ between the two proton velocity vectors is given by the expression

$$\tan\phi = 2c^2(1-V^2/c^2)^{\frac{1}{2}}/V^2\sin\theta^*,$$

where θ^* is the angle of scattering in the center of gravity system; c is the velocity of light; and V is the velocity of the protons relative to the center of gravity. For the relativistic case V is given by

$$V = v/[1+(1-v^2/c^2)^{\frac{1}{2}}],$$

where v is the velocity of the incident proton in the laboratory system. When the scattering angle in the laboratory system is between 45° and 15°, $89\frac{1}{2}°$ is a satisfactory value for ϕ since the angular aperture of the monitoring counter is several degrees. The exact value of ϕ for various proton energies is given below; for $\theta^* = 90°$

Proton Energy (Mev)	ϕ
0	90°
8	89° 52′ 40″
16	89° 44′ 40″
25	89° 36′ 34″
50	89° 14′ 20″
100	88° 30′ 50″
1000	77° 51′ 30″

[8] E. J. Williams, Proc. Roy. Soc. **169**, 531 (1939).

[9] This is defined by

$$n(\theta)d\theta = [2/\pi\langle\theta^2\rangle]^{\frac{1}{2}}\cdot\exp(-\theta^2/2\langle\theta^2\rangle)\cdot d\theta$$

where $\langle\theta^2\rangle$ is the mean square deflection.

TABLE I. Collected scattering data.*

Date	Holder	Scattering angle $=\theta$	$C=\frac{\text{counts}}{8}$	Mean square error (%)	Total galv. defl. $=D$	$\frac{C}{D}$	Window	$\frac{C}{D\cos\theta}$	Angles for which ratio of yields is taken	Ratio of yields	M.s.e. of ratio (%)
1/21/41	90°	45°	903	1.2	17.27	52.3	1/8″	74.0	48–45	1.04	2.2
1/21/41	90°	48°	258	2.0	5.00	51.6	1/8″	77.1	48–45		
3/24/41	90°	50°	634	1.5	18.6	34.1	1/8″	53.2	50–45	0.97	2.0
3/24/41	90°	45°	813	1.2	20.9	38.9	1/8″	55.0	50–45		
3/25/41	90°	45°	302	2	7.76	38.91	1/8″	55.0	35–45	1.02	2.4
3/25/41	90°	35°	598	1.4	13.00	46.1	1/8″	56.2	35–45		
3/25/41	90°	45°	441	1.8	46.07	9.58	1/16″	13.5	35–45	1.03	1.8
3/25/41	90°	35°	235	2.5	20.67	11.4	1/16″	13.9	35–45		
3/30/41	90°	30°	693	1.3	24.70	28.1	1/8″	32.4	30–45	1.02	1.8
3/30/41	90°	45°	686	1.3	30.57	22.5	1/8″	31.8	30–45		
3/30/41	90°	40°	508	1.6	20.00	25.4	1/8″	33.2	40–45	1.01	2.0
3/30/41	90°	35°	481	1.6	18.00	26.7	1/8″	32.6	35–45	1.02	2.2
4/12/41	90°	45°	905	1.2	147.31	6.15	1/16″	8.70	30–45	1.01	1.7
4/12/41	90°	30°	815	1.2	107.40	7.58	1/16″	8.76	30–45		
4/14/41	90°	45°	493	1.6	86.44	5.71	1/16″	8.08	30–45	1.01	2.0
4/14/41	90°	30°	869	1.2	122.40	7.09	1/16″	8.18	30–45		
4/19/41	90°	45°	2135	0.8	30.07	71.0	1/8″	100.3	35–45	1.01	1.2
4/19/41	90°	35°	1862	0.8	22.58	82.6	1/8″	101.0	35–45		
6/20/41	40°	30°	2243	0.8	52.21	43.1	1/8″	49.7	25–30	0.96	1.2
6/20/41	40°	25°	1972	0.8	45.49	43.3	1/8″	47.8	25–30		
7/3/41	40°	30°	797	1.2	30.85	25.8	3/32″	29.8	25–30	0.99	2.0
7/3/41	40°	25°	523	1.6	19.56	26.8	3/32″	29.6	25–30		
7/9/41	30°	25°	2062	0.8	68.87	29.9	3/32″	33.0	20–25	0.97	1.2
7/9/41	30°	20°	1951	0.8	64.95	30.1	3/32″	32.0	20–25		
7/12/41	30°	25°	2063	0.8	181.84	11.35	1/16″	12.52	20–25	0.94	1.2
7/12/41	30°	20°	2012	0.8	181.95	11.05	1/16″	11.75	20–25		
7/12/41	30°	15°	1297	1.0	116.17	11.15	1/16″	11.55	15–25	0.92	1.3

**Summary of Table I:*

Angles for which ratio of yields is taken	Weighted average of yield ratio	M.s.e. of ratio (%)
50–45	0.97	2.0
48–45	1.04	2.2
40–45	1.01	2.0
35–45	1.01^7	0.9
30–45	1.01^3	1.1
25–30	0.96^8	1.0
20–25	0.95^5	0.9
15–25	0.92	1.3

Angles for which ratio of yields is calculated from Table I	Weighted average of yield ratio	M.s.e. of ratio (%)
25–45	0.98^0	1.5
20–45	0.93^7	1.7
15–45	0.90	2.1

scatterer which is placed at 30° with respect to the direction of the beam. Then all the "conjugate" protons (i.e., the recoil protons at 90° to the scattered protons) would fall into the shaded area in the monitor opening, if there were no multiple scattering. This area was found by a simple geometrical construction. The distribution of the conjugate protons within the shaded area was not found; it would obviously not be uniform. However, as long as the limits of the area fall within the opening of the monitor counter, then no counts should be lost. In some of our earlier work, larger apertures were used on the defining counter so that the shaded area overlapped the opening of the monitor counter and hence some counts were lost.

Now let us consider the effect of multiple scattering due to a Cellophane foil 0.1 mil thick. The 8 Mev protons scattered at 15° will have their energy reduced by the collision to 7.5 Mev ($=E_0\cos^2\theta$). The thickness of the foil (at 30° to direction of beam) (see Table I) for protons passing through at 15° is $0.1/\sin\theta=0.4$ mil. Hence the root mean square deflection according to Eq. (3) is 0.21×10^{-2} radians or 0.12°. The recoil or conjugate protons at 75° have their energy reduced to 0.54 Mev, and the foil thickness in that direction is 0.1 mil. The root mean square deflection for the recoil protons, then, is 1.5×10^{-2} radian or 0.85°. Thus the total root mean square deviation from 90° between recoil and scattered protons is $(0.85^2+0.12^2)^{\frac{1}{2}}=0.86°$. This causes the limits of the shaded area of Fig. 3 to become diffuse. If all the protons were concentrated on the limiting edge of the shaded area without multiple scattering, then the dotted line represents the root mean square deflection outside the shaded area with multiple scattering. The extreme loss is then given by

$$1-\left(\frac{2}{\pi^{\frac{1}{2}}}\right)\int_0^{X_{\max}}\exp(-X^2)dX$$

where

$$X_{\max}=\theta_{\max}/2^{\frac{1}{2}}\langle\theta^2\rangle^{\frac{1}{2}},$$

and θ is the angle between the edge of the shaded area and the edge of the aperture. For our geometry shown in Fig. 3, $\theta_{\max}/\langle\theta^2\rangle^{\frac{1}{2}}$ is about 2.5 so not over 1.3 percent would be scattered outside the monitor counter window. Actually the loss should be far less as the density of protons will be greatest at the center of the shaded area rather than at the edges as we have assumed.

We have considered the worst case at 15°. At larger scattering angles the energy of the proton scattered into the monitor counter rapidly increases and the multiple scattering then decreases rapidly. At some of the larger angles a $\frac{1}{8}''$ diameter aperture could be used in addition to the $\frac{1}{16}''$ diameter aperture.

The effect was studied experimentally by measuring the yield of scattered protons per unit solid angle as a function of the solid angle (defining counter) and as a function of the thickness of the scattering foil. Effects could be produced using very thick foils or very large solid angles, but for the conditions used in taking the final data no multiple scattering effects were observed. To minimize any possible effects of multiple scattering, the scattering foil was not always placed normally to the incident proton beam but was placed at such an angle that the low energy protons scattered into the monitor counter would pass through a minimum of scattering foil, i.e., come out of the scattering foil normally. This was done by making several holders which fit snugly into the magnetic shield, and which were cut off at various angles on the end to which the foil was cemented. Thus for comparing the yields at 15°, 20°, and 25°, a holder cut off at an angle of 30° was used. For scattering at 25°, 30°, and 35°, one cut off at 40° was used, while for measuring at 30°, 35°, 40°, and 45°, one cut at 60° was used. For the absolute yield determination at 45° the foil was held normally to the incident beam, and not cemented, but supported in a removable cap so it could be weighed before and after use.

6. CHARGE MEASUREMENT

The incident proton current was collected in a faraday cup, which could be removed by means of an insulated sliding seal when it was desired to allow the beam to pass into the energy measuring system. Various magnetic fields and voltages were applied to the cup to study the effect of secondary electrons. That no effect on the yield was observed for fields up to 1000 gauss is probably because of the fact that the stray cyclotron field was about 100 gauss which kept secondaries from getting out. From the faraday cup a concentric evacuated cable led to a switching arrangement and thence to a specially constructed evacuated condenser. The concentric cable consisted of 1″ brass tubing soldered into standard stream-lined copper elbows. At each elbow (3 in all) were placed two thin lucite wafers fitting snugly inside and held in place by the inserted brass tubing. The wafers were perforated with several holes to decrease their conduction and to increase pumping speed through the cable, while through the center hole was inserted a piece of $\frac{1}{8}''$ copper tubing, extending around the bend. The conductor in the cable was 0.006″ steel wire passed through the $\frac{1}{8}''$ tubing around the elbows and held firmly at the ends of the cable by low electrical leakage lucite fittings. This construction served the following purposes: (a) the brass tubing provided a shield against radio-frequency pick-up which might have been rectified in the switch or elsewhere to produce spurious charges, and (b) the evacuated region around the wire prevented loss of charge due to ionization from the cyclotron radiation.

The condenser on which the charge was accumulated, and which was later discharged through a ballistic galvanometer, was designed to be as free from leakage as possible. It consisted of two interlaced stacks of copper plates $3''\times 4''$ in area and $\frac{1}{16}''$ thick piled up with brass spacers $\frac{1}{8}''$ thick at the ends of each plate so that the two consecutive plates of one stack, placed crosswise to the intervening ones of the other stack, were separated from it by $\frac{1}{32}''$. One stack was supported by lucite pillars at the bottom, which provided the only leakage path between it and the other (grounded) set, except for the lucite insulated lead-in which passed through the vacuum jacket. This jacket consisted of a piece of brass tubing sealed by neoprene gaskets into the end plates, and clamped by bolts extending from end to end. A pump-out valve and vacuum-pressure gauge were provided, so that if desired, the condenser could be used for a pressure ionization chamber. The capacity was measured as 0.00937 μf. Extensive leakage tests were made with the cyclotron running, so a small correction could be made in determining the absolute number of protons incident on the scattering foil. For the relative angular distribution measurements this correction was not made, since all runs in a given set were made for the same length of time, with a nearly constant beam intensity. A great advantage of the vacuum condenser was the total absence of soakage of charge into the dielectric. This soakage effect was found troublesome with several standard mica condensers tried out. Two or three minutes after these condensers were discharged, a second discharge showed that a percent or so of the original charge was left. The almost complete elimination of dielectric material in the vacuum cable and condenser system prevented this difficulty.

The absolute charge sensitivity of the galvanometer was determined in two independent ways; namely, by the current-time method, and by the potential-capacity method. In the first case a small current obtained from a stabilized 2000 volt supply and S. S. White resistors was fed into the condenser for various measured times. The current was measured with a sensitive galvanometer. The charged condenser was then discharged through the ballistic galvanometer. The system was found to be linear within 0.5 percent for throws from 2 to 25 centimeters. This calibration was made frequently, and always immediately before and after an absolute yield run. For the second method of calibration of the charge measuring system, the capacity of the condenser was measured with two different bridges. Both bridges gave the value 0.00937 ±0.00003 μf, the second one showing the capacity to be independent of frequency from 60 to 1000 cycles per second. A dry cell, reserved for this purpose, was then connected across the condenser through a high resistance, its potential difference measured, and the condenser then disconnected and discharged.

Typical values for the first method are:

Current	Time	Charge	Ballistic throw	Coulomb/mm
2.87×10^{-9} amp	30 sec	8.61×10^{-8} coulomb	12.23 cm	6.54×10^{-10}

And for the second method:

Cell e.m.f.	Capacity of condenser	Charge	Ballistic throw	Coulomb/mm
1.365 v	0.00937 μf	1.279×10^{-8} coulomb	1.95 cm	6.55×10^{-10}

Agreement of the two methods was always better than one-half percent. Both methods ultimately depend on the e.m.f. of a standard cell, since the calibration of the current galvanometer in the first, and the measurement of the dry cell in the second, each made use of it.

7. ENERGY MEASUREMENT

The energy of the protons emerging from the 3 slits was measured by means of an auxiliary magnetic field deflecting system.[10] This device was capable of measuring the energy to within about 1 percent, and showed that the selected beam was homogeneous to this degree. The energy of the protons used in these experiments was 8.0±0.1 Mev. Accuracy in this value is of no theoretical importance, inasmuch as other duties prevented the carrying out of the experiments over a range of energies, which would be useful for an accurate determination of the range of nuclear forces.

8. CELLOPHANE

It was early decided that Cellophane would be a useful material for the scattering foil because it is tough, contains a relatively large percentage of hydrogen by weight (6.22 percent) and presumably has a known empirical formula—$X(C_6H_{10}O_5)$. Commercial Cellophane contains a small amount of glycerine to keep it from becoming brittle, but since it was desired to determine the number of hydrogen atoms per square centimeter of the foil by weighing, a pure chemical compound was required. The usefulness of Cellophane in these experiments is owing to the cooperation of Dr. Nelson Allen of the Cellophane Analytical Research Division of E. I. du Pont de Nemours and Co. From him were obtained several batches of very pure Cellophane, cast in special thin sheets, down to 0.00008″. These thin foils were necessary to minimize the multiple scattering effect discussed above.

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[10] E. Creutz and R. Wilson, Rev. Sci. Inst. **17**, 385 (1946).

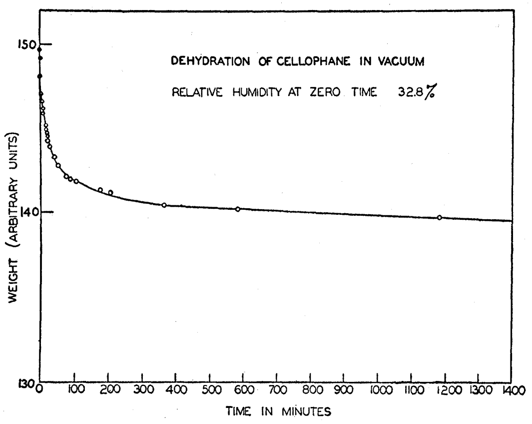

FIG. 4. Weight of 0.005 inch thick Cellophane foil ½″ in diameter as a function of time in vacuum. The decrease in weight is because of dehydration. Relative humidity of the air with which the foil was originally in equilibrium was 32.8 percent.

The foils used were punched out of sheet as discs ⅜″ in diameter. The punch used was made of drill rod, hardened and ground, and its diameter was measured before and after punching out a foil. The diameter of aluminum disks punched out by it were also measured as a check. The Cellophane disks were then weighed on a quartz fiber torsion microbalance which follows the same general design as given in Strong,[11] except that it was built into a chamber which could be evacuated. The weight of the foil was observed as a function of the time after evacuation, while a large part of the absorbed water was removed. It was observed[12] that the dehydration proceeded rapidly at first (probably corresponding to loss of water absorbed on the surface), and then much more slowly, presumably as water diffused out of the interior of the cellophane and then evaporated. This effect is shown in Fig. 4. With the 0.0005″ foil about 20 hours were required for the weight to arrive within 0.5 percent of its final equilibrium value. With 0.0001″ foil the "volume effect" was much less pronounced, and the weight became essentially stationary in about four hours. The same effect was noticed by the variation of the yield of scattered protons from a foil freshly put into the scattering chamber. After about a day the yield settled down and remained constant, showing that there was no appreciable deterioration of the Cellophane due to the beam's passing through it.

Since it was not known if all of the absorbed water had left the foil even after the weight had become constant, it was desirable to have an analysis of the material made under as nearly as possible the conditions obtained in the scattering chamber. Mr. E. L. Stanley, of the Department of Chemistry at Princeton University, kindly made some micro-analyses of the Cellophane. In foils which had been in vacuum for several days he found (6.6 ± 0.3) percent hydrogen. Later the National Bureau of Standards made some analyses, obtaining (6.45 ± 0.1) percent. Further analyses by a modified technique were made by Dr. Yensen, of Westinghouse Research Laboratories, whose results did not conflict with these. Considering the theoretical value of 6.22 percent, one sees an unpleasant uncertainty in the hydrogen content of the scatterer used for the absolute yield determination, which would need to be cleared up before an accuracy better than a few percent could be hoped for by this method. This difficulty, however, does not affect the relative angular distribution measurements of scattered protons.

9. METHOD OF TAKING THE DATA

Although the counters were constructed to be rather insensitive to neutrons, more or less background in each single counter was always found even with the proton beam kept out of the scattering chamber by means of a shutter. This was in a large part probably owing to the fact that the gas used in the counters was air, providing a source of alpha-particles from the reaction $N^{14}(n,\alpha)B^{11}$. However, since the resolving time of the coincidence system was measured to be sufficiently small, it was not difficult to keep the individual counting rates (including the protons scattered from the oxygen and carbon of the foil) down so that the accidental coincidence rate was low. In all runs, repeated checks were made on this background rate, and in the worst cases (where very small proton admitting apertures were used on the defining counter, so that a rather large beam was required, which not only increased the neutron intensity but also the spurious proton rate in the monitor

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[11] J. Strong and others, *Procedures in experimental physics* (McGraw-Hill Book Company, Inc. 1942).

[12] E. Creutz and R. Wilson, J. Chem. Phys. **14**, 725 (1946).

counter) it amounted to 3 or 4 percent. At angles from 45° to 30° where larger apertures could be used, so that the total beam required to obtain data in a reasonable time was smaller, the background coincidence rate was negligible, amounting to less than 0.5 percent. In all cases it was found advisable to keep the pressure in the cyclotron low to decrease the number of neutrons produced inside the dees.

The runs made, the foil holder and aperture used, the number of counts with the mean square percentage error, the ballistic galvanometer deflection, the number of counts divided by this deflection, this quotient divided by the cosine of the angle of scattering, and the yield ratios obtained are listed in Table I. The fact that different yields are obtained for the same angle in some cases, means that the foil was changed between runs. The parenthesis indicates runs for which the same foil was used.

In Fig. 5 are plotted the ratios of the scattering yields per unit solid angle in the center of gravity system, measured at the laboratory angle θ, to that at 45°. The vertical lines indicate the uncertainty corresponding to the mean square counting error. The mean square errors are computed from the square root of the number of counts and increase at smaller angles because in calculating the relative cross section for, say 20°, several ratios must be taken, namely 20° to 25°, 25° to 30°, and 30° to 45°, each one of which adds to the error. Any errors in alignment of the apparatus would be larger at smaller angles than at 45°, so all points would be raised by the elimination of such errors.

The point at 15° is least certain because possible effects due to misalignment and multiple scattering are greatest at small angles. Both effects tend to lower the experimental result. Another source of error at 15° can arise because the protons entering the monitor counter have an energy of only 0.54 Mev. Hence they barely penetrate the thin (about 0.1 mil) Cellophane scattering foil and window of the counter. Because of the straggling of range, it is possible that all protons will not penetrate the two foils. This effect will also tend to lower the experimental result. Thus the cross section at 15° can be regarded as a lower limit as the arrow in Fig. 5 indicates. All the above effects should become much smaller at 20° where the protons entering the monitor counter now have an energy of about one Mev. Since the cross section at 15° has a reasonable value, we can regard the value at 20° as being quite reliable.

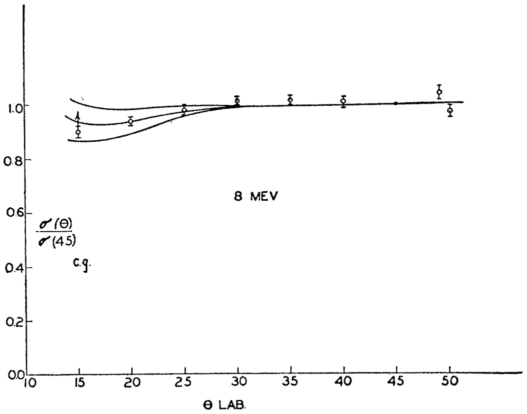

FIG. 5. Ratio of the proton-proton scattering yield at various angles to the yield at 45° in the laboratory system. The vertical lines are drawn to correspond to the mean square counting error. However, as explained in the text, the point at 15° is a definite lower limit, the upper limit is uncertain. The solid curves are calculated from a square potential well 10.5 Mev deep and of radius e^2/mc^2. Middle curve is calculated on the assumption of S scattering only. Upper and lower curves include the effect of P scattering for repulsive and attractive potential respectively.

10. ABSOLUTE YIELD

The absolute yield determinations were made at 45°. The results of two such runs are shown in Table II.

The cross section per unit solid angle for the scattering process is defined in the following way:

$$\sigma = (N_s/N_i)(1/\rho\Omega),$$

where N_s is the number of protons scattered into the solid angle Ω out of an incident group N_i by a stationary group of areal density ρ. The measurement of N_s, N_i, and ρ have been discussed. The solid angle Ω was determined by measuring four diameters of the nearly circular defining aperture by means of a traveling microscope. Typical values are 0.3230, 0.3231, 0.3229, 0.3240 centimeters. The average value was used to compute the area. The distance of the aperture to the scattering foil was measured with calipers to be 7.60±0.01 centimeters. The angle Ω is thus determined as $1.40\times10^{-3}\pm0.01\times10^{-3}$ sterad. The scattering foil was weighed before and after the

TABLE II. Absolute yield determinations of proton-proton scattering. σ is the laboratory cross section for 8 Mev protons scattered at 90° in the C. G. System (45° in laboratory system).

Run	Foil wt.	Foil area	Foil density	Fraction by wgt. of hyd.	ρ	N_s	N_i	σ
1	0.785 mg.	2.053 cm^2	$3.82\times10^{-4}\ \frac{\text{gms}}{\text{cm}^2}$	0.0645	$1.48\times10^{19}\ \frac{\text{proton}}{\text{cm}^2}$	5520	1.45×10^{12}	1.8×10^{-25} cm^2
2	0.785 mg.	2.053 cm^2	$3.82\times10^{-4}\ \frac{\text{gms}}{\text{cm}^2}$	0.0645	$1.48\times10^{19}\ \frac{\text{proton}}{\text{cm}^2}$	2480	0.746×10^{12}	1.6×10^{-25} cm^2

runs and no change could be observed. More significant is the fact that during a run the yield did not change. The microbalance was calibrated by weighing small lengths of platinum wire which had been weighed previously together on an analytical balance. The area of the foil was assumed to be the same as the area of the punch, whose diameter was measured as 1.6152±0.0005 centimeters.

11. COMPARISON WITH THEORY

The expected value of the cross section for proton-proton scattering has been calculated by L. B. Eisenbud on the assumption of a square well of depth 10.5 Mev and width (e^2/mc^2), both for S wave scattering alone and for $S+P$ wave scattering with the potential for the P wave both attractive and repulsive. These calculations were made at 7 Mev and 10 Mev proton energy. Since the experiment was at 8 Mev, a linear interpolation of the calculated values was carried out for comparison. The relative angular distribution values for the three cases, S wave only, S wave plus P wave scattered by attractive potential, and S wave plus P wave scattered by repulsive potential, are plotted with the experimental data in Fig. 5. It is seen that the data are most consistent with the curve calculated for S wave scattering only but that the accuracy of the experiment is not great enough to exclude definitely P wave scattering effects positive or negative.

The absolute value of the cross section at 45° in the laboratory system (90° in the center of gravity C. G. system at which angle there is no P scattering) is calculated from the above well to be 1.80×10^{-25} cm^2, if the forces are central in character. The experimental value $1.7\pm0.1\times10^{-25}$ cm^2 agrees with this to within the uncertainty in the hydrogen concentration in the Cellophane.

It should be emphasized that the work was terminated before all the desired checks for systematic errors could be made, hence statistical errors indicated in Fig. 5 should be regarded as lower limits for the actual errors.