The Scattering of Protons by Protons*

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By counting several thousand scattered protons at each angle and voltage with a linear amplifier, the numbers of protons scattered or projected by recoil through angles from 15° to 45° from a carefully defined mono-energetic proton beam in passing through 2 mm path length of pure hydrogen gas at a pressure of 12 mm have been measured for proton beam energies of 600, 700, 800, and 900 kv. The angular resolution for the slit systems was about 2°. The high voltage was constant to within one percent and was measured directly to about two percent with a specially calibrated 10,000-megohm corona free voltmeter resistor. The spread in energy of the primary protons did not exceed one percent. At 600 kv the observed numbers at all angles are roughly two-thirds of the values predicted by Mott's formula. The curves for this observed "Mott ratio" *versus* angle change progressively as the voltage is increased and at 900 kv the observations show two-thirds of the Mott value at 15°, 1.4 times Mott at 30°, and 4.0 times Mott at 45°. Measurements of the scattering of protons by deuterium, helium, and air, together with "vacuum-scattering" tests which eliminate slit scattering and unknown vapors, have led to the conclusion that the observed anomaly is not due to a contamination and must be ascribed to a proton-proton interaction at close distances (less than 5×10^{-13} cm) which involves a marked departure from the ordinary Coulomb forces. The observed curves lead quantitatively to a simple theoretical interpretation on the basis of wave mechanics, as shown in the accompanying paper by Breit, Condon and Present. A new scattering apparatus is under construction to eliminate possible small errors in the angular measurements and to permit observations (with Geiger point-counters) at lower voltages.

(A) INTRODUCTION

THE statistical study of collision processes, by observations on the number, energy, and angular distribution of the scattered particles after collision, has been recognized for many years as a basic method for obtaining intimate knowledge of the nature and magnitude of the interaction forces between particles when they are brought into close proximity with each other. The application of this method by Rutherford and his colleagues using alpha-particles for the quantitative demonstration that atoms have a nuclear structure was followed by their similar studies demonstrating the failure of the Coulomb law of repulsion when alpha-particles and other atomic nuclei approach within distances of the order of 10^{-12} cm between centers. The study of the scattering of protons by protons in order to acquire basic information regarding the interaction forces between these primary constituents of nuclear structure (then thought to be protons and electrons) was one of the stated objectives of the program of high voltage research begun here in 1926 with the general aim of investigating the simplest and most basic manifestations of magnetic and electric forces which can be conceived or enunciated. At about the same time Gerthsen[1] initiated a series of researches on the properties of high speed protons in the region below 100 kv, culminating (1931) in his verification (for this range of energy) of Mott's theoretical formula for the scattering of protons by protons which is based on the wave mechanics and on the Coulomb law of repulsion.[2] Since the classical "closest distance of approach" at these voltages is of the order of 10^{-11} cm it was not surprising to find agreement with predictions based on the Coulomb law. However, if the proton energy is raised to 400 kv all large angle collisions involve protons which have approached (classically) to a distance between centers which is smaller than the distance 4×10^{-13} cm for which Chadwick and Bieler demonstrated (1921) the breakdown of the Coulomb law between protons and helium nuclei (for head-on collisions of fast alpha-particles in hydrogen; 8×10^{-13} cm for oblique collisions). Anomalous deviations from Mott's formula might accordingly be expected at large

* A brief account of this paper was delivered at the Tercentenary Conference of Arts and Sciences at Harvard University, September, 1936.

[1] Gerthsen, Ann. d. Physik **86**, 1025–1036 (1928); **3**, 373–408 (1929); **9**, 769–786 (1931).

[2] N. F. Mott, Proc. Roy. Soc. **A126**, 259–267 (1930); also Mott and Massey, *Theory of Atomic Collisions* (Oxford, 1933).

angles (limiting angle 45°) for proton-proton collisions at voltages of this order or higher, since it has long seemed probable that the proton must have a "size" (region of dimensions in which the Coulomb repulsion fails to hold) much in excess of its "classical diameter" (10^{-16} cm) and roughly of the dimensions of the other nuclei of which it is a demonstrated constituent.

The first attack on the experimental problem of proton-proton scattering at high voltages was made by Wells[3] in this laboratory in 1933–34. He photographed in a hydrogen filled cloud chamber the tracks of the recoil protons of various velocities produced by polonium alpha-particles bombarding thin Cellophane or paraffin sheets. Stereoscopic pictures of 200,000 tracks (15,000 expansions) resulted in a total of only 33 collisions which were finally accepted as valid; of this number 11 collisions were in the range 450 to 900 kv, only three of these lying in the interesting range 25°–45°. Collisions observed along tracks in a cloud chamber are twice distributed—with respect to voltage (distance from end of track) and with respect to angle—and consequently large numbers of collisions must be observed before statistical validity is achieved. The problem of establishing suitable criteria for accepting or rejecting collision forks is another difficulty inherent in this method. No theoretical conclusions were drawn from Wells' experiments and this method was abandoned by us since the possibility existed of carrying out the experiment of directly counting the protons scattered in hydrogen gas with our high voltage technique, then in process of perfection for quantitative work.

Similar cloud chamber experiments were carried out by White[4] at Berkeley in 1934–35 who used protons from a small cyclotron. The spread in energy among and along White's proton tracks (roughly 1000 kv to zero for most tracks) was somewhat smaller than for Wells' (maximum 1500 kv to zero; half of tracks 750 kv to zero) tending to a slightly increased emphasis in White's data on the collisions above 500 kv. In a total of 300,000 tracks White observed a total of 95 collisions occuring at energies between 450 and 900 kv. White concluded that Mott's formula was valid below 600 kv, and concluded further that a large anomaly became evident for large angle collisions occurring in the region of 600–750 kv (scattering too infrequent in the range 25° to 30° and too frequent by a factor of about 10 at 40° to 45°). This conclusion was based on the observation of "13.5 collisions" in the range 35° to 45°, where two collisions were expected, and on the observation of "1.5 collisions" in the range 25° to 30° where three collisions were expected on the basis of Mott's formula. A total of five collisions observed by White between 25° and 45° in the range 750 to 900 kv gave a crude check on this anomaly. A comparison of White's results with the data we have obtained by electrical counting methods is shown in Fig. 10. Although we find a considerable anomaly at 900 kv our results differ from those of White in the region 600 to 750 kv covered by his data. Within the statistical accuracy of his experiments the anomaly we find would not be detectable.

The fact that Bethe's correction (unpublished) of the usual range energy curve for protons raises the center of gravity of White's group for 600 to 750 kv to an actual voltage of about 720 kv, with corresponding changes in the other cloud chamber numbers, gives rise to no important alterations in the above discussion. White's conclusions as to the existence of an anomaly was based on a total of 18 observed particles at high angles with energies over 600 kv. In our final experiments a total of 21,540 particles in the same region were observed.

Profiting by our experience with Wells' work here, we chose to defer work on the proton-scattering problem until it became feasible to make a direct measurement by electrical methods of the scattering of large numbers of protons in gaseous hydrogen from the proton beam produced by our 1200-kv electrostatic generator and accelerating tube. For such a quantitative problem, however, it was clearly essential to have sufficient steadiness of experimental conditions as well as accurate knowledge and control of the voltage and composition of the ion beam. The discovery during 1934–35 of sharp nuclear resonance phenomena under bombardment by protons gave us a suitable test object for our technique. It also showed the primary need for

[3] W. H. Wells, Phys. Rev. **47**, 591–596 (1935).
[4] White, Phys. Rev. **49**, 309–316 (1936).

an accurate and reliable voltmeter, and for a tube having properly aligned electrodes before repeatable results could be obtained.

The need for a suitable voltmeter was met by the development of a 10,000-megohm corona-free voltmeter resistor which was constructed and tested during the summer of 1935 with the help of Dr. R. G. Herb. This voltmeter, together with a new tube with accurately aligned electrodes, was used for a study of the proton resonances with lithium and fluorine targets until a reference voltage scale was established by sharp resonances at 320, 440, 890, and 940 kv.[5] As already reported, the limit of fluctuation of the voltage was measured and found to be less than ±0.5 percent R.M.S. The quantitative "repeatability" of observations with this equipment and technique was carefully tested and adequately demonstrated during these studies of nuclear effects varying extremely rapidly with voltage.

Having thus finally satisfied ourselves that quantitatively reliable results could be obtained, we returned to the proton-scattering problem. In this paper we will describe our experiments as thoroughly as possible in order to give an adequate critical basis for their evaluation. The theoretical aspects of the results are being very completely treated in the accompanying paper by Breit, Condon, and Present.

(B) Numerical Values for Coulomb Scattering

The classical formulas for nuclear scattering* based on the perfectly elastic collisions of massive charged particles obeying the inverse square law of Coulomb repulsion were given by Rutherford[6] and Darwin.[7] For convenient reference the formulas are again recorded here, with slight changes in notation which make them more immediately applicable to collisions of unlike particles. For incident particles of mass M impinging on "target" nuclei of mass m, the general formula can be resolved into special formulas for the three cases $M<m$, $M=m$, and $M>m$. If N_0 is the number of particles per second in the incident beam, having mass M, charge Ze, and kinetic energy T, then the numbers of primary particles N_s scattered per second into a solid angle ω at an angle θ with respect to the initial beam by a "target" having N_t nuclei per unit area of mass m and charge $Z'e$ are as follows: For $M<m$,

$$N_s=(1/4)K(ZZ')^2\{\csc^4(\theta/2)-2(M/m)^2 +[1-(3/2)\sin^2\theta](M/m)^4+\cdots\},$$

where $K=N_0N_t\omega e^4/4T^2=0.512$ for $T=1000$ ekv and $(N_0N_t\omega)=10^{26}$. For $M=m$, the recoil nuclei (N_R) are indistinguishable from the scattered particles (N_S), and for the sum of the two the formula is

$$N_S+N_R=4K(ZZ')^2\cos\theta\csc^4\theta(1+\tan^4\theta).$$

For $M>m$, the recoil particles alone will in general be observed and for these the formula is

$$N_R=K(ZZ')^2(M/m)^2\sec^3\theta.$$

With an initial beam intensity of 10^{10} particles per second, and a target density $N_t=10^{18}$ nuclei per square centimeter (about 0.5-mm equivalent stopping power of air) the calculated number of scattered particles per second N_s to be expected in a solid angle $\omega=0.01$ steradian at a primary beam velocity corresponding to 1000 ekv (1.39×10^9 cm/sec. for protons; 0.98×10^4 cm/sec. for deuterons; 0.70×10^9 cm/sec. for alpha-particles) as calculated from the above formulas for a series of typical elements and angles are listed in Table I. The orders of magnitude of the expected scattering for various elements, voltages, and angles are important considerations in connection with the effects of possible contaminations. To convert to a primary beam energy of V kv multiply the tabulated values by $(1000/V)^2$. The use of 4.80×10^{-10} instead of 4.77×10^{-10} for the value of e would raise the values given in this table by nearly three percent.

For the collisions of like particles, that is, protons in hydrogen or alpha-particles in helium, Mott[2] worked out the corrections to be applied on account of the quantum-mechanical identity of the two particles. For angles near zero the Mott formula predicts the same scattering as the Rutherford-Darwin values for all velocities and at 45° the Mott value is always half that of

[5] Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 504 (1936).

* A misprint occurs in the formula given in Rutherford, Chadwick, and Ellis, *Radiations from Radioactive Substances* (Cambridge, 1930), p. 243, Eq. (8).

[6] Rutherford, Phil. Mag. **21**, 669–688 (1911).

[7] Darwin, Phil. Mag. **27**, 499–506 (1914).

TABLE I. *Numbers of scattered particles predicted by the Rutherford-Darwin formulas.* Initial energy, 1000 kv (500 kv accelerating potential for alpha-particles); initial beam $N_0=10^{10}$ primary particles; target-density $N_t=10^{18}$ nuclei per cm^2; solid angle of detection $\omega=10^{-2}$ steradian.

Proton scattering

	Scattered and recoil protons		Scattered protons				
Angle	H^1	(H^1 Mott)*	D^2	He^4	Li^7	C^{12}	Al^{27}
°							
10	2213	2150	2218	8875	19940	79900	375000
15	443	416	439	1757	3954	15840	74300
20	142	124	140	562	1264	5015	23720
25	60.7	45.2	58.0	232	525	2092	9820
27.5	42.9	32.0	....	....	....	....	....
30	31.5	22.0	28.4	114	256	1026	4823
32.5	23.5	15.7	....	....	....	....	....
35	19.1	11.6	15.6	62.5	141	563	2644
37.5	14.9	8.94	....	....	....	....	....
40	13.7	7.25	9.26	37.3	83.8	335	1578
42.5	12.2	6.26	....	....	....	....	....
45	11.6	5.78	5.89	23.8	53.7	214	1006
50	11.5	6.06	....	....	....	....	....
60	16.9	11.9	1.98	8.18	18.4	73.7	346
90	....	....	0.443	1.98	4.56	18.4	86.3
135	....	....	0.102	0.637	1.53	6.28	29.6
150	....	....	0.0877	0.522	1.27	5.24	24.7

	Deuteron scattering				Alpha-particle scattering				
	Recoil protons	Scattered and recoil	Scattered deuterons		Recoils only		Scattered and recoil	Scattered alpha-particles	
Angle	H^1	D^2	He^4	Be^9	H^1	H^2	He^4	C^{12}	Al^{27}
°									
10	4.83	2213	8870	35460	53.6	19.3	35420	319200	1500000
20	5.55	142	560	2243	61.7	22.2	2280	20200	94900
30	7.08	31.5	114	456	78.6	28.3	504	4100	19200
40	10.2	13.7	37.0	149	114	40.8	220	1338	6300
45	13.0	11.6	23.6	95.3	145	52.2	185	855	4028
60	36.8	16.9	7.92	32.5	408	147	270	290	1380
90	∞	....	1.77	7.98	∞	∞	....	69.5	342
135	....	....	0.450	2.60	....	....	....	21.2	115
150	....	....	0.348	2.14	....	....	....	17.2	95.3

* Values predicted by Mott's formula.

Rutherford and Darwin, while the corrections for other angles depend on the velocity as indicated in Fig. 1 taken from Mott's paper. For the values of primary proton energy we have examined experimentally, the dependence on velocity is about one percent and we have used the Mott correction for $v=\infty$ (curve I in Fig. 1) in computing our predicted Mott values. A tabulation of these calculated values, for the actual thickness of target, solid angle, and other constants of our apparatus, together with the ratios of our observed values to the Mott values, is given in Table II (see Section F).

(C) Design and Constants of the Scattering Apparatus

The construction of the scattering chamber is indicated in Figs. 2 and 3. The primary proton beam, freed from other ions to a high degree of purity by magnetic analysis, was intentionally spread into a diffuse target spot 1.5 to 3 cm in diameter by a slight defocusing of the tube (slight change of voltage across the first tube section, next to the ion source). This insured a nearly constant proton current entering the 2.0-mm hole of the diaphragm system which

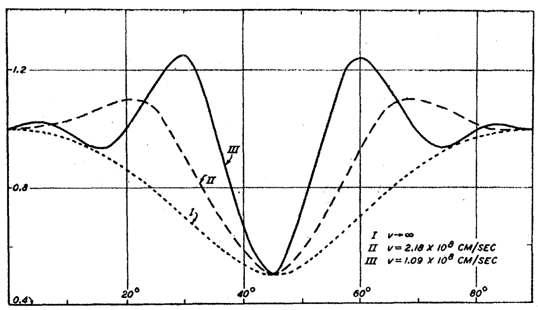

FIG. 1. Ratio of quantum theory scattering to classical scattering for protons, according to Mott.

defines the proton beam in the scattering chamber, regardless of slight motions of the (magnetically deflected) proton spot due to residual voltage fluctuations. The total proton current was of the order of several microamperes, whereas the proton beam passing through the scattering chamber was between 0.005 and 0.03 microampere in the different runs. The apertures of these diaphragms and of the detector slit system were selected to give a reasonable number of scattered protons (at least 50 per minute) into the ionization chamber at the highest voltages and angles, without giving rise to overwhelming numbers of counts at the lower angles and voltages, the hydrogen pressure and proton current necessarily being held constant during each run.

The slit systems

In experiments on alpha-particle scattering it has been customary to use very crude angular resolution, the observations frequently covering a zone of 20° or more. In the present experiment ample primary intensity was available and corresponding resolution could be obtained. The angular resolution of our slit systems was approximately 2°. The details of the diaphragms and slits are shown in Fig. 4. The terms "central zone" and "extreme limits" used in Fig. 4 to describe the angular definition may be understood by reference to Fig. 5. To make clear the fact that scattering from the whole diameter of the primary beam is observable in the ionization chamber the "plan" of the detector slit system, viewed from the direction of the primary beam when set for a scattering angle of 90°, is shown in Fig. 6.

The mounting of the slit systems to insure that the axis of rotation of the ground joint is perpendicular to the beam and to the detector slits, and furthermore intersected by the axis of the detector slit system, is a matter of importance when angular measurements with an accuracy of one-fifth degree become necessary or desirable, as is the case for proton scattering at 15° or less. A new scattering chamber designed for greater angular accuracy is now under construction, but it seems likely that in this original apparatus the requirements of perpendicularity must have been met within at least 1° or 2°. The intersection of the axes of the ground joint, primary beam diaphragms and detector slits was examined by the insertion of rods in the diaphragm and slit systems and the junction of the rods at the axis of rotation was watched while changing the "angle of scattering" through 90°. No appreciable error was visible, indicating that the axes intersected within perhaps $\frac{1}{2}$ mm or better. The zero position of the angular scale was similarly checked by inspection. After considering second-order angular corrections of various kinds, we have concluded that except for possible errors contributing effectively to the zero error in the angular scale, this apparatus seems to have been essentially satisfactory in respect to angular measurements.

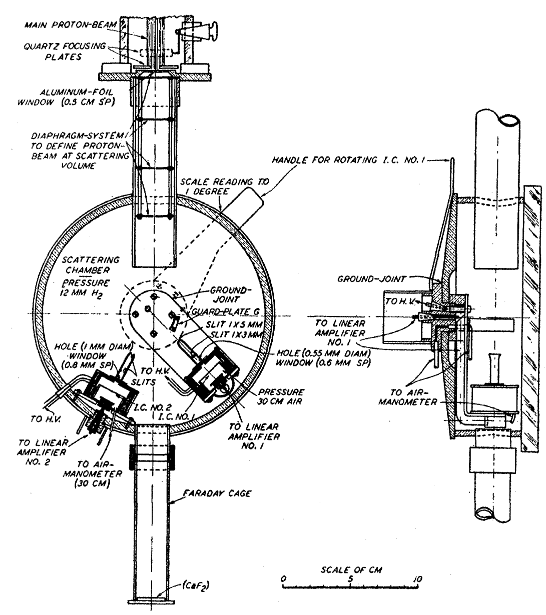

FIG. 2. Proton-scattering apparatus.

No special effort was made in the design to insure the accuracy of the "zero" of the scale for it appeared advisable in any case to eliminate the error from this cause by taking observations at both sides of the beam. However, in practice, early tests for protons scattered in the detecting chamber with a vacuum in the scattering chamber showed the presence of some multiply-scattered protons from slit edges of the diaphragm system at angles of 20° and less and caused us to insert the guard plate *G* shown in Fig. 4 (in the right-hand diagram the guard *G* appears as an unlabeled rectangle projecting into the scattering chamber). Since the presence of this plate precluded the possibility of observations on both sides of the beam, the second ionization chamber was also installed for use as a "current monitor" as will be discussed below.

A special series of observations to determine the zero might well have been taken after the measurements reported in this paper were completed, but by an oversight the assembly screws holding the ionization chamber and arm were

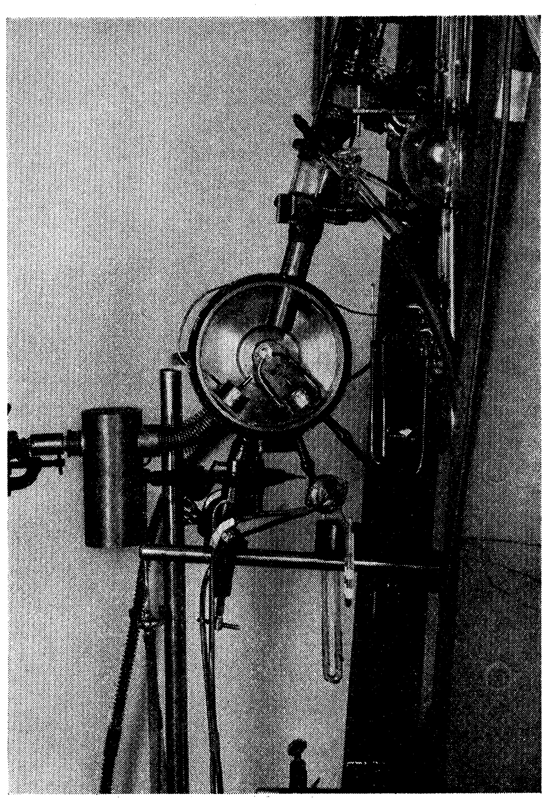

FIG. 3. View of proton-scattering apparatus.

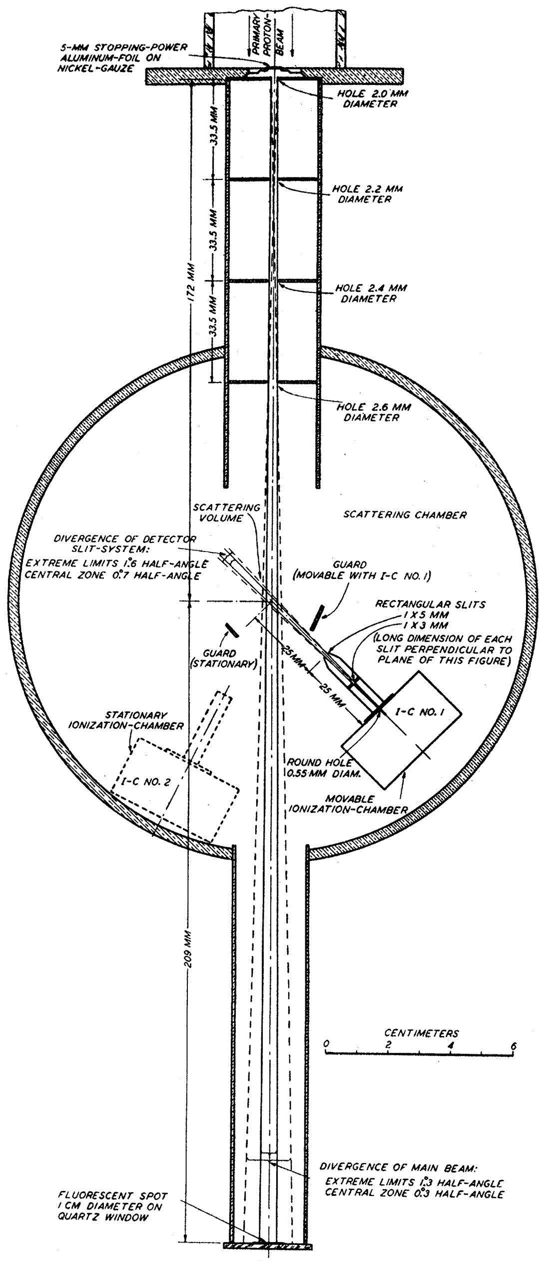

FIG. 4. Detail of slit systems, proton-scattering apparatus.

removed and replaced before such observations were made, and careful examination showed that we could not be certain that the original setting for zero angle could be reproduced by such replacement with sufficient accuracy.

The scattering gas

As may be seen from a consideration of the diagrams in Figs. 4 and 5, the actual gas target

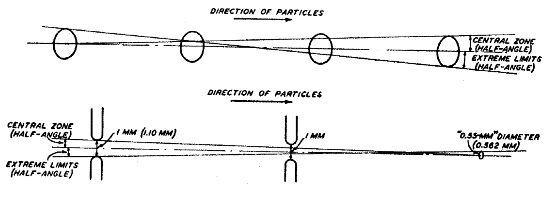

FIG. 5 (above). Diaphragm system—primary beam and (below) slits and diaphragm detecting chamber. These sketches are not drawn to scale.

which scatters protons into the detecting chamber is an odd shaped section of the path of the primary beam and its volume, as well as shape, depends on the angular setting of the detecting chamber. When the latter is at 90°, the scattering volume is a drum shaped section of the primary beam with its flat faces (not quite parallel) separated by about 2 mm. As the angle of observation is decreased toward 0° it is obvious that the principal effect is an increase in the thickness of the scattering volume (measured along the primary beam), which varies inversely with the sine of the angle of observation. As stated previously, the whole cross-sectional area of the primary beam is included in the solid angle subtended by the detector slit system, and the dimensions of the latter along the beam, by determining the thickness of the target volume, determines the number of target atoms which scatter toward the small hole in the detecting chamber. Hence to obtain the number of scattered protons to be expected at any angle on the basis of Mott's formula we have taken for the target volume at the angle θ the target volume at 90° divided by $\sin\theta$, neglecting all other corrections as of the second order and unimportant. The solid angle subtended by the detector is obviously independent of the rectangular slits and depends on the round hole in the detecting chamber only, but the size of this hole and the short dimension of the 1 mm by 5 mm detector slit together determine the scattering volume.

The actual pressure of hydrogen gas used in all of our experiments to date has been 12.0 mm, measured by a small mercury manometer with an accuracy probably not much better than five percent. The manometer was connected to the scattering chamber through a U-tube immersed in a slush of solid CO_2 and alcohol. As each series of observations is made on a separate filling of hydrogen the error in the pressure measurement should average out to within several percent over a number of runs at one voltage. The number of target nuclei was computed for a temperature of 20°C and no temperature corrections were made, the temperature of our basement observing laboratory being within about 3°C of this value at all times during the observations.

That multiple scattering in the gas may be neglected is apparent from the fact that taking account of all of the small angle deflections at this pressure in a path length of 10 cm above the scattering volume, by calculation a scattering through 2.5° followed by a second deflection of 17.5° would account for only one in 2000 of the protons observed at 20°. For higher values of these angles the multiple scattering correction becomes rapidly even less. Upper limits for the values of these corrections have been estimated from the Rutherford-Darwin scattering values for an energy of 500 kv. The total number of protons scattered or recoiling from the scattering volume under observation through all angles above 15° (to 75°) is approximately one in 10^6 at 800 kv, the actual number observed at 45° being about 10^{-11} of the original beam.

The purity of the hydrogen used to fill the scattering chamber is of obvious importance, and tests for contaminations will be described below. For filling the chamber we used a palladium tube immersed in a bulb of tank hydrogen and heated by radiation from a nearby coil of resistance wire to perhaps 300°C (far below any visible glow). The U-tube of the manometer, cooled to CO_2 temperature for at least an hour in advance of any measurements, insured against mercury or other local vapors, and a "thermocouple Pirani-gauge," connected to the scattering volume and capable of detecting a few thousandths of a

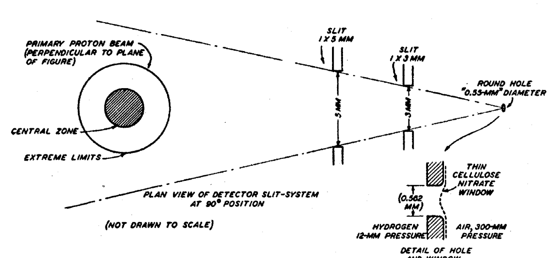

FIG. 6. Detector slit system as viewed along primary beam when set for scattering angle of 90°.

millimeter pressure, showed no appreciable development of pressure in the scattering chamber when pumped out to a high vacuum and left disconnected from the pumps for some hours. A manometer indicating the pressure of air in the ionization chambers showed no appreciable change over a period of several weeks, indicating that the thin windows did not leak.

Since the final result of our experiments is a series of ratios of absolute values, for different voltages and angles, the observed numbers of scattered particles divided by expected numbers predicted by Mott's formula, without any reference value to which the results may be "normalized" or by which these ratios may be checked, it is highly important at every point to guard against slips or omissions which will affect the absolute values of either the expected Mott numbers or the observed numbers of scattered particles. Consequently separate and independent calculations were made by four individuals for the number of scattered protons to be expected on the basis of Mott's formula for the dimensions of apparatus given in Fig. 4, each making a separate estimate of the corrections to be applied for the peculiar solid angle situation arising from the round-and-square combination of the detector slit system. These calculations agreed within one-half percent in giving a value of 464 scattered and recoil protons (indistinguishable) per minute per microampere into the detecting chamber, for a primary proton beam energy of 1000 kv and an angle of 45°, including the correction $1/\sin\theta$ for variation of target volume with angle. This number is for a hydrogen pressure of 12 mm at 20°C. Accurate measurements of the exact dimensions of the detector slit system were intentionally postponed until all other observations were completed. Hence throughout our work, and in all of the curves and comparisons in this paper except Table II and the final curves (see Fig. 15), the value 464 given above was taken as the "Mott standard."

The number of protons in the primary beam

One of the major problems of the experiment was that of obtaining a sufficiently accurate measurement at all times of the number of protons per second which pass through the scattering volume as the primary beam, a quantity which obviously affects in direct ratio the absolute value which is arrived at as the "observed scattering" and which must be compared finally to another absolute value calculated from Mott's formula. To eliminate a suspected source of error the Faraday cage at the bottom of Fig. 2 was increased to 60 cm length. However, this deep Faraday cage beyond the scattering volume is obviously useless when the apparatus is filled with hydrogen for scattering observations, since each proton in the main beam produces about 20 ion pairs per mm path in the gas, and the collection of a small percentage of these ions, due to contact potentials or other stray effect, gives rise to enormous errors in the current measurement (observed currents under these conditions were actually -10 to $+20$ times the known current in the beam).

Although a better method undoubtedly can be achieved later for measuring the proton current continuously in these experiments, we have made use of the known constancy of our experimental conditions and obtained our proton beam current values as follows: The equipment was first operated at the desired voltage and current for half an hour to attain maximum steadiness, then a current measurement was made by means of the Faraday cage with a high vacuum in the scattering chamber, then the chamber was filled with hydrogen and scattering observations were made at the various angles; finally the scattering chamber was pumped out again to a high vacuum and the measurement of "vacuum current" was repeated. If the latter failed to agree with the current measured at the start within the necessary limits the whole "run" was discarded. Each "run" required from 50 to 80 minutes, usually not over 60 minutes. During all of our final "runs" only one or two were discarded from this cause, however, as more or less continuous check on the current was obtained by using the 20° scattering as a "monitor" position, repeated after every one or two observations at any other angle. Any abrupt change in the 20°-value called our attention to trouble, and stopped the run. This happened once or twice by reason of trouble in the amplifier or ion source circuits. A progressive change up to say 15 percent between initial and final "vacuum currents" was permissible because the monitor readings (at 20°)

made the necessary correction possible to within the desired accuracy of say three percent for single observations. A further check on the constancy of the current was obtained by measuring the total proton current striking the aluminum foil window above the 2-mm beam diaphragm. This current was very steady but of course took no account of the lack of perfectly uniform current density in the diffused spot, which moved slightly on account of various causes, including changes in temperature of the deflecting magnet. The whole apparatus shown in Fig. 2 was insulated from ground and at the bottom of a deep Faraday cage to permit this measurement. A much better arrangement would have been to have selected by a preceding diaphragm system a portion, roughly 3 mm in diameter, of the diffuse spot above the aluminum foil window centered on the 2-mm diaphragm beneath, for this "total current monitor." The beam currents in various runs were set as desired for suitable numbers of counts (depending on voltage and on the range of angle in which greatest accuracy was desired in a particular run), and ranged from 0.005 to 0.03 microampere. These Faraday cage currents were measured on a sensitive galvanometer permanently mounted and calibrated at various scale values at frequent intervals during the weeks of observation. The calibrations of the galvanometer were made with two completely different sets of resistances and Weston voltmeters which agreed within one percent.

The chief objection to our current measurements arises from the presence during some of the days of an erratic changing of the current through a range as large as 10 or even 15 percent with steady periods of one-half to two minutes between shifts. With this happening we endeavored to obtain average values by observing counts and currents during periods of many minutes. Another circumstance required the discarding of a few of our values for the "final vacuum current." This was the fact that the scattering chamber was evacuated at the end of a "run" by means of a Hyvac pump, the final pumping to a high vacuum being done by opening a cock to the main tube (above the aluminum foil window). If this cock was opened too hurriedly a burst of hydrogen would be let into the high voltage tube while operating, with a resultant disturbance of the steady conditions which sometimes altered the current into the scattering apparatus by 50 percent, an actual shift or other effect on the focal spot being visible. The readings of the monitor at 20° allowed the "initial vacuum current" to be used for computing these runs.

As described below, we finally chose to reduce the effect of the uncertainty of our current values by making a considerable number of independent runs at such voltages taking the averages of scattering values (Mott ratios) obtained as the true value, with the fluctuations among all observations giving some criterion of the errors arising from all nonsystematic causes.

Velocity of the protons at the scattering volume

Since the theoretical scattering varies inversely as the square of the energy a small systematic error in the voltage measurements might easily give rise to a small apparent but false anomaly or, given a true anomaly of considerable magnitude such as we have found, might cause a specious variation of the observed anomaly with voltage in a way which might be very confusing in any theoretical analysis of the results. This was one of the reasons for the development of the 10,000-megohm voltmeter resistor, use of which gave a direct measurement (to two percent, differences to one percent) of the energy of the primary protons striking the aluminum foil window of the scattering chamber. This foil was estimated by weight to have a stopping power of 5-mm air equivalent. As a check on this thickness a calcium fluoride crystal was placed at the bottom of the Faraday cage (see Fig. 4) and with a vacuum in the scattering chamber the tube voltage was measured which gave the protons sufficient energy to excite the known fluorine gamma-ray resonances (890 and 940 kv) after passing through the aluminum window. At the voltages of these resonances the stopping power of the window was found to correspond to 5-mm air equivalent. At the usual pressure of 12.0 mm, the loss in range (energy) of the primary beam in passing through the hydrogen between the window and the scattering volume under observation was 0.5-mm air equivalent by calculation from ordinary stopping power values. To obtain

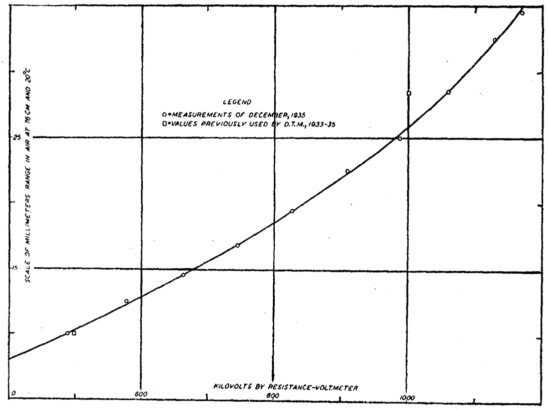

FIG. 7. Visual range curve for proton beam in air.

the actual energy of the protons at the scattering volume the slight differences between aluminum, hydrogen, and air in the rate of variation of proton range with voltage were neglected (obviously trivial) and the constant value of 5.5 mm was subtracted from the range of protons at the actual measured voltage to give the range, and hence the voltage, of the protons at the scattering volume. For making this correction it was sufficiently accurate to use our own curve for the "visual range" of protons as a function of voltage, shown in Fig. 7. This curve was obtained with the 10,000-megohm voltmeter resistor, and is based on the visually estimated range in air of the direct proton beam passing out from the tube through a copper-foil window, correction for which was made by inserting duplicate copper foils and noting the decreased visual range. It is possible that the proton range measured in this way exceeds by one or two mm the "extrapolated range" customarily meant in range measurements, but this should not give rise to any serious error in our estimates of the proton energy at the scattering volume.

Counting the scattered particles

To avoid ambiguity or misidentification of the particles entering the observing chamber, a linear amplifier was used for detection, with continuous monitoring of the counted particles by means of a cathode-ray oscillograph. A considerable restriction of the range of voltage and of higher angles over which scattering observations could be made arose from the use of this detector, since the scattered protons were required to have a definite and rather large residual range after collision or they would not be counted. The linear amplifier operates under a serious handicap with this apparatus because of the large electrical capacity of the connection from the ionization chamber through the rotating ground joint to the input grid. This wire gave trouble at first from mechanical vibration (which was electrically reproduced by the amplifier) and had to be surrounded by ceresin throughout its long shielding tube down the rotating arm and out through the ground joint. The high voltage lead to the chamber had to be similarly shielded by a grounded metal tube to prevent a glow discharge in the low pressure gas in the scattering chamber. Similarly the high voltage electrode of the chamber had to be entirely enclosed inside the grounded sheath containing the window (see Fig. 2). With its usual ionization chamber this linear amplifier will record moderately fast protons with a chamber depth of only two mm, whereas the lower limit for satisfactory recording with this scattering chamber has been found both by variation of angle and of voltage to be 7.4 mm (normal air) residual range for slow protons. The ionization chamber, 15 mm deep, was filled with air to a pressure of about 30 cm. The window covering the hole in the ionization chamber, to keep this air from the scattering chamber, was made by dropping collodion on a water surface. These films were found by a rough interferometer measurement to have a stopping power of 0.6 to 1.0 mm, and accordingly the slight bulge of the window into the hole due to the air pressure (see Fig. 6) made no appreciable difference in the counting as might be feared by reason of the particles traveling through the window thickness at an angle less than 90° near the edges of the hole. The lower limit of proton range to which the amplifier will respond reliably is of particular importance in connection with the expected symmetry of proton-proton scattering about 45° and will be discussed below.

The actual counting of the particles was carried out by a scale-of-eight thyratron circuit (Wynn-Williams) which had previously been used with the same linear amplifier and had been tested for missing at high speeds and other features during extended quantitative observations on the alpha-particle excitation function of lithium, and numerous other less exact investigations.

It would have been a great relief to have had a check on the absolute value features of our results by making observations on the scattering of protons by some gas which could be relied on to show no anomaly at these voltages, just as the gold foils were used in the classical alpha-particle experiments. Bromine or iodine might serve if the chamber were properly designed, but problems of purification and the necessity for an atomic number of uncertain but considerable magnitude to avoid a possible anomaly seem to eliminate nearly all other gases except possibly argon. Due to difficulties in accurately measuring the small number of scattering atoms of high atomic number which would be required, no metal foil substitute for a gas target seems feasible. In the face of the difficulties which arise when such an absolute value calibration by a heavy atom target is attempted we decided that our results would be more reliable if we made in the first experiments a straightforward absolute comparison with Mott's formula which depended on slit dimensions, gas pressure, and proton current measurements.

(D) Preliminary Survey Observations

As usual, the first month of observations was spent in eliminating troubles and reducing the errors from various causes which were found to be important. By the beginning of February, 1936, it seemed definitely necessary to conclude that the counts differed from our expectations on Mott's formula in their variation with angle and with voltage as well as in absolute magnitude. Accordingly we undertook to make a preliminary survey over the range of voltage available, to indicate the magnitude of the deviations found within an error of perhaps 20 percent.

Two sets of curves were obtained, one involving observations at arbitrary fixed voltages varying from 625 to 981 kv (at the scattering volume) and a second set attempting to obtain the variation in counts at fixed angles as the voltage was changed. The latter was very difficult, or rather unreliable, due to the small but important changes in the target current and target spot area with voltage (the deflecting magnet naturally requires a different setting for each voltage) even though the focus controls were left unaltered or so changed as to duplicate the same appearance of spot at each voltage. These curves were taken during a period of about two weeks and are shown in Figs. 8 and 9. Fresh hydrogen was used for each curve, sometimes several different fillings being used for different points or portions of a curve. Some of the measurements made were discarded because of current measurement troubles. Among the fixed voltage curves of Fig. 8, the curve for 696 kv was considered as definitely too low, other separate observations so indicating as well as the variable voltage data of Fig. 9. The curve for 981 kv was based on only the four observations shown and was included primarily for "inspection purposes" as the voltage could be held steadily at this value (actual tube voltage about 1100 kv) during only 15 minutes on a single day. However, the data of Fig. 9 for fixed angles, taken independently from the data on Fig. 8 and much of it only one or two points per filling of hydrogen (several points per day), seemed to check reasonably enough for the purposes of a survey demonstrating the existence of an anomaly. The dotted portions of the curves of Fig. 9 are filled in from the data of Fig. 8, indicating this agreement. A comparison of these data also was made with the results of White as shown in Fig. 10.

These survey data, in the form of Figs. 8 and 9, were sent to Professor Breit, then at the Institute for Advanced Study at Princeton, February 15, 1936. Professor Breit and Professor Condon had already calculated the various numerical tables for the computation of the phase shifts and the expected deviations from Mott's formulas using different assumed potential distributions to represent a proton-proton interaction, and they promptly informed us of the theoretical possibilities by which our observed results might be accounted for at different voltages. Their theoretical analysis showed that a potential smaller than the "^1S neutron-proton potential" did not account for the observed anomaly unless the magnitude of the potential was varied with the incident proton energy. In view of the possible importance of such a conclusion, as well as the desirability of not causing unnecessary confusion, it was decided to postpone detailed publication

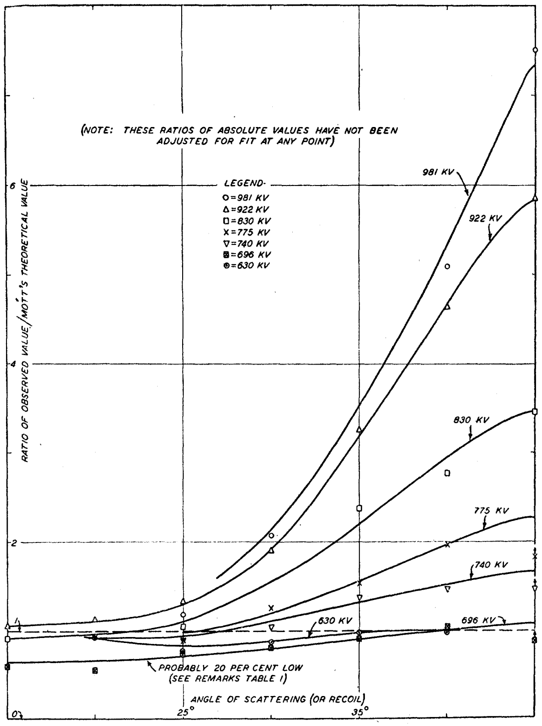

FIG. 8. Scattering of protons by protons for constant voltages at different angles [preliminary survey].

until possible errors could be ascertained by an extensive repetition of the experiments. These survey observations essentially comprised only a single curve for each voltage, and weighty conclusions regarding the success or failure of representing the proton-proton interaction by a potential function seemed premature. Our observations taken since and reported at the April meeting of the Physical Society have confirmed the magnitude of the interaction potential obtained in the above preliminary survey almost exactly for 800 kv. The unaccountable variation with the voltage of the incident protons disappeared when the data from numerous runs at each voltage were averaged, as reported below.

In response to several requests for these preliminary data on the part of other theoretical physicists working on mass defects and other problems involving an assumed proton-proton interaction, however, we sent copies of these two sets of survey curves March 18, 1936, to those interested, accompanied by a memorandum written by Professors Breit and Condon giving the results of their calculations using exact theoretical equations and the conclusions to be drawn from these data as to the magnitude of the interaction potential indicated if later experimental results removed the disturbing variation of the interaction potential with voltage. This material reached Professor Bethe just in time to be discussed by him in his excellent paper in the April issue of the *Reviews of Modern Physics*, where he presents an essentially similar, although approximate, theoretical treatment.

(E) Search for Errors Arising from Contaminations or Other Causes

It is to a considerable extent a dangerous procedure to ascribe an apparent anomaly, that is, an observation of excess scattering at high angles, to an actual deviation of the proton-proton forces from the Coulomb law, since nearly every conceivable error in any scattering experiment leads to the expectation of an excess of counts at high angles, where the scattered particles should be relatively few. Furthermore, as mentioned above, it has been known for many years that protons of 400-kv energy colliding with other protons at rest must approach, on a Coulomb calculation, within a distance which is smaller than the distance for which the collisions of alpha-particles with protons already show an anomaly. This same approximate distance for the radius of action of non-Coulombian forces has been assumed from the first in all calculations of nuclear mass defects, so that the appearance of

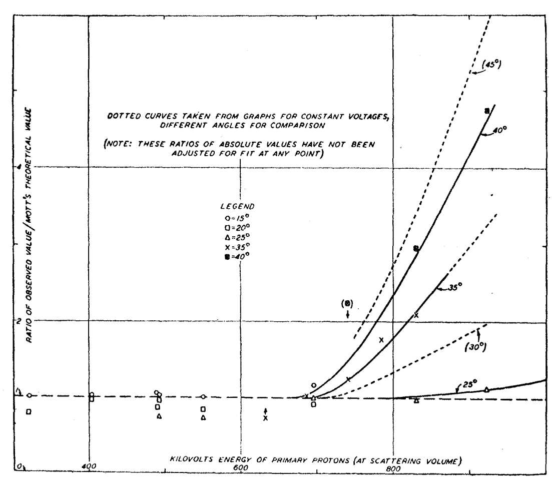

FIG. 9. Scattering of protons by protons for constant angles and different voltages [preliminary survey].

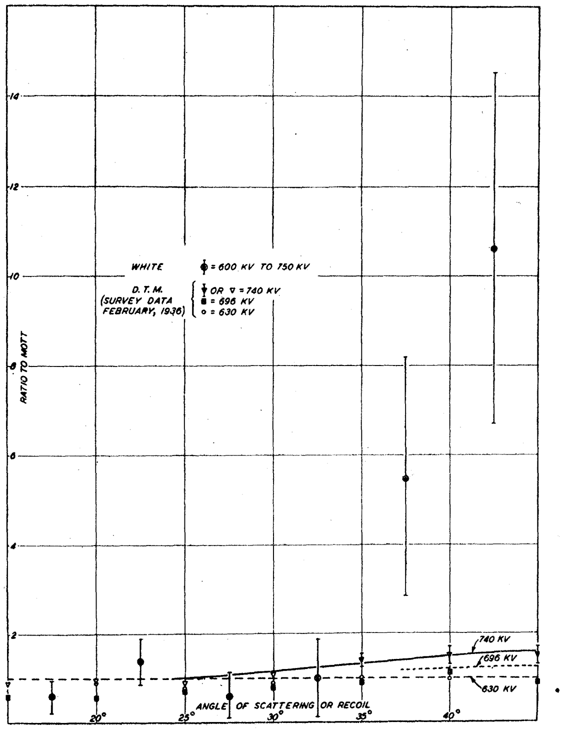

FIG. 10. Proton-proton scattering, comparison with White.

excess scattering at large angles, above 400 kv, simply indicating the existence of nuclear forces within this distance of approach which are considerably larger than the Coulomb repulsion, may make the observer unduly prone to accept such a result at face value. In view of this situation we spent the period from early February until the middle of April endeavoring to "break down" the results of our survey, to see whether the apparent anomaly might be explained in terms of an unsuspected contamination, multiple scattering, or other spurious cause.

The use of the linear amplifier as the detecting device removes at once a number of possible suspicions regarding our results, since the verification of the identity of the counted particles as protons, and also the measurement of their energy as the correct energy for primary protons which have lost approximately half of their initial energy in being scattered to about 45° by another proton, insures against counting, for example, any large number of protons which have been scattered by some heavier contamination. Such protons would retain nearly their entire primary energy and accordingly could be counted out to very high angles. Actually, for the highest voltage with which we have worked (900 kv) the amplifier is missing some of the counts at 50°, and counts no particles at all above 60° (fewer than five percent of 45° count). This observation alone puts certain limits on the number of scattered protons which might be due to the presence of a gas contamination of high atomic number, even though counts from such a cause do change rapidly with angle [varying as $Z^2 \operatorname{cosec}^4 (\theta/2)$].

To check on the possibility that an unknown vapor of condensible gas, such as an organic vapor, CO_2, or a trace of H_2O, might be present in the scattering chamber, several runs were made both with hydrogen and with a vacuum in the chamber during which the usual CO_2 slush on the mercury trap was replaced by liquid air. No differences from our usual results with CO_2 cooling were observed.

The possibility of multiple scattering in the hydrogen itself being responsible for the increased high angle counts was discussed and dismissed in an earlier section.

That the agent responsible for the observed anomaly could hardly be a frequent but "accidental" contamination of any kind, which should fluctuate in percentage in different runs or with length of time the scattering chamber had been filled before the observations were taken or otherwise show itself in the form of large fluctuations in the observed Mott ratios, seemed eliminated by the general consistency of our observations. The nonsystematic contamination of this kind which seemed reasonably possible was air, and accordingly observations with the same apparatus were made on the scattering of protons by air. Similarly, the only systematic contaminations which might be introduced while the scattering chamber was being filled through the palladium tube (other than vapors eliminated as above) seemed to be deuterium (a known contamination to something under one part in 1000) and possibly helium. Accordingly these gases were also investigated with the same apparatus.

For convenience in understanding the interpretation of the measurements on deuterium, helium, and air let us refer briefly to the hydrogen anomaly itself. Fig. 11 shows on a direct scale of counts *versus* angle (not Mott ratios as in Figs. 8 and 9) the magnitude of the anomaly to be explained. It is to be noted that at 15° the predicted Mott value (these counts all involve the $(1/\sin\theta)$-correction for change of scattering volume with angle) is only slightly below the Rutherford-Darwin ("classical") value, while the observed counts are lowest of all three. At 30° the observed counts lie between the Mott and the Rutherford-Darwin predictions, while at 45° the Mott, Rutherford-Darwin, and observed values are in the ratio 1 to 2 to 3. (These observed values are our averaged values for 800 kv.) Referring to Fig. 12, it is now seen that such an anomaly could not be produced by a contamination of the hydrogen by any one of the three suspected gases. If either helium or air gave rise to the anomaly at 45° they would correspondingly give such an anomaly at all lower angles since their observed variation with angle so nearly corresponds to the variation predicted for hydrogen by the Mott formula and indeed at 15° the observed counts should be higher than the Mott value by a factor of 3, instead of the observed counts of only 80 percent of the Mott values. It may be pointed out that the possibility that the observed anomaly might be ascribed to an error in the absolute value calibrations can be eliminated by a similar argument. The actual scattering observations with helium and air were made at arbitrarily higher pressures (just sufficient to be read feasibly on the manometer) and the number of counts reduced to correspond to the pressures shown in the left-hand box of Fig. 12 in order to bring the curves close together for comparison. The right-hand box gives the ratio of the observed counts for each gas at 12-mm pressure and 45° to the number of counts predicted by Mott's formula for pure hydrogen at the same pressure and angle, to give an indication of the amount of contaminating gas required to give the anomaly observed in the 45° counts.

The shape of the curve for the scattering of protons by 99 percent deuterium (similarly fed in through the palladium tube) is roughly that required to explain the observed hydrogen anomaly. However, the ratio of absolute magnitudes is such that about one-fifth of our tank hydrogen after passing through the palladium

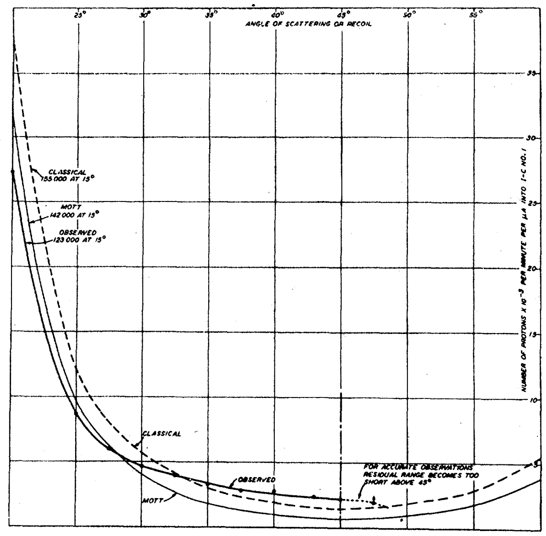

FIG. 11. Scattering of protons by protons at 800 kv, actual numbers of scattered particles as a function of angle.

would have to be deuterium to explain the anomaly! Even allowing for the known fractionation factor due to passage through (relatively cold) palladium we must consider this unreasonable by a factor of at least 1000 (and a still larger factor if our tank hydrogen was electrolytic, as was probable).

Because of its possible usefulness in connection with other problems such as that of proton-neutron interaction we show in Fig. 13 the results of our two separate sets of observations on the scattering of protons by deuterons. It must be remembered in this case that at any one angle there are two groups of detectable particles, the scattered protons and the recoil deuterons (heavier recoil nuclei such as helium or nitrogen do not acquire sufficient energy to penetrate the ionization chamber window and give a detectable amplifier-pulse). Thus at 30° we may observe the protons scattered through an angle of 30° and the recoil deuterons resulting from protons which have been scattered through 90°. As the latter travel slower than protons for a given residual kinetic energy they give rise to larger kicks than those due to protons, which have exactly twice as sharply peaked a maximum in the curve for ionization per mm path against residual range. The two groups of kicks are easily distinguishable, in fact very obviously, on the cathode-ray screen. In recording, the bias of the thyratrons is

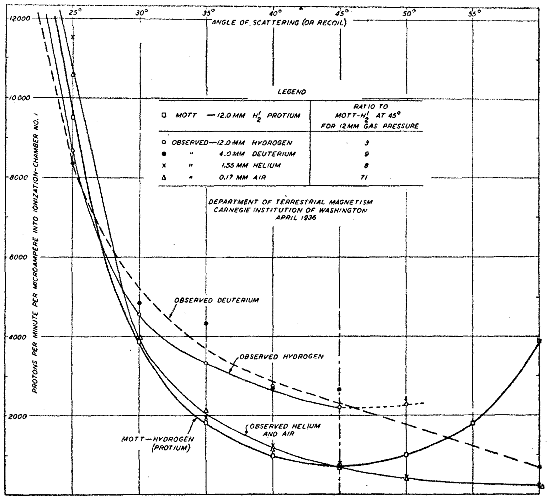

FIG. 12. Proton scattering in various gases, absolute values 800 kv.

set first to count all the particles and second to count only the large kicks, due to the recoil deuterons. The latter counts at various angles such as 15°, 20°, 25°, etc., serve to define the numbers of protons scattered through corresponding large angles (126°, 112°, 100°, etc.) and, again by subtraction of the deuteron counts, the proton scattering alone is obtained out to the point where the protons have lost too much energy to be accurately recorded further (about 50°; less proton energy is lost to a deuteron than in a proton-proton collision). The two sections of the curve so obtained are shown as curve A of Fig. 13, with the dots and circles indicating the agreement between the two separate days' observations. The ratio of the observed scattering to that predicted by the Rutherford-Darwin formula is shown as curve B.

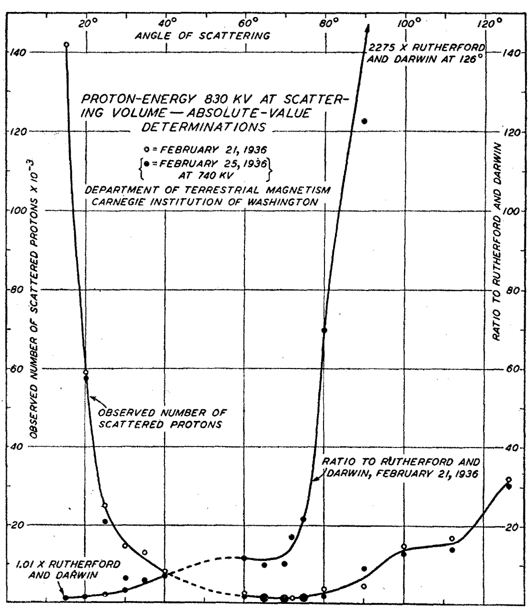

FIG. 13. Protons scattered by deuterons.

(F) Results Based on Averages of Many Independent Observations

Having reached the conclusion that the excess scattering at high angles observed in the preliminary experiments did not arise from a contamination or other spurious cause, we were faced with the choice of interrupting the observations to build an apparatus capable of better observations than were obtained in our preliminary survey, or of continuing the observations with the original apparatus in the expectation that the errors involved were mainly statistical and could be reduced by an averaging process. The current changes, of the order of 15 percent, showed no systematic trend. Largely because of the important divergence from current theory indicated by the variation with voltage in our survey observations we chose the latter alternative.

Clearly the least satisfying element in the measurements was that of the proton current passing through the scattering volume. To reduce errors from this cause steps were taken to provide the second ionization chamber with its associated amplifier and thyratron counter, to serve as a "current monitor." Pending completion of this apparatus observations were continued as before but with the additional precaution that observations at 20° were frequently interspersed between

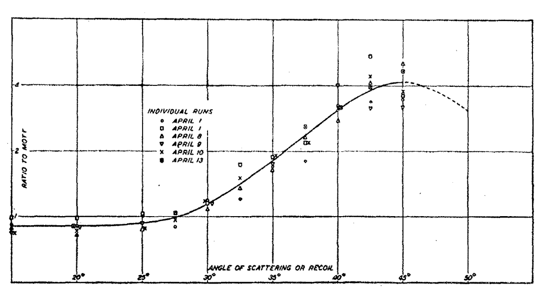

FIG. 14. Proton-proton scattering at 800 kv.

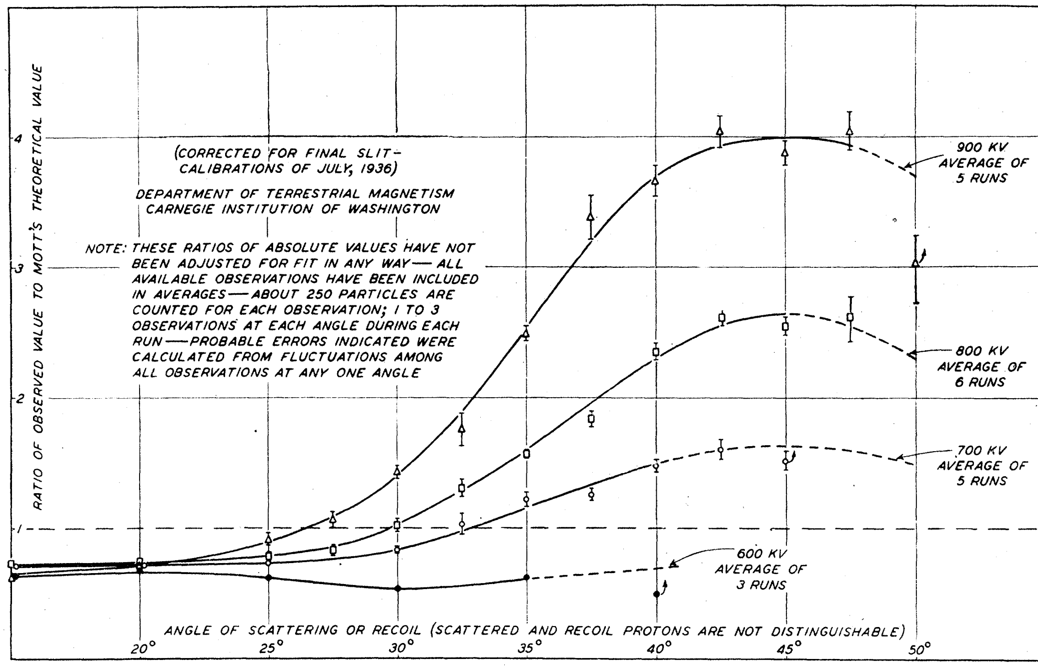

FIG. 15. Proton-proton scattering, curves obtained by averaging numerous independent observations at each angle for various voltages.

the observations at other angles in order to serve as a measure of the current variations. Fig. 14 shows a typical set of observations as obtained in this way involving six individual runs with independent fillings of hydrogen. Because of minor troubles with the second amplifier and "scale-of-eight" thyratron counter, observations at several voltages were completed before the "current monitor" was ready for use. The collected data for all the runs with the individual points averaged for each voltage is given in Fig. 15. The over-all error in the final Mott ratios, as indicated by the probable error calculated from the spread of all of the individual observations (shown by vertical bars through the points of Fig. 15) is two or three times the error to be expected from the number of counts alone and may be ascribed to current-fluctuations. Table II gives the data incorporated in these curves. Fig. 15 itself contains all essential information, although, in view of the fact that these results are much more nearly in agreement with a simple form of scattering theory than were our early survey results, it is not out of place to emphasize that *no selection of data has been made* for these final curves, all observations taken after April 15, 1936 (end of contamination studies) being included except for one or two cases where a breakdown interrupted a run. With the exception of the 700- and 600-kv curves of Fig. 15 and the final calibration of the detector slit system (see below) all of the data contained in this paper were presented and discussed at the Washington meeting of the Physical Society and at the Gibson Island (John Hopkins) and Ithaca (Cornell) conferences.

One particular feature of our curves disturbed us from the first, namely, an apparent lack of symmetry about 45°. Since this might constitute the best kind of evidence for a contamination of higher atomic number we examined carefully whether the discrepancy might arise from the rapid decrease in energy of the scattered (and recoil) protons above 45°. In checking over all of our numerical values before publication it was discovered, however, that most of the apparent dissymmetry in our curves was due to an error. The Mott values were originally calculated to 45° only and when it became obvious during the observations that the expected symmetry about 45° should be examined, the Mott numbers for 42.5° and 40° were taken offhand as applicable

TABLE II. *Summary of final averaged data.* The Mott values represent the numbers of protons per minute per microampere expected on the basis of Mott's formula to be scattered into ionization chamber 1 when pure H_2^1 at 12-mm pressure 20°C occupies the scattering volume; the Mott ratio is the observed counting rate divded by the Mott value; the probable errors are calculated from the spread of individual Mott ratios observed; the total number of observed counts, irrespective of rate, is given for each point as an indication of its statistical reliability.

Voltage	No. of runs	Item	Angle 15°	20°	25°	27.5°	30°	32.5°	35°	37.5°	40°	42.5°	45°	47.5°
kv 900	5	Mott value	128700	28920	8570	5530	3530	2335	1610	1175	903	741	654	602
		Mott ratio	0.62	0.71	0.91	1.06	1.43	1.76	2.49	3.38	3.66	4.04	3.88	4.05
		Prob. error, ±	small	small	0.032	0.047	0.039	0.111	0.045	0.146	0.102	0.100	0.074	0.152
		Tot. obs. counts	2638	7640	880	408	1040	568	678	776	1488	1664	1152	648
800	6	Mott value	162700	36650	10850	7010	4470	2955	2036	1488	1143	939	828	762
		Mott ratio	0.73	0.73	0.78	0.83	1.02	1.31	1.57	1.84	2.36	2.59	2.55	2.62
		Prob. error, ±	0.018	0.016	0.028	0.029	0.042	0.066	0.023	0.043	0.049	0.048	0.054	..
		Tot. obs. counts	16360	7432	2104	1216	1248	920	1224	1432	1712	2208	1896	440
700	5	Mott value	212600	47780	14170	9170	5830	3860	2660	1942	1492	1224	1082	..
		Mott ratio	0.71	0.72	0.73	..	0.83	1.03	1.22	1.26	1.48	1.61	1.52	..
		Prob. error, ±	small	small	small	..	0.020	0.070	0.048	0.039	0.038	0.067	0.064	..
		Tot. obs. counts	3232	10800	992	..	1272	1000	1232	880	960	1432	936	..
600	3	Mott value	289200	65100	19270	..	7950	..	3620	..	2032	..	1473	..
		Mott ratio	0.64	0.68	0.61	..	0.53	..	0.61	..	0.57	..	..	..
		Prob. error, ±	small	small	0.020	..	0.017	..	0.027	..	0.114	..	..	..
		Tot. obs. counts	4904	7128	936	..	1776	..	664	..	28	..	..	..

for the symmetrical angles above 45°. Due to the motion of the center of mass of the two colliding protons the expected numbers of counts are not symmetrical, however. When this error was corrected the 47.5° values at 900 kv and 800 kv gave symmetry within the limits of experimental error, as shown in Fig. 15, although the value for 50° at 900 kv indicates that some counts are being missed, and from visual observation on the cathode-ray monitor the notation "missing counts" was recorded while this observation was being taken.

The data bearing on the angle at which counts begin to be missed by reason of having lost too much energy are shown in Fig. 16. A photographic record was made of the sizes of the deflections produced on the cathode-ray monitor by the scattered particles at various angles and at a voltage of 800 kv. At the same time a calibration was made to determine the cut-off point for the thyratrons, that is, the minimum size of deflection which would produce a count. Sizes of deflections are plotted to the right in Fig. 16. The left-hand margin corresponds to the zero position of the cathode-ray spot, and the shaded area corresponds to the zero noise of the amplifier, not as it looks on the photographic record, but defined by the maximum size of noise peak obtained during typical periods of two minutes, with the scattered particles prevented from entering the ionization chamber but with the high voltage and ion beam operating as usual. The frequency distributions of the sizes of the proton deflections recorded at the different angles are shown as the heavily shaded blocks. It is to be noted that at 40° the protons already are slowed down until their residual range just extends across the ionization chamber, giving the maximum size of kick. At 45° they fall short of crossing the chamber and at 47.5° they are on the average only two-thirds as large (total deflection) as at 45° and appear to straggle somewhat more in size. Bearing in mind that the ionization chamber itself corresponds to a depth of about 6 mm and that the variation of the ionization power per millimeter of path against the residual range is approximately as shown in Fig. 16, it is clear that those scattered particles which have only slightly less than the average residual range at 47.5° or 50°, due to an expected (slight) straggling in the two windows, will abruptly fail to be counted. There is further to be considered here the spread in energies of the scattered particles due to the finite angular resolution of the slit systems (about 2°) and the fact that a failure to count, say, ten percent of the protons makes a very obvious dissymmetry. On the basis of the measurements of Fig. 16 one may say that a minimum residual range of 7.8 mm (normal air), corresponding to 45° at 800 kv, is necessary for accurate counting. At 900 kv this minimum is reached for 48°. Thus the dissymmetry should not be expected at 900 kv, 47.5°, and a dissymmetry is not indicated by the measurement for this point. This same residual range corresponds to 41° at 700 kv and 36° at 600 kv, hence one may say that the 45°-value at 700 kv and even the 40°-value at 600 kv, are definitely low, as indicated on Fig. 15.

It may be noted that the curves of Fig. 14 (800-kv curve alone) and Fig. 15 (all four final curves) disagree due to a change in the scale of ordinates (Mott ratios). This is intentional and arises from the fact that the curve of Fig. 14 (800 kv alone) shows the original data as obtained and without correcting for the final slit calibrations. As mentioned under section C above, as an extra precaution against personal bias in accepting or rejecting observations during an experiment we have made it a practice to carry out only rough calibrations of the critical parts of an apparatus at first, reserving the final calibrations until after all other experimental observations have been completed. The final calibration of the detector slit system, which together with the absolute measurement of the proton current through the scattering volume, determines the Mott ratios which form the final result, was made early in July after dismantling this original scattering apparatus to replace it with a more accurate unit. The "1 by 5 mm slit" indicated in Fig. 4 was found to be 1.10 mm wide (high), thereby showing that the size of the scattering volume actually observed was ten percent greater than originally supposed. Furthermore, the "0.55-mm hole" into the detecting chamber (drilled with a No. 74 drill) was found to measure actually 0.562 mm, an increase in area of four percent. These calibrations were made in terms of arbitrary microscope scale-readings, again avoiding any possibility of bias (the theoretical predictions by this time being known). Thus our original figure (see Section C) of 464 counts per minute per microampere as the "Mott standard" should have been 14 percent greater. This reduced all of our original Mott ratios (provisional until the final slit calibrations) by a similar percentage, with the resulting final curves of Fig. 15. None of the other curves in this paper have been corrected for these final slit values, it should be remarked.

The possible effects of certain errors not already considered remain to be discussed, together with the directions in which we hope to improve and extend the experiments using a new apparatus now under construction.

One such item is the constancy of the calibration of our voltmeter. The latter was carefully calibrated and used when new for the accurate location of the lithium and fluorine resonances (2 months). During the proton scattering ob-

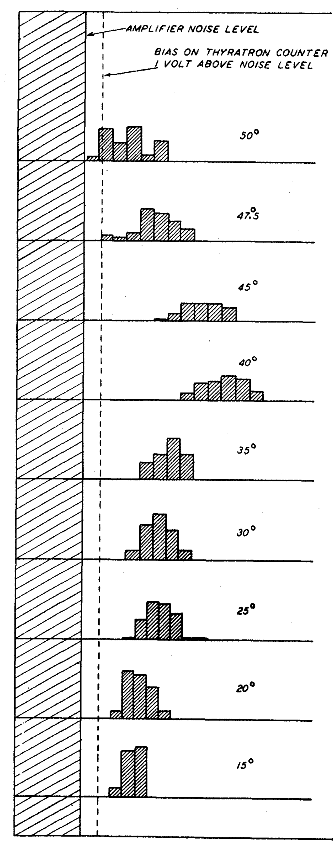

FIG. 16. Sizes of deflections produced by scattered particles entering ionization chamber at different angles of scattering. From photographic records using cathode-ray oscillograph. Proton-proton scattering 800 kv.

servations no check on the calibration was possible (only one target position was available on our apparatus until very recently). Although in May it was found that a "low voltage open circuit" had developed in the voltmeter (as measured using 100 volts), no other evidence of trouble was noticed. It is probable that one of the soldered joints between the 1000-ohm resistors broke open under the constant vibration of operation and the small meter-current easily bridged the gap with a voltage drop of five or ten kv. When the scattering apparatus was dismantled, the lithium evaporator was replaced and a new measurement made on the lithium resonance without any other changes and with the voltmeter still "defective." The 440-kv resonance in these measurements appeared at an apparent voltage of 435 ± 1 kv, thus showing that the voltmeter was indicating about one percent low, or possibly instead of a constant percentage error a nearly constant voltage error of five kv (low). This error is not large enough to affect any of our conclusions above.

The importance of a possible error as small as one-half degree in the zero position of the angular scale used with the movable scattering chamber was not fully realized until after the series of final runs at 900 to 600 kv had been completed and the scattering chamber taken down; the apparatus had been operated throughout this final series without opening it for regreasing the ground joint or any other purpose. Unfortunately, the arm carrying the ionization chamber was fastened to the core of the ground joint and to the ionization chamber itself by means of screws and without pins which would govern the precision of angles and positions in reassembly. Consequently, after once disturbing the instrument we were unable to reassemble it for a more accurate check on the zero position of the scale during our scattering measurements. The accuracy of setting at the individual angles for our measurements was probably within $\frac{1}{4}$ degree with respect to the zero of the scale itself. The maximum shift in angle permitted by all of the screw holes of the assembly corresponded to nearly $\pm$ one-half degree and although it is highly likely that the screws were nearly in the center of their proper holes when assembled as it was in use, the actual zero position of the scale cannot be said with certainty to have had an error less than three-fourths degree. This would not affect the measured Mott ratios for angles above 30° as the number of counts does not vary rapidly with angle at long angles, but at 15° it might account for a large part of the whole observed anomaly, or conversely might result in an apparent anomaly of roughly half of the true amount, since the number of counts varies so rapidly with angle in this region. Thus the observed Mott ratio at 800 kv and 20° is 0.73, and an error of three-fourths degree in the angular measurement would make this ratio 0.57 or 0.86. It is probable that our 15°-values are at neither one extreme nor the other, but absolute certainty on this point, which is of importance in determining whether phase shifts in the higher order de Broglie waves also come into account, must await measurements with an apparatus (such as we have under construction) giving an accuracy of the order of one-fifth degree in the angular measurements. In connection with these same measurements at 15° a second-order correction due to our angular spread of 2° might arise, the increased counts from the 14° to 15° zone more than balancing the decreased counts between 15° and 16°. This error has been examined and is not serious enough to warrant any correction of our present measurements.

As already mentioned, our new apparatus is being built to accommodate Geiger point-counters as detectors, primarily to extend the measurements to the region below 600 kv, where in a certain voltage region the scattering at 45° should approach or reach a small fraction of the Mott value, due to the compensating effects of the Coulomb repulsion and the attractive interaction for certain angles and "distances of approach."

(G) Discussion

A complete discussion of the theoretical significance of these results is given in the accompanying paper by Breit, Condon and Present. This may be summarized by the statement that these proton-scattering experiments demonstrate the existence of a proton-proton interaction which is violently different from the Coulomb repulsion for distances of separation of the order of 10^{-13} cm. The measurements are quantitatively in agreement, as regards magnitudes, variation with angle, and variation with voltage, with a simple phase shift of the spherically symmetrical de Broglie wave ("S wave") due to the collision or scattering, corresponding to a new attractive force overpowering the Coulomb repulsion, and give a rather accurate measure of the "potential well" which is therefore permissible as representing the interaction. Interestingly enough, this potential well appears to be identical, within the limits of error of both determinations, with the potential well which represents the proton-neutron interaction as derived from the scattering and absorption of slow neutrons. Furthermore, the magnitude of interactions thus determined by scattering experiments is in very satisfactory agreement with that used successfully for calculations of mass defects of light nuclei.* It thus appears that a real beginning has been made toward an accurate and intimate knowledge of the forces which bind together the "primary particles" into the heavier nuclei so important in the structure and energetics of the material universe.

* A very readable discussion in this connection is given by Bethe in Rev. Mod. Phys. **8**, 82 (1936).

(H) Acknowledgments

The writers are especially indebted to Professor G. Breit for stimulus and guidance in this problem in which he has been interested since the inception of the high voltage program in this department under his immediate supervision in 1926. We take pleasure also in expressing our indebtedness to Dr. J. A. Fleming for his courageous support of the whole program during the long period of development, and to Odd Dahl, our former colleague now in Norway, for construction of the scattering apparatus as well as for his numerous other ingenious contributions to our apparatus and technique.

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Theory of Scattering of Protons by Protons*

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The experiments of Tuve, Heydenburg and Hafstad and those of White are discussed by means of the standard theory of scattering in central fields. The theoretical formulas are presented in a form convenient for numerical computation and are supplemented by tables. These are arranged so as to enable an experimentalist to compute the effect of phase shifts due to angular momenta $L=0$, $\hbar$, $2\hbar$, and to infer these phase shifts from the experimental material (Tables I, II, III, IV, V, VI, VII, VIII, IX). Tables of necessary Coulomb wave functions are also given for zero angular momentum. By means of these the interaction energy can be computed from the experimental material (Tables X, XI, XII, XIII).

Statistical fluctuations make conclusions drawn from White's data somewhat uncertain. The experiments of Tuve, Heydenburg and Hafstad are comparatively free of statistical effects and their comparison with theory shows that (a) There is an unmistakable difference between the observed scattering and that to be expected according to Mott's formula which uses the inverse square law. (b) This difference can be explained by using practically entirely effects of the phase shift in the partial wave having $L=0$ (head on collisions; s wave distortions). The distortion of p and d waves ($L=\hbar$, $2\hbar$) is secondary and the experimental accuracy does not yet suffice to enable their quantitative determination. (c) The variation of the scattering anomaly with proton energy is in approximate agreement with that to be expected from an interaction potential independent of the energy. (d) For a given range of nuclear forces the interaction potential is accurately determined by the data. The values obtained are in good agreement with those found by Feenberg and Knipp and by Bethe from the mass defects of H^2, H^3, He^4 provided the mass defect calculations are made on the basis of a proton-neutron interaction which depends on the relative orientation of the spins of proton and neutron in accordance with Wigner's explanation of the large scattering of slow neutrons by hydrogen. Mass defect calculations based on a proton-neutron interaction indicated by the binding energy of H^2 without dependence on the spin orientation give a much lower value for the interaction between like particles than that obtained from the proton-proton scattering experiments. The "like-particle" interaction for a Gauss error potential is $39mc^2e^{-17r^2}$ with 8.97×10^{-13} cm as the unit of length and the interaction energy is 11.1 mev for a potential which is constant (except for its Coulombian part) within a distance

* A paper delivered at the Tercentary Conference of Arts and Sciences at Harvard University, September, 1936.

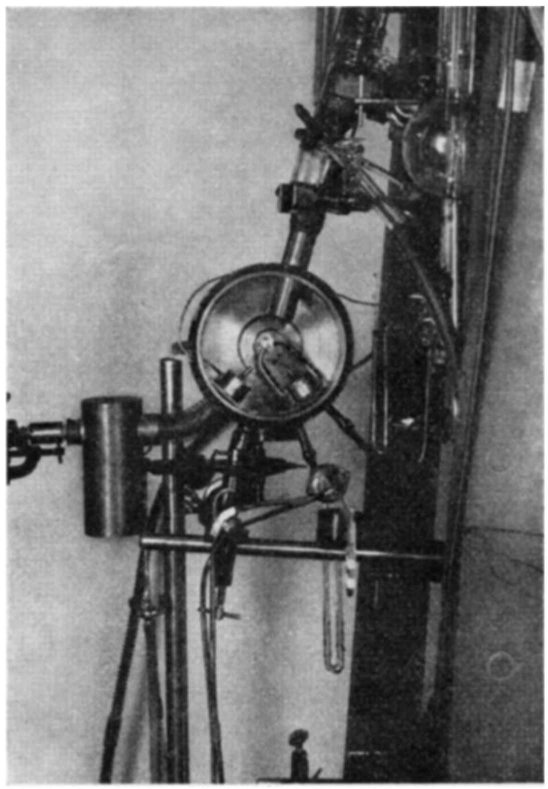

FIG. 3. View of proton-scattering apparatus.