The Scattering of Protons by Protons

R. G. HERB, D. W. KERST,* D. B. PARKINSON† AND G. J. PLAIN
University of Wisconsin, Madison, Wisconsin

(Received April 19, 1939)

The cross section for scattering of protons by protons has been measured at angles from 15° to 45° for protons of energies 860, 1200, 1390, 2105 and 2392 kev. Observed scattering cross sections at 15° are close to Mott values for all energies. Ratios of observed cross section to Mott cross section rise with increasing angle and with increasing proton energy. At 45° the ratio rises from 3.90 at 860 kev to 42.9 at 2392 kev. At 1830 kev measurements were made at scattering angles up to 60° and the scattering cross section showed the theoretically expected asymmetry (cos θ) about 45°. As a check on the proton-proton measurements the scattering of protons from argon and krypton was investigated with protons of energies between 850 kev and 2440 kev.

INTRODUCTION

THE scattering of protons by protons was investigated by Tuve, Heydenburg and Hafstad[1] in 1936 using protons in the energy region between 600 kev and 900 kev. At small scattering angles their observed yields were fairly close to the Mott values, but at large angles they found that the ratio of observed yield to Mott yield rises with voltage and reaches a value of approximately 4 at 900 kev and 45°. Breit, Condon and Present[2] found that the results of THH could be fitted by assuming an attractive interaction between protons in the ^1S state. They were able to determine the magnitude of this interaction within fairly close limits and found that it is nearly the same as that between a proton and a neutron in a ^1S state. Breit, Condon and Present showed that accurate scattering measurements over a wide voltage region might offer the possibility of an accurate determination of the range of the ^1S interaction between protons.

Upon completion of the generator at Wisconsin in April, 1936, Professor Breit pointed out the desirability of extending the measurements of THH to the higher energies available at this laboratory. Measurements were started early in January, 1937 and by August, 1937 data had been obtained over the energy range from 900 kev to 2400 kev. The data were sufficiently consistent, but it was thought that the results might be subject to systematic errors. Improvements were made in apparatus and several months were then spent in a thorough investigation of all phases of the experimental work. Several sources of small systematic errors were discovered and eliminated, and experimental techniques were improved. Scattering measurements were then made over the entire energy range from 860 kev to 2392 kev. The consistency of the entire series of measurements and the satisfactory outcome of check work indicate that the results are reliable. These results are presented in this paper.

GENERAL DESIGN OF SCATTERING CHAMBER

The scattering chamber used in these experiments is shown in Figs. 1 and 2. High velocity protons from the generator pass through an aluminum foil covering a hole in disk A. This foil separates the main vacuum system from the scattering chamber, which contained hydrogen at a pressure of about 11 mm Hg during most of the scattering measurements. After passing through the collimating slit system the proton beam goes through the chamber, through aluminum foil F, and into collector cup G. The region around the collector cup is evacuated so that ionization currents cannot vitiate measurements of proton current.

The ionization chamber for detection of scattered protons is equipped with an analyzing slit system which limits the effective scattering volume to a small region near the center of the chamber, and which selects only protons which are scattered into a small angular region. A graduated disk serves as a support for the

* Now at the University of Illinois, Urbana, Illinois.
† Now at the Bell Telephone Laboratories, New York, New York.
[1] M. A. Tuve, N. P. Heydenburg and L. R. Hafstad, Phys. Rev. **50**, 806 (1936).
[2] G. Breit, E. U. Condon and R. D. Present, Phys. Rev. **50**, 825 (1936).

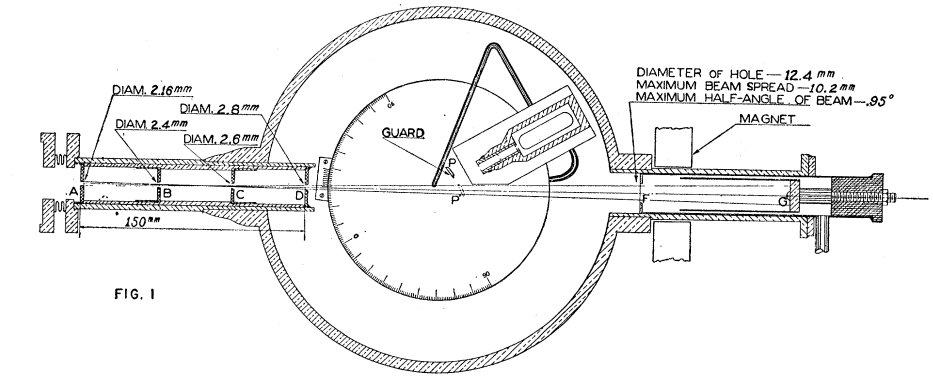

FIG. 1

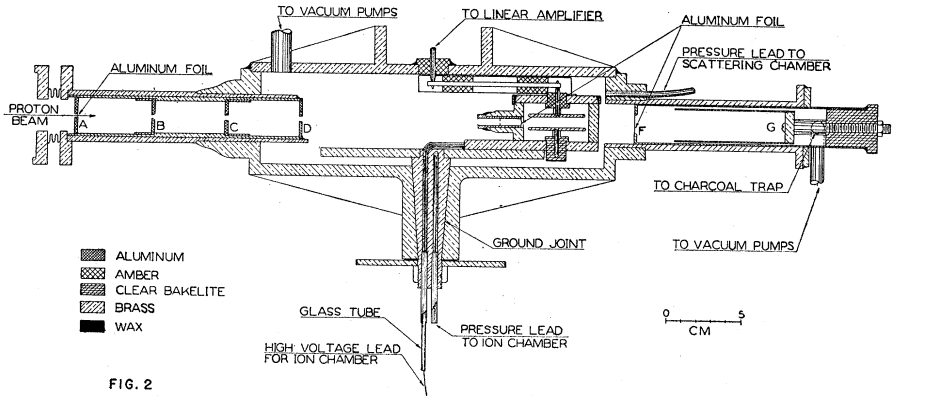

FIG. 2

FIGS. 1 and 2. Two views of proton scattering chamber.

ionization chamber. It can be rotated through a ground joint and angular settings can be read through a window in the cover of the scattering chamber. An aluminum foil covers a hole at the inner end of the slit system and isolates the ionization chamber. During scattering experiments the ionization chamber is filled with air at pressures up to approximately one-half atmosphere. Pulses from the ionization chamber go to a linear amplifier, which is connected through a scaling circuit to a counter.

MECHANICAL DETAILS OF SCATTERING CHAMBER

The scattering chamber and its cover are brass castings. They were first turned down to approximately the desired dimensions, were annealed by a heat treatment, and then were allowed to age for a period of five weeks before the final turning. In finishing the holes for the two necks which carry the collimating slit system and the collector cup system the procedure was as follows: The chamber was clamped to the carriage of a lathe. A boring bar was mounted so as to turn between centers, and the two holes were bored (equal diameters) without unclamping the chamber. These holes were therefore accurately in line.

For good geometry the axis of the collimating slit system must intersect the axis about which the ionization chamber turns and must be perpendicular to it. For accurate fulfillment of these requirements the following procedure was used in finishing the hole for the ground brass plug: A mandrel of solid cold-rolled steel 20 inches long was accurately turned between centers to a tight slip fit in the holes for the two necks and was put in place with its ends protruding through the holes. The chamber was mounted in a four-jaw chuck and a sensitive gauge (Universal dial indicator) was mounted on the carriage about 3 inches off center with its stem pointed toward the chuck. As the chuck was turned and the mandrel swung over the ball of the gauge the maximum gauge deflection was noted. The chuck was then turned a half revolution and the maximum gauge

deflection was noted as the mandrel again moved past the gauge. The back of the chamber rested against studs which had been threaded into the face of the chuck and by means of these the chamber was adjusted until the gauge deflections were equal to within approximately 0.0002 inch. This adjustment provided for perpendicularity of the two axes referred to above. To provide for intersection of the two axes a further adjustment was made. The gauge was mounted on the carriage with its stem vertical and with its ball below center by an amount slightly less than the radius of the mandrel, and the chuck was turned so that the mandrel was horizontal. The carriage was moved so that the ball of the gauge passed beneath one end of the mandrel where it protruded from the chamber and the gauge deflection was noted. The gauge was then moved to the other end of the mandrel and the deflection was again noted. These measurements were repeated after the chuck had been turned through an angle of 180° and the chamber was adjusted until gauge deflections at each end of the mandrel were equal to within 0.0002 inch for the two angular positions of the chamber. Since adjustment for intersection of the axes disturbed the adjustment for their perpendicularity it was necessary to make successive repetitions of the two adjustments until both requirements were accurately fulfilled. With the chamber thus adjusted the tapered hole for the ground plug was finished.

Heavy-walled brass tubing turned inside and outside was used for the two necks. They were turned to a press fit for the holes and were soldered into place with the least possible heating of the chamber. Greater dependability would have been assured if the necks had been soldered into place before the final turning, but this method could not be used because the complete chamber could not be swung in the largest of the lathes available.

The ground plug and rotating disk were roughed out, soldered together, and the system was then mounted on a lathe between centers for the final turning. A dividing head dependable to 0.01 degree was used for graduating the rotating disk. Graduation lines on both disk and vernier index were fine and accurately made, and settings on an integral tenth degree could be made to within approximately 0.01 degree. A spring washer clamped by a nut held the ground plug in place, and a gear reduction system was provided to facilitate accurate angular setting.

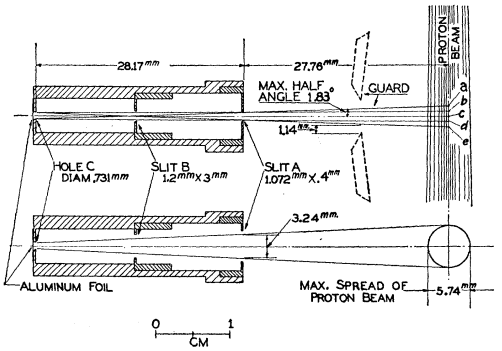

FIG. 3. Analyzing slit system set perpendicular to the proton beam. This slit system slips into the nose of the ionization chamber. The two possible positions of the guard are outlined by a broken line.

IONIZATION CHAMBER

The nose, front face and two sides of the ion chamber were machined as a unit from a solid brass block. Plates for the back end and base were fastened with screws and soldered. The top plate (removable) was fastened by screws and was sealed with wax. For alignment of the ion chamber a solid brass mandrel was turned to form a tight slip fit into the neck of the scattering chamber, and one end was turned down to a tight slip fit into the nose of the ion chamber. By means of a special arbor the ion chamber could be mounted on a lathe. The base plate was faced off until the mandrel could be slipped into the nose of the ion chamber with the ion chamber clamped in place on the graduated disk, with grease on the ground plug, and with the mandrel extending through the neck and across the scattering chamber. This gave assurance that the axis of the analyzing slit system passed through the point of intersection of the axis of the collimating neck with the axis of the rotating disk. With the ion chamber clamped in place, holes were drilled, and the base of the ion chamber was pinned to the disk. Four screws were provided to clamp the base of the ion chamber to the disk, since the pins were only for alignment.

The brass tube carrying the collimating disks was machined from solid rod (tight slip fit into neck), and precautions were taken to assure that the inner surface was made accurately concentric with the outer surface. The collimating disks were made of hard aluminum sheet which machines easily, and the holes were accurately centered. Two holes were drilled through the ground plug, one for the high voltage lead and one for a gas line, to the ionization chamber. The gas line extends approximately radially through the disk, and connection is made to the ionization chamber.

Slit System

Figure 3 shows the analyzing slit system. It was made to have a tight slip fit into the nose of the ionization chamber. Hole C was turned on a lathe with a fine tool and was therefore accurately centered with respect to the outer cylindrical surface of the slit system. The hole was beveled with the smaller diameter toward the inside, and the aluminum foil was placed over the outer edge of the hole so that protons could not go through the foil in a small region around its edge. Slits A and B were made of brass 0.2 mm thick and were finished with a fine file. Slit B was made sufficiently large so that it did not define the incoming proton stream. As shown in Fig. 3 (lower view), slit A is sufficiently long so that the entire width of the proton beam is included in the effective scattering volume, and it was therefore not essential to provide accurate centering of the slit along this dimension with respect to the outer surface of the cylindrical holder. However, the edges of slit A shown in the upper view of Fig. 3 define the effective scattering volume and determine the average scattering angle. The slit defined by these edges must be accurately centered with respect to the holder. To check the centering of slit A the holder was inserted into a hole (slip fit) in a brass block and a cross hair of a comparator was set on, and parallel to one slit edge. The cylindrical holder was then turned through 180° and the comparator was adjusted until the cross hair was on the second edge. By successive repetition of this procedure the slit was shown to be off center by less than 0.01 millimeter. Slit-edge roughness limited the accuracy of the check, but the limit set on the accuracy of centering is very satisfactory.

The thickness of the scattering volume measured along the central axis of the proton beam is determined by the width of slit A. When the slit system is perpendicular to the central axis of the beam any element of area in the plane of hole C can see a section of the beam of thickness $T=2bR_0/h$ where $2b$ is the width of slit A, h is the distance from hole C to slit A, and R_0 is the distance from hole C to the center of the proton beam. When the slit system is set at any angle θ with respect to the proton beam the effective target thickness, measured along the axis of the beam will be $T/\sin\theta$. The solid angle Ω subtended by the hole C is given by A/R_0^2 where A is the area of hole C. If Y is the number of counts for a given number N of incident protons, then $Y=T\Omega\sigma Nn/\sin\theta$ where n is the number of target protons per cm^3 and σ is the scattering cross section per unit solid angle. Substituting for T and Ω this expression becomes

$$Y=2bANn\sigma/R_0h\sin\theta=Nn\sigma G/\sin\theta$$

or $\sigma=Y\sin\theta/NnG$ where $G=2bA/R_0h$ is a geometric constant which must be accurately determined by measurement.

The diameter of hole C was measured with a Zeiss microscope equipped with a scale (AA objective, 20X eyepiece calibrated by Zeiss, 0.1-mm scale). The hole was not round (maximum variation of diameter 2 percent), but the edge was smooth and sharp. Readings were taken at uniformly spaced intervals of 15°, and values of the area were consistent to within 0.3 percent.

Measurement of the width of slit A caused difficulty because of surface roughness. Accurately ground knife edges would have been more satisfactory than the slit used. A comparator was tried for this measurement, but it proved to be less satisfactory than the Zeiss microscope. Microscope readings of the width were taken at intervals of 0.2 mm along the length of the slit. Within a central region 2 mm wide (1 mm from each side of the center) the maximum variation in width was 0.8 percent, and the average width, obtained April, 1938, was 1.0725 mm. Most of the protons will enter in this region, but taking into consideration the maximum possible spread of the main proton beam (5.74 mm at center of

chamber) protons can enter this slit in a region 3.24 mm long. The average width of the outer region was 1.065 mm, but since most of the protons enter the central region the value 1.072 mm was assumed for the width of the slit. A micrometer comparator was used to determine the distance from slit A to hole C. This determination is dependable to within approximately 0.1 percent. For determining the distance from slit A to the center of the scattering chamber the microscope of a comparator was sighted on the end of the slit system, the ion chamber was turned through 180°, and the carriage was then moved to the new position of the slit system. This gave double the distance desired, and the value determined in the April, 1938 measurements for the distance in question was 27.76 mm (dependable to better than 0.1 percent).

All measurements were made several times, and by at least two persons before scattering observations were started. In April, 1937 these measurements were gone into more thoroughly. Three persons worked approximately a week on the determinations before they were considered dependable. The values obtained were: $T=2.12$ mm, $\Omega=1.344\times10^{-4}$ steradian, and $G=2.850\times10^{-5}$ cm. In April, 1938 three persons again spent several days on the measurements. Techniques were improved and the final values obtained were: $T=2.129$ mm, $\Omega=1.341\times10^{-4}$ steradian, and $G=2.855\times10^{-5}$ cm. The April, 1938 value of G is considered to be more reliable than those obtained previously and was used for computation of the final data. Estimates of the probable error involved in the measurements are difficult to make. In spite of the time spent on check work and the precautions taken, small systematic errors may still be present. It is considered unlikely, however, that the final value of G is off by more than 0.5 percent.

For convenience in the experimental work the proton-proton scattering yield Y was expressed in counts per microcoulomb of incident protons per mm of oil pressure. The value of N was computed to be 6.250×10^{12} protons per microcoulomb using $e=4.80\times10^{-10}$ e.s.u. The value of n was found to be 4.492×10^{15} atoms per cm³ at 0°C per mm of oil pressure. The oil density was assumed to be 0.864 which is the density of Apiezon oil B at 26°. In computing n the value 6.023×10^{23} was used for Avogadro's number. Substitution of the values of G, N and n into the expression for σ gives $\sigma=Y\sin\theta\times1.247\times10^{-24}$ cm².

In computing the expression for σ a number of approximations were used which must be given some consideration. The scattering angle θ was taken as the angle between the central axes of the collimating slit system and the analyzing slit system. The maximum half-angle spread of the collimated proton beam is 0.95°. The maximum half-angle spread allowed by the analyzing slit system is 1.83° in the plane determined by axes of the slit systems. If $d^2Y/d\theta^2$ were zero, where Y is the scattering yield, the experimental values of σ would not be affected by the angular spread of the slit systems. At large scattering angles effects are negligible since $d^2Y/d\theta^2$ is small for Rutherford scattering, and it is still smaller for proton-proton scattering yields. Calculations in the paper by Breit, Thaxton and Eisenbud show that at 15° $d^2Y/d\theta^2$ is sufficiently large to cause an appreciable shift in experimental values of σ. At 20° the effect is also appreciable at the low proton energies.

Other factors in addition to those described can affect the experimental values of σ. A thorough analysis of the problem is given in the paper by Breit, Thaxton and Eisenbud in this issue. They find that because of the approximations used in computing σ experimental values of the scattering cross section are probably too high by about 2.5 percent at 15° and by about half that amount at 20° in the lower energy region. These corrections were not applied to the data. The approximate expression was used for σ and no adjustments were made in experimental values.

Errors due to imperfections in the mechanical construction of the scattering chamber appear to be entirely negligible. After completion of the scattering measurements the chamber was examined to see if warping had taken place during the two years it was used. The collimating slit system was removed and mandrels of cold-rolled steel having tight slip fits in the collimating neck were used for checking alignment of the apparatus. The axis of the graduated disk was found to be 0.067° off from perpendicularity with respect to the axis of the collimating neck. The position of the analyzing slit system depends on the thickness of the grease film on the ground

plug and with a very thin film the axis of this slit system was 0.20 mm below (orientation of Fig. 2) the axis of the collimating neck. Errors due to these two imperfections add but they are entirely negligible. With the ionization chamber set at an indicated angle of 15° the true scattering angle is 0.002° greater because of these imperfections. At larger scattering angles the angular shifts are smaller. When the apparatus was first assembled the vernier index (Fig. 1) was not accurately set to read true scattering angle. It was set only approximately since it seemed desirable to determine the zero angle or angle of symmetry by yield measurements. Scattering measurements showed that the yield values were very nearly equal when angular settings were made at $+14.8°$ and $-15.2°$ where angles on one side of the beam are referred to as positive and angles on the other side as negative. In all yield measurements the angular reading $-0.2°$ was taken as the true zero angle and in making a measurement at 30°, for example, angular settings were made at $+29.8°$ and at $-30.2°$.

During the examination of the chamber a mandrel, inserted in the collimating neck, was used to check the angle of symmetry. One end of the mandrel was turned down to give a tight slip fit in the nose of the ionization chamber. With the mandrel in place pushed into the nose of the ionization chamber the angular reading of the vernier index was $-0.2°\pm0.015°$. Thus the zero angle determined by mechanical alignment agreed with the zero angle determined by scattering measurements. When the mandrel was first tried the grease film on the ground plug was very thin and the ground plug had to be pushed inward about 0.2 mm before the mandrel would enter the nose of the ionization chamber. Grease was then applied to the plug and after a short period of "working in" the ion chamber was at the proper level so that the mandrel entered the nose with the ground plug seated. The zero angle reading was again $-0.2°\pm0.015$.

The axis of the graduated disk was found to be displaced by 0.05 mm from the axis of the collimating neck, but errors due to this displacement are entirely negligible because of the following considerations. First, the check on the zero angle showed that when the reading of the vernier index was $-0.2°$ the axis of the analyzing slits coincided with the axis of the collimating neck and thus angular readings were accurate. Second, the distance R_0 from hole C to the center of the scattering chamber enters only to the minus first power in G and it was taken as one-half the distance between diametrically opposite positions of hole C. At each angle θ equal numbers of counts were taken at $+\theta$ and $-\theta$ and thus errors cancel out except for second-order effects which are smaller than one part in 10^6.

The hole covered by foil F was found to be 0.4 mm off center with respect to the axis of the collimating neck but allowing for this displacement protons in the beam defined by the collimating slits could come no closer than 0.7 mm to the edge of the hole.

Aluminum Foils

Aluminum foil $\sim1.44\times10^{-4}$ cm thick was used to cover the hole over the collector cup chamber, and also to cover hole C, Fig. 3. For the hole over the collimating slits, aluminum foil with a thickness of $\sim0.97\times10^{-4}$ cm was used. Foils were cut sufficiently large so that they overlapped the supporting disks well. After a foil had been centered over a hole its edge was wetted with a 2-percent solution of collodion in amyl acetate applied with a small brush. This application caused the foil to adhere to the supporting disk and to stretch out smoothly over the hole. Red sealing wax was then applied around the edge of the foil to form a ring which covered the foil near its edge and extended over the supporting disk. As the wax cooled it stretched the foil tight and left it smooth. A careful examination was then made to see that no wax had flowed past the edge of the disk where it would block out part of the hole. To plug small holes in the foils they were painted with a 5-percent solution of collodion in amyl acetate. This solution was spread on as evenly as possible and measurements showed that the energy loss of protons in the collodion film was less than 5 kev for protons in the energy region of 900 kev. For an accurate determination of the absorption thickness of the foil over hole A the following procedure was used. The collector cup and the chamber which surrounds it were removed from the scattering chamber and another collector cup with a

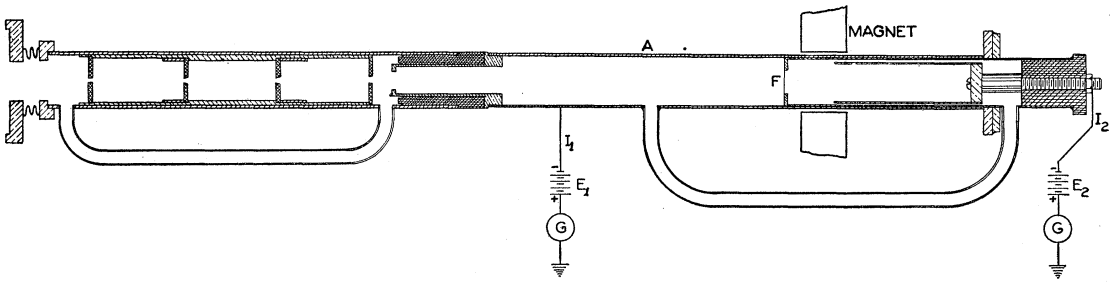

FIG. 4. Apparatus for checking the method of measuring proton current.

calcium fluoride crystal at its base was substituted. To prevent the crystal from charging up when bombarded by protons it was covered with fine mesh nickel gauze. With the scattering chamber evacuated the gamma-ray yield was investigated in the region of the 862-kev and the 927-kev fluorine resonances, and the generator voltages at which these resonances appeared were accurately determined. These measurements gave the energy loss of protons at only two voltages, but the energy loss at any other voltage could then be determined by means of the "range in aluminum *versus* proton energy" curve which had been previously determined.[3] Determination of the absorption thickness of the foil over hole *A* was complicated further because of the formation of a carbon deposit on the foil which increased in thickness with bombardment time. In early proton scattering measurements no correction was made for this additional absorption thickness and the results were therefore inaccurate. During the course of the final measurements which yielded the results given in this paper periodic determinations were made of foil thickness. The carbon deposit was assumed to increase in thickness linearly with bombardment time, and its thickness was determined for each series of scattering experiments.

The absorption thickness of newly installed foils for disk *A* varied from 54 kev to 46 kev for emergent protons of 862 kev, and absorption thickness was found to increase on the average by 1 kev for each scattering run where "run" is used to designate a series of yield measurements as a function of scattering angle at constant voltage. Each run required approximately $3\frac{1}{2}$ hours of bombardment time. The final absorption thicknesses of the two foils used after July 28 were 74 kev and 60 kev.

[3] D. B. Parkinson, R. G. Herb, J. C. Bellamy and C. M. Hudson. Phys. Rev. **52**, 75 (1937).

MEASUREMENT OF PROTON CURRENT

Only a negligible fraction of protons are scattered out of the main beam in going through the hydrogen. The beam has a maximum possible spread of 10.2 mm at aluminum foil *F*, Fig. 1, and the foil covers a hole 12.4 mm in diameter. Charge due to protons entering collector cup *G*, Fig. 1, was stored on a condenser when scattered protons were being counted. A magnetic field of 600 gauss (position of magnet shown in Fig. 1) prevented secondary electrons from vitiating charge measurement. Special contact points on a charge and discharge key were arranged so that when one button was pressed the Cenco counter started, and charge started accumulating on the condenser. Pressing a second button stopped the counter and discharged the condenser through a ballistic galvanometer. A 1-microfarad mica condenser was used, and when taking data the potential on the condenser was never allowed to build up to more than 10 volts. The charge and discharge key was enclosed in a de-humidified case, and the lead from the collector cup was supported by paraffin blocks. Before taking data the system was checked for leakage in the following way. A small "*C*" battery with a tap at approximately 10.5 volts was used for charging the condenser, and the ballistic galvanometer deflections were determined as a function of time between charge and discharge. In the final measurements on scattering yield these checks showed that with the values of condenser voltage and leakage time used in obtaining data leakage could not give an error of more than 0.2 percent.

The charge and discharge key was provided with hard rubber insulation and with tungsten contact points. Tests were frequently made with a constant voltage from a battery for charging the condenser, and ballistic galvanometer deflections were always consistent to within 0.1 percent for all voltages tried.

When taking data on proton scattering the potential of the collector cup becomes positive with respect to the surrounding cylinder which is grounded, and if the region around the cup is not well evacuated, ionization current will cause charge leakage. A charcoal trap was provided for the region around the collector cup. Before taking data on proton scattering, this trap was heated by a special furnace and was well outgassed. A stopcock in the lead to the vacuum system was then closed, and the trap was immersed in liquid air. To check for ionization currents the following procedure was used. The yield of scattered protons was determined in the usual way by taking approximately 10,000 counts at a particular angle and voltage. Then a $10\frac{1}{2}$ (sometimes $22\frac{1}{2}$)-volt battery was connected in the lead to the collector cup, and scattering yield was determined first with the collector cup negative with respect to the condenser and then with the polarity of the battery reversed. Reversing the connections of the battery reverses the direction of an ionization current, and since the battery voltage was as high as or higher than the maximum voltage on the condenser, effects of ionization current on yield determinations should have been magnified several times. This check was frequently used after completion of a series of proton scattering yields. When foil F, Fig. 1, was in good condition no check showed any ionization current, and

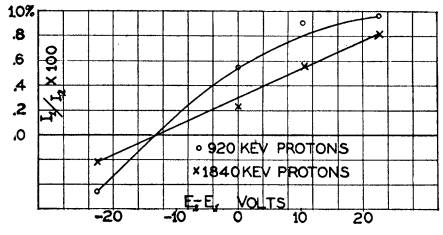

FIG. 5. Current measurement test: foil over collector cup, no foil over collimating slits. I_1/I_2 is the ratio of current from chamber A to current from the collector cup. (E_2-E_1) is the potential difference between the collector cup and the chamber. The slopes of the curves are probably due entirely to ionization current.

with 10,000 counts a yield change of 1 percent would have been detected. Changing the potential on the collector cup should also change a secondary electron current, and since the change in yield was less than 1 percent when a $22\frac{1}{2}$-volt battery was used the effect of secondary electrons on proton scattering results must have been negligible.

The dependability of the method of current measurement might be questioned because of the

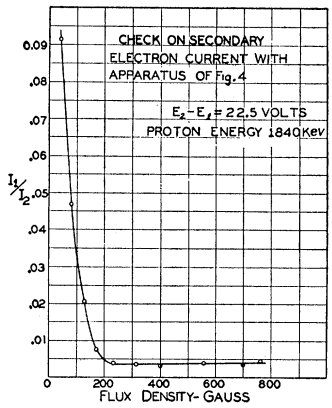

FIG. 6. Showing variation of I_1/I_2 with the strength of the magnetic field used for suppression of secondary electron currents. In proton scattering work a field of 600 gauss was used.

possibility that an appreciable fraction of the protons are neutral as they leave the aluminum foil and enter the collector cup. As neutralization effects could not be easily investigated with the proton scattering set up, the arrangement shown in Fig. 4 was used. This arrangement also provided the opportunity for further checks on secondary electron currents and ionization currents. The collimating slit system and the collector cup with its surrounding chamber were removed from the scattering chamber and were installed in this apparatus with distances from collimating slits to foil and collector cup the same as in the scattering chamber. The same magnet was used for suppression of secondary electrons as in the scattering apparatus, and the magnet was placed in the same position with respect to the end of the collector cup. Chamber A was ordinarily kept at a potential of -45 volts (E_1) to prevent entrance of secondary electrons. Proton current entering chamber A is given by I_1+I_2, and if the collector cup system were

perfect I_1 would be zero. The apparatus was well insulated and, when tests were made with no protons entering the chamber, no leakage currents could be detected. In proton scattering experiments the potential of the collector cup rises from zero to a maximum of 10 volts (average of 5 volts) as the condenser charges, and the chamber around the collector cup is grounded. In this check work E_2-E_1 was varied from $+22\frac{1}{2}$ volts to $-22\frac{1}{2}$ volts, and the ratio I_1/I_2 was determined.

To investigate neutralization of protons the foil over the collimating slits was removed so that no protons were neutral in the chamber A. Fig. 5 shows ratios of I_1/I_2 as a function of E_2-E_1. The slope of the curves indicates that there was either ionization current or secondary electron current, and the values of I_1/I_2 for $E_2-E_1=0$ indicates that either there was neutralization or else the system was not properly aligned, and some protons were hitting outside the hole covered by foil F. To investigate secondary electron current, I_1/I_2 was determined as a function of magnetic field strength with generator voltage set at 1840 kv and $E_2-E_1=22\frac{1}{2}$ volts (Fig. 6). Since I_1/I_2 showed no change as the magnetic field was decreased from 760 gauss to 250 gauss it seems safe to conclude that secondary electron current was negligible, and that the slopes of the curves of Fig. 5 must have been due to ionization current. Further considerations as explained below substantiated this conclusion. In obtaining the experimental results shown in Fig. 5 the test chamber was connected to the main vacuum system which was at a pressure of approximately 10^{-5} mm Hg with the ion source running. Rough computations showed that ionization currents of a few tenths of one percent should be obtained.

Values were obtained for I_1/I_2 as a function of E_2-E_1 with the collimating slit foil in place and with foil F removed. For this experiment the apparatus was modified so that the test chamber could be isolated from the main vacuum system, and a charcoal trap was used in an attempt to improve vacuum conditions. Results of one run are shown in Fig. 7. Values of I_1/I_2 vary only slowly with E_2-E_1 which shows that ionization currents were small, yet the pressure was much higher than that maintained in the collector cup chamber during proton scattering measurements.

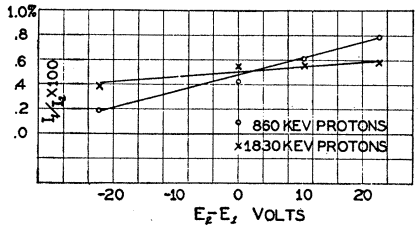

FIG. 7. Current measurement test: no foil over collector cup, foil over collimating slits. Showing I_1/I_2 as a function of E_2-E_1. Since foil F was removed for this work neutralization of protons could have given no contribution to I_1. During this work the vacuum in the test chamber was better than for the work of Fig. 5 and ionization currents were smaller.

At the conclusion of this run, when the test chamber was connected to the main vacuum system, the ionization gauge showed a pressure rise of 10^{-6} mm Hg. In similar checks after all proton scattering runs which were included in the final data the pressure rise was never greater than 5×10^{-8} mm Hg.

Since foil F was not in place during the experiment giving the data shown in Fig. 7, neutralization of protons could give no contribution to I_1. A comparison of the results shown in Fig. 7 with the results of Fig. 5 indicates that neutralization effects must be small, probably negligible. Further experiments were tried with both foils in place, but these data yielded little additional information.

When the apparatus was removed from the generator it was examined for alignment. The hole which is ordinarily covered by foil F was found to be off center with respect to the axis of the slit system. No accurate measurement was made of the displacement, but careful sighting through the system showed that a small percentage of protons coming through the collimating slits could miss the hole. It is probable that the finite values of I_1/I_2 for $E_2-E_1=0$ and the lack of consistency in results were caused by protons missing the hole.

A more thorough investigation of the method of current measurement would have required a new test chamber of special construction to provide accurate alignment of the system. Since alignment in the proton scattering chamber was satisfactory, this error could not have entered. It seems safe to conclude that the collector cup system used for proton scattering could have introduced an error no greater than 0.5 percent.

Calibration of Ballistic Galvanometer

As explained previously, current from the collector cup flows onto a mica condenser while scattered protons are being counted, and charge is measured by means of a ballistic galvanometer. The ballistic galvanometer was equipped with an Ayrton shunt providing a number of different sensitivities, three of which were used in proton scattering measurements. After careful adjustment had been made for linearity of the ballistic galvanometer its sensitivity varied by less than 0.1 percent for deflections in the region between 30 cm and 50 cm (50-cm scale, 170 cm from galvanometer). During measurements on proton-proton scattering only this region of the scale was used, and a constant value was assumed for sensitivity.

The capacity of the mica condenser was not accurately known, and after investigation there seemed to be difficulty in obtaining an accurate determination of its value. To make the calibration of the ballistic galvanometer independent of the capacity of the mica condenser the following method was used. Current from a 400-volt B eliminator supplied by a Raytheon voltage regulator was fed onto the mica condenser through a high resistance (S.S. White resistors). This current was measured by a calibrated galvanometer, and it was fed onto the condenser through the charge and discharge key in exactly the same way that proton current flows onto the condenser during proton scattering experiments. The current was allowed to flow for a known time, and it was then interrupted by the key, and the condenser was discharged through the ballistic galvanometer. Several periods of current flow were used ranging from $\frac{1}{2}$ minute to 4 minutes to check the consistency, and several values of current were used for each calibration. Current was read at 5, 10, or 15 second intervals, and readings were averaged. With this system the ballistic galvanometer was calibrated for each of the sensitivities used in scattering experiments.

A careful search was made for possible systematic errors. Leakage was found to be negligible from any part of the system. Ordinarily in the calibration work the current galvanometer was connected in the ground lead of the mica condenser, but it was changed to the high voltage terminal of the condenser, and results were not changed. Tests showed that the measurement of time for a minute interval was dependable to approximately 0.02 percent. For calibration of the current galvanometer a known fraction of the voltage of a dry cell was picked off by a voltage divider (Leeds and Northrup resistance boxes), and current was fed through a 100,000-ohm resistance box to the galvanometer. The e.m.f. of the dry cell was determined immediately before use by means of a Wolff potentiometer and a standard cell, and all resistances used were checked on a Post Office box and were found to be accurate to within 0.1 percent.

During the course of the proton scattering experiments the ballistic galvanometer was calibrated five times. Before each calibration the current galvanometer was calibrated with standard cells which had been calibrated at the National Bureau of Standards and were reserved for calibration work.

There seemed to be little possibility that the calibration of the ballistic galvanometer could be off by more than 0.3 percent, but after completion of the scattering experiments it was thought advisable to try an entirely different method of calibration. A General Radio precision air condenser with a maximum capacity of 1435.66 $\mu\mu$f was charged to high voltage (maximum 400 volts) by B batteries, and was discharged through the ballistic galvanometer. The air condenser was calibrated especially for this work by the General Radio Company. Voltage was measured by a voltmeter which was calibrated at the Standards Laboratory of the University of Wisconsin. Values were determined for the sensitivity of the ballistic galvanometer with five different condenser settings ranging from 917.31 $\mu\mu$f to 1435.66 $\mu\mu$f. Potentials in the region of 390 volts and in the region of 280 volts were used. The percentage differences between these values of the sensitivity and the "current-time" value ranged from -0.88 percent to -0.42 percent with an average of -0.76 percent.

No investigation was made of the cause of the discrepancy since the air condenser method was not very satisfactory for precise work. The maximum charge available gave a deflection of less than half-scale with the galvanometer set for maximum sensitivity. The current-time method

was least accurate with the ballistic galvanometer at maximum sensitivity, and in proton scattering experiments this sensitivity was never used. In computing proton scattering yields the "current-time" values for the sensitivity of the ballistic galvanometer were used.

Measurement of Proton Energies

The generating voltmeter used for measurement of generator voltage has been described in previous publications.[4] For calibration of the voltmeter the gamma-ray yield from lithium was investigated and the value 440 kev was assumed for the energy position of the resonance. In recent calibrations diatomic ions were used and the generator voltage at which the lithium resonance appeared was assumed to be 880 kev. Calibrations were made with lithium on May 17 and on August 15; and the calibration was checked by investigation of the 862-kev fluorine resonance on August 17, August 26, September 17 and October 8.

During the course of the experimental work carried out since the construction of the generator frequent checks have been made on the performance of the voltmeter and no departure from linearity has ever been detected. In work on the 927-kev fluorine resonance with protons and hydrogen diatomic ions no shift was observed in the sensitivity of the voltmeter between 927 kev and 1854 kev although a shift of 0.2 percent could have been detected. Proton scattering yields from krypton serve as a rough check on the linearity of the voltmeter up to 2473 kev (2440 kev-protons at the center of the scattering chamber). Because of difficulty in the measurement of proton current the krypton results do not set close limits on the linearity of the voltmeter, but they indicate that the voltmeter could have changed in sensitivity by no more than 0.5 percent between 1850 kev and 2470 kev.

Since May 1938 the current output of the generating voltmeter has remained constant to within 0.1 percent at 7.035×10^{-10} amp. per kilovolt. The galvanometer used for measuring current from the voltmeter has changed in sensitivity several times during the past year, but during the final work on proton scattering galvanometer sensitivity was checked frequently, usually before a series of scattering measurements, and this instrument could have caused no error in voltage measurement. Proton energies were corrected for absorption loss in the foil over the collimating slits and a correction was applied for absorption loss in the gas between the foil and the center of the scattering chamber. It is believed that the greatest uncertainty in the values assumed for the proton energies at the center of the scattering chamber is due to the uncertainty in the position of the "440 kev" lithium resonance which was used for calibration of the generating voltmeter.

Detection of Scattered Protons

A linear amplifier of the Dunning type was used for detection of scattered protons. Voltage for the high potential plate of the ionization chamber was supplied by a voltage regulator circuit. Usually this potential was set at about 700 volts. The first stage of the amplifier was mounted on the scattering chamber, and the 259B-tube was carried by a heavy piano wire spring which served as a floating support. The scattering chamber was rigidly clamped to a heavy support (weight 500 lb.) which rested on sponge rubber, and the chamber was connected to the magnetic analyzer by a sylphon bellows. Very little change in amplifier background could be noticed when the generator was started. A constant check on noise level and pulse size was maintained by means of a cathode-ray oscilloscope which was connected to the output stage of the amplifier. Pulses from the amplifier were fed into a scale-of-ten counter,[5] and the output pulses from the scaling circuit were fed into an 885 recorder circuit which operated a Cenco high impedance counter. A set of earphones was connected across the input (885) tube of the scaling circuit. *C* bias on the 885 tube was adjusted while watching the oscilloscope and listening to the breakdown of the tube by means of the earphones. For the smallest pulses obtained in the scattering measurements, those due to proton-proton scattering at 860 kev and 45 degrees, the ratio of pulse size to noise level was sufficiently great to give dependable counting.

[4] D. B. Parkinson, R. G. Herb, E. J. Bernet and J. L. McKibben. Phys. Rev. **53**, 642 (1938).

[5] D. W. Kerst, Rev. Sci. Inst. **9**, 131 (1938).

The entire counting arrangement caused very little trouble. Once during two years' work the scale-of-ten counter failed because of a punctured condenser, and at another time high humidity caused leakage in the scaling circuit which made the scaling ratio undependable. An accurate and convenient check on the scaling ratio can be made by feeding pulses at 120 cycles into the amplifier and by determining the number of output pulses per minute. This check was always made before and after taking data on proton scattering. Additional checks were also made occasionally. The scale-of-ten circuit was connected in parallel with a scale-of-eight circuit of standard design, and the two were found to check perfectly. The scaling ratio was also checked for counting rates much lower than any used in the proton scattering work, and the ratio was found to be dependable. The counting rate was always kept below 20 pulses per second (two pulses per second from scaling circuit), and since the longest time constant was 1/2000 second (input of scaling circuit) the correction for counts missed was negligible.

Air pressure in the ionization chamber was measured by means of a small dial gauge. For high energy protons the pressure was not critical and was usually set at about one-half atmosphere, and for the slowest protons the pressure was adjusted for maximum pulse size. At 860 kev and 45 degrees the optimum pressure was approximately $\frac{1}{8}$ atmosphere.

A considerable amount of check work was done on the counting system. Proton scattering yields were studied as a function of (1) counting speed, (2) pressure in the ionization chamber, (3) setting of the C bias of the input tube of the scaling circuit, (4) potential on the high voltage plate of the ionization chamber. All results indicated that the counting system was dependable.

Hydrogen Supply and Pressure Measurements

Hydrogen from a supply tank (commercial hydrogen) was passed through a palladium tube into the scattering chamber. A tungsten filament around the palladium tube served to control its temperature, and when filling the scattering chamber the filament was kept well below red heat. Hydrogen pressure in the chamber was measured by means of a manometer containing Apiezon oil B. One end of the manometer was connected to the vacuum system. The glass U-tube was made sufficiently large in diameter (inside diameter $\frac{1}{2}$ inch), so the effects of capillary attraction were negligible. A steel scale graduated in $\frac{1}{2}$ mm was mounted between the arms of the manometer, and oil levels were read by means of a telescope equipped with cross hairs mounted at a distance of $3\frac{1}{2}$ feet from the manometer. The telescope was well mounted, and readings of hydrogen pressure were always consistent to better than 0.1 percent. An Invar tape which was accurate to within 0.003 percent was used to check the steel scale and the steel scale was found to be off by less than 0.03 percent. The density of the Apiezon oil was carefully measured and was found to be 0.864 at 26 degrees C. This value checks the results of O. Beeck[6] to within 0.02 percent. A mercury thermometer held against the scattering chamber by Plasticine served to determine hydrogen temperature. To avoid errors due to changing room temperatures, hydrogen temperature and pressure were always read simultaneously. For convenience, pressures were reduced to P_0 (pressure at 0°C). The value of P_0 was found to remain constant when the temperature changed showing that the thermometer as mounted was dependable for determining hydrogen temperature. Values of hydrogen pressure P_0 are considered to be reliable to approximately 0.2 percent.

Slit Edge Scattering

When scattering experiments were first tried with the chamber evacuated a large yield was obtained at small angles due to scattering from slit edges. A consideration of the geometry showed that protons scattered from the edge of the last collimating slit could enter the ionization chamber if they were re-scattered from the edge of the first analyzing slit. To reduce the slit edge yield a beveled aluminum sheet 20 mm long by 9 mm wide was placed as shown in Fig. 1 and Fig. 3. It is mounted on an arm equipped with a toggle joint and is automatically swung from position P Fig. 1 to position P' as the ionization

[6] O. Beeck, Rev. Sci. Inst. 6, 399 (1935).

TABLE I. *Proton-proton scattering results.*

DATE	PROTON ENERGY (KEV)	ANGLE 15°	20°	25°	30°	35°	40°	45°
Aug. 2	2392	2.56	1.286	1.000				0.498
Aug. 3	2392	2.56	1.312	1.010	0.839	0.704	0.604	
Aug. 4	2392	2.50	1.306	1.000	0.833	0.702	0.595	0.498
2392 Average		2.54	1.301	1.003	0.836	0.703	0.600	0.498
2392 Mott		2.262	0.5180	0.1626	0.06275	0.02880	0.01606	0.01162
Ratio		1.124	2.51	6.17	13.31	24.4	37.4	42.9
July 29	2105	2.95	1.376	1.050	0.858	0.740	0.600	0.530
July 30	2105	2.87	1.433	1.027	0.853	0.746	0.608	0.520
2105 Average		2.91	1.405	1.039	0.855	0.743	0.604	0.525
2105 Mott		2.925	0.6698	0.2102	0.08114	0.03720	0.02074	0.01501
Ratio		0.993	2.098	4.95	10.54	19.98	29.1	35.0
July 28	1840	3.37	1.454	1.084	0.876	0.737	0.643	0.540
Aug. 23	1848	3.36			0.892		0.637	
Aug. 5	1812	3.53	1.488	1.084	0.889	0.756	0.623	0.543
July 28	1830*	3.40	1.457	1.084	0.876	0.737	0.643	0.540
Aug. 23	1830*	3.43			0.892		0.637	
Aug. 5	1830*	3.48	1.482	1.084	0.889	0.756	0.623	0.543
Sept. 15	1830	3.38	1.480	1.058	0.881	0.729	0.636	
1830 Average		3.42	1.473	1.075	0.885	0.741	0.635	0.542
1830 Mott		3.871	0.8868	0.2784	0.1074	0.04929	0.02746	0.01986
Ratio		0.884	1.661	3.862	8.24	15.04	23.12	27.28
Oct. 5	1390	5.16	1.645	1.065	0.855		0.609	0.509
Oct. 7	1390	5.28	1.677	1.054	0.856	0.703	0.602	0.514
1390 Average		5.22	1.661	1.060	0.856	0.703	0.606	0.512
1390 Mott		6.720	1.538	0.4831	0.1865	0.08540	0.04760	0.03442
Ratio		0.777	1.080	2.196	4.59	8.23	12.74	14.88
Oct. 3	1200	6.70	1.866	1.043	0.800	0.672	0.576	0.476
Oct. 6	1200	6.69	1.857	1.020	0.799	0.682	0.565	0.478
1200 Average		6.70	1.862	1.032	0.800	0.677	0.571	0.477
1200 Mott		9.019	2.066	0.6485	0.2501	0.1147	0.06388	0.04620
Ratio		0.743	0.901	1.590	3.20	5.90	8.93	10.32
Sept. 30	854	13.55	2.77	1.044	0.641	0.493	0.420	0.345
Sept. 30	860*	13.38	2.75	1.044	0.644	0.499	0.424	0.349
Aug. 26	860	12.97	2.71		0.644		0.425	
Sept. 14	860	13.23	2.68	1.012	0.633	0.498	0.420	0.354
Sept. 16	860	13.20	2.71	1.026	0.649	0.501	0.416	0.349
860 Average		13.19	2.71	1.027	0.643	0.499	0.421	0.351
860 Mott		17.60	4.032	1.266	0.4882	0.2239	0.1245	0.08998
Ratio		0.750	0.672	0.811	1.317	2.229	3.38	3.90

chamber moves through the position of zero angle. Both positions of the guard were determined by stops which were accurately set by means of a special mandrel. The mechanism was ruggedly built and never caused any difficulty. Periodic checks were made of the stops, and they were always found to be satisfactory. After installation of the guard, measurements at 860 kev and at 1830 kev for angles from 15° to 45° with the chamber evacuated gave yields at each angle which were less than 0.05 percent of the corresponding yields obtained from hydrogen at the usual pressure.

HYDROGEN CONTAMINATION

Apiezon grease L was used for all stopcocks which were connected to the proton scattering chamber. American Express wax No. 2 was used for all wax joints inside the chamber and Picein was used on joints for which wax was applied to the outside of the chamber. In the early scattering experiments no trap was provided for condensation of vapors in the scattering chamber, and contaminants gave a large contribution to the scattering yield. The contribution of contaminants was reduced by the installation of a

liquid-air trap on the scattering chamber. An investigation of the scattering from contaminants was then made in the following way. After the chamber had been evacuated it was isolated, the trap was immersed in liquid air, and the contamination yield at 15° was studied as a function of time. After a period of approximately four hours the yield was investigated at two different voltages as a function of angle. Yields were found to increase approximately linearly with time and varied with angle and voltage according to the Rutherford formula.

During the experimental work on proton-proton scattering which gave the final results the contamination yields were measured and corrections were applied by the following method: After the scattering chamber had been filled with hydrogen to the desired pressure the generator voltage was set to give protons with an energy of 860 kev at the center of the scattering chamber, and the ionization chamber was set to detect protons scattered at 35°. Pressure in the ionization chamber was then adjusted so that pulses due to protons scattered by protons were of just sufficient size to permit accurate counting. Protons scattered by contaminant atoms suffered little loss in energy and gave large pulses which could be easily distinguished from the small proton-proton pulses by observation of the cathode-ray oscilloscope. For a determination of contamination yield large pulses were counted by visual observation while the regular counter system received a total of 2500 pulses. This contamination measurement was made immediately before and after each series of measurements on proton-proton scattering. From the observed contamination yields at 860 kev and 35° corrections were computed for all angles and voltages.

Procedure in Scattering Measurements

Difficulty in early measurements had shown the necessity for thorough check work, and in the scattering measurements giving the final data, the procedure was as follows: The charcoal trap (connection shown in Fig. 1) was heated by means of a furnace for a period varying from $\frac{3}{4}$ hour to 2 hours for thorough outgassing. During this time the apparatus and leads for measurement of proton current was checked for leakage, and the scale-of-ten counter was checked for reliability. Usually at this time the sensitivity of the voltmeter galvanometer was checked. After the charcoal trap had cooled the scattering chamber was pumped out to a pressure of approximately 2×10^{-6} mm Hg. The palladium tube for purification of hydrogen was then heated somewhat hotter than for the final filling for about five minutes, and the hydrogen was pumped out through the chamber. The palladium tube was then allowed to cool, and after the scattering chamber and hydrogen lead were again pumped down to a good vacuum, a stopcock was turned which isolated the chamber from the vacuum system. The palladium tube was then heated (heating filament not red) until the oil manometer connected to the chamber showed a pressure of approximately 180 mm. While the scattering chamber was being filled with hydrogen a flask of liquid air was put around the trap which was connected to the scattering chamber. Immediately after the chamber had been filled, liquid air was put around the charcoal trap, and the apparatus was then ready for scattering measurements. Before each series of scattering measurements generator voltage was first set to give 860-kev protons at the center of the scattering chamber, time was noted, and a determination was made of the contamination yield. The average initial contamination yield at 35° and 860 kev for all runs was 0.73 percent of the total yield. Generator voltage was then set for investigation of 1830-kev protons, and the scattering yield was determined at 15°. For this determination 12,000 counts were taken, 6000 on one side of the beam and 6000 on the other side. This standard yield served to interlock all scattering measurements and gave protection against errors

Table IA. *Percentage corrections to be applied to yield values because of the variation of oil density with temperature. Positive correction percentages are to be added to the yield values and negative corrections are to be subtracted.*

Proton energy kev	Scattering Angle						
	15°	20°	25°	30°	35°	40°	45°
2392	+0.22	+0.22	+0.22	+0.13	+0.13	+0.13	+0.22
2100	+ .22	+ .22	+ .22	+ .22	+ .22	+ .22	+ .22
1830	+ .11	+ .08	+ .08	+ .11	+ .08	+ .11	+ .08
1390	+ .05	+ .05	+ .05	+ .05	+ .05	+ .05	+ .05
1200	+ .14	+ .14	+ .14	+ .14	+ .14	+ .14	+ .14
860	− .05	− .05	− .05	− .05	− .05	− .05	− .05

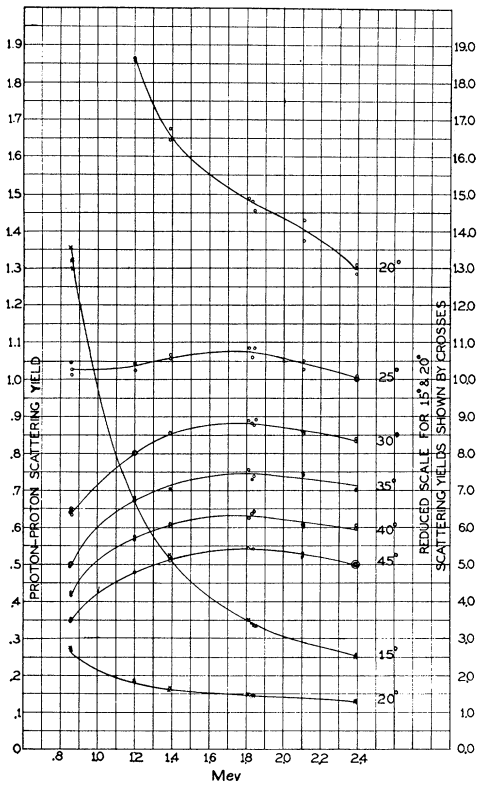

FIG. 8. Showing proton-proton scattering yields as a function of proton energy. The yield values of Table I are plotted with yields given in counts per microcoulomb of incident protons per mm oil pressure at 0°C. These values multiplied by sin $\theta \times 1.247 \times 10^{-24}$ cm^2 give values of the scattering cross section σ. In plotting yield values which coincide or are very close circles of different diameters were used so that they can be distinguished.

which might be introduced by faulty apparatus or a shift in the sensitivity of some instrument. It served only to call attention to trouble and was not used to adjust other yield values. After completion of the standard check measurements, generator voltage was set to give protons at the center of the chamber of the energy desired for yield measurements. The usual order of procedure was to start at 15°, go progressively to larger angles up to 45° and then go back to 15° for a check measurement. Usually 12,000 counts were taken at 15°, 8000 counts at 45°, and at intermediate angles the number of counts was between the two values given above. At each angle half of the counts were taken on one side of the beam and half on the other. To guard against the introduction of systematic errors several series of measurements were made in different order. Yields at all angles were found to be independent of the order in which they were investigated. After completion of a series of yield measurements, which usually took from three to four hours, the voltage was again set to give 860-kev protons and another determination was made of the contamination yield (average, 2.3 percent of total). Since time was recorded frequently during a scattering run, the contamination correction could be computed for the yield at each scattering angle. This correction was always made although for large scattering angles and high voltage it was negligible. The generator was shut down after the contamination determination, and after the pressure in the main vacuum system dropped to a steady value (1 to 2×10^{-6} mm Hg), the pressure reading was watched while a stopcock was opened connecting the chamber around the collector cup to the vacuum system. This check was made after all measurements included in the final data, and in each case the pressure rise was less than 5×10^{-8} mm Hg. Other check work had shown that a pressure rise of the order of 1×10^{-6} mm Hg should be expected if pressure in the collector cup were sufficiently high to cause a noticeable shift in scattering yield.

The scale counter was again checked after completion of scattering measurements. Hydrogen pressure and temperature were usually measured twice during the course of the scattering measurements, and values of P_0 (pressure at 0°C) rarely differed by more than 0.1 percent.

All scattering measurements made before July 28, 1938 were discarded. These yields were considered to be unreliable since up to that time no measurements had been made of the absorption thickness of the carbon deposit on the collimation slit foil. Some of the results obtained before July 28, 1938 were off still further because of a shift in the sensitivity of the voltmeter galvanometer (galvanometer which measures the output of the generating voltmeter). All results on proton-proton scattering from July 28, 1938 up to the time of the last measurement on October 7, 1938 are included in the data shown in Table I and in Figs. 8 and 9. At least two separate runs were made at each voltage, and the runs were not made in regular order. For example, runs at 1830 kev, were made on July 28, August 5, August 23, and on September 15. The

results show no trend with time. For all of the measurements giving the final data (measurements after July 28) values of the hydrogen pressure P_0 were between 160 mm and 170 mm of oil. Previous work had shown that yields were independent of hydrogen pressure. With protons having an energy of 860 kev at the center of the scattering chamber two series of measurements were made. In the first of these, June 28, P_0 had the value 167.1 mm, and in the second, on June 29, the value of P_0 was 82.5 mm. Yields at all angles for these two runs agreed very closely, with a maximum difference between corresponding yields of 1.2 percent.

The aluminum foil over the collimating slits was replaced once during the course of the final measurements and yield values were unchanged. The absorption thickness of the first foil was measured on August 16 and was found to be 75 kev. Further use of this foil was considered undesirable because the energy spread introduced by straggling causes a shift in scattering yield which might have become appreciable for the lower part of the 860-kev to 2492-kev region. A new foil was installed August 23, and its absorption thickness was found to be 46 kev. Yield measurements at 1830 kev were made before and after August 23, and the values show no shift although small angle scattering yields at 1830 kev are sensitive to proton energy.

On September 17, the foil over hole C of the analyzing slit system was replaced and yield values showed no shift. The foil over the collector cup chamber was not replaced after July 28, but during the measurements made over a period of almost two years this foil was replaced several times and no replacement caused a noticeable shift in yield values.

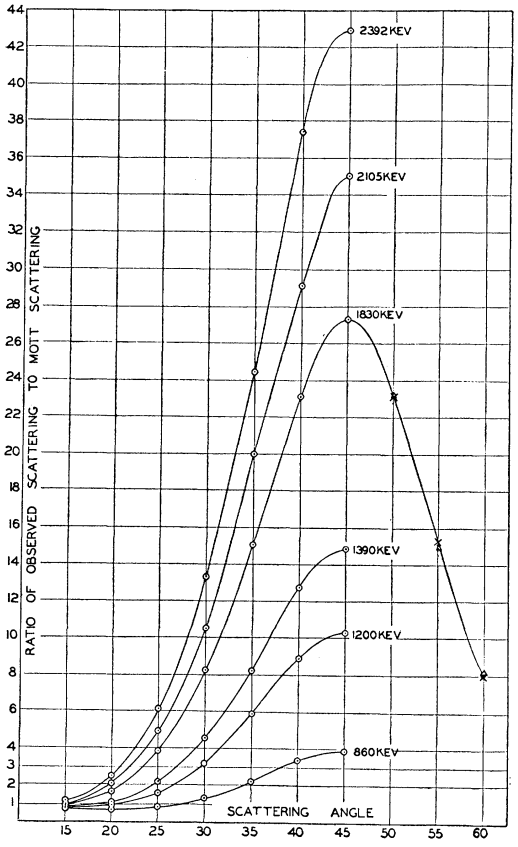

FIG. 9. Ratios of observed scattering yields to computed Mott values. The ratios of Table I are plotted.

RESULTS

Proton-proton scattering results obtained after July 28, 1938 are shown in Table I. Some measurements were made at 840 kev, but they were intended only for check work on the apparatus and are therefore not included in the tabulated results. One run at 860 kev was discarded because the contamination correction was three times as large as the average. Yield values at 15° and 1830 kev which were taken to provide a standard check are not included in the table. All other results obtained after July 28 are included, and except for the contamination correction experimental yield values were not adjusted before tabulation. For all but seven of the tabulated yield values 8000 or more protons were counted and for these seven the number of counts was between 7000 and 8000. For 44 percent of the values the number of counts was 9000 or more. Four series of measurements were made at energies slightly off from the standard values. The experimental energies and yield values are given for these runs, but before averaging the yield values they were adjusted to the standard energies. A star after an energy value indicates that the corresponding yield values have been adjusted (method of adjustment described below) from experimental values listed above.

The experimental yield values of Table I, unadjusted, are plotted in Fig. 8 to show the

variation of yield with voltage at constant angle. At all angles above 20° the yield goes through a maximum which appears to be at approximately 1650 kev for 25° and at approximately 1800 kev for higher angles. After the curves of Fig. 8 had been drawn in they were utilized for adjustment of yield values which had been taken at energies slightly off from the standard energies. A shift ΔY in a value was determined by multiplying the slope of the curve at that point by the required shift in energy. Since all of the adjustments were small this method was sufficiently accurate. After these adjustments had been made yield values were averaged, and each average was divided by the corresponding Mott value. For computing Mott values the tabulated values given by Breit, Condon and Present were used. Values of "ratio to Mott" in Table I are plotted in Fig. 9.

At 1830 kev two runs were taken up to scattering angles of 60°. Results are shown in Table II and in Fig. 9. One of the runs was taken on July 12, and the proton energy is not known to the accuracy which was obtained in the work after July 28, but the values shown in Table II are considered to be reliable since at 1830 kev large angle scattering yields change very slowly with proton energy. Yield values in the July 12 work at 30°, 35°, 40° and 45° were in very good agreement with the corresponding average yields of Table I. This agreement provided additional evidence for the reliability of the July 12 values shown in Table II.

The cross section for scattering of protons by protons should vary as $\cos\theta$ about the angle $\theta=45°$, and the "ratio to Mott" should be symmetric about 45°. This relation provided an opportunity for valuable checks on the geometrical accuracy of the proton scattering chamber and the accuracy of the apparatus for counting protons. Since a proton scattered at 30° has 87 percent of its original energy, and a proton scattered at 60° has only 25 percent of its original energy, agreement of the experimental "ratios to Mott" would indicate that protons over a wide energy range are accurately counted.

TABLE II. *Experimental results for scattering angles above 45°. The experimental "ratios to Mott" were compared with the average 1830-kev ratios of Table I for corresponding angles below 45°, and the percentage differences are given.*

	July 12			August 5		
Angle	Ratio to Mott	Percentage Difference	No. of Counts	Ratio to Mott	Percentage Difference	No. of Counts
50°	23.16	+0.17	9100	23.16	+0.17	7200
55°	14.90	−0.93	9100	15.23	+1.26	8000
60°	8.19	−0.61	6000	8.04	−2.43	7200

The curves of Fig. 9 and the tabulated values of Table II show that agreement is satisfactory. Percentage differences given in Table II show very little trend with angle and are approximately as great as should be expected from statistical fluctuations.

All values of Table I were computed with 0.864 as the density of Apiezon oil B. This value is correct at 26°C, but temperatures were slightly off from this value when the data were taken. The error was noticed after the curves of Fig. 8 and Fig. 9 were plotted. Table IA gives the percentage corrections which must be applied to the values of Table I to correct for the variation of oil density with temperature. Breit, Thaxton and Eisenbud have applied additional small corrections to the values of Table I. Their computation of expected Mott yield (Eq. (3.4) of BTE) is independent of fundamental constants other than the velocity of light and the value of the Faraday. The value of c, the velocity of light, enters to the fourth power in their equation and their correction is largely due to the use of $c=2.99796\times10^{10}$ cm/sec. rather than $c=3\times10^{10}$ cm/sec. which was used in computing the values of Table I.

Scattering of Protons by Argon and by Krypton

In the determination of proton-proton scattering cross sections a large number of absolute measurements are involved. All of these measurements, with the exception of generator voltage, appear to be dependable to 0.5 percent or better. Errors probably compensate one another to a large extent, but if most of the errors shifted values of scattering cross sections in the same direction, the final results might be off by a considerable amount. In an attempt to check the over-all accuracy of the method, scattering yields from argon and krypton were investigated.

The Coulomb field of an argon nucleus is sufficiently great so that scattering yields would

be expected to follow the Rutherford formula if there were no pronounced resonance penetration. Scattering yields from krypton were investigated as a check on the argon work since there seemed to be little possibility that krypton scattering yields would deviate from the Rutherford values. Argon and krypton for this work were obtained from the Linde Air Products Company. The argon was spectroscopically pure and was sealed in $\frac{1}{2}$-liter Pyrex flasks. The krypton, sealed in 5-cc Pyrex bulbs, was guaranteed to contain less than 1.5 percent of xenon and negligible amounts of other impurities. Precautions were taken to avoid contamination of the gas when it was admitted to the scattering chamber, and scattering measurements were always made as soon as possible after the seal on the Pyrex container was broken. Accurate measurements of scattering yield from argon and krypton could not be made over a wide angular region because of the rapid variation of yield with angle. At 860 kev measurements were not attempted at angles below 20° or above 50°. For protons of 1830 kev or above the usable angular region was between 15° and 40° for the gas pressures chosen in most of the work. Expected yields were calculated under the assumption that the scattering obeyed the Rutherford formula, and these values were compared with experimental yield values.

Results from argon

The first measurements on argon were made with 1830-kev protons and with $P_0=27.5$ mm of oil. Results of these experiments are shown in the second column of Table III where percentage differences between observed yields and calculated Rutherford yields are given. The high yield values were disturbing since they indicated that the proton-proton measurements were inaccurate. Scattering yields were then investigated with protons having energies in the region of 1830 kev and 860 kev for several different values of argon pressure. All of the results are shown in Table III. The excess in observed yield values over calculated Rutherford values increases with argon pressure, and for a given pressure the excess in observed yield is greater at low voltage than at high voltage. Values in each of the rows of Table III were averaged, and the averages are plotted in Fig. 10.

TABLE III. *The scattering of protons by argon. Experimental scattering yields were compared to computed Rutherford yields and the percentage differences are given. All experimental yields were higher than Rutherford values and thus all tabulated percentages are positive. The Sept. 28 value 8.7* at 20° differs widely from the 30° and 40° values. Since an error in the reading of some instrument may have caused the discrepancy this value was not included in the average plotted in Fig. 10.*

Date	Argon Pressure P_0	Proton Energy kev	Scattering Angle 15°	20°	30°	40°	50°
Sept. 28	15.88	1826	6.0	6.6	3.6	2.3	—
Sept. 26	27.78	1830	4.5	5.0	1.3	2.6	—
Sept. 27	28.77	1830	5.7	5.0	4.5	2.8	—
Sept. 27	57.02	1819	—	6.3	8.0	9.4	—
Sept. 28	119.4	1832	—	8.7*	16.2	15.8	—
Sept. 27	15.46	866	—	3.2	7.8	4.7	3.6
Sept. 26	27.58	862	—	11.6	10.0	9.5	11.5
Sept. 27	54.73	846	—	25.1	26.0	24.5	23.7

A consideration of the variation in excess scattering as a function of argon pressure and proton energy indicated that the effect was caused by multiple small angle scattering which spread the main proton beam so that protons missed the hole covered by foil F, Fig. 1. Calculations by Professor Breit substantiated this assumption. Since the structure of the proton beam is not known, the percentage of protons which miss hole A cannot be calculated accurately. The variation of this percentage with proton energy and argon pressure also depends on the structure of the proton beam and cannot be calculated accurately. However, the calculations showed that if the beam spread is S_1 with the proton energy at E_1 and argon pressure at P_1, then with a proton energy $E_2=2E_1$ the beam spread S_2 should be equal to S_1 for $P_2=3.4P_1$. This relationship should be fairly independent of the structure of the beam for high argon pressure. The values of P_0 from curves A and B which give a percentage difference of 16 percent are 39 mm and 120 mm, respectively. Thus, for a constant beam spread the pressure had to be increased by a factor of 3.03 when the voltage was raised by a factor of 2.13. Considering the approximations used in the calculations the agreement is satisfactory.

The scatter in the points of the 1830-kev argon curve in the low pressure region is probably due partially to errors in pressure measurement since for $P_0=15$ mm the pressure measurement was not considered dependable to better than 1

percent. Inconsistent yield values may also be caused by changes in the structure of the main proton beam. The data of Table III show that for protons in the energy region of 860 kev the variation of scattering yields as a function of angle agree fairly well with the Rutherford formula. There are, however, some inconsistent values, but these may be due to variations in the structure of the proton beam which could cause changes in the percentage of protons that miss hole A. This source of difficulty would not be present in the proton-proton scattering work.

In high voltage argon measurements for which P_0 had the values of 27.78, 28.77 and 15.88 mm of oil the excess in observed yield relative to Rutherford yield is greater at 15° and 20° than at the higher angles.

For each of these runs the average of the 30° and 40° values shown in Table III was subtracted from the 15° value. The average of the differences obtained in this way for each of the three runs was 2.6 percent. When the 20° values were compared with the 30° and 40° values in the same way an average difference of 2.7 percent was obtained. The average difference of 2.6 percent for the 15° values is approximately what should be expected because of the finite size of the collimating and analyzing slits, but at 20° this average difference should be approximately 0.56 as great as at 15°. Thus the average 20° difference appears to be too large by 1.2 percent. This discrepancy also appears in the krypton results and may have been caused by some defect in one of the instruments used for the scattering measurements. If the curves of Fig. 10 are extrapolated to $P_0=0$ the yield values determined will be free from error due to spreading of the beam. Extrapolations are not very dependable because yield values for $P_0=15$ mm of oil are not accurate, and for lower pressures little is known about the form of the curves. It seems safe, however, to assume that the curves are horizontal at $P_0=0$ since the extreme outer edges of the beam must move out 0.7 mm before any protons can miss the hole over the collector cup. Reasonable extrapolations indicate that observed yields from argon do not differ from calculated Rutherford yields by more than about 2.5 percent.

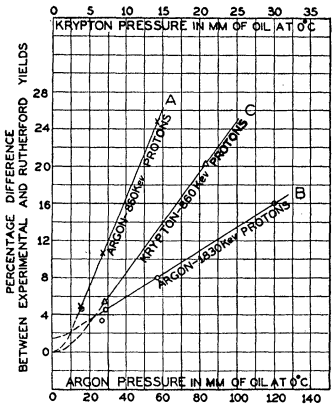

FIG. 10. Percentage differences between experimental scattering yields from argon and krypton and computed Rutherford yields are plotted to show the variations of percentages difference with argon and krypton pressure. Values of Tables III and IV were averaged with respect to scattering angle to give the values for these curves.

Results from krypton

For most of the measurements with krypton the values of P_0 were between 8 and 9 mm of oil, and pressure measurements were dependable to about 1.5 percent. The xenon impurity could be responsible for an excess of 1.9 percent in observed yields over the calculated values. Because of these factors absolute yield values from krypton are not as dependable as the argon results. All results obtained after July 28 are shown in Table IV.

The variations of yield with angle shows approximately the same behavior as the argon results. Scattering yields from krypton for protons in the energy region of 860 kev were investigated at pressures of 8.73 and 20.76 mm of oil, and results are shown in Fig. 10. If the curve determined by these two points is extrapolated to $P_0=0$ the yield value obtained is in satisfactory agreement with the Rutherford value.

It was at first expected that for a given voltage the beam spread due to krypton (atomic number 36) at a pressure P should be the same as the spread due to argon (atomic number 18) at a pressure $4P$. Curves C and A show that the pressure at which argon gives a beam spread S is approximately 2.34 times the pressure at which krypton gives the same beam spread. The apparent discrepancy can be explained in

the following way: Calculations showed that multiple small angle scattering is chiefly responsible for the spread of the proton beam. Electronic screening will cause a considerable reduction in the cross section of nuclei for small angle scattering and calculations by Professor Breit show that the magnitude of the screening effect should increase with an increase in the atomic number of the target element. Results of these calculations, which are given in the section "Spread of Beam" of the paper by BTE, are in satisfactory agreement with the experimental results of Fig. 10.

Conclusion

The outcome of the scattering experiments with argon and krypton was disappointing. Because of the difficulty with measurement of the proton current the results do not serve as a close check on the accuracy of the proton-proton yields. The authors believe, however, that the proton-proton values are not greatly in error since results of other check work were for the most part satisfactory. Yield measurements at 1830 kev showed the expected variation about 45°. Yields were independent of hydrogen pressure, and the repeatability of yield values during the entire period of the final measurements tends to increase confidence in their reliability.

Because of the nature of the experiment an estimate of the probable error in the yield values is difficult to make and has not been attempted. The authors feel that their experimental work should be repeated with different apparatus and preferable at another laboratory. The work of Breit, Thaxton and Eisenbud in this issue demonstrates the remarkable possibilities presented by precise data on proton-proton scattering for quantitative information on the interaction potential between protons. More data of greater precision are needed before all of these possibilities can be utilized.

We are indebted to Dr. E. J. Bernet, Dr. R. J. Havens, Mr. R. E. Warren and Mr. C. M. Hudson for help in this work. Professor G. Breit suggested the problem and by his encouragement and advice during the course of the work contributed much to its success. Mr. J. R. Foerst and Mr. J. P. Johnson deserve much credit for their excellent work on the construction of the scattering chamber. Many details of the design are due to Mr. Foerst. We are indebted to the Wisconsin Alumni Research Foundation and to the American Philosophical Society for financial assistance.

TABLE IV. *The scattering of protons by krypton. Experimental scattering yields were compared to computed Rutherford yields and the percentage differences are given. All experimental yields were higher than Rutherford yields and thus all of the tabulated values are positive.*

Date	Krypton Pressure P_0	Proton Energy kev	Scattering Angle 15°	20°	30°	40°	50°
Aug. 8	9.14	2440	4.4	3.5	2.9	3.8	—
Aug. 8	9.07	1849	5.5	6.6	3.9	2.0	—
Oct. 13	8.09	1835	4.8	6.2	2.0	3.8	—
Oct. 13	8.06	864	—	4.9	4.5	6.0	6.0
Oct. 14	8.73	860	—	5.8	5.2	7.2	5.6
Oct. 14	20.76	850	—	—	17.4	20.5	23.0