The Scattering of 2.4- to 3.5-Mev Protons by Protons

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Collimated monoenergetic protons, accelerated by the Minnesota electrostatic generator to energies of 2.42, 3.04, 3.27, and 3.53 Mev, were scattered by hydrogen gas and detected at well defined angles from 8° to 45°. The observations at each angle and energy have been reduced to values of the absolute cross section for proton-proton scattering per unit solid angle. These cross sections are considered to be reliable to ±1.6 percent.

I. INTRODUCTION

THE scattering of protons by protons has been investigated extensively during the past decade. The pioneering work of Tuve, Heydenburg, and Hafstad[1] in the energy region from 600 to 900 kev served to demonstrate clearly the existence of an attractive nuclear interaction between two protons. Breit, Condon, and Present[2] showed that the observations of the elastic scattering cross section as a function of proton energy and angle of scattering could be described by a combination of Coulomb scattering and phase shifts of the spherically symmetrical S-wave. They were able to evaluate the interdependent constants for the square well potential function which determine the nuclear scattering, i.e., the radius e^2/m_0c^2, and the depth 10.66 Mev.

The exceedingly careful work of Herb, Kerst, Parkinson, and Plain[3] confirmed the early work and extended the observations up to 2.4 Mev. The results of these experiments were analyzed by Breit, Thaxton, and Eisenbud[4] who found that the dimensions of the square well representing the S-wave interaction could be given with higher precision as $r=e^2/m_0c^2$ and depth 10.50 Mev without Coulomb potential inside the well and that the data could be fitted without assuming any p-wave interaction. Wilson and Creutz[5] investigated the relative cross section for proton-proton scattering as a function of angle with 8-Mev protons. The results could be described in terms of Coulomb and S-wave scattering alone, but the accuracy was not sufficient to exclude a p-wave anomaly.

Wilson[6] next investigated the proton-proton scattering with 10-Mev protons and concluded that the interaction excluded the possibility of an attractive p-wave potential. The evidence from these experiments for a repulsive p-wave potential was not conclusive.[7]

The recent work of Wilson, Lofgren, Richardson, Wright, and Shankland[8] with 14.5-Mev protons has been interpreted by Foldy and by Lopes and Tiomno.[9] These experiments confirm the conclusion that an attractive p-wave interaction is excluded and strengthen the evidence for repulsive p-wave effects.

During the progress of the experiments reported in this paper, the results of Dearnley, Oxley, and Perry[10] with 7-Mev protons scattered through angles in the range 9° to 45° became available. These results indicate a very small deviation from pure S-wave scattering.

The present experiments were undertaken with a purpose of duplicating the highest energy of the Wisconsin group[3] and extending similar

[1] M. A. Tuve, N. P. Heydenburg, and L. R. Hafstad, Phys. Rev. **50**, 806 (1936); L. R. Hafstad, N. P. Heydenburg, and M. A. Tuve, Phys. Rev. **53**, 239 (1938); N. P. Heydenburg, L. R. Hafstad, and M. A. Tuve, Phys. Rev. **56**, 1078 (1939).

[2] G. Breit, E. U. Condon, and R. D. Present, Phys. Rev. **50**, 825 (1936).

[3] R. G. Herb, D. W. Kerst, D. B. Parkinson, and G. J. Plain, Phys. Rev. **55**, 998 (1939).

[4] G. Breit, H. M. Thaxton, and L. Eisenbud, Phys. Rev. **55**, 1018 (1939).

[5] R. R. Wilson and E. C. Creutz, Phys. Rev. **71**, 339 (1947).

[6] R. R. Wilson, Phys. Rev. **71**, 384 (1947).

[7] L. L. Foldy, Phys. Rev. **72**, 125 (1947). R. E. Peierls and M. A. Preston, Phys. Rev. **72**, 250 (1947). L. L. Foldy, Phys. Rev. **72**, 731 (1947).

[8] R. R. Wilson, E. J. Lofgren, J. R. Richardson, B. T. Wright, and R. S. Shankland, Phys. Rev. **71**, 560 (1947); Phys. Rev. **72**, 1131 (1947).

[9] J. L. Lopes and J. Tiomno, Phys. Rev. **72**, 731 (1947).

[10] I. H. Darnley, C. L. Oxley, and J. E. Perry, Jr., Phys. Rev. **72**, 169 (A) (1947). We are also indebted to these authors for a copy of their forthcoming paper in the Physical Review.

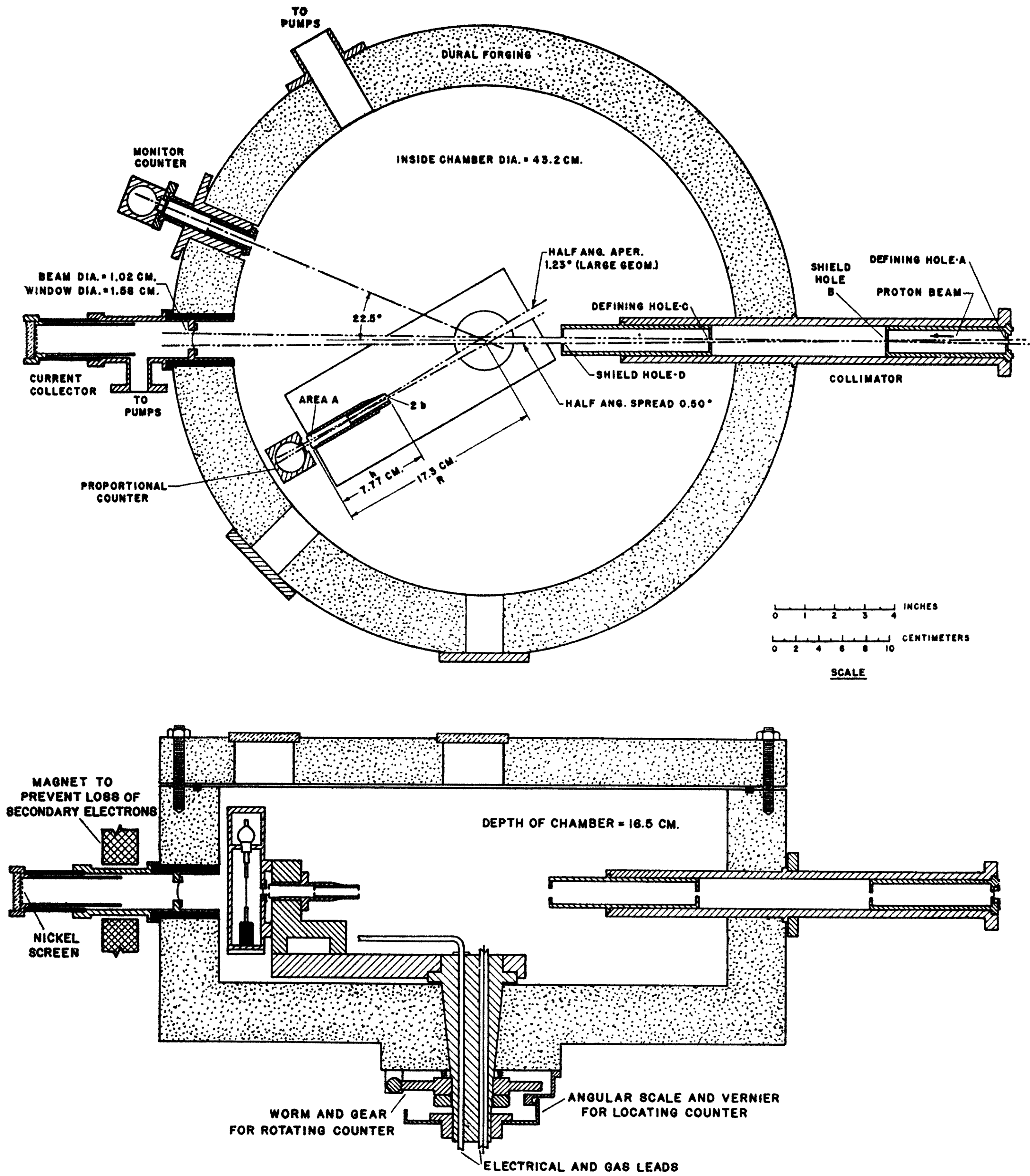

FIG. 1. Plan and elevation of the scattering chamber. Upper figure is a section through the plane of the incident beam and the beam scattered through the analyzer slits and detectors. Elevation is a section through the incident beam. The moveable analyzer slits and detector are not in the same position in the two sections.

observations to higher energies in order to establish more firmly the nature of the S-wave interaction. At the suggestion of Professor C. L. Critchfield, we planned to make observations of the absolute cross section for proton-proton scattering at smaller angles, 8°, than had previously been studied, because it is in this angular range that the interference of a small P-wave interaction with the Coulomb field would be most evident.

II. DESIGN OF SCATTERING CHAMBER

Our measurements were carried out by a method essentially the same as that of Herb, Kerst, Parkinson, and Plain[3] (hereafter referred to as HKPP) and the apparatus was in many respects similar to that used by Sherr and coworkers for experiments on proton-deuteron scattering.[11]

The scattering chamber is shown in Fig. 1. It was turned from an aluminum alloy forging and had an outside diameter of 21 inches, walls 2 inches thick, and a depth inside of $6\frac{1}{2}$ inches. The large diameter made possible observations at smaller angles than those available in the previous experiments, and allowed small angular apertures with slits of accurately measurable size.

The beam of protons from the Van de Graaff machine entered the scattering chamber through a series of collimating diaphragms centered in a brass tube which extended radially from one side of the chamber. To reduce slit edge scattering, the diaphragms were shaped so that the edges of the holes were about 0.010 inch thick. The first defining hole, A, was 0.085 inch in diameter. The shield hole, B, 4 inches farther along, was 0.094 inch in diameter. The second defining hole, C, 9.90 inches from the first, was 0.090 inch in diameter. Five inches beyond the second defining hole was the final shield hole, D, whose diameter was 0.180 inch. This diaphragm prevented most of the protons scattered by the edge of the second defining hole from going through the chamber. The maximum spread of the beam of incident protons was 0.55 degree from the axis of the collimator.

Immediately before the incident protons reached the first defining hole they passed through a window of sheet Nylon approximately 0.0002 inch thick. When new, this window had a stopping power of 40 to 50 kev for 2-Mev protons. The stopping power of the window before and after use was measured, as explained below, and the energy of the protons corrected accordingly.

After going across the scattering chamber, the beam of protons passed through another Nylon window into the current collector cup, which is described below in the section on current measurement.

The scattering chamber could be evacuated by an oil diffusion pump and fore pump and isolated from the pumps with a large gate valve. Between the valve and the chamber there was a projecting tube which could be cooled with liquid nitrogen to trap condensable vapors. Near the trap the line from the palladium tube for filling the scattering chamber with hydrogen and the line from the oil manometer for measuring the hydrogen pressure joined the system.

The scattered protons were detected by two proportional counters. One of these, used as a monitor, was mounted on the outside of the scattering chamber with its analyzing slit system projecting through a radial hole in the chamber wall. This slit system had a half-angular aperature of 3.52° and its axis made an angle of $22\frac{1}{2}°$ with the central proton beam.

The other proportional counter was mounted inside the chamber on a plate which was fastened to a tapered plug projecting through the center of the bottom of the chamber. The angular position of this counter could be adjusted by a worm and gear outside the chamber and read on a scale and vernier graduated in minutes of arc. During the construction of the chamber great care was taken to make the axis of this plug intersect and be perpendicular to the axis of the collimating diaphragms through which the protons enter the chamber.

The internal dimensions of the two proportional counters were the same, so that they could be filled simultaneously and use the same high voltage supply. The inside diameters were one inch and the wires were 0.010 inch Nichrome. The active lengths of the counters were limited to one inch by pieces of 0.028-inch diameter stainless steel tubing around the wire at each end. The entrance windows were off center by $\frac{1}{8}$ inch so that the incoming protons would not strike the central wire, and were covered with the same Nylon material used for the collimator window.

The analyzing slit system, which defined the region from which particles could be scattered into the movable counter and the solid angle subtended by the counter, consisted of a slit approximately 9.5 cm from the center of the chamber and a round hole approximately 17.3 cm from the center (marked $2b$ and area A, respectively, in Fig. 1). Between them was a larger slit to intercept particles scattered by the wall of the tube.

[11] R. Sherr, J. M. Blair, H. R. Kratz, C. L. Bailey, and R. F. Taschek, Phys. Rev. **72**, 662 (1947).

The first slit was made of two pieces of Nichrome, 0.006 inch thick, with edges ground straight and smooth, which were welded to the supporting tube. The width of this slit varied by 1.5 percent from one end to the other, and the average width was $2b=0.10530\pm0.00010$ cm. Because of the great variation with angle of the counting rate of scattered particles, two different defining holes were used, the larger for measurements at angles of 15° and larger, the smaller for angles of 15° and smaller. These holes were bored in brass thimbles which could be interchanged in the supporting tube without disturbing the general line up of the analyzing slit system. The window in the proportional counter was large enough so that all particles passing through the analyzing slit system would enter the counter.

The large hole was found to vary in diameter by 0.3 percent and the average diameter was 0.2283 ± 0.0002 cm. The smaller hole varied in diameter by 1.3 percent with an average diameter of 0.07341 ± 0.00014 cm. The distance between the first slit and the hole, designated by h, was found to be 7.775 ± 0.001 cm with the small hole in place and 7.771 ± 0.001 cm with the large hole. The distance R from the hole to the center of the chamber was determined with the aid of a mandril inserted in the analyzing system and a traveling microscope. $R=17.322\pm0.002$ cm for the small hole and 17.318 ± 0.002 cm for the large hole. In the computation of the data, these dimensions are combined into a geometrical constant

$$G=2bA/Rh, \tag{1}$$

where A is the area of the final hole. G had the value $(3.2036\pm0.0007)\times10^{-5}$ cm when the large hole was used and $(3.3094\pm0.0008)\times10^{-6}$ cm for the small hole. For the monitor counter $G=1.4\times10^{-4}$ cm.

During the assembly of the scattering chamber the bracket supporting the movable proportional counter and the analyzing slit system was shimmed up so that the axis of this slit system intersected the axis of the beam collimator diaphragms to within ±0.005 inch and that of the tapered plug to within ±0.002 inch. This was checked with micrometers and dial gauges and with the aid of a removable pin which could be fitted into a socket in the center of the tapered plug. The accuracy of this centering was checked by revolving the plug while the top of the pin was viewed with a microscope.

These alignments, as well as the zero reading on the scale for measuring the angular position of the movable counter, were further checked by using the collimating and analyzing slit systems to define beams of light which would intersect each other and the end of the removable pin at the center of the chamber. At the center of the chamber the beam of protons was 0.230 inch in diameter, while the regions from which scattered particles could pass through the analyzer and reach the counter were 0.270 and 0.340 inch high when the large and small holes, respectively, were in the analyzer. This assured that every point in the defining hole of the analyzer could "see" all of the proton beam.

III. THE CHARGE MEASURING SYSTEM

To permit accurate measurement of the number of protons which traversed the scattering volume, the collimated beam passed out of the chamber through a Nylon window into an evacuated region and was collected in an insulated cup. The window support and outer case of the evacuated region were also insulated from the scattering chamber so that checks on the efficiency of current collection, production of secondary electrons, ionization currents, etc., could be made. The window diameter was 0.625 inch while the diameter of the proton beam at that point, as determined by the diaphragms in the collimator tube, was 0.40 inch. Calculations showed that the fraction of the beam scattered by the gas beyond the edge of the window was negligible. The checks on the efficiency of current collection were similar to those made on the Los Alamos chamber.[11] As in that case, it was found that a magnetic field across the end of the current collecting cup of approximately 300 gauss was sufficient to prevent secondary electrons from entering or leaving the cup. The potential between the collector cup and the case, to which the Nylon window was sealed, could be varied over a 60-volt range without causing more than 10^{-11} ampere to flow between the cup and the case. During a run the collector cup was not allowed to charge to more than ten volts. While data were being taken, the region around the collector cup was connected to the oil diffusion pump so that the pressure was approximately 3×10^{-6} mm of Hg. It was found that increasing this pressure to 10^{-5} mm Hg did not cause an appreciable ionization current to flow between the cup and the case. As a result of these tests we concluded that errors in collecting the proton current amounted to less than one-tenth of one percent.

The total number of incident protons in a given observation was determined by allowing the collector cup and a 0.5-μf condenser to build up to a potential of less than ten volts and then discharging this capacitance through a ballistic galvanometer. The calibration of this system was accomplished by two methods. First the system was compared to two "standard" condensers by charging them separately to a potential of 10.50 volts, as determined by a Wolff potentiometer, and discharging them through the ballistic galvanometer.

Since we were not completely confident of the capacitance of these standard condensers, an alternative calibration method was used which simulated the operating conditions more closely. A current of the order of 10^{-7} ampere, supplied by a 2000-volt battery pack and a series resistance of 2×10^{10} ohms, was allowed to flow on to the collector cup condenser system. The exact value of this current was measured by a galvanometer connected between the series resistance and the condenser. Various battery voltages and times of charging were used to determine the constancy of the charge measuring system to make sure the calibration was independent of these factors.

The calibration procedure was as follows. The current was allowed to flow for a given time and read at frequent intervals, the charging circuit was opened, and the ballistic galvanometer was then shorted across the condenser and its deflection recorded. The current galvanometer was then switched into a calibration circuit consisting of a standard one-megohm resistance (several standards intercompared) and a low resistance type K Leeds and Northrup potentiometer used as the source of a known voltage. The potentiometer was adjusted to give galvanometer readings equal to the initial and final deflection when charging the condenser. In this way, the average current used in the condenser charging cycle was determined.

In such calibrations and in the actual employment of a condenser system, extreme care must be taken to avoid effects due to "charge soakage" and leakage resistance. The first effect was minimized during our early scattering observations by removing charge from the previously shorted condenser by carrying the condenser through a "hysteresis cycle" of diminishing amplitude with a six-volt, 60-cycle voltage supply whose output potential was gradually reduced to zero. In later work, a polystyrene condenser* of admirable soakage and leakage properties eliminated most of these uncertainties. In either case the "current-time" method of calibration simulated the operating conditions so closely that errors due to faulty condenser properties were largely eliminated. Other sources of error in this method, such as leakage of charge to ground from the galvanometer in the calibrating circuit, resistance leakage of the condenser, lag of calibrating galvanometer readings behind true current during time of charging, and non-linearity of ballistic galvanometer readings were considered, and minor corrections were applied.

Unfortunately, the two methods of calibrating the charge measuring system gave results which differed by one percent. We attributed this difference principally to a difference between the conditions under which we used the standard condensers and those under which they were calibrated. Therefore, we have based our calibration on the "current-time" method and have estimated a probable error from this cause in the measured cross section of ±1 percent.

IV. MEASUREMENT OF PROTON ENERGY

The voltage of the modified Minnesota electrostatic generator[12] was measured and controlled by means of an electrostatic analyzer of the type described by Hanson.[13] The $Li^7(p,n)Be^7$ reaction threshold was used as a reference point for the calibration of this instrument. Considering recent measurements at Wisconsin,[14] we have taken the threshold of this reaction to be the value 1.883 Mev given by Hanson and Benedict.[15] For con-

* John E. Fast Company, Chicago, Illinois.

[12] J. H. Williams, L. H. Rumbaugh, and J. T. Tate, Rev. Sci. Inst. **13**, 202 (1942).

[13] A. O. Hanson, Rev. Sci. Inst. **15**, 57 (1944).

[14] R. G. Herb, Bull. Am. Phys. Soc. **23**, No. 4, p. 7 (1948).

[15] A. O. Hanson and D. L. Benedict, Phys. Rev. **65**, 33 (1944).

venience in such calibrations and for measuring the thickness of the foil over the entrance to the collimator tube, a nickel screen onto which some LiF had been melted was mounted on an arm which could be turned into position by means of a tapered plug which entered the scattering chamber through the center of the lid. Below the scattering chamber, in line with the axis of the proton beam, there was placed a paraffin-covered BF_3 proportional counter for detecting the neutrons produced in the calibration measurements.

At generator voltages below the threshold for the Li(p,n) reaction the number of counts from the neutron detector was negligible and the rise upon reaching the threshold was sharp and reproducible to one part in five hundred. To calibrate the electrostatic analyzer, a threshold measurement was made with no foil over the collimator. Measurements were also made with a clean piece of Nylon in place and with one which had been used for some time. During use, a layer of carbon collects on such foils, increasing their stopping power.

The energy loss of the protons in traversing the window was obtained from the displacement of the curve for yield of neutrons *vs.* generator voltage taken with a foil in place as compared with the curve taken with no foil. With a foil in place, there was a noticeable tail on the low voltage end of the yield curve indicating a spread in energy of the protons passing through the foil. This variation is included in the energy uncertainty in the tabulated data. The increase in stopping power of the foils was assumed linear with generator running time, and the proton energies were corrected accordingly.

V. DETECTION OF SCATTERED PROTONS

The two proportional counters used to count scattered protons were sufficiently alike so that a common high voltage supply and gas filling could be used. The center wires were held at a potential of about +900 volts with respect to the counter bodies. The gas used was a mixture of argon at 14.5 cm Hg pressure and CH_4 at 0.2 cm Hg pressure. The counter gas was separated from the scattering gas by a Nylon foil of the same thickness as on the other windows. The electrical pulses were taken from the high voltage leads and passed through preamplifiers and amplifiers similar to the Los Alamos type 100 circuits. The pulses were counted by scaling circuits described by Higinbotham, Gallagher, and Sands.[16]

The discriminator bias curves of the counters operated under these conditions had broad, flat plateaus. To check the operation of the movable counter while data were being taken, two identical scale-of-64 circuits were used, one being operated with its discriminator bias set 50 percent higher than the other. Any discrepancy in the number of counts recorded by the two scalers indicated an undesirable variation in the operating conditions so that run would be discarded.

VI. HYDROGEN SUPPLY AND PRESSURE MEASUREMENTS

Before admitting hydrogen to the scattering chamber, it was evacuated with an oil diffusion pump to a pressure of approximately 5×10^{-6} mm Hg. The hydrogen was admitted to the chamber through a heated palladium tube. The pressure of hydrogen in the scattering chamber was measured with a manometer filled with Apiezon oil B. The difference in level between the two sides of the manometer was measured with a cathetometer which could be read to one-hundredth of a millimeter. Measurements were made with a modified Mohr's balance of the density of this manometer oil as a function of temperature. The specific gravity was found to be 0.862 ± 0.001 g/cm³ at 20°C and the volume coefficient of expansion was found to have the value 83×10^{-5} per degree centigrade.

VII. PROCEDURE

Except for second-order effects, the cross section per unit solid angle for proton-proton scattering is given by

$$\sigma = Y \sin\theta / NnG, \tag{2}$$

where Y is the number of scattered protons detected by the proportional counter when N protons of energy Ep are incident on $(n/2)$ molecules/cm³ of hydrogen gas and the detected protons are scattered through a laboratory angle θ. The factor $G=2bA/Rh$ is a measure of the gas scattering volume and solid angle defined by the entrance slits and final aperture of the analyzing system between the scattering volume

[16] W. A. Higinbotham, J. Gallagher, and M. Sands, Rev. Sci. Inst. 18, 706 (1947).

and the counter, and has been described earlier in this report, Eq. (1).

The ratio Y/N was determined by counting the number of scattered protons which entered the slit system and passed through the aperture of area A into the proportional counter during a run of two to five minutes while a charge Q was collected on a condenser attached to the collector cup. Q was determined with the calibrated ballistic galvanometer and could be translated into a value for N with the assumed value of 6.250×10^{12} protons per microcoulomb.

The number of scattering protons per cm^3, n, was determined from the pressure of molecular hydrogen in the scattering chamber as measured by the oil manometer described above and by assuming 6.023×10^{23} molecules in 22,412 cm^3 at normal temperature and pressure.

Any asymmetry of the incident beam and of the analyzing slit system with respect to the central axis of rotation of the detector, and the consequent uncertainty in θ and R, were essentially eliminated by taking observations of Y at approximately equal angles on either side of the experimentally determined zero. This zero was known only to within an accuracy of two or three minutes of arc, but the total included angle, 2θ, between observing positions on the two sides was known to an accuracy limited principally by the accuracy of reading a vernier with graduations of one minute. The absolute angles in the range 8° to 15° were checked by careful triangulation measurements and were found to agree with those read on the scale to within 0.5 minute.

Observations of Y and Q at the two angles $\pm\theta$ were taken for a measured n and a G which was appropriate to the θ under examination. Records were kept of the time of run, time elapsed since filling the chamber with H_2, and the number of protons which entered the monitor counter at $22\frac{1}{2}$°. In general, at least ten thousand scattered protons were observed for each angle at each energy. The counting rates were such that this required several independent sets of observations of Y, Q, and θ, and served to eliminate gross errors of observation.

The observations of Y had to be corrected for a sum of minor background counts. These arose from the following causes and were directly measured and subtracted. With the shutter above the entrance window to the scattering chamber closed, the number of counts per minute due to generator instabilities, alpha-contamination, counter discharges, amplifier noise, etc., was measured. This contribution was, in general, less than 0.1 percent of Y. With the chamber evacuated and cut off from the pumps so that gas contamination could build up, the number of protons scattered from the contaminating gases at each energy was followed as a function of θ for an hour or more. This contribution to Y was kept less than one percent in scattering runs by evacuating and refilling the scattering chamber from fresh H_2 at appropriate intervals.

A small correction, 0.2 percent, was applied to our observations of Y/Q to allow for switching delays in removing the shutter from the beam before turning on the scaling circuits which record Y, and in stopping the recording of Y before the protons were cut off from entering the collector cup.

Other sources of extra and missed counts have been investigated. Since the path through the scattering gas traversed by the primary protons from the collimating apertures to the collector cup is 12.6 inches, and the path of the scattered protons from the center of the chamber to the counter window is 7.07 inches, a possibility of double scattering difficulties exists. In order to evaluate these effects, we have measured the cross section for scattering of 3-Mev protons at 8° as a function of the H_2 pressure in the scattering chamber. Any part of the yield due to double scattering would be expected to depend on the square of the pressure. Changes in pressure by a factor of four are seen from Fig. 2 to produce no appreciable change in the value of the cross section determined under the usual conditions of 16 cm of oil pressure. In fact, the negative

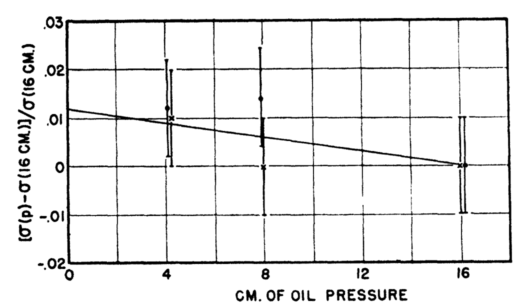

FIG. 2. The fractional change in the measured cross section for scattering through 8° of 2.42-Mev protons as a function of the pressure, p, of the hydrogen filling the scattering chamber.

TABLE I. Proton-proton scattering cross section per unit solid angle in the laboratory system as a function of incident proton energy E_p in Mev and laboratory angle θ. Cross sections are in barns (10^{-24} cm^2).

$\theta \setminus E_p$	2.42 ± 0.02	3.04 ± 0.02	3.27 ± 0.02	3.53 ± 0.02
8°	7.770 ± 0.100	4.930 ± 0.070	4.390 ± 0.050	3.700 ± 0.060
10°	3.050 ± 0.040	1.990 ± 0.020	1.770 ± 0.020	1.530 ± 0.030
12.5°	1.340 ± 0.020	0.963 ± 0.014	0.864 ± 0.012	0.773 ± 0.012
15°	0.796 ± 0.008	0.626 ± 0.008	0.600 ± 0.005	0.550 ± 0.008
17.5°	0.628 ± 0.007	0.537 ± 0.005	0.512 ± 0.006	0.473 ± 0.005
20°	0.562 ± 0.004	0.493 ± 0.005	0.478 ± 0.006	0.462 ± 0.005
25°	0.528 ± 0.006	0.483 ± 0.006	0.473 ± 0.005	0.442 ± 0.005
30°	0.528 ± 0.010	0.469 ± 0.009	0.450 ± 0.005	0.428 ± 0.005
35°	0.503 ± 0.010	0.450 ± 0.005	0.441 ± 0.005	0.418 ± 0.004
40°	0.475 ± 0.008	0.425 ± 0.008	0.410 ± 0.005	0.397 ± 0.004
45°	0.443 ± 0.006	0.402 ± 0.005	0.380 ± 0.004	0.366 ± 0.004

slope $d\sigma/dp$ is contrary to expectations and is probably not significant.

The scattering of primary protons by the collimating diaphragms directly into the analyzing system and counter was observed by allowing the beam to pass through the evacuated chamber. The detector system could be set down to angles of less than 7° before protons scattered from the slits entered the detector.

A possible contribution to Y could arise from the scattering of protons by the finite thickness, 0.006 inch, of Nichrome metal forming the two sets of slits in the analyzer. In order to measure this, we replaced these slits with special slits made of 0.025-inch Nichrome. A series of observations of the cross section for scattering of 2.4 Mev protons at 8° with these thick slits agreed to within $1\frac{1}{2}$ percent with the average value of the cross sections obtained with 0.006-inch thick slits. Since this is well within the expected reproducibility of independent sets of data, we concluded that contributions from scattering by the 0.006-inch slits were negligible.

We were aware of the difficulties of alignment of a collimating system of the type used in these experiments and, consequently, made several complete changes of the final collimating slit assembly. In particular, the barrel which held the slit of width $2b$ and the hole of area A was changed to one of increased internal diameter to test the possibilities of surface scattering which might possibly have existed in our early observations. None of these changes led to significant differences in the measured cross sections.

One of the disturbing discrepancies which exists in our observations is the disagreement between the values of σ at $\theta = 15°$ taken with the two values of G. The larger apertures used in the range 15° to 45° give a more reliable value of $\sigma(15°)$ from a statistical point of view, and we have given these values more weight in arriving at the values listed in Table I. The values for $\sigma(15°)$ at various energies for two values of G, which differ by an order of magnitude, are shown in Table II. There is no significant evidence indicating an error in the relative G values, but the differences in $\sigma(15°)$ between the two experimental conditions certainly exceed the differences expected on the basis of the reproducibility of the data. A partial explanation may be that the values of E_p were not exactly the same under both conditions of observation.

VIII. RESULTS

Values of σ, the cross section per unit solid angle for protons of energy E_p scattered at the laboratory angles θ, are given in Table I. The uncertainties shown for the values of σ in this table were determined by the reproducibility of values of σ from week to week. The uncertainties given for the values of E_p are estimates of our lack of knowledge of the beam energy at the center of the scattering chamber due to the non-uniformity of Nylon windows, lack of information on the exact amount of carbon deposited on these windows at the time of the observation, and fluctuations in the accelerating potential. The non-uniformity of the windows makes it difficult to specify E_p exactly, and we have chosen to give a value of E_p which is a minimum value. From the appearance of the Li(p,n) threshold curves taken with the protons passing through typical Nylon foils, we judge that approximately ten percent of the protons may have had energies as much as 10 kev greater than the value listed. Values for the cross section per unit solid angle in the center of mass system have been calculated by multiplying the values given in Table I by $\frac{1}{4}$ sec. θ. These center of mass cross sections are plotted as a function of $\Theta = 2\theta$ in Fig. 3.

In addition to the experimental uncertainties described in the previous paragraph, there are inherent errors in measuring N, n, and G. We estimate as discussed previously that the probable error in these factors is 1.0, 0.2, and 0.25 percent, respectively. The combined probable error of the cross sections as read from a smooth curve drawn through the points in Fig. 3 is therefore thought to be ± 1.6 percent.

The values shown in Table I for σ have been corrected for second-order geometry effects due to the finite solid angles subtended by the detector system and to the spread of the incident beam of protons. These calculations have been made by Professor C. L. Critchfield and are similar to, but more complete, than those discussed by Breit, Thaxton, and Eisenbud.[4] The percentage correction by which the observed σ's calculated from Eq. (2) are reduced is, of course, a function of E_p, θ, and G and is, at most, about two percent at 8° and is negligible above 30°.

In addition to the data shown in Table I and Fig. 3, we have made less careful measurements of the cross sections at 8° and 10° for protons of energy, 2.05, 1.76, 1.32, 1.12, and 0.915 Mev. These results serve to extend the observations of HKPP to smaller angles than the minimum value of 15° used in their experiments. These low energy results have been compared to those of HKPP by interpolating the value of K_0, the phase shift of the S-wave, from the phase shift values calculated by Breit, Thaxton, and Eisenbud. This interpolation was necessary because our values of E_p did not agree exactly with those used by HKPP. Our results are in excellent agreement with those expected from an extension of the HKPP observations.

At 2.42 ± 0.02 Mev our measurements can be directly compared to those of HKPP, whose highest energy was given as 2.392 Mev. There is reason to believe[14] that this energy, on the new voltage scale, should be interpreted as 2.42 Mev. The surprising agreement to within $\frac{1}{3}$ of one percent between our observations in the angular region from 15° to 45° and those of HKPP is probably fortuitous since neither set of data is thought to be accurate to better than one percent.

The interpretation of the data presented here is being undertaken by Professor C. L. Critchfield and will appear in a later publication. These experiments confirm and extend the earlier data on proton-proton scattering in the energy region where S-wave nuclear interaction is preponderant. It is expected that an analysis of the results will increase our knowledge of the range and strength of the proton-proton interaction.

TABLE II. Experimental results of the cross section for scattering through 15° per unit solid angle, in barns, at different values of incident proton energy, E_p in Mev, for the two analyzing slit geometries described in the text.

E_p	2.42	3.04	3.27	3.53
Small	0.788 ± 0.008	0.638 ± 0.008	0.600 ± 0.005	0.560 ± 0.009
Large	0.802 ± 0.008	0.618 ± 0.005	0.600 ± 0.005	0.544 ± 0.005

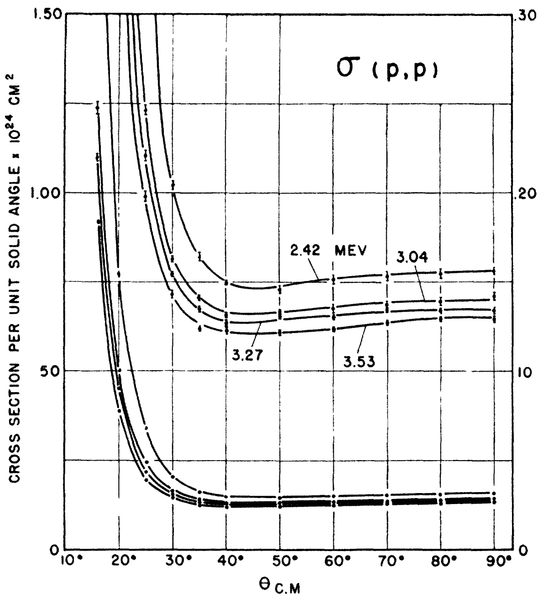

FIG. 3. The cross section per unit solid angle in the center of mass system of coordinates as a function of angle, with parameters of incident proton energy in the laboratory system. The lower curves are to the vertical scale shown on the left. The upper curves are to the scale shown on the right.

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