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Scattering of Protons by Deuterons†

R. Sherr,* J. M. Blair,** H. R. Kratz,*** C. L. Bailey,** and R. F. Taschek
Los Alamos Scientific Laboratories, Sante Fe, New Mexico

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Utilizing a scattering chamber based upon the successful design used by Herb, Kerst, Parkinson, and Plain (HKPP) in the measurement of proton-proton scattering, experimental data on the scattering of protons by deuterons have been obtained. The incident protons were accelerated by the 3.5-Mev Wisconsin generator ("long tank") which was used by the Manhattan Project at Los Alamos, New Mexico. The geometry, and the current and pressure measurements were checked by comparing the measurements of proton-proton scattering at 2.1 Mev with the work of HKPP. Results on proton-deuteron scattering at 0.825, 1.51, 2.08, 2.53, 3.00, and 3.49 Mev were obtained. The absolute cross sections per unit solid angle show the presence at all energies studied of higher order waves. A minimum in the scattering is observed near 90° at the low energies; the minimum shifts to larger angles with increasing energy. The cross sections at all angles decrease with increasing energy but the ratio of the cross section at 150° to the minimum increases gradually from 2.3 at 1.51 Mev to 3.0 at 3.49 Mev. The present results at 825 kev do not show the large anomaly found by Tuve, Heydenburg, and Hafstad at 830 kev.

INTRODUCTION

The general theoretical interest in the scattering of light particles has led us to perform a series of measurements on the scattering of protons by deuterons. The earlier experimental work by Tuve, Heydenburg, and Hafstad[1] showed a large anomaly at 830 kev. Subsequent theoretical papers have tried to explain this anomaly with little success.[2,3] Measurements were made by Taschek[4] at very low energies. It was decided to perform the present experiments at the high energies available to us in the operation of the 3.5-Mev Wisconsin generator ("long tank") designed by Herb, *et al.*[5] This generator was used by the Manhattan Project at Los Alamos, and was scheduled to be returned to Wisconsin within several months after the present work was begun. It was considered advisable to follow as closely as possible the successful experiments of Herb, Kerst, Parkinson, and Plain[6] (hereafter referred to as HKPP) on the scattering of protons by protons. Several changes were made in the design of the scattering chamber and detecting equipment. For the sake of completeness we shall describe our apparatus in detail.

MECHANICAL DETAILS OF SCATTERING CHAMBER

The scattering chamber (Fig. 1) was turned from a single piece of aluminum $17\frac{1}{2}$ inches in diameter. The inside hollow was 14 inches in diameter and 4 inches deep. Around the wall were several accurately placed holes. The brass tube which held the collimating diaphragms for defining the incoming beam of ions, was inserted into one of these holes. In a diametrically opposite hole was pressed the tube which held the current collecting cup. A port at 90° connected the chamber to the liquid-air trap and vacuum pumps. There were four other holes, at 15°, 135°, 225°, and 345°, into which the defining slit systems of proportional counters used for monitoring could be placed.

The movable proportional counter and its slit system were mounted on a 10-inch diameter disk which was screwed onto a tapered plug fitting

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* Now at Princeton University, Princeton, New Jersey.

** Now at the University of Minnesota, Minneapolis, Minnesota.

*** Now at General Electric Company, Schenectady, New York.

[1] H. A. Tuve, N. P. Heydenburg, and L. R. Hafstad, Phys. Rev. **50**, 806 (1936).

[2] H. Primakoff, Phys. Rev. **52**, 1000 (1937).

[3] K. Ochial, Phys. Rev. **52**, 1221 (1937).

[4] R. F. Taschek, Phys. Rev. **61**, 13 (1942).

[5] R. G. Herb, C. M. Turner, C. M. Hudson, and R. E. Warren, Phys. Rev. **58**, 579 (1940).

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

into a hole through the bottom of the chamber. The axis of this tapered hole intersected, and was perpendicular to, the line joining the holes mentioned above which held the collimating-diaphragm system and current-collection system. The gas and electrical leads to the movable proportional counter were brought out of the scattering chamber through holes bored through this tapered plug. Outside of the chamber a 6-inch diameter gear was clamped to the plug. This gear was driven by a smaller gear to rotate the disk and counter inside the scattering chamber. The larger diameter of the plug was on the inside of the chamber to allow the plug to be inserted in its hole after the disk had been screwed on. Four springs pressing against the gear on the bottom of the plug prevented the plug from being pushed in by atmospheric pressure when the

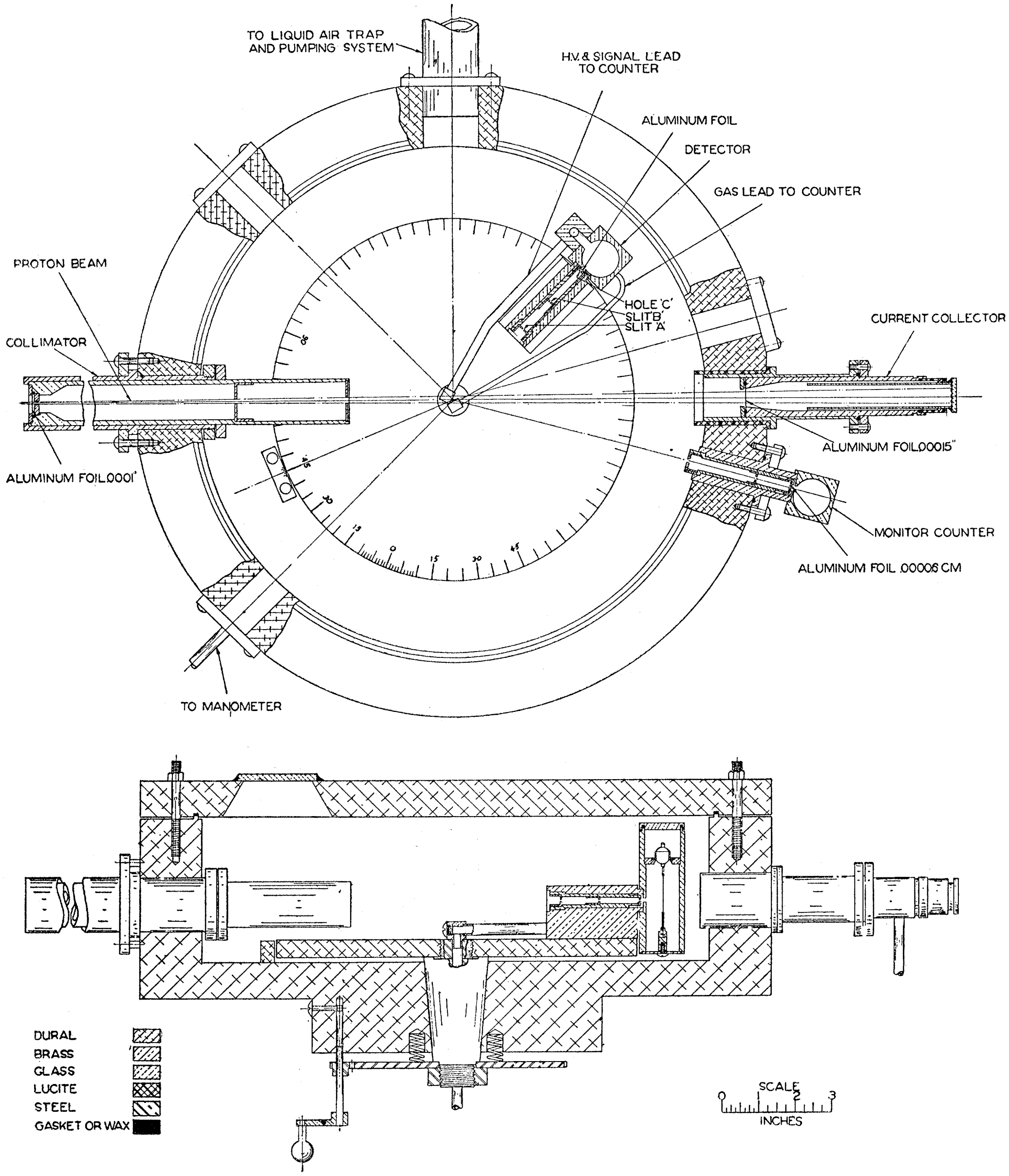

FIG. 1. Views of Scattering Chamber.

chamber was evacuated. The springs fitted into four recesses in the bottom of the chamber.

The periphery of the disk inside the chamber was graduated in degrees. These graduations were read against a vernier marked to tenths of a degree. The graduations were numbered so that the reading was zero when the movable proportional counter was on the side of the chamber opposite the beam-collimating diaphragms.

The lid of the scattering chamber was made of Dural, one inch thick. It had a gasket groove which contained a gasket of silicone material. A tongue projecting from the upper edge of the wall of the scattering chamber fitted into this groove. The lid had a glass window in it which allowed the graduations on the disk and vernier to be read.

COLLIMATOR

The brass tube which held the collimating-diaphragm assembly was pressed into the hole in the wall of the chamber and was sealed in vacuum-tight with glyptal. A section of sylphon tubing connected the brass tube to the target tube of the electrostatic generator.

The defining diaphragms were fastened into another brass tube which was a tight fit into the above mentioned tube. The first diaphragm which the beam encountered had a hole, 0.085 inch in diameter on the front side and tapered slightly to a larger diameter on the back, so that the beam was defined by a sharp edge to reduce scattering. An aluminum foil on the back side of this diaphragm served to separate the chamber from the target tube. This foil was 0.0001 inch thick (70-kev stopping power for 2-Mev protons) and was cemented in place with Glyptal. To facilitate replacement of this foil the diaphragm was removable, being held in place by a Neoprene gasket and a clamp ring.

The second defining diaphragm was ten inches further along the tube. It also had a hole 0.085 inch in diameter, tapered like the first one. These two holes defined the beam of incoming ions so that its total width was limited to 0.215 inch at the center of the scattering chamber, and to 0.355 inch at the foil in front of the current-collector cup. The maximum angle away from the axis of these holes, which an ion path could make, was 0.6 degree.

To prevent the entrance into the chamber of ions which were scattered by the edge of the second diaphragm, a third diaphragm with a 0.175-inch hole was placed at the end of the collimating tube. Tests made with the chamber evacuated indicated that this system effectively eliminated slit-edge scattering for all angular settings of the counter (15° and higher).

The tube which held these diaphragms was sealed into its supporting tube by a gasket of $\frac{1}{16}$-inch-square Neoprene strip and a clamp ring which were just inside the chamber wall.

CURRENT COLLECTOR

Into the hole on the opposite side of the chamber was pressed a Lucite insulating tube of $\frac{1}{8}$-inch wall thickness. A brass tube which supported the insulator for the collector cup slipped into the Lucite tube. With this arrangement the brass tube could be used as a guard ring for testing the efficiency of collection of the beam current. To facilitate the assembly of the current-collection system this tube was made in two parts, sealed together with a Neoprene strip gasket.

The insulator which supported the current-collector cup was a piece of glass tubing, one-inch outside diameter, sealed to the brass with hard wax. The collector cup itself was a piece of brass tubing, $\frac{3}{4}$-inch inside diameter, which extended out through the glass tube insulator and had its rear end covered with a piece of vicor glass .To eliminate charging of this glass plate, it was covered on the inside with a fine-mesh nickel screen. This window on the back of the collector cup was used in order that the chamber as a whole could be more easily lined up with respect to the ion beam of the generator by observing the fluorescent spot on the glass.

To prevent erroneous results in the current collection because of ionization current around the collector, the collector-cup assembly was separated from the rest of the chamber by a thin aluminum foil (0.0015 inch thick). A separate lead to the fore vac and high vac manifolds was provided for evacuating the collector-cup chamber.

DETECTORS

The movable proportional counter was bored out of a brass block. Its inside diameter was one inch, and its central wire was 0.010 inch in diameter. The wire was supported at one end by a procelain insulator, and at the other end passed out of the counter into a connection box just above through a Kovar-glass seal. To keep the active region of the counter from being too large and yet not distort the field near the center to any extent, the central wire was enlarged for about three-eighths of an inch at each end by placing over it sections of stainless-steel tubing, 0.025-inch outside diameter. These sections reduced the field on the ends to too low a value to cause appreciable multiplication of ions. The section of bare wire in the center was one inch long.

The scattered particles entered the proportional counter through a defining system consisting of two slits and a hole.[††] The first slit and the hole defined the space from which scattered particles could enter the counter, while the intermediate slit cut off particles scattered from the walls of the slit system.

To make sure that the slit system of the counter was pointed directly at the center of the chamber, it was lined up by using a pointed mandrel, which was a tight fit into the holder for the slit system, and another pointed rod which was pressed into a hole exactly in the center of the tapered plug. The alignment was checked by setting the counter at zero degrees and sighting into the chamber and counter through the holes which define the original beam of ions entering the chamber. During this process it was found that the axis of the tapered plug was 0.007 inch off of the axis of the beam-collimating system, but seemed to be perpendicular to it nevertheless.

The center of the counter slit system was a little below the axis of the beam-collimating holes so the proportional counter assembly was shimmed up into position. After the position of the counter had been checked for height, orientation, and position with respect to the zero of the disk graduations, it was pinned in place with two tapered pins so that it could be removed and yet replaced exactly as it was. The critical dimensions of the slit system required for conversion of the observed yield to absolute cross sections are, in the notation of HKPP, the width $2b$ of the first detector slit (slit A, Fig. 1), the area A of the last detector hole (hole C, Fig. 1), the separation h between these apertures, and the distance R_0 from the hole C to the center of the beam. Careful measurements were made of each of these quantities, with the following results: $2b=0.2067$ cm; $A=2.094\times 10^{-2}$ cm^2; $h=6.988$ cm; and $R_0=12.893$ cm. The slit and hole were somewhat irregular in shape so that the values of $2b$ and A represent the averages of a number of width measurements along the slit and diameter measurements at eight different angles across the hole. These values for the geometrical constants give a value of 4.796×10^{-5} cm for the quantity $G=2bA/R_0h$ (see HKPP). The accuracy of this constant is estimated to be 0.5 percent; the greatest uncertainty is contributed by the irregularity of the hole.

After passing through the last dector hole, the scattered particles passed through a thin window of aluminum 0.00006 centimeter thick into the counter. The aluminum was coated with a 5 percent solution of collodion in order to cover the pinholes in the foil. This combination aluminum and collodion window is thinner than one made of pure aluminum which is without pinholes, and is more reliable than a window made of collodion alone. Such a window easily withstood the 5-cm Hg pressure of the gas inside the counter. The scattered particles passed through the counter in a plane perpendicular to the counter wire and $\frac{1}{8}$ inch away from the wire. Tests of this arrangement with a polonium source gave very satisfactory results. With a gas filling of 5 cm of butane and a multiplication of about 150, the α-particle pulses gave a distribution with a half-width of 5 to 7 percent.

The outside of the proportional counter was at ground potential and the central wire was maintained at high voltage. Since the wire also collects the signal which is to be amplified, it is essential to prevent corona trouble and spark-over to the high voltage lead going to the central wire. The high voltage lead was brought up through the tapered plug and over to the connection box on top of the counter through a tube which was maintained at atmospheric pressure. The connection box at the top of the counter, also at atmospheric pressure, was covered with a brass plate and isolated from the vacuum by a

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[††] See reference 6, Fig. 3, p. 1000. See also detail in Fig. 1.

Neoprene strip gasket. The lead wire was insulated with a continuous plastic tube from a coaxial cable.

Outside the chamber, the electrical lead passed through a flexible joint to another connection box where the signal was separated from the high voltage by a decoupling resistance of 10 Meg in the high voltage supply line. A coupling capacitance of 100 $\mu\mu$f fed the signals to the preamplifier. From there the signal passed on to the amplifier and discriminator. The gas lead to the counter went through the tapered plug directly to a hole in the counter wall. A piece of rubber tubing connected this lead to the gas-filling system external to the chamber.

The monitor counter, which fitted into a hole in the wall of the scattering chamber at 15° with respect to the proton beam, was essentially the same as the movable counter inside the chamber. Since it was somewhat further away from the center of the chamber, the slit system was a little larger to prevent reduction of its counting rate.

The two counters were enough alike that they could be filled simultaneously and could use the same high voltage supply.

MEASUREMENT OF PROTON ENERGY

To calibrate the electrostatic analyzer[7] of the generator, the $Li^7(p,n)Be^7$ reaction was used. The threshold was assumed to be 1.860 Mev.[8] A small crystal of LiF was placed on a magnetically operated shutter already installed in the target tube of the generator. When the crystal was raised into the proton beam, the neutrons produced could be detected by a BF_3 neutron counter placed beyond the scattering chamber.

To know accurately the energy of the ions inside the scattering chamber a correction must be made for the stopping power of the aluminum foil over the first defining diaphragm. To obtain the stopping power of this foil another LiF crystal was placed in a special holder at the entrance to the current-collector guard ring. When the $Li(p,n)$ threshold is checked first with the crystal in the target tube and then with the one inside the chamber, the difference gives the stopping power of the foil. Measurements at the beginning and at the end of this experiment gave values of 70 and 90 kev, respectively, for the stopping power of the foil at 1.86 Mev. The increase was undoubtedly due to carbon deposited during the course of operation. Measurements on the threshold, before and after the present experiments, indicated no noticeable change in the calibration of the analyzer.

CURRENT MEASUREMENT

In order to check the efficiency of the current collector, a series of tests, similar to those described by HKPP††† were made. A brass tube was inserted in the Lucite sleeve, described above, and was in contact with the brass guard ring. The inserted tube extended to, but did not touch, the exit slit of the collimator. The guard-ring system and the cup were separately connected to sensitive galvanometers and tests on secondary electrons, leakage, foil scattering, and neutralization were carried out. These tests showed that with a vacuum of 4×10^{-6} mm Hg around the cup, a magnetic field at the entrance to the cup of 300 gauss, and a voltage of 45 volts between cup and guard ring (cup negative), the error in measuring the current, introduced by the factors mentioned above, was less than 0.1 percent.

Two methods of measuring the beam current were employed. The generator-current integrator[9] was used in the preliminary measurements. It was calibrated by feeding current from a +400-volt supply through a high resistance onto the input condenser of the integrator. The collector cup and connecting lead had an appreciable capacitance so that they were left connected to the integrator during the calibration. The high resistance box also was left permanently in place. The current was determined by measuring the voltage across a 3-meg. resistor with a type *K* potentiometer. The 3-meg. resistor had been previously calibrated against precision resistances and was inserted between the high voltage

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[7] A. O. Hanson, R.S.I. **15**, 57 (1944).

[8] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. A. Wells, Phys. Rev. **58**, 1035 (1940); A. O. Hanson and D. L. Benedict, Phys. Rev. **65**, 33 (1944). The former group obtained 1.856 Mev for the threshold while the latter investigators found 1.883 Mev. The value 1.860 Mev has been generally used in this laboratory.

††† See reference 6, p. 1004.

[9] J. M. Blair, Rev. Sci. Inst. **14**, 64 (1943).

supply and the high resistance. This system eliminated the introduction of unwanted capacitances in parallel with the input condenser of the integrator. The integrator was biased so that it operated between −45 volts and ground. Calibration to a fraction of a percent was possible, but was found to be unnecessarily refined, since it was discovered during preliminary scattering measurements that the calibration varied irregularly over the course of time by as much as 5 percent. Since the method of calibration outlined above was too cumbersome for frequent use, it was decided to use a monitor chamber and, in addition, to calibrate the monitor counter with a standard condenser and ballistic galvanometer. For the greater part of each run (angular distributions at a fixed energy) the current integrator was used. Then for several angular settings of the rotating counter the Leeds and Northrup 1-microfarad standard condenser was connected to the collector cup, and the charge corresponding to a given number of monitor counts (6400) was measured. Preceding each such measurement, the ballistic galvanometer was calibrated by charging the standard condenser to an accurately measured voltage and subsequently discharging it through the galvanometer.

Monitor counts were taken at each position of the rotating counter and current-integrator readings were taken except during the calibrations. It was, therefore, possible to compare the number of monitor counts (per microcoulomb per mm of pressure) obtained with the current integrator with the number of monitor counts (per microcoulomb per mm of pressure) obtained with the condenser-ballistic galvanometer. By averaging the former values a number was obtained which agreed within several percent with the latter values but were consistently lower. For the final calculation of the number of scattered particles per microcoulomb per mm of pressure, the current integrator and the condenser-ballistic galvanometer results were averaged. This procedure was adopted since time did not permit a thorough investigation of either method. It is felt that the problem of current measurement is the greatest single course of error in the determination of the absolute cross sections. A reasonable estimate of the probable error in the current measurement is 2 percent.

The number of scattered particles per microcoulomb per mm of pressure was determined by multiplying the ratio of detector counts to monitor counts by the value of monitor counts per microcoulomb per mm of pressure, obtained as outlined in the preceding paragraph. Since the monitor was located at 15°, its counting rate was very high and the accuracy in the ratio of detector to monitor counts was limited by the counting rate of the detector. As mentioned above, the runs were made at constant energy. The relative cross sections at a particular energy are more accurate than the absolute values, since errors in the determination of the "microcoulombs" and the "mm of pressure" are eliminated.

GAS SYSTEM

The scattering chamber was filled with the scattering gas to a pressure of approximately 1-cm Hg through a palladium spiral which was directly heated. The pressure in the chamber was measured with a manometer of 2-cm diameter glass tubing, attached directly to the chamber. The Apiezon B oil used in the manometer was outgassed by torching during evacuation. A microscope with a micrometer screw was mounted on a swinging vertical bar so that, with the aid of fiducial marks, the levels of the oil in both arms of the manometer could be read to an accuracy of 0.1 mm. As the difference in oil levels was usually 150 mm, the pressure could be read to an accuracy of 0.15 percent. A thermometer was placed on top of the scattering chamber to give the chamber temperature.

A stainless-steel liquid-air trap, attached to the chamber, was constantly in use. Because of rapid conduction by the hydrogen-scattering gas, the level of the liquid air changed rapidly and had to be refilled every hour. The pressure in the chamber varied by several millimeters as the liquid-air level changed. Consequently, pressure readings were taken immediately preceding and following each measurement at a particular angle and energy, and the pressure (corrected for temperature to 0°C) was taken to correspond to the mid-time of each measurement. The estimated accuracy in the pressure values is 0.5 percent. This figure includes possible errors introduced by assuming that the oil density was

0.864, whereas the actual density was found to vary from 0.858 at 25°C to 0.864 at 15°.

Tests were made to determine the effect of impurities. Since the chamber was isolated for five or six hours during each run, measurements of scattering of the proton beam were made with the chamber evacuated and isolated, with the liquid-air trap in operation. These measurements showed that impurities built up by gassing of the chamber contributed a negligible amount to the gas-filled yield. The palladium tube was tested for a possible contribution by a simulated filling, with negative results. Before changing from hydrogen to deuterium gas, and *vice versa*, the palladium tube and chamber were flushed several times with the new gas before measurements were begun. The effectiveness of this procedure was adequately checked by the absence of recoil deuterons when hydrogen was substituted for deuterium.

RECORDING APPARATUS

The present experiments were begun shortly after the completion of a new 10-channel amplitude recorder designed by M. Sands of the Electronics group. This instrument was available and proved to be a thoroughly reliable and extremely useful recording device for our measurements. The details of this multi-channeled discriminator will be described in detail in a future publication,[10] but in essence it consists of 10 discriminator and scaling units. The discriminators are successively biased by equal increments. Each channel is connected with its neighbors by anti-coincidence circuits and an incoming pulse is registered in that channel which is in anti-coincidence with the following channel (except for the tenth channel which records all pulses higher than its bias setting.) One, therefore, obtains a "differential bias curve" for the incoming pulses. The width of the channels could be selected to be 2, 5, or 10 volts, and the minimum bias on the set of channels could be varied. With these two adjustments it was possible, in a simple manner, to adjust the resolution of the instrument to our particular requirements.

The time-saving features of the 10-channel discriminator are immediately obvious for the $p-d$ scattering measurements, since both scattered protons and recoil deuterons enter the detector at angles below 90°. The relative and absolute pulse amplitudes of the two groups vary from angle to angle as will be shown below (Fig. 2). The proper settings of the amplifier gain and channel position and width could be determined in a matter of minutes before actual measurements were made. Since the two groups could be adequately resolved at most angles a higher accuracy is achieved by this method of recording over a single discriminator for the same total number of counts. Another simplification was introduced by obtaining the background for each group. At low accelerating voltages, this background was more or less randomly distributed. At higher energies (about 3 Mev), an appreciable background, generated by protons striking the collimator slits, was observed which had a distribution which was high in the lower channels and rapidly decreased. Backgrounds were measured after each run with the scattering chamber evacuated at the same angular, amplifier, and discriminator settings which were used in the scattering measurements.

The linear amplifiers,[11] used with the movable detector and the monitor counter, had a rise time of 0.5 microsecond and were stabilized by inverse feedback. The low frequency response was limited to allow quick recovery (within several microseconds). Since the monitor counter detected the two groups of particles at constant amplitudes for a given energy setting, its pulses were recorded with two "integral-bias" discriminators. Bias curves were taken at each energy and the two groups were found to have excellent plateaus. The two discriminators were then set on the deuteron plateaus, one at the middle and the other at a lower bias as a check for drift of the plateau.

PROTON-PROTON SCATTERING

In the notation of HKPP the yield of detected particles is given by

$$Y = Nn\sigma G/\sin\theta, \tag{1}$$

where N is the number of incident particles, n is the number of scattering particles per cm^3, and σ is the scattering cross section (in laboratory

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[10] Los Alamos Technical Series **1**, Part 1, Section 4.5.

[11] Los Alamos Technical Series, **1**, Part 1, Section 3.6.

coordinates) per unit solid angle at the angle θ. The factor $G/\sin\theta$ defines the target volume and detector efficiency. In view of the short time available for the present experiment, it was considered advisable to check our experimental arrangement and procedures by measuring proton-proton scattering for comparison with the careful experiment of HKPP. By these measurements it was felt that systematic errors would be discovered quickly. One series of such measurements were made before the proton-deuteron tests, and a second set of data was taken after completion of the latter measurements. These results are summarized in Table I. The incident-proton energy was 2.08 Mev. Measurements made at different pressures gave identical results for the yield per mm. Measurements were also made with angular settings on both sides of the incident beam, but no systematic difference was observed. The first set of data was taken using the current integrator. The second set was taken using the condenser-ballistic galvanometer-monitor counter method of current measurement, in addition to the current integrator; the final results were evaluated as described in the section on "current measurements." For a direct comparison with the data of HKPP, our yields were divided by 1.680, which is the ratio of our value of G to the value of G given by HKPP.

TABLE I. Comparison of proton-proton scattering yields at 2.08 Mev with the yields obtained by HKPP. The upper set was measured before the proton-deuteron experiments, the lower set after the completion of the latter measurements.

Angle (degrees)	15	20	25	30	35	40	45
Yield/μC/mm	5.09	2.38	1.81		1.23		0.887
Corrected yield	3.03	1.42	1.08		0.732		0.528
HKPP yield	2.91	1.405	1.039		0.743		0.525
Percentage difference	+4.1	+1.1	+3.9		−1.4		+0.5
Angle (degrees)	15	20	25	30	35	40	45
Yield/μC/mm	4.90	2.32	1.76	1.46	1.22	1.009	0.880
Corrected yield	2.92	1.38	1.05	0.866	0.725	0.600	0.524
HKPP yield	2.91	1.405	1.039	0.855	0.743	0.604	0.525
Percentage difference	+0.3	−1.8	+1.0	+1.3	−2.4	−0.7	−0.2

In Table I the first row gives the angular setting (laboratory coordinates); the second row is the yield per microcoulomb per mm of pressure at 0°C. Row three shows the yields corrected by the factor 1.680, while the fourth row gives the data obtained by HKPP. The last row indicates the percentage differences. The improvement in our measurements on using the monitor counter and ballistic galvanometer method of current calibration is apparent from the second set of data in Table I. From the estimates given above for the accuracy in the determination of N, n, and G, one obtains a probable error of 2.2 percent in the determination of NnG. The number of counts taken at each setting in the second experiment was in the neighborhood of 8000, leading to

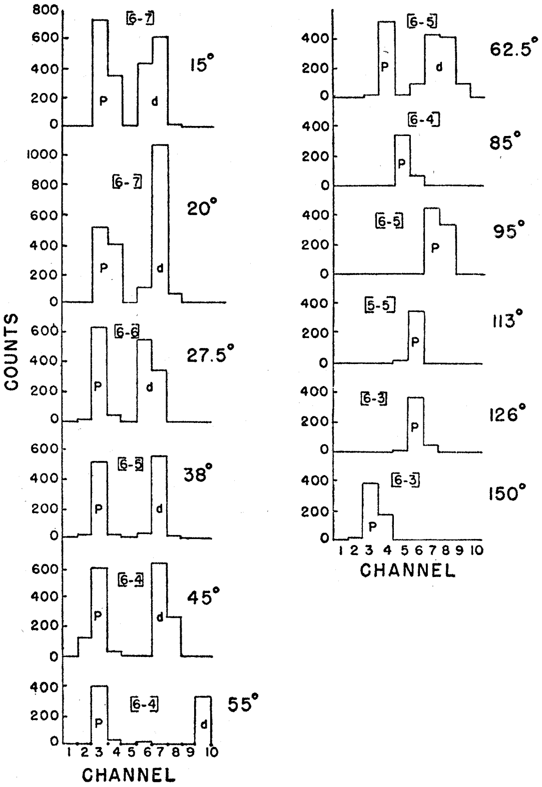

FIG. 2. Scattered-proton (p) and recoil-deuteron (d) yields at 2.08 Mev obtained with the 10-channel amplitude recorder. The ordinates are the observed counting rates, the abscissa are the various channels. The bracketed quantities represent the amplifier gain, larger numbers corresponding to higher gain.

TABLE II. Conversion factors for determining of absolute cross sections per unit solid angle in the center of mass system from the observed yields of protons and deuterons. The angles ϕ and ϵ are the laboratory angles (degrees) for the protons and deuterons, the values of β are the corresponding center of mass angles.

ϕ	15	20	27.5	38	45	55	62.5	85	95
β	22.5	29.9	40.9	55.9	65.7	79.2	88.8	114.9	124.9
$F(\phi)$	0.1180	0.1592	0.2240	0.3235	0.398	0.520	0.626	1.041	1.273
ϕ	113	126	150						
β	140.4	149.9	164.5						
$F(\phi)$	1.704	1.918	1.691						
ϵ	15	20	27.5	38	45	55	62.5		
β	150	140	125	104	90	70	55		
$F(\epsilon)$	0.0670	0.0910	0.1302	0.1953	0.2500	0.3570	0.4803		

TABLE III. Summary of proton-deuteron scattering experiments. The yield is the number of scattered protons or recoil deuterons per microcoulomb of incident protons per millimeter of oil pressure. The cross section per unit solid angle in center of mass coordinates $\sigma(\beta)$ is given in units of 10^{-24} cm^2.

																				Energy (Mev)
Proton angle φ	15	20	27.5		38	45		55	62.5			85	95			113	126		150	
Deuteron angle ϵ				62.5			55			45	38			27.5	20			15		
Center of mass angle β	22.5	29.9	40.9	55	55.9	65.7	70	79.2	88.8	90	104	114.9	124.9	125	140	140.4	149.9	150	164.5	
Yield	34.0	9.24	2.64											2.18	3.69			5.26		0.825
$\sigma(\beta)$	2.98	1.09	0.439											0.210	0.247			0.261		
Yield	11.18	3.73	1.55		0.765	0.576	0.584	0.387		0.784	1.10	0.228	0.226	2.32	4.37	0.227	0.225	6.72	0.331	1.51
$\sigma(\beta)$	0.980	0.441	0.258		0.184	0.170	0.154	0.149		0.145	0.159	0.176	0.214	0.224	0.294	0.286	0.320	0.334	0.417	
Yield	6.08	2.67	1.29	0.487	0.738	0.527	0.548	0.340	0.258	0.632	0.830	0.180	0.179	1.76	3.69	0.194	0.204	5.94	0.292	2.08
$\sigma(\beta)$	0.533	0.315	0.214	0.174	0.177	0.156	0.145	0.131	0.120	0.117	0.120	0.139	0.169	0.170	0.247	0.245	0.290	0.295	0.367	
Yield	4.97	2.28	1.30	0.503	0.736	0.534	0.537	0.330	0.242	0.588	0.724	0.149	0.150	1.52	3.15	0.171	0.191	5.69	0.272	2.53
$\sigma(\beta)$	0.436	0.270	0.216	0.179	0.177	0.158	0.142	0.127	0.113	0.109	0.105	0.116	0.142	0.147	0.213	0.217	0.271	0.282	0.342	
Yield	3.92	2.05	1.24	0.474	0.688	0.492	0.517	0.316	0.230	0.540	0.603	0.125	0.125	1.26	2.73	0.148	0.175	5.06	0.271	3.00
$\sigma(\beta)$	0.344	0.242	0.207	0.169	0.166	0.145	0.137	0.122	0.107	0.100	0.0878	0.0968	0.118	0.122	0.186	0.187	0.251	0.251	0.343	
Yield	3.48	1.95	1.20	0.404	0.679	0.480	0.474	0.272	0.173	0.499	0.528	0.128	0.117	1.03	2.44	0.126	0.151	4.58		3.49
$\sigma(\beta)$	0.304	0.229	0.198	0.144	0.163	0.141	0.125	0.104	0.0802	0.0922	0.0764	0.0975	0.110	0.0986	0.165	0.160	0.215	0.227		

a total probable error in the yield of 2.5 percent. The agreement between these two independent measurements of the proton-proton scattering is very satisfactory.

Data were taken at angles beyond 45° (up to 70°) and were found to agree well with the measurements below 45°, indicating that our instrumentation would be satisfactory for the larger angular range covered in the proton-deuteron scattering.

PROTON-DEUTERON SCATTERING

In the measurement of proton-deuteron scattering, scattered protons and recoil deuterons enter the detecting counter. It is necessary to separate the two groups in order to determine the angular cross sections. As mentioned above, this separation was accomplished by means of a 10-channel amplitude recorder. Typical results obtained with this device are shown in Fig. 2. The bracketed numbers represent the amplifier gain, higher numbers referring to higher gain settings. Bearing these numbers in mind, we can see the general trend of the amplitudes of the two groups. The counter depth is small compared with the particle range at low angles so that at 15°, the deuteron pulse is roughly twice as large as the proton pulse. The deuteron energy falls off relatively more rapidly with angle than the proton energy, so that both groups increase in amplitude, the deuteron group increasing more rapidly. A maximum separation in the groups occurs at about 55°. Beyond this point the proton pulses continue to increase, but the deuteron pulses begin to decrease as the residual deuteron range (beyond the counter window) becomes smaller than the counter depth. At about 70° the proton and deuteron groups overlap with the latter disappearing rapidly beyond this angle. The proton pulses continue to increase in amplitude to 113° beyond which they decrease. An additional point of interest is the counts observed in channel 6 at 55°. These correspond to protons scattered from hydrogen contamination in the deuterium gas. (The apparent narrowness of the deuterium group at 55° is fictitious, since channel 10 actually records all amplitudes greater than those which would fall in channel 9.) Mass-spectrographic analysis‡ of the deuterium gas gave a composition of 99.1 percent deuterium and 0.9 percent hydrogen.

If β is the angle of scattering of the proton in center of mass coordinates, and ϕ and ϵ are the corresponding angles in the laboratory system of the scattered proton and recoil deuteron, one obtains the following relationships:

$$\epsilon=\pi/2-\beta/2 \tag{2}$$

and

$$\sin(\beta-\phi)=\tfrac{1}{2}\sin\phi. \tag{3}$$

To convert the laboratory angular cross sections, obtained from the yields by Eq. (1),

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‡ Analysis was made at the Metallurgical Laboratory in Chicago.

to angular cross sections in the center of mass system, one has

$$\sigma(\beta)\sin\beta d\beta=\sigma(\phi)\sin\phi d\phi.$$

Combining this equation with Eq. (3) one finds

$$\sigma(\beta)=\sigma(\phi)\cos(\beta-\phi)[(\sin\phi)/(\sin\beta)]^2.$$

Since $\sigma(\phi)$ is given by Eq. (1), one obtains

$$\sigma(\beta)=(1/NnG)\,Y(\phi)F(\phi),\qquad(4)$$

where

$$F(\phi)=[(\sin^3\phi)/(\sin^2\beta)]\cos(\beta-\phi).\qquad(5)$$

Similarly, from the deuteron yields

$$\sigma(\beta)=(1/NnG)\,Y(\epsilon)F(\epsilon),\qquad(6)$$

where

$$F(\epsilon)=\tfrac{1}{4}\tan\epsilon.\qquad(7)$$

The conversion factors $F(\phi)$ and $F(\epsilon)$ were evaluated from these equations and are listed in Table II. These results were used to convert the measured yields to cross sections per unit solid angle in the center of mass system. The value of $(NnG)^{-1}$ for 1 microcoulomb and 1 mm of oil pressure is 0.742×10^{-24} cm^2.

RESULTS

A series of runs was made to scan the energy interval 0.8 to 3.5 Mev to see if any pronounced dependence on energy was to be observed. The dependence on energy appears to be gradual, so that final results were obtained at intervals of approximately 500 kv. These results are summarized in Table III. The yields have been cor-

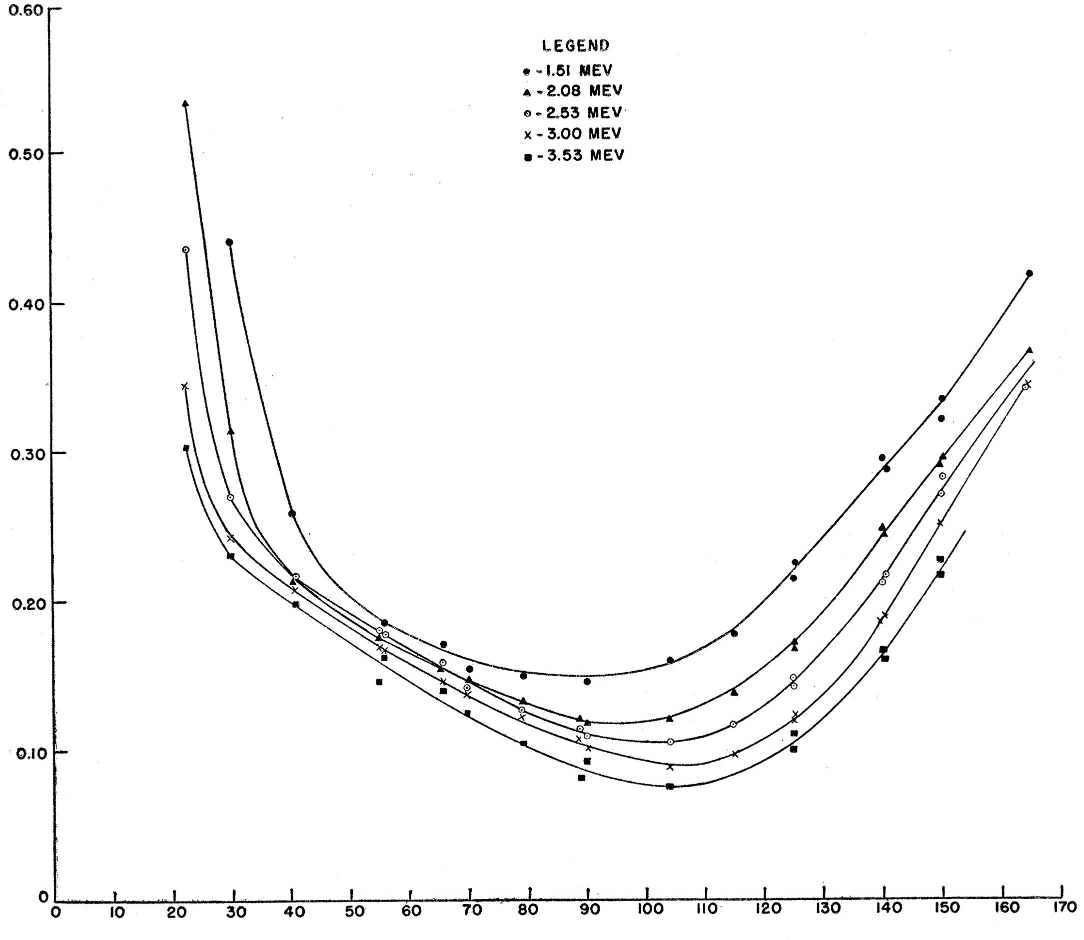

FIG. 3. Angular distribution of protons scattered by deuterons (see Table III).

TABLE IV. Ratio of observed scattering cross sections to Rutherford cross sections for various energies and angles.

E (Mev)	Scattering Angle β 45°	60°	90°	120°	150°
1.51	3.68	8.65	28.3	87	224
2.08	6.44	15.2	43.8	128	377
2.53	9.76	22.9	60.1	158	524
3.00	13.1	30.5	79.3	186	670
3.49	16.6	37.8	89.6	215	798

TABLE V. Proton-deuteron scattering results at 825 kev. The ratio of observed cross section to Rutherford cross section is given in rows labelled R.

(a) Results of present experiment at 825 kev.

β	22.5°	29.9°	40.9°	125°	140°	150°
$\sigma(\beta)$	2.98	1.09	0.439	0.210	0.247	0.261
R	0.997	1.12	1.52	30.4	45.6	53.1

(b) Results obtained by Tuve *et al.* (tabulated by Primakoff) at 830 kev.

β	30°	45°	59°	110°	120°	150°
R	2	5	8	70	124	2275
R theory	2	4	7	35	40	61

rected for background and for hydrogen contamination. The latter correction was made for all deuteron angles and for proton angles greater than 55°. At lower angles, the protons scattered by hydrogen and deuterium were indistinguishable. No correction was made at these angles, but since the scattering by the two nuclei is of the same order of magnitude, the negligence introduces a trivial error. No geometrical corrections have been applied to the cross sections; such corrections would increase the value at 15° (for the protons) a few percent, but would be negligible at higher angles. The energy values are believed to be correct to ±30 kev relative to the value of 1.860 Mev for the threshold of the Li(p,n) reaction which was used to calibrate the energy scale. The entrance foil was taken to be 80-kev equivalent at 2.1 Mev, since the rate of deposition of carbon on this foil was unknown. The estimated accuracy of ±30 kev also includes the uncertainty in the linearity of the electrostatic analysis. Counts of 2500 or more were taken at each setting so that the statistical weight of the yields is 2 percent or better, leading to a probable error of the order of 3 percent when the uncertainty in the determination of NnG is included. The last run at 3.49 Mev is considerably less accurate as a result of generator difficulties and the failure to take a background run at this energy. The background was fairly high and an estimate of it was made for this set of data. However, it is felt that the errors of this run are probably not greater than 10 percent. The data taken at 1.51, 2.08, 2.53, 3.00, and 3.49 Mev are shown in Fig. 3, where $\sigma(\beta)$ is plotted against β. The excellent agreement between the cross sections obtained independently from the deuteron and proton yields may be noted.

The presence of nuclear scattering is quite apparent from these curves. At angles beyond 45° it represents the major fraction of the scattering cross section. The increase of cross section at large angles and the shifting of the minimum show that waves of higher order than the spherically symmetrical S-wave must be effective. The ratios of the observed cross sections to Rutherford cross sections are given in Table IV for several angles.

As was mentioned in the introduction to this paper, Tuve, Heydenburg, and Hafstad[1] obtained very anomalous results in the proton-deuteron scattering at 830 kv which subsequent theoretical work by Primakoff[2] and Occhai[3] attempted to explain. The present data do not agree with these previous results. In Table V our measurements expressed as "ratio to Rutherford" may be compared with the earlier work. The theoretical values of R calculated by Primakoff are in fair agreement with the present measurements at the larger angles, but give too high values at low angles.

In conclusion we take pleasure in acknowledging the helpful suggestions and interest of Drs. A. O. Hanson, J. L. McKibben, C. M. Turner, and J. H. Williams. This experiment could not have been completed within the short time available without the generous assistance of Dr. A. Hemmindinger and Messrs. E. Klema, R. Perry, and L. W. Seagondollar in taking data and operating the electrostatic generator. We are indebted to Mr. E. W. Dexter of the electronics group for his assistance in periodically checking the operation of the 10-channel discriminator.