Differential Cross-Section Measurements for the Scattering of Protons by Deuterons*

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The differential cross section for protons elastically scattered by an incident deuteron beam has been measured in the energy range 0.96 Mev to 3.22 Mev. This corresponds to an extension of previous *p-d* scattering data down to an energy of 0.48 Mev incident proton energy. The angular range in the c.m. system of coordinates is from 67° to 126° with the cross section showing characteristic minima in the neighborhood of 90° at each energy considered. Values of the cross section vary from 0.147 to 0.280×10^{-24} cm^2 over this range of parameters.

INTRODUCTION

The interest in interactions among a small number of nucleons has led us to extend more completely the measurements of *p-d* scattering[1–6] into lower energy regions. Considerable theoretical work has been done[7–11] on this problem in an attempt to evaluate the equivalence between *n-n* forces and *n-p* forces and explain the "anomalous" behavior of the angular distributions. The measurements of Sherr *et al.*[3] covered most extensively the range of working energies of an electrostatic generator when incident protons with laboratory energies in the range of 0.825 Mev to 3.49 Mev were scattered from a deuterium gas target. These data were subsequently analyzed by Critchfield.[9] We have extended the energy range of the measurements for this interaction by reversing the roles of the proton and deuteron while working in the same range of machine energies. An equivalent center-of-mass energy for the interaction is realized in these two experiments when the energy of an incident deuteron beam is twice that of an incident proton beam, so that by working in approximately the same range of machine energies, we have extended the energy range of the earlier data down to 0.48 Mev.

In order to make it easier for the reader to compare results of this experiment with the earlier measurements at Los Alamos and the analysis of the Los Alamos data by Critchfield,[9] we will reduce all of our final data to their equivalent in an experiment where incident protons are scattered by deuterons and present these data as an extension of the earlier work. However, to satisfactorily describe the measurements in the laboratory, we will describe the experiment in terms of measured laboratory coordinates and parameters and then change to the equivalent case in the final tabulation of the data.

SCATTERING CHAMBER

The scattering chamber used in this experiment is shown in Fig. 1. It is the same chamber used for measuring the scattering of protons by tritons[12] with the following modification. The volume of the chamber has been increased from 90 cm^3 to 200 cm^3 by milling out a large pill-box cavity surrounding the effective scattering volume defined by the incident beam collimating holes and the counter collimating slits. This enlargement moved the walls of the scattering chamber farther from the collimated beam and reduced the amount of gas-to-wall-to-counter scattering which had previously restricted reliable measurements to scattering angles greater than 40°. The enlargement allowed us to go to angles as low as 30° before this trouble again became serious. Data were taken at 26.8°, and the large specified error in these measurements at this angle is due mostly to this phenomenon.

The counter slit system was measured with a comparator and gave a geometry factor $G=2bA/Rh=1.2802\times10^{-4}$ cm, where $A=0.10021$ cm^2 is the area of the round hole at the counter, which is at a distance $R=13.670$ cm from the center of the effective scattering volume. The defining slit of width $2b=0.1753$ cm is located a distance $h=10.038$ cm away from the counter hole A.

The incident beam was collimated by holes A and C, which have respective diameters of 0.1079 cm and 0.1187 cm. These holes were 5.87 cm apart, thus allowing the beam to diverge into a 1.1° half-angle cone.

The entrance window was of nominally 0.2-mil aluminum foil. The measured energy loss of 1.88-Mev protons in this foil was 130 kev. The exit window to the collector cup was 0.25-mil Mylar[13] coated with a thin layer of evaporated aluminum to help dissipate power from beam losses. This foil would become slightly charred from long use. The centering of the charred

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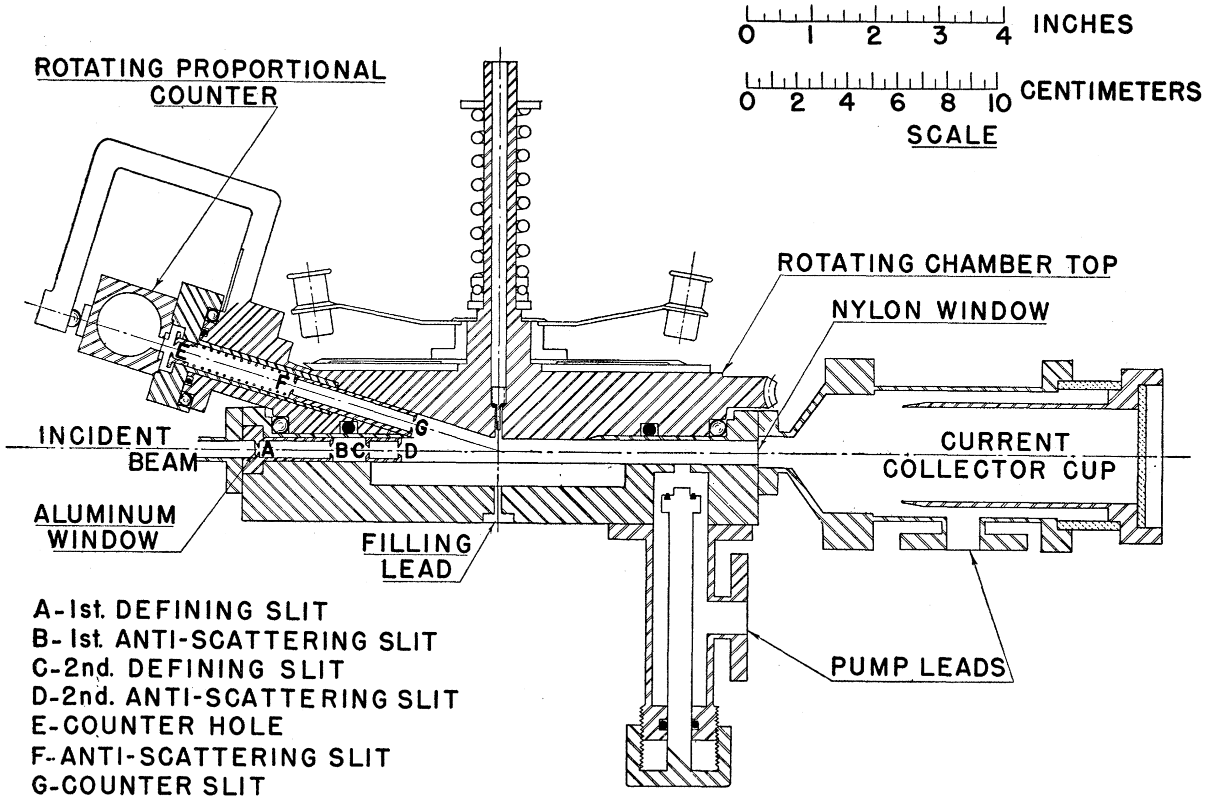

FIG. 1. View of scattering chamber. The figure shows a plane containing the axis of the beam and the axis of cylindrical symmetry of the chamber with the counter set at a maximum scattering angle.

spot indicated that the beam had been passing symmetrically through the chamber and that all of it was properly entering the collector cup. The alignment of the beam was also checked by noting the centering of the fluorescent spot on the quartz window at the far end of the Faraday collector cup.

The integrated incident flux of deuterons which had passed through the chamber into the collector cup was determined by measuring the charge which had accumulated on the cup and a 0.5-μf polystyrene condenser in parallel with the cup. Loss of secondary electrons from the collector cup was prevented by a transverse magnetic field and an electrostatic bias. The accumulated charge was measured with a calibrated ballistic galvanometer at the end of a run. This calibration was checked periodically during the course of the experiment.

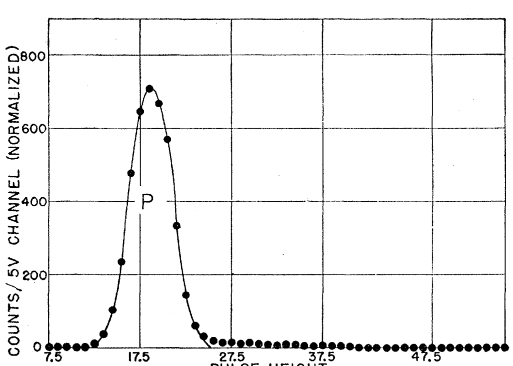

FIG. 2. Typical pulse-height distribution. The tail on the right is due to particles which have suffered gas-to-wall-to-counter scattering and extends into the main peak so as to require a −3 percent correction at this angle.

The scattered particles, which had passed through the counter defining slits, entered the proportional counter through either a thin window made from alternate layers of zapon and evaporated aluminum or a 0.17-mil aluminum window. Our angular range of measurements was limited by the maximum angle at which we could still obtain recoil protons with sufficient energy to give measurable pulses; therefore, the counter window was, in general, made as thin as possible and yet be able to withstand counter gas pressures. The aluminum layers gave the windows added strength and made them impervious to tritium used in a concurrent experiment.

The proportional counter was filled with a mixture of Argon and CO_2 at various pressures between 6 and 15 cm of Hg, adjusted with the window thickness to give maximum pulse height and still allow particles to pass completely through the counter. CO_2 was used as a quenching gas, rather than methane, to cut down the size of pulses caused by atoms in the counter gas which were recoiling from fast neutrons in the machine background.

The pulses from the counter were amplified by a Model 100 preamplifier and amplifier of Los Alamos design[14] and registered on a 10-channel pulse-height discriminator, also of Los Alamos design. The circuits were modified, and the procedure of taking data was arranged so that a pulse-height distribution was determined from 50 measured points.

The mechanics of this elastic scattering interaction allows no deuteron to be scattered at a laboratory angle greater than 30° so that at all angles between 30° and 90° only a group of recoil protons are involved. At angles less than 30° the scattered deuteron energies are double valued. Measurements were made at only one angle less than 30°—namely, 26.8°, and at this angle sufficient absorbing material was inserted in the counter window to stop the slow group of deuterons, leaving the group of fast deuterons and recoil protons to be resolved. A typical pulse distribution for recoil protons is shown in Fig. 2. The normalized yield was determined by extrapolating the steep edges of the pulse distribution to zero and integrating. This was then corrected for the contribution of a "tail" of large pulses which extended into the main peak. The details of determining the magnitude of this correction are given in a later paragraph.

The number of effective scattering centers was determined from the geometry factors of the counter slit system and the slit system which defined the incident beam. Together these gave an effective scattering volume containing a number of atoms that depended on the measured pressure and temperature of the gas, according to the ideal-gas law.

The pressure was measured with a Wallace and Tiernan differential manometer which was periodically calibrated with a manometer containing Apiezon oil *B* having a measured density of 0.862±0.001 g cm^3 at 20°C and a volume coefficient of expansion of 83×10^{-5} per decree centigrade. The working range of pressure was from 2.0 to 4.0 cm of Hg.

The temperature of the scattering gas was measured with a thermometer in contact with the scattering chamber.

The entire system was checked before and during the experiment by switching to an incident proton beam and scattering protons from protons, protons from helium, and scattering protons from a mixture of hydrogen and helium, at various angles and energies. Further checks were made by scattering deuterons from protons with 3.02-Mev incident deuterons and scattering protons from deuterons with 1.51-Mev incident protons. In all cases we found that at angles of 45° or less, corrections had to be applied similar to those in reference 12. Even though the volume of the scattering

TABLE I. Cross sections of protons scattered by deuterons.

Lab angle α		26.8	31.6	34.55	40	44.39[a]	45	49.8	56.3
C.m. angle θ		126.4	116.8	110.9	100	91.22	90	80.4	67.4
E_D 0.96 Mev	$\sigma(\theta)$ barn	0.276	0.260	0.251	0.250	0.260	0.255		
	$k^2\sigma(\theta)$	0.285	0.268	0.259	0.258	0.268	0.264		
E_D 1.20 Mev	$\sigma(\theta)$	0.291	0.252	0.238	0.234	0.226	0.225		
	$k^2\sigma(\theta)$	0.376	0.325	0.307	0.302	0.292	0.290		
E_D 1.46 Mev	$\sigma(\theta)$	0.272	0.230	0.216	0.206	0.218	0.208	0.212	0.240
	$k^2\sigma(\theta)$	0.427	0.361	0.339	0.324	0.342	0.326	0.333	0.377
E_D 1.97 Mev	$\sigma(\theta)$	0.256		0.208	0.188	0.184	0.180	0.182	0.190
	$k^2\sigma(\theta)$	0.543		0.441	0.398	0.390	0.382	0.386	0.403
E_D 2.21 Mev	$\sigma(\theta)$	0.257		0.201	0.184	0.176	0.178	0.174	0.187
	$k^2\sigma(\theta)$	0.610		0.478	0.437	0.418	0.423	0.413	0.445
E_D 2.46 Mev	$\sigma(\theta)$	0.244		0.191	0.173	0.162	0.164	0.160	0.178
	$k^2\sigma(\theta)$	0.645		0.505	0.457	0.428	0.433	0.422	0.470
E_D 2.71 Mev	$\sigma(\theta)$	0.232		0.182	0.164	0.156	0.153	0.155	
	$k^2\sigma(\theta)$	0.676		0.530	0.478	0.455	0.445	0.452	
E_D 2.99 Mev	$\sigma(\theta)$	0.226		0.175	0.160	0.147	0.150	0.152	0.165
	$k^2\sigma(\theta)$	0.725		0.562	0.515	0.472	0.482	0.489	0.530
E_D 3.22 Mev	$\sigma(\theta)$			0.168	0.151	0.147	0.148	0.148	0.161
	$k^2\sigma(\theta)$			0.581	0.523	0.509	0.512	0.512	0.557

[a] Data at 44.39 were obtained by counting deuterons scattered by protons at 26.8 in the laboratory. Data at all other angles were obtained by counting recoil protons.

chamber had been enlarged, there was evidence of some gas-to-chamber wall-to-counter scattering of the incident particles, which caused the pulse distributions to have a slightly skewed shape arising from counted particles with energies lower than the main group. There were no pulses when the beam passed through an empty chamber. The gas-to-wall-to-counter scattering effect disappeared for deuterons scattered from protons, where the mechanics of the scattering restricts all scattered deuterons to remain within a cone of 30° half-angle and consequently cannot strike the chamber wall area seen by the counter geometry. The corrections applied to the data were −4.5 percent at 26.8°, −4

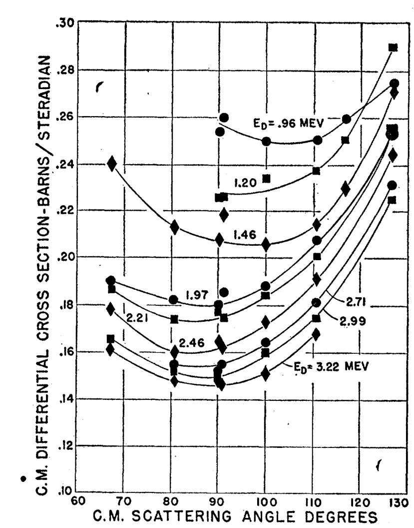

FIG. 3. Center-of-mass cross section in barns/steradian plotted as a function of c.m. scattering angle with incident laboratory deuteron energy as a parameter. The equivalent incident laboratory proton energy would be half of the given deuteron energy. (Note that origin of ordinate is not zero.)

[14] W. C. Elmore and M. Sands, *Electronics* (McGraw-Hill Book Company, Inc., New York, 1949), p. 166.

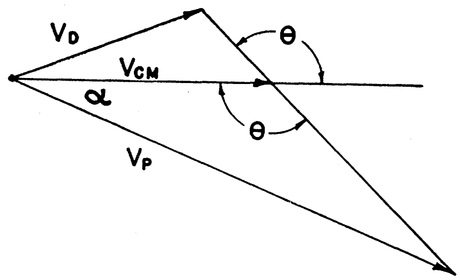

FIG. 4. Vector diagram of laboratory velocities showing angles used in tabulating data. V_P=laboratory velocity of recoil proton at laboratory angle α. θ=center-of-mass angle for a proton scattered from a deuteron at a laboratory angle equal to one-half the given incident deuteron laboratory energy.

percent at 31.6°, −3 percent at 34.5°, −2 percent at 40°, and −1 percent at 45°.

The presence of any contaminant in the scattering gas or the presence of molecular hydrogen in the incident beam could easily be detected by looking for additional small peaks in our pulse distribution curves at angles greater than 30°. Pulse sizes from recoil protons would shift rapidly with changing angle, and deuterons could not be scattered more than 30°, so any scattering from atoms heavier than hydrogen could quickly be detected. The possibility of scattering from large hydrocarbon molecules was ruled out by passing the beam through an empty chamber. No measurable contamination effects were observed.

PROCEDURE

When not in use, the chamber was maintained at approximately 3×10^{-6} mm of Hg with an oil diffusion pump. After the angles and energies were set, the chamber was filled with hydrogen to a pressure of from 2 cm to 4 cm of Hg. The yield was obtained from the integrated pulse distribution curve which required five independent runs to give a smooth curve with well-defined peaks. Data which did not fit onto a smooth pulse distribution curve were rejected. The pressure gauge and galvanometer were read at the end of each of these five runs. This procedure was repeated at an equal angle on the opposite side of the incident beam.

Except for second-order effects, the differential cross section was obtained from the formula

$$\sigma=(Y\sin\alpha)/NnG,$$

where Y is the normalized, integrated, and corrected yield of particles from the pulse distribution curves obtained at the angle α, and N is the number of deuterons incident on the n scattering centers of hydrogen in a volume defined by G. The determination of the yield, Y, as described above involved at least 8000 counts at each angle and energy.

The hydrogen gas was changed before each new angle and energy setting.

RESULTS

The corrected measurements of the differential cross section for protons scattered by deuterons, transformed to the center-of-mass coordinate system, are tabulated in Table I and shown graphically in Fig. 3. The notation for the angles used can be understood best by observing the velocity vector diagram in Fig. 4.

CORRECTIONS

These data have been corrected for the gas-to-wall-to-counter scattering described above. The error in charge measurement was less than ±1 percent. The pressure and geometry measurements were good to $\pm\frac{1}{2}$ percent. We feel that the over-all probable error in the tabulated results is ±2.5 percent for incident deuteron energies greater than 1.20 Mev and ±3.0 percent for incident deuteron energies of 0.96 Mev and 1.20 Mev except at the laboratory angle of 26.8°, where the probable errors are ±4 percent and ±5 percent respectively for these energy ranges. Second-order geometry corrections were found to be negligible.

Incident energies were corrected for loss in the entrance window and loss in the gas target. The quoted values of energy are reliable to ±1 percent.

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