Scattering of 119-Mev Pions by Deuterium*

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The angular distributions for the scattering of negative pions by liquid deuterium were measured, using the 119-Mev pion beam of the Chicago cyclotron and scintillation counters. The values of the nonexchange scattering differential cross section in the laboratory system for angles of 45°, 90°, and 135° are 8.50 ± 0.31, 5.31 ± 0.20, and 8.36 ± 0.29 in units 10^{-27} cm² steradian^{-1}. The differential cross sections for the production of photons at the same angles and in the same units are 2.20 ± 0.27, 2.41 ± 0.28, and 3.40 ± 0.38. The total cross section from transmission measurements is $(132\pm7)\times10^{-27}$ cm². These values are somewhat less than the sum of the previously measured cross sections for positive and for negative pions on hydrogen.

INTRODUCTION

THE following reactions are expected between a fast negative pion and a deuteron:

$$\pi^-+d\rightarrow\pi^-+d \text{ (elastic scattering)}, \quad (1a)$$

$$\pi^-+d\rightarrow\pi^-+n+p \text{ (inelastic scattering)}, \quad (1b)$$

$$\pi^-+d\rightarrow\pi^0+n+n \text{ (charge exchange scattering)}, \quad (2)$$

$$\pi^-+d\rightarrow n+n \text{ (absorption)}, \quad (3)$$

$$\pi^-+d\rightarrow n+n+\gamma \text{ (radiative absorption)}. \quad (4)$$

Five similar reactions may be written by exchanging π^+ for π^- wherever it appears, and exchanging neutrons and protons. The principle of charge symmetry for meson-nucleon interactions implies that each of the above reactions would occur with the same probability as its charge image reaction, except for Coulomb effects.

In the limiting case where the deuteron is regarded as unbound, charge symmetry being assumed, the deuterium cross section is expected to be the sum of the cross sections for positive pions and for negative pions scattered by hydrogen. In fact, the recent transmission experiments indicate that this is approximately true[1,2] but that the deuterium total cross section is less than the sum of the hydrogen cross sections.[3] It is of considerable interest to extend the measurements to the differential cross sections.

Measurements of the differential cross sections for the scattering by hydrogen of 120-Mev pions have been reported.[3] The following describes measurements of the differential cross sections for the scattering of 119-Mev negative pions by deuterium, that is, reactions (1a), (1b), and (2) above. Scintillation counters and a liquid deuterium target were used, in a geometrical arrangement similar to that used for hydrogen.[3] A measurement of the distribution in range of the scattered pions was included, and a measurement of the total cross section.

* Research supported by a joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] Anderson, Fermi, Martin, Nagle, and Yodh, Phys. Rev. **86**, 413 (1952).

[2] Isaacs, Sachs, and Steinberger, Phys. Rev. **85**, 803 (1952).

[3] Anderson, Fermi, Martin, and Nagle, Phys. Rev. **91**, 155 (1953).

I. EXPERIMENTAL ARRANGEMENT

The pion beam was produced by 450-Mev protons in the Chicago synchrocyclotron striking a beryllium target at 76-inch radius. Negative pions emitted in the forward direction were bent outward by the fringing magnetic field of the cyclotron, and emerged through a thin aluminum window in the vacuum chamber of the machine. The pions passed through a channel cut through the 12-foot shield surrounding the cyclotron, and on the experimental side of the shield were further deflected by an analyzing magnet. The pions passed through two counters, called the doubles counters, which were 2-inch diameter scintillation counters (No. 1 and No. 2 in Table I) and then entered the deuterium container. A scintillation counter telescope could be placed to detect the scattered particles at any chosen angle. The number of coincidences recorded with the doubles counters measured the number of pions falling on the scatterer. The coincidences of the scattered particle counters with the doubles counters measured the number of particles scattered within the solid angle of the detector telescope. The ratio of these numbers was essentially the fraction of the incident beam which scattered into that solid angle.

II. SCINTILLATION COUNTING EQUIPMENT

The scintillation counters used are listed in Table I. The scintillating liquid was phenylcyclohexane with 3 g per liter of terphenyl and 10 mg per liter of diphenylhexatriene dissolved in it.[4]

The pulses from the photomultiplier anodes were fed through a preamplifier and pulse shaping circuit attached to the counter case. The output pulses were roughly square and about 2.5×10^{-8} sec long. After amplification in two distributed amplifiers they went into coincidence circuits. For the measurement of the scattering of pions (see Fig. 4) pulses from counters No. 1 and No. 2 were brought into a circuit "B," one output of which led to a Hewlett Packard Model 520A tenth microsecond scale of one hundred and another output to a triple coincidence circuit. Pulses from counters No. 5 and No. 4 were brought into coincidence

[4] H. Kallmann and M. Furst, Phys. Rev. **81**, 853 (1951).

in a second circuit "D," and the output into the triples circuit. The output pulses of "B," "C," and "D" were each 5×10^{-8} sec long. The triples circuit in turn drove another Hewlett Packard tenth microsecond scaler. The Hewlett-Packard scalers drove Atomic Instrument scalers. The overall resolving time of the system was about 2.5×10^{-8} sec and the dead time, principally due to the scalers, was 0.1 microsecond. The doubles counting rate was kept nearly constant throughout these experiments at 250 000/min. Because of the duty factor of the cyclotron (about 60), this amounted to a loss in doubles counts in the scaler of about 2.5 percent. The equipment was designed by Anderson, Glicksman, and Martin, and has been described in detail by them.[5]

III. DEUTERIUM CONTAINER

The deuterium was condensed from the gas using liquid hydrogen as the refrigerant. A cross-sectional view of the apparatus is shown in Fig. 1; it is essentially a continuously pumped metal dewar, holding about six liters of liquid hydrogen. Evaporating hydrogen gas cools one set of coils of a heat exchanger; a second set of coils in contact with the first cools the incoming deuterium gas. Finally a third coil wound around the hydrogen reservoir condenses the deuterium. The liquid collects in the deuterium reservoir and in the scattering chamber. The scattering chamber is a brass cylindrical container 4.250 inches inner diameter and 5 inches high at room temperature. The piping is arranged so that by closing the valve separating the heat exchanger from the deuterium reservoir, the liquid deuterium will stay in either the reservoir or the scattering chamber, whichever is colder; since either can be heated electrically, the liquid can be switched from one to the other chamber. In this way observations can be made of the fraction of pions scattered with and without liquid in the scattering chamber. Capacitance type level indicators are used to display the level of the liquid deuterium. The mean length in the deuterium is 4.10 inches, including a profile factor (Sec. IV).

TABLE I. Characteristics of the scintillating counters.

Counter No.	Scintillator Dimensions	Material	Photomultiplier type
1	2 inches diam $\times \frac{1}{8}$ inch	plastic	RCA 5819
2	2 inches diam $\times \frac{3}{16}$ inch	liquid	RCA 5819
3	4 inches $\times$ 6 inches $\times \frac{1}{2}$ inch	liquid	RCA C7157
4	4 inches $\times$ 6 inches $\times \frac{1}{2}$ inch	liquid	RCA C7157
5	4 inches $\times$ 6 inches $\times \frac{1}{2}$ inch	liquid	RCA C7157
6 and 7	8 inches diam $\times \frac{3}{4}$ inch	liquid	RCA C7157

[5] Anderson, Martin, and Glicksman, Proc. Natl. Electronics Conf. 9, 483 (1953).

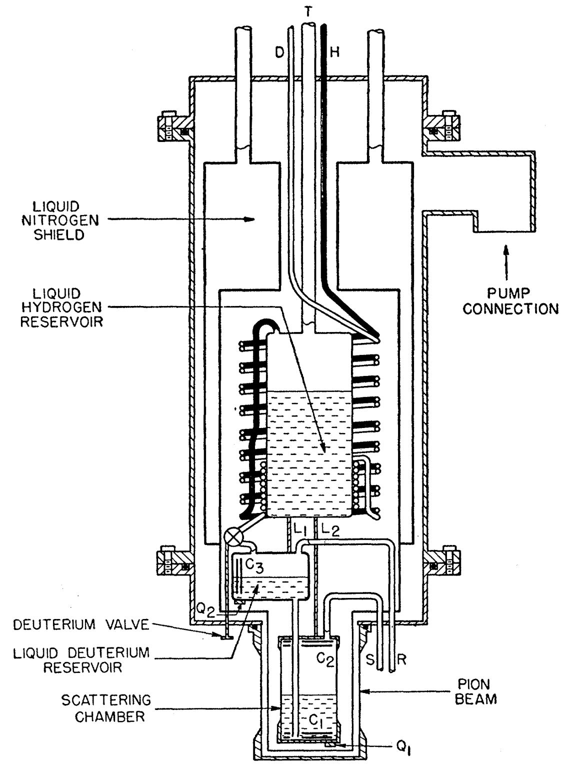

FIG. 1. Liquid deuterium container—section through a vertical axis.

The temperature of the liquid deuterium, estimated from the vapor pressure, is 24°K. If one uses the data of Woolley *et al.*,[6] the net number of atoms/cm² (liquid less gas) is 4.813×10^{23}/cm² (1 ± 0.018). Of these 98.9 percent are deuterium and 1.1 percent are hydrogen atoms, so that the number of d atoms/cm² is 4.76×10^{23}.[7]

The pion beam on entering or leaving the target must pass through metal walls of thickness 0.22 g/cm² of Al and 0.12 g/cm² of brass.

IV. ENERGY, COMPOSITION, AND PROFILE OF THE PRIMARY BEAM

The energy of the beam has been studied at various times by measurements of the magnetic rigidity, of the Panofsky effect, and of the range curve.[5] The results agree well; only the range curve is here presented.

For this purpose, the deuterium target was removed from the beam and the counters placed in line as shown in Fig. 2. The double coincidence of counters No. 1 and No. 2, and the quintuple coincidences were recorded. Figure 3 is a plot of the first difference of Q/D against thickness of copper absorber. The curve is a smooth

[6] Woolley, Scott, and Brickwedde, J. Research Natl. Bur. Standards 41, 379 (1948).

[7] Professor M. G. Inghram very kindly made this measurement for us.

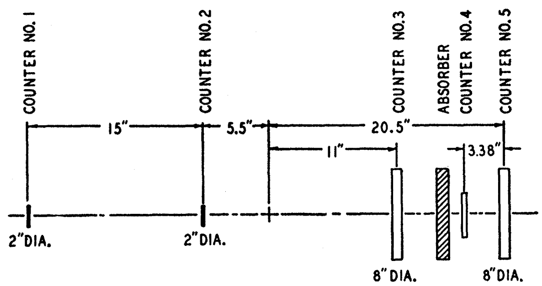

FIG. 2. Plan view of the geometry of the counters for taking range curves.

one drawn through the points; it shows a large peak due to pions and a smaller one due to muons. The uncorrected range of the pions is 47.2 g of copper; to which is added the copper equivalent of counters No. 3 and No. 4, plus a wall of No. 5, namely 5.1 g. To get the range from the center of the deuterium, there must be subtracted the copper equivalent of the walls and half the deuterium, namely 1.6 g. The net range, 50.7 g, corresponds to a kinetic energy of 119 Mev if one uses the tables of Aron[8] of ranges for protons and adopts the ratio 6.72 of proton mass to pion mass. The fraction of pions in the beam is estimated from the curve as 0.93. To measure the profile of the beam, a piece of plastic scintillator of cross section $\frac{3}{16}$ inch by $\frac{5}{16}$ inch was mounted on a Lucite light pipe leading to

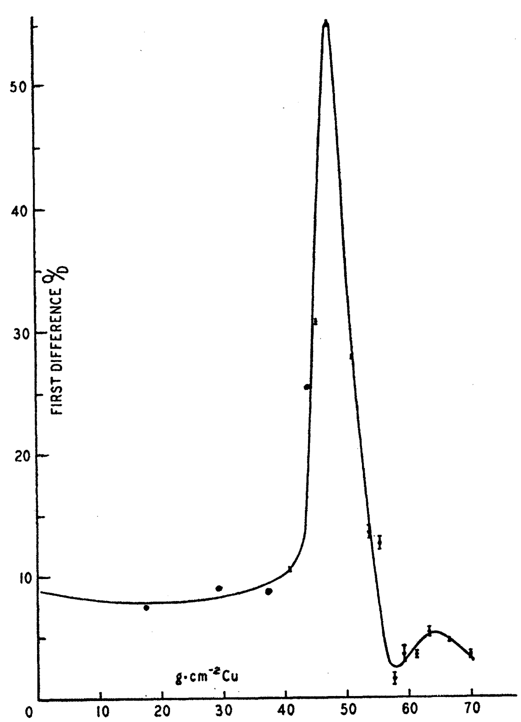

FIG. 3. Differential range curve in copper of the 120-Mev π^- beam.

[8] W. A. Aron, University of California Radiation Laboratory Report UCRL-1325, 1951 (unpublished).

a 5819 photomultiplier. The coincidence of this counter with the doubles of the counters No. 1 and No. 2 described above were recorded, and the ratio of triple coincidences to doubles of one and two plotted as a function of position of the third. This measurement was made at the beginning of each cyclotron run. It showed a beam whose intensity for a traverse across the horizontal plane showed a plateau shaped curve which dipped sharply at about $\frac{3}{4}$-inch radius from the target location. Because of this extent of the beam the number of atoms of deuterium per cm^2 quoted in Sec. III includes a factor of 0.97, the so-called profile factor.

V. MEASUREMENT OF THE CROSS SECTION FOR PRODUCTION OF PHOTONS

The charge-exchange scattering leads to production of photons from the decay of the neutral meson. There are in addition a much smaller number of photons from the radiative absorption. Figure 4 shows a plan view of the arrangement used to count photons. An

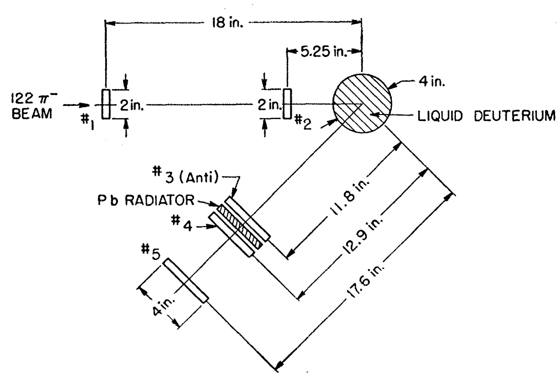

FIG. 4. Geometry of the counters for measurements of scattering.

event typical of those recorded was that a pion in the beam passed through counters No. 1 and No. 2, scattered with charge exchange in the deuterium, producing a neutral meson which decayed to produce a photon traveling in the line of counters Nos. 3, 4, and 5. Such a photon, if it materialized in the lead radiator (7.33 g cm^{-2}), produced an electron or pair which gave a coincidence pulse between 4, 5, 1, and 2, but no pulse in No. 3, which was connected in anticoincidence. The ratio Q/D of quadruple coincidences to doubles of No. 1 and No. 2 is a measure of the number of photons produced within the solid angle of the detector telescope. Table II lists the observed values of Q/D for three angular positions of the photon counter. The data were taken on two occasions, labelled Run A and Run B in the table. In Run B additional lead shielding was placed near the steering magnet, which helped to reduce the background. The errors listed are statistical only. The difference of the Q/D values with and without liquid deuterium, the net value, is listed in the last column. The net values for both runs are combined according to their statistical weights, and listed at the bottom of the table.

The sensitivity of the detecting counters is calculated in a manner similar to that used in previous experiments on hydrogen.[3] The introduction of the anticoincidence technique in the present experiment, and slight differences in the geometry necessitate changes in the details of the computation. However, the resulting cross sections for photon production may be compared with the hydrogen cross sections without much disturbance from any inadequacy in the calculation.

Some of the photons materialize before reaching the anticoincidence counter and consequently are not counted. This materialization (cross section for pair production × atoms/cm²) is the sum of contributions from the liquid deuterium, dewar walls, the anticoincidence counter, and the internal conversion of the photon, giving a net value 0.031 for 90-Mev photons, or 0.032 for 135-Mev photons. The materialization after

TABLE II. Observed values of $10^6 G/D$ for the photon counter.

Angle	With deuterium	Without deuterium	Net
		Run A	
45°	94.1±4.0	52.7±5.0	41.4±6.4
90°	150.7±4.3	103.1±3.8	47.6±5.7
135°	128.1±4.6	67.3±3.7	60.8±5.9
		Run B	
45°	68.3±2.9	26.8±1.4	41.5±3.2
90°	61.9±2.7	20.0±1.3	41.9±3.0
135°	92.2±3.0	31.5±2.0	60.7±3.6
		Runs A and B combined	
45°			41.5±2.9
90°			43.1±2.7
135°			60.7±3.1

the anticoincidence counter is due to the 7.3 g of lead plus a small contribution from counter No. 4. It has the value 0.677 for 90-Mev photons and 0.731 for 135-Mev photons.

The efficiency ϵ_γ of the counter for detecting a photon is computed, taking into account: (a) materialization before and after anticoincidence counter, (b) absorption of the electrons in the lead, and (c) the geometrical effect due to multiple scattering of the electrons in the lead. This gives a very slightly different effect at 90° than at 45° or 135°, because of the difference in the effective lengths of the source of photons. The results are listed in Table III. The efficiencies are lower than in the previous arrangement[3] because (a) the prematerialization now lowers instead of raising the efficiency, and (b) the geometrical effects of multiple scattering are smaller. The anticoincidence arrangement has the advantage of a rather low background. The net Q/D for photons is related to the cross section

TABLE III. Efficiency for photons.

Angle of scattering	90 Mev	135 Mev
45° or 135°	0.470	0.556
90°	0.466	0.556

for photon production by the equation:

$$\left(\frac{Q}{D}\right)_\gamma = \frac{d\sigma_D}{d\omega}\left[1+0.011\frac{d\sigma_H}{d\omega}\Big/\frac{d\sigma_D}{d\omega}\right]C\epsilon_\gamma.$$

The second factor on the right is the correction due to hydrogen atoms and has the value 1.012. C contains the following factors: the solid angle, the number of D atoms/cm², the fraction of pions in the beam, the mean transmission excluding scattering to the center of the deuterium, and mean number of double coincidences per doubles scaler count. In that order the factors are $C=0.0772\times4.76\times10^{22}/\text{cm}^2\times0.93\times0.992\times1.025$. The values of $(d\sigma_D/d\omega)_\gamma$ and the previous values[3] of $(d\sigma_H/d\omega)_\gamma$ are listed in Table IV. The errors in $(d\sigma_D/d\omega)_\gamma$ are compounded of the statistical error plus 10 percent of the cross section, which is an estimate of the uncertainties arising from the efficiency calculation, pion fraction, doubles loss, and number of D atoms/cm².

VI. SCATTERING WITHOUT EXCHANGE OF CHARGE

The cross sections for scattering without charge exchange were also measured with the arrangement of Fig. 4, except that counter No. 3 was disconnected from the circuits. The observed ratios of quadruples to doubles at angles of 45, 90, and 135 degrees appears in Table V. Here three runs are combined.

The Q/D values are related to the cross sections by the equation

$$\frac{Q}{D}=\frac{d\sigma_D}{d\omega}\left[1+\frac{n_H\sigma_H}{n_D\sigma_D}\right]C\epsilon_\pi+\Gamma.$$

The second factor is here 1.001. C has the value given in Sec. V. The efficiency for counting pions, ϵ_π, differs from unity because of roughly equal losses from multiple scattering and nuclear absorption. The values of ϵ_π are 0.922, 0.919, and 0.915 at 45°, 90°, and 135° respectively. Γ is a small contribution to Q/D from photons converted in counters Nos. 3 and 4, which is 0.031 times the photon flux δ (Sec. V). The computed values of $d\sigma_D/d\omega$ are listed in Table VI, and, for com-

TABLE IV. Differential cross sections for the production of photons (laboratory system). Units are 10^{-27} cm²/sterad.

Angle	$(d\sigma_D/d\omega)_\gamma$	$(d\sigma_H/d\omega)_\gamma$
45°	2.20±0.27	2.64±0.36
90°	2.41±0.28	3.08±0.37
135°	3.40±0.38	4.53±0.51

TABLE V. Observed values of $10^6 Q/D$ for scattering of negative pions without charge exchange.

Angle	With deuterium	Without deuterium	Net (Without Pb)
		Run A	
45°	553.3±10.0	249.0±8.4	304.3±13.0
90°	307.8± 6.0	119.7±3.8	188.1± 7.1
135°	424.6± 8.8	149.1±5.6	275.5±10.4
		Run B	
45°	438.3± 7.4	165.4±5.3	272.9± 9.1
90°	218.3± 5.2	56.1±3.1	162.2± 6.1
135°	360.9± 6.6	91.8±3.9	269.1± 7.7
		Run C	
45°	476.6± 4.9	195.8±4.9	280.8± 6.8
90°	238.6± 6.5	60.6±3.2	178.0± 7.2
135°	378.8± 6.1	97.6±4.4	281.2± 7.5
		Runs A, B, and C combined	
45°			282 ± 5.0
90°			175 ± 3.9
135°			275 ± 4.8

parison, the sum of the hydrogen ordinary scattering cross sections for positive and for negative pions. The errors are the statistical one compounded with 3 percent, which is our estimate of the errors in C and ϵ_π.

VII. ENERGIES OF THE SCATTERED PIONS

An attempt was made to find the energy distributions of the scattered pions by taking range curves. Figure 5 shows the experimental arrangement. Double coincidences of counters No. 1 and No. 2, quintuple coincidences were recorded. Counter No. 3 serves to reduce the background due to neutrons or photons, and counter No. 4 defines the solid angle of the counter telescope. Counter No. 5 is chosen to have a large solid angle in order to effectively eliminate the loss of coincidences due to multiple scattering in the absorbers.

The observed values of Q/D are presented in Table VII in various absorber thicknesses at the three laboratory angles of 45°, 90°, and 135°. The values given are net (deuterium in minus deuterium out) and include a small correction made for the nuclear absorption in copper.[9,10] In Fig. 6 is plotted the first difference of Q/D divided by the difference in absorber thickness, *vs* the mean absorber thickness. The smooth curves of Fig. 6 have been computed as follows: from the 0° range curve, Fig. 3, the mean energy of pions at the center of the deuterium was estimated as 119 Mev. The pion peak at 0° is approximately gaussian in shape with a root mean square width about 2.5 g of copper. The energy of elastically scattered pions can be calculated at each scattering angle from simple kinematics, as can the energy of a pion scattered from a free proton. An approximate fit is obtained by assuming the points are represented by the sum of two Gaussians centered about the elastic energy and the free proton energy. The width of the elastic Gaussian is taken as 2.5 g in the 0° case, since the effects of straggling, the deuterium, and the walls do not appreciably broaden the peak. The width of the free-proton Gaussian and the amplitudes of the Gaussians are treated as parameters in a least-squares analysis. The results are the smooth curves plotted. The widths of the free-proton Gaussian are 4 g, 4 g, and 5 g at the three angles. The percent elastic scattering at the angles of 45°, 90°, and 135° are 30 percent, 18 percent, and 21 percent by this method, giving 2.6 mb/steradian, 0.95 mb/steradian, and 1.8 mb/steradian for the differential cross sections for elastic scattering at the corresponding three angles. The barycentric cross sections and angles are 2.2, 0.95, and 2.2 mb/steradian at 50.3, 97.3, and 140.0° respectively.

The method is very rough, especially at forward angles since the elastic and the "free-proton" peaks become too close to allow resolving the peaks. The

TABLE VI. Differential cross sections in the laboratory system for the scattering of negative pions without charge exchange. Units are 10^{-27} cm²/sterad.

Laboratory angle	$d\sigma_D/d\omega$	$d\sigma_{H^+}/d\omega + d\sigma_{H^-}/d\omega$
45°	8.50±0.31	7.22±1.58
90°	5.31±0.20	5.94±1.11
135°	8.36±0.29	11.57±1.24

TABLE VII. Observed values of Q/D for the scattered pions.

Angle	Absorber thickness grams of copper	$10^6 Q/D$ (net)
45°	0	249.1±11.0
	11.5	219.7± 8.8
	20	167.8±11.0
	24.1	169.7±10.8
	28.3	144.9± 8.1
	32.5	119.5± 8.7
	36.7	82.3± 8.4
	41.0	27.6± 6.6
	45.2	5.7± 4.7
90°	0	169.4± 9.4
	8.47	137.6± 7.8
	15.8	104.5±11.7
	20.0	76.5± 5.5
	24.2	54.9± 4.6
	28.4	22.9± 4.6
	32.6	11.2± 2.9
	36.8	3.8± 2.6
	41.0	3.8± 1.8
135°	0	272 ±13
	4.2	250.4±13.5
	8.5	187.0±11.0
	11.5	134.0± 8.5
	15.8	77.0± 6.5
	20.0	52.4± 5.1
	24.2	19.2± 4.0
	28.4	6.8± 3.4
	32.6	5.5± 2.5

[9] Chedester, Isaacs, Sachs, and Steinberger, Phys. Rev. **82**, 958 (1951).

[10] Martin, Anderson, and Yodh, Phys. Rev. **85**, 486 (1952).

points of Fig. 6 indicate that the elastic scattering cross section is small at 90° and 135° and suggest that it is somewhat larger at 45°. There appears to be a considerable number (about 25 percent of the total) of pions at all angles with energies lower than the free nucleon energy.

VIII. TOTAL CROSS SECTIONS

The total cross section has been obtained by transmission measurements. The old value from heavy water-light water difference was 128 ± 11 mb for 120 Mev negative pions.[1] The value from transmission in liquid deuterium gave 132 ± 7 mb. These have been corrected for reaction products recorded by the final counters.

Integration of the differential cross sections gives for the cross section for scattering without exchange of charge 96 ± 5 mb and for charge exchange 14 ± 2 mb. The radiative absorption may be estimated as 1 mb. The absorption process $(\pi^+ + d \rightarrow p + p)$ has been studied by Stadler[11] in this laboratory. He finds the total cross section to be 7.4 ± 1.2 mb for 91-Mev pions and 9.7 ± 1.2 mb for 114-Mev pions. Invoking charge symmetry and extrapolating his values to 119 Mev we adopt 11 ± 2 mb for the absorption cross section. The radiative absorption cross section may be estimated as 1 mb. The sum of cross section for the four processes gives 122 ± 6 mb, in good agreement with the transmission values. For comparison, the sum of the total cross sections in hydrogen for positive and negative pions gives 130 ± 11 mb from the integration of the angular distributions and 147 ± 14 mb from the transmission experiments.[1] The integrated values are believed more reliable.

IX. DISCUSSION

The experimental results of Tables IV and VI indicate that simple additivity of the cross sections for free nucleons is a fair approximation to the deuteron cross section at this energy. The deuteron cross sections however are less than the sum of the hydrogen values, the deviations ranging from ten to thirty percent. (One exception is the 45° ordinary scattering.)

Several theoretical discussions have been given of the relationship of the pion-deuteron and the pion-hydrogen scattering processes,[12,13] making use of the impulse approximation.[14] Fernbach *et al.*[12] have made extensive use of the closure approximation. In this approximation particularly simple expressions are obtained, which can be evaluated using the pion-hydrogen phase shifts. The cross section for charge-exchange scattering in this approximation is the hydrogen charge-exchange cross section multiplied by a factor depending on the phase shifts and the scattering angle. The angular distributions for photons calculated from this expression agree, within the experimental error, with the observed cross sections.

However the ordinary-scattering cross sections in the closure approximation at this energy should be greater than the sum for hydrogen, contrary to observation.

Brueckner[13] has shown that, in the case of elastic scattering, a calculation based on a model, which takes into account multiple scattering of the pion from the

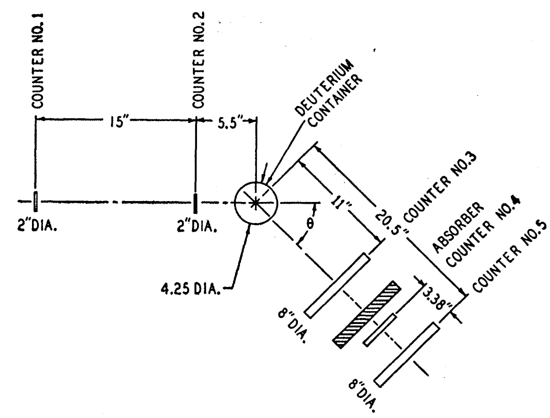

FIG. 5. Experimental arrangement for taking ranges of the scattered pions.

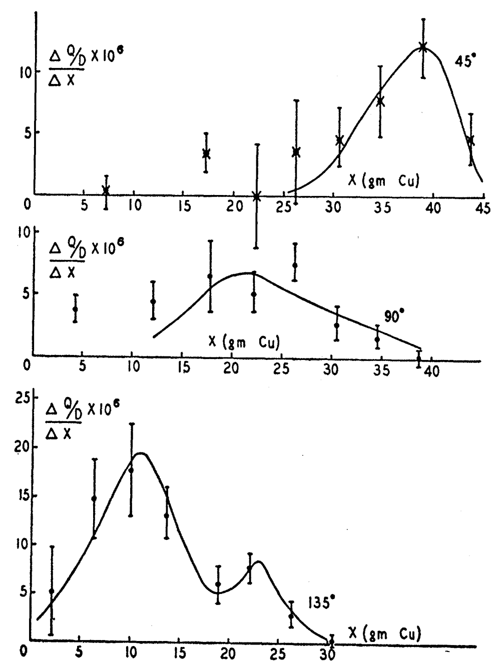

FIG. 6. Differential range curves for the scattered pions. The effective ranges corresponding to elastic scattering at 45°, 90°, and 135° are 40, 32, and 23 g/cm², respectively. For free-nucleon scattering the corresponding effective ranges are 36, 21, and 11 g/cm².

[11] H. Stadler, Ph.D. Thesis, University of Chicago, 1954 [Phys. Rev. **96**, 496 (1954)].

[12] Fernbach, Green, and Watson, Phys. Rev. **84**, 1084 (1951); Fernbach, Green, and Watson, Phys. Rev. **89**, 834 (1953); Thomas A. Green, Phys. Rev. **90**, 161 (1953).

[13] K. A. Brueckner, Phys. Rev. **90**, 715 (1953); K. A. Brueckner, Phys. Rev. **89**, 834 (1953).

[14] G. F. Chew, Phys. Rev. **80**, 196 (1950); G. F. Chew and M. L. Goldberger, Phys. Rev. **87**, 778 (1952).

two nucleons, can lead to a cross section smaller than given by the previous calculations based on the impulse approximation, especially where the phase shift α_{33} is large, as is here the case. The experiments suggest that such effects may be important.[15]

[15] Noteworthy in this connection are the experiments of Arase, Goldhaber, and Goldhaber, Phys. Rev. **90**, 160 (1953). Their cross sections for elastic scattering are much smaller than the earlier calculation (see reference 12) would predict.

X. ACKNOWLEDGMENTS

I wish to thank Professors Earl A. Long and Lothar Meyer for much helpful advice and assistance in the construction of the deuterium target, Professor Herbert L. Anderson for the use of his counting equipment, and Charles Cohn, Henry Stadler, and Willard Skolnik for help in taking data. I wish also to acknowledge the help of a grant from the Guggenheim Foundation.

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Landau Distribution and Density Effect at High Gas Pressures*

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Studies of the ionization energy losses of fast μ mesons have been carried out in a specially constructed proportional counter with argon gas at pressures up to 40 atmospheres. With increasing pressure, a strong reduction in the relativistic rise was observed; the extent of the reduction being at least as great as that expected from Sternheimer's calculation of the density effect. Furthermore, the distribution in energy losses, which at low pressures is much wider than expected from theoretical considerations, was observed to become narrower with increasing pressure. At our highest pressure, however, the energy loss distribution was still considerably wider than predicted by the Landau theory.

I. INTRODUCTION

PUBLISHED studies of the ionization energy losses of fast μ mesons confirm the existence of the relativistic rise in dispersed media[1–4] as well as the modifications of this rise (the density effect) caused by the dielectric polarization, when the medium is condensed.[5–10] Some observations also indicate the onset of the density effect, even at low pressures in gases, provided the meson energy is sufficiently high.[2,4,11]

The general features of the distribution in energy loss, as developed by Landau[12] have also been confirmed, for both dispersed and condensed media. In general, however, with small thicknesses of absorber, the widths of the observed distributions are found to be much greater than those predicted by the theory of Landau or by the modified theory of Blunck and Leisegang.[13] It should be noted, for the case of low-energy electrons traversing thin foils that a similar disagreement was reported although recent work appears to have eliminated the discrepancy.[14,15] The half-maximum widths observed with large thicknesses of absorber are generally in much better agreement with theory.[5,9]

This report deals with a study of μ-meson ionization energy losses, carried out in argon gas at pressures up to 40 atmospheres, in an attempt to observe the onset and the development of the density effect and the behavior of the Landau distribution in the transition region between the dispersed and condensed phases of matter.

II. DESCRIPTION OF APPARATUS

The apparatus used in this work, in particular the electronic and recording portions, was quite similar to that used in our previous studies,[3] in this laboratory. It consisted essentially of four parallel Geiger counter telescopes, with enough lead absorber to insure that four well collimated beams of mesons were obtained; two proportional counters located within the telescopes; lead absorber and range trays; plus the required re-

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