give

$$|d_p| = (+7 \pm 9)\times 10^{-21}e \text{ cm}.$$

This result is more than 5 orders of magnitude lower than the previously available limit[7] of $3\times 10^{-15}e$ cm which was obtained from a precession experiment on free protons. An improved version of this experiment is now being designed, and we expect to be able to increase the sensitivity by a further factor of at least 100. A more detailed description of the molecular-beam and on-line computer techniques used in this experiment will be published elsewhere.

[1]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).

[2]W. B. Dress, J. K. Baird, P. D. Miller, and N. F. Ramsey, Phys. Rev. 170, 1200 (1968), and Bull. Am. Phys. Soc. 13, 1380 (1968); J. K. Baird, P. D. Miller, W. B. Dress, and N. F. Ramsey, Phys. Rev. 179, 1285 (1969). See also V. W. Cohen, R. Nathans, H. B. Silsbee, E. Lipworth, and N. F. Ramsey, Phys. Rev. 177, 1942 (1969).

[3]L. I. Schiff, Phys. Rev. 132, 2194 (1963).

[4]P. G. H. Sandars, Phys. Rev. Letters 19, 1396 (1967).

[5]N. F. Ramsey, Molecular Beams (Clarendon Press, Oxford, England, 1956), Chap. V.

[6]G. K. Woodgate and P. G. H. Sandars, Nature 181, 1395 (1958).

[7]B. Rose, in Proceedings of the Tenth Annual International Conference on High-Energy Physics, Rochester, New York, 1960, edited by E. C. G. Sudarshan, J. H. Tinlot, and A. C. Melissinos (Interscience Publishers, Inc., New York, 1960), p. 787.

ELASTIC SCATTERING OF NEGATIVE PIONS FROM DEUTERONS AT 2.01, 3.77, AND 5.53 GeV/c *

M. Fellinger, E. Gutman, R. C. Lamb, F. C. Peterson, and L. S. Schroeder
Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa 50010

and

R. C. Chase, E. Coleman, and T. G. Rhoades
School of Physics, University of Minnesota, Minneapolis, Minnesota 55455

(Received 24 April 1969)

The differential cross sections for the elastic scattering of negative pions by deuterons have been measured for 2.01-, 3.77-, and 5.53-GeV/c incident pion momenta, over an interval of the squared four-momentum transfer from -0.25 (GeV/c)^2 to ~ -1.0 (GeV/c)^2. The results are consistent with calculations based on a Glauber model of the scattering process.

We have measured the differential cross section for elastic scattering of negative pions from deuterons at 2.01, 3.77, and 5.53 GeV/c. Our preliminary data at 3.77 GeV/c have already been presented.[1] Other differential cross-section measurements of high-energy scattering from deuterium have been made in the past.[2]

Measurements of πd elastic scattering test various multiple-scattering theories such as the Glauber formalism[3] or Regge-pole models.[4] Our measurements were performed in the four-momentum transfer region which, in the context of the Glauber model, is sensitive to both single and double scattering in the deuteron. The data are consistent with calculations based on the Glauber model using a deuteron wave function with a 7% D state and no variation of the phase of the πN scattering amplitude with scattering angle.

The experiment was performed in the 17° beam of the zero-gradient synchrotron of the Argonne National Laboratory. The beam transport system determined the momentum of the pions to ±1% and brought the beam to a final focus on a 2.31-in.-long liquid-deuterium target. The beam intensity varied from $(3\text{ to }7)\times 10^5$ pions/pulse depending on the beam momentum, with a pulse repetition rate of 1000 pulses/h. The beam angular divergence was ±5 mrad horizontally and ±3 mrad vertically.[5] The experimental apparatus used to detect the elastic events is shown in Fig. 1. The pion beam was counted by a series of scintillation counters labeled S_1, S_2, S_3, and S_4. Counters S_1 and S_2 are not shown in the figure and are located near the first focus of the 17° beam. The beam size was defined by S_4, a $\frac{3}{4}$-in.$\times\frac{3}{4}$-in. counter.

Elastic events were detected in a double-arm spectrometer consisting of the two bending magnets $M1$ and $M2$ and scintillation counter arrays A, B, and D. Each of the A and B arrays consisted of 16 elements; the D array consisted of 30 elements. The dimensions for the A, B, and

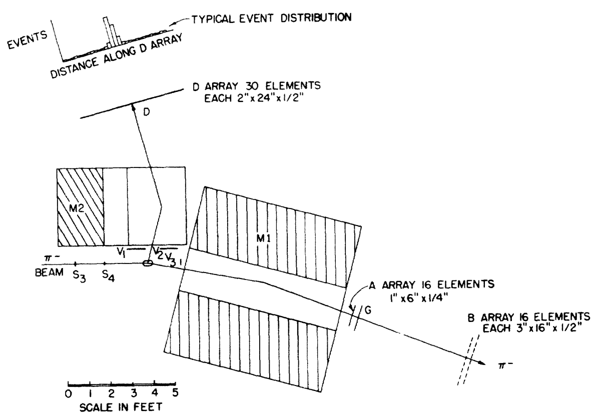

FIG. 1. Plan view of apparatus. A typical event distribution is plotted above the D array.

D elements are shown on Fig. 1. Negative particles traversed $M1$ and were detected by corresponding pairs of the A and B elements. The width of an A array element determined the scattering-angle acceptance for each data point. The presence of 16 elements allowed 16 simultaneous differential cross sections to be measured. A single scintillation counter G behind the A array determined the azimuthal angular acceptance. The recoil deuterons traversed $M2$ and were detected by the D array. The use of magnet $M2$ eliminates any possible contamination from the process $\pi d \to \pi d^*$, where d^* denotes an np system with low relative kinetic energy. The protons associated with d^* production have approximately $\frac{1}{2}$ the momentum of the elastic deuteron and are therefore swept away by the magnet. The $V1$ and $V2$ counters were used to veto particles which did not satisfy the angular restrictions of πd elastic-scattering kinematics. The $V3$ counter was used as an additional anticoincidence counter to veto beam pions that did not interact in the target. Events satisfying the following electronic coincidence requirements were selected and stored in a multichannel analyzer: (a) a count in beam counters $(S_1S_2S_3S_4)$, (b) no count in veto counters $(\bar{V}_1\bar{V}_2\bar{V}_3)$, (c) a count in corresponding A and B counters in coincidence with a count in <u>any</u> of the D counters, and (d) a count in G. These events were sorted into 16 different groups corresponding to the 16 AB pairs. For each pair the distribution of events along the D array was obtained. A typical distribution of events is sketched above the D array in Fig. 1. In each of the 16 separate distributions, the elastic-scattering events appeared as a peak above a background. The elastic peaks appeared in the locations predicted by a Monte Carlo simulation of the experiment.

The background under the elastic peaks in each of the 16 separate distributions was obtained from a combination of the following information: (1) the distribution of events on either side of the elastic peak and (2) the distribution of events obtained from scattering in carbon and in an empty target. The background determined in this way was found to vary from 5 to 20 % of the elastic-event rate depending on angle and was typically 10 %. One of the principal factors for this low background level was the stringent timing requirements placed upon the D counter signals. The recoil deuteron momentum varied from 500 to 1300 MeV/c over the angular range covered so that the elastically scattered deuterons had flight times over the 90-in. flight path at least 4 nsec longer than protons of the same momentum and 6 nsec longer than particles traveling at the speed of light. By variations in the time-of-flight requirements on the deuteron array the background was determined to be almost exclusively protons in coincidence with the beam.

The differential cross section is given by the formula

$$d\sigma/dt = E/N_\pi N_d \Delta t,$$

where E is the number of events, N_π is the number of incident pions, N_d is the number/cm^2 of target deuterons, and Δt is the interval of the squared four-momentum transfer associated with the instrumental solid angle. The number of events was determined from the counts in the elastic peak, with the appropriate background subtraction. The number of beam pions was determined from the number of beam counts, $S_1S_2S_3S_4$. The number of deuterons/cm^2 was determined from a knowledge of the length of the target and the known density of liquid deuterium at a vapor pressure of 1 atm, $\rho_D = 0.1625 \pm 0.002$ gm/cm^3.[6] The solid angle was determined by a Monte Carlo computer program and checked by a hand calculation.

Corrections were applied to the data for muon and electron contamination of the pion beam, for decay of the scattered pion, for electronic dead-time effects due to $V1$, $V2$, and $V3$, and for absorption of particles in scintillators, liquid deuterium, and other material. Typical corrections due to these effects varied from 15 to 30 %, depending on incident momentum and scattering angle.

Table I. πd elastic scattering.

$-t$ $(\mathrm{GeV}/c)^2$	$d\sigma/dt$ $\mu\mathrm{b}/(\mathrm{GeV}/c)^2$	Statistical error $\mu\mathrm{b}/(\mathrm{GeV}/c)^2$	$-t$ $(\mathrm{GeV}/c)^2$	$d\sigma/dt$ $\mu\mathrm{b}/(\mathrm{GeV}/c)^2$	Statistical error $\mu\mathrm{b}/(\mathrm{GeV}/c)^2$	$-t$ $(\mathrm{GeV}/c)^2$	$d\sigma/dt$ $\mu\mathrm{b}/(\mathrm{GeV}/c)^2$	Statistical error $\mu\mathrm{b}/(\mathrm{GeV}/c)^2$
	2.01 GeV/c			3.77 GeV/c			5.53 GeV/c	
0.262	514.9	20.4	0.282	248.7	5.0	0.291	204.8	5.6
0.296	254.5	9.8	0.316	154.5	3.9	0.342	94.0	3.7
0.331	126.3	6.7	0.352	81.5	2.8	0.397	46.6	2.6
0.369	72.9	4.9	0.389	49.5	2.2	0.456	28.8	2.0
0.407	53.2	4.0	0.428	39.2	1.9	0.518	22.2	1.6
0.447	52.4	3.9	0.469	26.3	1.5	0.584	16.9	1.4
0.489	52.0	3.8	0.511	20.5	1.3	0.654	13.8	1.2
0.532	45.5	3.6	0.555	20.1	1.4	0.728	13.6	1.1
0.546	55.8	3.7	0.600	19.7	1.4	0.804	11.30	0.96
0.590	49.7	3.5	0.647	21.6	1.3	0.884	8.31	0.81
0.635	43.4	3.3	0.695	19.1	1.2	0.967	5.57	0.65
0.683	37.9	3.1	0.743	14.65	0.93	1.053	4.10	0.55
0.730	30.9	2.9	0.794	13.57	0.87	1.141	2.51	0.43
0.778	30.2	2.8	0.847	11.35	0.75	1.232	2.76	0.43
0.828	24.0	2.6	0.898	8.78	0.67			
0.878	21.0	2.4						

An overall check of the system was provided by filling the target with liquid hydrogen and measuring the π^-p elastic differential cross section at several momenta. These measurements are in agreement with published π^-p measurements.[7]

The πd differential cross sections for the three momenta are listed in Table I and are plotted in Fig. 2. The errors are statistical errors associated with event counts only. In addition to this point-to-point error, there is an overall uncertainty of ±7% to be associated uniformly with all data points.

The Glauber high-energy approximation[8] gives the amplitudes for the scattering of pions from deuterons as

$$\langle m'|F_d(\vec{q})|m\rangle = [f_n(\vec{q})+f_p(\vec{q})]S_{m',m}(\tfrac{1}{2}\vec{q}) + \frac{i}{2\pi k}\int S_{m',m}f_n(\tfrac{1}{2}\vec{q}+\vec{q}\,')f_p(\tfrac{1}{2}\vec{q}-\vec{q}\,')d^2q'$$

with

$$S_{0,0}(\vec{q}) = S_0(q) + (8\pi/5)^{1/2}S_2(q)Y_{2,0}(\hat{q}),$$
$$S_{1,1}(\vec{q}) = S_0(q) - (2\pi/5)^{1/2}S_2(q)Y_{2,0}(\hat{q}) = S_{-1,-1}(\vec{q}),$$
$$S_{1,0}(\vec{q}) = \tfrac{3}{2}(8\pi/15)^{1/2}S_2(q)Y_{2,1}{}^*(\hat{q}) = -S_{-1,0}(\vec{q}),$$
$$S_{1,-1}(\vec{q}) = -(12\pi/5)^{1/2}S_2(q)Y_{2,2}{}^*(\hat{q}),$$
$$\hat{q} = \vec{q}/|\vec{q}|,\quad S_{m',m} = S_{m,m'}{}^*,$$

where f_n and f_p are the pion-neutron and pion-proton elastic-scattering amplitudes, respectively, k is the momentum, and $\vec{q}$ is the three-momentum transfer in the pion-deuteron c.m. system. The m and m' are the initial and final projections of the deuteron spin, the $Y_{L,m}$ are the spherical harmonics, and the $S_0(q)$ and $S_2(q)$ are the spherical and quadrupole form factors of the deuteron given by

$$S_0(q) = \int_0^\infty [u^2(r)+w^2(r)]j_0(qr)dr,$$
$$S_2(q) = \int_0^\infty [2u(r)w(r)-w^2(r)/\sqrt{2}]j_2(qr)dr$$

with j_0 and j_2 the spherical Bessel functions and $u(r)/r$ and $w(r)/r$ the radial parts of the S and D waves of the deuteron wave function.

The differential cross section for elastic scattering without observing the deuteron polariza-

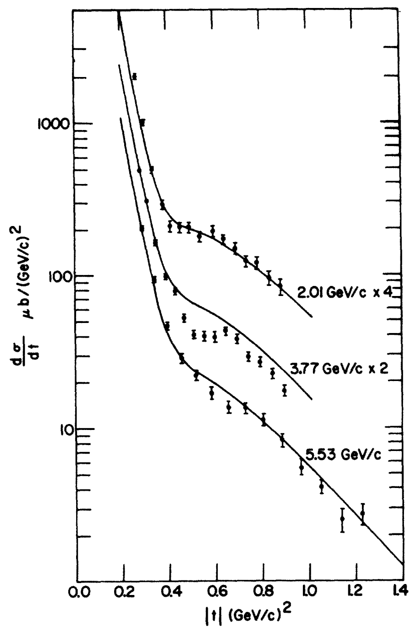

FIG. 2. Differential cross sections for 2.01, 3.77, and 5.53 GeV/c. The 2.01- and 3.77-GeV/c points have been multiplied by factors of 4 and 2, respectively, for the purpose of illustration. The error bars are statistical and do not reflect an overall ±7% uncertainty applied uniformly to all points. The solid curves are the result of theoretical calculations based on the Glauber model. The curves are discussed in the text.

tion[9] is

$$\frac{d\sigma}{dt}=\frac{\pi}{k^2}\frac{1}{3}\sum_{m,m'}|\langle m'|F_d(\vec{q})|m\rangle|^2.$$

The pion-nucleon amplitudes in the forward direction may be represented by

$$f_N(\vec{q})=\frac{k\sigma_N}{4\pi}[i+\alpha_N(t)]\left(\frac{1+\alpha_N^{\,2}(0)}{1+\alpha_N^{\,2}(t)}\right)^{1/2}\exp(\tfrac{1}{2}A_N t),$$

$$N=n \text{ or } p,\ t=-q^2,$$

where σ_N is the total pion-nucleon cross section, $\alpha_N(t)$ is the ratio of real part to the imaginary part of the amplitude, and A_N is the slope of an exponential fit to the pion-nucleon differential cross sections. For π^-n parameters we have used π^+p parameters since they are equal by charge symmetry.

The solid curves in Fig. 2 are the results of a calculation with $\alpha_N(t)=\alpha_N(0)$ and the double-charge-exchange correction noted by Wilkin.[10] The values of σ_p and σ_n were obtained from Carter et al.[11] and Citron et al.,[12] $\alpha_p(0)$ and $\alpha_n(0)$ from Lasinski, Levi Setti, and Predazzi,[13] and A_p and A_n from Barashenkov.[14] Form factors were obtained from the Hamada-Johnston deuteron wave function.[15] There are no free parameters in the theoretical calculations.

At 2.01 and 5.53 GeV/c our data are seen to be in good agreement with the calculation described above. At 3.77 GeV/c a 3.5% increase in A_n and A_p (consistent with the probable errors in these parameters) gives good agreement except for $0.45\leq|t|\leq 0.65$. The energy dependence of the double-scattering shoulder is in reasonable agreement with the Glauber model. A Regge-pole-dominance model[4] suggests a larger energy dependence of the secondary scattering shoulder than the Glauber model.

As previously stated, the calculations were made with $\alpha_N(t)=\alpha_N(0)$. Phase-shift analyses[16] below 1.7 GeV/c indicate that the variation of $\alpha_N(t)$ is small except near a dip in the pion-nucleon differential cross section, near $|t|=0.8$. Our data are also consistent with this type of variation in $\alpha_N(t)$.

We appreciate the fine technical support offered by the zero-gradient synchrotron personnel, in particular Tony Passi. We thank Dr. R. A. Lundy for a very helpful experimental suggestion, and Professor H. W. J. Courant, Professor W. J. Kernan, and Professor M. Ross for useful discussions. We appreciate the assistance of P. N. Scharbach, G. Mrozek, and T. Curtright during part of the experiment. We also appreciate the capable technical help of Stephen Mosher and William Glass of Ames Laboratory.

*Work supported in part by the Ames Laboratory of the U. S. Atomic Energy Commission (Contract No. 2539) and the National Aeronautics and Space Administration.

[1]R. C. Chase, E. Coleman, T. G. Rhoades, M. Fellinger, E. Gutman, R. C. Lamb, and L. S. Schroeder, in Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, Austria, 1968 (unpublished).

[2]E. Coleman, R. M. Heinz, O. E. Overseth, and D. E. Pellett, Phys. Rev. 164, 1655 (1967); G. W. Bennett, J. L. Friedes, H. Palevsky, R. J. Sutter, G. J. Igo, W. D. Simpson, G. C. Phillips, R. L. Stearns, and D. M. Corley, Phys. Rev. Letters 19, 387 (1967); H. C. Hsiung, E. Coleman, B. Roe, D. Sinclair, and J. Van der Velde, Phys. Rev. Letters 21, 187 (1968); F. Bradamante, S. Conetti, G. Fidecaro, M. Fidecaro, M. Giorgi, A. Penzo, L. Piemontese, F. Sauli, and P. Schiavon, Phys. Letters 28B, 193 (1968).

[3]R. J. Glauber, in Lectures in Theoretical Physics, edited by W. E. Brittin et al. (Interscience Publishers, Inc., New York, 1959), Vol I; R. J. Glauber, Phys.

Rev. 100, 242 (1955).

[4]E. S. Abers, H. Burkhardt, V. L. Teplitz, and C. Wilkin, Nuovo Cimento 42A, 365 (1966), and Phys. Letters 21, 339 (1966).

[5]K. Terwilliger et al., "Summary of Beam Design Studies for 17° Secondary Beam," University of Michigan Report, 1964 (unpublished).

[6]National Bureau of Standards Cryogenic Data Center Memorandum No. M4 (unpublished).

[7]C. T. Coffin, N. Dikmen, L. Ettlinger, D. Meyer, A. Saulys, K. Terwilliger, and D. Williams, Phys. Rev. 159, 1169 (1967).

[8]V. Franco and R. J. Glauber, Phys. Rev. 142, 1195 (1966).

[9]D. R. Harrington, Phys. Rev. Letters 21, 1496 (1968).

[10]C. W. Wilkin, Phys. Rev. Letters 17, 561 (1966).

[11]A. Carter, K. Riley, R. Tapper, D. Bugg, R. Gilmore, K. Knight, D. Salter, G. Stafford, E. Wilson, J. Davies, J. Dowell, P. Hattersley, R. Homer, and A. O'Dell, Phys. Rev. 168, 1457 (1968).

[12]A. Citron, W. Galbraith, T. F. Kycia, B. A. Leontić, R. Phillips, and A. Rousset, Phys. Rev. 144, 1101 (1966).

[13]T. Lasinski, R. Levi Setti, and E. Predazzi, University of Chicago Report No. UC-247, 1968 (to be published).

[14]V. S. Barashenkov, Fortschr. Physik 14, 741 (1966).

[15]T. Hamada and I. D. Johnston, Nucl. Phys. 34, 382 (1962).

[16]P. Bareyre, C. Bricman, and G. Villet, Phys. Rev. 165, 1731 (1968).

μ:e RATIO IN $\eta^0 \to \pi^0 l^+ l^-$ AND $X^0 \to \eta^0 l^+ l^-$ AS A TEST OF ELECTROMAGNETIC C NONINVARIANCE

L. M. Sehgal
Tata Institute of Fundamental Research, Bombay, India
(Received 23 April 1969)

If the decays $\eta^0 \to \pi^0 l^+ l^-$ occur via a C-nonconserving (isovector) electromagnetic interaction, the ratio $\Gamma(\eta^0 \to \pi^0 e^+ e^-)/\Gamma(\eta^0 \to \pi^0 \mu^+ \mu^-)$ should be 3.3. Similarly, if the decays $X^0 \to \eta^0 l^+ l^-$ are induced by a C-nonconserving (isoscalar) interaction, the ratio $\Gamma(X^0 \to \eta^0 e^+ e^-)/\Gamma(X^0 \to \eta^0 \mu^+ \mu^-)$ should be 2.9.

In connection with the hypothesis that the electromagnetic current of the hadrons contains a part that is even under charge conjugation,[1] one decay that has received attention is $\eta^0 \to \pi^0 e^+ e^-$.[2] If the C-even current K_μ has an isovector component, the decay can proceed with an amplitude of order α, since a one-photon intermediate state is possible. However, several factors can contribute to a suppression of the $\eta\pi\gamma$ vertex, and no reliable guide as to the "radius" of this vertex is available, rendering difficult an estimate of the decay rate. Indeed, it is possible that the rate from one-photon exchange is depressed to an extent that it becomes comparable with the rate expected on the basis of the C-conserving, two-photon-exchange mechanism, for which the amplitude is of order α^2. In view of the possibility that the decay $\eta^0 \to \pi^0 e^+ e^-$ will be detected in future experiments, it is desirable to have a simple criterion for interpreting the observations.

We wish to point out that one such criterion is provided by the ratio of the decay rates of $\eta^0 \to \pi^0 e^+ e^-$ and $\eta^0 \to \pi^0 \mu^+ \mu^-$. In the case where the decays proceed via one-photon exchange, it is possible to predict the ratio e:μ uniquely, without needing to know the "radius" of the $\eta\pi\gamma$ vertex. Defining

$$\langle \pi^0 | K_\mu(0) | \eta^0 \rangle = (e/6)\langle r^2 \rangle q^2 [P_\mu + \xi q_\mu], \quad (1)$$

where $q = p_\eta - p_\pi$ and $P = p_\eta + p_\pi$ (p_η and p_π being the four-momenta of η and π), the invariant amplitude for $\eta^0 \to \pi^0 l^+ l^-$ is (using current conservation and the Dirac equation)

$$\mathfrak{M} = \tfrac{1}{3} e^2 \langle r^2 \rangle \bar{u}(l) \not{p}_\pi v(\bar{l}) \quad (2)$$

(l and $\bar{l}$ are momenta of l^- and l^+). This leads to the differential decay rate

$$\frac{d\Gamma}{dE} = \frac{\alpha^2}{27\pi} (\langle r^2 \rangle M_\pi^{\,2})^2 \left(\frac{M_\eta}{M\pi}\right) \left(\frac{E^2}{M_\pi^{\,2}} - 1\right)^{3/2} \left(1 - \frac{4M_l^{\,2}}{M_\eta^{\,2} + M_\pi^{\,2} - 2M_\eta E}\right)^{1/2} \left(1 + \frac{2M_l^{\,2}}{M_\eta^{\,2} + M_\pi^{\,2} - 2M_\eta E}\right), \quad (3)$$

where E is the pion energy, and M_l, M_π, and M_η are the respective masses of the lepton, π^0, and η^0.[3]