posium on Multinucleon Transfer Reactions, September 1971 (to be published).
[10]C. D. Zafiratos, C. Dêtraz, C. E. Moss, and C. S. Zaidins, Phys. Rev. Lett. 27, 437 (1971).
[11]M. R. Cates, J. B. Ball, and E. Newman, Phys. Rev. 187, 1682 (1969).
[12]J. Picard and G. Bassani, Nucl. Phys. A131, 636 (1969).

Deuteron Alignment in Deuteron-Proton Elastic Scattering at 3.6 GeV/c*

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We have performed a deuteron-proton double-scattering experiment with a 3.6-GeV/c deuteron beam to study the spin alignment of the elastically scattered deuterons. We observed scattered beams of polarized deuterons and have measured the spin alignment and vector polarization in the four-momentum-transfer interval of $\Delta^2 = 0.13$ to 0.54 (GeV/c)^2. Multiple-scattering model fits are presented to our alignment and polarization data as well as to existing differential-cross-section data.

An important ingredient in the Glauber model[1] for p-d and π-d forward differential cross sections above 1 GeV is the D-state deuteron form factor which fills in a dip in the cross section near $|\Delta|^2 = 0.3$ (GeV/c)^2 to give the experimentally observed shoulder in the interference region between single and double scattering. It was shown by Franco and Glauber[2] that the D-state form factor should lead to a strong dependence of the p-d differential cross section on the deuteron spin direction. Harrington[3] has pointed out that this spin dependence could also be studied in a double-scattering experiment in which a high-energy deuteron beam was scattered from two hydrogen targets in succession.

In a double-scattering experiment in which a deuteron beam is polarized by the first scatterer and analyzed by the second scatterer, the differential cross section of the second scattering can be written $I = I_0[1 + a_1 b_1 + a_2 b_2 \cos 2\varphi + (a_3 b_3 - a_4 b_4) \times \cos\varphi]$, where I_0 is the unpolarized differential cross section, φ is the azimuthal angle, a_i describe the deuteron polarization in the first scattering, and b_i describe the analyzing power in the second scattering. The terms $a_1 b_1$, $a_2 b_2$, and $a_3 b_3$ are due to alignment, or tensor polarization, while $a_4 b_4$ is the usual vector-polarization term. For elastic scattering, $a_i = b_i$ assuming time-reversal invariance. The $a_i(\Delta)$ are functions of the spin expectation values.[4] In Harrington's model the coefficients a_1, a_2 depend upon the quadrupole form factor of the deuteron, and the coefficients a_3, a_4 vanish. In the experiment reported here the azimuthal asymmetry $N(\varphi)$ was measured, and it was compared to the formula $N(\varphi) = N_0(1 + A \cos 2\varphi + B \cos\varphi)$, where allowance has been made for nonzero coefficients a_3, a_4.

Figure 1 shows the configuration for the first and second scatterings. The external deuteron beam of the Princeton-Pennsylvania Accelerator at 3.6 GeV/c [5] was aligned by the first scattering at momentum transfer Δ_a and formed a secondary scattered beam. Deuterons in the scattered beam had a momentum higher than that kinematically allowed for any contamination, so the beam-line magnets served to furnish a pure deuteron beam incident on the second target. The momentum transfer Δ_a was varied by moving the position of the first target T_a and retuning the magnet system. Some data were also taken at higher and lower incident momenta than 3.6 GeV/c to obtain extreme values of momentum transfer. Typical external deuteron beam intensity was 8×10^{11} d/sec which gave about 10^4 aligned deuterons in a 5-cm-diam circle at the second scattering target T_b. The slit system defined $|\Delta|^2$ to ± 0.01 (GeV/c)^2.

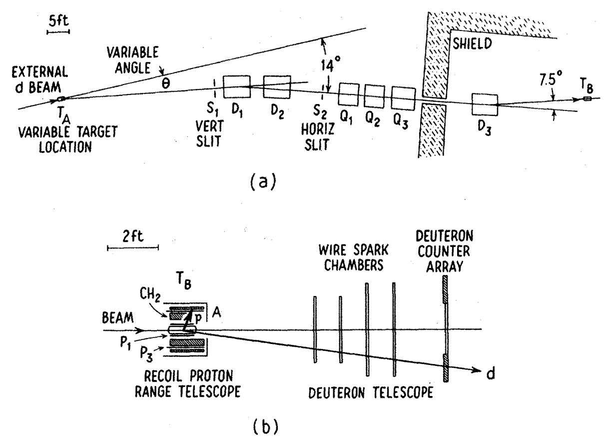

FIG. 1. (a) First-scattering geometry. A quadrupole triplet focused the scattered beam on the target. (b) Second-scattering geometry. The recoil-proton range telescope was cylindrically symmetrical. Scattered deuteron trajectories were recorded in the four wire spark chambers.

The momentum transfer at the second scatterer was fixed by requiring the recoil protons to have an energy of 128 ± 8 MeV by range. This set $\Delta_b^2 = 0.23 \pm 0.016$ (GeV/c)^2. The scattered deuterons and inelastic protons (background) which accompanied the proton recoils were detected in four scintillation counters placed downstream and subtending 90° each in azimuth. Rough coplanarity within 90° azimuth was required between the deuteron and the recoil proton. Four magnetostrictive-readout wire spark chambers were used to determine the deuteron trajectory in space. Elastic deuterons were limited in polar angle θ by the recoil-proton range requirement so that the inelastic background could be eliminated from the sharply peaked elastic signal by a subtraction in the spark-chamber data. Typically, the elastic signal and background were of equal magnitude. In this manner the azimuthal asymmetry could be measured for each value of Δ_a at fixed Δ_b. The data were divided into twelve intervals in azimuth, the background subtracted for each interval, and a least-squares fit of the elastic signal was made to determine the best values for the asymmetry coefficients A and B. This process was repeated for a number of values of Δ_a. The results are presented in Table I and Fig. 2.

The alignment asymmetry parameter A rises to a maximum value of 0.67 at $\Delta_a^2 \simeq 0.25$, decreases and goes through zero at $\Delta_a^2 \cong 0.41$, and goes negative for larger Δ_a. The results for A are quite independent of background subtraction.[6] The

TABLE I. Results. Fits are to $N(\varphi) = N_0(1 + A\cos 2\varphi + B\cos\varphi)$. Primary beam momentum is 3.57 GeV/c, unless otherwise noted. Error in Δ^2 is ±0.01 (GeV/c)^2.

Δ^2	A	B
0.13[a]	0.40 ± 0.04	0.16 ± 0.06
0.19[b]	0.61 ± 0.04	0.37 ± 0.06
0.23	0.63 ± 0.06	0.07 ± 0.10
0.24	0.66 ± 0.04	0.32 ± 0.05
0.24[b]	0.67 ± 0.03	0.13 ± 0.06
0.24[a]	0.65 ± 0.06	-0.03 ± 0.11
0.25	0.53 ± 0.05	0.29 ± 0.07
0.28	0.67 ± 0.03	0.25 ± 0.05
0.30	0.54 ± 0.06	0.23 ± 0.09
0.32	0.46 ± 0.04	0.14 ± 0.06
0.33[b]	0.45 ± 0.05	0.11 ± 0.07
0.34	0.29 ± 0.04	0.26 ± 0.05
0.38	0.15 ± 0.06	0.33 ± 0.08
0.40	0.08 ± 0.08	0.54 ± 0.10
0.43	-0.14 ± 0.04	0.23 ± 0.06
0.48	-0.19 ± 0.04	0.09 ± 0.05
0.51	-0.26 ± 0.05	0.18 ± 0.07
0.54[c]	-0.37 ± 0.11	-0.18 ± 0.15

[a]2.64 GeV/c. [b]3.16 GeV/c. [c]3.70 GeV/c.

absence of a systematic up-right–type asymmetry in the apparatus was demonstrated by tuning the secondary beam to half-momentum, where it consisted primarily of stripped protons, and observing no such effect. The $\cos\varphi$ asymmetry parameter B varies slowly with momentum transfer and has a magnitude of about 0.25 in the interval studied. The data were also analyzed for $\sin\varphi$ asymmetry. Typical values for such asymmetry were 0.02 ± 0.04 indicating little systematic up-down bias in our experiment. The errors quoted for A and B are 1-standard-deviation statistical errors.

The model of Harrington[3] was extended in a simple way to include nucleon spin-orbit effects in an attempt to fit the observed B term in $N(\varphi)$. The nucleon-nucleon scattering amplitude of Harrington, $f = (k\sigma_{\text{tot}}/4\pi)(i+\alpha)\exp(-b\Delta^2/2)$, was multiplied by a factor $1 + (C|\Delta|/k)\vec{\sigma}\cdot\hat{n}$, where $\vec{\sigma}$ is the Pauli spin operator for one of the nucleons in the deuteron, $\hat{n}$ is perpendicular to the nucleon-nucleon scattering plane, and C was chosen to give a nucleon-nucleon polarization $P=0.45$ at $\Delta^2=0.3$ $(\mathrm{GeV}/c)^2$ and incident momentum 1.7 GeV/c.[7] Average parameters σ_{tot} and b for p-p and n-p

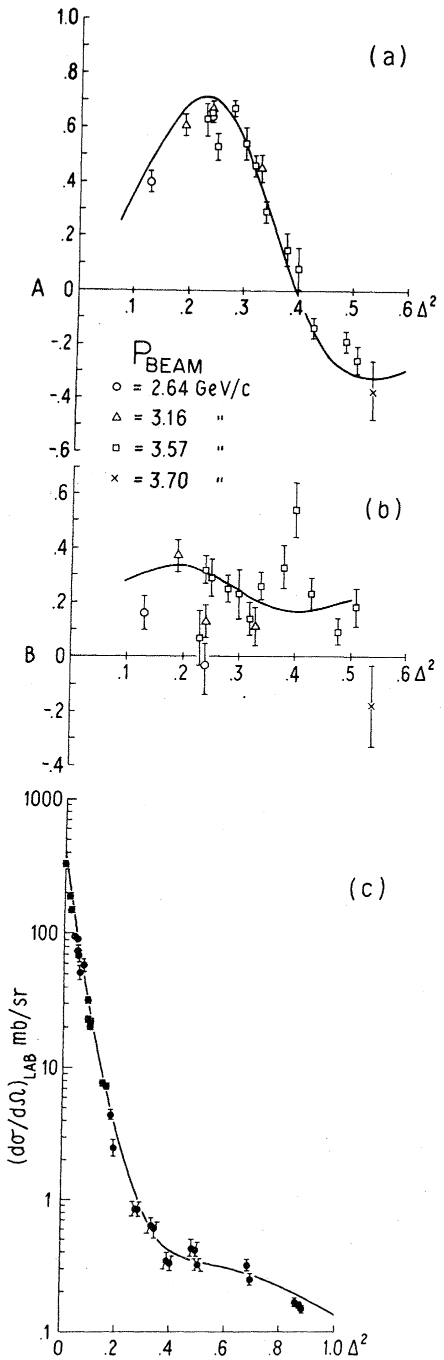

FIG. 2. Fits to the data using the Glauber model. (a) A term in $N(\varphi)=N_0(1+A\cos 2\varphi+B\cos\varphi)$; (b) B term; (c) $d\sigma/d\Omega$ from Ref. 5.

scattering were used in the calculations,[8] but the average real α and the D-state probability P_d were allowed to vary. The analytic form of the D-state form factor given by Alberi, Bertocchi, and Bialkowsky[9] was used. Their normalization corresponded to a D-state probability $P_d=6.5\%$. The calculations were compared to the $N(\varphi)$ data of the present experiment and the differential-cross-section data of Ref. 5.

The results of the calculation are shown in Fig. 2. The B term was quite insensitive to the free parameters α and P_d, depending primarily on the polarization constant C. The calculated cross section in the interference region around $\Delta^2=0.3$ $(\mathrm{GeV}/c)^2$ increased when either α or P_d was increased. The calculated A term in the asymmetry, on the other hand, increased in peak value with larger P_d, but decreased in peak value with larger α. The solutions stabilized unambiguously at $|\alpha|=0.65\pm0.15$ and $P_d=(6.5\pm2.0)\%$. While this is a reasonable value for P_d, our result for $|\alpha|$ is larger than the value of $\alpha=-0.30\pm0.10$ determined from measurements[10] on pp and pd scattering at 1 GeV in the region of Coulomb interference. Moreover, Glauber-model fits have been made to differential-cross-section data on the scattering of 1-GeV protons on helium with $\alpha=-0.33$,[11] on carbon with $\alpha=-0.33$,[12] and on oxygen with $\alpha=-0.40$.[12] In the Harrington model it turns out that the maximum value of the alignment parameter A is a sensitive function of α, and it is our observation that $A_{max}\approx 0.7$ that requires the large value of this parameter[13] for a good fit to our data.

In conclusion, this experiment has observed the D-state contribution directly by measuring deuteron alignment in d-p scattering. This alignment is not strongly energy dependent and should persist at higher energies. The vector polarization found in this experiment could be used as a source of polarized neutrons. An extension of the Glauber model to include spin-orbit effects satisfactorily accounts for the vector polarization. The Glauber model applied to differential cross sections and alignments in p-d scattering furnishes a method for measuring the real parts of nucleon-nucleon amplitudes at high energy and an independent method of determining the deuteron D-state probability.

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[1]For an excellent review of the theory and the experimental information on hadron-deuteron scattering, see R. J. Glauber, in *Proceedings of the Third International Conference on High Energy Physics and Nuclear Structure, New York, N. Y., 1969*, edited by S. Devons (Plenum, New York, 1970), p. 207.

[2]V. Franco and R. J. Glauber, Phys. Rev. Lett. 22, 370 (1969).

[3]D. R. Harrington, Phys. Lett. 29B, 188 (1969).

[4]S. E. Darden, Amer. J. Phys. 35, 727 (1967).

[5]This momentum corresponds to p-d scattering at 1.0 GeV where differential-cross-section data exist. G. W. Bennett *et al.*, Phys. Rev. Lett. 19, 387 (1967).

[6]In particular, for the maximum value of A to exceed 0.8 would require an absurd background subtraction. Also, any subtraction procedure raising the maximum positive asymmetry tends to wash out the negative asymmetry at large momentum transfers.

[7]M. J. Longo, H. A. Neal, and O. E. Overseth, Phys. Rev. Lett. 16, 536 (1966); Particle Data Group, UCRL Report No. UCRL-20000NN, 1970 (unpublished). The Glauber-model calculation is made in the rest frame of the deuteron.

[8]The values used were $b=5.4\ (\mathrm{GeV}/c)^{-2}$ and $\sigma=42$ mb, taken from the compilation cited in Ref. 7.

[9]G. Alberi, L. Bertocchi, and G. Bialkowsky, Nucl. Phys. B17, 621 (1970).

[10]L. M. C. Dutton, R. J. W. Howells, J. D. Jafar, and H. B. Van der Raay, Phys. Lett. 25B, 245 (1967).

[11]W. Czyż and L. Leśniak, Phys. Lett. 24B, 227 (1967); R. Bassel and C. Wilkin, Phys. Rev. Lett. 18, 871 (1967).

[12]L. Leśniak and H. Wolek, Nucl. Phys. A125, 665 (1969).

[13]For example, for $\alpha=-0.30$, $P_d=6.5\%$, the analysis gives $A_{\mathrm{max}}=0.90$ (see Ref. 6). Or, alternatively, for $\alpha=-0.30$, $A_{\mathrm{max}}=0.70$ requires the unreasonably low value of $P_d=2.5\%$. Moreover, both of these choices of parameters give poorer fits to the differential-cross-section data. These results follow from the Harrington model and are independent of the inclusion of spin-orbit effects.

Role of $\gamma+\gamma\to e^++e^-+e^++e^-$ in the High-Energy Cross Section for $\gamma+Z\to Z+e^++e^-+e^++e^-$†

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We discuss the possibility that the interesting large, high-energy cross section for $\gamma+\gamma\to e^++e^-+e^++e^-$ can be indirectly tested via the reaction $\gamma+Z\to Z+e^++e^-+e^++e^-$. As a by-product, the background caused by the former process in the Primakoff-Stodolsky method for measuring the total photon-photon cross section into hadrons is shown to be substantially reduced beyond naive expectations.

The possibility of measuring photon-photon cross sections via a "generalized Primakoff" reaction has recently been emphasized by Stodolsky.[1] In particular, the interesting large, constant (6.45 μb), high-energy total cross section[2] for the α^4 reaction

$$\gamma+\gamma\to e^++e^-+e^++e^-, \tag{i}$$

which is present as an important background for $\gamma+\gamma\to$ hadrons, appears amenable to experimental check via the α^5 process

$$\gamma+Z\to Z+e^++e^-+e^++e^-. \tag{ii}$$

This would provide a test of high-order quantum electrodynamics at high energies.

We report here the results of detailed calculations of the dominant diagrams for these reactions which display the critical effects of the change of the scale $(\mathrm{mass})^{-2}$ characterizing the size of the cross section (i) when one or both of the pho-