Measurement of the Proton-Neutron Elastic-Scattering Polarization from 2 to 6 GeV/c*

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(Received 23 June 1975)

Left-right asymmetries from a deuterium target in a polarized-proton beam were observed with the Argonne National Laboratory effective-mass spectrometer. Results were obtained for both pp and pn elastic scattering from $-t=0.15$ to 1.0 GeV^2 at 2, 3, 4, and 6 GeV/c. For $-t \lesssim 0.6$ GeV^2 the pn polarization was found to have the same sign as for pp, but with faster energy dependence, the ratio $P(pn)/P(pp)$ at $-t=0.3$ GeV^2 falling from 0.78 ± 0.02 at 2 GeV/c to 0.22 ± 0.03 at 6 GeV/c.

Polarization effects in the processes

$$pp \to pp , \qquad (1)$$

$$pn \to pn , \qquad (2)$$

are closely related to one another, and together can be used to separate the $I=0$ and $I=1$ t-channel exchange contributions to the spin-flip amplitude. Pure $I=0$ exchange, as might be expected in optical models,[1] would result in equal polarizations for the two reactions. Since the $I=1$ exchange amplitudes have opposite signs for the two reactions, a single-spin-flip amplitude with pure $I=1$ exchange would give mirror symmetry, $P(pn)=-P(pp)$, similar to that for $\pi^{\pm}p$ elastic scattering.[2]

Using the polarized-proton beam[3] at the zero-gradient synchrotron (ZGS), we have measured both $P(pp)$ and $P(pn)$ at 2, 3, 4, and 6 GeV/c with typically 400 000 events at each energy. This is the first measurement of the pn polarization asymmetry above cyclotron energies.[4]

The beam was scattered in a 20-in. liquid-deuterium target upstream of the Argonne National Laboratory effective-mass spectrometer.[5] The spectrometer measured the angle and momentum of the fast scattered proton, and from this the square of the recoil missing mass, M_x^2, was calculated. Fermi motion in the target nucleus generally did not affect the missing-mass resolution appreciably and a clean signal was obtained, similar to that in a previous experiment.[5]

A cut on M_x^2 from 0.7 to 1.1 GeV^2 was used at all momenta to define the sample of interest. The background in this interval from inelastic reactions was typically 1%. A more important background was coherent scattering, $pd \to pd$. In the worst case considered ($-t=0.15$ GeV^2), the coherent cross section was about 15% of that for Reaction (1) or (2), but fell rapidly at larger t.

Reactions (1) and (2) were separated by means of scintillation counters along the sides of the target. An event was put into the pp sample if the counter on the side of the recoiling nucleon fired; otherwise it was placed in the pn sample. Events were rejected if the calculated recoil trajectory did not pass through a recoil counter.

The beam polarization was reversed each ZGS pulse and asymmetries were obtained by comparing scatters from "up" and "down" pulses. This procedure canceled the effects of any asymmetries in the apparatus.

Several small effects caused crosstalk between the pp and pn samples, resulting in some of the events being placed in the wrong sample. Contributors to the cross talk included δ rays, which caused a few percent of the pn events to fall in the pp sample, interactions of the recoil nucleons in the target or in a recoil counter (~1%), and protons missing the recoil counters ($\lesssim 3\%$). The crosstalk varied between 2 and 15%, depending on the energy and momentum transfer, and the systematic uncertainty in the correction led to an uncertainty of typically ± 2% of the difference $P(pp)-P(pn)$.

Double scattering of the fast polarized proton from two different nucleons, either in the same deuteron or in different ones, was observed in the M_x^2 distribution at the larger values of t. Since each scatter could contribute to the asymmetry, such events had a larger asymmetry than for single scattering. Fortunately, the missing-mass cut eliminated most of the double scatters at large t where the effect is important. The correction to the pp asymmetry at each energy was $\lesssim (3 \pm 2)\%$ of the maximum asymmetry near $-t=0.25$ GeV^2. The pn correction was about $\frac{1}{3}$ of this.

The beam polarization was determined by fitting our corrected pp asymmetries with the empirical formula

$$P=\sqrt{-t}\,(a+bt+ct^2), \qquad (3)$$

TABLE I. Polarization asymmetry in percent for pp and pn elastic scattering for 2- to 6-GeV/c incident beam momentum. Errors shown are statistical only.

$-t$ (GeV^2)	2 GeV/c		3 GeV/c		4 GeV/c		6 GeV/c	
	P(pp)	P(pn)	P(pp)	P(pn)	P(pp)	P(pn)	P(pp)	P(pn)
0.15	34.4 ± 1.7	29.9 ± 1.5	23.6 ± 1.8	13.8 ± 1.4	19.0 ± 1.6	7.0 ± 1.2	13.0 ± 2.0	2.1 ± 1.5
0.17	40.0 ± 1.7	26.7 ± 1.6	24.5 ± 1.8	12.7 ± 1.5	18.3 ± 1.7	8.1 ± 1.3	11.2 ± 2.1	2.4 ± 1.5
0.19	36.7 ± 1.8	28.2 ± 1.7	28.6 ± 1.9	13.7 ± 1.6	14.3 ± 1.8	7.3 ± 1.4	11.5 ± 2.1	2.2 ± 1.6
0.22	36.9 ± 1.0	31.5 ± 0.8	26.0 ± 1.4	13.2 ± 1.3	18.8 ± 1.1	8.3 ± 0.8	10.2 ± 1.0	3.2 ± 0.8
0.26	36.8 ± 0.9	28.8 ± 0.8	25.2 ± 1.3	13.4 ± 1.1	19.3 ± 1.2	9.7 ± 0.9	12.3 ± 1.1	3.0 ± 0.8
0.30	36.4 ± 1.1	28.9 ± 0.9	25.6 ± 1.1	12.4 ± 0.9	19.0 ± 1.2	9.2 ± 0.9	13.1 ± 1.2	3.3 ± 0.9
0.34	34.5 ± 1.5	26.6 ± 1.3	29.0 ± 1.1	12.9 ± 0.9	20.5 ± 1.3	9.5 ± 0.9	12.2 ± 1.3	3.3 ± 1.0
0.38	30.3 ± 2.1	24.0 ± 1.7	25.7 ± 1.2	11.3 ± 1.0	17.8 ± 1.5	8.6 ± 1.1	13.9 ± 1.5	3.0 ± 1.2
0.45	31.1 ± 1.7	20.9 ± 1.4	24.4 ± 0.9	11.7 ± 0.7	17.2 ± 1.2	8.3 ± 0.8	11.8 ± 1.1	1.2 ± 0.8
0.55	23.1 ± 2.3	15.6 ± 1.9	20.0 ± 1.3	10.0 ± 1.0	15.1 ± 1.6	5.8 ± 1.1	8.9 ± 1.2	-0.7 ± 0.9
0.65	17.5 ± 3.3	12.6 ± 2.6	17.9 ± 1.8	3.8 ± 1.3	13.3 ± 2.2	3.7 ± 1.5	9.5 ± 1.6	-1.9 ± 1.2
0.75	6.8 ± 8.4	10.2 ± 5.6	13.8 ± 2.6	1.0 ± 1.8	11.9 ± 3.0	-3.0 ± 1.9	7.3 ± 2.2	-3.7 ± 1.5
0.90			13.7 ± 3.3	-0.2 ± 2.3	16.9 ± 3.4	-3.7 ± 2.1	12.8 ± 2.2	-6.4 ± 1.6
1.10			6.1 ± 7.1	-10.1 ± 3.9	9.6 ± 8.6	-7.8 ± 4.4	11.1 ± 3.6	-5.3 ± 2.4
1.30							19.0 ± 6.3	2.2 ± 3.9
1.50							22.8 ± 11.4	-1.6 ± 6.8

and comparing the results at $-t = 0.3\ \mathrm{GeV}^2$ with those from previous experiments.[6] The average beam polarization was found to be 0.70, with a fractional uncertainty of ±6%, our largest systematic uncertainty.

The polarization asymmetries from this experiment are shown in Table I and Fig. 1. As in previous experiments,[4,7] there are no apparent systematic biases from the use of a deuterium target instead of a free-nucleon target. In particular, the t dependence of the pp asymmetry agreed well with previous experiments, while the value of the observed pp asymmetry gave a beam polarization in good agreement with that expected from other measurements.[8]

Both the pp and pn polarizations show a broad positive maximum near $-t = 0.25\ \mathrm{GeV}^2$. As was known from previous experiments,[6] the pp maximum falls roughly as $0.75/p$, where p is the beam momentum in GeV/c. The pn maximum drops much faster, falling from 0.30 ± 0.02 at 2 GeV/c to 0.032 ± 0.005 at 6 GeV/c. Being neither equal nor mirror symmetric, the polarizations require both $I=0$ and $I=1$ exchanges in the single-spin-flip amplitude.

Since there are five independent amplitudes for elastic nucleon-nucleon scattering, we are far from having a complete set of measurements for amplitude analysis. In spite of this, the present results can be combined with the differential cross sections to yield information on the single-spin-flip amplitude. Following Halzen and Thomas[9] we write

$$\frac{d\sigma}{dt} = |N_0|^2 + 2|N_1|^2 + |N_2|^2 + |\pi^2| + |A|^2, \tag{4}$$

$$P\frac{d\sigma}{dt} = 2\,\mathrm{Im}(N_0 - N_2)^* N_1. \tag{5}$$

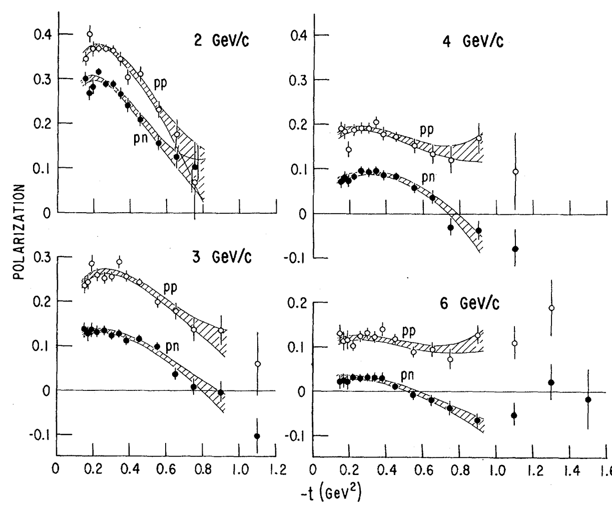

FIG. 1. Polarization asymmetries for pp and pn elastic scattering at four incident momenta. The errors are statistical only and do not include the ±6% scale uncertainty from the beam polarization. Fits to the data from 0.15 to 1.0 GeV^2 using Eq. (3) are shown as bands (±1 standard deviation).

Note that Eq. (5) depends only on the amplitudes N_0, N_1, and N_2, all with natural-parity exchange in the t channel. Near the forward direction the diffractive spin-nonflip amplitude N_0 dominates, and $|N_0| \approx (d\sigma/dt)^{1/2}$. The polarization then gives the component of the single-spin-flip amplitude orthogonal to N_0 in the complex plane, $N_{1\perp} \approx \frac{1}{2}P(d\sigma/dt)^{1/2}$.

Assuming that N_0 is dominated by $I=0$ exchange (diffraction), the $I=0$ and $I=1$ contributions to the single-spin-flip amplitude can be separated as

$$N_{1\perp}(I=0) \approx \tfrac{1}{4}\{[P(d\sigma/dt)^{1/2}]_{pp}+[P(d\sigma/dt)^{1/2}]_{pn}\}, \quad (6)$$

$$N_{1\perp}(I=1) \approx \tfrac{1}{4}\{[P(d\sigma/dt)^{1/2}]_{pp}-[P(d\sigma/dt)^{1/2}]_{pn}\}. \quad (7)$$

These relations were evaluated using pp differential cross sections at 3, 4, and 6 GeV/c from a previous experiment with the same spectrometer,[5] while those at 2 GeV/c were taken from Albrow *et al.*[6] The pn differential cross sections are known[10] to have a shape similar to those for pp and were estimated by multiplying the pp values by the ratio suggested by the optical theorem, $[\sigma_{tot}(pn)/\sigma_{tot}(pp)]^2$. Typical results are shown in Fig. 2(a).

The energy dependence of $N_{1\perp}$ was studied by fitting 3-, 4-, and 6-GeV/c results with

$$N_{1\perp} \propto p^{\alpha_{eff}-1}. \quad (8)$$

A sample of these fits is shown in Fig. 2(a). In spite of the low energy, the fits extrapolate well to the 2-GeV/c data. The $I=1$ values for α_{eff} shown in Fig. 2(b) are consistent with the trajectory expected for ρ and A_2 Regge-pole exchange, $\alpha_{eff} \approx 0.5+t$. In contrast, the $I=0$ amplitude has a much steeper energy dependence, giving a typical value of $\alpha_{eff} = -0.6$ at $-t=0.3$ GeV^2. This poses a problem for Regge models which would again expect $\alpha_{eff} \approx 0.5+t$ for ω and f exchange. One way to explain the $I=0$ spin-flip amplitude would be as the difference of two components having different energy dependences, for example, ω (or f) and Pomeron exchanges.[11]

We would like to thank R. I. Koda and J. S. Wakefield for their assistance in data collection, and Dr. E. Berger, Dr. A. Irving, Dr. G. Kane, and Dr. G. Thomas for stimulating discussions.

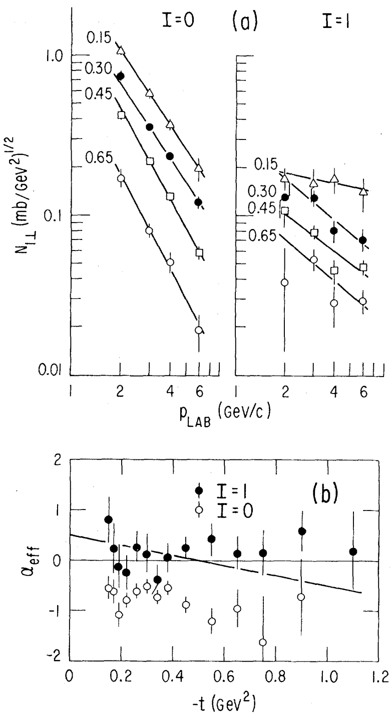

FIG. 2. (a) Momentum dependence of the $I=0$ and $I=1$ exchange contributions to the single-spin-flip amplitude at the $-t$ values (GeV^2) indicated. The lines are the results of fits by Eq. (8) from 3 to 6 GeV/c. (b) Power-law dependence of the $I=0$ and $I=1$ exchange components as functions of momentum transfer, from the fits in (a). In addition to the statistical errors shown, there is a systematic uncertainty in α_{eff} of ± 0.12. The straight line shows the energy dependence expected from Regge-pole exchange with $\alpha_{eff}=0.5+t$.

We are indebted to I. Ambats, L. Filips, E. Walschon, and the staff of the Accelerator Research Facilities Division for making this experiment possible.

*Work supported by the U. S. Energy Research and Development Administration.

[1]See, for example, A. W. Hendry and G. W. Abshire, Phys. Rev. D 10, 3662 (1974); F. Halzen, ANL Report No. ANL/HEP-75-02, 1974 (unpublished) p. XXIV-1.

[2]The nucleon-nucleon polarization differs from that for $\pi^{\pm}p$ in that it involves a single-spin-flip amplitude which is the product of a nucleon spin-nonflip coupling at one vertex and a spin-flip coupling at the other.

[3]E. F. Parker *et al.*, Phys. Rev. Lett. 31, 783 (1973).

[4]D. Cheng *et al.*, Phys. Rev. 163, 1470 (1967).

[5]I. Ambats *et al.*, Phys. Rev. D 9, 1179 (1974).

[6]The following experiments were used to estimate the pp polarization at $-t=0.3$ GeV^2 [$P(pp)=0.361$, 0.267,

0.188 and 0.121 at 2, 3, 4, and 6 GeV/c, respectively): H. A. Neal and M. J. Longo, Phys. Rev. 161, 1374 (1967); G. Cozzika *et al.*, Phys. Rev. 164, 1672 (1967); M. G. Albrow *et al.*, Nucl. Phys. B23, 445 (1970); M. Borghini *et al.*, Phys. Lett. 31B, 405 (1970); J. H. Parry *et al.*, Phys. Rev. D 8, 45 (1973).

[7]M. G. Albrow *et al.*, Phys. Lett. 35B, 247 (1971).

[8]The beam polarization was measured at 50 MeV before acceleration in the ZGS (see Ref. 3) and at high energy by another experiment (K. Terwilliger, private communication).

[9]F. Halzen and G. H. Thomas, Phys. Rev. D 10, 344 (1974).

[10]J. Engler *et al.*, Phys. Lett. 29B, 321 (1969); M. L. Perl *et al.*, Phys. Rev. D 1, 1857 (1970).

[11]A. C. Irving, private communication.

Possibility that Charmed Vector Mesons are Lighter than Charmed Pseudoscalars

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(Received 17 July 1975)

In view of the possible observation at SPEAR of events which could be interpreted as the production of charmed mesons followed by decays into purely leptonic channels, we suggest the possibility that the stable charmed mesons may be vectors rather than pseudoscalars. Estimates of decay rates and branching ratios are given in this case.

It has been generally assumed that the lowest-lying charmed mesons[1] are the pseudoscalar mesons: D^+ $(c\bar{d})$, D^0 $(c\bar{u})$, S^+ $(c\bar{s})$, and their antiparticles. These particles would then be the only weakly decaying charmed mesons, while the corresponding vector mesons, D^{*+}, D^{*0}, S^{*+}, would decay either by pion or by γ emission into the pseudoscalars.

In this note we will discuss possible consequences of the alternative possibility that the lowest-lying mesonic charmed states, i.e., those which are stable except for weak decays, are the vector particles. The main motivation for this discussion arises from the possible observation[2] at SPEAR of events of the kind

$$e^+e^- \to e^\pm + \mu^\mp + \text{undetected neutrals}, \qquad (1)$$

which could be interpreted as the production of a pair of charmed mesons which subsequently undergo a purely leptonic decay:

$$e^+e^- \to C^+C^- \to e^+\nu_e + \mu^-\bar{\nu}_\mu \text{ or } e^-\bar{\nu}_e + \mu^+\nu_\mu. \qquad (2)$$

This interpretation would only be possible if $C^\pm$ are vector particles (V). Purely leptonic decays of pseudoscalar mesons (PS) are strongly suppressed by helicity selection rules. This is particularly true for the electron mode, which is smaller by a factor $(m_e/m_\mu)^2 \simeq 2.3\times 10^{-5}$ than the muon mode which is itself suppressed.

The expectation that M(charmed V) > M(charmed PS) is not a firm prediction of the charm scheme. Broken SU(8) mass formulas[3,4] indicate that mass differences between corresponding V and PS mesons are very small, of the order of 100 MeV. This is a small fraction of the scale of SU(4) breaking, so that first-order mass formulas cannot be relied upon to predict the order of levels.

In fact it will be very difficult to settle the issue of V-PS splittings solely on theoretical grounds. Current ideas on the dynamics of quark-antiquark systems indicate that the forces involved can be roughly divided into two components.[5] At short distances, according to the asymptotic-freedom idea, these forces should be dominated by Coulomb-like exchange of massless colored gluons. At larger distances, the Coulomb law should be modified to give rise to quark confinement. The short-distance component gives rise[5] to a small hyperfine splitting which raises vector states [e.g., $M(S^*) - M(S) \simeq 80$ MeV]. The nature of the long-range part of the force is, however, much less well understood. It is quite possible that this part contains, in addition to large spin-independent terms, a certain amount of tensor force.[6] Tensor forces cause a mixing between $L=0$ and $L=2$ triplet states, which lowers the mass of the