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Measurement of Tensor Polarization and Cross Section for the Reaction $^2H(\pi^+, \pi^+)^2H$ at 180°

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This Letter reports the first measurement of tensor polarization (t_{20}) in π-d elastic scattering and also measurements of the π-d elastic-scattering cross section at 180°. The measurements were performed using the low-energy pion channel at Clinton P. Anderson Meson Physics Facility and a novel high-efficiency deuteron polarimeter. The result of the polarization measurement, $t_{20} = -0.23 \pm 0.15$ at $T_{\pi^+} = 140$ MeV, is in disagreement with all theoretical predictions.

Recently, the interest in both pion elastic scattering and absorption by the deuteron has intensified. The π-d system is particularly important since the three-body problem can be solved exactly and the nuclear structure of the deuteron is relatively simple. Moreover, pion absorption in nuclei is believed to occur predominantly on two nucleons so that studies of the π-d system provide an excellent test of proposed π-nucleus reaction mechanisms. Therefore, we have measured, for the first time, the tensor polarization t_{20} for the $^2H(\pi^+, \pi^+)^2H_{pol}$ reaction at $T_{\pi^+} = 140$ MeV and at a reaction angle of 180°. In addition, the cross section for this reaction was measured between $T_\pi = 60$ and 140 MeV at $\theta = 180°$.

Theoretical studies of π-d elastic scattering have achieved a high level of sophistication during the past five years. Rinat and Thomas[1] applied the Faddeev approach with full relativistic kinematics to the solution of the πNN system. Giraud and co-workers,[2,3] improved upon the basic π-d scattering matrix of Ref. 1 by considering nondiagonal elements and a more realistic deuteron wave function. Rinat *et al.*[4] studied the effects of the pion-absorption channel ($\pi^+ d \rightarrow 2p$) upon the elastic channel. The manner in which pion absorption by nuclei should be described is somewhat controversial, particularly for the deuteron. For example, Brack, Riska, and Weise[5] predicted that ρ exchange should have an extraordinarily large effect on the calculated cross sections for the $\pi d \rightarrow 2p$ reaction, whereas Pong[6] estimated that the effect from ρ exchange should be very small. Nevertheless the latest theoretical treatments,[1-4,7] regardless of the inclusion of absorption effects, agree rather well with the ob-

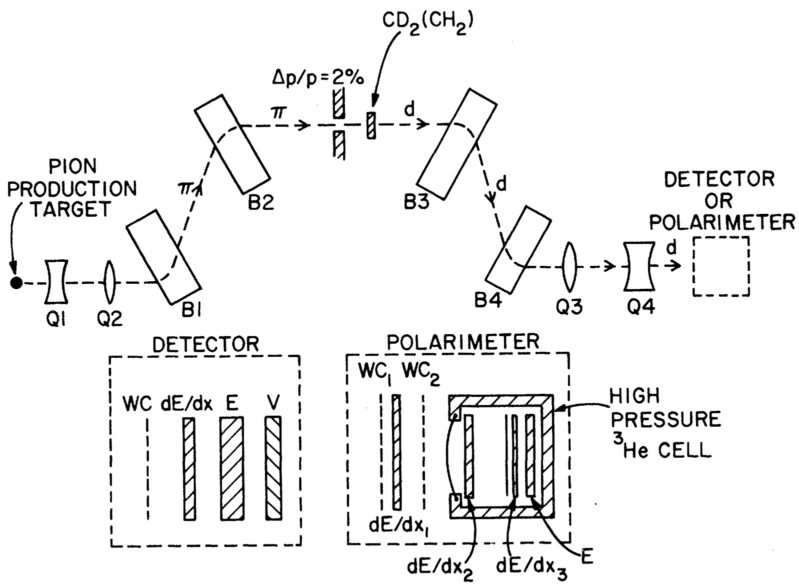

FIG. 1. Schematic diagram of the experimental arrangement. The LEP channel is used as both a pion spectrometer and a 0° deuteron spectrometer. The detector and the polarimeter are shown separately below.

served elastic-scattering cross sections[8] below 180 MeV. However, the predicted polarizations for the recoil deuterons from the $^2H(\pi, \pi)^2H_{pol}$ reaction, especially the tensor polarization t_{20}, appear to depend sensitively upon the effects of absorption. The predicted effect of pion absorption is most dramatic at large reaction angles, where the momentum transfer is large.

In order to perform these measurements at a reaction angle of 180°, the low-energy-pion (LEP) channel at the Clinton P. Anderson Meson Physics Facility (LAMPF) was operated in the mode shown schematically in Fig. 1. The upstream half of the channel was used to focus pions of momentum spread $\Delta p/p = 2\%$ full width onto a CD_2 target positioned in the center of the channel, while the downstream half of the channel was operated as a 0° deuteron spectrometer. The CD_2 target thicknesses were 16 and 30 mg/cm^2 for the cross-section work and 84 mg/cm^2 for the polarization measurement. Samples of CH_2 with equivalent numbers of atoms per unit area were used to measure the background. The intensity of the π^+ beam on the CD_2 target during the polarization measurement was $\sim 1.6\times10^8\ \pi^+/s$. The cross sections were measured using the detector stack shown schematically in the lower left part of Fig. 1. The deuterons were identified with (dE/dx)-E plastic scintillators. A veto counter (V) was located at the end of the detector stack in order to eliminate particles (p, π, μ, e) of longer range than the deuteron. Deuterons from the target were focused onto the wire chamber (WC) in the spectrometer dispersion plane with use of the quadrupole doublets $Q3$ and $Q4$. The deuteron spectra from the wire chamber are shown for $T_{\pi^+} = 100$ MeV in Fig. 2 for a CD_2 and a CH_2 sam-

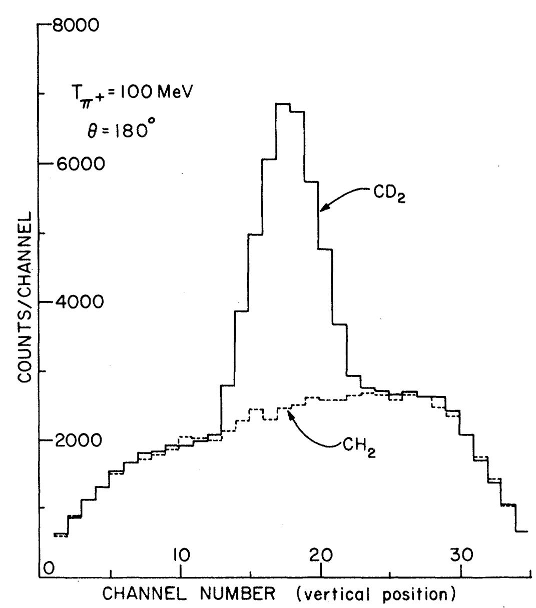

FIG. 2. Wire-chamber spectra with the CD_2 sample and with the background CH_2 sample.

ple. From this figure, it is clear that the signal and background are readily separable. The relative π flux was monitored with an ion chamber viewing the pion production target and also with a current integrator on the primary proton beam. The absolute π flux was determined by transporting the π beam through the channel and focusing it onto a plastic scintillator. The π flux was then calibrated, with use of an activation technique, relative to the measured[9] cross section for the $^{12}C(\pi, \pi N)^{11}C$ reaction. The uncertainty in this cross section contributes the largest uncertainty in the present cross-section measurement. The solid angle of the downstream half of the LEP channel was determined with the use of relatively well-known[10] π^+-p elastic-scattering cross sections by tuning the downstream half of the channel for protons and replacing the CD_2 target with CH_2. The solid angle was found to be 7.12 msr in agreement with Monte Carlo calculations. The cross sections for the $^2H(\pi, \pi)^2H$ reaction at 180° are given in Table I. The π^+ and π^- cross sections are consistent with one another within the error limits. Between 60 and 120 MeV, the cross section is almost constant at 2.1 mb/sr.

In order to observe the tensor polarization of the deuterons, the detector stack was replaced with a high-efficiency polarimeter shown schematically in the lower right part of Fig. 1. The details of the polarimeter are discussed elsewhere[11] and only the essential elements will be described here. The polarimeter makes use of the forward-angle $^3He(d_{pol}, p)^4He$ reaction below 15 MeV, where the cross section is known[12] to be large and forward peaked and the magnitude of the tensor analyzing power T_{20} is large. In addition, this reaction has a high Q value so that the emitted protons are easily identified. The incident deuterons were identified by two plastic scintillators, dE/dx_1 and dE/dx_2, and degraded from an energy of ~47 MeV to ~15 MeV before entering

TABLE I. Differential cross sections for the $^2H(\pi, \pi)^2H$ reaction at an angle of 180°.

T_π (MeV)	$d\sigma/d\Omega_{c.m.}$ (mb/sr) π^+	π^-
60	2.06 ± 0.41	...
80	1.89 ± 0.29	2.31 ± 0.64
100	2.12 ± 0.15	2.04 ± 0.27
120	2.23 ± 0.17	1.82 ± 0.12
140	1.62 ± 0.13	1.51 ± 0.10

the active volume of the polarimeter. The angles of incidence of the deuterons were determined using two wire chambers (WC_1, WC_2). The density of ^3He gas in the polarimeter was chosen to correspond to the range of 15-MeV deuterons. A 0.25-mm thick steel foil was placed at the end of the active volume to prevent deuterons which were not stopped in the ^3He gas from reaching the final (dE/dx)-E detectors. These detectors were used to measure the yield of protons from the $^3He(d, p)^4He$ reaction. In this polarimeter, the quantity measured is the ratio ϵ of protons from the $^3He(d, p)^4He$ reaction to the number of incident deuterons. This ratio depends on the tensor polarization t_{20} of the incident beam in the following way:

$$\epsilon = \epsilon_0(1 + t_{20}T_{20}),$$

where ϵ_0 is the efficiency ratio for unpolarized deuterons. The quantities ϵ_0 and T_{20} for the polarimeter were determined[11] using a calibrated[13] polarized deuteron beam at the Berkeley 88-in cyclotron. In order to accomodate a relatively large-area beam, the polarimeter was designed to have an 81-cm^2 active area. During the calibration procedure at Berkeley, the sensitivity of ϵ_0 and T_{20} to incident deuteron energy, position and angle of incidence was determined. The deuteron beam from the LEP channel spanned an area of only 21 cm^2 and contained angles of incidence of $\lesssim 5°$ from normal, so that the effects of position and angle of incidence had a small influence ($\Delta t_{20} \approx 0.01$) on the final results. The energy-averaged values of ϵ_0 and T_{20} used in the present work are $\epsilon_0 = 1.52 \pm 0.06 \times 10^{-4}$ and $T_{20} = -0.60 \pm 0.05$. This represents the most efficient deuteron polarimeter available.

At LAMPF the CD_2 and CH_2 runs were alternated approximately every 4 hours in order to minimize effects of possible long-term drifts in the apparatus. The major contributions to the uncertainty in the measurement of t_{20} are (i) the statistical precision of the measurement of ϵ at LAMPF ($\delta t_{20} = 0.10$), (ii) the systematic uncertainty in background subtraction for the determination of ϵ_0 during the calibration procedure ($\delta t_{20} = 0.08$), and (iii) the uncertainty in the energy of the deuteron beam (±90 keV) incident on the polarimeter ($\delta t_{20} = 0.06$), and (iv) the statistical precision of the determination of ϵ_0 ($\delta t_{20} = 0.04$). Other sources of uncertainty such as position, energy distribution, angle of incidence of deuterons on the polarimeter, accuracy of the determination of T_{20}, and background-subtraction effects were consid-

TABLE II. Comparison of the present $\theta = 180°$ measurements for $T_{\pi^+} = 140$ MeV with theoretical calculations with $T_\pi = 142$ MeV.

References	$d\sigma/d\Omega_{c.m.}$ (mb/sr) $P_d = 6.7\%$	$P_d = 4\%$	t_{20} $P_d = 6.7\%$	$P_d = 4\%$
Giraud *et al.* (Ref. 2)	1.60	1.59	−0.67	−0.56
Rinat *et al.* (Ref. 4)	1.36 ± 0.07	1.65 ± 0.08	−0.78	−0.61
Rinat *et al.* (Ref. 4) (with absorption)	1.03 ± 0.05	1.29 ± 0.06	+0.24	+0.22
Present measurement:				
π^+	1.62 ± 0.13		−0.23 ± 0.15	
π^-	1.51 ± 0.10			

ered and found to add only 0.01 to the uncertainty in t_{20}.

The measured value $t_{20} = -0.23 \pm 0.15$ is compared with theoretical predictions in Table II. The calculations were performed for two values of the deuteron D-state admixture: $P_d = 4\%$ and 6.7%. The back-angle cross section shows almost no sensitivity to D-state admixture. Since the sensitivity to D-state admixture in any one calculation of t_{20} is less than the difference between the various calculations as shown in the table, it is clear that the π-nucleus reaction mechanism is not understood well enough to allow determination of the effect of the D state from a measurement of t_{20}. Indeed, the measured tensor polarization is in disagreement with all theoretical predictions. The theories that do not include the pion absorption channel are in better agreement with the present cross-section measurements. It is clear from the present cross section and polarization measurements that further experimental and theoretical work is required in order to understand the elastic scattering amplitude of the π-d system. We plan to perform additional polarization measurements at other angles in future experiments.

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