Tensor Analyzing Power in πd Elastic Scattering

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A tensor-polarized deuteron target has been employed for the first measurements of the tensor analyzing power T_{20} in πd elastic scattering. Data at six angles were measured at pion bombarding energies of 133.8 and 150.9 MeV. The results settle a long-standing controversy over conflicting measurements of the tensor polarization t_{20}, and dispute evidence for dibaryon resonances predicated on one of these t_{20} measurements. The data are shown to be in reasonable agreement with recent Faddeev calculations which have reduced contributions from pion absorption.

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For the past several years, one of the most intriguing questions in intermediate-energy pion physics has revolved around two sets of conflicting measurements of the tensor polarization t_{20} in πd elastic scattering. One set of measurements[1] was performed by a group from Eidgenössische Technische Hochschule (ETH) at Schweizerisches Institut für Nuklearforschung (SIN), and indicated that t_{20} is mostly positive, with striking, oscillatory angular distributions at $T_\pi = 134$ MeV. Two peaks were observed near $\theta_d = 15°$ and 30° with tensor polarization as high as 0.6. At neighboring energies as close as 120 and 151 MeV, the angular dependence was almost completely flattened. The resulting peak in the $\theta_d = 15°$ excitation function was so narrow ($\Delta E \sim 15$ MeV) that these data were considered evidence for the existence of a dibaryon resonance.

However, independent measurements at $T_\pi = 142$ MeV made by an experimental group[2] at the Clinton P. Anderson Meson Physics Facility (LAMPF) revealed a flat angular distribution of negative t_{20} values. The LAMPF excitation curve was smooth, and generally consistent with conventional calculations if pion absorption terms were not included.

Both experiments were similar in that recoil deuterons from πd elastic scattering events were analyzed in a second scattering with a polarimeter based on the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction. Both experiments were subjected to intense scrutiny, but the source of the experimental discrepancy remained unclear.

Recently, an independent measurement of t_{20} was carried out at TRIUMF[3] which again employed a ^{3}He polarimeter. The TRIUMF data agreed with the LAMPF results. Although this experiment appeared to have resolved the discrepancy, some doubts remained. The technique and the geometry of the TRIUMF polarimeter was rather similar to the one used at LAMPF. Also, in the meantime the ETH group reproduced their earlier results with a completely redesigned polarimeter.[4]

Obviously, a completely different experimental approach was required to resolve the controversy. The most ideal solution is to measure the tensor analyzing power T_{20} for πd elastic scattering with a tensor-polarized deuteron target in a single-scattering experiment. This observable can then be related to the tensor polarization of the recoil deuteron, t_{20}, measured in the double-scattering experiments via the relation[5]

$$t_{20}^{\mathrm{lab}}(\theta_d) = T_{20}^{\mathrm{c.m.}}(\theta_d)\, d_{00}^2(\theta_d) - 2\,T_{21}^{\mathrm{c.m.}}(\theta_d)\, d_{10}^2(\theta_d) + 2\,T_{22}^{\mathrm{c.m.}}(\theta_d)\, d_{20}^2(\theta_d), \tag{1}$$

where the $d_{jk}^i(\theta_d)$ are the usual Wigner d functions. The conversion arises because the T_{20} are measured in a coordinate system in which the z axis is along the incident beam momentum, and the t_{20} are measured in the laboratory system in which the z axis points in the direction of the outgoing deuteron momentum. A conversion of t_{20}^{lab} to $t_{20}^{\mathrm{c.m.}}$ requires a coordinate-system rotation, which admixes the tensor components t_{21} and t_{22}. In the angular range where t_{20} data[1-3] already exist, the influence of $T_{21}^{\mathrm{c.m.}}$ and $T_{22}^{\mathrm{c.m.}}$ is small.

We report in this Letter the first measurements of the tensor analyzing power T_{20} in the πd elastic-scattering reaction. The experiment is the first to employ a tensor-polarized deuteron target in a hadronic interaction. The experiment was performed on the M11 beam line at TRIUMF.

The tensor-polarized target, to be described more completely in a future publication, consisted of frozen 1-mm-diam beads contained in a Teflon basket measuring $16\times16\times5$ mm^3. The basket was immersed in a mixture of ^{3}He and ^{4}He in the mixing chamber of a dilution refrigerator. The beads were formed from a mixture of 95% fully deuterated n-butyl alcohol and 5% D_2O into which EHBA-(Cr$^{\mathrm{V}}$) was dissolved[6] to a molecular density of 6×10^{19}/ml. The polarizing field of 2.5 T was provided by a superconducting split-pair solenoid with a magnetic-field axis along that of the incident beam. The field orientation was carefully checked to within 0.3° in a series of magnetic-field measurements at various points in space downstream of the polarized target after it was installed in the M11 area. The average target tensor polarization (p_{zz}) achieved was 0.085 ± 0.008.

The polarization was measured with three independent techniques. In the first two techniques, the relationship between the vector polarization, p_z, and p_{zz} given by $p_{zz}=2-(4-3p_z^2)^{1/2}$ was used. The standard method of comparing the area of the dynamically polarized deuteron NMR signal with the area of the thermal-equilibrium NMR signal was employed to obtain an average p_z of 0.328 ± 0.020, which corresponds to a p_{zz} of 0.082 ± 0.010.

The second technique[7] involved analysis of the asymmetry in the peak shape of the dynamically polarized NMR signal for every signal measured just after polarization, and just before depolarization. Explicit measurements of the NMR background accompanied each of these NMR measurements. The results of this technique were consistent with those of the thermal-equilibrium technique. The actual value of p_z used in the analysis of each πd elastic-scattering data set was the average of the values obtained with the thermal-equilibrium and asymmetry methods. The overall average was $p_z=0.333\pm0.015$, or $p_{zz}=0.085\pm0.008$.

Finally, p_{zz} was measured directly by utilizing the known tensor analyzing power at 90° (c.m.) in the πd to $2p$ reaction, as first suggested by Niskanen.[8] The incident pion energy for this measurement was 80 MeV. Two scintillators and two x-y wire chambers were centered at 82.5° (lab) on each side of the target. The value of the tensor analyzing power was determined from a phase-shift analysis of existing $pp\rightarrow\pi d$ data to be -1.30 ± 0.03, a value consistent with that yielded by a special relationship[9] between T_{20} and A_{yy} which exists for the $pp\rightarrow\pi d$ reaction at 90° (c.m.), namely $T_{20}=(\sqrt{2}/4)(3A_{yy}-1)$, which gives $T_{20}=-1.27\pm0.05$ at this energy. The value of p_{zz} measured in this special calibration configuration was 0.102 ± 0.022, in agreement with the other two techniques.

The detection system for the πd elastic-scattering measurements was an improved version of a time-of-flight (TOF) spectrometer used for earlier measurements of iT_{11} in this reaction.[10] The main improvement was the addition of a thick (1.25-cm) scintillator for measuring the energy of stopped deuterons. The main characteristics of the detection system are as follows: The solid angle of 30 msr for each of six independent arms was defined by a pion scintillator ($\pi 2i$) located 1 m from the polarized target, and viewed at each end by a photomultiplier tube for optimum time resolution. Together with another scintillator ($\pi 1i$) at 0.5-m radius, this constituted one of the six pion telescopes, each of which was in coincidence with a corresponding recoil-deuteron scintillator ($D1i$) at a radius of 1.3 m from the target. This thin (3.1 mm) scintillator was also viewed at each end by a photomultiplier tube, and provided TOF as well as energy-loss information. Following this scintillator was an aluminum absorber, whose thickness was adjusted so that deuterons stopped in the following 1.25-cm-thick scintillator ($D2i$). Following this was a veto scintillator ($D3i$). The angular acceptance of the apparatus was ±2.5°. The experimental arrangement is shown in Fig. 1.

The data were collected in sequences of polarized and unpolarized runs, in order to check for possible systematic errors. Each sequence, including 3 polarized and 3 unpolarized runs, was repeated five times at 134 MeV and three times at 151 MeV. The relative differential cross sections were calculated from the following simple expression: $\sigma=Y/(NC_{\mathrm{eff}})$, where Y is the πd elastic yield, N the number of incident beam particles counted in S1 and S2, and C_{eff} the computer efficiency (typically 99%). The uncertainty associated with the relative cross sections was $\lesssim1\%$ for each sequence. The incident beam was counted directly with scintillators S1 and S2. Protons in the incident beam were reduced by using a differential degrader (2 mm of CH_2) near the midplane of the M11 channel. Those remaining in the beam were eliminated by placing pulse-height requirements on S1 and S2 in the trigger, which was $\mathrm{S1}\cdot\mathrm{S2}\cdot\overline{\mathrm{S1}}\cdot\overline{\mathrm{S2}}\cdot\pi 1i\cdot\pi 2i\cdot \mathrm{D1}i\cdot\overline{\mathrm{D3}i}$. The spatial stability of the incident beam was constant-

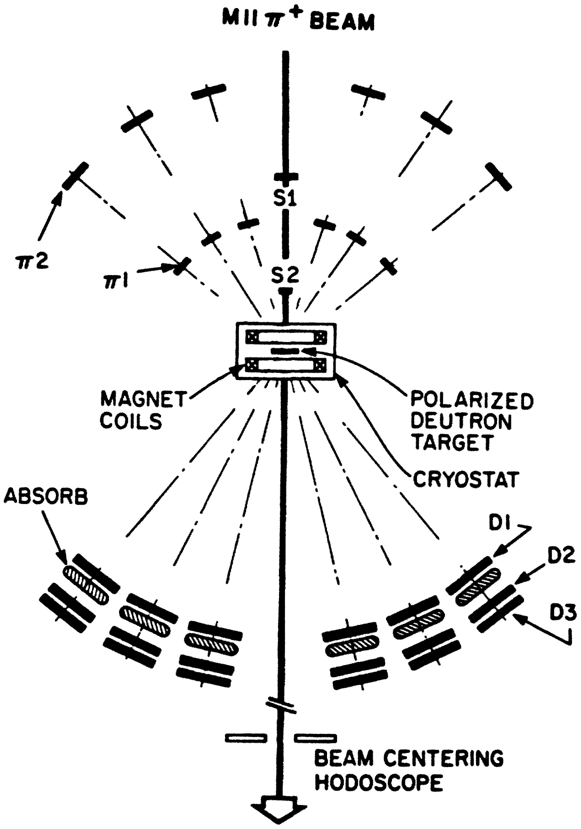

FIG. 1. The experimental layout is shown, with the pion beam incident from the top. The meaning of the various detectors is explained in the text.

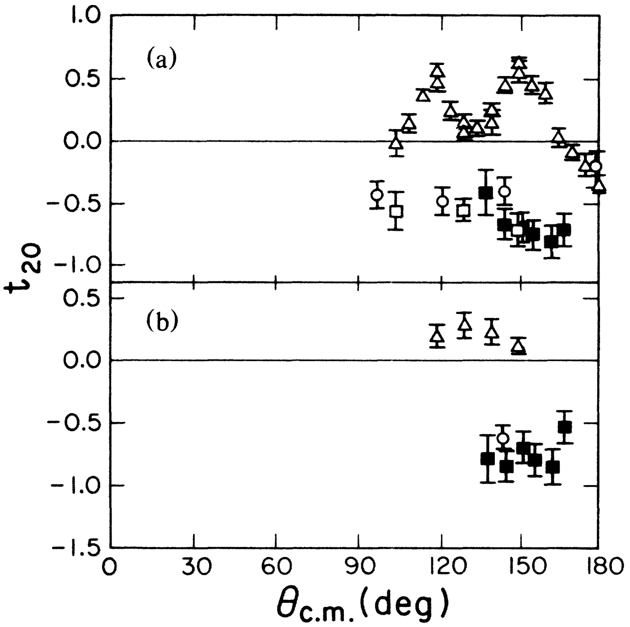

FIG. 2. Angular distributions of the tensor polarization t_{20}^{lab} are shown at (a) $T_\pi = 134$ and (b) $T_\pi = 151$ MeV. The measured tensor analyzing powers $T_{20}^{\text{c.m.}}$ of this experiment have been converted to tensor polarizations t_{20}^{lab} in this figure by admixing calculated values of $T_{21}^{\text{c.m.}}$ and $T_{22}^{\text{c.m.}}$ (see text). The other t_{20}^{lab} data, obtained from double-scattering experiments, are from SIN (Ref. 1) (open triangles), LAMPF (Ref. 2, $T_\pi = 142$ MeV) (open circles), and from TRIUMF (Ref. 3) (open squares).

ly monitored with a split scintillator sensitive to shifts of $\gtrsim 100$ μm either horizontally or vertically in the beam position. The incident flux was also kept constant at 2×10^6 π^+/s. The position of the target within the cryostat was verified with x-ray photographs. The M11-beam-line momenta used for this experiment were 236.0 MeV/*c* (134.7 MeV) and 255.7 MeV/*c* (151.7 MeV), corresponding to interaction energies at the center of the polarized target of 133.8 ±0.5 and 150.9 ±0.5 MeV. The momentum acceptance of the channel was $\Delta p/p = \pm 2.5\%$. The horizontal (vertical) angular divergence of the incident beam was constrained to ±0.5° (±1.0°). The effect of the beam divergence is estimated to be on the order of $\frac{1}{10}$ the size of the uncertainty quoted for the T_{20} data presented here.

The data were analyzed in several ways. Software polygons were drawn around the πd elastic events identified in two-dimensional histograms of E vs ΔE, $E+\Delta E$ vs TOF, ΔE vs TOF, and E vs TOF, where ΔE corresponded to the pulse height in D1, E to the pulse height in D2, and the TOF was taken between π2 and D1. The data were replayed with different combinations of these requirements. The results of the different analyses were consistent with one another.

The spherical tensor analyzing power was calculated from the expression

$$T_{20} = (\sqrt{2}/p_{zz})(\sigma_p/\sigma_0 - 1), \tag{2}$$

where p_{zz} is the target tensor polarization in Cartesian form, and σ_p (σ_0) the relative πd elastic differential cross section measured with the target polarized (unpolarized). The uncertainty in T_{20} includes statistical uncertainties in the relative cross sections, as well as an absolute uncertainty of 0.008 in the magnitude of p_{zz}. An overall normalization uncertainty factor of 5% (relative), arising from the uncertainty in calibrating the absolute target polarization, is not included in this expression. From Eq. (2) it is clear that the possible sources of systematic errors in this experiment are totally different and fewer in number than those associated with the more difficult double-scattering experiments performed earlier.

A direct comparison of t_{20}^{lab} with $T_{20}^{\text{c.m.}}$ requires a knowledge of T_{21} and T_{22}, as mentioned earlier. These observables have not yet been measured. Therefore, we have chosen to admix the calculated T_{21} and T_{22} of Garcilazo,[11] weighted according to Eq. (1), with our measured T_{20} in order to compare to the earlier t_{20}^{lab} data. The results are shown in Fig. 2, along with the earlier double-scattering measurements from SIN,[1] LAMPF,[2] and TRIUMF.[3] Our results are consistent with those of the LAMPF and TRIUMF experiments at 134 MeV, and with those of LAMPF at 151 MeV. Our results are not consistent with those of the SIN experiment at either energy.

A model-independent comparison of $t_{20}^{\rm lab}$ and $T_{20}^{\rm c.m.}$ can be made by using the maximum theoretically possible bounds on T_{21} and T_{22} in Eq. (1). These bounds are $\pm\sqrt{3}/2$, although the bounds on T_{21} can be reduced slightly to ± 0.77 using Lakin cone arguments.[12] The band of allowable $t_{20}^{\rm lab}$ determined from our $T_{20}^{\rm c.m.}$ data and these limits on T_{21} and T_{22} is entirely negative for c.m. angles greater than 145°, where the SIN $t_{20}^{\rm lab}$ data reach positive values as high as $+0.6$.

Our $T_{20}^{\rm c.m.}$ data are compared to the predictions of Garcilazo,[11] and Blankleider and Afnan,[13] in Fig. 3. Both predictions are Faddeev calculations, but they differ in some important practical aspects. In particular, they differ in the way in which pion absorption is handled via the P_{11} πN partial wave input. The predictions of T_{20} are quite sensitive to this aspect of the calculation. Garcilazo has chosen to treat all pion-nucleon partial-wave channels on an equal basis in terms of experimentally defined t-matrix elements. This effectively reduced the contribution from pion absorption in his calculations. The traditional approach[13,14] argues that a correct treatment of the P_{11} term necessitates splitting it into pole and nonpole terms. Such a treatment leads to a larger absorptive component than does Garcilazo's. Other calculations,[13,15,16] of which those of Ref. 13 are representative, incorporate this approach. This impact of the P_{11} term in the calculations of Ref. 13 may be gauged by a comparison to calculations in which this term is left out. It is interesting that the calculations with no absorption are the ones in best agreement with the data. Whether this supports the assumptions involved in Garcilazo's calculations, or simply indicates that the effects of pion absorption are being overestimated in the other calculations, is still an open theoretical question. Clearly, more comprehensive measurements of T_{20} and other spin observables in the πd elastic-scattering reaction will provide crucial tests needed to answer this question.

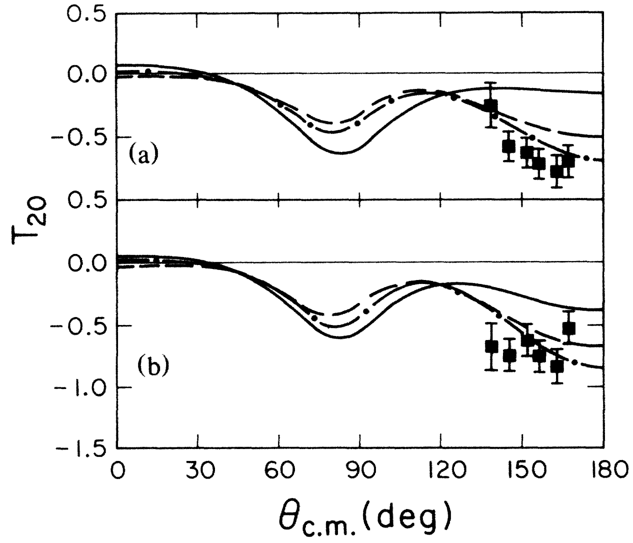

FIG. 3. The tensor analyzing power $T_{20}^{\rm c.m.}$ data obtained in this experiment are compared to calculations at (a) $T_\pi = 134$ MeV and (b) $T_\pi = 151$ MeV. The solid curves (full calculation) and dash-dotted curves (no P_{11} rescattering and no absorption) are from Blankleider and Afnan (Ref. 13). The dashed curves are from Garcilazo (Ref. 11).

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