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Measurement of the tensor analyzing power T_{21} in πd elastic scattering

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The first measurements of the tensor analyzing power T_{21} in the πd elastic scattering reaction have been made using a tensor polarized deuteron target. Eleven angles were studied at a pion bombarding energy of 180 MeV. The results are shown to be in agreement with Faddeev calculations.

The πd elastic scattering reaction has been the focus of an increasing number of experimental and theoretical efforts in the last few years. Before that time, only measurements of the differential cross section were available. Our knowledge of this fundamental reaction has, however, recently been supplemented by measurements of the vector analyzing power iT_{11},[1] the tensor analyzing power T_{20},[2] and the tensor polarization t_{20}.[3-5] These new spin observables have provided crucial tests for sophisticated three body treatments of the πNN system. In particular, the treatment of pion absorption via the $P_{11}\pi$N amplitude has been seriously challenged by the new data. Knowledge of the behavior of other spin observables is regarded as crucial to solving this and other theoretical puzzles.

In addition, measurements of spin observables are necessary in order to perform reliable partial wave analyses of the πd elastic scattering reaction. The reaction may be described by four helicity amplitudes, therefore seven observables need to be measured in order to determine the amplitudes up to a common phase. The behavior of the amplitudes has been of particular interest due to predictions that this reaction may be sensitive to the existence of dibaryon resonances. Indeed, several phase-shift analyses performed in recent years,[6,7] in spite of the paucity of data available, tended to support this conjecture. The sensitivity of spin observables to the interference of smaller amplitudes with the larger ones which dominate spin-averaged observables like the differential cross section make them essential ingredients in such an analysis.

We report the first measurements of the tensor analyzing power T_{21} and the πd elastic scattering reaction. This observable was obtained from measurements of πd elastic scattering differential cross sections using a tensor polarized deuteron target on the M11 beamline at TRIUMF.

The coordinate frame of the scattering is one in which the z axis lies along the incident pion momentum, and the y axis lies along the direction of the cross product $\mathbf{k}\times\mathbf{k}'$ between incident ($\mathbf{k}$) and scattered ($\mathbf{k}'$) pion momenta. The differential cross section σ(pol) for scattering from a polarized target may be expressed in terms of the cross section σ(unp) for scattering from an unpolarized target, and the various spin observables T_{kq} according to[8,9]

$$\sigma(\text{pol})=\sigma(\text{unp})(1+a_{11}iT_{11}+a_{20}T_{20}+a_{21}T_{21}+a_{22}T_{22}), \quad (1)$$

where

$$a_{11}=\sqrt{3}p_z\sin\alpha\cos\beta ,$$

$$a_{20}=\frac{p_{zz}}{\sqrt{2}}\frac{3\cos^2\alpha-1}{2} ,$$

$$a_{21}=\sqrt{3}p_{zz}\sin\alpha\cos\alpha\sin\beta ,$$

and

$$a_{22}=-\frac{\sqrt{3}}{2}p_{zz}\sin^2\alpha\cos2\beta .$$

In the coefficients a_{kq}, p_z (p_{zz}) denotes the target vector (tensor) polarization. The Euler angles α and β refer, respectively, to the polar angle between the incident pion beam and the target magnetic field, and the angle between the y axis and the projection of the target magnetic field on the x-y plane. In order to emphasize the spin observable T_{21}, the appropriate choices of α and β are $\alpha=57.3°$ (to eliminate the T_{20} term) and $\beta=90°$ (to eliminate the iT_{11} term). Unfortunately, the geometry of the polarized deuteron target is such that the angular region (in the horizontal plane) from 50° to 78° and from 102° to 130° is inaccessible. Therefore, for purely experimental reasons, α was chosen to be 45° for the T_{21} measurements, and β 90°. With these choices for α and β, Eq. (2) can be written as

$$\tau_{21}=T_{21}+\frac{1}{2}\left[\frac{T_{20}}{\sqrt{6}}+T_{22}\right] \tag{2}$$

$$=\frac{2}{\sqrt{3}p_{zz}}\left[\frac{\sigma(\text{pol})}{\sigma(\text{unp})}-1\right] . \tag{3}$$

The experimentally measured quantities are the target tensor polarization, p_{zz}, and the relative πd elastic scattering differential cross sections $\sigma(\text{pol})$ and $\sigma(\text{unp})$. The quantity in parentheses in Eq. (2) is what is actually measured in a T_{22} experiment.[10] In a T_{21} experiment, such as reported here, the quantity actually measured is a mixture of T_{21}, T_{20}, and T_{22}, according to Eq. (2), which shall be referred to as τ_{21} in this article. The dominant contribution to τ_{21} comes from T_{21}, since the T_{20} term is weighted by $1/(2\sqrt{6})$ and the T_{22} term is predicted to be small in the backward hemisphere where this experiment was performed.[11-13]

The tensor polarized target consisted of frozen 1-mm diameter beads contained in a thin-walled Teflon basket measuring $22\times18\times6$ mm^3. The basket was immersed in a mixture of ^{3}He/^{4}He in the mixing chamber of a dilution refrigerator. The beads were composed of a mixture of 95% fully deuterated N-butyl alcohol and 5% D_2O into which deuterated EHBA-CR^V (Ref. 14) was dissolved 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 horizontal magnetic field axis 45° to the incident beam. This alignment was carefully checked to within 0.3° by means of a series of magnetic field measurements at various points in space downstream of the polarized target. The T_{21} data were acquired with the target in frozen spin mode at a holding field of 1.25 T. The average target tensor polarization achieved in this experiment was 0.109 ± 0.010.

The target polarization was obtained from analysis of the nuclear magnetic resonance (NMR) signals using two independent techniques. Both techniques rely on the relationship between p_z and p_{zz} given by $p_{zz}=2-\sqrt{4-3p_z^2}$. One technique involved comparing the area of the dynamically polarized deuteron NMR signal with the area of the thermal equilibrium NMR signal. The thermal equilibrium polarization is a known function of temperature and magnetic field. For a second technique, the asymmetry in the peak shape of the dynamically polarized NMR signal was analyzed. The validity of these techniques has been confirmed in an independent experiment[15] which measured the target tensor polarization directly, by utilizing the known tensor analyzing power T_{20} at 90° (c.m.) in the πd to 2p reaction. In practice, the values of target polarization used in the experiment reported here were obtained from the average of the two (consistent) NMR signal techniques.

The detection system used for the measurement of τ_{21} in the πd elastic scattering reaction is similar to systems used for measurements of iT_{11} (Ref. 1) and T_{20} (Ref. 2), and is shown in Fig. 1. The main characteristics of the detection system can be summarized as follows: A solid angle of 30 msr for each of six independent arms was defined by a pion scintillator ($\pi 2_i$) located 1 m from the polarized target. Together with another scintillator ($\pi 1_i$) at 0.5-m radius, this constituted one of six pion telescopes, each of which was tilted and raised or lowered vertically to correspond to the actual pion trajectories deflected through the holding field of the polarized target.

Each pion telescope was placed in coincidence with an associated recoil deuteron arm consisting of three scintillators. The first scintillator ($D1_i$) at a radius of 1.3 m from the target was a thin (3 mm) scintillator which provided time-of-flight (TOF) as well as energy loss (ΔE) information. Following this scintillator was an aluminum absorber, whose thickness was adjusted so that deuterons stopped in the following 1.3-cm-thick scintillator ($D2_i$). The third was a veto scintillator ($D3_i$).

The flux of the incident beam was counted directly with scintillators S1 and S2 in coincidence. The size of S2 was chosen such that its image at the target would be smaller than the target itself. Protons in the incident beam were reduced by using a differential degrader (2 mm) 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, defined by $S1\cdot S2\cdot\overline{S1}\cdot\overline{S2}\cdot\pi1_i\cdot\pi2_i\cdot D1_i\cdot\overline{D3_i}$. The incident flux was typically $2\times10^6\pi^+$/sec. The position of the target within the cryostat was verified with x-ray pictures. The horizontal and vertical divergences of the beam were less than 1°.

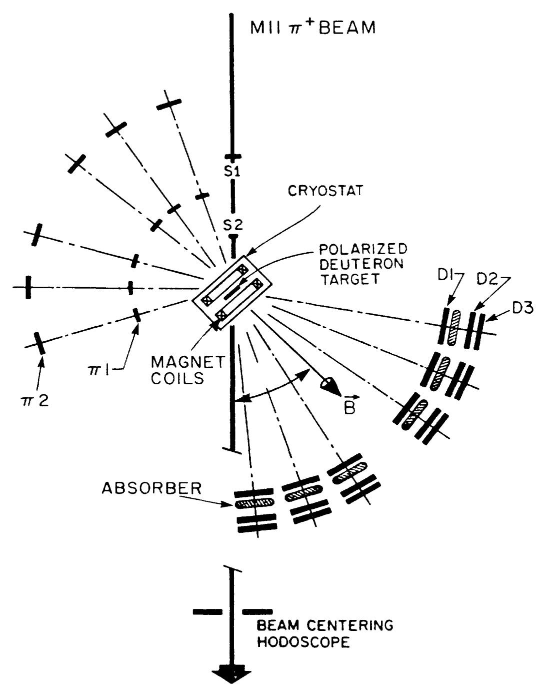

FIG. 1. The experimental layout is shown, with the pion beam incident from the top. The target magnetic field axis was oriented 45° with respect to the incident beam. The meaning of the various detector rings is explained in the text.

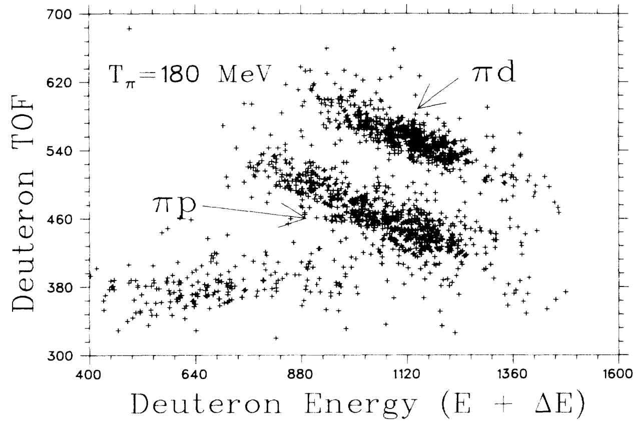

FIG. 2. A typical two-dimensional spectrum of the deuteron TOF (vertical axis) vs the sum of the deuteron pulse heights in the ΔE counter (D1) and the E counter (D2) is shown. The deuteron band is enclosed by the polygon. The other events are protons from quasielastic scattering, absorption, and deuteron breakup reactions. The c.m. angle corresponding to this histogram was 140°.

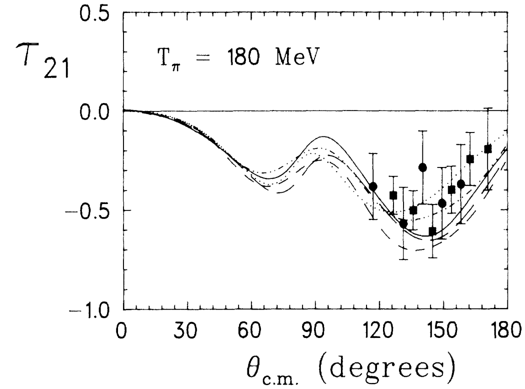

FIG. 3. The measured tensor analyzing power τ_{21} at 180 MeV is compared to Faddeev calculations from Blankleider and Afnan (Ref. 11, solid curve, full calculation; long dashed curve, no P_{11} and no pion absorption), Fayard, Lamot, and Mizutani (Ref. 12, dotted curve), Garcilazo (Ref. 16, short dashed curve), and Rinat and Starkand (Ref. 13, dash-dotted curve).

The incident beam energy was 180.0 ± 0.5 MeV, and the momentum acceptance of the channel was $\delta p/p = \pm 1\%$.

Explicit measurements of the background arising from quasielastic πd scattering from the contaminant carbon and oxygen nuclei in the polarized target were also made by replacing the deuterated butanol target with an equivalent amount of nondeuterated butanol. The resulting yield was subtracted from the foreground yield to obtain background free results.

The final analysis of the data was performed by constructing polygons around the πd elastic events identified in two-dimensional histograms of the deuteron TOF versus the deuteron total energy $E + \Delta E$, where ΔE corresponded to the pulse height in D1 and E to the pulse height in D2. A typical (foreground) scatterplot of these quantities is shown in Fig. 2.

The uncertainty in T_{21} includes the statistical uncertainties in the relative cross sections (typically 1%), as well as an uncertainty of either 0.010 (angle set 1) or 0.022 (angle set 2) in p_{zz}. The greater uncertainty in the target polarization associated with the second detector setting (of five angles) arose from a deterioration of the target NMR system during the last half of the experiment. The overall normalization uncertainty of 4.4% (relative), arising from the uncertainty in calibrating the absolute target polarization and uncertainties in the fitting procedure, is included in the quoted uncertainties for T_{21}.

The results of this experiment at $T_\pi = 180$ MeV are shown in Fig. 3, along with the results of several three-body calculations. Each of the curves shown is actually an admixture of calculated T_{20}, T_{21}, and T_{22}, weighted according to Eq. (3), in order to compare to the measured quantity τ_{21}. The predictions are from Garcilazo,[16] Blankleider and Afnan,[11] Rinat and Starkand,[13] and the Lyon group.[12] All the predictions are Faddeev calculations, but they differ in some important practical aspects, the most significant of which is the treatment of pion absorption via the $P_{11}\pi$N partial wave input. At $T_\pi = 180$ MeV, however, the influence of this aspect of the calculations is minimal. The predictions of T_{21} and in particular T_{20}, are quite sensitive to this aspect of the calculations at other bombarding energies, as will be discussed in detail in a forthcoming publication.[17] The theoretical results at $T_\pi = 180$ MeV may be considered as a benchmark with which to test the agreement of the theoretical calculations to the experimental data without the puzzling and troublesome effects arising from the various splitting of the P_{11} term.

The insensitivity of the τ_{21} predictions at $T_\pi = 180$ MeV to the P_{11} partial wave input may be observed by comparing the full calculation of Ref. 11 to a calculation from the same group in which pion absorption and the P_{11} input has been turned off. As can be seen from Fig. 3, there is surprisingly little change between the two curves, in contrast to the case for other bombarding energies. This insensitivity of the calculations to the treatment of the P_{11} is probably responsible for the clustering of the various theoretical predictions, and their good agreement with the data. Clearly, now that the validity of the Faddeev predictions at this benchmark energy has been established with the experimental results presented here, it would be interesting to explore the effects of pion absorption by comparison to τ_{21} measurements at other bombarding energies.

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