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Meson-exchange approach to the tensor analyzing power in elastic pd backward scattering

A. Boudard
Department de Physique Nucleaire a Moyenne Energies, Centre d'Etude Nucleaires de Saclay, F-91191 Gif-Sur-Yvette Cedex, France

M. Dillig
Department de Physique Nucleaire a Moyenne Energies, Centre d'Etude Nucleaires de Saclay, F-91191 Gif-Sur-Yvette Cedex, France and Institute for Theoretical Physics, University Erlangen-Nürnberg, D-8520 Erlangen, West Germany

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Motivated by a recent experiment, the differential cross section and the tensor analyzing power T_{20} for elastic pd backward scattering is calculated in a microscopic model, which includes both the conventional one-nucleon exchange mechanism and rescattering contributions from the $\Delta(1236)$ resonance. If supplemented by multiple scattering corrections, the model qualitatively accounts for the large negative values of T_{20} for deuteron energies up to 2.3 GeV; however, it fails to reproduce the dip structures observed experimentally. Possible extensions of the model are briefly discussed.

In recent experiments performed at Saturne, the differential cross section[1] and, in particular, the tensor analyzing power T_{20} have been measured for the reaction $\text{pd}\rightarrow\text{dp}$ at deuteron energies T_d between 0.3 and 2.3 GeV.[2] As the main result, large negative values for T_{20} were found for energies $T_d \gtrsim 1$ GeV, together with a second shallow dip around 1.4 GeV. These results are in striking disagreement with both previous measurements[3] and with practically all theoretical calculations. Various approaches, such as the one-nucleon exchange mechanism supplemented by N* exchange,[4] the multiple scattering approach,[5] $\Delta(1236)$ isobar rescattering via the triangle mechanism,[6] or by an off-shell corrected $\text{pp}\rightarrow \text{d}\pi^+$ subamplitude fitted to pion production on the deuteron,[7] predict, as a trend for T_{20}, a very smooth transition from slightly negative to positive values with increasing deuteron energies beyond 1 GeV. Though the inclusion of possible tribaryon resonances introduces oscillations in the analyzing power,[8] the average value of T_{20} is still much too small and compatible with zero. In this Rapid Communication we report on an approach, which at least qualitatively accounts for the new data although it does not provide a quantitative description.

In formulating our model, we note two features of the experimental data, the steep falloff of the differential cross section and the sharp minimum of T_{20} at $T_d \simeq 0.5$ GeV, reflecting the dominance of the one-nucleon exchange mechanism, and the relative plateau in the differential cross section at T_d between 1 and 1.2 GeV due to the rescattering of the real Δ isobar. Consequently we include in the transition amplitude genuine two- and three-nucleon contributions (Fig. 1)

$$T_{M\mu}^{M'\mu'}=\left\langle M'\mu'(1,2,3)\left|\sum_{i>j} V_{\text{NN}}^{(2)}(i,j)+\sum_{i>j>k} V^{(3)}(i,j,k)\right|M\mu(1,2,3,)\right\rangle \ . \tag{1}$$

Here $|M\mu\rangle$ and $|M'\mu'\rangle$ denote the properly antisymmetrized proton-deuteron wave function; the two-body operator [Fig. 1(a)] involves the conventional NN interaction (see, for example, Ref. 9). The typical structure of the three-body operator [Fig. 1(b)] is given as

$$V^{(3)}(i,j,k)=V_{\text{NN}\rightarrow\Delta\text{N}}(i,j)G_\Delta(j)V_{\Delta\text{N}\rightarrow\text{NN}}(j,k) \ . \tag{2}$$

Here the $\text{NN}\rightarrow\Delta\text{N}$ transition potentials are generated as π and ρ exchange potentials from effective, nonrelativistic Lagrangians with recoil corrections up to first order. Finite range corrections at the vertices are taken into account by phenomenological form factors; in addition, corrections from repulsive short range correlations are included. In detail, $V_{\text{NN}\rightarrow\text{N}\Delta}(i,j)$ reads, keeping for transparency only static vertices,

$$V_{\text{NN}\rightarrow\text{N}\Delta}(i,j)=-\frac{1}{3}\frac{f_\pi(q^2)f_\pi^*(q^2)}{m_\pi^2}(\vec{\tau}_i\vec{T}_j^+)\left[(3\vec{\sigma}_i\hat{q}\vec{S}_j^+\hat{q}-\vec{\sigma}_i\vec{S}_j^+)[1-\epsilon_T(q,\omega)]\frac{\vec{q}^2}{\vec{q}^2+m_\pi^{*2}}-\vec{\sigma}_i\vec{S}_j^+[1-\epsilon_S(\vec{q},\omega)]\frac{m_\pi^{*2}}{\vec{q}^2+m_\pi^{*2}}\right] \ . \tag{3}$$

The functions $\epsilon_I(\vec{q},\omega)$, which incorporate π,ρ exchange, and short range correlations, are derived similarly as in Ref. 10; explicitly they are given by

$$\epsilon_I(\vec{q},\omega)=\frac{\vec{q}^2+m_\pi^{*2}}{\vec{q}^2+q_c^2+m_\pi^{*2}}+c_I\frac{f_\rho(q^2)f_\rho^*(q^2)m_\pi^2}{f_\pi(q^2)f_\pi^*(q^2)m_\rho^2}\left[\frac{\vec{q}^2+m_\pi^{*2}}{\vec{q}^2+m_\rho^{*2}}-\frac{\vec{q}^2+m_\pi^{*2}}{\vec{q}^2-q_c^2+m_\rho^{*2}}\right] \ , \tag{4}$$

with $c_S=2$ and $c_T=-1$. Above $m^{*2}=m^2-\omega^2$ is an effective mass, corrected for the energy transfer ω; $q_c \simeq m_\omega$ (i.e., the

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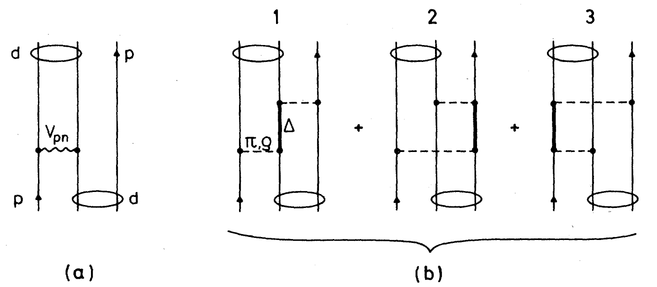

FIG. 1. One-nucleon exchange (a) and Δ-rescattering contribution (b) to the pd→ dp amplitude.

mass of the omega meson) sets the scale for the short range correlations; finally

$$f(q^2)=f(q^2=m^2)(\Lambda^2-m^2)/(\Lambda^2-q^2) \qquad (5)$$

involves the phenomenological cutoff mass Λ (note that $q^2=\omega^2-q^2$; f is the meson-NN, f^* the meson-ΔN coupling constant). We remark that contrary to the well established π,ρ exchange mechanism,[9,10] the parametrization of the very short range part of the ΔN interaction and its interplay with finite range corrections involves severe phenomenology; prescriptions different from the one used above can be found in the literature.[11] For the isobar poropagator we follow the parametrization of Ref. 12

$$G_\Delta(j)=G_\Delta=F_\Delta(k^2)/[M_\Delta-i\Gamma_\Delta(\omega)/2-E_p-\Sigma_\Delta] \ , \qquad (6)$$

with $\Gamma_\Delta(\omega)=\Gamma_{\exp}(k/k_R)^3$ (thereby E_p denotes the total energy of the incoming proton in the overall c.m. system; furthermore we use $\Gamma_{\exp}=120$ MeV) and include corrections for the Δ isobar off its pole via the form factor

$$F_\Delta(k^2)=\frac{\Lambda_\Delta^2+k_R^2}{\Lambda_\Delta^2+k^2} \qquad (7)$$

both in the numerator and in the isobar width (above $k_R\simeq 230$ MeV/c and k are the pion momentum at the Δ pole and for the actual energy of the Δ in the reaction, respectively). In addition, we allow for moderate medium corrections for the Δ isobar by the self-energy term $\Sigma_\Delta=30$ MeV $+i20$ MeV (compare Ref. 13).

Given $T_{M\mu}^{M'\mu'}$, the experimental quantities are easily derived; referring for details to Ref. 14, here we only quote the structure of the tensor polarization, given—in the Madison convention[15]—by

$$T_{20}=\frac{1}{\sqrt{2}}\frac{\sum\limits_{M\mu\mu'}(|T_{M\mu}^{1\mu'}|^2+|T_{M\mu}^{-1\mu'}|^2-2|T_{M\mu}^{0\mu'}|^2)}{\sum\limits_{MM'\mu\mu'}|T_{M\mu}^{M'\mu'}|^2} \ . \qquad (8)$$

In the actual calculation, we simplified the numerics for the rescattering term by choosing the momenta $\vec{q}$ and $\vec{q}\,'$ of the virtual mesons along the scattering axis (defined by the asymptotic momentum of the proton). As in the plane wave limit with the Fermi motion neglected, the particular kinematics of the scattering process indeed forces the meson-exchange along the scattering axis, we expect our approximation to be excellent for pd backward scattering around and above the Δ-isobar region.

Typical results of our calculation are presented in two of the figures. Figure 2 shows the differential cross section and T_{20} as a function of the kinetic energy of the proton. As elementary input parameters $f_\pi^2/4\pi=0.08$, $f_\pi^{*2}/4\pi=0.27$ (Ref. 16), $\Lambda_\pi=530$ MeV, and $\Lambda_\Delta=200$ MeV were used together with the deuteron wave function generated from the Paris potential[17] (the low cutoff mass for the πNN and the πNΔ vertex, which is in line with estimates in the cloudy bag model,[18] reflects to some extent the omission of the ρ-meson exchange and other short range exchanges, as pointed out below in context with Fig. 3). Note that the nonrelativistic momentum transfer variable

$$\vec{q}=\vec{k}_p-\vec{k}_d/2 \qquad (9)$$

was used; initial and final state interactions were not included.

As seen from the results, both the one-nucleon exchange amplitude (ONE) and the meson-exchange contribution (TME) are very energy dependent and of different influence on the differential cross section and the tensor polarization. At low proton energies, there is a clear dominance of the ONE term in both observables; with serious discrepancies both in the cross section (which is overestimated by more than a factor of 2) as well as in T_{20} (the first minimum

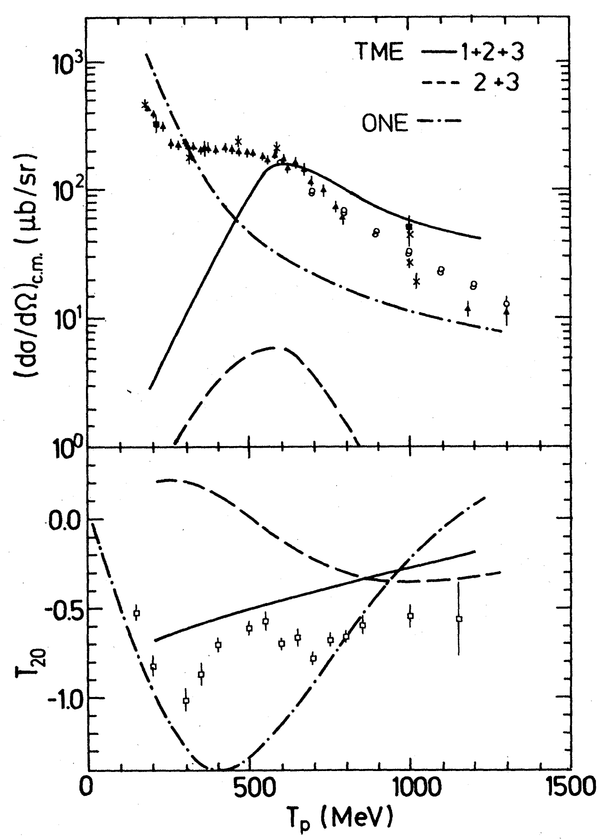

FIG. 2. Contribution of the pion-induced Δ-rescattering piece (TME) and the ONE amplitude to the differential cross section and the tensor polarization T_{20} as a function of the proton energy T_p in the laboratory system. For the rescattering mechanism, the full contribution (full line) is compared to the contribution from diagrams 2 and 3 (dashed line; further details are given in the text).

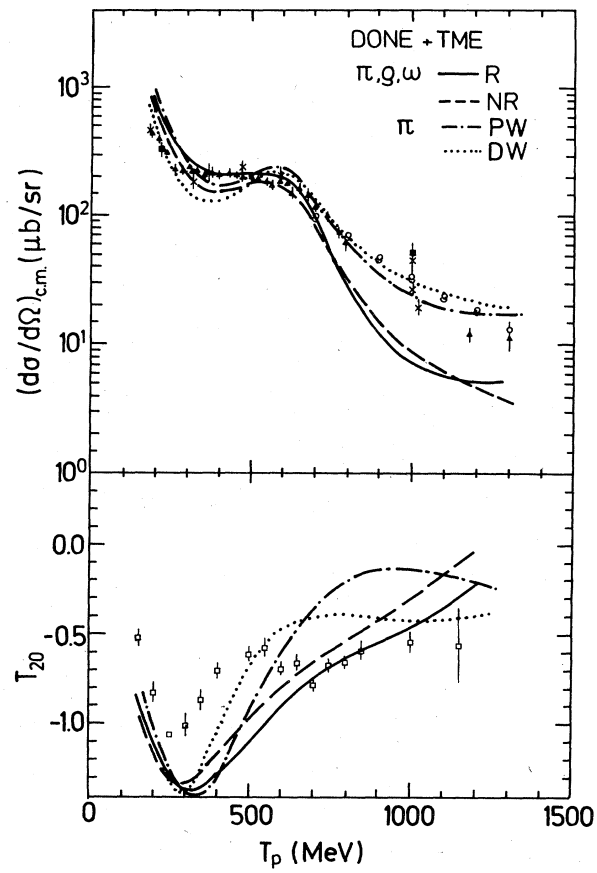

FIG. 3. Sensitivity of the experimental observables in pd → dp to different microscopic agencies. The full TME contribution, with DW included in the ONE term (DONE), for the R (full line) and NR (long dashed line) of the momentum transfer variable are presented and compared with the pion-induced rescattering contribution alone for the nonrelativistic momentum transfer with PW (dashed-dotted lines) and DW (short dashed line) in the ONE amplitude (for further details see text).

shows up at too large proton energies and is too steep). At intermediate energies around 600 MeV there is a clear dominance of the TME (evidently the Δ-isobar excitation is responsible for the shoulder in the differential cross section), which persists for the tensor polarization to the higher energies, whereas in the cross section the ONE mechanism gains comparable importance for $T_p \gtrsim 1$ GeV. Furthermore, the T_{20} is rather sensitive to subtle details as a comparison of the full meson-exchange calculation with the contribution from diagram 2 and 3 [Fig. 1(b)] demonstrates.

Typical results from the full calculation, which includes coherently the ONE piece and the TME, are shown in Fig. 3. In addition, the calculation includes distorted waves (DW) from initial and final state interactions in the ONE amplitude in form of an effective deuteron wave function

$$\tilde{\phi}_M(\vec{q}) = \phi_M(\vec{q}) - i(U+iW)\frac{2R_d E_d}{(2\pi)^{3/2}k_d} \times \int e^{i\vec{q}\cdot\vec{r}}\rho_d(\vec{r})\phi_M(r)\,d\vec{r} \qquad (10)$$

with the parameters U and W from Ref. 19 [above R_d and $\rho_d(\vec{r})$ represent the radius and the density of the deuteron]. Multiple scattering corrections, which are expected to be very important at low energies, where the ONE term dominates, were left out in the TME amplitude to reduce double counting.

The main results of the comparison with the experiment are as follows. We find good agreement with data for the pion-induced rescattering contribution, if DW are included (we use the same cutoff mass and the nonrelativistic momentum transfer variable as for Fig. 2), both the absolute normalization of the differential cross section at low energies as well as the position of the first minimum in T_{20} are better reproduced (compare the short-dashed line (DW) and the dotted-dashed line [plane waves (PW)]). Unfortunately, a more elaborate calculation of the TME term, including ρ exchange and short range correlations, does not improve the agreement with experiment: for cutoff masses and coupling constants taken from a similar calculation of proton-induced pion production on the deuteron[20] (with $f_\rho^2/4\pi = 4.9$, $f_\rho^* = 1.7 f_\rho$; $\Lambda_\pi = 1200$ MeV, and $\Lambda_\rho = 1500$ MeV) both the cross section and the tensor polarization vary too strongly at energies above 1 GeV. A semirelativistic calculation of the effective momentum transfer[21]

$$|\vec{q}| = \frac{1}{2M_d}\{[u-(M_d-M_p)^2][u-(M_d+M_p)^2]\}^{1/2}, \qquad (11)$$

with $u = (E_p - E_d)^2 - (\vec{k}_p - \vec{k}_d)^2$, influences the result quantitatively [full line (R)], without changing the gross features [the dashed line (NR) refers to the same calculation with the nonrelativistic $\vec{q}$ from Eq. (9)].

We summarize our main findings: a microscopic model, with one-nucleon exchange; Δ, isobar induced three-body interactions;[22] and multiple scattering corrections in lowest order, qualitatively accounts for the experimental pd → dp data. In particular, T_{20} shows an improvement both at low energies—with the first minimum closer to the experimental value—as well as a higher energies, reaching beyond $T_p = 1.5$ GeV a fairly negative plateau around $T_p = -0.4$. Unfortunately, the results are sensitive to many subtle details. Most urgently needed is a relativistic evaluation of both the one-nucleon (compare Ref. 23) and the rescattering term as well as a more realistic model for the short ranged NΔ interaction. Beyond that, especially with respect to the second dip in T_{20} at $T_p \simeq 0.7$ GeV, the model has to be supplemented by additional mechanisms—a natural extension includes virtual and real (i.e., near mass shell) excitations of higher resonances or the double $\Delta\Delta$ excitation —prior to more exotic components like di- or tribaryon resonances.[24]

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