Projectile Δ excitations in ^{1}H$(p,n)N\pi$ reactions

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It has recently been proved from measurements of the spin-transfer coefficients D_{xx} and D_{zz} that there is a small but nonvanishing $\Delta S=0$ component σ_0 in the inclusive $p(p,n)N\pi$ differential reaction cross section σ in the forward direction. It is shown that the dominant part of the measured σ_0 at forward neutron angles can be explained in terms of the projectile Δ excitation mechanism. An estimate is further made of contributions to σ_0 from s-wave rescattering processes. It is found that the s-wave rescattering contribution is much smaller than the contribution coming from the projectile Δ excitation mechanism. The addition of an s-wave rescattering contribution to the dominant part, however, improves the fit to the data. [S0556-2813(96)04008-3]

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The $p(p,n)N\pi$ reaction at intermediate energies has been a subject of a number of studies from both experimental [1–5] and theoretical [6–9] point of views. The understanding of the reaction is important in its own sake; it is one of the basic processes in intermediate energy nuclear physics. One of the dynamical processes involved in the reaction is the *projectile* Δ *excitation process* [in the following, we abbreviate this process as the PDP (the PDP is defined as the projectile Δ excitation process)]. The PDP is usually ignored in inclusive (p,n) cross section σ calculations, since for forward angles σ is dominated by the contribution coming from the *target* Δ *excitation process* [in the following, we abbreviate this process as the TDP (the TDP is defined as the target Δ excitation process)]. The contribution from the PDP for forward neutron angles gives only a small correction to the dominant TDP cross section. Therefore, it has been difficult to test the predicted PDP cross section by the inclusive cross section data.

Recently, however, several measurements of the spin-transfer coefficients D_{xx} and D_{zz} have been made [1,2,5]. Using these coefficients, it is possible to extract the no-spin-transfer ($\Delta S=0$) component σ_0 from the inclusive cross section σ. In fact, we show that the extracted σ_0 from the inclusive cross section σ and spin transfer coefficients [see Eq. (1)], can be explained well in terms of the PDP. In the present study, we restrict our interests to the zero degrees case, i.e., the case where the neutron is emitted at zero-degree ($\theta_n=0°$) with respect to the incident beam. Under this restriction, σ_0 can be expressed in terms of the observed inclusive cross section σ and the spin-transfer coefficients D_{xx} and D_{zz} as

$$\sigma_0=\frac{1}{4}\sigma(1+2D_{xx}+D_{zz}). \tag{1}$$

In order to present the theoretical cross sections σ_0 and σ, let us denote the $p(p,n)N\pi$ reaction as $a+A\rightarrow b+B+\pi^\alpha$, where a (b) and A (B) denote the projectile (ejectile) and target (residual nucleus), respectively, and π^α is the emitted pion that carries the charge α. In the center of mass system, the differential inclusive cross section σ may be written as

$$\sigma=\frac{d^2\sigma}{dE_b d\Omega_b}\Big|_{\theta_b=0}=\frac{m_a m_b m_A m_B}{(2\pi)^5 2\sqrt{s}}\frac{p_b}{p_a}\int d\Omega_\pi^d\frac{p_\pi^d}{s_d}\overline{|T|^2}, \tag{2}$$

where m_i and p_i ($i=a,b,A,B$) are the mass and the four-momentum of the particle i, s_d is the invariant mass of the final $N+\pi$ system, and $s=(p_a+p_A)^2$. Further, Ω_π^d and p_π^d are the solid angle and the momentum of the emitted pion in the $N+\pi$ rest frame, while T is the Lorentz-invariant transition amplitude. $\overline{|T|^2}$ means to take the sum over both initial and final spin states and the average over the initial spin states, namely,

$$\overline{|T|^2}=\frac{1}{4}\sum_{\text{all spin}}|T|^2. \tag{3}$$

All possible diagrams for Δ excitation processes are shown in Figs. 1(a)–1(d), where p_1 and p_2 denote the four-momenta of the projectile and target protons, respectively. Then it is clear that Figs. 1(a) and 1(c) represent the diagrams for the TDP and PDP processes, respectively, while Figs. 1(b) and 1(d) are the corresponding exchange diagrams coming from the antisymmetrization of the incident and target protons. The contributions from these exchange diagrams for the (p,n) reaction to the forward direction are expected to be negligibly small and hence we neglect the contributions in the present calculations. Note, however, that we take into account the s-wave rescattering processes as schematically shown in Figs. 1(e) and 1(f).

The Δ excitation processes [for both the PDP and TDP in Figs. 1(a) and 1(c), respectively] are treated by means of the transition amplitude $\hat{t}_{NN,N\Delta}$ used in Ref. [10] and Δ decay Hamiltonian. The explicit form of $\hat{t}_{NN,N\Delta}$ is

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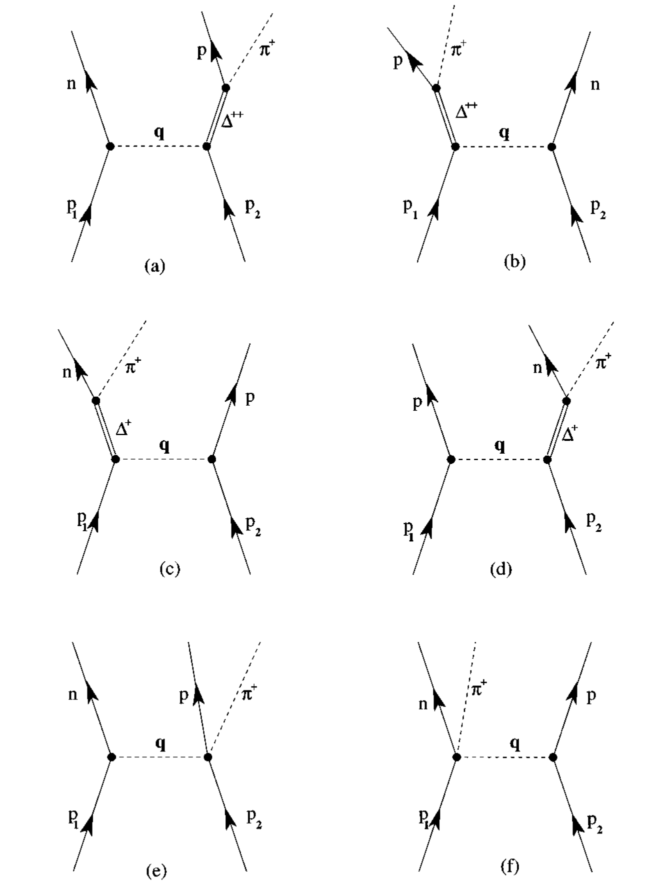

FIG. 1. Feynman diagrams for $p(p,n)N\pi$ reaction. (a), (b), (c), and (d) show the p-wave interaction (Δ excitations) in the target and the projectile, respectively, while (e) and (f) show s-wave rescatterings in the target and the projectile. p_1 and p_2 are the four-momenta of the projectile and target protons, respectively.

$$\hat{t}_{NN,N\Delta}=V_L(\hat{q}\cdot\vec{\sigma})(\hat{q}\cdot\vec{S}^\dagger)+V_T(\hat{q}\times\vec{\sigma})\cdot(\hat{q}\times\vec{S}^\dagger), \tag{4}$$

where $\hat{q}$ is a unit vector whose direction is that of the momentum transfer involved in the excitation process, $\vec{\sigma}$ is the Pauli spin operator, and $\vec{S}^\dagger$ is the spin operator for the $N\rightarrow\Delta$ transition. V_L and V_T are the strength parameters of the spin-longitudinal (LO) and spin-transverse (TR) directions which are used in Ref. [10]. These are parametrized as

$$V_L\approx V_T=t'_{N\Delta}J_{\pi N\Delta}\left(\frac{\Lambda_\pi^{\prime 2}-m_\pi^2}{\Lambda_\pi^{\prime 2}-t}\right)^2. \tag{5}$$

The strength parameter $t'_{N\Delta}$ and the cutoff mass Λ'_π are adjusted to experimental data such as $p(p,n)\Delta^{++}$ and $p(^3\mathrm{H}_e,t)\Delta^{++}$ (see Sec. III A of Ref. [10] for details). The coupling $J_{\pi N\Delta}=f_{\pi\pi N}f_{\pi N\Delta}/m_\pi$. The Hamiltonian for the Δ decay is

$$H_{\pi N\Delta}=\frac{f^*}{\mu}(\vec{p}_\pi\cdot\vec{S}^\dagger)T^\alpha+\mathrm{H.c.}, \tag{6}$$

where μ denotes pion mass and T^α is isospin transition operator with charge α. For the coupling constant we take $f^{*2}/4\pi=0.36$.

The s-wave rescattering processes are calculated as in Ref. [11]. The basic couplings in this process are $NN\pi$ coupling and $N\pi\rightarrow N\pi$ s-wave amplitude. The $NN\pi$ coupling is given by

$$H_{\pi NN}=\frac{f}{\mu}(\vec{p}_\pi\cdot\vec{\sigma})\tau^\alpha, \tag{7}$$

where $\vec{p}_\pi$ is the momentum of the pion and the coupling is given as $f^2/4\pi=0.08$. The Hamiltonian for the s-wave $N\pi\rightarrow N\pi$ is given as

$$H_{\pi\pi NN}=4\pi\delta_{m_s m_s'}\left\{\frac{2\lambda_1}{\mu}\delta_{m_t m_t'}\delta_{\lambda\lambda'}+i\epsilon_{\alpha\lambda\lambda'}\frac{2\lambda_2}{\mu}\langle m_t'|\tau^\alpha|m_t\rangle\right\}, \tag{8}$$

where the indices m_s,m_s',m_t,m_t' are the spin and isospin variables of the incoming and outgoing nucleons. For the couplings, we take [11]

$$\lambda_1=\lambda_1'+0.000\,222[\mathrm{MeV}^{-1}](\sqrt{s}-\mu-M),$$
$$\lambda_1'=0.0075,\quad \lambda_2=0.0528, \tag{9}$$

where s is the Mandelstam variable for the πN system and M is the nucleon mass.

The total T amplitude can then be given as

$$-iT=\sum_{s_1\mu_1s_2\mu_2}(-1)^{1/2-m_a}\langle\tfrac{1}{2},m_b;\tfrac{1}{2},-m_a|s_1,\mu_1\rangle(-1)^{1/2-m_A}\langle\tfrac{1}{2},m_B;\tfrac{1}{2},-m_A|s_2,\mu_2\rangle C_{s_1\mu_1s_2\mu_2}, \tag{10}$$

where (s_1,μ_1) and (s_2,μ_2) represent the spin transfers involved in the $a\rightarrow b$ and $A\rightarrow B$ transition processes, respectively. The partial amplitude $C_{s_1\mu_1s_2\mu_2}$ may be decomposed into the two contributions $A_{s_1\mu_1s_2\mu_2}$ and $B_{s_1\mu_1s_2\mu_2}$, coming from the Δ excitation and s-wave rescattering processes, respectively:

$$C_{s_1\mu_1s_2\mu_2}=A_{s_1\mu_1s_2\mu_2}+B_{s_1\mu_1s_2\mu_2}, \tag{11}$$

where

$$A_{0000}=0.0, \tag{12}$$

$$A_{1\mu00}=-\frac{4}{3}\frac{f}{\mu}\{(\hat{q}\cdot\vec{p}_\pi)\hat{q}_\mu^*V_L+[\vec{p}^*_{\pi\mu}-(\hat{q}\cdot\vec{p}_\pi)\hat{q}^*_\mu]V_T\}G_tC_t, \tag{13}$$

$$A_{001\mu}=\frac{4}{3}\frac{f}{\mu}\{(\hat{q}'\cdot\vec{p}_\pi')\hat{q}'^*_\mu V_L+(\vec{p}'^*_{\pi\mu}-(\hat{q}'\cdot\vec{p}_\pi')\hat{q}'^*_\mu]V_T\}G_pC_p, \tag{14}$$

$$A_{1\mu_1 1\mu_2}=-\frac{2\sqrt{2}}{3}\frac{f}{\mu}[\hat{q}^*_{\mu_1}(\hat{q}\cdot\vec{p}_\pi)^*_{\mu_2}(V_L-V_T)G_tC_t+ (-1)^{\mu_1}\langle 1,-\mu_1;1,\nu_2|\,1,\mu_2\rangle p^*_{\pi\nu_2}V_TG_tC_t -\hat{q}'^*_{\mu_2}(\hat{q}'\cdot\vec{p}'_\pi)^*_{\mu_1}(V_L-V_T)G_pC_p +(-1)^{\mu_2}\langle 1,-\mu_2;1,\nu_2|\,1,\mu_1\rangle p'^*_{\pi\nu_2}V_TG_pC_p, \tag{15}$$

$$B_{s_1\mu_1 s_2\mu_2}=8\pi\frac{f}{\mu}[-\delta_{s_1 1}\delta_{s_2 0}\hat{q}^*_{\mu_1}\sqrt{2}\lambda_+ +\delta_{s_1 0}\delta_{s_2 1}\hat{q}'^*_{\mu_2}\lambda_0 D_\pi F_\pi. \tag{16}$$

In the above expressions, λ_0 and λ_+ are given as

$$\lambda_0=-\frac{2\sqrt{2}}{\mu}\lambda_2,\quad \lambda_+=\frac{2}{\mu}(\lambda_1+\lambda_2), \tag{17}$$

C_i is the isospin factor for $\pi N\Delta$ vertexes which are given as $C_t=-\sqrt{2}$ and $C_p=-\sqrt{2}/3$, and the index i refers to both target (t) and projectile (p) Δ excitations. The propagators and the pion form factor are defined as

$$G_i=\frac{1}{\sqrt{s_i}-M_\Delta+i\Gamma(s_i)/2},\ \Delta\ \text{propagator}, \tag{18}$$

$$D_\pi=\frac{1}{\omega^2-q^2-\mu^2},\ \pi\ \text{propagator}, \tag{19}$$

$$F_\pi=\frac{\Lambda^2-m_\pi^2}{\Lambda^2-t},\ \pi NN\ \text{form factor with}\ \Lambda=1200\ \text{MeV}. \tag{20}$$

It is then easy to see that

$$\overline{|T|^2}=\frac{1}{4}\sum_{s_1\mu_1 s_2\mu_2}|C_{s_1\mu_1 s_2\mu_2}|^2. \tag{21}$$

We further note that σ_0 can be evaluated by simply picking up the component with $(s_1,\mu_1)=(0,0)$, which comes from both PDP and s-wave rescattering from the projectile. Thus, defining $\overline{|T_0|^2}$ as

$$\overline{|T_0|^2}=\frac{1}{4}\sum_{s_2\mu_2}|C_{00s_2\mu_2}|^2, \tag{22}$$

σ_0 can be given as

$$\sigma_0=\frac{d^2\sigma_0}{dE_b d\Omega_b}\Big|_{\theta_b=0}=\frac{m_a m_b m_A m_B}{(2\pi)^5 2\sqrt{s}}\frac{p_b}{p_a}\int d\Omega_\pi^d\frac{p_\pi^d}{s_d}\overline{|T_0|^2}. \tag{23}$$

Figures 2(a) and 2(b) show the final results of σ and $R\equiv\sigma_0/\sigma$. They are compared with the experimental data. The solid lines are our final results including both PDP and s-wave scattering, while the dotted line shown in Fig. 2(b) represents the result obtained when only the contribution from PDP is taken into account. obtaining Comparing the two theoretical cross sections in Fig. 2(b), it can be seen that the PDP dominates σ_0. The contribution from the s-wave rescattering process to σ_0 is thus small, though it helps to improve the fit of the calculated final σ_0 to the experimental data, particularly at the off-resonance region. The experimental inclusive cross section data σ^{expt} are taken from Ref. [5], while the experimental R (R^{expt}) are obtained by D_{xx} and D_{zz} of Refs. [2,5] and σ^{expt} of Ref. [5]. As seen in the Fig. 2(a), σ^{expt} is reproduced very well by the calculation. In the resonance region, the R^{expt} values are rather small, $R^{\text{expt}}\approx 0.025$, implying that σ^{expt} contributes only about 2.5% to the total exclusive cross section. However, R^{expt} becomes larger at both tail regions of the resonance.

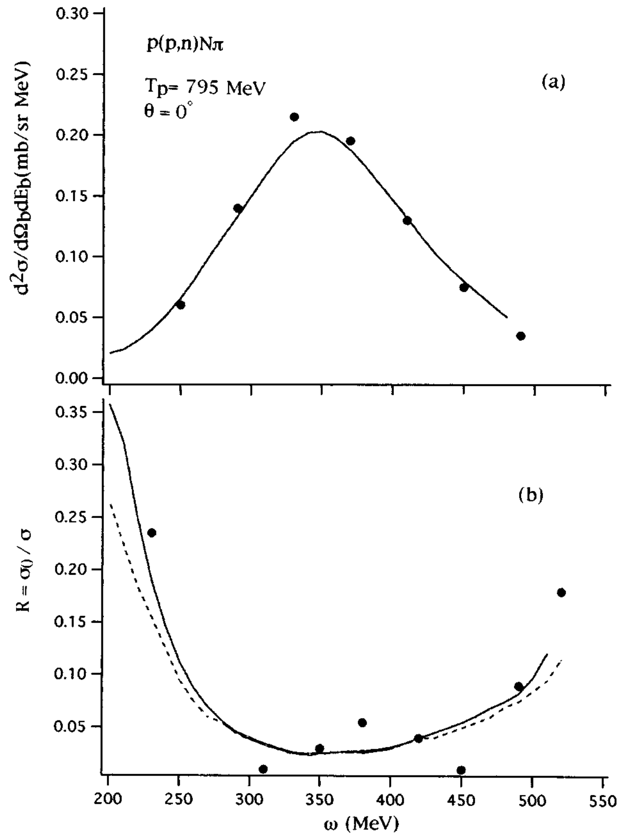

FIG. 2. Zero-degree neutron spectra for the reaction $p(p,n)N\pi$ at $E_p=795$ MeV. The inclusive cross section (a) and the ratio $R=\sigma_0/\sigma$ (b) are shown. See text for details.

The good fit of the calculated R to the data seems to support strongly that the observed σ_0 indeed comes from the PDP. This conclusion is further supported by the data of R for nuclear targets available for the d, ^{12}C, ^{40}Ca, and ^{208}Pb targets. In the case of the deuteron target, for example, the R^{expt} values are larger by a factor of about 2–4 as compared with those of the proton target. The R values for other nuclear targets are about the same as those of the deuteron target. The observed increase of the R values for the nuclei target may be easily understood if one assumes that σ_0 comes from the PDP. Since the dominant part of σ comes from the TDP, σ for the deuteron target is expected to be about 4/3 times of that for the proton target due to isospin, while σ_0 of the deuteron should be about 4 times of σ_0 for the proton target. Thus, it is expected that the R values may become larger by a factor of about 3 for the deuteron target case, as compared with the proton target case. This agrees very well with the experimental factor of 2–4. Since the ratio of the number of protons to that of neutrons contributing to the reaction may roughly stay as unity, the R value for the heavy nuclei should roughly be equal to that of the deuteron target case, which also agrees with the observation.

Finally, we remark that σ_0 may come from the TDP via the $\Delta S=0$ interaction term involved in the $\hat{t}_{NN,\Delta N}$. Such a term has recently been determined from the analysis of the $p(p,n)\Delta^{++}$ reaction data [9]. Using the $\hat{t}_{NN,\Delta N}$ operator determined in Ref. [9], one can estimate σ_0. It has been found that both the magnitude and energy dependences of σ_0 thus estimated do not fit the data very well; the magnitude is larger by about a factor of 2 than R^{expt}, and also the ω dependence is quite different from what is observed. This might have been caused by the fact that the analysis made in Ref. [9] is done without taking into account the PDP.

In summary, we have shown that σ_0, deduced from the data of the spin-transfer data D_{xx} and D_{zz} together with the inclusive cross section σ, can be well explained by the calculations that take into account the PDP and s-wave rescattering effects.

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