# Spin Decomposition of the Δ Resonance Cross Section Using the $^{12}C(\vec{p},\vec{n})$ Reaction at $E_p = 795$ MeV

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The first $(p,n)$ polarization-transfer measurements for delta production on a nuclear target are presented for the $^{12}C(\vec{p},\vec{n})$ reaction at 0° and 795 MeV. Polarization observables are used to extract the spin-longitudinal, spin-transverse, and spin-independent partial cross sections. In the spin-longitudinal channel, fair agreement is found between experiment and a model which includes a strongly attractive residual interaction. A large unexpected enhancement in the spin-transverse cross section is observed. [S0031-9007(96)00416-4]

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A prominent feature of double differential cross section spectra resulting from the $(p,n)$ and $(^3\text{He},t)$ reactions at sufficiently high beam energies is a broad peak attributed to excitation of the Δ resonance [1]. This peak appears at a significantly smaller value of energy loss $\omega$, the difference between projectile and ejectile energies, for nuclear targets compared to the proton target. These charge exchange reactions excite both the isovector spin-longitudinal ($\boldsymbol{S}\cdot\hat{\boldsymbol{q}}$) and spin-transverse ($\boldsymbol{S}\times\hat{\boldsymbol{q}}$) nuclear responses. In contrast, electromagnetic probes excite the Δ resonance through a predominantly spin-transverse coupling. Cross section data taken using these probes reveal little energy shift in the Δ resonance peak position in nuclear targets compared to the proton. This suggests that collectivity in the spin-longitudinal channel, arising from an attractive pion field [2] could be responsible for the shift seen using the $(^3\text{He},t)$ and $(p,n)$ reactions [3,4]. This interpretation is also supported by recent theoretical results [5,6] and by several experiments which are discussed below. Measurements that can isolate the spin-longitudinal component of the nuclear response for Δ production will contribute significantly to our understanding of mesonic fields in the nucleus [1].

Details of the nuclear spin response may be investigated through measurements of polarization-transfer (PT) observables [7]. We report the first measurement of $(\vec{p},\vec{n})$ PT observables for the Δ resonance in nuclear targets [8], from which separate spin-longitudinal and spin-transverse partial cross sections have been extracted.

The data were taken with the neutron time-of-flight (NTOF) Facility at the Los Alamos Meson Physics Facility. The PT observables $D_{NN}$ and $D_{LL}$ were measured for the $(\vec{p},\vec{n})$ reaction on natural C (98.9% $^{12}$C) and $CD_2$. Differential cross section spectra were measured for $CH_2$, $CD_2$, C, and $^7$Li. The proton beam energy was 795 MeV with a beam current between 20 and 40 nA and a typical polarization of 0.65. The scattering angle was 0° and the neutron flight path was 200 m. Cross section measurements were normalized to the $^7\text{Li}(p,n)^7\text{Be}$(g.s. + 0.43-MeV) transition at 0° [$\sigma_{\text{c.m.}}(0°) = 27$ mb/sr] [9].

A formal definition of the expressions we use to extract the partial cross sections from our data is set forth in Refs. [10,11]. These cross sections are defined with respect to a set of center-of-mass unit vectors and represent the cross section for flipping the nucleon spin along each of these vectors. The vector $\hat{\boldsymbol{n}}$ is normal to the scattering plane, $\hat{\boldsymbol{q}}$ is in the direction of momentum transfer, and $\hat{\boldsymbol{p}} = \hat{\boldsymbol{q}}\times\hat{\boldsymbol{n}}$. At 0° these partial cross sections may be obtained from the PT observables and the unpolarized cross section ($I_u$) according to

$$I_0 = \tfrac{1}{4}I_u(1 + 2D_{NN} + D_{LL}), \quad (1)$$

$$I_q = \tfrac{1}{4}I_u(1 - 2D_{NN} + D_{LL}), \quad (2)$$

$$I_p = I_n = \tfrac{1}{4}I_u(1 - D_{LL}), \quad (3)$$

where $I_0$, $I_q$, $I_p$, and $I_n$ correspond to the spin-independent, spin-longitudinal, and two spin-transverse partial cross sections, respectively. [These relations can be obtained from Eqs. (12)–(15) in Ref. [10] by setting $\theta_p = \pi/2$.]

We compare our data to the results of a finite-nucleus calculation that uses the distorted waves impulse approximation (DWIA) [7]. Delta production is treated

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using the isobar-hole model, and nuclear correlations are accounted for in the Tamm-Dancoff approximation through a particle-hole residual interaction ($v_{\rm ph}$) based on the "$\pi + \rho + g'$" model also used in calculations of quasielastic responses [12]. The residual interaction contains delta-hole ($\Delta N^{-1}$) couplings with $g'_{NN} = 0.6$ and $g'_{\Delta N} = g'_{\Delta\Delta} = 0.4$. The calculated residual interaction in the spin-transverse (rho) channel is mildly repulsive, which results in a decrease in the magnitude of the calculated $\Delta$ resonance spin-transverse cross section ($I_p + I_n$) and produces a small shift in the peak of this cross section to higher energy loss. The spin-longitudinal (pion) interaction is strongly attractive causing an increase in the magnitude of the calculated spin-longitudinal cross section ($I_q$) and a shift in the location of the peak of the $\Delta$ resonance to lower energy loss. The correlations considered in the spin-longitudinal channel are closely associated with the presence of an enhanced pion field in nuclei [2].

For the distorted waves calculations the following form for the nucleon-delta transition amplitude has been used:

$$t_{NN,N\Delta} = \beta''\boldsymbol{\sigma} \cdot \hat{\boldsymbol{n}}\boldsymbol{S} \cdot \hat{\boldsymbol{n}} + \varepsilon''\boldsymbol{\sigma} \cdot \hat{\boldsymbol{p}}\boldsymbol{S} \cdot \hat{\boldsymbol{p}} + \delta\boldsymbol{\sigma} \cdot \hat{\boldsymbol{q}}\boldsymbol{S} \cdot \hat{\boldsymbol{q}}\,, \quad (4)$$

where $\boldsymbol{S}$ is a vector spin operator for the transition of a spin-$\frac{1}{2}$ target nucleon to a spin-$\frac{3}{2}$ delta and is a generalization of the Pauli matrices. We have used $\varepsilon'' = \beta'' = \delta = t'_{N\Delta} J_{\pi N\Delta}[(\Lambda'^2_\pi - m^2_\pi)/(\Lambda'^2_\pi - \omega^2 + q^2)]^2$ and $J_{\pi N\Delta} = 800$ MeV fm$^3$. The strength parameter $t'_{N\Delta}$ and the cutoff mass $\Lambda'_\pi$ are adjusted to reproduce the $^1$H$(p,n)$ double differential cross section measured during this experiment. The theoretical results displayed in all the figures were calculated with the value of $t'_{N\Delta}$ set to 0.69 and the value of $\Lambda'_\pi$ set to 650 MeV. The values of $D_{LL}$ and $D_{NN}$ from 0° PT measurements of the $^1$H$(p,n)$ reaction [13] are very close to $-\frac{1}{3}$. This value can only be obtained from Eq. (4) if $\varepsilon''$, $\beta''$, and $\delta$ are equal in magnitude [7]. Such a transition is a purely central spin-dependent excitation with one spin-longitudinal and two spin-transverse parts.

In a recent calculation, Ray [14] has indicated additional terms to those in Eq. (4) may contribute significantly to the spin-independent and spin-transverse cross sections. Of these additional amplitudes, the magnitude of the spin-independent term is the largest and is as large as the magnitude of each of the vector amplitudes shown in Eq. (4). Application of Eqs. (1) and (2) to the hydrogen data from Ref. [13] may provide a test of this assertion. In Table I we show the fractional contribution from each spin channel to the hydrogen and carbon cross section summed about the peak of the $\Delta$ resonance. Each of the spin-dependent partial cross sections contributes about $\frac{1}{3}$ of the cross section. The spin-independent carbon cross section is quite small implying only a weak contribution from this additional term. The strength of the additional spin-dependent amplitudes cannot be assessed; however, these amplitudes are effectively included in the two transverse terms, indicated by the double primes on the coefficients in Eq. (4).

TABLE I. The ratio of partial cross sections, $I_k$, to unpolarized cross section, $I_u$, over a 100 MeV bin around the delta resonance peak as determined through Eqs. (1) and (2) for the hydrogen data from Ref. [13] and for our carbon data.

| Ratio | $^1$H | C |
|---|---|---|
| $I_q/I_u$ | 0.318 ± 0.004 | 0.284 ± 0.006 |
| $I_p/I_u$ | 0.326 ± 0.002 | 0.310 ± 0.004 |
| $I_n/I_u$ | 0.326 ± 0.002 | 0.310 ± 0.004 |
| $I_0/I_u$ | 0.030 ± 0.005 | 0.100 ± 0.006 |

The dependence of the polarization observables on the relative strengths of the partial cross sections can be obtained from Eqs. (1) and (2). A purely spin-longitudinal cross section ($I_u = I_q$) would yield values of $+1$ for $D_{LL}$ and $-1$ for $D_{NN}$, while a purely spin-transverse cross section results in values of $-1$ and 0 for $D_{LL}$ and $D_{NN}$, respectively.

The carbon and hydrogen cross section data are shown in Fig. 1(a). The solid curve represents the full DWIA finite-nucleus calculation for carbon [7]. The difference in the peak position between carbon and hydrogen is 55 MeV. To produce the shift in the peak of the calculated carbon spectrum the value of $g'_{\Delta\Delta}$ in the residual interaction was set to 0.4. This is larger than the value of 0.33 used previously in Ref. [7]. The value of 0.4 is, however, still in agreement with an analysis [15] of the exclusive pion production cross section measured in the $^{12}$C($^3$He$, t\pi^+)^{12}$C$_{\rm g.s.}$ reaction [16]. The latter reaction is very sensitive to the spin-longitudinal response function. While in Fig. 1(a) the shape and peak position of the $\Delta$ resonance cross section are well reproduced by the result of the calculation, the magnitude of the calculated carbon cross section is significantly smaller than what is observed.

The measured and calculated PT observables for carbon are compared in Figs. 1(b) and 1(c). The solid curve represents the full DWIA calculation while the dotted line, $-\frac{1}{3}$, corresponds to the calculation performed without nuclear correlations ($v_{\rm ph} = 0$). For both $D_{LL}$ and $D_{NN}$ around 200 MeV energy loss, a significant difference exists between the results for the full calculation and the results obtained from the calculation with no residual interaction ($v_{\rm ph} = 0$). This difference arises from the increase in magnitude of the calculated spin-longitudinal response with respect to the spin-transverse response resulting from the effects of the residual interaction used in the full calculation. However, the experimental PT observables are not described well by the results of either calculation in this region of energy loss.

A possible reason for the disagreement between the data and the results of the full calculation can be seen by comparing the measured and predicted partial cross sections. The spin-transverse cross section shown in Fig. 2(b) is not

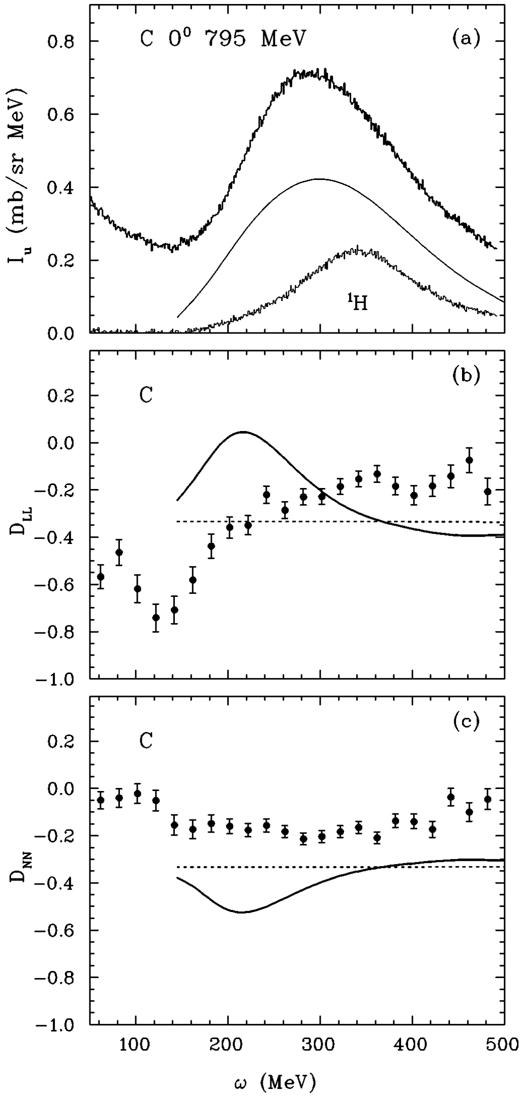


FIG. 1. In (a) the double differential cross sections for $^{12}$C$(p,n)$ (dark histogram) and $^1$H$(p,n)$ (light histogram) are shown. Below this appears the values for (b) $D_{LL}$ and (c) $D_{NN}$ for $^{12}$C$(\vec{p},\vec{n})$. The dark curves presented in these figures correspond to the result for the full (correlated) DWIA calculation that includes the residual interaction described in the text, while the dotted line in (b) and (c) represents the result from the same calculation with the residual interaction set to zero (uncorrelated).

reproduced by the results of either our full (solid) calculation or by our calculation performed with $v_{\rm ph}$ set to zero (dotted). The peak of this partial cross section appears at 30 MeV lower energy loss than the prediction, and the magnitude of the cross section is substantially smaller than the prediction. Conversely, the shape and magnitude of the observed spin-longitudinal cross section are reproduced reasonably well by the results of the full DWIA calculation, although the calculated cross section at an energy loss greater than the Δ resonance peak is too low by about 15%. The partial cross section data therefore reveal that the larger-than-expected cross section in Fig. 1(a) can be

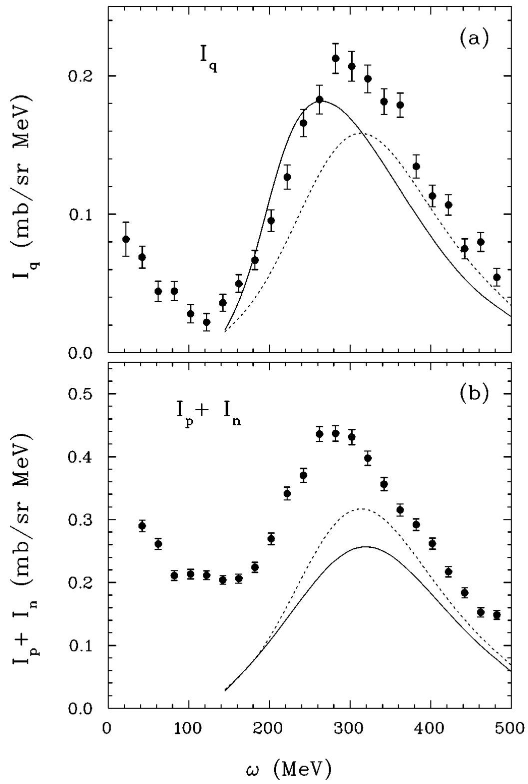


FIG. 2. The (a) spin-longitudinal and (b) spin-transverse partial cross sections for carbon are compared to the results of the DWIA calculations with (solid line) and without (dotted line) correlations.

attributed mainly to extra strength in the transverse channel. The extra transverse strength also tends to dominate the spin observables, $D_{NN}$ and $D_{LL}$, and thus masks the expected signature of correlations in the spin-longitudinal channel.

A study of deuterium and carbon using the $(\vec{d},2p)$ reaction determined the ratio of the isovector spin-transverse to spin-longitudinal partial cross section [17]. The ratios for deuterium and carbon were $1.71 \pm 0.09$ and $2.99 \pm 0.23$, respectively, and were reported to be constant over the region of the energy loss spectrum dominated by the Δ resonance. In a 35 MeV bin at the peak of the Δ resonance, we find a ratio of $1.68 \pm 0.14$ for our deuterium data and $2.15 \pm 0.06$ for carbon [8]. The ratio for the $^2$H$(\vec{p},\vec{n})$ reaction is consistent with that of the $^2$H$(\vec{d},2p)$ reaction. However, for our carbon data, this ratio rises substantially with decreasing energy loss.

The results presented here for the Δ resonance are closely related to and consistent with a recent report on the spin decomposition of the *quasielastic* scattering cross section using the $(\vec{p},\vec{n})$ reaction [18]. In that article, the spin-longitudinal and spin-transverse responses were compared to results of a DWIA calculation that employed residual interactions based on the $\pi + \rho + g'$ model. The calculated spin-longitudinal response was found to agree reasonably well with data, while in the spin-transverse channel the measured response was larger than the prediction by as much as a factor of 2. Contrary to previous conclusions [10,19], these data were thus judged to be consistent with theoretical predictions for the pion channel and do not rule out the existence of an attractive pion field in nuclei.

A more positive statement can be made concerning pion correlations in the excitation of the spin-longitudinal component of the $\Delta$ resonance. As in the experiment concerning quasielastic scattering just discussed, the agreement between the spin-longitudinal data and the results of the full DWIA calculation is only fair. However, it must also be noted that these data are consistent with the interpretation of exclusive measurements of coherent pion production performed at SATURNE and KEK [16,20]. The coherent pion production cross section [21,22] is well described by the same model [7,15] to which we compare our data. The combination of both experiments is quite suggestive of pion correlations.

The unexpectedly large spin-transverse cross section is also of high interest. Indeed, the spin-transverse channel dominates the cross section in the region of energy loss between 50 and about 200 MeV known as the “dip” region. The cross section in this region is not reproduced by the results of the calculation and probably arises from processes that are beyond the one-particle-one-hole (1p-1h) response assumed in the model [7].

Similarly, experimental studies of the $\Delta$ resonance using the $^{12}\mathrm{C}(e,e')$ reaction also show a significant spin-transverse cross section in the dip region [23], which has been attributed to 2p-2h excitations [24]. In addition, the results of exact calculations for quasielastic scattering using the $^{4}\mathrm{He}(e,e')$ reaction are in excellent agreement with data and show a strong enhancement in the transverse channel due to meson-exchange currents [25]. Such processes may account for the excess cross section in the spin-transverse channel we observe in our data. More theoretical work on the role of 2p-2h excitations and meson-exchange currents in hadron reactions is needed to help understand these data.

Together the quasielastic and quasifree delta resonance data present a consistent picture. In both sets of data, the longitudinal response is fairly well described by results of DWIA calculations that include an attractive residual interaction in the pion channel. On the other hand, in both data sets, more cross section in the spin-transverse channel is observed than expected. This consistent effect seen in both quasielastic scattering and quasifree delta production should stimulate some reevaluation of the roles played by mesonic fields in nuclei.

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