Sensitivity of quasielastic $(\vec{p},\vec{n})$ spin-transfer observables to relativistic Dirac effects

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Spin-transfer observables have been calculated for the quasielastic $(\vec{p},\vec{n})$ reaction according to the relativistic plane wave impulse approximation, using two different parametrizations of the *NN* interaction. The target nucleus is ^{40}Ca and the proton lab energies range from 135 to 500 MeV, while the momentum transfer is kept fixed at a (fairly large) value of 1.97 fm^{-1}. An analysis is made of the sensitivity of these spin observables with respect to relativistic Dirac effects, the form of the πN vertex and exchange contributions to the *NN* amplitudes. These sensitivities are found to be selective with respect to the different spin observables over the whole proton energy range. The results are also compared to those of the corresponding $(\vec{p},\vec{p}\,')$ reaction, which we formerly presented.

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In recent years considerable attention has been devoted to the measurement and interpretation of inclusive $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ polarization observables at the quasielastic peak [1–9]. At moderate momentum transfers ($q \geqslant 0.5$ fm^{-1}) quasielastic scattering is the dominant mechanism for nuclear excitation. This process is characterized by a broad structure in the excitation spectrum, with a centroid near an energy transfer $\omega \approx |\vec{q}|^2/2M$ (M being the free nucleon mass) corresponding to free nucleon-nucleon (*NN*) scattering and a width resulting from the initial momentum distribution of the struck nucleon in the nucleus. The mechanism is considered to be a single-step process whereby a projectile particle knocks out a single bound nucleon in a target nucleus while the remainder of the nucleons act as "spectators" [10]. Consequently these reactions offer a means to study how the fundamental free nucleon-nucleon interaction is modified by the surrounding medium of the nucleus in which it occurs.

Recently [11] we investigated the sensitivity of a complete set of quasielastic $(\vec{p},\vec{p}\,')$ spin observables (A_y, $D_{n'n}$, $D_{s's}$, $D_{l'l}$, $D_{s'l}$, and $D_{l's}$) with respect to relativistic Dirac effects, the form of the πN vertex, and exchange contributions to the *NN* amplitudes. For a fairly large fixed momentum transfer of 1.97 fm^{-1}, our chosen lab energies ranged from 135 to 500 MeV and target nuclei from ^{12}C to ^{208}Pb. We concluded that most $(\vec{p},\vec{p}\,')$ spin observables are sensitive to these effects at energies lower than 200 MeV.

In this paper we now also investigate the sensitivity of quasielastic $(\vec{p},\vec{n})$ spin observables with respect to the above mentioned effects. Compared to the $(\vec{p},\vec{p}\,')$ reaction, the quasielastic $(\vec{p},\vec{n})$ reaction is much "cleaner" because, within our model, it probes only the isovector parts of the *NN* interaction, whereas the $(\vec{p},\vec{p}\,')$ spin observables sample both isovector and isoscalar components. Furthermore, since the Lorentz character of the isovector amplitudes is totally different from the isoscalar amplitudes, one expects quasielastic $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ spin observables to exhibit different behavior with respect to the above-mentioned effects.

The spin observables are calculated within the framework of the relativistic plane wave impulse approximation (RPWIA) which treats the broad quasielastic peak as the scattering of the projectile proton by a single target nucleon in a Fermi gas nucleus [2]. Nuclear distortions of the plane wave are incorporated via effective projectile and target nucleon masses within the context of the mean field theory of Serot and Walecka [12]. These two masses were respectively calculated from optical and self-consistent Dirac potentials, both averaged over the dominant nuclear region for quasielastic scattering. This region, calculated by means of an eikonal approximation [1,13] of the incoming beam, was found to be in the nuclear surface where only a limited number of target nucleons effectively partake in the quasielastic scattering process.

We have used a Lorentz invariant parametrization of the *NN* interaction based on the standard five relativistic invariants (scalar, pseudoscalar, vector, axial-vector, and tensor: the so-called SPVAT form) where the free nucleon Dirac-spinor matrix elements of the invariant *NN* scattering operator are directly related to the conventional Wolfenstein amplitudes [14]. Relativistic or medium effects are incorporated by replacing the free nucleon masses with effective nucleon masses.

Since we are only investigating general trends, the spin observables for a quasielastic reaction are calculated for a typical target nucleus, say ^{40}Ca, and are presented in Figs. 1–3. The incident laboratory proton energies range from 135 to 420 MeV, at a fixed momentum transfer of 1.97 fm^{-1}. These parameter values are chosen in order to compare trends in the $(\vec{p},\vec{n})$ spin observables to the corresponding

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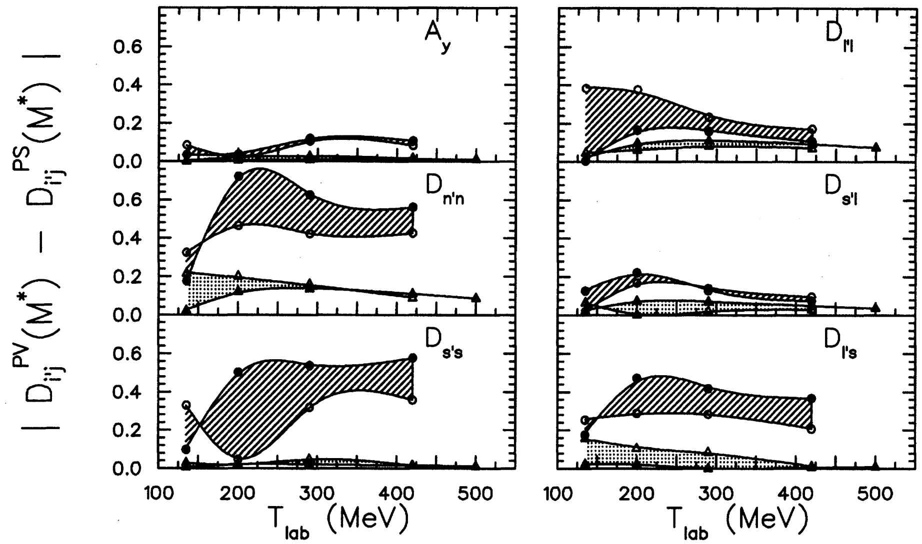

FIG. 1. The difference, $|D^{PV}_{i'j}(M^*) - D^{PS}_{i'j}(M^*)|$, between the spin-transfer $(\vec{p},\vec{n}')$ observables $D_{i'j}$ calculated with a pseudovector (PV) and a pseudoscalar (PS) term in the NN interaction, respectively, as a function of laboratory energy and *at the quasielastic peak*. The solid circles represent calculations based on method A (relativistic SPVAT parametrization of the NN amplitudes) whereas the open circles are calculated using method B (HLF model). The triangles, however, represent $(\vec{p},\vec{p}')$ spin observables; solid triangles for method A and open triangles for method B. The solid lines serve merely to guide the eye to one data set.

$(\vec{p},\vec{p}')$ results of Ref. [11], which are also presented in Figs. 1–3. Note that all figures display the spin observables at the centroid of the quasielastic peak. The quasielastic proton-nucleus spin observables are calculated in terms of NN amplitudes, evaluated at the equivalent energy of the projectile proton in the rest frame of the target nucleon [2], where the momentum distribution of the target nucleon is taken into account.

As in Ref. [11], we present two sets of calculations called method A and method B. Method A refers to a relativistic SPVAT parametrization of the NN amplitudes and method B employs the relativistic Horowitz-Love-Franey (HLF) model [15] for the NN interaction. The latter models the SVPAT nucleon-nucleon amplitudes as a sum of Yukawa-type terms and considers the direct and exchange contributions separately. The real and imaginary meson coupling constants and meson-nucleon cutoff parameters are constrained by fitting to the on-shell SVPAT values. Note that, although the SPVAT form is useful for impulse approximation applications [14,16], it is limited in that it does not address the exchange behavior of the NN amplitudes in the nuclear medium. Since published HLF parameters only exist at 135, 200, 300, 400, and 500 MeV, the present calculations employ the HLF parameter set closest to the effective laboratory kinetic energy.

We start by investigating the sensitivity of quasielastic

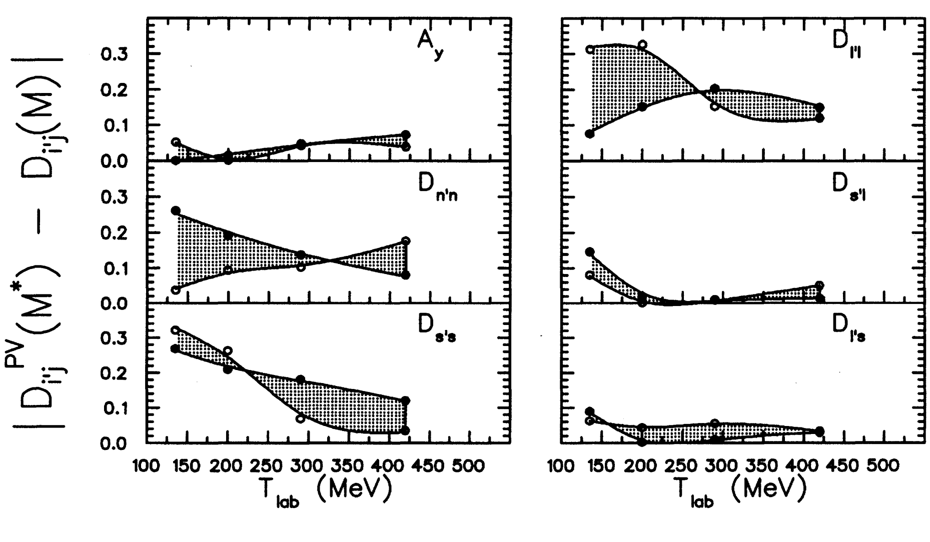

FIG. 2. The values of $|D^{PV}_{i'j}(M^*) - D^{PV}_{i'j}(M)|$, calculated according to method B, for $(\vec{p},\vec{n})$ (open circles) and $(\vec{p},\vec{p}')$ (solid circles) scattering, are plotted in precisely the same way as in Fig. 1.

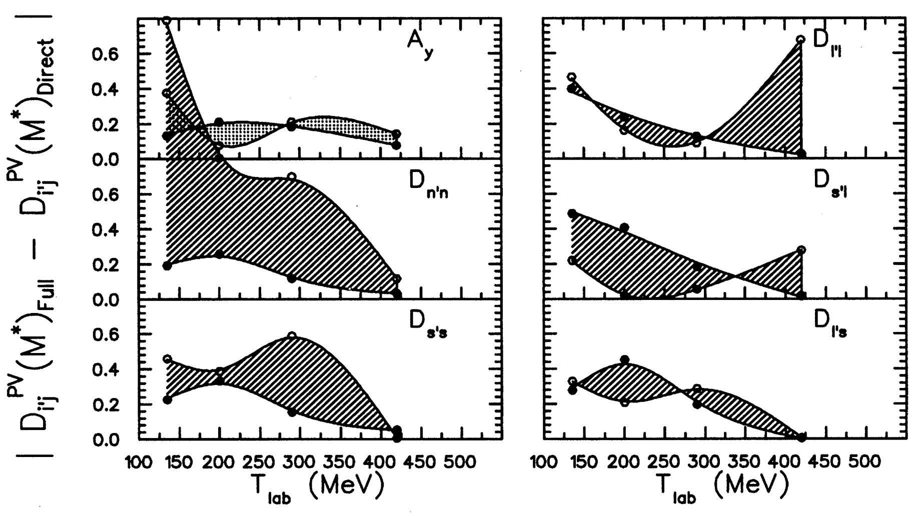

FIG. 3. The values of $|D^{PV}_{i'j}(M^*)_{\rm full} - D^{PV}_{i'j}(M^*)_{\rm Direct}|$ are presented again similarly as in Figs. 1 and 2. Open circles represent $(\vec{p},\vec{n})$ scattering, whereas solid circles represent $(\vec{p},\vec{p}\,')$ scattering. The subscripts "direct" and "full" refer to calculations where the exchange terms have been neglected and included, respectively.

$(\vec{p},\vec{n})$ spin observables to pseudoscalar (PS) versus pseudovector (PV) treatments of the πN vertex and, as for the other two effects to be considered hereafter, compare it to the former $(\vec{p},\vec{p}\,')$ results. PV coupling is generally preferred over PS coupling from considerations of elastic scattering and chiral invariance [16,17]. Moreover, most calculations to date have been based on method A and seem to favor the pseudovector parametrization when compared to data [9,18]. However, these calculations ignore exchange contributions to the medium modified NN amplitudes and will thus, compared to method B, yield different results for a fixed choice of the πN coupling. We therefore compare methods A and B in terms of the sensitivity of spin observables to PS and PV forms of the πN vertex and introduce $D^{\rm PS}_{i'j}(M^*)$ and $D^{\rm PV}_{i'j}(M^*)$ to refer to spin observables calculated by using respectively a PS and a PV coupling for the "pion," both with an effective mass M^*. The effective mass values were obtained from Table II in Ref. [11] and typically range from 0.8 M to 0.9 M. Figure 1 compares for all $(\vec{p},\vec{n})$ spin observables $D_{i'j}$, the values of $|D^{\rm PV}_{i'j}(M^*) - D^{\rm PS}_{i'j}(M^*)|$ calculated by method A (solid circles) and method B (open circles). The solid and open triangles refer to the corresponding $(\vec{p},\vec{p}\,')$ calculations based on methods A and B and the hatched areas emphasize the differences between their respective results. Over the entire energy range, all the quasielastic $(\vec{p},\vec{n})$ spin observables are clearly much more sensitive to the PS versus PV treatment of the pion than the $(\vec{p},\vec{p}\,')$ spin observables, $D_{n'n}$ being by far the most sensitive observable. Contrary to $(\vec{p},\vec{p}\,')$ scattering, both $(\vec{p},\vec{n})$ spin observables $D_{s's}$ (except at 200 MeV) and $D_{l's}$ depend substantially on the πN coupling terms. Furthermore, it is particularly noticeable that, in contrast to the $(\vec{p},\vec{p}\,')$ observables, at *high energies* methods A and B give significantly different results for the $(\vec{p},\vec{n})$ observables $D_{n'n}$, $D_{s's}$, and $D_{l's}$; all three of these observables clearly point to the necessity of a meson-exchange model for the NN interaction in order to correctly distinguish between pseudoscalar and pseudovector forms of the pion. At about 200 MeV method A exhibits maximum sensitivity for $D_{s's}$ whereas method B exhibits minimum sensitivity. On the other hand, A_y is totally insensitive to the differences between methods A and B regarding the form of the πN vertex. To summarize, the widely used method A must be employed with caution when PV spin observables are calculated; method B which treats exchange contributions of the NN amplitudes in the nuclear medium should rather be used. Unfortunately HLF parameters exist at only a few energies, hence we could not calculate PV spin observables quantitatively.

Next, for reasons already mentioned, we choose the PV form of the πN vertex, and study the difference between effective mass and free mass calculations. Figure 2 displays the energy variation of $|D^{\rm PV}_{i'j}(M^*) - D^{\rm PV}_{i'j}(M)|$ values which serves as a measure of the sensitivity to relativity of the specific spin observable $D_{i'j}$. These values have been calculated using method B. The solid and open circles represent the $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ results, respectively. The hatched areas display the differences between the $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ results. Over the entire energy range $D_{l'l}$ is extremely sensitive to relativistic M^* effects. In addition, for $(\vec{p},\vec{n})$ scattering at energies above 200 MeV, $D_{n'n}$ is much more sensitive to relativistic effects than the celebrated "relativistic signature" exhibited by A_y at 500 MeV [2]. It would be interesting to measure $D_{n'n}$ at energies lower than 200 MeV since $(\vec{p},\vec{n})$ and $(\vec{p},\vec{p}\,')$ scattering exhibit minimum and maximum sensitivity, respectively, to relativistic effects.

Exchange is a fundamental phenomenon and in principle should be included in all calculations of $(\vec{p},\vec{n})$ and $(\vec{p},\vec{p}\,')$ spin observables [16,19]. However, in the first calculations [2] of spin observables using the RPWIA model, proton energies of 290 MeV and higher were involved and at these higher energies the exchange terms of the NN interaction were assumed to be relatively small and could be neglected to simplify calculations. This we explained in Ref. [11] in terms of the high momentum cutoff of the exchange term form factor and then also demonstrated that for the calculation of quasielastic $(\vec{p},\vec{p}\,')$ spin observables at energies lower than 200 MeV, the exchange contributions are important indeed. We now investigate this relative contribution of the NN exchange terms to the quasielastic $(\vec{p},\vec{n})$ spin observables, and illustrate in Fig. 3 the differences between corresponding spin observables (as a function of energy) if the exchange terms are included or not. The solid and open circles represent the $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ results, respectively, and the hatched areas accentuate the differences between the latter reactions. As expected, at low energies the exchange terms again contribute significantly and are generally more pronounced than for the $(\vec{p},\vec{p}\,')$ case. Note the extreme importance of exchange effects on $D_{n'n}$. In addition, at *higher energies* the contributions of exchange become important again for some spin observables, e.g., $D_{l'l}$ and $D_{s'l}$, contrary to the former case of $(\vec{p},\vec{p}\,')$ scattering. Hence we conclude that in practice one cannot neglect exchange, not even at 500 MeV, especially when calculating isovector medium-modified NN amplitudes.

To summarize, we have compared the sensitivity of both quasielastic $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ spin observables to pseudoscalar versus pseudovector forms of the πN vertex, relativistic effects, and exchange contributions to the NN amplitudes. The tendencies displayed in the figures speak for themselves. Generally the $(\vec{p},\vec{n})$ spin observables $D_{n'n}$, $D_{s's}$, and $D_{l'l}$ exhibit the highest sensitivities to all these effects over the whole energy range. If a complete set of $(\vec{p},\vec{n})$ spin observables cannot be measured, data in at least the latter three spin observables over the whole energy range can provide guidance in developing and refining various theoretical models of the quasielastic scattering process. Relative to the above-mentioned observables, A_y is insensitive to all these effects for the $(\vec{p},\vec{n})$ reaction. We also showed that, contrary to former expectations, exchange contributions cannot be neglected in the entire 135 to 500 MeV range.

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