Nuclear medium modifications of the NN interaction via quasileastic ($\vec{p}, \vec{p}'$) and ($\vec{p}, \vec{n}$) scattering *

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Abstract

Within the relativistic PWIA, spin observables have been recalculated for quasilelastic ($\vec{p}, \vec{p}'$) and ($\vec{p}, \vec{n}$) reactions on a $^{40}$Ca target. The incident proton energy ranges from 135 to 300 MeV while the transferred momentum is kept fixed at 1.97 fm$^{-1}$. In the present calculations, new Horowitz–Love–Franey relativistic NN amplitudes have been generated in order to yield improved and more quantitative spin observable values than before. The sensitivities of the various spin observables to the NN interaction parameters, such as (1) the presence of the surrounding nuclear medium, (2) a pseudoscalar versus a pseudovector interaction term, and (3) exchange effects, point to spin observables which should preferably be measured at certain laboratory proton energies, in order to test current nuclear models. This study also shows that nuclear medium effects become more important at lower proton energies ($\leq$ 200 MeV). A comparison to the limited available data indicates that the relativistic parametrization of the NN scattering amplitudes in terms of only the five Fermi invariants (the SVPAT form) is questionable.

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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 \([1, 2, 3]\). At moderate momentum transfers \((1 \leq q \leq 2 \text{ fm}^{-1})\) quasielastic scattering becomes the dominant mechanism for nuclear excitation. It 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 remain inert. This process is characterized by a broad bump in the excitation spectrum, the centroid of which nearly corresponds to free NN kinematics, and a width resulting from the initial momentum distribution of the struck nucleon. At the momentum transfers of interest, shell effects are unimportant \([4]\) and the quasielastic peak is well separated from discrete states in the excitation spectrum. Hence, deviations of the polarization transfer observables from the corresponding free NN values could be attributed to medium modifications of the free NN interaction.

The failure of all nonrelativistic Schrödinger–based models \([1]\) to describe the quasielastic \((\vec{p}, \vec{p}')\) analyzing power at 500 MeV lead to the development of the Relativistic (Dirac) Plane Wave Impulse Approximation (RPWIA) \([5, 6, 7]\), where the NN amplitudes are based on the Lorentz invariant parametrization of the standard five Fermi invariants (the so–called SVPAT form) and the target nucleus is treated as a Fermi gas. Medium effects (often referred to as relativistic effects) are incorporated by replacing free nucleon masses in the Dirac plane waves with effective projectile and target nucleon masses in the context of the Walecka model \([8]\).

Despite the successful RPWIA prediction of \(A_y\) \([7]\), most of the other five independent spin transfer observables allowed by parity and time-reversal invariance, \(D_{nn}, D_{s's}, D_{\ell'\ell}, D_{s'\ell}\) and \(D_{\ell's}\), seem to favor relativistic calculations based on free nucleon masses. However, the original RPWIA predictions \([2, 3, 4, 5]\) were based on crude assumptions and unrefined input. For example, a 10% uncertainty in effective mass values translates into 30% effects on some polarization transfer observables \([10]\). Rather than abandon the RPWIA in favor of more sophisticated relativistic models, our approach has been to critically review the approximations and perform more refined calculations in order to reveal the limitations of the model.

In recent papers \([10, 11]\) we calculated better effective masses and qualitatively analyzed the sensitivity of complete sets of quasielastic \((\vec{p}, \vec{p}')\) and \((\vec{p}, \vec{n})\) polarization transfer observables to medium effects, different forms of the \(\pi\)NN vertex, exchange contributions to the nucleon–nucleon (NN) amplitudes, and also spin–orbit distortions. We emphasized that the much–used SVPAT form \([12]\) is limited in that it does not properly address the exchange behavior of the NN amplitudes in the nuclear medium, and does not properly distinguishing between pseudoscalar (PS) and pseudovector (PV) forms of the \(\pi\)NN vertex. Instead, we advocated the use of a meson–exchange model to explicitly include pions as one of the mediators of the NN interaction. For simplicity we considered the phenomenological Horowitz–Love–Franey (HLF) model \([13]\) which parametrizes the relativistic SVPAT amplitudes as a sum of Yukawa–like meson exchanges in first Born approximation, and considers direct and exchange diagrams separately. Compared to the \((\vec{p}, \vec{p}')\) polarization transfer observables the corresponding \((\vec{p}, \vec{n})\) observables are generally more sensitive to PS versus PV forms of the \(\pi\)NN vertex. Furthermore, most observables exhibited maxi-
mum sensitivity to nuclear medium effects at energies lower than 200 MeV. We also showed that, contrary to former expectations, exchange contributions are important in the entire 135 to 500 MeV range.

Although our previous results stressed the potential value of quasielastic polarization transfer observables for studying nuclear medium effects, it failed to give an indication of the experimental statistical uncertainty required for distinguishing between the various model predictions. This was due to the fact that, although the Fermi motion of the target nucleons yields NN scattering amplitudes over a wide range of energies, in practice the lack of published HLF parameter sets (at 135, 200, 300, 400 and 500 MeV) restricted us to consider only the parameter set closest to the incident laboratory kinetic energy for all effective laboratory kinetic energies. Hence, our results were merely qualitative and served only to give an initial “feel” for the sensitivities of observables to nuclear medium effects.

The aim of this paper, therefore, is to perform a similar, but quantitative study. For a ⁴⁰Ca target and a fixed momentum transfer of 1.97 fm⁻¹, we systematically investigate the sensitivity of complete sets of quasielastic (⃗p, ⃗p′) and (⃗p, ⃗n) polarization transfer observables to medium effects, PS versus PV forms of the πNN vertex, and exchange contributions to the relativistic NN amplitudes. We have generated new HLF parameters (to be published in a future paper) between 80 and 195 MeV in 5–MeV intervals, and utilized the recent Maxwell parametrization [14], with both energy-dependent coupling constants and cutoff parameters between 200 and 500 MeV. The Fermi–averaging procedure, together with the availability of HLF parameters and reaction kinematics of interest, restrict calculations to incident laboratory energies between 135 and 300 MeV.

Results are presented as “difference ” graphs in Figs. 1 – 4: the solid and open circles respectively denote our calculated (⃗p, ⃗p′) and (⃗p, ⃗n) values at the centroid of the quasielastic peak (ω ≈ 80 MeV), whereas the solid lines serve merely to guide the eye. We introduce the notation D_{P^S}^{i′j}(M^*) and D_{P^V}^{i′j}(M^*) to refer to polarization transfer observables calculated using respectively a PS and a PV coupling for the “pion”, both with the more refined effective masses $M^*_{SC}$ from Table II in Ref. [11]. The shaded areas accentuate differences between (⃗p, ⃗p′) and (⃗p, ⃗n) predictions.

Per construction, the HLF– and SVPAT–based $D_{P^S}^{i′j}(M^*)$ observables are identical. However, the Fermi–averaging procedure involves integrating over many amplitudes, and since the HLF parameter–fits are not perfect, slight differences on individual amplitudes could add constructively, thus translating to relatively large differences. For polarization transfer observables, we found this theoretical uncertainty to be always smaller 0.04 and hence does not affect any of the conclusions drawn in this paper.

The sensitivity of polarization observables to PS versus PV forms of the πNN vertex is denoted by $|D_{P^V}^{i′j}(M^*) - D_{P^S}^{i′j}(M^*)|$ in Fig. 1.

For (⃗p, ⃗n) scattering, all the observables, except $A_y$, exhibit largest sensitivities to different pion couplings over the entire energy range. Generally, the sensitivities of the (⃗p, ⃗n) polarization transfer observables completely overshadow the corresponding (⃗p, ⃗p′) observables. Measurements of $D_{nn}$ for both (⃗p, ⃗n) and (⃗p, ⃗p′) scattering, particularly at low energies, would be extremely useful in shedding light on the preferred
Figure 1: The difference, $|D_{ij}^{PV}(M^*) - D_{ij}^{PS}(M^*)|$, for $(\vec{p}, \vec{p}')$ and $(\vec{p}, \vec{n})$ polarization transfer observables calculated with a pseudovector (PV) and a pseudoscalar (PS) term in the NN interaction, respectively, as a function of laboratory energy and at the centroid of the quasielastic peak. Open circles represent $(\vec{p}, \vec{n})$ scattering, whereas solid circles represent $(\vec{p}, \vec{p}')$ scattering. The solid lines serve merely to guide the eye.

form of the $\pi$NN vertex.

Next, we choose a PS $\pi$NN vertex, and display the difference between effective–mass ($M^*$) and free–mass ($M$) calculations in Fig. 2, denoted by $|D_{ij}^{PS}(M^*) - D_{ij}(M)|$. These differences accentuate the importance of nuclear medium effects in polarization transfer observables. Compared to $(\vec{p}, \vec{p'})$ scattering, the $(\vec{p}, \vec{n})$ polarization transfer observables $D_{nn}$ and $D_{s'\ell}$ are more sensitive to medium effects over the entire energy range. At higher energies for $(\vec{p}, \vec{p'})$ scattering, $D_{nn}$, $D_{s'\ell}$ and $D_{e'n}$ observables are insensitive and correspond to free NN scattering. Note that $D_{nn}$ exhibits maximum and minimum sensitivity to medium effects for $(\vec{p}, \vec{p'})$ and $(\vec{p}, \vec{n})$ scattering respectively.

We now choose the PV form of the $\pi$NN vertex, and study the difference between effective–mass ($M^*$) and free–mass ($M$) calculations. This is denoted by $|D_{ij}^{PV}(M^*) - D_{ij}(M)|$ in Fig. 3. Compared to $(\vec{p}, \vec{n})$ scattering, the $(\vec{p}, \vec{p'})$ polarization transfer observables $D_{nn}$ and $D_{s's}$ are more sensitive to medium effects over the entire energy range. This is totally the opposite effect compared to the case with PS coupling. Hence, the effect of the nuclear medium depends critically on the type of pion coupling for both $(\vec{p}, \vec{n})$ and $(\vec{p}, \vec{p'})$ scattering, particularly at low energies. Comparison with experimental data (see later) will shed light on the type of coupling favored. At higher energies all the $(\vec{p}, \vec{n})$ observables are insensitive to medium effects and yield results...
Figure 2: Similar to Fig. 1, except that the values of $|D_{ij}^{PS}(M^*) - D_{ij}(M)|$ are plotted.

similar to free NN scattering. Note the enhanced sensitivity of $D_{nn}$ and $D_{s's}$ at low energies for both $(\vec{p}, \vec{n})$ and $(\vec{p}, \vec{p}')$ scattering.

Fig. 4 displays the sensitivity of polarization transfer observables to exchange contributions. For illustrative purposes, we choose the PV $\pi$NN vertex, and plot the difference $|D_{ij}^{PV}(M^*)_{Full} - D_{ij}(M)_{Direct}|$ as a function of incident laboratory energy at the centroid of the quasielastic peak. The subscript “Full” refers to the direct plus exchange amplitudes, whereas the subscript “Direct” specifies amplitudes where exchange contributions are ignored. As in Ref. [11], we see that for some polarization transfer observables the exchange contributions become more important at higher energies. In particular, for $(\vec{p}, \vec{p}')$ scattering, $A_y$ and $D_{s'ls}$ are sensitive to exchange contributions over the entire energy range. Note the extreme sensitivity of $D_{nn}$ at low energies and $D_{s'ls}$ at higher energies for $(\vec{p}, \vec{n})$ scattering.

Finally, we compare HLF–model based RPWIA calculations to published experimental data. Results are displayed in Figs. 5 – 6 and exclude spin–orbit distortions. The effect of spin–orbit distortions can be inferred from Ref. [10]. The meaning of the various line–types is indicated in the figure captions. The difference between the PS($M^*$)–SVPAT and PS($M^*$)–HLF calculations gives an indication of the theoretical uncertainty attributed to the HLF model parameters: this is typically much smaller than the statistical error bars.

Fig. 5 compares our calculations to $^{12}$C$(\vec{p}, \vec{n})$ data at an incident energy of 186 MeV and momentum transfer 1.1 fm$^{-1}$ [13]. The centroid of the quasielastic peak is located at $\omega \approx 50$ MeV. The energy transfer $\omega$ includes the reaction $Q$–value of $-18.6$ MeV. $D_{nn}$ clearly favors a PV treatment of the $\pi$NN coupling, whereas $A_y$ fails to distinguish
between PS and PV forms of the coupling. Note however, that both the free–mass and PV($M^*$)–HLF calculations describe the data equally well. The largest difference for the latter predictions occurs for $D_{\ell\ell}$; unfortunately the theoretical uncertainty is also the largest for this observable. Hence, for all practical purposes, the PV($M^*$) calculations are identical to the free–mass calculations. It would be interesting to see whether this is verified experimentally by comparing complete sets of $^{12}\text{C}(\vec{p}, \vec{n})$ and $^2\text{H}(\vec{p}, \vec{n})$ polarization transfer observables at 186 MeV.

Fig. 6 displays calculations for $^{12}\text{C}(\vec{p}, \vec{p}')$ at an incident energy of 290 MeV and momentum transfer $1.97\text{ fm}^{-1}$. The centroid of the quasielastic peak is located at $\omega \approx 80\text{ MeV}$.

We see that $D_{nn}$, $D_{s's'}$, $D_{s'\ell}$ and $D_{\ell's}$ correspond to the free–mass predictions. Note that most of the observables favor a PS $\pi\text{NN}$ vertex in contrast to the PV form suggested by $(\vec{p}, \vec{n})$ scattering. None of the calculations predict $A_y$. However, the inclusion of spin–orbit distortion moves most of the medium–modified polarization transfer observables, including $A_y$, closer to the data. The effect of relativity is to quench $A_y$ for quasielastic $(\vec{p}, \vec{p}')$ scattering relative to the free mass values. To date all nonrelativistic models fail to predict this quenching effect. Note, however, that the celebrated “relativistic signature” is much smaller than relativistic effects predicted for other polarization transfer observables at lower energies. For $(\vec{p}, \vec{n})$ scattering with a PV $\pi\text{NN}$ vertex, we predict a sizable medium effect on $A_y$ at $q = 1.97\text{ fm}^{-1}$. However at $q = 1.1\text{ fm}^{-1}$ our calculations show no sensitivity to medium effects as is confirmed by the limited IUCF data set. Therefore it would be interesting to measure $A_y$.
Figure 4: Similar to Figs. 1 – 3, except that the values of $|D_{ij}^{PV}(M^*)_{Full} - D_{ij}^{PV}(M^*)_{Direct}|$ are plotted. The subscripts “Direct” and “Full” refer to calculations where the exchange terms have respectively been neglected and included respectively.

for a range of angles on a $^{12}$C target. Furthermore, we see that all calculations fail to describe the $D_{s's}$ data. As with the original RPWIA calculations, comparison with the small amount of available data still gives mixed but encouraging results. The $(\vec{p}, \vec{p}')$ data favor a PS coupling for the pion, whereas the limited $(\vec{p}, \vec{n})$ spin observable data suggest a PV form. The latter ambiguity can perhaps be attributed to the simple Born approximation embodied by the phenomenological HLF model. Furthermore, one should rather use a general Lorentz–invariant representation of the NN amplitudes as suggested by Tjon and Wallace [18], instead of only the 5 SVPAT Fermi invariants. Indeed we are currently investigating the former representation of the NN scattering amplitudes for quasielastic proton–nucleus scattering. A number of effects, which we have neglected, could also improve the theoretical description of the data. For example, multiple scattering effects become sizable in heavy nuclei and at large scattering angles [4]. Furthermore, although signatures of low–lying collective states and giant resonances disappear at the large excitation energies of interest, the nucleus continues to respond collectively through the residual particle–hole interaction. This collectivity manifests itself in gross features of the spectrum, such as shifts in the position of the quasielastic peak and deviations of polarization transfer observables from the free values. Recently Horowitz and Piekarewicz [17] improved the simple Fermi–gas treatment of the nucleus by considering a relativistic random–phase approximation to the Walecka model. Essentially this description takes into account the interactions between the nucleons in the medium at the mean–field level.
Figure 5: Polarization transfer observables as a function of transferred energy $\omega$ over the quasielastic peak for $^{12}\text{C}(\vec{p}, \vec{n})$ scattering at 186 MeV and $\theta_{\text{lab}}=20^\circ$. The centroid of the quasielastic peak is situated at $\omega \approx 50$ MeV. Data are from Ref. [15]. The solid lines indicate free–mass ($M$) calculations [Free $M$], dotted lines represent effective–mass ($M^*$) PV calculations based on the HLF model [PV($M^*$)–HLF], dashed lines display effective–mass ($M^*$) PS calculations based on the HLF–model [PS($M^*$)–HLF], and dashed-dotted lines show effective–mass ($M^*$) calculations based on a direct SVPAT parametrization of the Arndt phases [PS($M^*$)–SVPAT].

These relativistic RPA correlations give a good description of data and lead to an improvement over Fermi–gas predictions. Furthermore, the effect of relativistic distortions on quasielastic polarization transfer observables is still an open question. We are currently considering a full relativistic distorted wave description of quasielastic proton–nucleus scattering.

For both $(\vec{p}, \vec{p}')$ and $(\vec{p}, \vec{n})$ scattering, the number of observables that exhibit maximum sensitivity to nuclear medium effects, increase as the incident beam energy is lowered. In general, there is a lack of complete sets of published polarization data for quasielastic $(\vec{p}, \vec{p}')$ and $(\vec{p}, \vec{n})$ scattering at the intermediate energies of interest. In particular, at energies lower than 200 MeV there exists absolutely no complete published data set. Ideally one must measure complete sets of polarization transfer observables for both $(\vec{p}, \vec{p}')$ and $(\vec{p}, \vec{n})$ reactions for the same target, energy and momentum transfer.
\[ ^{12}\text{C}(p,p')_{\text{lab}} = 290 \text{ MeV}, \theta = 29.5^\circ \]

Figure 6: Similar to Fig. 5, except that we now plot the polarization transfer observables for quasielastic $^{12}\text{C} (\vec{p}, \vec{p}')$ scattering at 290 MeV and $\theta_{\text{lab}} = 29.5^\circ$. The centroid of the quasielastic peak is situated at $\omega \approx 80$ MeV. Data are from Ref. [16]. P and $A_y$ refer to the induced polarization and analyzing power respectively.

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