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

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Based on the relativistic plane-wave impulse approximation for quasielastic $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ polarization observables, we provide quantitative estimates of nuclear medium modifications of the *NN* interaction. We employ a ^{40}Ca target for proton energies ranging from 135 to 300 MeV at a momentum transfer of 1.97 fm^{-1}. Compared to former calculations, we have generated new meson-exchange parameters for the relativistic *NN* amplitudes between 80 and 200 MeV. Finally, the results are compared to the limited available data. [S0556-2813(97)01912-2]

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Quasielastic proton-nucleus scattering is considered to be a single-step, surface-peaked reaction whereby an incoming proton knocks out a single bound nucleon in the target nucleus. At moderate momentum transfers ($1 \leqslant q \leqslant 2$ fm^{-1}) it becomes the dominant mechanism for nuclear excitation and the quasielastic peak becomes well separated from discrete states in the excitation spectrum. Considerable attention is being devoted to the measurement and interpretation of inclusive $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ polarization transfer observables at the quasielastic peak [1–3]. New polarization data will soon become available from RCNP (Osaka, Japan) and IUCF (Indiana, USA) which can provide significant guidance for improving current theoretical models.

In two recent papers [4,5] we demonstrated the potential value of complete sets of $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ polarization transfer observables for studying nuclear medium modifications of the *NN* interaction. The quasielastic scattering process was modeled via the relativistic plane-wave impulse approximation (RPWIA) [6–8], where the *NN* amplitudes are based on a Lorentz invariant parametrization of the standard five Fermi invariants (the so-called SVPAT form). The target nucleus was treated as a Fermi gas, as nuclear shell effects seem to be unimportant at the above-mentioned momentum transfers [9]. Medium effects (often referred to as relativistic effects) were incorporated by replacing free-nucleon masses in the Dirac plane waves with improved effective projectile and target nucleon masses in the context of the Walecka model [10]. We showed that, compared to a meson-exchange model of the SVPAT amplitudes, a direct SVPAT parametrization [11] of the Arndt phases fails to describe observables based on a pseudovector coupling of the πNN vertex. This is because the SVPAT form does not properly address the exchange behavior of the *NN* amplitudes in the nuclear medium, and also makes no explicit reference to pions. The latter shortcomings were addressed by using the phenomenological Horowitz-Love-Franey (HLF) model [12] which parametrizes the relativistic SVPAT amplitudes as a sum of Yukawa-like meson exchanges in the first Born approximation, and considers direct and exchange diagrams separately. In general we saw that, (1) compared to the $(\vec{p},\vec{p}\,')$ polarization transfer observables, the corresponding $(\vec{p},\vec{n})$ observables are more sensitive to different forms [pseudoscalar (PS) and pseudovector (PV)] of the πNN vertex, (2) most observables exhibited maximum sensitivity to nuclear medium effects at energies lower than 200 MeV and (3), contrary to former approaches [6,8,11], exchange contributions cannot be neglected at energies as high as 500 MeV.

However, our former two calculations [4,5] had a severe shortcoming. In principle, for a fixed momentum and energy transfer, the HLF *NN* scattering amplitudes should be averaged over the wide energy range of the struck target nucleons. In practice, the severe shortage of published HLF parameter sets below 500 MeV (namely at 135, 200, 300, 400, and 500 MeV), restricted the averaging procedure to only the parameter set closest to the incident laboratory kinetic energy for all effective energy values. Hence, our former results were rather crude and merely qualitative, and served to provide only an initial feeling for the sensitivities of observables to nuclear medium effects. The above approximation inhibited proper comparisons to data, and also failed to provide an indication of the statistical uncertainty required by experiments for distinguishing between the various model predictions.

In the present project, in order to make a proper quantitative study of nuclear medium effects, without interpolating between the limited parameter sets, we first generated new HLF parameters between 80 and 195 MeV in small intervals of 5 MeV, according the procedure of Horowitz [12]. Between 200 and 500 MeV we use the recent Maxwell parametrization [13], with both energy-dependent coupling constants and cutoff parameters. The averaging procedure, now employing all the available HLF parameters and reaction kinematics of interest, restricts the calculations to incident laboratory energies between 135 and 300 MeV.

Per construction, the HLF and SVPAT calculated values are identical for polarization transfer observables using a PS coupling for the ‘‘pion’’ [designated by $D^{\mathrm{PS}}_{i'j}(M^*)$, where M^* denotes the use of the more refined effective nucleon masses, M^*_{SC}, from Table II in Ref. [4]]. However, the averaging procedure involves integrating over many amplitudes, and since the HLF parameter fits are not perfect, slight differences on individual amplitudes could add constructively and result in relatively large uncertainties for the polarization transfer observables. We found these theoretical uncertain-

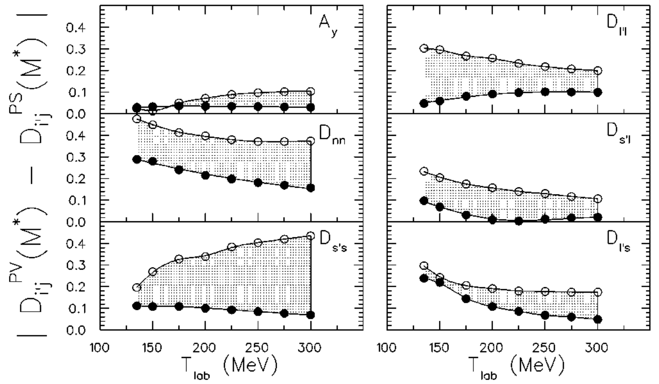

FIG. 1. The difference, $|D^{PV}_{i'j}(M^*)-D^{PS}_{i'j}(M^*)|$, for $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ polarization transfer observables $D_{i'j}$ calculated with a pseudovector (PV) and a pseudoscalar (PS) term in the NN interaction, respectively, as a function of laboratory energy and at the 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.

ties to be always smaller than 0.04 and hence they do not affect any of the conclusions drawn in this paper.

The results for the complete sets of quasielastic $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ polarization transfer observables are presented in Figs. 1–3. As in Refs. [4,5], these are ''difference '' graphs, calculated for quasielastic $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ scattering as a function of incident laboratory energy and at the centroid of the peak ($\omega \approx 80$ MeV). The shaded areas accentuate differences between $(\vec{p},\vec{p}\,')$ and $(\vec{p},\vec{n})$ predictions. As these graphs are fairly self-explanatory, we will discuss each very briefly below.

In Fig. 1 we present the sensitivity of polarization observables to PS versus PV forms of the πNN vertex, denoted by $|D^{PV}_{i'j}(M^*)-D^{PS}_{i'j}(M^*)|$. Generally, the sensitivities of the $(\vec{p},\vec{n})$ spin observables completely exceed those of the corresponding $(\vec{p},\vec{p}\,')$ observables over the full energy range.

In Fig. 2 we choose a PS πNN vertex, and display the difference between effective-mass (M^*) and free-mass (M) calculations, denoted by $|D^{PS}_{i'j}(M^*)-D_{i'j}(M)|$. Clearly, the $(\vec{p},\vec{n})$ polarization transfer observables D_{nn} and $D_{s'\ell}$ are generally the most sensitive to medium effects over the entire energy range.

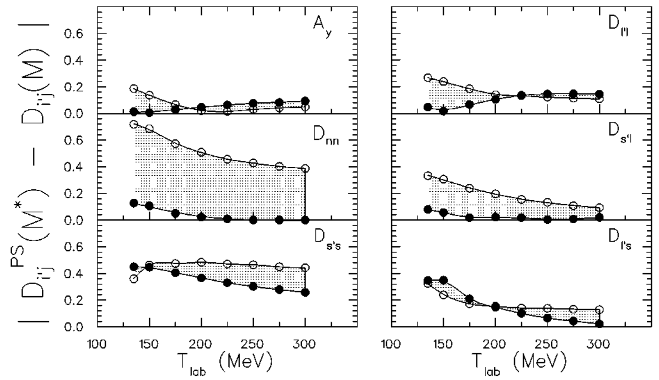

FIG. 2. Similar to Fig. 1, except that the values of $|D^{PS}_{i'j}(M^*)-D_{i'j}(M)|$ are plotted.

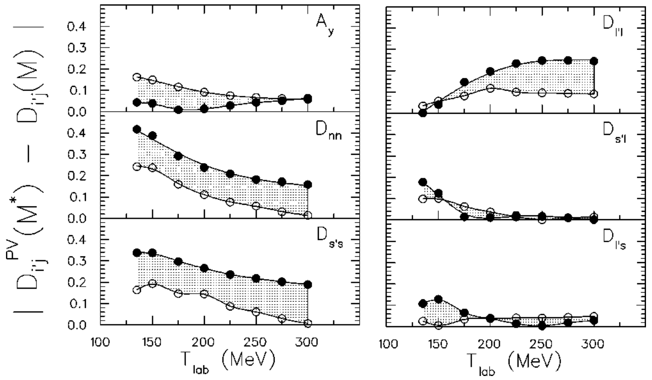

FIG. 3. Similar to Figs. 1 and 2, except that the values of $|D^{PV}_{i'j}(M^*)-D_{i'j}(M)|$ are plotted.

We now choose the PV form of the πNN vertex, and display the difference between effective-mass (M^*) and free-mass (M) calculations, denoted by $|D^{PV}_{i'j}(M^*) -D_{i'j}(M)|$ in Fig. 3. Contrary to the previous graph set for PS coupling, the $(\vec{p},\vec{p}\,')$ polarization transfer observables, especially D_{nn} and $D_{s's}$, are here more sensitive to medium effects over the entire energy range. 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 may shed light on the type of coupling favored.

Finally, we compare HLF-model based RPWIA calculations to published experimental data. Results are displayed in Figs. 4 and 5. 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; fortunately it is less than the statistical error bars of the few presently available data. Although none of these comparisons really favors a specific model, we briefly remark on each of them below.

Figure 4 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} [14]. The centroid of the quasielastic peak is located at an energy transfer $\omega \approx 50$ MeV, where ω includes the reaction Q value of -18.6 MeV. It mainly shows that, where D_{nn} clearly favors a PV to a PS treatment of the πNN coupling, A_y fails to distinguish between them. Note however, that both the free-mass and PV(M^*)-HLF calculations describe the data equally well.

Figure 5 displays calculations for ^{12}C$(\vec{p},\vec{p}\,')$ at an incident energy of 290 MeV and momentum transfer 1.97 fm^{-1} [15]. The centroid of the quasielastic peak is located at $\omega \approx 80$ MeV. We note that D_{nn}, $D_{s's}$, $D_{s'l}$, and $D_{l's}$ correspond to the free-mass predictions. Most of the observables favor a PS πNN vertex in contrast to the PV form suggested by $(\vec{p},\vec{n})$ scattering (the former figure). None of the relativistic calculations predict A_y correctly; however, they do better than all nonrelativistic models to date. In general, the inclusion of spin-orbit distortion, which has been neglected here but can be inferred from Ref. [4], shifts most of the medium-modified spin observables, including A_y, closer to the data.

As with the original RPWIA calculations, comparison

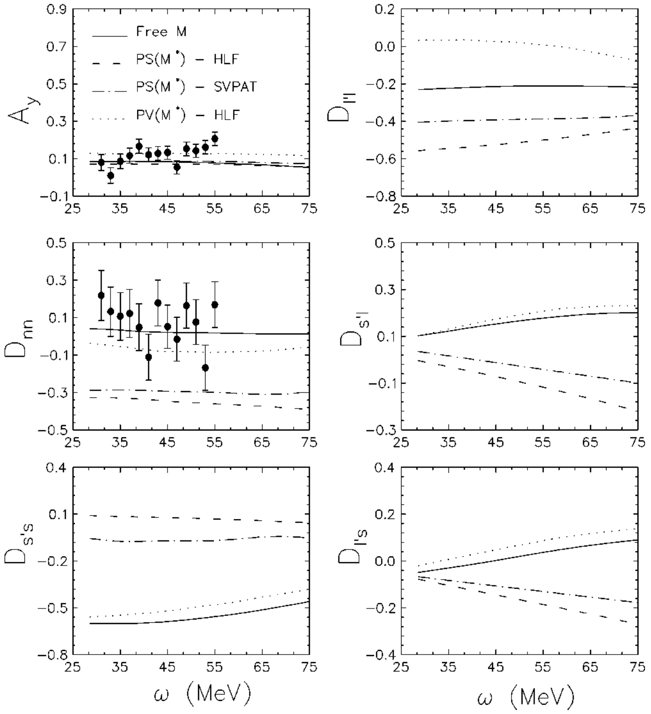

FIG. 4. Polarization transfer observables as a function of transferred energy ω over the quasielastic peak for $^{12}\mathrm{C}(\vec{p},\vec{n})$ scattering at 186 MeV and $\theta_{\mathrm{lab}}=20°$. The centroid of the quasielastic peak is situated at $\omega\approx 50$ MeV. Data are from Ref. [14]. 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 dash-dotted lines show effective-mass (M^*) calculations based on a direct SVPAT parametrization of the Arndt phases [PS(M^*)-SVPAT].

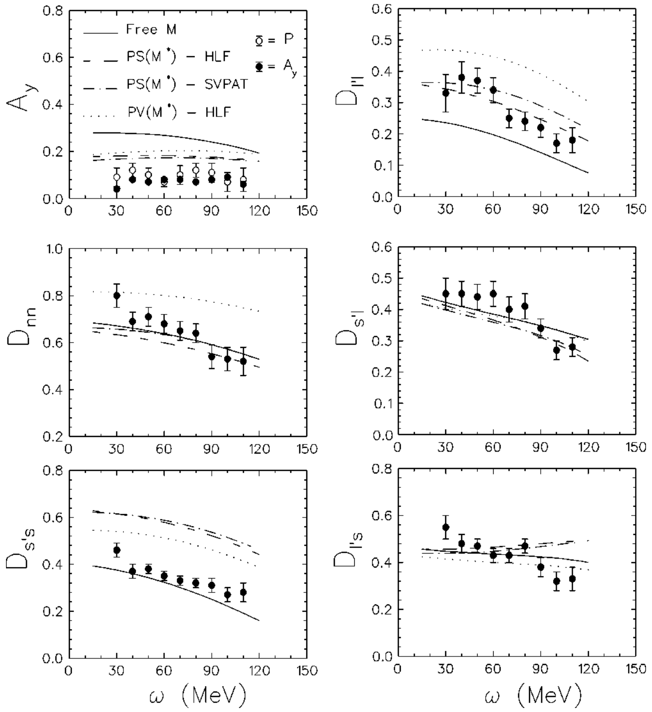

FIG. 5. Similar to Fig. 4, except that we now plot the polarization transfer observables for quasielastic $^{12}\mathrm{C}(\vec{p},\vec{p}\,')$ scattering at 290 MeV and $\theta_{\mathrm{lab}}=29.5°$. The centroid of the quasielastic peak is situated at $\omega\approx 80$ MeV. Data are from Ref. [15]. P and A_y refer to the induced polarization and analyzing power, respectively.

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 use of the five SVPAT invariants, rather than a general Lorentz-invariant representation of the NN amplitudes. Although the SVPAT approximation has worked surprisingly for relativistic descriptions of elastic scattering [16] and proton-knockout reactions [17], our analysis suggests that this approach may be too simplistic for inclusive quasielastic reactions. The inclusion of full relativistic distortions in the incident and exit channels may also improve our results.

We must emphasize again the general lack of data, especially for complete sets of polarization transfer observables, and in particular for any spin observable at incident energies below 200 MeV.

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[1] *Proceedings of the International Conference on Spin Observables of Nuclear Probes*, edited by C. J. Horowitz, C. D. Goodman, and G. E. Walker (Plenum Press, New York, 1988).

[2] *Proceedings of the International Conference on Spin and Isospin in Nuclear Reactions*, edited by S. W. Wissink, C. D. Goodman, and G. E. Walker (Plenum Press, New York, 1991).

[3] *Proceedings of the International Conference on Spin-Isospin Responses and Weak Processes in Hadrons and Nuclei*, edited by H. Ejiri, Y. Mizuno, and T. Suzuki [Nucl. Phys. **A577**, 1c (1994)].

[4] G. C. Hillhouse and P. R. De Kock, Phys. Rev. C **49**, 391 (1994).

[5] G. C. Hillhouse and P. R. De Kock, Phys. Rev. C **52**, 2796 (1995).

[6] C. J. Horowitz and M. J. Iqbal, Phys. Rev. C **33**, 2059 (1986).

[7] C. J. Horowitz and M. J. Iqbal, Phys. Rev. C **34**, 2012 (1986).

[8] C. J. Horowitz and D. P. Murdock, Phys. Rev. C **37**, 2032 (1988).

[9] C. Chan, T. E. Drake, R. Abegg, D. Frekers, O. Häusser, K. Hicks, D. A. Hutcheon, L. Lee, C. A. Miller, R. Schubank, E. J. Stephenson, and S. Yen, J. Phys. G **15**, L55 (1989).

[10] B. D. Serot and J. D. Walecka, in *Advances in Nuclear Physics*, edited by J. W. Negele and E. Vogt (Plenum Press, New York, 1986), Vol. 16.

[11] J. A. McNeil, L. Ray, and S. J. Wallace, Phys. Rev. C **27**, 2123 (1983).

[12] C. J. Horowitz, Phys. Rev. C **31**, 1340 (1985).

[13] O. V. Maxwell, Nucl. Phys. **A600**, 509 (1996).

[14] L. Wang, X. Yang, J. Rapaport, C. D. Goodman, C. C. Foster, Y. Wang, J. Piekarewicz, E. Sugarbaker, D. Marchlenski, S. de

Lucia, B. Luther, L. Rybarcyk, T. N. Taddeucci, and B. K. Park, Phys. Rev. C **50**, 2438 (1994).
[15] C. Chan, T. E. Drake, R. Abegg, D. Frekers, O. Häusser, K. Hicks, D. A. Hutcheon, L. Lee, C. A. Miller, R. Schubank, and S. Yen, Nucl. Phys. **A510**, 713 (1990).
[16] D. P. Murdock and C. J. Horowitz, Phys. Rev. C **35**, 1442 (1987).
[17] Y. Ikebata, Phys. Rev. C **52**, 890 (1995).