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Framework for using $(\vec{p},\vec{p}\,')$ reactions to characterize new medium modifications to the nucleon-nucleon interaction

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Comparing with intermediate-energy data for $(\vec{p},\vec{p}\,')$ spin-flip transitions, such as the one to the 6^-, $T=1$ state in ^{28}Si, we examine distorted-wave impulse-approximation predictions based on effective interactions derived from modern, high-precision nucleon-nucleon potentials. This establishes a reliable point of reference from which we explore medium effects in the context of a microscopic nucleon-nucleon G matrix and estimate the reliability with which the scale and character of any novel medium effects could be determined. [S0556-2813(98)04107-7]

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INTRODUCTION

A knowledge of the interaction between two nucleons should lead directly to a description of the dynamics of nuclear reactions. But in the many-nucleon system it is possible to generate a very large number of intermediate states that make the description of reactions from first principles a complicated task. A more economical way to proceed is to view some of the effects of the many-body environment as modifications to the nucleon-nucleon (NN) interaction used in the nuclear reaction models. These effects can be calculated for infinite, symmetric ($N=Z$) nuclear matter and then incorporated into an effective, density-dependent NN interaction to be used in simplified treatments of the nuclear reaction process.

A number of nuclear medium effects have been investigated in this way. One arises from the presence of a nuclear mean field that binds the nucleons in the nucleus and moves the scattering kinematics off shell. Another comes from the exclusion principle and prevents scattering into occupied states. These two medium effects are the main aspects of what is known as the Brueckner G-matrix approach [1–5]. Its relativistic extension is based upon the Dirac equation for single-particle motion in nuclear matter and has become known as the Dirac-Brueckner approach [6–14]. After considerable effort, the handling of these medium effects has evolved toward an accepted, and by now conventional, method.

Driven in part by the inability of these medium-modified models to describe some nuclear structure and reaction systematics, and in part by considerations of nuclear matter (including subnucleonic structure) under conditions of extreme density and temperature, additional medium modifications to the effective NN interaction have been proposed. Prominent among these are suggestions that the properties of mesons and nucleons (such as masses and coupling constants) should be modified based on considerations of quark condensates in nuclear matter [15–18] or the formation of intermediate states or resonances [19]. Since these changes are substantial and of leading order in the NN potential, such effects should appear clearly in nuclear reaction observables. But their detection and characterization through a comparison to the reaction data require, as a starting point, a reliable baseline in which the NN interaction describes the free NN scattering data very well, and where the established medium effects have been included as completely and accurately as possible.

In this paper, we will investigate the status of this baseline as it affects the calculation of cross section and polarization observables for nucleon-induced reactions such as $(\vec{p},\vec{p}\,')$ inelastic scattering or $(\vec{p},\vec{n})$ charge exchange at intermediate energies. Some groups of transitions, such as those exciting natural parity, isoscalar states with considerable collective character, show large effects from Brueckner and Dirac-Brueckner modifications to the effective NN interaction. Near 200 MeV, the energy we will use as an example in this paper, these effects have been described phenomenologically and compared with various theoretical models [20,21]. But with large effects and only a qualitative ability to predict them, it is difficult to judge whether other physical processes might be involved. Fortunately, novel nuclear medium modifications, such as those suggested in Refs. [15–18] that involve changes to the ρ-meson spectral properties, predict substantial effects for the spin-dependent parts of isovector transitions, where conventional modifications produce only small changes [4]. To emphasize the prospects for this case, we have chosen a reaction where there are still notable differences between data and predictions. This scenario will hopefully provide the best chance to observe a new medium effect. Specifically, we will show calculations for the $^{28}\mathrm{Si}(\vec{p},\vec{p}\,')^{28}\mathrm{Si}$ reaction at 200 MeV to the 6^-, $T=1$ state at an excitation energy of 14.35 MeV. By comparing against these data [22], we will be able to estimate how reliably we can identify and characterize any proposed change to the NN interaction used as the basis for such reaction calculations, given the present state of both theory and experiment. By looking at a case where a large number of polarization observables have been measured [22,23], direct connections [24,25] to the structure of the NN amplitudes for each spin and isospin operator involved should provide a characterization that can be compared in detail to the predictions of any new effects.

Among the *NN* potentials available today, some have reached a level of sophistication where they describe free *NN* scattering data (selected for high reliability) to within the quoted experimental errors [26–28]. In particular, we will use in this work the potentials of Nijmegen [26], Reid [26], and CD-Bonn [28]. A comparison will also be made to some older, popular potentials to illustrate to which extent the accuracy of the fit to the *NN* data has impact on this reaction.

We will then produce a medium-modified *NN* interaction from each of these potentials based on conventional Brueckner theory. This will illustrate the size of such medium effects, and in addition reveal any sensitivity there may be to differences among the modern potentials in the way they describe *NN* scattering off shell. We will then use the comparison to the $^{28}\mathrm{Si}(\vec{p},\vec{p}\,')^{28}\mathrm{Si}$ data to assess the impact of theoretical and experimental issues on our ability to test for nonconventional medium effects.

DWIA CALCULATIONS

In this section we describe the distorted-wave impulse approximation (DWIA) calculations for the $(\vec{p},\vec{p}\,')$ reaction. This one step perturbative approach is well suited to this case since the cross section (with a maximum near 0.1 mb/sr) is both much less than the elastic scattering cross section (thus making coupled-channel contributions unimportant), and prominent among the inelastic transitions (which suppresses multistep amplitudes relative to single step).

The 6^-, $T=1$ transition in $^{28}\mathrm{Si}(\vec{p},\vec{p}\,')^{28}\mathrm{Si}$ was chosen in part because a number of other experiments provide data that constrain the ingredients of the DWIA calculations. This is necessary if we expect later to interpret any differences between data and DWIA predictions as evidence for new contributions to the in-medium effective interaction. The measurements were made with 198-MeV polarized protons using the high-resolution K600 spectrometer at IUCF, and have been described briefly elsewhere [22].

We have chosen to take the optical potentials that determine the entrance and exit channel distorted waves from fits to the elastic scattering differential cross section and analyzing power. The data near 200 MeV for the entrance channel was measured and described by an optical potential by Liu [29]. For the excited state exit channel distorted waves, we use the 180-MeV data and potential by Olmer [30]. These two potentials are part of a larger set whose parameters vary smoothly with energy.

The transition under consideration is isovector and easily observed in magnetic electron scattering. Since the probe in this case is well described, we used the transverse form factor to constrain the DWIA transition density. This density was the overlap of a $d_{5/2}$ hole state and an $f_{7/2}$ particle state, coupled to the maximal spin and parity of 6^-. The particle and hole wave functions were described using bound states in a Wood-Saxon well whose geometry was chosen to match the q dependence of the (e,e') data [31], and whose depth gave a bound state energy consistent with the lowest particle separation energy for each spin and parity. The normalization, or spectroscopic factor, was chosen to match the scale of the (e,e') data.

The $(\vec{p},\vec{p}\,')$ reaction can support both isoscalar and isovector contributions. Since these components of the *NN* interaction are substantially different, knowing the proper mix is important. Data from $(\pi^\pm,\pi^\pm)$ reactions [32] would suggest a small enhancement to the proton contributions to this transition, but they are poor enough that considerable latitude for adjustment is still available. On the other hand, a comparison of the spectroscopic strengths for the $^{27}\mathrm{Al}(^3\mathrm{He},d)^{28}\mathrm{Si}$ reaction to the two 6^- transitions places slightly more proton strength in the lower $T=0$ member of this pair [33]. The weak binding of the proton particle in the $f_{7/2}$ orbit would enhance the proton contribution for peripheral reactions such as pion inelastic scattering relative to (p,p'), whose form factor favors smaller reaction radii than either $(\pi^\pm,\pi^\pm)$ or $(^3\mathrm{He},d)$. The Coulomb part of the particle-hole matrix element that mixes the $T=0$ and $T=1$ components of the two strong 6^- transitions in $^{28}\mathrm{Si}(p,p')^{28}\mathrm{Si}$ would increase the neutron component of the nominally $T=1$ transition. Adjusting the mix to best reproduce the (p,p') polarization data supports the enhancement of the neutron part of the transition density, and here we will use the mixing determined elsewhere with this data [34].

The *NN* interaction inside the DWIA calculation was described by a set of Yukawa functions whose coefficients and ranges were chosen to reproduce the t or G matrix near its on-shell value [35]. As the half off-shell t or G matrix moves away from the on-shell point in momentum space, its contribution to the fit was reduced by including in the minimization process the Gaussian weighting function $\exp[-(k'-k)^2/\beta^2]$, with $\beta=0.3\ \mathrm{fm}^{-1}$ [35]. The DWIA calculations were performed using the computer code DWBA91 [36].

FREE-SPACE INTERACTIONS

We will begin our comparison of various potential models of the *NN* interaction by using the free-space t matrix as the starting point for the $(\vec{p},\vec{p}\,')$ calculation. The t matrix for *NN* scattering is the solution of the Lippman-Schwinger equation which has the schematic form

$$t=V+V\left(\frac{1}{e}\right)t, \tag{1}$$

with V the two-nucleon potential and $1/e$ the two-nucleon propagator.

In Fig. 1, we compare predictions based on t matrices derived from four high-precision *NN* potentials, CD-Bonn [28], Nijmegen-I, Nijmegen-II [26], and Reid93 [26]. CD-Bonn is a charge-dependent, one-boson exchange potential (OBEP). Being a meson-theoretic, relativistic potential, it is nonlocal. The other three potentials are based upon three-dimensional nonrelativistic invariants. However, while Nijmegen-II is entirely local, Nijmegen-I contains some nonlocalities in the central force. Reid93 is a regularized version of the older Reid potential [37] (Reid68) and is local.

All of these four potentials are essentially identical in their fit to the *NN* data, with a χ^2/datum approximately equal to one for the *NN* data below 350 MeV. We see from Fig. 1

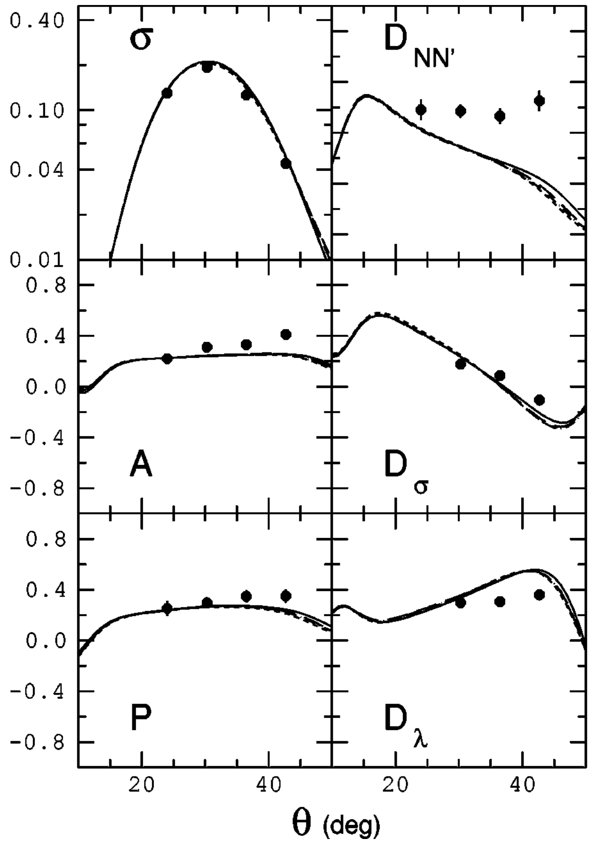

FIG. 1. Predictions for the cross section σ (in units of mb/sr), the analyzing power A, the polarization P, and three polarization transfer coefficients D_{NN}, D_σ, and D_λ, for the 6^-, $T=1$ state at 14.35 MeV in ^{28}Si($\vec{p},\vec{p}\,'$)^{28}Si. The predictions are based upon the t matrices as derived from four high-precision NN potentials. Solid curve: CD-Bonn [28]; dashed curve: Nijmegen I [26]; dash-dotted curve: Nijmegen II [26]; dotted curve: Reid93 [26]. Data from Ref. [22].

very little or no model dependence. Any of the four potentials would represent an equally acceptable starting point to explore further model modifications.

The DWIA calculation, because of the transformation between the nucleon-nucleon and the nucleon-nucleus frames of reference, and also because of the explicit treatment of the exchange amplitudes, depends to a considerable extent on the values of the t matrix off shell. From the close agreement among the four calculations shown in Fig. 1, we can conclude that the free t matrices (which are only constrained by NN data on shell) have only very minor off-shell differences at momenta relevant for this reaction. Those differences are displayed in Fig. 2 for the $^3S_1$ half off-shell transition amplitude. The on-shell point lies at 1.55 fm^{-1} for this proton bombarding energy.

To illustrate the importance of a high-quality fit to the NN data, we show in Fig. 3 one of the modern potentials (CD-Bonn, solid line) along with two older potentials, namely, Paris [38] and Reid68 [37]. These potentials do not fit the NN data as well, and they disagree noticeably with the CD-Bonn predictions for the ($\vec{p},\vec{p}\,'$) reaction. In fact, some of the most precise NN polarization data near 200 MeV laboratory energy was not available when these potentials were constructed. Thus, the advent of modern potentials greatly reduces the uncertainty in the evaluation of medium effects.

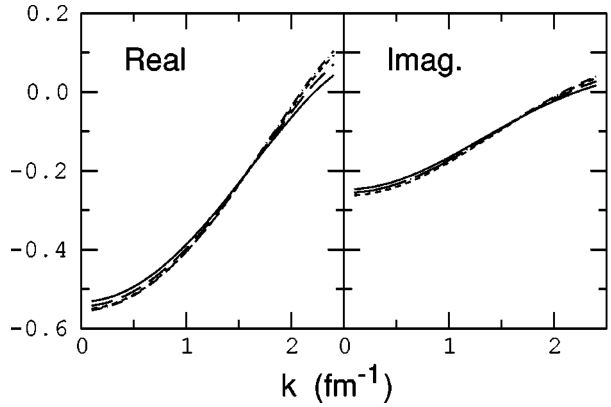

FIG. 2. Real part and imaginary part of the half-off-shell $^3S_1$ t matrix elements (in units of fm). The on-shell momentum is 1.55 fm^{-1}. The predictions are obtained with: CD-Bonn [28] (solid); Nijmegen I [26] (dashed); Nijmegen II [26] (dash-dotted); Reid93 [26] (dotted).

(Note: Differences similar to those seen among the predictions shown in Fig. 3 arise when comparing with the free-space t matrix of Franey and Love [39]. This interaction is not included in our comparison because it is a reproduction of the amplitudes in a global phase shift analysis and not a potential model. A potential model is required for a development of the medium effects discussed in the next section.)

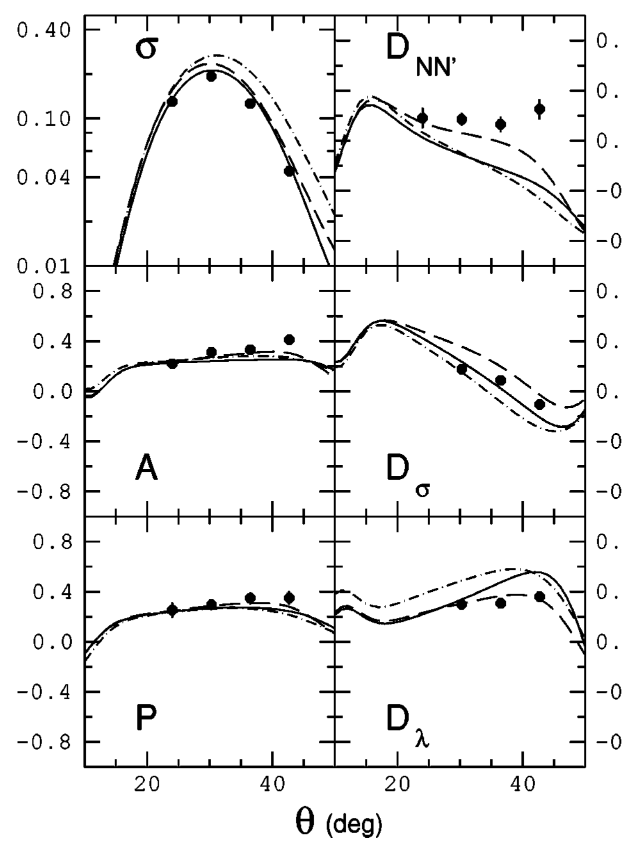

FIG. 3. Same observables as defined in Fig. 1, with predictions from the CD-Bonn [28] (solid), Reid68 [37] (dashed), and Paris [38] (dash-dotted) potentials. Data as in Fig. 1.

"CONVENTIONAL" MEDIUM EFFECTS

In this section, we move to the investigation of the effects of including Pauli blocking and nuclear binding in the NN interaction. While the t matrix (namely, the free-space interaction) was obtained from the Lippmann-Schwinger equation, the in-medium interaction, or G matrix, is a solution of the Bethe-Goldstone equation, schematically written as

$$G = V + V\frac{Q}{e^*}G. \tag{2}$$

The energy denominator of the propagator is now modified as compared to the free-space one to reflect the binding energy of the nucleons in nuclear matter. Also, the Pauli projection operator Q has appeared to prevent nucleons from scattering into occupied states.

In order to make the in-medium calculation tractable, we follow the standard procedure of replacing the Pauli projector with its angle average [3]. The angle-averaged Pauli function approaches the exact value only when the center-of-mass momentum of the in-medium NN scattering approaches zero. In the context of nuclear matter saturation (negative incident energies), it has been shown that the angle averaging is a good approximation [40]. Cheon and Redish [41] have demonstrated that the quality of this approximation is still good for positive energies up to about 300 MeV and normal nuclear matter densities.

Another density-dependent feature of Eq. (2) is the nucleon mean field due to the medium, which reduces the mass of the nucleon and increases the magnitude of the energy denominator e^* as compared to Eq. (1). This has been known as the *dispersive effect*. In nuclear matter, the energy of a single nucleon with mass m and momentum p is

$$E(p,m) = T(p,m) + U(p) \tag{3}$$

with $U(p)$ the auxiliary potential and T the kinetic energy. The single-particle energy, $E(p,m)$ in Eq. (3), appears in the propagator of Eq. (2). Thus, the G matrix depends on $U(p)$. The potential $U(p)$ must be determined from the interactions of a nucleon with all the other nucleons in the Fermi sea, so it depends on the reaction G matrix. Therefore, a procedure has been developed to determine G and U self-consistently. For details, see Ref. [3].

For reasons of numerical simplification, we use the *effective mass* ansatz, which amounts to setting

$$T(p,m) + U(p) = T(p,m^*) + U_0. \tag{4}$$

The self-consistent (momentum-dependent) potential $U(p)$ is parametrized in terms of the effective mass m^* and a constant U_0. Again, this follows closely Ref. [3]. For a given value of the nuclear density, or Fermi momentum, the calculation outlined above is free of adjustable parameters.

At this point, the next natural step would be to include Dirac effects. However, this requires the NN potential to be constructed from Dirac spinors, which is the case for CD-Bonn (a relativistic, meson-theoretic potential), but not for the other high-precision potentials. Thus we are not able to extend the present comparison to a full Dirac-Brueckner calculation. This issue is left to a future confrontation with the data.

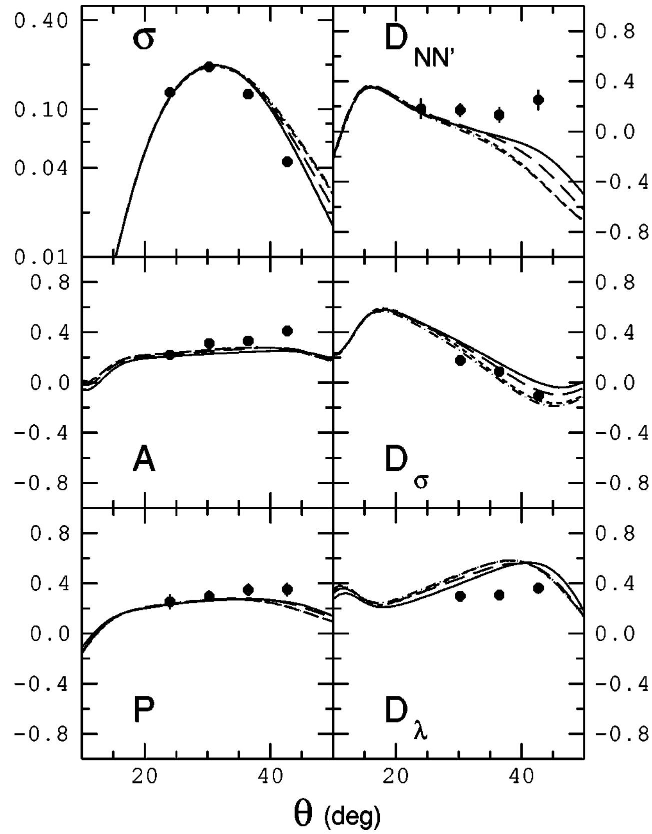

FIG. 4. Predictions based upon the G matrices derived from the same four high-precision potentials applied in Fig. 1. Observables and definition of curves as in Fig. 1. Data as in Fig. 1.

The medium-modified calculations for the $^{28}\mathrm{Si}(\vec{p},\vec{p}\,')^{28}\mathrm{Si}$ observables are shown in Fig. 4. Compared to Fig. 1, there is now considerably more scatter among the different calculations. These differences are now of a size that is comparable to, and in some cases larger than, the experimental errors. The predictions of the two entirely local potentials, namely, Nijmegen-II and Reid93, remain essentially indistinguishable, while the remaining two, CD-Bonn (nonlocal), and Nijmegen-I (containing some nonlocal terms), are separated away from the other potentials when medium effects are considered. This is also seen in Fig. 5, where we show predictions for the $D_{NN'}$ observable from the four potentials with (solid curve) and without (dashed) medium modifications. There is a small but noticeable tendency of medium-modified calculations to discriminate between local and nonlocal potentials. This could be due to the strength of the tensor force, typically different for local and nonlocal potentials [28].

In Fig. 6, we select one of the high-precision potentials (CD-Bonn) and show $(\vec{p},\vec{p}\,')$ observables with and without medium modifications. This way, we can assess the scale of the medium effects relative to the difference between calculation and experiment, and relative to the experimental errors. In general, medium effects are small since they enter only in second and higher order (the second term in the Bethe-Goldstone equation). For the central part of the NN

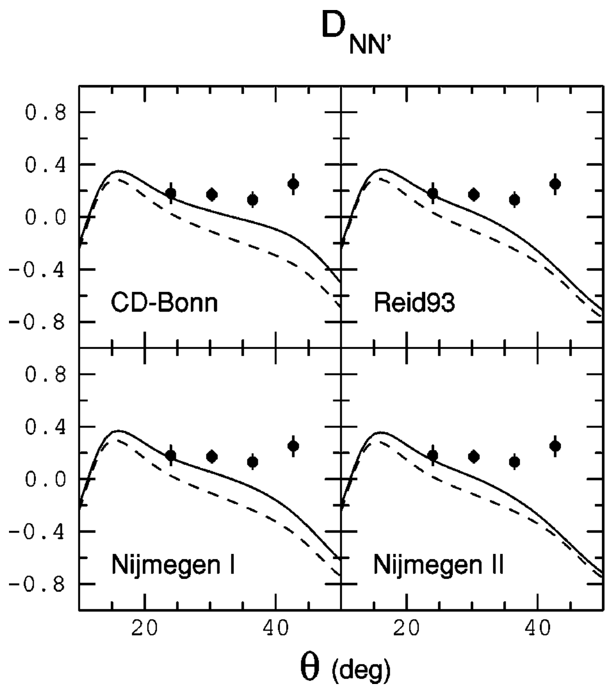

FIG. 5. Predictions for the $D_{NN'}$ coefficient from the four high-precision potentials of Fig. 1 with (solid curve) and without (dashed) medium modifications. Data as in Fig. 1.

interaction, the two terms in the Bethe-Goldstone equation are comparable, and substantial medium effects are seen. The 6^-, $T=1$ transition in $^{28}\mathrm{Si}(\vec{p},\vec{p}\,')^{28}\mathrm{Si}$, however, only depends on the spin-dependent parts of the NN force, namely, the tensor and the spin-orbit parts, for which the largest contribution is already contained in the first order term (namely, the bare potential). Thus, the conventional medium effects are small. This also means that any new medium effects that would change the NN potential should be readily observed in such transitions, and reactions such as the one illustrated here would be a suitable place to observe and characterize them.

The differences shown in Fig. 6 between the data and the medium-modified calculation (solid curves) can help us assess how well we might be able to measure the scale of any new medium effect (such as the chiral restoration parameter of Ref. [42]), provided it is able to account for these differences in all observables. This would mean, given the variety of polarization data available, that the spin structure of the proposed effect is appropriate. In addition to the experimental errors indicated for each data point, we also must consider off-shell differences among the calculations as shown in Fig. 4 and how well these interactions actually reproduce reported NN polarization data in the neighborhood of 200 MeV bombarding energy.

The rank-1 polarization observables are the analyzing power and the induced polarization (these are the same in the free NN system). High precision data for the NN analyzing power exists near 200 MeV [43,44], and modern potentials can reproduce it with differences typically less than 0.02 over the momentum transfer range where we have $(\vec{p},\vec{p}\,')$ data. Differences between the local and nonlocal medium-modified calculations for A or P are typically near 0.03 in the same range. Combining these contributions adds an uncertainty to the comparison of about 0.04. For a high spin state such as the 6^- in ^{28}Si, the angular distributions for A and P are similar since the contributions to the reaction from nuclear current terms are small [45]. This similarity exists also for the distorted-wave impulse-approximation predictions, thus these comments apply equally well to both observables. The disagreement between data and the medium-modified calculations of Fig. 6 rises with angle, and at the largest angle may depart from the calculation by 2 standard deviations when all contributions are included. Thus the best one could do is to determine the size of a new medium effect within that uncertainty, assuming the new effect had an adjustable scale that would bring the calculations into agreement with the data, and that such improvements were systematic.

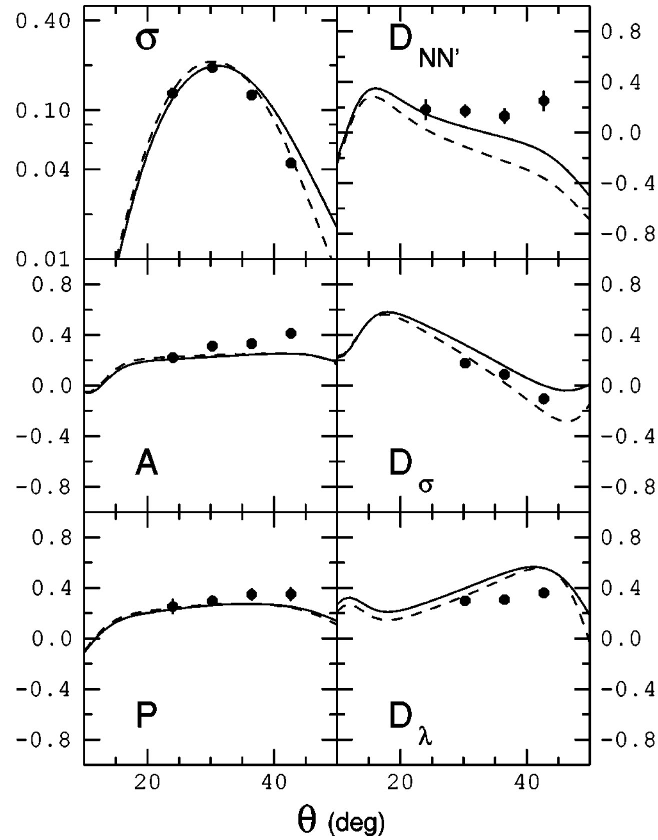

FIG. 6. Predictions from the CD-Bonn potential with (solid) and without (dashed) medium modifications. Observables as defined in Fig. 1. Data as in Fig. 1.

A similar evaluation may be made for the rank-2 polarization transfer coefficients. While the differences between data and calculations may be larger, especially for D_{NN}, so are the additional uncertainties from off-shell differences in the theory and from the agreement with the free NN polarization transfer data. Typical off-shell differences are larger than 0.05, and may exceed 0.1. Disagreements with the NN data are about the same. There is some tendency for the comparisons to be worse for the ''off-diagonal'' polarization transfer coefficients $D_{SL'}$ and $D_{LS'}$ than for the ''diagonal'' ones D_{NN}, D_{SS}, and D_{LL}. Thus the disagreements for D_σ and D_λ in Fig. 6 are of only marginal significance. D_{NN} may yield new information at the largest angle at a level of 3 standard deviations.

Other parts of the distorted wave calculations may give rise to additional uncertainties in the comparison. Sensitivity to the optical potential treatment of the distortions may be estimated by substituting a global optical potential for the ones we have used that were adjusted to reproduce a particular set of elastic scattering measurements. We have chosen the potential of Schwandt [46] since it covers the required range of mass and bombarding energy, and repeated the free space and the density-dependent calculations made with the CD-Bonn potential. The differences for the rank-1 observables in our selected angle range were typically less than 0.01. For the rank-2 polarization transfer, the differences were typically in the range 0.01 to 0.04 for the ''diagonal'' coefficients, and only slightly larger for the ''off diagonal.'' These changes are less than those arising from off-shell effects and from differences with the free *NN* polarization data, and hence do not add significantly to the theoretical uncertainties already discussed.

Clearly these estimates, made only for the 6^- state shown here, are more general only to the extent to which other cases resemble this one in ^{28}Si. (We have not included considerations of the cross section here since normalization and form factor errors also contribute, making such estimates more difficult.) We note that the disagreements shown here are both smooth and rise with increasing scattering angle. These observations would suggest that any new medium effects apply only at short range in the *NN* interaction. A mechanism which improves the agreement in this domain is more likely to produce improvement over the entire angle range of the data. By combining information from all polarization observables, the scale of such a change could at best be determined with a precision at or somewhat better than 3 standard deviations.

CONCLUSIONS

We have examined the baseline context for using data from nucleon-induced reactions to probe for new, systematic changes to the *NN* interaction inside nuclei. Some of these changes arise from considerations of nucleon substructure, and would play an important role in the description of nuclear matter at high temperatures and densities. The baseline context we have explored is given by the currently available *NN* potentials as well as the established medium modifications to the *NN* interaction.

We find that modern *NN* potentials have been developed to the point where the differences among them are well below the level where they would affect the characterization of any new medium effect. The same is not true for older *NN* potentials, and their use for nucleon-induced reaction calculations would affect the reliability of any conclusions concerning medium dependence. At the same time, there may remain some systematic differences between the observables from these potential models and the free *NN* polarization data, and we certainly cannot expect agreement with $(\vec{p},\vec{p}\,')$ at a better level.

When the G matrix is used in place of the t matrix, more variations are seen among modern *NN* potentials. These differences may be related to nonlocalities present in some of the potentials. They should be regarded as a theoretical uncertainty and included with other uncertainties. Variations within realistic limits in the parameters for the optical potential distortions do not add significantly to this theoretical uncertainty.

The combined uncertainties mean that the best one can expect to do with present theory and experimental data is to determine the size of a proposed medium effect (such as scaling of meson masses) to about 3 standard deviations. This estimate assumes that such an effect has the correct spin operator character and that agreement with all polarization observables improves simultaneously. At present, the rise in the disagreements with angle suggests that any such changes are of short range.

Clearly, any new hypothesis should be tested against a broad range of data. We have presented a single case for illustration, but comparisons with other cases are now easily realized.

The next step in our pursuit will be a complete Dirac-Brueckner calculation. This will be confronted with data from a large range of transitions, so that the quality of the established many-body effects can be evaluated even as new effects are explored.

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