Signatures of Density Dependence in the Two-Nucleon Effective Interaction near 150 MeV

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Definitive evidence for strong density dependence in the two-nucleon effective interaction is noted in inelastic (p,p') differential cross section and polarization data for $E_p \sim 150$ MeV. These effects are quite sensitive to variations in the nuclear medium and are well described, for inelastic scattering, by the local-density approximation with use of density-dependent effective interactions from nuclear matter.

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We present new results for normal-parity isoscalar excitations via the (p,p') reaction that demonstrate for the first time the importance of medium corrections to the isoscalar spin-independent central component of the two-nucleon effective interaction in the energy range $E_p = 100$–200 MeV.[1] New data for ^{16}O are presented[2] and calculations for existing ^{12}C and ^{40}Ca data[3-5] are also presented.

Although the distorted-wave impulse approximation[6] has had considerable success in describing the qualitative features of proton scattering near 150 MeV,[4,7-9] it is not sufficiently accurate to allow quantitative extraction of neutron transition densities except when proton-neutron differences are large.[1] In recent years there has been a concerted effort to deduce a two-nucleon effective interaction in the nuclear medium.[10,11] The t matrix describing the scattering of a continuum nucleon from a nucleon in infinite nuclear matter, including Pauli blocking effects, is reduced to a local form and applied in finite nuclei via the local-density approximation.[12] The present work is the first application of the nuclear-matter results of Ref. 11 to inelastic proton scattering at energies above 100 MeV.

The work of Refs. 10 and 11 provides density- and energy-dependent nuclear-matter optical potentials. Ref. 11 further provides a local t-matrix t_{NM} that is a function of internucleon separation $\vec{s} = \vec{r}_1 - \vec{r}_2$, the ground-state nuclear density $\rho_G(c)$ in the vicinity of the interacting nucleons $[\vec{c} = \frac{1}{2}(\vec{r}_1 + \vec{r}_2)]$, and the local energy of the incident nucleon $E(r_1)$, i.e., $t_{\text{eff}} = t_{NM}(s, \rho_G(c), E(r_1))$. At low density, these interactions reduce to the free two-nucleon t matrix $t_{\text{free}}(s, E_0)$. The impulse approximation (IA) neglects the dependence of the effective interaction on density, with use of $t_{\text{eff}} = t_{\text{free}}(s, E_0) \simeq t_{NM}(s, 0, E_0)$.

The scattering potentials $U^{fi}(\vec{r}_1)$ seen by the incident nucleon are obtained by averaging the effective interaction over the target transition densities.[7] For the strong normal-parity transitions $[0^+ \to J^\pi, \pi = (-1)^J]$ considered here, the transverse electromagnetic form factors are small, indicating that the spin transition densities are negligible. The scattering potential then contains only two important terms, obtained by averaging the central spin-independent and spin-orbit components of the two-nucleon effective interaction over the point-nucleon transition density $\rho_\tau^{fi}(\vec{r}_2)$ where $\tau = p$ or n, for proton or neutron, respectively. Specifically,

$$U^{fi}(\vec{r}_1) = U^C(\vec{r}_1) + \vec{U}^{LS}(\vec{r}_1) \times \vec{p}_1 \cdot \vec{\sigma}_1 \quad (1)$$

$$U^C(\vec{r}_1) = \sum_{\tau = p,n} \int d^3r_2 [t^{C,D}_{\text{eff},\tau}\, \rho_\tau^{fi}(\vec{r}_2) + j_0(ks) t^{C,\text{Ex}}_{\text{eff},\tau}\, \rho_\tau^{fi}(\vec{r}_1, \vec{r}_2)] \quad (2)$$

$$\vec{U}^{LS}(\vec{r}_1) = \sum_{\tau = p,n} \int d^3r_2 \vec{s}\, [t^{LS,D}_{\text{eff},\tau}\, \rho_\tau^{fi}(\vec{r}_2) + j_0(ks) t^{LS,\text{Ex}}_{\text{eff},\tau}\, \rho_\tau^{fi}(\vec{r}_1, \vec{r}_2)], \quad (3)$$

where the second terms of Eqs. (2) and (3) are a plane-wave local-momentum approximation[13] to knockon exchange, D and Ex denote direct and exchange, and k is the local wave number. The mixed density is approximated by $\rho(\vec{r}_1, \vec{r}_2) = \rho(\vec{r}_2) \times C(k_F s)$, where k_F is the local Fermi momentum. The results have been found insensitive, at these energies, to local variations of the wave number and to the choice of correlation function $C(k_F s)$. The calculations presented here use the asymptotic energy approximation (AEA),[13] which consists of replacing $C(k_F s)$ by unity and the local wave number k by the asymptotic wave number k_0.

Below we contrast the results of the IA with those using the nuclear-matter effective interaction and local-density approximation (LDA). The IA calculations use the free t matrix of Ref. 8. The LDA calculations use the density-dependent central t matrix of Ref. 11 and the spin-orbit t matrix of Ref. 8. The spin-orbit interaction of Ref. 11 is similar to that of Ref. 8 and nearly independent of density. The inelastic scattering calculations have been performed in distorted-wave approximation (DWA) with the above inelastic-scattering potentials and with distorted waves generated from either phenomenological optical potentials fitted to elastic-scattering data or from the "consistent" microscopic optical potentials calculated with the same interaction that induces the inelastic transition. In all calculations we assume that the neutron and proton densities are equal, and take the proton densities from electron scattering,[14-17] thereby minimizing the nuclear-structure uncertainties and isolating the effective interaction for study. The assumption $\rho_n = \rho_p$ should be reliable for the $N = Z$ nuclei considered here.

The ^{16}O data were obtained at the Indiana University Cyclotron Facility with 135-MeV protons and BeO foils.[2,14] This work is part of a program[1] whose goal is to exploit the complementary sensitivity of the (e,e'), (p,p') and (p,n) reactions to separate the roles of protons and neutrons in the oxygen isotopes. We consider the differential cross sections for the first 3^- and 1^-, $T = 0$ states of ^{16}O. The 1^- state is particularly interesting for the study of density dependence of the effective interaction because its transition density peaks in the high-density nuclear interior, where the medium effects should be largest.[1] We also consider differential-cross-section data ($E_p = 122$ MeV)[3] and polarization data ($E_p = 185$ MeV)[4] for the first 2^+ level of ^{12}C and polarization data ($E_p = 185$ MeV)[5] for the first 3^- level of ^{40}Ca.

The IA results, shown on the left-hand side of Fig. 1, give only a qualitative description of the differential–cross-section data, a very poor description of the polarization data, and are quite sensitive to the choice of distorted waves. On the other hand, the LDA results, shown on the right-hand side of Fig. 1, give a superb description of both the inelastic–differential–cross-section and polarization data. As expected, the 1^-, $T = 0$ excitation of ^{16}O is particularly sensitive to the density dependence and the difference between the IA and LDA results is particularly striking. Note specifically the characteristic shoulder in the differential cross sections at $q \sim 1.5$ fm^{-1} and the strikingly large negative polarizations at $q \sim 2.4$ fm^{-1} which occur in part because as the density increases the low-q (high-q) components of the LDA central interaction are suppressed (enhanced) relative to the IA central interaction. These effects are illustrated by the modulus of the spin-independent central interactions shown on the bottom of Fig. 1. We also note that the LDA results are considerably less sensitive to the choice between phenomenological or consistent distorted waves than are the IA results, and describe the differential–cross-section data far better with either choice. The polarizations are more sensitive to the distorted waves and favor, in the LDA, consistent distorted waves.

The remarkable success of the interaction of Ref. 11 in describing inelastic-scattering data provides the hope that 100–200-MeV proton scattering may soon be a quantitative probe of nuclear structure. The LDA with the local-momentum approximation for exchange also provides signifi-

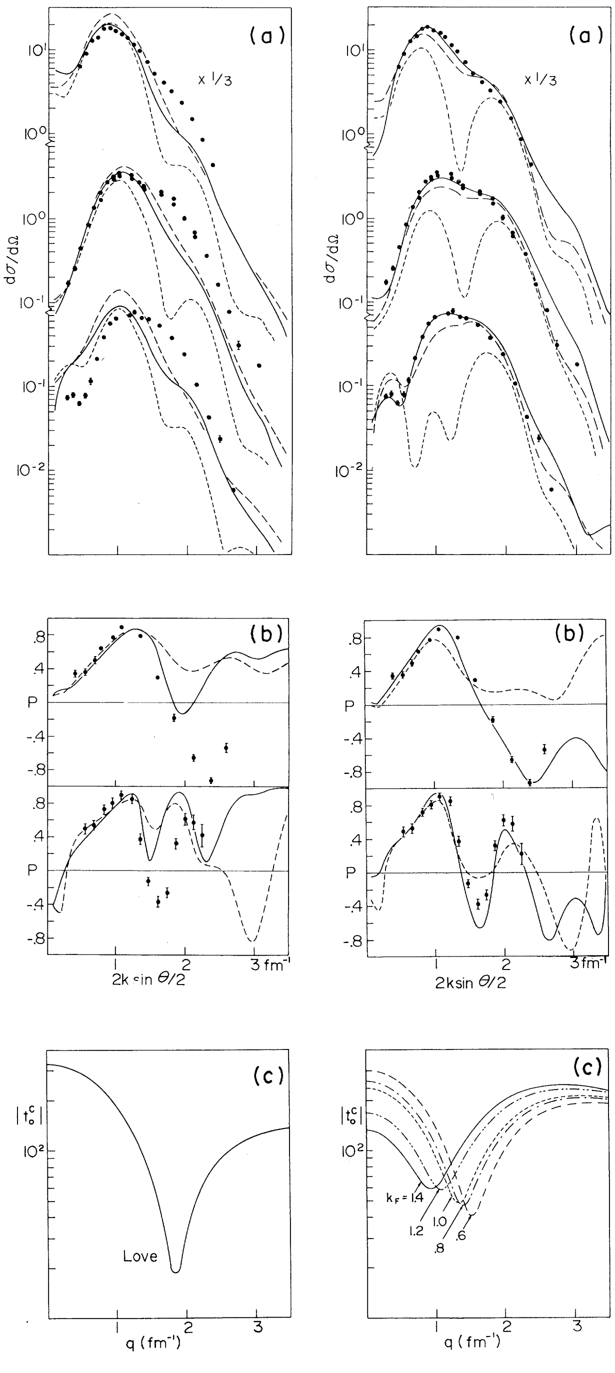

FIG. 1. Left-hand side, IA. Right-hand side, LDA. (a) Cross sections (mb/sr) from top: $^{12}C\ 2_1^+$ ($E_p = 122$ MeV), $^{16}O\ 3_1^-$ and 1_1^- ($E_p = 135$ MeV). (b) Top, $^{12}C\ 2_1^+$; bottom, $^{40}Ca\ 3_1^-$. Both at $E_p = 185$ MeV. (a), (b): Solid line, consistent distorted waves (DW); long dashes, phenomenological DW; short dashes, t_0^C only (omit t_0^{LS}) with phenomenological DW. (c) Modulus of the isoscalar spin-independent central interaction $|t_0^C(q)|$ at $E_p = 140$ MeV, including AEA exchange contribution. IA uses the Love interaction (Ref. 8).

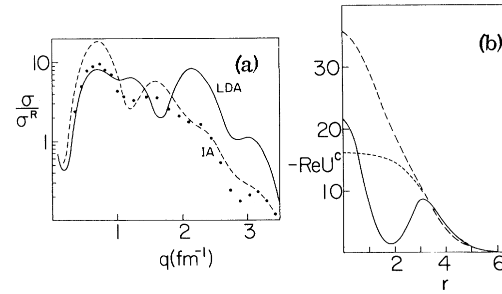

FIG. 2. (a) $^{16}O + p$ elastic scattering (ratio to Rutherford scattering), $E_p = 135$ MeV. (b) Real central optical potentials: solid line, LDA; long dashes, IA; short dashes, phenomenological.

cant improvements over the IA for elastic scattering. Although the IA appears to give a reasonable description of the elastic-scattering data, it overestimates the forward-angle elastic cross section and the reaction cross section considerably. The LDA reproduces the forward-angle elastic cross section and the reaction cross section, but fails completely to describe the backward-angle elastic cross section. This high-q scattering results from a sharp depression of the real central optical potential in the vicinity of the nuclear surface (see Fig. 2). These problems are directly due to the failure, for elastic scattering, of the local-momentum approximation for exchange. Bauhoff, von Geramb, and Pálla,[18] have demonstrated that the LDA provides a good description of elastic-scattering data if the exchange nonlocality is treated exactly. The exact treatment of exchange nonlocality is expected to have little effect on the inelastic–differential–cross-section predictions, but the effect of the exact distorted waves upon the polarization predictions is not known.

In summary, we have identified several distinct signatures of density dependence in the two-nucleon effective interaction in the differential–cross-section and polarization data for normal-parity isoscalar excitations via the (p, p') reaction at $E_p \sim 150$ MeV. These signatures include suppression (enhancement) of the central interaction for q less (greater) than 1.5 fm^{-1} and large negative polarizations at $q \sim 2.4$ fm^{-1}. The inelastic-scattering data are well described by the local-density approximation with use of the nuclear-matter effective interactions of Brieva and Rook[11] and consistent distorted waves.

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Comparison of Pion- and Photon-Induced Reactions on ^{12}C

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The proton spectra from pion- and photon-induced reactions on ^{12}C at the $\Delta(\frac{3}{2},\frac{3}{2})$ resonance are found to be very similar in shape, and in their variation with angle. It seems reasonable to assume that these protons arise from a common reaction mechanism (Δ production) for the two projectiles. The absolute cross sections for producing protons with pions and with photons are in roughly the same ratio as the total inelastic pion yield to the total photopion yield.

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In the energy region of the $\Delta(\frac{3}{2},\frac{3}{2})$ resonance, the interaction of photons with nucleons is dominated by pion production, and the resonant behavior of this cross section indicates that the reaction proceeds through formation of a Δ.[1] The fact that the π interaction on these nuclei also proceeds through the Δ implies that a comparison between pion- and photon-induced reactions