

Microscopic model analyses of select scattering of 135 MeV protons from ^{12}C

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An effective interaction based upon two nucleon g matrices has been used in a fully microscopic calculation of the nonlocal proton- ^{12}C optical potential at 135 MeV. Excellent predictions of the differential cross section from elastic scattering result. The same effective interaction, combined with one body density matrix elements specified by a large basis shell model for ^{12}C (^{12}N), and with the relative motion wave functions from the nonlocal optical potentials define the distorted wave approximation that is employed to analyze cross sections from inelastic proton scattering. With that approximation, inelastic scattering cross sections from various states in ^{12}C and from the charge exchange reactions leading to the low excitation states of ^{12}N have been evaluated. Our results indicate a problem with the structure model when $3\hbar\omega$ components are considered. [S0556-2813(97)04905-4]

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In a recent set of papers [1,2], we specified a fully microscopic (Schrödinger) approach to analyze proton scattering from nuclei, both elastically and inelastically to discrete final states. That model also is appropriate to use in analyses of charge exchange (p,n) scattering. Such an approach requires three ingredients. First, one must have a nucleon-based model of nuclear structure from which one-body density matrix elements (OBDME's) can be obtained. In most cases, a realistic set can be assured only if a multi- $\hbar\omega$ shell model space is used for the structure calculations. A complete $(0+2)\hbar\omega$ space, for example, was needed for studies of scattering from light nuclei, and ^{12}C in particular [1]. In the cases of ^{14}N and ^{16}O , a complete $(0+2+4)\hbar\omega$ space was used [2]. For those nuclei, the (large basis) shell model OBDME's were obtained by using the codes OXBASH [3] and the Dubach-Haxton version of the GLASGOW program [4]. Use of those OBDME's gave good to excellent fits to electron scattering form factors, especially if Woods-Saxon potential wave functions were used for the single nucleon bound states. The second ingredient is a properly defined effective two nucleon (NN) interaction in the nuclear medium. For protons with energies of 200 MeV and more, they were found from an accurate mapping of the relevant NN g matrices, i.e., solutions of the Brueckner-Bethe-Goldstone equations for infinite nuclear matter [5]. Details of the techniques involved are given elsewhere [1,6] and the results, based upon the Paris interaction [7], have been tabulated [8]. Finally those effective interactions must be folded with the target states' density matrices to specify the proton optical potentials (for both the ground and excited states of interest). The antisymmetrization of the many-body ($A+1$ nucleons) wave functions engenders those optical potentials to be nonlocal. While there are schemes to specify an equivalent local interaction, we retained the full nonlocality resulting and solved the associated inhomogeneous forms of the Schrödinger equations to find the elastic scattering phase shifts (and thus cross sections, analyzing powers etc.) and also to

specify the distorted wave functions for use in the distorted wave approximation (DWA) analyses of the inelastic scattering data. The results we obtain are from "single shot" calculations with the ingredients set by use of other data (such as electron scattering form factors) to specify details. The elastic, inelastic, and charge exchange cross sections are found by single runs of the DWA code of Raynal [9]. No adjustments are made to either the shape or the magnitude of any result.

In this paper, we report on the results of using the fully microscopic model of proton-nucleus scattering defined above, in analyses of the cross-section data taken from the elastic scattering of 135 MeV protons from ^{12}C , from the inelastic scattering of those protons leading to the $2^+;0$ (4.43 MeV), the $1^+;1$ (15.11 MeV), the $2^+;1$ (16.11 MeV), and the $2^-;1$ (16.57 MeV) states of ^{12}C [10], and from the charge exchange scattering of 135 MeV protons leading to the ground and to the (combined) first and second excited states of ^{12}N [11]. The isovector states of ^{12}C are the analogs of those observed in the charge exchange reactions and charge independence of the NN effective interaction dictates that the charge exchange cross sections then should be simply a factor of 2 larger than the appropriate inelastic scattering ones. That has been shown [11] essentially to be the case.

The model of nuclear structure used in our scattering calculations is that reported previously [1]. The spectrum of ^{12}C was calculated using the program OXBASH [3] and with the MK3W interaction (see Ref. [1]). The positive parity states of ^{12}C were calculated in a complete $(0+2)\hbar\omega$ space using this interaction, while the negative parity states were calculated in a restricted $(1+3)\hbar\omega$ space. In both calculations the same single particle basis of $0s$ up to and including the $0f1p$ shell was used. Hence the restriction from a full $(1+3)\hbar\omega$ study is that we have not included the $0g1d2s$ shell. With exceptions, most notably the superdeformed $0_1^+;0$ state at 7.65 MeV, our calculated spectrum to 20 MeV excitation agreed well with observation, with all established

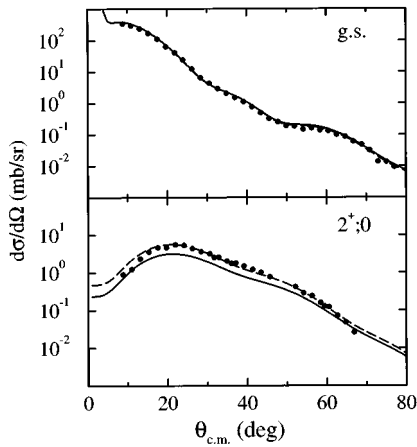


FIG. 1. The differential cross-section data [10] (dots) from the elastic scattering of 135 MeV protons off ^{12}C compared with the result of our microscopic optical potential calculations (top) and of our DWA calculations of the excitation of the $2^+;0$ (4.43 MeV) state (bottom). The solid and dashed curves display the results of the DWA calculations made using the OBDME's from the $0\hbar\omega$ and $(0+2)\hbar\omega$ models of spectroscopy.

spin-parity assignments matched by our large basis shell model calculations [1].

From those structure calculations, the OBDME's extracted were used in analyses of inelastic proton scattering data (for 200 to 800 MeV incident energies) as well as in analyses of electron scattering form factors [1]. Also with these OBDME's, very good fits to the relevant electron scattering form factors were found, especially when the single nucleon bound states were generated from Woods-Saxon potentials. The longitudinal (elastic) form factor was fit well to 4 fm^{-1} momentum transfer as was the transverse magnetic one from the excitation of the $1^+;1$ (15.11 MeV) state for momentum transfers up to 1.5 fm^{-1} . The higher momentum (second peak) values of that transverse magnetic form factor are influenced by specific meson exchange current effects [12].

Folding our effective interaction with the density matrix elements of the ground state of ^{12}C specifies the nonlocal optical potential to be used in the calculation of the (135 MeV proton) elastic scattering observables. That potential also was used to define the incident projectile distorted wave function in our DWA calculations of inelastic scattering and charge exchange (p,n) reactions from ^{12}C . With density matrices taken from the $(0+2)\hbar\omega$ structure model calculations, the elastic scattering cross section resulting from use of that nonlocal Schrödinger potential is displayed by the dashed curve in the top section of Fig. 1. The Coulomb interaction was taken to be that of a uniformly charged sphere. The solid curve shown in that same figure is the result when the simpler $0\hbar\omega$ model information is used in the folding. Clearly there is excellent agreement with the data (dots) and the two model structures give essentially indistinguishable results. As with other elastic scattering potential calculations [1] the primary shells (as specified by the $0\hbar\omega$ model) so dominate the nucleon occupancies that higher shell contributions to the folding of the effective interaction are not significant. But the use of larger model space calculations of nuclear structure markedly changes the OBDME's for most inelastic transi-

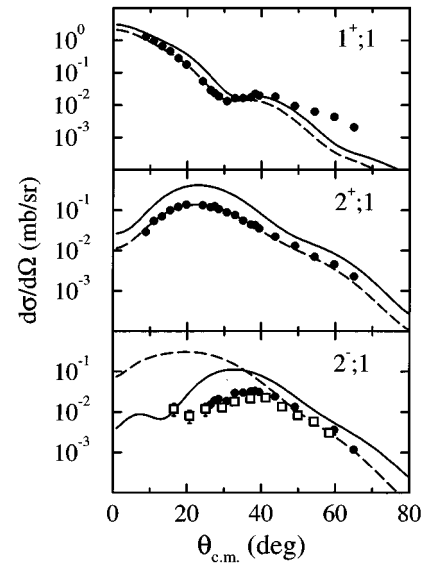


FIG. 2. The differential cross section from the inelastic scattering of 135 MeV protons leading to the the $1^+;1$; (15.11 MeV) state in ^{12}C , to the $2^+;1$ (16.11 MeV) state in ^{12}C (middle), and to the $2^-;1$ (16.57 MeV) state in ^{12}C (bottom). The solid and dashed curves display the results of the DWA calculations made using the OBDME's from the $0\hbar\omega$ ($1\hbar\omega$) and $(0+2)\hbar\omega$ [$(1+3)\hbar\omega$] models of spectroscopy.

tions from their $0\hbar\omega$ model values. For example, the end effect is to increase the magnitude of the predicted cross section. That is displayed in the bottom section of Fig. 1 in which the cross-section data from Ref. [10] are compared with our DWA results. Use of the $0\hbar\omega$ model OBDME yields the solid curve while use of the $(0+2)\hbar\omega$ model set results in the dashed curve. The large basis structure results are in excellent agreement with the observations, as they were with our previous calculations [1] of 200 to 800 MeV proton scattering to this state.

With unnatural parity and isovector transitions, however, the larger space OBDME lead usually to a reduction in the predicted cross sections. Such is the case of the isovector excitation of the 15.11 MeV $1^+;1$, of the 16.11 MeV $2^+;1$, and of the 16.57 MeV $2^-;1$ states in ^{12}C . That is demonstrated in Fig. 2 wherein the inelastic scattering data [10] are displayed by the solid circles. The calculated results shown by the dashed and solid curves were obtained using the OBDME's from the $(0+2)\hbar\omega$ and from the $0\hbar\omega$ models of structure for the positive parity state excitations, respectively. The respective lines display results found using the $(1+3)\hbar\omega$ and $1\hbar\omega$ models for the structure of the $2^-;1$ state. We have added the inelastic scattering data measured at 122 MeV [11] (shown by the open squares) as they further indicate the trend of the $2^-;1$ transition. Clearly the $1^+;1$ the $2^+;1$ data are reproduced well within a large basis calculation, to about 40° and 60° respectively, but the $2^-;1$ set below 40° is not. The results of DWA calculations made using the large basis structure OBDME's are significantly reduced from those found with the small basis set. These results are very similar to those found at 200 MeV and higher [1] with the same basic microscopic model approach. But for the $2^-;1$ transition, the data essentially are just large angle (large momentum transfer) peaks. We anticipate the

small angle cross sections to be small given that such is observed also in the electron scattering form factor for this state. Our DWA calculation thus overpredicts what may be inferred from the cross-section data. We confirm that is so with the analyses of the charge exchange cross-section data.

The charge exchange cross-section data from the excitation of the ground state in ^{12}N scales very well to the inelastic scattering cross section from the excitation of its analog, the $1^+;1$ 15.11 MeV state in ^{12}N . That data is displayed by the filled circles in the top segment of Fig. 3 as are the data from the (summed) excitation of the $2^+;1$ (0.96 MeV) and $2^-;1$ (1.19 MeV) excited states which are displayed in the bottom segment of Fig. 3. In that bottom segment, the (appropriately scaled) data from the inelastic scattering cross sections to their analogs, the 16.11 MeV $2^+;1$ and the 16.57 MeV $2^-;1$ states, are also shown. Specifically, the (scaled) data from inelastic scattering to the $2^+;1$ and $2^-;1$ states are given by the open circles and open squares, respectively. The three curves displayed in the bottom section of Fig. 3 are the individual (scaled inelastic scattering) DWA results for the $2^+;1$ (small dashed curve) and $2^-;1$ (large dashed curve) excitations, and the solid curve is their sum. Clearly the forward angle data, dominated by the $2^+;1$ transition is well fit by our calculation of just that transition alone, but the $2^-;1$ effect is in error. This result confirms the expectation that the $2^-;1$ excitation is quite weak at small momentum transfer values. Thus the current structure model for this $2^-;1$ state is inadequate.

Millener [13] has noted that the $2^-;1$ transition must be dominated by the $p \rightarrow d$ OBDME's which primarily have transition quantum numbers $L=S=1$, since the $p \rightarrow s$ OBDME's, which favor $L=1, S=0$, give considerable transition strength at low momentum transfer values.

Our results extend the successes of previous analyses of proton elastic and inelastic scattering data made using a completely microscopic model of the reactions downward in energy (to 135 MeV). They indicate also that the discrepancies between our results and the data we have studied are due to

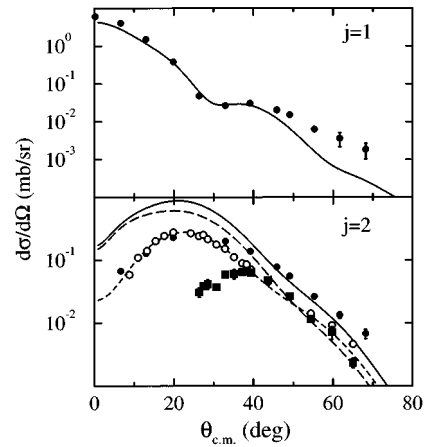


FIG. 3. The differential cross sections (solid circles) from the charge exchange scattering of 135 MeV protons leading to the 1^+1 (ground state) of ^{12}N (top and labeled $j=1$) and to the (summed) $2^+;1$ (0.96 MeV) and $2^-;1$ (1.19 MeV) states in ^{12}N (bottom and labeled $j=2$). In the bottom segment, the cross-section data from 135 MeV proton inelastic scattering to the analogs, the 16.11 MeV $2^+;1$; and the 16.57 MeV $2^-;1$ states, after appropriately scaling by a factor of 2, are shown by the open circles and open squares, respectively. The three curves displayed in the bottom section are the individual (scaled inelastic scattering) DWA results for the $2^+;1$ (small dashed curve) and $2^-;1$ (large dashed curve) excitations and the solid curve is their sum. The OBDME from the large basis model of structure were used in the calculations.

inadequate specification of the OBDME's. For a reasonable description of the negative parity spectrum of ^{12}C , it seems necessary to use a shell model calculated in a $(1+3+5)\hbar\omega$ space, at least.

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