Fully microscopic model analysis of the elastic and inelastic scattering of protons from ^{12}C and for energies in the range 200 to 800 MeV

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Medium modified effective two nucleon interactions are defined for protons incident upon ^{12}C with energies in the range 200 to 800 MeV. Those effective interactions have been folded with the ground-state density to specify nonlocal optical potentials that were then used to analyze the elastic scattering differential cross sections and analyzing powers. A select set of isoscalar and isovector, positive and negative parity, inelastic proton scattering transitions have also been analyzed using the same (microscopic) optical models to define the distorted wave functions needed in distorted wave approximation (DWA) calculations of the associated differential cross sections and analyzing powers. All results are compared with ones found using the Love-Franey effective interactions. The nuclear structure relating to these transitions was chosen from $(0+2)\hbar\omega$ and $(1+3)\hbar\omega$ shell model calculations of the positive and negative parity spectra of ^{12}C, respectively. In comparison to previous DWA analyses, very good fits to most data over a range of energies are achieved with no variation being made to any of the input details, save for the choice of the effective interaction. Evidence of limitations of the spectroscopy and of specifics in the defined effective interactions at higher energies is found.

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I. INTRODUCTION

There exist extensive data sets on $^{12}C(\vec{p},p')$ reactions at various incident energies and for a large number of inelastic transitions [1–5]. Of these, the cross sections and analyzing powers from the inelastic scattering of protons from ^{12}C to a number of low-lying discrete excited states at incident proton energies ranging from 200 to 800 MeV have been analyzed recently [5] and in a distorted wave approximation (DWA). Therein the Love-Franey (LF) force [6] was used as the transition operator and the nuclear structure information required in such a study was obtained from the Cohen-Kurath (CK) [7] or Millener-Kurath (MK) [8] wave functions. However, that analysis was not fully microscopic since it employed phenomenological (complex, local) optical model potentials to determine the distorted wave functions. The parameters of those optical potentials were set by finding optimal fits to the relevant elastic scattering data. Also an arbitrary normalization was used with all calculated inelastic scattering cross sections to take into account the fact that the structures used were obtained from quite limited bases and so required corrections, i.e., core polarization. In that way, relatively good fits for cross-section data were obtained for scattering to a number of states in ^{12}C up to an excitation energy of 20 MeV. The analyzing powers, however, were not well described. Though these semi-microscopic calculations are generally good, the various *ad hoc* fittings required preclude any clear indication being made of strengths and weaknesses within the (then) current models of nucleon-nucleus (NA) reactions.

Other studies of (some of) these data were made, and to the strongly collective states [0^+_1;0 (g.s.), 2^+_1;0, 3^-_1;0 and 4^+_1;0 specifically] by using a coupled-channels (CC) formalism based upon either the Schrödinger equation [4] or the Dirac equation [9]. Those studies sought energy dependences of multipole deformation parameters. Considerable improvements in fits to data were obtained by using the Dirac equation rather than the nonrelativistic Schrödinger equation approach, with no energy dependences being found for the nuclear deformation parameters. Recently, a fully microscopic model of proton elastic and inelastic scattering has been developed [10]. In it large basis spectroscopy was used, either a full $(0+2)\hbar\omega$ (for positive parity states) or a restricted $(1+3)\hbar\omega$ (for negative parity states) shell model space calculations [11], as was a density-dependent (DD) effective interaction based upon nucleon-nucleon (NN) g matrices [12]. The results were in excellent agreement with the elastic and a number of inelastic scattering data obtained from the scattering of polarized protons from ^{12}C at 200 MeV without the need for any renormalizations. Herein we report on the results obtained using this new fully microscopic prescription to analyze the available data from the $^{12}C(\vec{p},p')$ reaction between 200 and 800 MeV. They are compared with those found using the LF force in place of our DD version. In all cases, relativistic kinematics has been used in the DWA. A number of final states in the spectrum of ^{12}C are studied.

In Sec. II, a brief discussion is given of the scattering models upon which the calculations are based. The results are presented and discussed in Sec. III of both the elastic scattering cross sections and analyzing powers and of those from a number of inelastic transitions.

II. THEORY

In a previous paper [10], we described in some detail the prescription of a fully microscopic model of elastic and in-

elastic scattering of protons from nuclei, the latter within a DWA framework. Application was made therein to analyze the differential cross sections and analyzing powers from the elastic and inelastic scattering of 200 MeV protons from ^{12}C. Thus, we give only a brief outline of the process here, referring the reader to Ref. [10] and references contained therein for more details.

In a "microscopic" DWA theory of inelastic scattering, there are three general attributes to be specified so that observables for a given NA scattering system can be predicted. They are the structure of the nucleus, the transition operator (the effective NN interaction between the probe and each and every nucleon within the target), and the optical potentials with which the "distorted" waves are generated.

To set the first attribute of such a microscopic theory of scattering, the structure of the nucleus, a nucleon-based model of the ground and excited states, is required. For inelastic scattering in the DWA, there are two kinds of spectroscopic information to be specified. The first quantities needed are the one-body (transition) density matrix elements (OBDME)

$$S_{j_1 j_2 I}=\langle \Psi_{J_f} \| [a^{\dagger}_{j_2} \times \tilde{a}_{j_1}]^I \| \Psi_{J_i} \rangle \ , \tag{1}$$

which weight the allowed individual nucleon particle-hole (j_2-j_1) excitations effecting the transition when an angular momentum transfer of I is involved. Here Ψ_{J_i} (Ψ_{J_f}) represents the initial (final) state. In the case of elastic scattering, these reduce to being the shell occupancies for the ground state. The shell occupancies of each state in the (calculated) spectrum up to 20 MeV as well as the OBDME for their excitation from the ground have been determined using a large basis shell model for ^{12}C [11]. The other structure information required with the DWA (and for a microscopic definition of optical potentials) is the specification of the single-nucleon shell bound states. Frequently in DWA analyses these have been chosen as harmonic oscillator wave functions, but, and as seen previously [10] and for ^{12}C specifically, a more realistic representation is to use Woods-Saxon bound state wave functions, i.e., eigenfunctions of the single-particle Hamiltonian with

$$V=V_0\left[1+2\lambda[\mathbf{l}\cdot\mathbf{s}]\left(\frac{\hbar}{m_\pi c}\right)^2\frac{1}{r}\frac{d}{dr}\right]f(r,R,a) \ , \tag{2}$$

where, with $R=r_0 A^{1/3}$,

$$f(r,R,a)=\left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1} \ . \tag{3}$$

The values of the Woods-Saxon potential parameters appropriate to describe states in ^{12}C are listed in Table II of Ref. [10]. They were determined as the most appropriate from a fit to the measured elastic electron scattering form factor.

With most studies needing the nucleon-based properties of ^{12}C, $0p$- or at best $(0p,1s,0d)$-shell model calculations [7,8] of the structure have been used, although they are known to be limited. Such models predict a spectrum with which large effective charges are needed to map measured electromagnetic transition rates. This is not the case with the recent larger space calculations of structure. Thus, as in Ref. [10], we have used the full $(0+2)\hbar\omega$ space (for positive parity states) and a restricted $(1+3)\hbar\omega$ space (for negative parity states) to describe the transitions of interest. The restriction is not severe as it is simply the neglect of single particle $3\hbar\omega$ excitations from the $0p$ shell to the $(0g,1d,2s)$ shell. Thereby the positive and negative parity states of ^{12}C were all obtained using the same single-particle basis and shell model interaction. All known negative states to 20 MeV excitation are matched by candidates from this structure model and to within 2 MeV [10]. Indeed use of this spectroscopy in an analysis of 200 and 398 MeV inelastic proton scattering cross sections and analyzing powers enabled us to suggest a means of determining $J^{\pi};T$ values for states in ^{12}C that hitherto had uncertain assignments [13]. One problem with the use of incomplete spaces is that there can be spurious center of mass motion involved with the state specifications. An important test of this is in the study of the isoscalar dipole excitation for which the center of mass position expectation should vanish. With our structure model that is so to within a thousandth of a fermi (for the excitation by center of mass motion of the $1^-;0$ state at 10.85 MeV). Details of these structure models are given elsewhere [10,11].

The effective interaction between two nucleons, one the projectile and the other a bound particle in the nucleus, is required in a fully microscopic DWA analysis of inelastic nucleon scattering and in two ways. First this effective interaction is required as the transition operator by which the nucleon inelastic scattering process is effected. To use it with the DWBA91 code of Raynal [14,15], that effective interaction must be specified in coordinate space and as a combination of central, tensor and two-body spin-orbit terms. Each term can have a linear combination of Yukawa functions as its form factor, and those form factors may vary with the density of the nuclear medium at the location where the two nucleons interact. This effective interaction has been defined (in coordinate space) by optimally mapping the half-off-shell (momentum space) NN g-matrix elements determined from solutions of the Brueckner-Bethe-Goldstone (BBG) equations [16]

$$\begin{aligned} g^{(JST)}_{LL'}(p',p;k,k_f) &= V^{(JST)}_{LL'}(p',p) \\ &+ \frac{2}{\pi}\sum_l \int_0^\infty V^{(JST)}_{Ll}(p',q)[\mathscr{K}] g^{(JST)}_{lL'}(q,p;k,k_f)\ q^2 dq \ . \end{aligned} \tag{4}$$

The "propagator" defined above is given by

$$\mathscr{K}(q,k,K,k_f)=\frac{\bar{Q}(q,K;k_f)}{\bar{E}(q,K;k_f)-\bar{E}(k,K;k_f)-i\varepsilon} \ , \tag{5}$$

where $\bar{Q}(q,K;k_f)$ is the Pauli blocking operator and the energies in the denominator include the mass operator to first order, i.e., the effect of an averaged background field. In all cases considered to date, the initializing NN potential used was that of the Paris group [17]. The mapping process involves a double Bessel transformation of $g^{(JST)}_{LL'}(p',k;k,k_f)$, to cast these matrix elements in the form of a spin- and isospin-dependent, coordinate space quantities $[g^{ST}_{\rm eff}(r;E,k_f)]$. Those quantities are then mapped to a set of

Yukawa functions for each of the central, tensor, and two-body spin-orbit components of the interaction [10,18,19]. The strengths and ranges of the effective (DD) interactions so specified and for incident proton energies in the range 120–800 MeV have been tabulated [12].

The same effective interactions are used to define the optical potentials with which the "distorted" waves themselves are generated. That is done by folding the effective interaction with the shell occupancies of the ground state of the target (and of the excited state for the exit channel), allowing full antisymmetry and so giving a nonlocal proton-nucleus potential [10,14]. The attendant Schrödinger equations are solved numerically (with DWBA91) to determine the elastic scattering phase shifts, and hence the elastic scattering differential cross section and analyzing power, also giving the "distorted" wave functions that enter the DWA evaluation of the inelastic scattering amplitudes.

III. RESULTS

We have studied the elastic and inelastic scattering differential cross sections and analyzing powers from the scattering of 200, 398, 597, 698, and 800 MeV protons from ^{12}C. The data at 200 MeV were taken from Ref. [3], those for energies of 398, 597, and 698 MeV from Refs. [4,5], and the 800 MeV data from Ref. [2]. All of those data have been analyzed in the past using the LF force and phenomenological optical model potentials. We have analyzed them using the fully microscopic scheme described above, with our DD interaction and also by using the LF one [6]. These may be compared directly with a recent semimicroscopic analysis [5]. In all of the figures presented, the solid lines display results obtained using the DD interaction, while the dashed lines show those found with the LF interaction.

Eight transitions have been considered in particular and at each energy. The first is the elastic scattering (designated by "g.s." in the diagrams) and the remaining are all inelastic transitions. Specifically, we consider the 2^+ isoscalar (4.44 MeV), the 3^- isoscalar (9.64 MeV), the 1^- isoscalar (10.84 MeV), the 1^+ isoscalar (12.71 MeV), the 1^+ isovector (15.11 MeV), the 2^+ isovector (16.11 MeV), and the 4^+ isoscalar (14.08 MeV) transitions.

The 200 MeV data and the results of our calculations are compared in Figs. 1 and 2 for the differential cross sections and analyzing powers, respectively. Of these, the elastic data, cross section, and analyzing power are well described by the DD interaction results as are the data from the excitations of the $2^+;0$, $3^-;0$, and the $2^+;1$ states (to 40° in particular). The results found using the LF force do not fit the data as well, and the difference between the two calculations, especially of the analyzing power, for the elastic scattering is marked. That is consistent with the past observation [10,18] of the sensitivity of elastic scattering and DWA inelastic scattering predictions of cross sections and, especially, analyzing powers, to medium effects in the effective interaction. From analyses of the cross sections for the excitation of the $1^-;0$ state by 200 MeV protons, one might conjecture that the LF force gives the better fit of the two calculations to the (cross-section) data because, although the shape given by the DD interaction calculation is preferable, that result has slightly too large a magnitude. Yet the DD result is the better of the

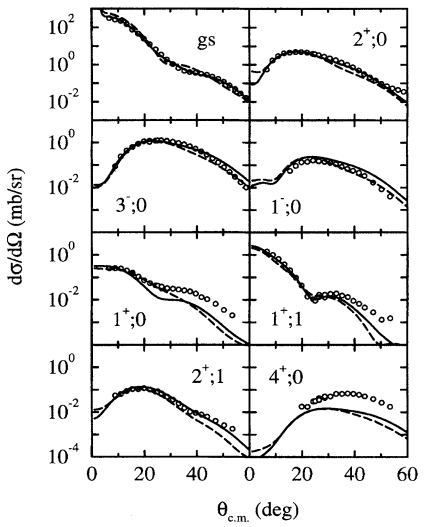

FIG. 1. Differential cross sections for 200 MeV protons scattering off ^{12}C and for the elastic and select set of inelastic channels as indicated. The solid lines are the results obtained from our calculations made using the DD force while the dashed lines are the equivalent ones found by using the LF force. The data were taken from Ref. [3].

two for the analyzing power data and quite noticeably so. Perhaps an even larger space structure model would reduce the net strength of this isoscalar dipole excitation, an excitation that has a particularly stringent constraint on the transition form factors to ensure no spurious components due to center of mass motion. While both calculations reproduce the forward angle ($<20°$) isoscalar and isovector magnetic dipole cross-section data, and, to a lesser extent, the analyzing power data, neither satisfactorily matches the observations at larger scattering angles. It is not surprising that the calculated results with either interaction do not describe the $4^+;0$ data.

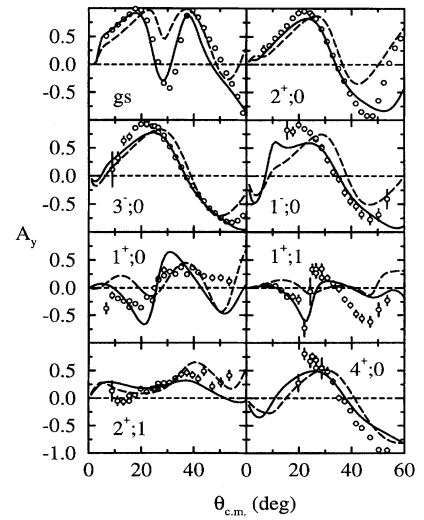

FIG. 2. As for Fig. 1 but for analyzing powers. The data were taken from Ref. [3].

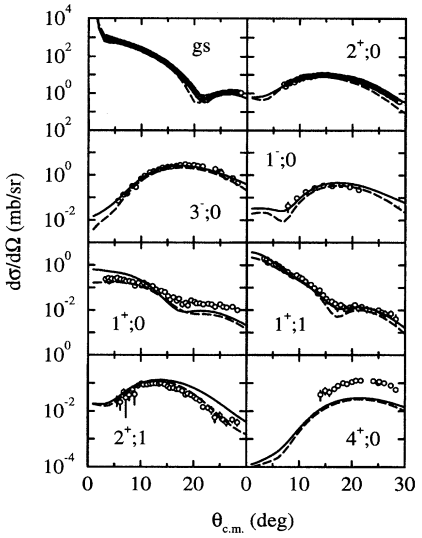

FIG. 3. As for Fig. 1 but for an energy of 398 MeV. The data were taken from Refs. [4,5].

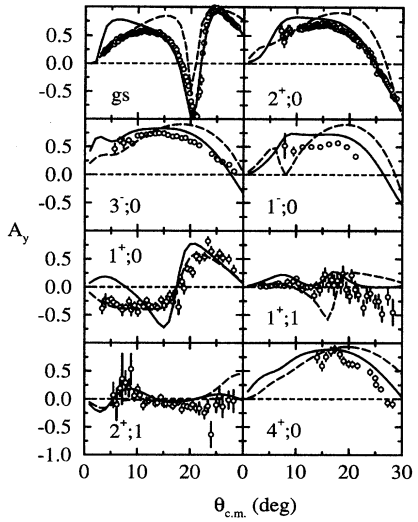

FIG. 4. As for Fig. 2 but for an energy of 398 MeV. The data were taken from Refs. [4,5].

In part, this is a reflection of the limitation of the spectroscopy; i.e., a reasonable description of the 4^+ transition requires a structure calculation involving at least a $(0+2+4)\hbar\omega$ shell model space [10]. In addition, we expect channel coupling in the reaction mechanism to give enhancement to this cross section. We anticipate the latter from the results found for the 200 MeV scattering [10] using a large basis projected Hartree-Fock (PHF) model for the structure and excitation of the $4^+;0$ state. That PHF model allowed some $>2\hbar\omega$ excitations and gave the strength in calculation of the $4^+;0$ longitudinal electron scattering form factor needed to match the data. The $(0+2)\hbar\omega$ shell model structure did not. However, when the same PHF structure was used in a DWA calculation of inelastic proton scattering, an enhancement to the 200 MeV cross section compared to that found by using the $(0+2)\hbar\omega$ shell model structure was seen but it was insufficient to match observation. Even so, the shapes of both $d\sigma/d\Omega$ and A_y are well described the present calculations.

The 398 MeV cross section and analyzing power data are compared with the results of our calculations in Figs. 3 and 4, respectively. As at 200 MeV, the elastic scattering cross-section data are better fit, and well fit, by the results calculated using the DD effective interaction. The prediction for the analyzing power is improved, compared to the LF result. Likewise the DD results for the excitation of the $2^+;0$, the $3^-;0$, the $1^-;0$, and now of the $1^+;1$ states are in better agreement with observation, compared to the LF results, both for cross sections and analyzing powers. Again a slight reduction to the $1^-;0$ transition strength would be favored on the basis of our DD result. The LF result does well with the $1^+;0$ and the $2^+;1$ excitations. As with the 200 MeV results, both calculations underestimate the strength of excitation of the $4^+;0$ state. The shape of the cross section is found and the DD result gives an appropriate form for the analyzing power. While not in complete agreement with data, this analysis shows that a fully microscopic DWA calculation with a realistic density-dependent interaction well describes the important features of the cross section and analyzing power.

The results at 597 MeV are shown in Figs. 5 and 6 for the cross sections and analyzing powers, respectively. At this energy the DD effective interaction has developed an interesting attribute, but one that is not supported by analyses of the proton-^{12}C scattering data. The cross-section data from the elastic scattering (except for the actual depth of the minimum at 17°) and from the isoscalar excitations of the 2^+, 3^-, and 1^- states are all well described by the calculations made using the DD interaction (although there are only four data points for this $1^-;0$ transition). The DD force calculations give reasonable agreement with the $1^+;0$ and $1^+;1$ measured cross sections but the LF force now is much the

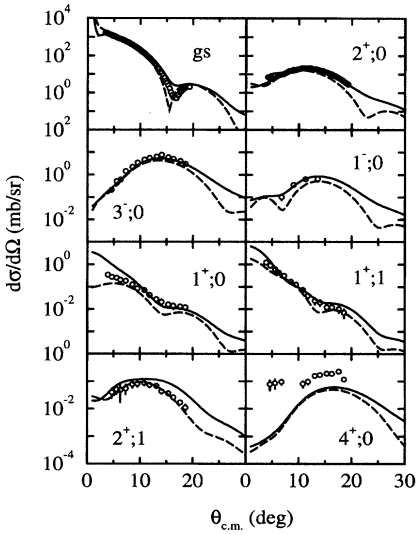

FIG. 5. As for Fig. 1 but for an energy of 597 MeV. The data were taken from Refs. [4,5].

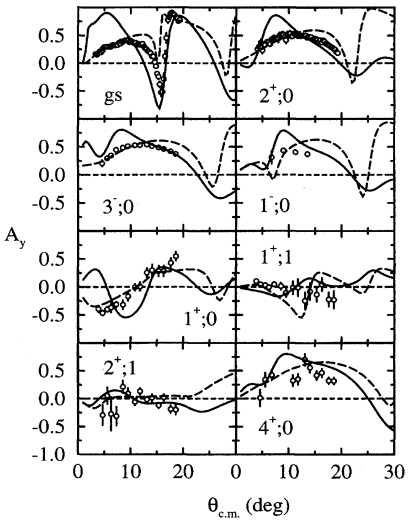

FIG. 6. As for Fig. 2 but for an energy of 597 MeV. The data were taken from Refs. [4,5].

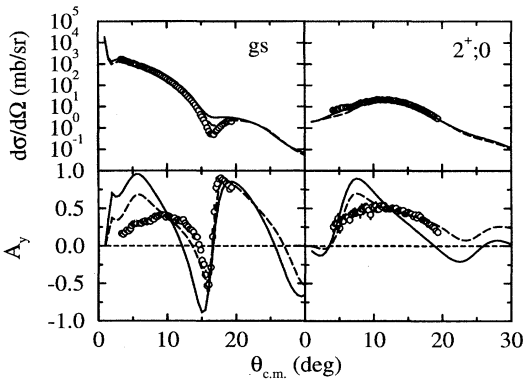

FIG. 7. The cross sections (top) and analyzing powers (bottom) from the scattering of 597 MeV protons from ^{12}C, elastically (left) and inelastically to the $2^+;0$ (4.44 MeV) state (right). The results of our complete microscopic model calculations are displayed by the solid curves while those found by omitting the $S=1;T=0$ spin–orbit component of the effective interaction are shown by the dashed curves.

better one when the cross section from the isovector 2^+ transition is considered. The $4^+;0$ excitation again needs scaling to bring calculated results into agreement with the magnitude of the data. But the analyzing power results, being sensitive to the various components of the interaction, are most revealing at this energy. Overall the DD calculations give the better reproduction of the data save for those from the excitation of the $2^+;1$ and $1^+;0$ states. In all isoscalar excitations the analyzing powers predicted using the DD force, there is a distinctive but unphysical small angle peak. In large part this feature is due to the $S=1;T=0$ spin-orbit component of the DD force. That component is not very important in the overall transition operator for elastic and the other isoscalar excitations. Indeed, the $S=1;T=1$ elements of the DD effective interaction are the strongest contributing components in the elastic cross-section calculation. But the analyzing power is extremely sensitive to the $S=1;T=0$ spin-orbit component. In fact, we observe that if this component of the DD interaction is removed, then the notable small angle peaks in the analyzing power for both the ground state and $2^+;0$ transitions weaken significantly and in the direction of the data. That is shown in Fig. 7 wherein the solid curves are the complete calculation results while those displayed by the dashed curves were found by omitting the $S=1;T=0$ spin-orbit component entirely from the calculations. Clearly the omission gives a better fit to the elastic scattering cross-section data and in the region of the minimum particularly. While the $2^+;0$ excitation cross section is hardly changed, a large effect is seen in the analyzing power results. Omitting the spin-orbit component gives improved results in the direction of the data and with the unphysical forward peak much reduced, although it has not been eliminated totally. We surmise that the mapping process need be weighted more carefully to reduce the contributions from the $S=1;T=0$ spin-orbit component. In addition though, the "data" to which the effective interaction is mapped need be reconsidered. At energies of 400 MeV and above, details of the coupled-channels NN scattering phase shifts, especially the ε_J, are not well established. Thus there is some flexibility as to the determination of any model NN potential at these energies. Consequently, there is some uncertainty about values of the the g matrices to be used in the mapping procedure. Details of the effective interactions then may not be the optimal ones for use in NA scattering studies.

The results at 698 MeV are displayed in Figs. 8 and 9. Considering the cross sections first, it is clear from Fig. 8 that the DD results are in better agreement with most of the data, both in structure and magnitude. The analyzing power data are better reproduced by the DD calculations in comparison to the LF ones. Here, again, and as with the 597 MeV results, an unphysical low angle peak appears in the analyzing powers calculated using the DD force (see Fig. 9), and for the collective 2^+, 3^-, and 4^+ states as well as to the

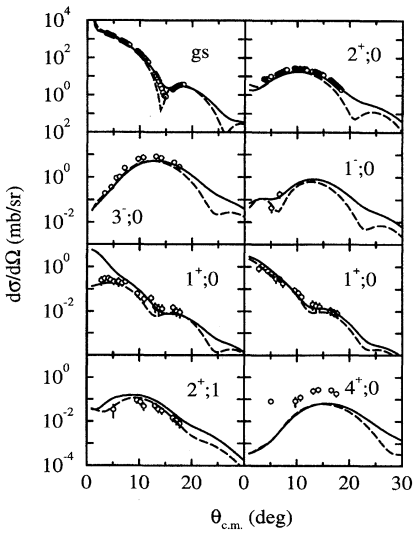

FIG. 8. As for Fig. 1 but for an energy of 698 MeV. The data were taken from Refs. [4,5].

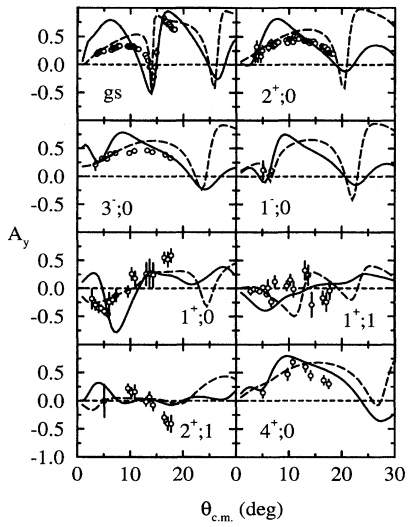

FIG. 9. As for Fig. 2 but for an energy of 698 MeV. The data were taken from Refs. [4,5].

1^- state and in the elastic scattering. This effect is due in large part to the $S=1;T=0$ spin-orbit contributions at this energy.

Finally, at 800 MeV, our calculated results are compared with the data in Figs. 10 and 11. Herein there is a limited data set available but for it both the LF and DD force calculations describe quite well the measured cross sections (Fig. 10) and reasonably well the trends of the analyzing powers (Fig. 11). At this energy, medium modifications to the effective interactions are small and so we expect that use of even a free NN interaction for the transition operator should reproduce the data equally as well. This is demonstrated in Fig. 12 for the elastic scattering cross section and analyzing power. Therein the data are compared with the results found using our microscopic model and the DD force (solid curves) and with those found by using an effective interaction mapped to the free NN t matrices based upon the Paris interaction. There are only small differences between the two results. The elastic cross-section data are quite well fit but not so the elastic scattering analyzing power. Again there is

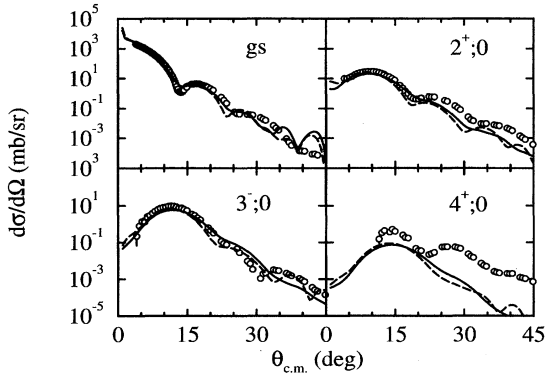

FIG. 10. The differential cross sections from the scattering of 800 MeV protons off ^{12}C. The data were taken from Ref. [2].

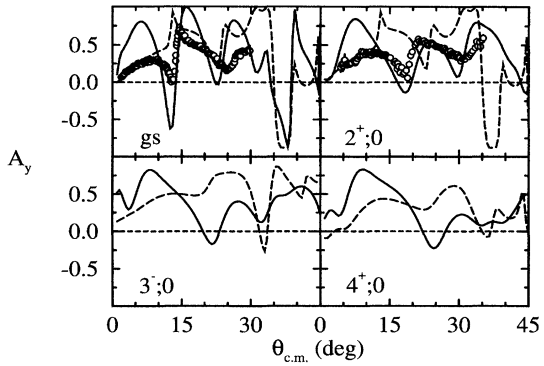

FIG. 11. The analyzing powers from the scattering of 800 MeV protons off ^{12}C. The data were taken from Ref. [2].

the unphysical forward peak in both calculated analyzing powers due largely to the $S=1;T=0$ spin-orbit contributions. Thus the medium modifications themselves are not the cause of the perceived problem with the (small details) of the effective interactions.

IV. CONCLUSIONS

Fully microscopic model calculations of elastic and (select) inelastic scattering data taken with incident protons at energies in the range from 200 to 800 MeV have been made. Both differential cross-section and analyzing power data have been analyzed. The elastic scattering data have been analyzed by forming optical potentials via folding effective NN interactions with the density matrices of the ground state of ^{12}C. The results are complex, nonlocal proton-^{12}C potentials with which good to excellent fits were found to both the elastic cross sections and analyzing powers. Two effective interactions were used with that folding procedure. The first, identified as the DD effective interaction, we obtained for each energy by a mapping to the NN g matrix solutions of the BBG equations predicated upon the Paris potential. The second (identified by LF) was the interaction proposed by

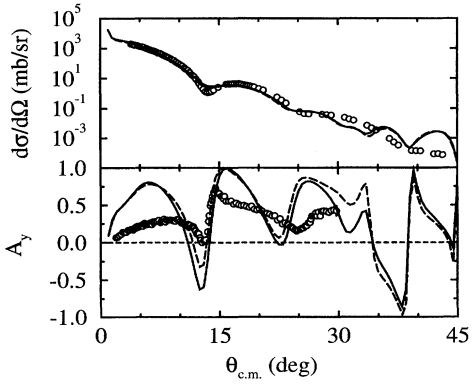

FIG. 12. The cross section and analyzing power from the elastic scattering of 800 MeV protons from ^{12}C compared with the results of our microscopic model calculations made using the DD effective interaction (solid curves) and with an effective interaction mapped to the free NN (Paris) t matrices (dashed curves).

Franey and Love [6]. The DD force gave notable better results for the elastic scattering analyses especially at the lower energies and for the analyzing powers.

Those two *NN* effective interactions were then used as the transition operators in a DWA study of the various inelastic scatterings considered. The distorted waves were found consistently with those same interactions by the folding of the state density matrices, both of the ground and also of the excited state involved in each case.

The spectroscopy of the states of interest in ^{12}C were found from a complete $(0+2)\hbar\omega$ shell model calculation for the positive parity states (the ground and the $2_1^+;0$, the $1_1^+;0$, the $1_1^+;1$, the $2_1^+;1$, and the $4_1^+;0$ states specifically) and from a restricted $(1+3)\hbar\omega$ shell model calculation for the negative parity states (the $3_1^-:0$ and $1_1^-;0$ states in particular).

With both forces, the cross sections are all fit quite well, save for the $1_1^+;0$ transition (for the lower energies in particular) and for the $4_1^+;0$ excitation. The latter transition is not well defined by this spectroscopy with our calculated cross sections being much smaller in magnitude than observed. The $1^+;0$ excitation is not as well understood when one considers the data at all energies. There may be a problem with the spectroscopy or one concerning details of the effective interaction. Our results in comparison to the data do not vary consistently with energy as one may expect with inadequate spectroscopy alone. Furthermore, it has been noted [20] that DWA calculations of this transition are sensitive to use of any quadratic spin-orbit component in the effective interaction. No such component has been considered in our force.

The fits to the inelastic scattering analyzing powers are more revealing. At 200 MeV and to a lesser extent at 398 MeV, the DD results are much better overall than those obtained with the LF force. At the higher energies, the LF force gives overall better results although the DD results for the analyzing powers are strongly affected by a rather weak component (as far as contributions to the cross sections are concerned), namely, the $S=1;T=0$ spin-orbit interaction. There is some question of details of the starting forces for energies above 400 MeV and so we need to reappraise the *NN g* matrices against which our effective interaction is mapped. Perhaps a more relevant interaction at these energies would be that obtained by inversion of the latest *NN* phase shift set [21].

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