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Density dependent interaction applied to low-multipole (p,p') and (p,n) transitions in light nuclei

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The density-dependent interaction based on the Bonn-Jülich G-matrix NN interaction was used in a distorted-wave Born approximation analysis of (p,p') and (p,n) data for p-shell nuclei at $E_p=35$ MeV. Calculations with this interaction fit the data as well as the commonly used density-independent interaction M3Y and gave significant improvement for analyzing powers of unnatural-parity transitions. Most of the improvement was found to be due to the tensor part of the interaction.

Several effective interactions are now available[1-3] for analyses of low-energy (p,p') and (p,n) reactions. G matrices are usually evaluated in a harmonic oscillator basis. Resultant effective interactions are real, density independent, and expressed in convenient functional forms. Most frequently used among those is the M3Y interaction derived by Bertsch *et al.*[1] based on the Reid soft core, Hamada-Johnston, and Elliott forces. Although the M3Y interaction has been applied successfully for many cases, it sometimes fails to give a good account of the experimental data.

Density dependence of the effective interaction arises in a rigorous treatment of the G-matrix propagator which includes Pauli blocking and other medium effects. Density-dependent effective interactions have been obtained by several authors,[4,5] and have been successfully applied for analyses of elastic and inelastic scattering data. However, the density-dependent interaction in some cases does not reduce to the free nucleon-nucleon (NN) t matrix at zero density.

Recently a new density-dependent effective interaction (GBJ) has been derived by Nakayama *et al.*[6] This interaction is based on a Bonn NN potential, and obtained with the constraint that it reduce to the free NN t matrix in the limit of $k_f \rightarrow 0$. We have tested this new density-dependent effective interaction in an analysis of 35 MeV (p,p') and (p,n) data, and compared the results with those obtained using the density-independent M3Y interaction. It has been shown previously[7] that the use of different density-independent interactions does not introduce significant differences in the calculated results.

1p-shell nuclei are a most suitable place to test such density-dependent interactions, since (1) they have larger nuclear surface regions, where the density changes rapidly, than do heavier nuclei, and (2) shell-model wave functions are available that describe the main features of the low-lying levels in these nuclei reasonably well. We have measured (p,p') cross sections and analyzing powers for typical low-multipole transitions.

The experiment was done at the Institute for Nuclear Study, University of Tokyo. A 35-MeV polarized proton beam from the sector focusing cyclotron and a magnetic spectrometer system[8] were used in the measurements. Details of the experiment are similar to those previously described.[9] In some cases (p,n) cross sections were also measured to compare with analog (p,p') transitions. For (p,n) experiments, a 35-MeV proton beam and the time-of-flight (TOF) system[10] at the Cyclotron and Radioisotope Center at Tohoku University were used.

The distorted-wave Born approximation (DWBA) analysis employed the shell-model wave functions of Cohen and Kurath[11] unless otherwise noted. Radial forms of the transition densities were calculated using single-particle wave functions generated in Woods-Saxon potentials. A version of the code *DWBA*-70,[12] modified to incorporate density dependence of the effective interaction, was used in the calculation. For details of the analysis and the ambiguities in the analysis, see Ref. 7.

At the top of Fig. 1 are shown cross section and analyzing power angular distributions for the ^{12}C(p,p')^{12}C(12.71 MeV, $1^+,T=0$) reaction. Solid lines represent the calculation with GBJ, and the dotted lines with M3Y. Proton distorting potential parameters were obtained from Ref. 13. The DWBA calculation with the M3Y interaction fails to reproduce the experimental analyzing power data. Similar failures have been observed in many previous analyses[14] of this transition. A considerable improvement of the calculated analyzing power is observed when GBJ is used. The cross section magnitude is underpredicted by about 50% by GBJ. Nevertheless the overall angular distribution shape is in good agreement with the data. The results for the ^{12}C(p,p')^{12}C(15.11 MeV, $1^+,T=1$) and the ^{12}C(p,p')^{12}C(16.11 MeV, $2^+,T=1$) are shown in Fig. 1 for comparison. In these cases, and in many other cases as well, M3Y and GBJ give equally good fits to both the analyzing power and cross section data.

Decomposition of the interaction has been made to uncover similarities and differences between M3Y and GBJ. It was found that the imaginary parts of the GBJ interaction have small effects on the calculated observables at this energy. Calculations with only the central parts of M3Y and GBJ give similar results. Differences have been observed, however, in the calculations with only the tensor parts. Therefore no significant change is expected in the calculations when the major contribution comes from the central interaction, as in the case of the ^{12}C(p,p')^{12}C(15.11 MeV, $1^+,T=1$) transition. On the other hand the tensor exchange amplitude is most important in the ^{12}C(p,p')^{12}C(12.71 MeV, $1^+,T=0$) transition. Indeed Fox *et al.*[14] had to modify the tensor part of their "standard" interaction[15] drastically to fit the (p,p') data for the 12.71-MeV state at $E_p=65$ MeV.[16]

The present analysis suggests that the most significant improvement of the medium correction manifested in the density dependence of the GBJ interaction is in the tensor part of the effective interaction. Nakayama and collaborators[17] have shown that the magnitude of the real part of the effective isovector interaction increases strongly with increasing density. This density dependence is due to short range correlations induced by the Pauli blocking, which are larger at high density. Near the central densi-

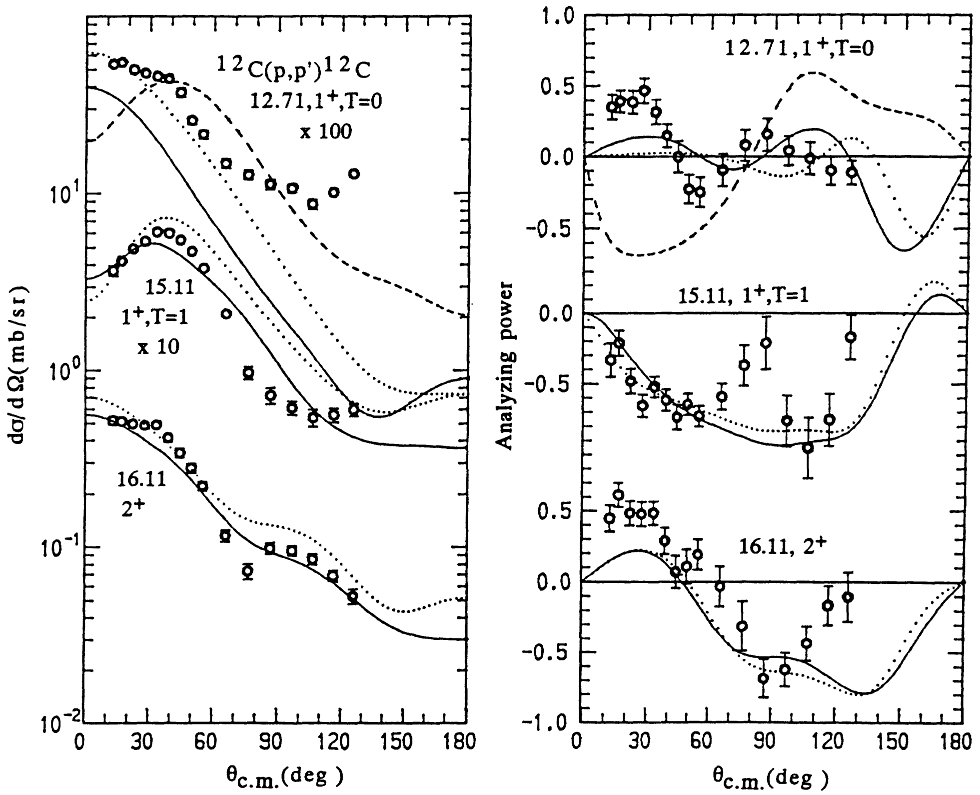

FIG. 1. Cross section and analyzing power angular distributions for the ^{12}C(p,p')^{12}C reaction. The solid curves are DWBA calculations with the density-dependent GBJ interaction, and the dotted curves those with M3Y. The dashed curve shows a calculation with the GBJ interaction but with the tensor part replaced by that of the free *NN* *t* matrix.

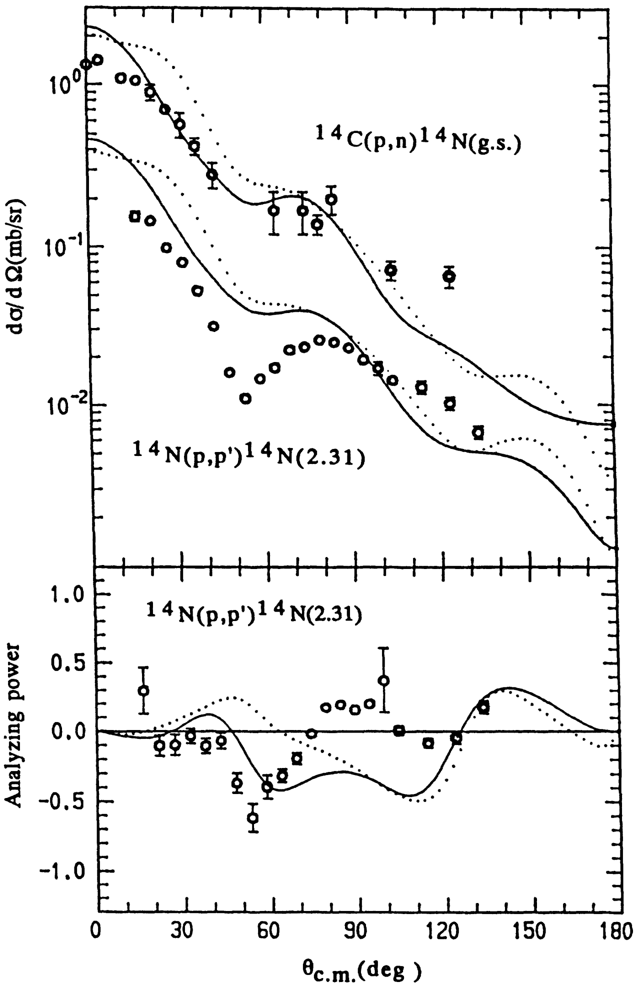

FIG. 2. Cross section and analyzing power angular distributions for the ^{14}N(p,p')^{14}N(2.31 MeV, 1^+) reaction. Cross section angular distribution for the ^{14}C(p,n)^{14}N(g.s.) reaction is also shown. The solid and dotted curves were calculated using GBJ and M3Y, respectively.

ty, M3Y and GBJ have comparable real isovector tensor interactions because the correlations included in their derivations are similar.

For both M3Y and GBJ, the isoscalar tensor interaction is dominated by the real exchange component for which M3Y is about 10% larger at the central density and about a factor of 2 times the GBJ magnitude at zero density. The corresponding M3Y and GBJ direct parts are very different in magnitude and shape. In order to illustrate the effect of the density dependence of the GBJ isoscalar tensor interaction, we have calculated the ^{12}C(p,p')^{12}C($1^+,T=0$) reaction replacing the GBJ tensor force with that of the free NN t matrix. The result is shown in Fig. 1 by the dashed lines.

Another example in which the tensor interaction dominates is the ^{14}N(p,p')^{14}N(2.31 MeV, $0^+,T=1$) transition. In this case the $\Delta J(\Delta T,\Delta S)=1(0,1)$ component of the transition density almost vanishes, corresponding to the large logft value of the ^{14}C(g.s., $0^+,T=1$)$\rightarrow$^{14}N(g.s., $1^+,T=0$) β^- decay. The reaction ^{14}N(p,p')^{14}N has been studied at $E_p=22$ MeV,[18] 30–45 MeV,[19] and 160 MeV.[20] In all previous analyses the DWBA fails to give a reasonable account of the experimental data, especially the analyzing power data measured at 22 and 160 MeV. Since only cross section data are available in between these energies, we have measured the analyzing power at $E_p=35$ MeV. Both N_2 gas and melamine were used as targets.

The results are shown in Fig. 2 along with DWBA calculations. In the analysis, proton potential parameters were searched in order to fit the elastic cross section and analyzing power data measured at the same time in the present work. Starting parameters in the search were those obtained in Ref. 19 from the fit to the elastic cross section data only. As shown in Fig. 2, the M3Y interaction gives large positive analyzing powers around 50°, where the data show large negative values, whereas the analyzing powers calculated with GBJ again give a much better description of the data. Slight improvement is also seen in the fit to the cross section angular distribution, although the difference between M3Y and GBJ is not as evident as for the analyzing powers. In this case the interference between the central and the tensor interaction in the dominant $\Delta J(\Delta L,\Delta S)=1(2,1)$ channel is quite important.

Similar improvements have been observed in the fit to the cross section angular distribution for the ^{14}C(p,n)^{14}N(g.s.,$1^+,T=0$) and ^{14}N(p,n)^{14}O(g.s.,$0^+,T=1$), which are analog to the ^{14}N(p,p')^{14}N(2.31 MeV, $0^+,T=1$). Only the results for the former reaction are displayed in Fig. 2, since the data and the calculation for these two reactions are very similar. Neutron potential parameters used in the calculation were obtained from Ref. 21.

In summary, we have measured cross section and analyzing power angular distribuitons for several low-multipole transitions in p-shell nuclei. Use of the density-dependent GBJ interaction improves the fit to the data for unnatural-parity transitions, especially the analyzing power data, for which density-independent interactions give very poor fits. Data for many other transitions are reasonably well described by density-independent interactions such as M3Y, and in those cases GBJ gives a good, or slightly better, description of the data. It has been found that the most significant difference in the calculations with and without the density dependence comes from the tensor part of the interaction. Much better agreement between the data and calculation is obtained with the GBJ interaction, therefore, when the tensor interaction is important in the transition.

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