MICROSCOPIC (p, p′) CALCULATIONS AND POLARIZATION CHARGES WITH LARGE BASIS SHELL-MODEL WAVE FUNCTIONS*

Duane LARSON, S.M. AUSTIN and B.H. WILDENTHAL

Cyclotron Laboratory, Department of Physics, Michigan State University, East Lansing, Michigan 48823, USA

Received 25 September 1972

Techniques have been developed for performing microscopic model DWBA calculations of inelastic nucleon-nucleus scattering using large basis shell-model wave functions to describe the nuclear states involved. For the case of ^{138}Ba at a bombarding energy of 30 MeV, we obtain good fits to the data by including the exchange amplitude in the DWBA and assuming a state and multipole independent polarization charge.

Major advances in the microscopic describtion of inelastic proton scattering are being made through the use of realistic effective interactions [1, 2], the treatment of "core polarization" [3–8], and inclusion of the exchange amplitude in the distorted wave calculation [1, 9–11]. The evolution from a ubiquitous collective model approach to a realistic microscopic approach has recently been reviewed by Satchler [12]. Microscopic analyses of the (p, p′) reaction have to date concentrated on doubly closed shell nuclei such as ^{16}O and ^{40}Ca, for which particle-hole wave functions are available, and on nuclei with one or two valence nucleons, where simple shell-model wave functions can be used. This note describes the expansion of such microscopic analyses to the much larger number of nuclei which have many active valence particles and whose states can be described by large basis shell-model wave functions.

We have made an initial application to the N = 82 nucleus ^{138}Ba. For ^{138}Ba, we obtain good fits to the shapes of the angular distributions and find polarization charges which are essentially independent of the multipolarity of the transition.

The experimental data, shown in figs. 1 and 2, were obtained at 30 MeV bombarding energy, using protons from the MSU sector-focussed cyclotron and an Enge split-pole spectrograph to detect the scattered particles. Energy resolution was approximately 8 keV, FWHM. A full discussion of the experimental work will be given elsewhere [13].

* Research supported in part by the U.S. National Science Foundation

Proton [14, 15] and neutron [16, 17] transfer reactions on the N = 82 nuclei indicate that Z = 50, N = 82 forms a good doubly closed core. The N = 82 nuclei are formed by adding protons to this core; ^{138}Ba has six such valence protons. The basis space for the shell-model wave functions we use [18] consists of the $1g_{7/2}$ and $2d_{5/2}$ orbits, plus one-proton excitations from this subspace into the $3s_{1/2}$ or $2d_{3/2}$ orbits. The two-body interaction for the shell-model calculation was parameterized in terms of the modified surface delta interaction (MSDI), with the four single particle energies and the two MSDI parameters fixed by fitting to energy levels of known J^{π} in the N = 82 nuclei from ^{136}Xe through ^{140}Ce. Eigenvalues and eigenfunctions calculated for N = 82 nuclei from A = 134 – 140 with this interaction give good agreement with experimentally known energy levels, pickup and stripping spectroscopic factors and electromagnetic data [18, 19].

In order to calculate inelasic scattering cross sections from these wave functions, it is necessary to obtain the structure amplitudes $S(J_i J_f J; T_i T_f T; j_1 j_2)$, where the notation is that of Madsen [9, 20]. We have modified the Oak Ridge-Rochester shell-model codes [21] to calculate these amplitudes in a form convenient for use in DWBA calculations. The distorted wave calculations in the present case were performed with the code DWBA 70 [22] of Raynal and Schaeffer, which includes the knock-on exchange amplitude. This code is based on a helicity formalism [23] which automatically accounts for all values of orbital angular momentum L and spin angular momentum S that can be transferred in a given transition. The exchange contribution is

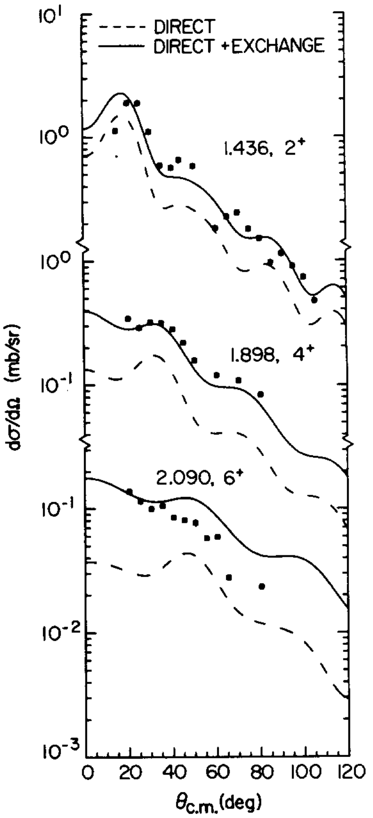

Fig. 1. Comparison of the direct (dashed line) and direct + exchange (solid line) calculations with the experimental data for 2_1^+, 4_1^+, and 6_1^+ states in ^{138}Ba. A polarization charge $\delta_e = 0.8$ was used in all of the illustrated calculations.

very important in these calculations, especially for the higher L transfers, as is seen in fig. 1.

The pertinent details of the inelastic scattering calculation are as follows. The optical model parameters of Becchetti and Greenlees [24], which provide a very good fit to our own elastic scattering data, are used to describe the entrance and axit channels. Harmonic oscillator wave functions with $\hbar\omega = 7.77$ MeV are used to describe the bound states. The two-body interaction between the projectile and target nucleons had a Serber exchange mixture and a Yukawa radial dependence. The range of the force was taken to be 1.4 F and its strength ($V_{\mathrm{pp}}^{S=0} = -9.0$ MeV, where $V_{\mathrm{pp}}^{S=0}$ is the $S = 0$ part of the proton-proton interaction) was chosen to be consistent with the results of a recent survey of inelastic scattering analyses [25].

The (p, p′) cross section we then calculate for the

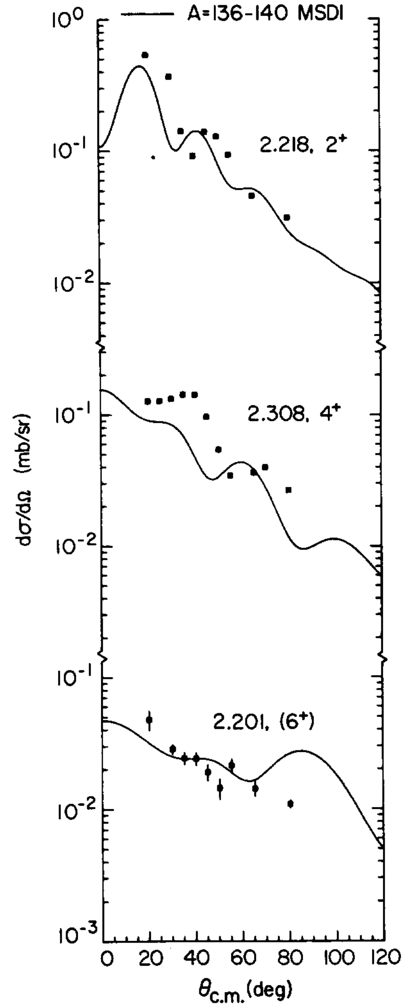

Fig. 2. Comparison of the direct + exchange calculations with the experimental data for 2_2^+, 4_2^+ and (6_2^+) states in ^{138}Ba. Again, $\delta_e = 0.8$ was used in the illustrated calculations.

first 2^+ state is a factor of 18 smaller than the data. Most of this difference is explained, however, if the contribution to the cross section from nucleons outside the explicit shell-model basis space is considered. In the case of electromagnetic transitions these effects are accounted for by renormalizing the charge on the nucleons, i.e., by introducing a "polarization charge".*

* The polarization charge is defined by $\delta_e = e_{\mathrm{eff}} - \frac{1}{2}(1 - \tau_z)e$. e_{eff} is the effective charge, and $\tau_z = +1$ for neutrons, -1 for protons. See refs. [8, 27].

Table 1
Effective charges for transitions in ^{138}Ba

Transition	L [b]	δ_e [c]	δ_e [c]
$0^+ \to 2_1^+$	2	0.82	1.17
$0^+ \to 4_1^+$	4	0.86	1,29
$0^+ \to 6_1^+$	6	0.61	0.53
$0^+ \to 2_2^+$	2	0.98	0.62
$0^+ \to 4_2^+$	4	1.07	0.62
$0^+ \to (6_2^+)$ [a]	6	0.73	0.63

[a] This state has not been unambiguously assigned 6^+, but its angular distribution, togther with the shell-model predictions, suggest this assignment.

[b] This is the L transfer for the dominant amplitude. Non-normal parity amplitudes also contribute to the cross section, and are included in the calculations, see ref. [1].

[c] Calculated from the relationship $[(1+\delta_e(1+2N/Z)]^2 = \sigma_{exp}/\sigma_{theory}$ where the theoretical cross section σ_{theory} is calculated using the complete wave functions as described in the text.

[d] Calculated as described in c, except that σ_{theory} is calculated using only the largest component of the particular wave functions involved. The shape of the predicted angular distributions for these wave functions is substantially poorer than that given by the complete wave functions, particularly for the high spin states.

Madsen [9] and McManus [8] have shown that one can similarly correct for finite basis-space effects in inelastic scattering by renormalizing the strength of the two-body force which mediates the transition. Thus one has an "effective force" for (p, p′) which is analogous to the "effective charge" for electromagnetic transitions.

One can get an idea of the amount of core participation in the low lying states of ^{138}Ba by noting that for the wave functions used here, the calculated $B(E2; 2_1^+ \to 0_1^+)$ is a factor of 3.2 too small [19] if no polarization charge δ_e is used. This implies that $(1+\delta_e)^2 = = 0.8$, or $\delta_e = 0.8$, To account for the contribution to the (p, p′) reaction of protons excited from the core, one therefore renormalizes the interaction strength V_{pp} to $(1+\delta_e)V_{pp}$. However, neutron core excitations also contribute to (p, p′) cross sections and are, in fact, more important than those for protons, since the proton-neutron two-body interaction V_{pn} is stronger than V_{pp}. If it is assumed, as has been found by Bernstein [26] and Astner et al. [27] that contributions from neutron and proton core excitations are approximately in the ratio of N/Z (the ratio expected in a collective model picture), we need an additional term, $(N/Z)\delta_e V_{pn}$. For the Serber exchange mixture we use, $V_{pn} = 2V_{pp}$. Thus one obtains a total effective force of $(1+\delta_e)V_{pp} + 2(N/Z)\delta_e V_{pp} = [1+\delta_e(1+ + 2N/Z)] V_{pp}$, i.e. the strength is increased by a factor of $(1+\delta_e(1+2N/Z))$. This simple but reasonable model for core excitation predicts an enhancement factor of 17.2, compared to the 18 which is required to normalize the 2^+ calculation to the data.

With this good agreement as evidence for the validity of our model, we have inverted the process and have used the measured enhancement factors to extract polarization charges for other transitions in ^{138}Ba, for which electromagnetic transition data are not available. Calculations of cross sections were performed for the 2_1^+, 2_2^+, 4_1^+, 4_2^+, 6_1^+ and 6_2^+states in ^{138}Ba. (The notation is J_i^π, where i refers to the first or second excited state of spin and parity J^π.) The enhancement factors were extracted by normalizing the experimental and theoretical integrated cross sections over the angular range of the data. The results are shown in column 3 of table 1 and we see that the δ_e are constant within the probable overall uncertainty in the analysis. The predicted angular distribution are shown in figs. 1 and 2. In all cases the theoretical curves shown have been calculated with $\delta_e = 0.8$, to show the agreement in both shape and magnitude which we obtain with a state and multipole independent polarization charge.

We have also performed calculations including tensor forces [25], and find that tensor force contributions are negligible. The spin -orbit force may be important for the 6^+ state [28] and this possibility is being investigated further.

We conclude with the following points. We have developed techniques for using large basis shell-model wave functions in microscopic DWBA calculations of inelastic proton scattering. Such wave functions are now invailable for most nuclei up through the nickel isotopes, and for the zirconium, $N = 82$, and lead regions, making it possible for the first time to treat inelastic scattering in a consistent fashion over a large part of the nuclidic chart. The first application has been to ^{138}Ba, and we obtain good agreement with the experimental angular distributions providing that the effect of exchange and core polarization are included. In addition, comparison of predicted and measured cross sections indicates that the polarization charge parameter δ_e for low-lying states in ^{138}Ba is essentially state and multipole independent, a result which does not follow (see table 1) if one component wave functions are used.

References

[1] W.G. Love and G.R. Satchler, Nucl. Phys. A159 (1970) 1.
[2] F. Petrovich, H. McManus, V.A. Madsen and J. Atkinson, Phys. Rev. Lett. 22 (1969) 895.
[3] R. Schaeffer, Nucl. Phys. A135 (1969) 231.
[4] W.G. Love and G.R. Satchler, Nucl. Phys. A101 (1967) 424.
[5] C. Glashausser et al., Phys. Rev. Lett. 21 (1968) 918.
[6] M.L. Whiten, A. Scott and G.R. Sathcler, Nucl, Phys. A181 (1972) 417.
[7] W.G. Love, Nucl. Phys. A127 (1969) 129.
[8] H. McManus, in The two-body force in nuclei, eds. S.M. Austin and G.M. Crawley (Plenum Press, New York 1972).
[9] J. Atkinson and V.A. Madsen, Phys. Rev. C1 (1970) 1377.
[10] H.V. Geramb and K.A. Amos, Nucl. Phys. A163 (1971) 337.
[11] J. Atkinson and V.A. Madsen, Phys. Rev. Lett 21 (1968) 295.
[12] G.R. Satchler, Comm. Nucl. Particle Physics 5 (1972) 39.
[13] D. Larson, S.M. Austin and B.H. Wildenthal, to be published.
[14] W.P Jones et al., Phys. Rev. C4 (1971) 580.
[15] B.H. Wildenthal, E. Newman and R.L. Auble, Phys. Rev. C3 (1971) 1199.
[16] D. Von Ehrenstein, G.C. Morrison, J.A. Nolen and N. Williams, Phys. Rev. C1 (1970) 2066.
[17] R.K. Jolly and E. Kashy, Phys. Rev. C4 (1971) 1398.
[18] B.H. Wildenthal and D. Larson, Phys. Lett. 37B (1971) 266.
[19] D. Larson and B.H. Wildenthal, Bull. Am. Phys..Soc. 17 (1972) 512.
[20] V.A. Madsen, Nucl. Phys. 80 (1966) 177.
[21] J.B. French, E.C. Halbert, J.B. McGrory and S.S.M. Wong, in Advances in nuclear physics, Vol III, eds. M. Baranger and E. Vogt (Plenum Press, New York, 1969).
[22] R. Schaeffer and J. Raynal, unpublished.
[23] J. Raynal, Nucl. Phys. A97 (1967) 572.
[24] F.D. Becchetti Jr. and G.W. Greenlees, Phys. Rev. 182 (1969) 1190.
[25] S.M. Austin, in The two-body force in nuclei, eds. S.M. Austin and G.M. Crawley (Plenum Press, New York, 1972).
[26] A.M. Bernstein, Phys Lett. 29B (1969) 335.
[27] G. Astner et al., Nucl. Phys. A182 (1972) 219.
[28] W.G. Love, Phys. Lett. 35B (1971) 371.