PHYSICAL REVIEW C VOLUME 38, NUMBER 4 OCTOBER 1988

Dirac coupled channels calculation for $p+{}^{40}$Ca inelastic scattering using the relativistic impulse approximation

S. Shim, B. C. Clark, and S. Hama
Department of Physics, Ohio State University, Columbus, Ohio 43210

E. D. Cooper
Department of Physics, McGill University, Montreal, Quebec, Canada H3A 2T8

R. L. Mercer
Thomas J. Watson Research Laboratory, IBM Corporation, Yorktown Heights, New York 10598

L. Ray and G. W. Hoffmann
Department of Physics, University of Texas, Austin, Austin, Texas 78712
(Received 8 August 1988)

Elastic and inelastic $p+{}^{40}$Ca observables are calculated using a relativistic impulse approximation model for the diagonal optical potential and a simple collective ansatz for the transition potentials. The calculations were performed using Dirac coupled channel codes. Agreement with large angle elastic-scattering data is greatly improved by the inclusion of strongly coupled, low-lying collective states.

In this paper we discuss results of a Dirac coupled channels calculation based on the usual relativistic impulse approximation (RIA).[1-4] This method of obtaining optical potentials for the elastic scattering of protons from spin-zero targets has proved to be quite successful for proton energies above 400 MeV and here we apply it to ^{40}Ca at 497.5 MeV, where a complete set of elastic observables as well as inelastic observables to low-lying collective states exists.[5-7] In particular, we address the question of high-momentum-transfer elastic-scattering data which is not well reproduced by RIA calculations.[6] We find that inclusion of several of the low-lying collective states improves this situation markedly.

The importance of strong coupling between the elastic and low-lying collective state channels in affecting the predicted large angle elastic-scattering observables has been previously demonstrated in nonrelativistic (NR) multiple scattering models for $p+{}^{208}$Pb at 800 MeV.[8,9] In Ref. 9 it was noted that first-order impulse approximation optical potentials do not account for nuclear collectivity. Inclusion of this important nuclear dynamics through channel coupling via first-order impulse approximation diagonal and transition potentials is well justified within standard NR multiple scattering theory. Because of the similarity in treatment between relativistic and NR models of proton+nucleus scattering,[3] the Dirac coupled channels relativistic impulse approximation model used herein is also well justified and is highly warranted for applications at large momentum transfers.

For the calculation presented here the diagonal scalar and vector optical potentials were obtained as in Ref. 2 and contain no free parameters. The input consists of the scalar and vector target densities obtained from the relativistic Hartree (RH) calculations of Horowitz and Serot[10] and free NN amplitudes given in Lorentz invariant form as in Ref. 11. The Sp 82 or the Sp 88 solutions[12] were used, and we found essentially no difference between the results obtained although, in the least-squares sense, the Sp 88 gave slightly better agreement with both elastic and inelastic data.

A simple collective model was used to obtain the transition potentials which were assumed to be proportional to either the derivative of the RIA potentials themselves, case 1, or obtained from folding the derivatives of the input RH densities with the appropriate invariant NN amplitudes, case 2. The parameters of the model are the scalar, δ_s, and vector, δ_v, deformation lengths. The small tensor RIA contribution was not included. Its effect will be investigated along with other terms which appear in a more sophisticated RIA calculation (see Ref. 13) in future work. In both cases the deformation lengths were adjusted to give good fits to the inelastic observables. The results of using these two procedures differed only slightly (see Table I). There are two free parameters for each

TABLE I. The deformation lengths determined from fitting 497.5 MeV ^{40}Ca(p,p') data. The first entry gives the results for the case 1 transition potential, the second for case 2. The Sp 88 NN amplitudes were used.

	Deformation length (fm)	
State, E_x	Vector	Scalar
2^+, 3.90 MeV	0.383	0.375
	0.373	0.362
3^-, 3.74 MeV	1.261	1.210
	1.231	1.173
5^-, 4.49 MeV	0.683	0.603
	0.666	0.583

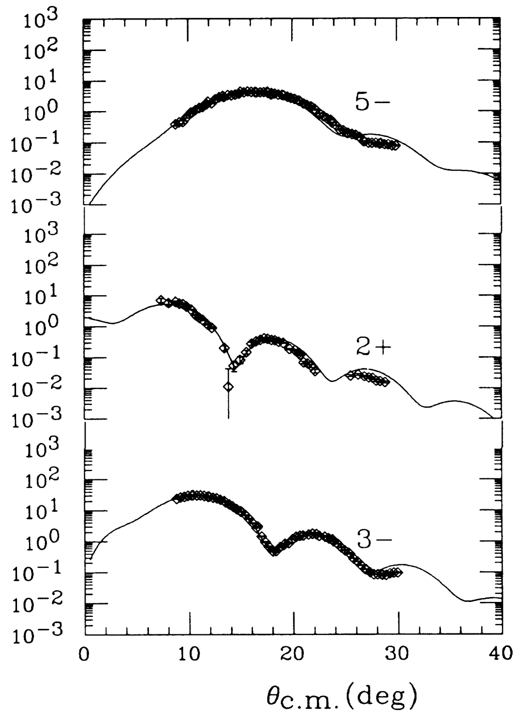

FIG. 1. Calculated inelastic cross sections for $p+{}^{40}$Ca for the 2^+, 3^-, and 5^- states using the case 1 transition potentials. The data are from Refs. 5 and 7.

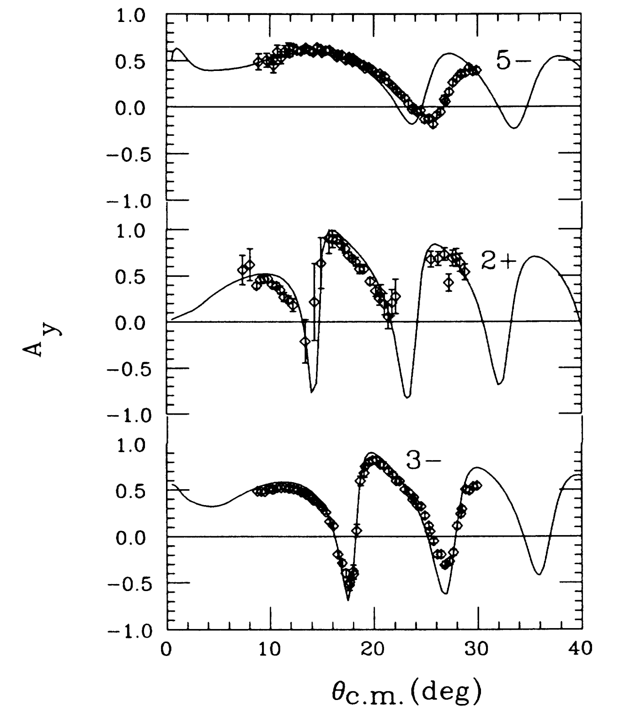

FIG. 2. Calculated analyzing powers for the same three states as in Fig. 1. The data are from Refs. 5 and 7.

state; the real and imaginary δ's were taken equal in these calculations. The observables were calculated using two independent Dirac coupled channel codes, ECIS87 written by J. Raynal,[14] and CENITH written by R. L. Mercer.[15] The extracted deformation lengths obtained from these two independent codes differ by less than 2.5%.

It is worth noting that one of the advantages of the Dirac approach is that the "spin-orbit" potential, in the sense of the second-order Dirac equation, is automatically deformed and, as a result, we found very good representations of the inelastic analyzing power measurements. In addition, the deformation lengths determined by fitting the data are in reasonable agreement with previous work.[5,16] Our values for these parameters for the first 2^+, 3^-, and 5^- states in ^{40}Ca are given in Table I and the calculated cross sections and analyzing powers for these three states using the transition potentials of case 1 are shown in Figs. 1 and 2.

The effect, on the elastic channel observables, of coupling to the collective states is most pronounced for the 3^- state, as would be expected due to its larger deformation length. Including the 2^+ and 5^- states does not appreciably alter these results. As shown in Figs. 3 and 4, the impact on the elastic observables, especially at angles beyond 35° is pronounced. The coupling of the low-lying excited states causes a marked improvement in the agreement with experiment. This is in disagreement with the results of Ref. 6 which were based on a NR coupled channels approach using the Schrödinger equation where no spin-orbit coupling was included.

In addition, we also carried out purely phenomenological studies of these data using Fermi shapes for the scalar and vector potentials. The direct potentials were obtained using the recent global fit of Ref. 17. This global fit gives very good representations of the elastic observables for $q<3.5\ \mathrm{fm}^{-1}$ for energies 160 to 1040 MeV. The strengths of these scalar and vector potentials, and the scalar and vector deformation lengths were allowed to vary in order to fit the inelastic data as well as the large angle elastic data. This added six more parameters to the

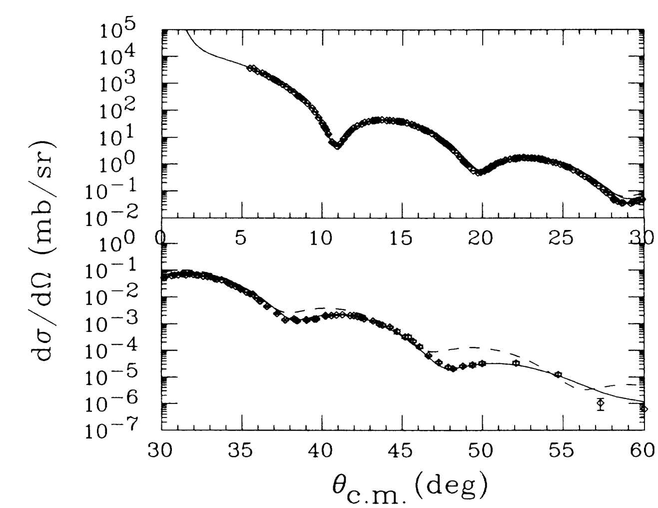

FIG. 3. RIA elastic cross sections for $p+{}^{40}$Ca at 497.5 MeV. The smooth line shows the results when the 3^- state is included, the dashed line shows the RIA results without this coupling. The data are from Ref. 6.

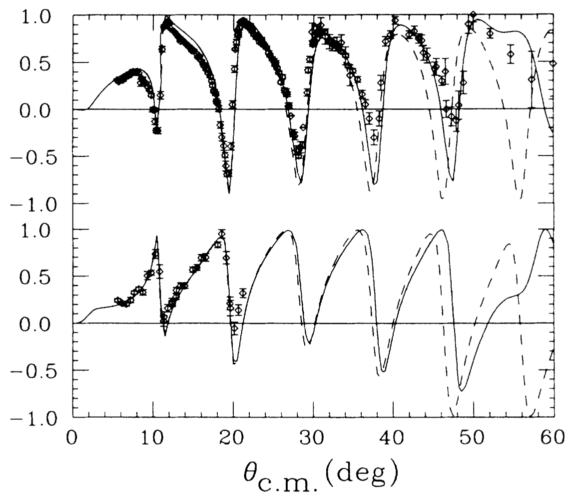

FIG. 4. The analyzing powers and spin rotation functions for the two cases shown in Fig. 3. The data are from Ref. 6.

calculation for each state. In the case of the 3^- coupling we find that it is possible to obtain good fits to the elastic data throughout the entire angular range. Again the strong coupling produces a large effect on the elastic observables. The deformation lengths obtained are in reasonable agreement with the results given in Table I and the strengths of the diagonal potentials did not change greatly from their global values. The largest change was a 7% increase in the imaginary vector potential strength.[18] This significant improvement in the phenomenological description of the large angle elastic-scattering data obtained as a result of coupling to the 3^- strong collective state has also been obtained by the authors of Ref. 19. It is, however, possible to obtain good fits to the large angle observables with local, spherical Dirac optical potentials if one uses a more general geometry for the scalar and vector imaginary potentials. This has been shown to be true for models containing both surface peaked and volume forms for the imaginary potentials[20,21] as well as in recent calculations using a more model independent approach employing a Fourier Bessel expansion[21] for the geometries of the scalar and vector potentials. In a purely phenomenological approach any statement that channel coupling is required to fit these large angle data is dependent on the model employed. It is clear, however, that channel-coupling effects are important and that a physically relevant phenomenology should take them into account.

In this paper we have presented coupled channels Dirac calculations of elastic and inelastic proton-nucleus observables based on the relativistic impulse approximation. We found a collective model with few parameters could be used to obtain a good fit to both elastic and inelastic $p+{}^{40}Ca$ observables. In addition, the agreement of the prediction with the elastic observables for $q > 3.5$ fm^{-1} was greatly improved when a few of the stronger excited states were included. Although these calculations do not incorporate microscopic transition potentials they do show the importance of including the low-lying strongly coupled excited states, such as the first 3^-, in the theoretical analysis of experimental data.

In future work we will investigate other target nuclei using both the RIA model and phenomenological treatments based on global optical potentials.

We are grateful to Dr. Jacques Raynal for the use of his computer code ECIS87 and for helpful conversations. We also thank Dr. Helmy Sherif for helpful suggestions and advice.

[1]J. A. McNeil, J. Shepard, and S. J. Wallace, Phys. Rev. Lett. **50**, 1439 (1983); **50**, 1443 (1983).

[2]B. C. Clark, S. Hama, R. L. Mercer, L. Ray, and B. D. Serot, Phys. Rev. Lett. **50**, 1644 (1983).

[3]L. Ray and G. W. Hoffmann, Phys. Rev. C **31**, 538 (1985).

[4]M. V. Hynes, A. Picklesimer, P. C. Tandy, and R. M. Thaler, Phys. Rev. Lett. **52**, 978 (1984); Phys. Rev. C **31**, 1438 (1985).

[5]K. K. Seth *et al.*, Phys. Lett. **158B**, 23 (1987).

[6]The elastic differential cross section and analyzing power data for angles less than 30° are from G. W. Hoffmann *et al.*, Phys. Rev. Lett. **47**, 1436 (1981); the larger angle data are from G. W. Hoffmann *et al.*, Phys. Rev. C **37**, 1307 (1988); and the elastic spin rotation data are from A. Rahbar *et al.*, Phys. Rev. Lett. **47**, 1811 (1981).

[7]M. L. Barlett, G. W. Hoffmann, and L. Ray, Phys. Rev. C **35**, 2185 (1987).

[8]R. D. Amado and D. A. Sparrow, Phys. Rev. C **29**, 932 (1984).

[9]L. Ray and G. W. Hoffmann, Phys. Rev. C **30**, 1593 (1984).

[10]C. J. Horowitz and B. D. Serot, Nucl. Phys. **A368**, 503 (1981).

[11]J. A. McNeil, L. Ray, and S. J. Wallace, Phys. Rev. C **27**, 2123 (1983).

[12]R. A. Arndt, J. S. Hyslop, and L. D. Roper, Phys. Rev. D **35**, 128 (1987); and R. A. Arndt *et al.*, *ibid.* **28**, 97 (1983).

[13]J. A. Tjon and S. J. Wallace, Phys. Rev. Lett. **54**, 1357 (1985).

[14]J. Raynal, Phys. Lett. B **196**, 7 (1987).

[15]R. L. Mercer, Phys. Rev. C **15**, 1786 (1977); R. L. Mercer and D. G. Ravenhall, *ibid.* **10**, 2002 (1974); R. L. Mercer, Ph.D. thesis, University of Illinois, 1972 (unpublished).

[16]J. I. Johansson, E. D. Cooper, and H. S. Sherif, Nucl. Phys. **A476**, 663 (1988).

[17]E. D. Cooper, B. C. Clark, R. Kozack, S. Shim, S. Hama, J. I. Johansson, R. L. Mercer, H. S. Sherif, and B. D. Seot, Phys. Rev. C **36**, 2170 (1987).

[18]S. Shim *et al.*, Bull. Am. Phys. Soc. **33**, 1080 (1988).

[19]J. Raynal, H. S. Sherif, A. M. Kobos, E. D. Cooper, and J. I. Johansson, Saclay Report No. PhT-88/096 (unpublished).

[20]B. C. Clark, S. Hama, E. D. Cooper, and R. L. Mercer, Ohio State University–National Science Foundation Report, 1988 (unpublished).

[21]E. D. Cooper, McGill report (unpublished).