Coupled-Channels Analysis of Inelastic Proton Scattering from ^{12}C at 0.8 GeV

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We present an analysis of new data for 0.8-GeV inelastic proton scattering to the 2^+ (4.4 MeV) and 4^+ (14.1 MeV) states of ^{12}C, using both distorted-wave Born-approximation and coupled-channels calculations with empirical, spherical, and deformed optical potentials. Both the deformation of the optical potential and the two-step transition via the 2^+ state are shown to influence strongly the shape and magnitude of the calculated 4^+ inelastic angular distribution.

It is known from low-energy ($E_{\text{inc}} \leqslant 50$ MeV) studies of nucleon inelastic scattering from deformed nuclei such as ^{12}C that channel-coupling effects are important.[1,2] However, at these energies inelastic excitation results in a significant reduction of the energy of the incident particle and, as a result, the kinematic features of the various inelastic transitions are quite different. This results in partial cross sections for the "direct" and "multistep" components which roughly have the same slope and shape, but differ in phase such that their coherent sum often resembles a smoothed version of the direct cross section only.[3,4] An example is seen in the 46-MeV $p+{}^{12}$C analysis of Satchler[1] for the 14.1-MeV 4^+ state[5]; however, neither the direct nor the multistep cross section, nor their coherent sum, reproduces the data.

At medium energies ($E_{\text{inc}} \simeq 1$ GeV), excitations of tens of MeV are negligible compared to the incident channel energy. The elastic and inelastic channels are kinematically equivalent, and nuclear structure, rather than Q value, is expected to control the competition between the direct and multistep processes. In addition, the short wavelength of the incident projectile and the large momentum transfers involved suggest sensitivity of the magnitudes and shapes of the inelastic angular distributions to the details of the shape of the target nucleus.

The possible importance of the ground-state deformation of ^{12}C and multistep processes in the excitation of the 4^+ (14.1-MeV) state at 1 GeV incident proton energy was suggested within the framework of Glauber theory by Abgrall *et al.*,[6] but sufficient data did not exist to support their conclusions.

In this Letter we report the results of an analysis of new data[7] for 0.8-GeV inelastic proton scattering to the 2^+ (4.4 MeV) and 4^+ (14.1 MeV) states of ^{12}C, using both distorted-wave Born-approximation (DWBA) and coupled-channels (CC) calculations with spherical and deformed empirical optical potentials. To our knowledge, this is the first CC calculation reported for the GeV region of proton-nucleus scattering. As demonstrated below, such medium-energy data clearly and unambiguously (as contrasted with low-energy data) require treatment of both the ^{12}C deformation and multistep processes for a proper theoretical description.

The calculation was divided into two stages of progressive complexity. In the first stage the $p+{}^{12}$C elastic scattering data were fitted with an empirical, spherical, optical-model potential. The potential obtained, in the usual low-energy notation[8] $V, W, W_D, r, a, r_W, a_W, r_D, a_D, r_C$, is -5.1, 79.2, and 18.0 MeV, 1.012, 0.531, 0.908, 0.500, 0.500, 0.600, and 1.05 fm, where no spin-orbit term was included for reasons to be discussed. This potential was used in DWBA calculations, as in Coker,[9] using a version of the program VENUS[10] modified to include relativistic kinematics. With this potential a good fit is obtained to the elastic and 2^+ inelastic cross sections with $|\beta_2 R| = 1.58$ fm. The length R is given by $r_W A^{1/3}$. However, a poor fit, shown as the dot-dashed curve in Fig. 1, was obtained for the 4^+ transi-

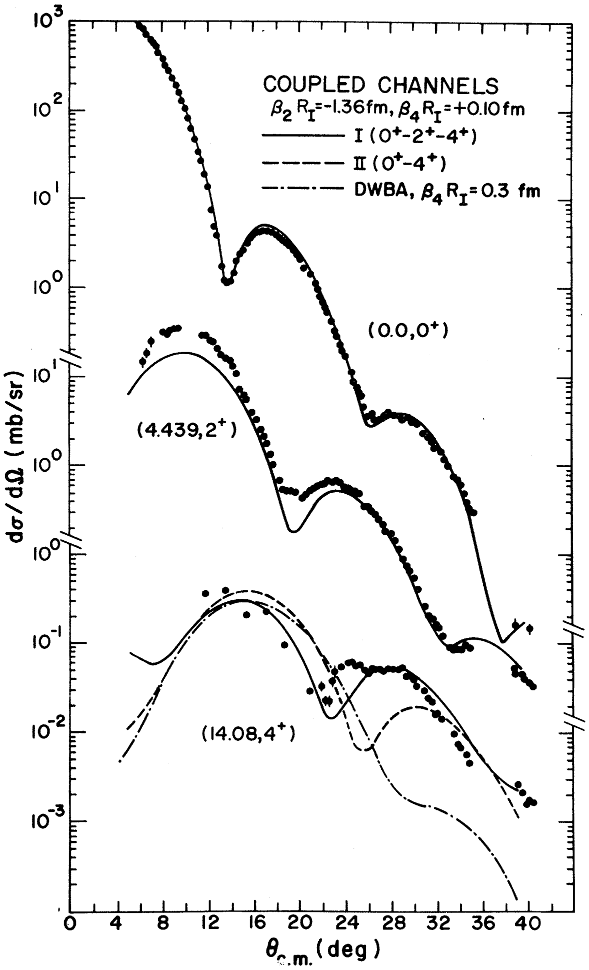

FIG. 1. Elastic and inelastic angular distributions for 0.8-GeV protons incident on ^{12}C. The meaning of the various theoretical curves is discussed in detail in the text. Solid curves are the results of full coupled-channels calculations. R_I equals $r_W A^{1/3}$, where the appropriate DWBA or coupled-channels value is used for r_W.

tion using a deformation length $|\beta_4 R| = 0.3$ fm which accounts for the size of the observed 4^+ cross section at about 12°. The calculation falls an order of magnitude below the data at 28° and shows no trace of the data's distinctive second maximum. This result is expected[1,2,6,9] and indicates the importance of the deformation of the ^{12}C ground state and of multistep inelastic processes that are most naturally treated in the coupled-channels formulation of reaction theory[3] which forms the second stage of this calculation.

The deformation of the potential shape was treated using the Legendre-polynomial-expansion procedure discussed by Tamura.[3] A corrected version of the program JUPITER[3] was modified to include relativistic kinematics. For these calculations spin-orbit coupling was neglected. It has been verified by a number of DWBA calculations[11,12] that when spin-orbit effects are omitted and the elastic-channel potential is empirically readjusted to recover the fit to the elastic cross section, fits to the inelastic cross sections are also recovered using essentially the same deformation parameters. Hence it is not expected that inclusion of spin-orbit effects will greatly modify the conclusions drawn herein.

By treatment of the 0^+, 2^+, and 4^+ states as a rotational band and assuming coupling between all three channels, the optical-potential parameters and deformation lengths, $\beta_2 R$ and $\beta_4 R$, were adjusted to simultaneously optimize and fits to the three angular distributions. The results are shown by the solid curves in Fig. 1. The potential parameters, in the same notation as above, are −7.05, 78.6, and 17.9 MeV, 0.975, 0.447, 0.911, 0.427, 0.506, 0.500, and 1.08 fm. The deformation lengths are $\beta_2 R = -1.36$ fm and $\beta_4 R = +0.10$ fm. The fit to the elastic data is primarily influenced by the imaginary potential, with the "surface" derivative term being used in both the CC and DWBA calculations to help fill in the second minimum at 26°. The value for $\beta_2 R$ of −1.36 fm is lower than the values of −1.43 to −1.71 fm found by Satchler[1] and will be discussed below.

The solid curve shown in Fig. 1 for the 4^+ state includes both multistep and deformation effects. In order to determine the importance of multistep processes in populating the 4^+ state, the CC calculation was repeated using the same deformation lengths, but omitting the coupling of the ground and 4^+ channels to the 2^+ channel. Deleting the 2^+ channel requires a 10% reduction in W and W_D in order to recover the fit to the elastic cross section. There still exist two paths by which the 4^+ is reached from the entrance channel, one directly via the $\beta_4 Y_4$ term in the optical potential, and another "indirectly" via the $(\beta_2 Y_2)^2$ that appears in the Legendre-polynomial expansion.[3] Thus, in this calculation, shown by the dashed curve in Fig. 1, the "indirect" step is due solely to the deformation of the optical potential. By comparing the three predictions for the 4^+ state it is seen that while deformation alone is sufficient to give the observed second peak in the angular distribution at 28°, coupling to the 2^+ channel is required in order to give the second peak a magnitude which is correct relative to that of the first peak.

We have accepted a rather poor fit to the 2^+ inelastic cross section and did not increase the value of $|\beta_2 R|$ to obtain a larger 2^+ cross section as well as better agreement between our value of $|\beta_2 R|$ and those found at lower energies.[1] The reason is that the predictions for the 4^+ (and to a lesser extent, the 2^+) are quite sensitive in magnitude to assumed values for $|\beta_6 R|$. Increasing $|\beta_2 R|$ would cause the 4^+ cross section to become too large at angles beyond 28°. The fit to the 4^+ state could be recovered if a nonzero value for $|\beta_6 R|$ were assumed. However, in all the calculations reported here, $\beta_6 R = 0$. If future experiments reveal a 6^+ state in ^{12}C at about 30 MeV, and if the angular distribution can be measured, the value of $\beta_6 R$ can be determined and the present analysis redone. It is somewhat surprising to see such a relatively large sensitivity to the value assigned to β_6 in the CC calculations. It is interesting to compare the ground-state deformation obtained here to that found from analysis of electron inelastic scattering data on ^{12}C where qualitative agreement is found.[13]

In further work on medium-energy proton inelastic scattering from ^{12}C one should employ a microscopic, proton-nucleus optical potential,[14] generated from a nonspherical nuclear density $\rho(\vec{r})$ which is consistent with electron scattering results.[13] The present data could also be usefully extended one further cycle of diffraction. Finally, it would be profitable to study similar transitions in other deformed or highly collective nuclei, in order to discover whether the clean separation of single-step and multistep excitation is indeed a characteristic of medium energies.

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[1] G. R. Satchler, Nucl. Phys. A100, 497 (1967).
[2] G. A. Grin *et al.*, Phys. Lett. 25B, 387 (1967).
[3] T. Tamura, Rev. Mod. Phys. 37, 679 (1965).
[4] T. Tamura, Annu. Rev. Nucl. Sci. 19, 99 (1969).
[5] R. McKeown and G. T. Garvey, Phys. Rev. C 16, 482 (1977).
[6] Y. Abgrall *et al.*, Nucl. Phys. A271, 477 (1976).
[7] G. S. Blanpied *et al.*, to be published.
[8] C. M. and F. G. Perey, At. Data Nucl. Data Tables 13, 293 (1974).
[9] W. R. Coker *et al.*, Phys. Lett. 64B, 403 (1976).
[10] T. Tamura *et al.*, Comput. Phys. Commun. 2, 94 (1971).
[11] R. L. Ray and W. R. Coker, University of Texas Report No. UTNT3, 1977 (unpublished).
[12] W. R. Coker, unpublished.
[13] A. Nakada *et al.*, Phys. Rev. Lett. 27, 745 (1971).
[14] H. Feshbach and J. Hüfner, Ann. Phys. (N.Y.) 56, 268 (1970).

Parity Dependence of the Heavy-Ion Optical Potential

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Recently measured gross structure in the 180° excitation function of ^{28}Si + ^{16}O elastic scattering is fitted very well by including a small parity-dependent term in an energy-dependent and surface-transparent optical potential. This interpretation is in contrast to a previous proposal suggesting that the structure is due to potential shape resonances of varying principal quantum numbers n and angular momenta L.

The recently measured[1] gross structure in the 180° excitation function for elastic and inelastic scattering of ^{28}Si + ^{16}O has attracted much attention[2] because of its possible connection with quasimolecular shape resonances. In this Letter we present an alternative interpretation of the elastic data which may be of considerable theoretical interest.

The Pauli principle is not properly taken into account in present folding models which are applied widely in analyses of heavy-ion elastic scattering data.[3] It has, however, been known for some time[4] that, in light-ion scattering, exchange effects arising from this principle lead to a Majorana space-exchange term in the optical potential. Specifically for the ^{3}He + α system it has