Multistep Processes in the Inelastic Scattering of 70.4-MeV ^{12}C from ^{144}Nd†

D. L. Hillis,* E. E. Gross, D. C Hensley, and L. D. Rickertsen
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

and

C. R. Bingham
University of Tennessee, Knoxville, Tennessee 37916

and

A. Scott and F. T. Baker
University of Georgia, Athens, Georgia 30601
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Inelastic scattering of ^{12}C projectiles from ^{144}Nd has been studied at an incident energy of 70.4 MeV. The differential cross sections for exciting low-lying collective states of the target and projectile are compared to distorted-wave Born-approximation (DWBA) and coupled-channels calculations. Standard DWBA calculations using known Coulomb matrix elements fail to fit the data. Coupled-channels calculations, however, can account for these data and show a strong sensitivity to target and projectile reorientation matrix elements.

The scattering of heavy ions with energies slightly above the Coulomb barrier has produced many examples[1-5] in which inelastic cross sections exhibit pronounced Coulomb-nuclear interference effects. Most of these data could be fitted by a single-step distorted-wave Born-approximation (DWBA) calculation only if nuclear deformation lengths were allowed to take on values which differed by 35–50% from their corresponding Coulomb deformation lengths. Such large differences between charge and matter distributions are not expected and are more likely symptomatic of an inadequate representation of the reaction mechanism. A further indication that the DWBA method is deficient for heavy-ion inelastic scattering is the failure to account for projectile excitations in the reaction[4] ^{88}Sr(^{20}Ne, ^{20}Ne*(2^+, 1.835 MeV))^{88}Sr and the reaction[5] ^{60}Ni(^{18}O, ^{18}O*(2^+, 1.98 MeV))^{60}Ni even when Coulomb and nuclear matrix elements are allowed to vary independently. A coupled-channels (CC) analysis of the latter reaction has revealed that multistep processes play an important role in projectile excitation.[5] In order to clarify the importance of processes neglected in first-order DWBA, we have undertaken a study of multistep processes in the scattering of ^{12}C by the even Nd isotopes. In this Letter we present the results for ^{144}Nd to illustrate these effects. The remaining data and analysis, with emphasis on systematics, will be published elsewhere.

A 70.4-MeV ^{12}C^{3+} beam from the Oak Ridge isochronous cyclotron was magnetically analyzed and transported to a 100-μg/cm^2 ^{144}Nd$_2$O$_3$ target evaporated onto a 40-μg/cm^2 carbon foil. Magnetic rigidities of the scattered particles were measured with a position-sensitive proportional counter located at the focal plane of a quadrupole–single-dipole magnetic spectrograph. With this arrangement we measured the absolute yields for exciting low-lying 2^+ (696 keV), 4^+ (1314 keV), and 3^- (1511 keV) states in ^{144}Nd, for exciting the 2^+ (4.43 MeV) state of ^{12}C, and for elastic scattering. Figure 1 displays differential cross-section data for elastic scattering and for excitation of the collective 2^+, 3^-, and 4^+ states in ^{144}Nd. Figure 2 contains the data for inelastic excitation of the 2^+ state in ^{12}C.

The optical-model search program GENOA[8] was used to obtain the elastic-scattering fit shown in Fig. 1. The parameters are $V_0 = 20.0$ MeV, $r_0 = 1.315$ fm, $a_0 = 0.562$ fm, $W = 12.1$ MeV, $r' = 1.341$ fm, and $a' = 0.433$ fm. Also shown as dashed curves in Fig. 1 are differential cross sections calculated using these optical-model parameters in the macroscopic collective-model DWBA formalism.[9] Both DWBA and CC calculations included 200 partial waves, and integrations were carried out to 50 fm in steps of 0.1 fm. Coulomb and nuclear deformation lengths were taken to be equal and related to previously measured excitation transition probabilities $B(E2;\uparrow)$[6] and $B(E3;\uparrow)$[7]

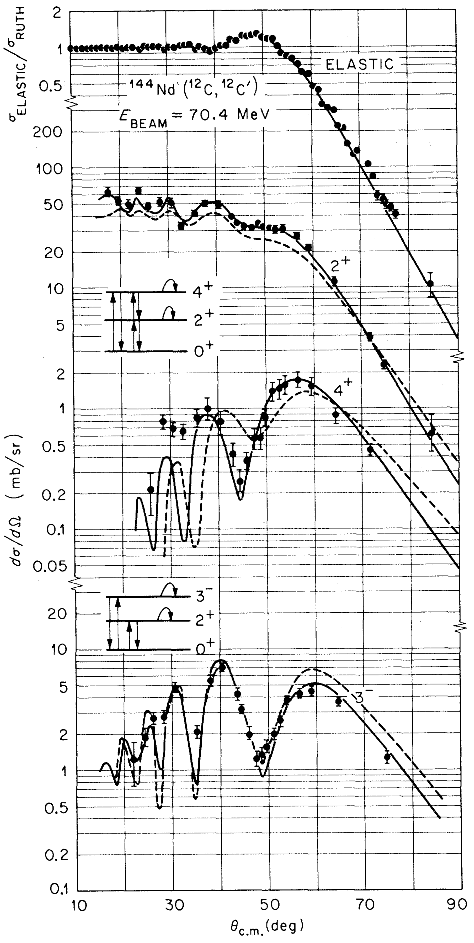

FIG. 1. 70.4-MeV ^{12}C elastic and inelastic scattering from ^{144}Nd. The dashed curves are DWBA calculations, and the solid curves are CC calculations including the couplings shown as insets. Known matrix elements (Refs. 6 and 7) are used throughout with $\beta_4{}^C = 0.053$ deduced from the CC analysis.

by the relation[10]

$$\beta_\lambda{}^N R_N = \beta_\lambda{}^C R_C = \frac{4\pi}{3Z_2 e (R_C)^{\lambda-1}}[B(E\lambda;\uparrow)]^{1/2}, \qquad (1)$$

where R_C and Z_2 are the Coulomb radius and charge of the target, respectively, R_N is the optical-model radius for the target, and $\beta_\lambda{}^C$ and $\beta_\lambda{}^N$ are Coulomb and nuclear deformation parameters, respectively. As can be seen in Fig. 1, the DWBA calculations fail to fit the data for the 2^+ and 3^- states of ^{144}Nd. Satisfactory fits could be obtained if nuclear deformation lengths were taken to be about 65% of their Coulomb counterparts, but the CC analysis below reveals that these parameter variations are masking multistep effects and fail altogether to account for the 4^+ excitation. Shown in Fig. 1 as a dashed curve is a sample DWBA calculation for the 4^+ state with $\beta_4{}^C = 0.06$ and $\beta_4{}^N = 0.08$.

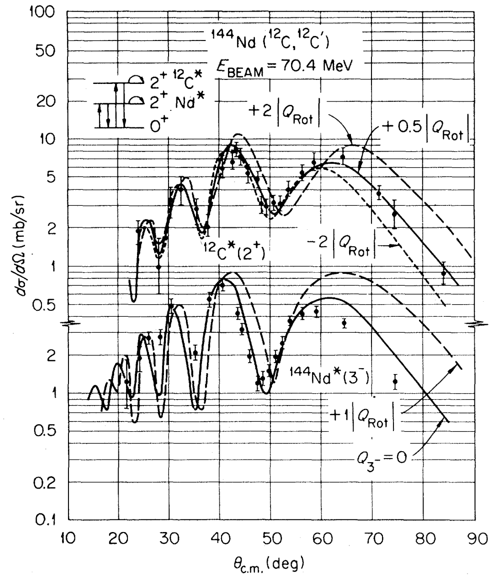

FIG. 2. Excitation of the 2^+ (4.43 MeV) state in the ^{12}C projectile and the 3^- (1.51 MeV) state in ^{144}Nd at 70.4-MeV lab energy. The curves are CC calculations which illustrate the sensitivity of the calculation and the data to the sign and magnitude of quadrupole moments. Couplings included in the calculations for ^{12}C are shown as an inset in this figure whereas the couplings used for the 3^- state in ^{144}Nd are shown in Fig. 1.

We now turn to the CC method,[11] results of which are displayed as solid curves in Fig. 1 for the ^{144}Nd states and by the curves in Fig. 2 for the 2^+ state of the ^{12}C projectile. These CC calculations were performed using the automatic search program ECIS.[12] Throughout the analysis $\beta_\lambda{}^C R_C$ was kept equal to $\beta_\lambda{}^N R_N$. Starting with GENOA optical-model parameters, searches were made with ECIS to obtain a mimimum-χ^2 fit to elastic scattering by varying W and a'. At this stage only the coupling of the ^{144}Nd 2^+ state to the ground state was included because coupling to this state represents the major influence on elastic scattering. The $0^+ \rightarrow 2^+$ coupling strength, represented by a β_2 deformation parameter, was obtained from the measured[6] $B(E2;\uparrow)$ using Eq. (1). The self-coupling strength (reorientation effect) was taken equal to the measured[6] 2^+ quadrupole moment, $Q_{2^+} = -0.6|Q_{\rm rot}|$, where $Q_{\rm rot}$ is the value consistent with the $B(E2;\uparrow)$ in the rotational model. Values of $W = 10.88$ MeV and $a' = 0.414$ fm resulted from this procedure. With this new optical potential (new values of W and a') a CC calculation involving all the couplings shown schematically in the upper inset of Fig. 1 resulted in 0^+, 2^+, and 4^+ predictions represented by the solid curves of Fig. 1. The couplings between the various states were assumed to be those of the rotational model, except for the quadrupole moment term, where the actual experimental value of Ref. 6 was used. The deformation parameter $\beta_4{}^C$ was varied until a fit to the 4^+ data was obtained. We find that $\beta_4{}^C = 0.053$ gives the fit shown. Coupling to the 4^+ state plays a significant role in achieving the excellent fit to the 2^+ data. A CC calculation for the 3^- state is also shown as a solid curve in Fig. 1 and included the couplings indicated in the lower inset of the figure. Matrix elements for the $0^+ \rightarrow 2^+$, $0^+ \rightarrow 3^-$, and $2^+ \rightarrow 2^+$ transitions were taken from Refs. 6 and 7. The $3^- \rightarrow 3^-$ $L = 2$ matrix element was estimated by deducing an intrinsic quadrupole moment from that of the 2^+ state and assuming the 3^- state to have $K = 0$. The sensitivity of the calculation to the magnitude and sign of Q_{3^-} is illustrated in the bottom half of Fig. 2. An analogous situation holds for excitation of the 2^+ state of the projectile. For the projectile CC calculations, we used[13] $\beta_2 = 0.6$ and included the couplings shown as an inset in Fig. 2. In Fig. 2 we show results for three assumed values of the ^{12}C 2^+-state quadrupole moment. A positive quadrupole moment for the 2^+ state (an oblate ground-state shape in a rotational model framework) is clearly preferred by the large-angle data ($\theta_{\text{c.m.}} > 50°$). A value $Q_{2^+} = +0.5|Q_{\text{rot}}|$ gives the best overall fit.

In summary, it is encouraging that a conventional CC analysis can account for heavy-ion inelastic scattering without the need for large discrepancies in Coulomb and nuclear matrix elements. The most important feature of the above observations is the sensitivity of heavy-ion inelastic scattering to quadrupole moments, a finding that is further supported by our data on the other Nd isotopes. This sensitivity is much more marked than for light-ion inelastic scattering[14] and provides an alternative method to Coulomb reorientation for measuring the sign and magnitude of quadrupole moments.

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*Oak Ridge Graduate Fellow from the University of Tennessee under appointment from Oak Ridge Associated Universities.

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