ONSET OF DIFFRACTION-LIKE ANGULAR DISTRIBUTIONS IN THE $^{40}Ca(^{13}C, ^{12}C)^{41}Ca$ REACTION*

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The angular distribution of the $^{40}Ca(^{13}C, ^{12}C)^{41}Ca(g.s.)$ reaction has been measured at incident energies of 60 and 68 MeV. Oscillations in the differential cross section were observed at these energies but not at previously measured, lower energies of 40 and 48 MeV. Arguments are presented which indicate that diffraction-like angular distributions are a systematic feature of heavy-ion reactions.

One- and two-nucleon transfer reactions induced by heavy ions on intermediate and heavy target nuclei have generally been described as dominated by the Coulomb interaction. This description along with a strongly absorbing optical potential successfully accounts for the many featureless "bell-shaped" angular distributions which have been reported in the literature [1]. Recently, however, several angular distributions, which deviate markedly from this bell-shaped behavior, have been reported. For example, in the $^{A}Ni(^{18}O, ^{16}O)^{A+2}Ni$ reactions a change of shape from a bell-shaped to a forward rising angular distribution was observed [2] as a function of mass number. An almost diffraction-like angular distribution has been obtained [3] for the $^{26}Mg(^{16}O, ^{14}C)^{28}Si$ reaction. One-particle transfer on intermediate mass targets which exhibits structure not characteristic of a strongly absorbing, grazing collision has been reported by Schneider et al. [4, 5] for the $^{48}Ca(^{14}N, ^{13}C)^{49}Sc$ reaction. The cross sections for this reaction, studied at an incident energy of 50 MeV, showed oscillations superimposed on the bell shape and a strong at forward angles.

The experiments reported here exhibit the transition from smooth to oscillatory angular distributions for the reaction $^{40}Ca(^{13}C, ^{12}C)^{41}Ca(g.s.)$ as the bombarding energy is increased from 40 to 68 MeV. These data suggest that diffraction-like angular distributions are a general feature of heavy-ion transfer reaction systematics, for intermediate mass as well as light targets [6]. The low-energy data at 40 and 48 MeV have been reported [7] and show a smooth peak at the "grazing" angle. The 60 and 68 MeV data were measured using a ^{13}C beam from the recently upgraded BNL MP tandem Van de Graaff. Outgoing particles were detected in two counter telescopes separated by 15° and data points were measured at one degree intervals in the laboratory system. Standard pulse multiplication techniques were used to identify the mass and charge of the outgoing particles. The angular resolution of the counters was restricted to 0.2° by collimation, and an energy resolation of about 300 keV was obtained. Beam normalization was obtained by use of a fixed monitor placed at 15° in the lab. At forward angles (< 10° lab) it was most important to be able to count at high rates and still maintain reasonable energy resolution. In addition to reducing beam currents, delay line clipped (250 ns) amplifiers, complete DC coupling of high level signals, and pile-up rejection of pulse pairs separated by times between 15 ns and 3 μs were employed. Absolute cross sections were obtained by assuming forward angle elastic scattering to be Rutherford.

The elastic scattering of ^{13}C and the $^{40}Ca(^{13}C, ^{12}C)^{41}Ca(g.s.)$ reactions at all four bombarding energies is shown in fig. 1. In the 40 and 48 MeV transfer data there is little evidence for "wiggles", while strong oscillations are observed at 60 and especially at 68 MeV. These data strongly suggest that the data of refs. [3, 5] are not anomalous; such diffraction-like angular distributions clearly are to be expected with increased bombarding energy.

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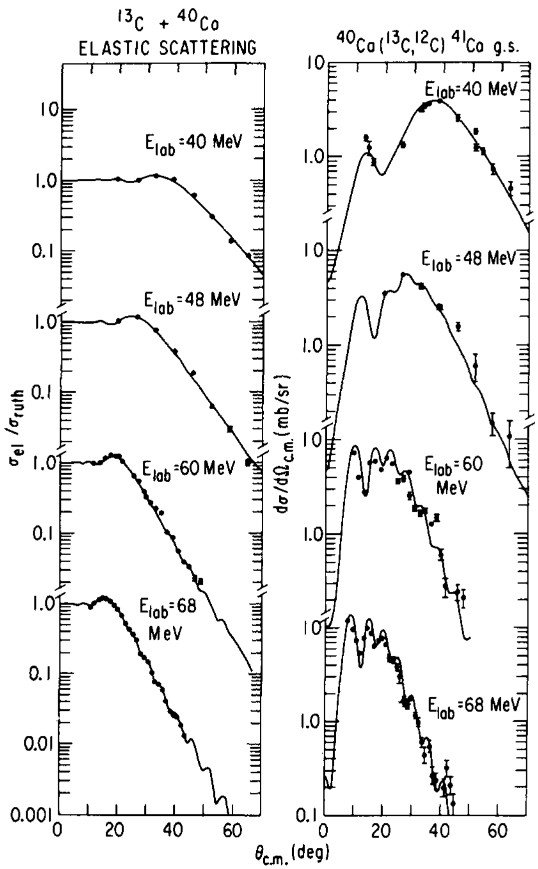

^{13}C elastic scattering on ^{40}Ca and the ^{40}Ca(^{13}C, ^{12}C)^{41}Ca(g.s.) angular distributions measured at 40, 48, 60 and 68 MeV incident energies. The solid lines on the elastic scattering curves correspond to calculations of the code ABACUS with parameters stated in the text. The theoretical transfer cross sections (solid lines), calculated with the code RDRC, have been multiplied by the same normalization at all energies.

A fit to the ^{13}C elastic scattering data was obtained using the optical model code, ABACUS‡ [8]. A single set of Saxon–Woods parameters V = 33.6 MeV, W = 18 MeV, r_0 = 1.27 fm, and a = 0.55 fm, were used to calculate the elastic scattering in the carbon channels at all energies (see fig. 1). The distorted wave Born approximation calculations shown in fig. 1 were calculated with the code RDRC [9] using these optical parameters and bound-state parameters of r_0 = 1.20 fm and a = 0.65 fm. With spectroscopic factors of 0.75 for the $p_{1/2}$ neutron in ^{13}C [10] and 0.80 for the $f_{7/2}$ neutron in ^{41}Ca [11], the same normalization factor of 1.5 is needed to multiply the theoretical cross section at all energies. DWBA calculations also have been made which include recoil effects using the perturbative recoil method of Baltz and Kahana [12]. Such calculations increase the magnitude of the cross sections compared with the no-recoil calculations, thereby reducing the normalization factor to 1.1, while leaving the angular distribution shapes essentially unchanged. Contributions of the non-normal l = 3 transfer were predicted to be small compared to the normal l = 4 transfer.

‡ ABACUS II modified for heavy ions.

It is possible to explain simply the transition from smooth to oscillatory distributions. While this change of shape has been described previously in the framework of a diffraction model [13, 14], we use the formulation of Chasman et al. [5], which is based upon DWBA calculations. The transition amplitudes were approximated as Gaussian in l space with a width Γ and with a maximum at partial wave l_0. The phases of the amplitudes were assumed to vary linearly with l near l_0. This rate of change of phase, Ψ, would be the classical scattering angle for a particle with angular momentum l_0 on a pure Coulomb trajectory. The result of Chasman et al., which holds for scattering angles $\theta \gg 1/l_0$ and which is similar to the results of refs. [13, 14] is

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{\sin\theta}\,[\exp\{-\tfrac{1}{2}\Gamma^2(\theta-\Psi)^2\}+\exp\{-\tfrac{1}{2}\Gamma^2(\theta+\Psi)^2\} + 2\exp\{-\tfrac{1}{2}\Gamma^2(\theta^2+\Psi^2)\}\cos((2l_0+1)\theta-\tfrac{1}{2}\pi)]\ . \quad (1)$$

While the expression is valid for a transferred L of zero, it should explain the energy dependence of angular distribution shapes.

The three terms in (1) correspond to a bell-shaped curve centered at $\theta = \Psi$, a bell-shaped curve centered at the (unphysical) angle $-\Psi$, and an interference term which contains the oscillatory part of the cross section and whose magnitude is largest at forward angles ($\propto 2\exp\{-\Gamma^2\Psi^2/2\}$. For an interaction which takes place in a given radial interval one would expect the width Γ of the transition amplitudes to increase with energy and this is confirmed by the DWBA. As expected from Coulomb scattering, Ψ decreases dramatically with increasing energy, resulting in increased magnitude of oscillation. We find from DWBA calculations for our reaction at 40 MeV, $\Gamma \approx 5$ and $\Psi \approx 0.7$, while at 68 MeV, $\Gamma \approx 5$ and $\Psi \approx 0.3$. Thus at 40 MeV the first term in the expression (1) dominates resulting in a bell-shaped angular distribution, while at 68 MeV there should be very noticeable oscillations on the bell-shaped distribution which are largest in the forward direction. The period of oscillation by inspection of (1) is given to a good approximation by $(2l_0 + 1)\Delta\theta = 2\pi$. The 68 MeV data indicates $\Delta\theta \approx 5°$ hence l_0 should be about 35, in agreement with the DWBA calculation.

In conclusion, the shape of the angular distribution for the ^{40}Ca(^{13}C, ^{12}C) transition to the ^{41}Ca ground state changes with increasing incident energy from that characteristic of a strongly absorbing grazing collision to one which oscillates. Both the shape and magnitude of the differential cross sections are well reproduced at all energies by DWBA calculations. The observed and predicted transition to diffractive angular distributions with increased bombarding energies indicates that such shapes should be as characteristic of heavy-ion transfer reactions as are the smooth bell-shaped distributions.

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