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Elastic-scattering angular distributions for ^{40}Ca + ^{48}Ca near the Coulomb barrier

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Elastic-scattering angular distributions are presented for the ^{40}Ca+^{48}Ca system at $E_{\text{c.m.}}=59.5$ and 63.1 MeV. Qualitative agreement is observed at both energies with a coupled-channels calculation which includes inelastic scattering and single-nucleon transfer channels, together with an additional positive Q value channel with coupling strength adjusted to fit the sub-barrier fusion yield.

In the past few years, much effort has been devoted to the study of heavy-ion reactions at energies near to and below the Coulomb barrier. A major part of this effort has been directed towards the investigation of low-energy fusion rates. The failure of conventional barrier penetration models to explain the enhanced sub-barrier fusion cross sections has led to an examination of effects due to the structure of the colliding nuclei. One way to approach this problem is through the coupled-channels formalism, wherein direct reaction processes are explicitly included. The fusion cross section is then assumed to be the difference between the total reaction cross section and the direct reaction yield. If the coupled-channels approach is consistent, then the coupling scheme which correctly predicts the low-energy fusion rates should simultaneously reproduce the elastic scattering. It is important to have a body of experimental data which includes measurements for as many of the reaction channels as possible to constrain the nuclear structure parameters in these calculations.

Attention has recently been focused on the relatively simple ^{40}Ca+^{40,44,48}Ca systems by Esbensen, Fricke, and Landowne,[1] who performed coupled-channels calculations in an attempt to understand the sub-barrier fusion yields measured by Aljuwair *et al.*[2] Good agreement was obtained with the measured ^{40}Ca+^{40}Ca fusion cross sections, as well as the elastic-scattering angular distributions near the Coulomb barrier, by including both the low-lying inelastic states and the dominant single-particle transfer channels.[1] However, the same calculation severely underpredicted the low-energy fusion yields for ^{40}Ca+^{44,48}Ca. Even though the single-nucleon transfer strength was predicted to increase strongly in going from ^{40}Ca to ^{44,48}Ca targets, the corresponding increased fusion enhancements were insufficient to explain the experimental yield. Similar failures have plagued all earlier attempts to understand ^{40}Ca+^{44,48}Ca sub-barrier fusion.[3-5] This situation is judged to be particularly serious for the ^{40}Ca+^{48}Ca system, which involves two doubly closed-shell nuclei.

The disparity between measured yields and those predicted by the coupled-channels formalism led Esbensen *et al.*[1] to consider the possibility that an additional reaction channel is strongly coupled to the initial state of the ^{40}Ca+^{48}Ca system. Two cases were investigated, corresponding to the assumption that the additional channel had an effective Q value (rather arbitrarily chosen) of either $+1$ or -3 MeV. In both cases, the form factor was proportional to the derivative of the ion-ion potential (as is appropriate for a two-nucleon transfer channel) and the strength of the coupling was adjusted to fit the fusion data. Comparable fits could be obtained with either the positive or negative Q value assumption. However, both calculations predict a cross section for the additional strongly coupled channel which is comparable to that for single-nucleon transfer. This seems unreasonably large for two-nucleon transfer channels, but no data exist for any transfer reaction from ^{40}Ca+^{48}Ca. The corresponding elastic-scattering predictions are also significantly different for the two cases, and both differ markedly from the "standard" coupled-channels calculation which does not include the additional strongly coupled channel. Again, no data exist for comparison purposes. We therefore decided to measure the elastic-scattering angular distributions for ^{48}Ca+^{40}Ca near the barrier ($V_b=51.3$ MeV, Ref. 2) in order to see what they could tell us about the origin of the sub-barrier fusion enhancements in this system.

The experiment was performed using 132 and 140 MeV ^{48}Ca beams from the tandem superconducting linear accelerator at the State University of New York (SUNY) at Stony Brook. Typical beam currents of 0.1 particle nA were incident on a natural Ca target of thickness 125 μg/cm^2, evaporated onto an 18 μg/cm^2 C backing. Scattered and recoil particles were detected in four silicon surface-barrier position sensitive detectors. A kinematic coincidence technique, which in principle would allow a simultaneous measurement of quasielastic reaction channels, was used. The detectors were mounted in two arrays, one on either side of the beam. Each set of detectors was oriented so that the plane of the face of the detectors was perpendicular to a line from the target to the center of the array, this perpendicular distance being 26.1 cm. All four of the detectors were fitted with collimators 12.7 mm high by 47.5 mm wide. Taking into account kinematic considerations, the arrays were aligned to include a wide range of angles for both singles and coincident events. One array covered laboratory angles in the range from 25° to 65° while the other array included the range from −20° to −50°. Four different detector arrangements allowed the elastic-scattering angular distributions to be obtained for cm angles from 55° to 120°, by detecting both the scattered and recoil particles in singles and also from coincident events. The coincidence data allowed us to verify that the "elastic-scattering" singles data excluded events corresponding to population of excited states in either the target or the projectile. Many overlap angles were included, which allowed us to check the relative normalizations between runs; a total of 70–80 individual measurements were made at each energy. Absolute cross sections were obtained by normalizing to Rutherford scattering at forward angles.

Our results (Fig. 1) show some interesting trends. First of all, it is clear that the standard coupled-channels calculation (solid curves) does not reproduce the elastic-scattering data at either energy, just as it was unable to account for the sub-barrier fusion yields.[1] Hence, both the fusion and the elastic data indicate that the standard calculation is incomplete for the ^{40}Ca+^{48}Ca system, although it describes both elastic scattering and fusion for ^{40}Ca+^{40}Ca rather well. Next, it appears that a negative Q value strongly coupled channel (dashed curves) can also be ruled out; the extra absorption introduced by this coupling further reduces the elastic yield beyond the grazing angle where it was already too low.

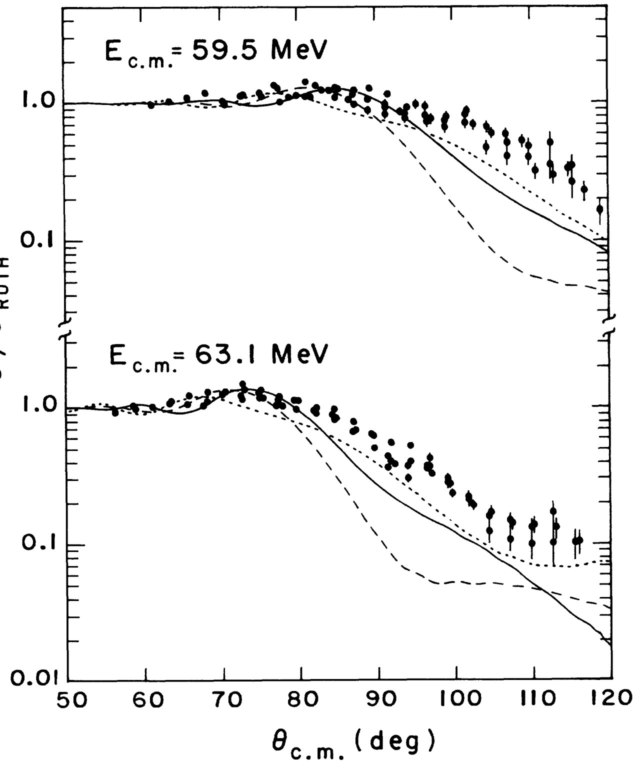

FIG. 1. Elastic-scattering angular distributions for the ^{40}Ca+^{48}Ca system. The solid curve is the standard calculation (see text), while the dashed and dotted curves include strong coupling to an additional channel having a Q value of −3 and +1 MeV, respectively.

Remarkably, however, our data very closely resemble the positive Q value prediction (dotted curves). Apparently, coupling to this positive Q value channel produces an attractive polarization potential in the elastic channel which enhances scattering to backward angles. The result is an angular distribution that is considerably different from the usual Fresnel shape, a difference which is reflected in our experimental data (Fig. 1). It is very interesting to note that the extra coupling to a positive Q value channel also markedly improves the agreement between the calculated fusion cross section and the experimental data at energies *above* the barrier, where other calculations tend to over predict the fusion yield (see Fig. 5 in Ref. 1).

Our experimental data suggest the need to couple to an even more positive Q value channel than those considered in Ref. 1 to improve the fits to both the back-angle elastic scattering and the above-barrier fusion yield. Such channels are available. For example, the ground state Q values for two proton ($2p$) pickup, two neutron ($2n$) stripping, and α-particle pickup for the ^{48}Ca+^{40}Ca entrance channel are +7.08, +2.62, and +0.637 MeV, respectively. It is worth noting that the $2p$ transfer Q value is the most positive of these, and that the standard calculation shows a dominance of single-proton transfer, for Q value reasons. Thus, one might suspect that the strongly coupled reaction channel of Esbensen *et al.* could be identified with $2p$ pickup to ^{50}Sc+^{38}Ar. On the other hand, the cross section for this transfer, as predicted by the calculation, is nearly equal to that for single-proton transfer. This seems to be unreasonably large for a two-nucleon channel. Thus, unique identification of the positive Q value coupling that is producing these effects becomes an important issue. Since we used the kinematic coincidence technique, it should in principle have been possible to distinguish among the various reaction channels, but an unexpected energy resolution problem led to an experimental mass resolution of 1.3 u which made exact mass identification impossible. This presented no problem in analyzing the elastic channel, as here we could simply fit a background to the unresolved nonzero Q value contributions; this background contributed at most a 5% correction to the elastic peaks. Furthermore, the energy resolution was sufficient to completely eliminate inelastic scattering to excited states of either the target or the projectile from the measured elastic yield. However, it was not possible to unambiguously identify individual transfer channels. We plan to measure these transfer cross sections in the near future using a modified experimental setup which will ensure our ability to distinguish individual channels by both mass and charge transfer.

In summary, we have measured elastic-scattering angular distribution for ^{40}Ca+^{48}Ca at two energies near the Coulomb barrier. Our data show remarkable similarities to the predictions of a coupled-channels calculation which includes an additional strongly coupled, positive Q value channel. The alternative coupling to a negative Q value channel can be ruled out. Since either strongly coupled calculation also reproduces the fusion yield, it appears that the remarkable differences in the sub-barrier fusion cross sections for the Ca+Ca systems may finally be on the way towards being understood.

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