PHYSICAL REVIEW C VOLUME 32, NUMBER 4 OCTOBER 1985

^{58}Ni + ^{64}Ni subbarrier fusion cross section

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(Received 24 May 1985)

The effects on the ^{58}Ni + ^{64}Ni fusion cross section due to the coupling of the entrance channel to inelastic and transfer channels with positive Q value are calculated, making use of macroscopic form factors for both processes. It is found that the effective lowering of the barrier amounts to ~ 8 MeV, consistent with recent experimental data. About 35% of this magnitude results from the positive Q-value transfer couplings.

Important progress has been made during the last few years in the study of subbarrier fusion reactions (cf. Ref. 1 and references therein). The most significant development in this area rests on the fact that it has been possible to relate the observed enhancement of the fusion cross sections to specific nuclear structure properties of the interacting nuclei.

Although a complete quantitative description of the observed phenomena does not yet exist, a consensus has been reached concerning the central role played by the coupling of the initial state to other reaction channels. Among these, the inelastic scattering processes are relatively well understood. The identification of effects due to the coupling to nucleon-transfer channels has, on the other hand, turned out to be a more elusive question. These degrees of freedom are especially interesting, since they offer the unique possibility of being sometimes associated with positive Q values. The significant distinction between positive and negative Q-value reaction channels has been discussed in the literature,[2] and there are indeed indications that two-particle transfer processes with $Q > 0$ have characteristic effects on the low-energy fusion rates.[3]

As far as concrete applications are concerned, a main difference has remained between the treatment given to inelastic and to two-nucleon transfer couplings. In fact, no satisfactory microscopic calculation of two-nucleon transfer cross sections exists at present (cf., e.g., Ref. 4). On the other hand, one can reliably calculate the corresponding quantities associated with inelastic processes (cf., e.g., Chapter IV in Ref. 5).

A macroscopic description of two-nucleon transfer form factors has recently been proposed,[6] which parallels the standard collective model for inelastic processes. Although many questions remain open concerning the accuracy of such a prescription, the effective deformation parameters which are needed to fit the experimental data are generally consistent with those calculated microscopically in a random phase approximation. In the present paper we apply this model to analyze recent ^{58}Ni + ^{64}Ni fusion cross section data.[7] These data extend almost one order of magnitude below the measurements of Ref. 8, but are otherwise in agreement with them.

The ingredients needed in the calculation are the ion-ion potential U_{aA} and the form factors associated with the collective vibrations excited in both the inelastic and pair-transfer processes. For the nuclear inelastic excitation of surface modes, the collective model leads to

$$[F_\lambda(r)]_s=(\beta_\lambda)_s R_0 \frac{\partial U_{aA}(r)}{\partial r} ,$$

where R_0 is the nuclear radius and $(\beta_\lambda)_s$ is the deformation parameter of the mode. Following Ref. 6, we use a similar expression for the pair modes, namely,

$$[F(r)]_p=\frac{\beta_p}{3A} R_0 \frac{\partial U_{aA}(r)}{\partial r} ,$$

where A is the mass number of the nucleus and β_p is now a measure of the amplitude of the vibrational motion in that coordinate. The deformation parameter can empirically be extracted from pair-transfer data in a manner similar to the way it is conventionally done for $(\beta_\lambda)_s$ in the case of surface modes.

The ^{58}Ni + ^{64}Ni reaction allows for two-neutron pickup and two-proton stripping reactions with positive effective Q values of $\tilde{Q}=3.9$ and 2.6 MeV, respectively (cf. Table I of Ref. 3). Previous analyses[9,10] of the fusion cross section for this case have inferred the importance of such transfer channels by making fits to the trends of the low-energy data of Ref. 8. Exploiting the new available data,[7] we have repeated the calculations of Ref. 9 making use of an improved algorithm which allows for more channels to be included explicitly. The deformation parameters for the inelastic couplings were fixed according to analyses of scattering data, as given in Table II of Ref. 9. We then allowed for the two additional transfer couplings with $Q > 0$, taking the deformation parameter $\beta_p \simeq 9$ obtained in Ref. 6 from the analysis of the ^{64}Ni (^{18}O,^{16}O) ^{66}Ni reaction. Potential parameters $V_0=-47.9$ MeV, $R_{aA}=9.5$ fm and $a=0.63$ fm were used (compare with Ref. 9).

The results of the calculations are compared to the full set of data points in Fig. 1. The dotted curve shows the results in the absence of coupling. The dashed curve corresponds to the inelastic excitation channels, while the solid curve includes the positive Q-value transfer channels. The total shift produced by the couplings at the 0.01 mb level is about 8 MeV, of which ~ 3 MeV arises from the $Q > 0$ transfer channels. It is satisfying to see that this predicted effect accounts for the trend of the low-energy fusion data.

We have also used the macroscopic form factor to esti-

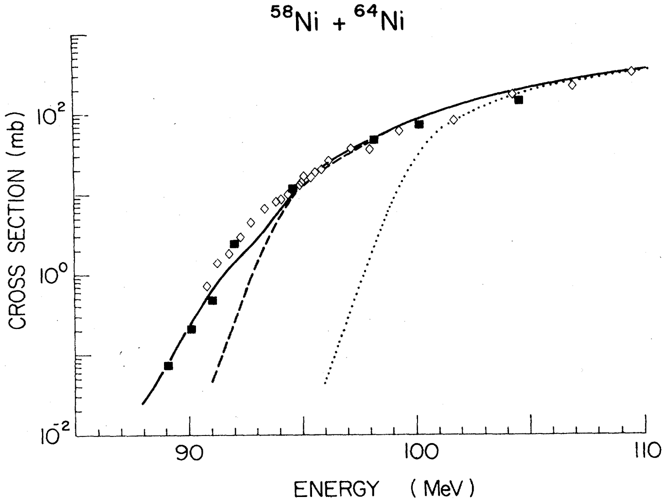

FIG. 1. Fusion cross section as a function of center of mass energy for the reaction ^{58}Ni + ^{64}Ni. The squares correspond to data extracted from Ref. 7, while the crosses are from Ref. 8. The dotted curve is a no-coupling calculation; the dashed curve is for the coupling to inelastic channels; and the solid curve includes the positive Q-value transfer channels.

mate the observable two-neutron transfer cross section. The calculation is carried out like a conventional inelastic excitation.[6] We have taken the same real potential as above and the same imaginary potential which was used for the ^{64}Ni (^{58}Ni, ^{60}Ni) ^{62}Ni calculations in Ref. 10. The results for the total integrated transfer cross section as a function of the center of mass energy are shown in Fig. 2. These cross sections are about an order of magnitude smaller than those of Ref. 10, where the transfer strength was adjusted to fit the fusion cross section within an absorption model. There was an error in the estimate for the cross section quoted in Ref. 9. Assuming a Rutherford trajectory for 180° scattering and for the parameters used there one obtains $d\sigma/d\Omega \sim 1$ mb/sr.

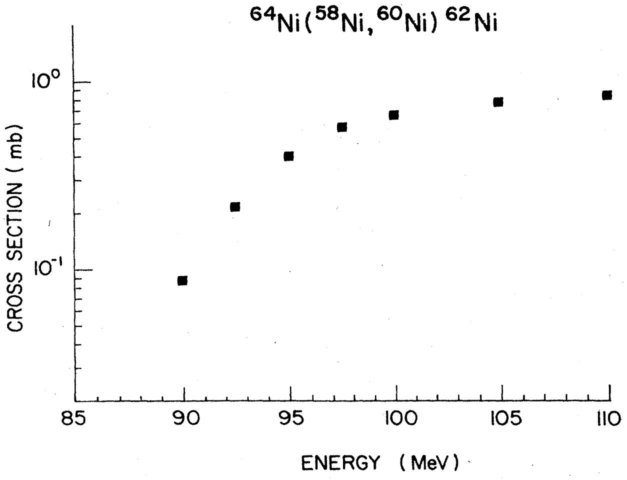

FIG. 2. Calculated cross section for the two-neutron transfer reaction ^{64}Ni (^{58}Ni ,^{60}Ni) ^{62}Ni as a function of the bombarding energy in the center of mass.

Since the theoretical description of the special effect of positive Q-value transfer on the low-energy fusion cross section is now reasonably well established, it would be interesting to confirm the existence of these transfer cross sections experimentally.

We thank R. C. Rohe for discussions and for making the experimental data available to us previous to publication. One of us (S.L.) has been supported by a grant of the Bundesministerium für Forschung und Technologie, Federal Republic of Germany.

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