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Transfer couplings and hindrance far below the barrier for ^{40}Ca + ^{96}Zr

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Abstract. The sub-barrier fusion excitation function of ^{40}Ca + ^{96}Zr has been measured down to cross sections $\simeq$2.4μb, i.e. two orders of magnitude smaller than obtained in the previous experiment, where the sub-barrier fusion of this system was found to be greatly enhanced with respect to ^{40}Ca + ^{90}Zr, and the need of coupling to transfer channels was suggested. The purpose of this work was to investigate the behavior of ^{40}Ca + ^{96}Zr fusion far below the barrier. The smooth trend of the excitation function has been found to continue, and the logarithmic slope increases very slowly. No indication of hindrance shows up, and a comparison with ^{48}Ca + ^{96}Zr is very useful in this respect. A new CC analysis of the complete excitation function has been performed, including explicitly one- and two-nucleon Q >0 transfer channels. Such transfer couplings bring significant cross section enhancements, even at the level of a few μb. Locating the hindrance threshold, if any, in ^{40}Ca + ^{96}Zr would require challenging measurements of cross sections in the sub-μb range.

1 Introduction

The role of couplings to nucleon transfer channels in heavy-ion sub-barrier fusion has never been unambiguously identified, after the early experiments of Beckerman et al. [1] on the various Ni+Ni systems. The more recent discovery [2] of the hindrance phenomenon at very low energies has made the situation more appealing, but more complex as well. Nucleon transfer effects should show up rather clearly down to those low energies, just where hindrance is expected, thus fusion cross sections are determined by the concurring contributions of hindrance and enhancement in that energy range.

The fusion of ^{40}Ca+^{96}Zr was investigated in [3] and its cross section was found to be greatly enhanced with respect to ^{40}Ca + ^{90}Zr. Its excitation function decreases remarkably slowly below the barrier, and the barrier distribution has a long tail toward low energies.

Coupled-channels (CC) calculations including low-lying surface vibrations, while nicely fitting the ^{40}Ca + ^{90}Zr excitation function, strongly underestimated the sub-barrier cross sections of ^{40}Ca+^{96}Zr. Neutron transfer channels with positive Q-values, only existing in ^{40}Ca+^{96}Zr, were suggested to be the reason of the difference.

Analogous trends have been observed in lighter systems. For example, the effect of transfer is strong and clear in ^{40}Ca+^{48}Ca [4, 5], whose cross sections exceed the ^{48}Ca + ^{48}Ca data at low energies (and are suppressed compared to the ^{40}Ca+^{40}Ca data at high energies). On the other side, the situation is different when considering heavier and soft systems. The investigation of ^{60,64}Ni + ^{100}Mo [6] brings evidence of the two excitation functions being very similar to each other down to $\simeq$2μb. Transfer couplings to Q >0 channels in ^{60}Ni + ^{100}Mo appear to play a marginal role, and hindrance appears for the system with ^{64}Ni in the sub-μb range. The requirement to place on more solid bases, theoretical predictions where very neutron-rich exotic beams are used, is generally felt. Indeed, in those cases large effects on sub-barrier fusion cross sections are qualitatively expected, but not sytematically found [7, 8].

For ^{40}Ca+^{96}Zr the lowest fusion cross section previously reported [3] is σ=0.16 mb. However, this is too large 1) to reveal the possible appearance of fusion hindrance, and 2) to try disentangling the interplay of effects due to inelastic couplings, transfer couplings and fusion hindrance, with the help of CC calculations. These two points were the purpose of the experiments reported here.

The present new results have extended the excitation function by almost two orders of magnitude down to $\sigma \simeq$ 2.4μb. CC calculations in the spirit of those of Ref. [3] have been performed. However, in the present case couplings to one- and two-nucleon transfer channels have

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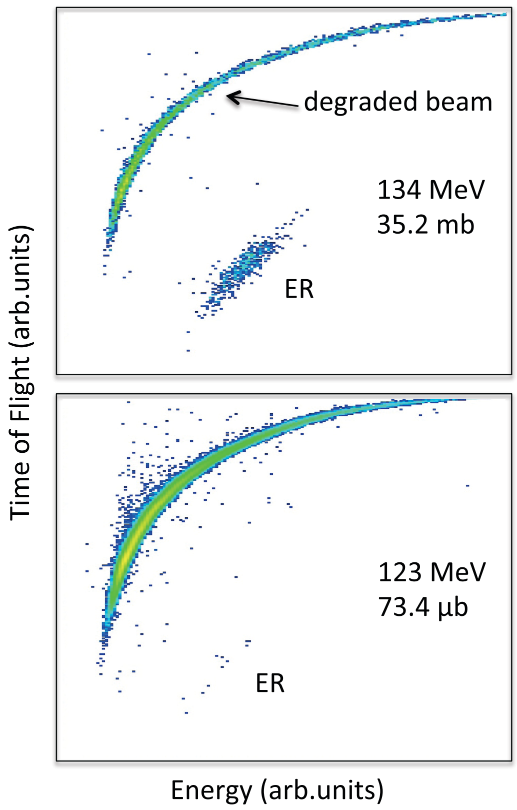

Figure 1. Two-dimensional Energy-TOF spectra obtained in the present experiment around (top) and below (bottom) the barrier.

explicitly been included, using the same formalism employed for the analysis of heavier (^{58}Ni + ^{124}Sn [9]) and lighter (^{32}S+^{48}Ca [10]) systems. A detailed account of this work has been recently published in Ref. [11]. This article summarizes and shows the main results of that paper.

2 Experiment and Results

Fusion-evaporation cross sections have been measured for ^{40}Ca+^{96}Zr at several energies from well below to well above the nominal Coulomb barrier $V_b \simeq 139$ MeV, using the ^{40}Ca beams of the XTU Tandem accelerator of INFN - Laboratori Nazionali di Legnaro (LNL). The five lowest measured energies (120, 121, 122, 123, 124 MeV) are below the limit of the previous experiment [3]. The beam intensity was ≃ 5 pnA (up to 10 pnA in some cases), and the targets were 50μg/cm^2 evaporations of isotopically enriched zirconium on carbon backings 15μg/cm^2

Evaporation residues (ER) were detected at 0° and at small angles by a ΔE-E-TOF telescope following beam rejection with the electrostatic deflector (see Refs. [10, 12] for details) systematically used for sub-barrier fusion measurements at LNL. Examples of two-dimensional spectra are shown in Fig. 1. Fusion-fission is negligible for ^{40}Ca + ^{96}Zr in the considered energy range. The measured fusion excitation function is shown in Fig. 2, where the reported errors are purely statistical. The absolute cross section scale is accurate to within ± 7-8%.

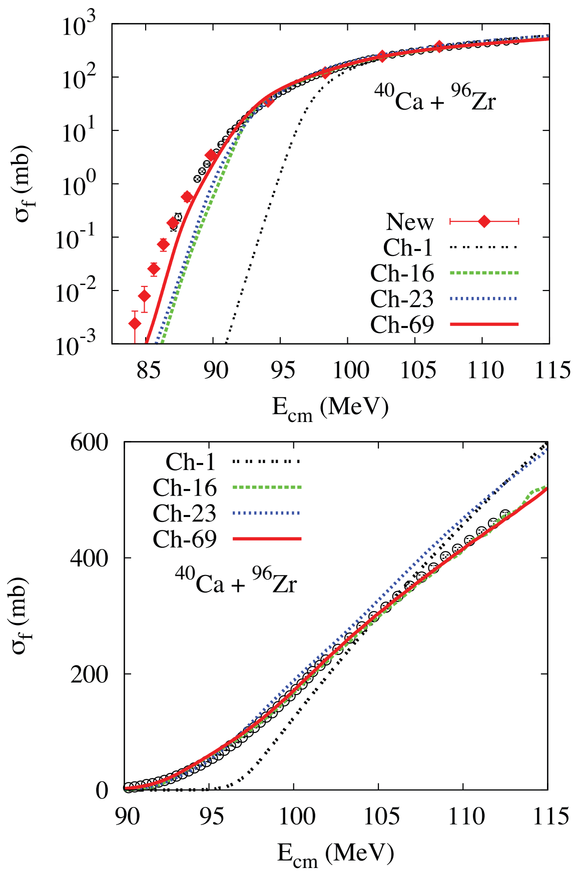

Figure 2. Excitation function of ^{40}Ca+^{96}Zr in a logarithmic (top) and linear (bottom) scale. The red and black symbols are the cross sections measured in this work and in Ref. [3], respectively. The lines are the results of the CC calculations described in the text (Ch-1 is the no-coupling limit).

3 Coupled-channels Analysis

A CC analysis has been performed, using the Woods-Saxon (WS) ion-ion potential derived from the Akiüz-Winther (AW) expression [13] with parameters V_0 = −73.98 MeV, R = 9.599 fm (r_0= 1.18 fm) and a = 0.673 fm. and the CC equations are solved using the same formalism described, e.g., in Refs. [10, 14]. The potential has been slightly modified so that the full calculation (Ch-69, see below) reproduces the data above 100 MeV, where the best normalized $\chi^2/N = 1.8$ is achieved with a radius shift ΔR = 0.18 fm. This produces a barrier V_b = 96.62 MeV.

The nuclear structure information used for the calculations is reported in Table I of Ref. [11]. The calculations include the two-phonon excitations of the 2^+ and 3^- states and mutual excitations of projectile and target. That gives a total of 16 channels and the calculation is called Ch-16. The results are sensitive to multi-phonon excitations because of the strong octupole excitation in ^{96}Zr. Similar to the recent analysis of the ^{48}Ca+^{96}Zr fusion data [15] we therefore include up to three-phonon excitations of this mode assuming that it is harmonic. We exclude mutual excitations in the same nucleus in order to limit the number of channels. This results in 23 channels (calculation Ch-23).

The calculations Ch-23 and Ch-16 do not differ too much from each other, and both of them strongly underestimate the sub-barrier cross sections. There is a clear need for additional (transfer) couplings at energies below 95 MeV, as pointed out in Ref. [3]. Therefore, we consider explicitly the influence of transfer on the fusion of ^{40}Ca+^{96}Zr in the CC calculations.

The ground state Q-values for one- and two-neutron pick-up channels are all positive (Q_{1n} = 0.51 MeV, Q_{2n} = 5.5 MeV). We include one-nucleon transfer couplings following the conventional shell-model description of the relevant nuclear states [16], used e.g. in Ref. [9] and more recently in [10]. Two-nucleon transfer channels were simulated in the calculations by one pair-transfer channel with an effective Q-value = 1 MeV and using the macroscopic form factor proposed by Dasso and Vitturi [17], with a transfer strength σ_{2n} = 0.5 fm. The calculation has a total of 69 channels (Ch-69) and gives the best fit to the data above 90 MeV, see Fig. 2 (bottom), with a χ^2/N = 2. The large 2n-strength may reflect that two-proton transfer also has a positive Q-value and gives a contribution. As recently calculated for ^{32}S+^{48}Ca [10], the largest effect on sub-barrier fusion is originated by the pair transfer 2N (2n and 2p).

In any case, it is seen that the full calculation Ch-69 *underestimates* the measured excitation function at the lowest energies, granted that the pair transfer is included in the coupling scheme in an approximate and schematic way. A hint on how one could improve the CC results comes from looking at the situation above the barrier. This is done in the linear plot of the excitation function of Fig. 2 (bottom), where the Ch-16 calculation fits the data, the Ch-23 calculation exceeds them at high energies, but the influence of transfer in the Ch-69 calculation restores the agreement. Increasing the 2N transfer strength would reduce the calculated cross section at high energy, while increasing the number of multi-phonon states would enhance that cross section.

In analogy with the two panels of Fig. 2, Fig. 3 shows the logarithmic (top) and linear (bottom) derivative of the energy-weighted excitation function, L(E) and d(Eσ)/dE respectively. As remarked above, the experimental slope L(E) remains small, and increases smoothly down to the lowest measured energies. The calculation Ch-69 is not far from the data. The trend suggested by the previous data at higher energies is confirmed by the present measurements, in agreement also with the phenomenological analysis of Ref. [15]. Locating the hindrance threshold in ^{40}Ca + ^{96}Zr is therefore a serious experimental challenge that will require cross section measurements in the sub-μb range.

The first derivative of the energy-weighted cross section, as calculated in Ch-69, is in remarkably good agreement with the data, in particular at high energies (bottom panel).

4 Fusion Hindrance

We have no indication for the fusion hindrance effect in ^{40}Ca+^{96}Zr. Indeed, the logarithmic slope remains very

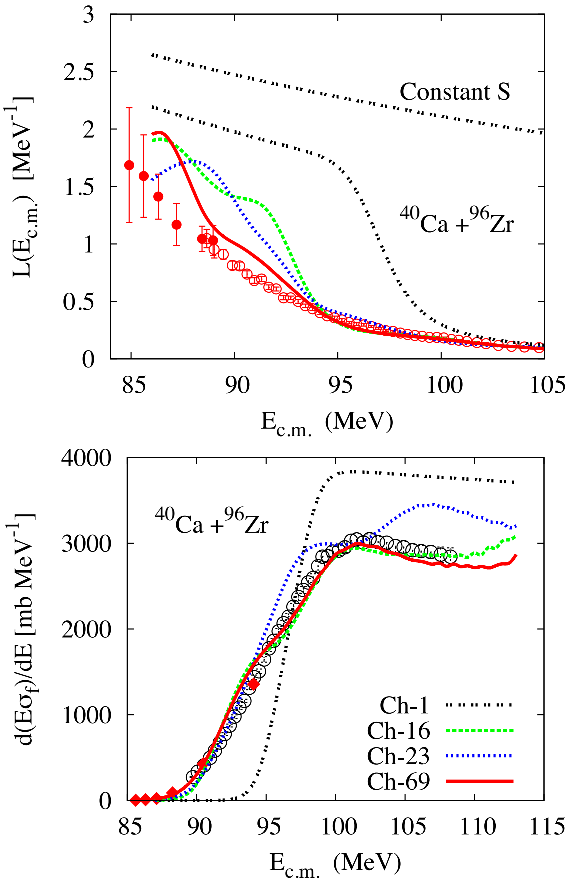

Figure 3. Logarithmic derivative (slope) of the fusion excitation function, obtained using both present and previous data, compared to CC results. The slope expected for a constant S factor is also reported (Constant S).

small compared to the value expected for a constant S factor well below the barrier, and the excitation function is even underestimated when using a standard WS potential in the CC calculations. Whether this situation is due to the strong transfer couplings that push the hindrance threshold lower in energy than the measured range, or it is the consequence of a different mechanism for deep sub-barrier in this system, cannot be inferred by the available data and calculations.

The present new data allow performing a significant comparison with the low-energy behavior of the excitation function of ^{48}Ca+^{96}Zr. This is done in Fig. 4: the cross section for ^{48}Ca+^{96}Zr decreases very sharply below the barrier and, indeed, this system shows hindrance (see also Refs. [15, 18]). On the contrary, the decrease of the excitation function for ^{40}Ca+^{96}Zr is by far slower. The inset is the same plot with a linear cross section scale, where the focus is on the energy range above the barrier. Beyond the trivial Coulomb barrier difference between the two systems, the slope is obviously smaller for ^{40}Ca+^{96}Zr. In the CC model, see above, this is explained by the strong transfer couplings in this system. Analogous considerations can be done by observing the low-energy slope difference of the two barrier distributions (bottom panel of Fig. 4).

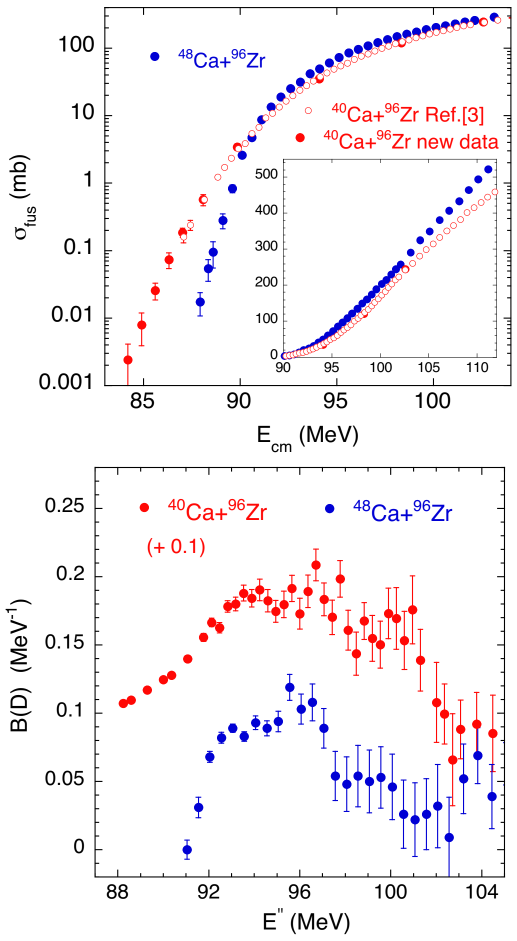

Figure 4. (top) Fusion cross sections of ^{40,48}Ca+^{96}Zr. The inset shows the two excitation functions in a linear scale. (bottom) Barrier distributions for the two systems.

5 Summary

We have measured very small fusion cross sections for the system ^{40}Ca + ^{96}Zr, whose excitation function has been extended by around two orders of magnitude below the previous limit. The present new measurements reveal a regular trend of the cross sections down to $\simeq 2.4 \mu$b, as well as a logarithmic slope increasing slowly and remaining very low with respect to the constant S factor value that would be reached, phenomenologically speaking, when a hindrance develops.

CC calculations using WS potentials have been used to analyze the present new data, and the excitation function of Ref. [3]. The nuclear structure of the two colliding nuclei has been taken into account by including the 2^+ states and multi-phonon excitations of the collective 3^- states. The excitation function is strongly *underestimated* below a few mb, and there is a clear need for additional couplings. One- and two-nucleon transfer channels have been included in the calculations, where the largest effect on sub-barrier fusion comes from the pair transfer. This makes the data fit much better, however, the sub-barrier data are still underpredicted.

On top of the strong effects produced by the low-lying surface vibrations in the near- and sub-barrier fusion of ^{40}Ca+^{96}Zr, couplings to $Q > 0$ transfer channels bring further significant enhancements, even at the level of a few μb, where no indication of hindrance appears yet.

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