Sub-barrier fusion of ^{40}Ca+^{94}Zr: Interplay of phonon and transfer couplings

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A precise fusion excitation function has been measured for ^{40}Ca+^{94}Zr at near- and sub-barrier energies, and the fusion barrier distribution has been extracted. Comparing with the existing data for ^{40,48}Ca+^{90,96}Zr shows that couplings to inelastic excitations determine the fusion cross sections and the shape of the barrier distributions near the barrier. At lower energies, the two systems possessing neutron-transfer channels with large positive Q-values (^{40}Ca+^{94,96}Zr) have remarkably similar cross sections, and both show a large enhancement with respect to the other systems and to coupled-channels calculations including up to three quadrupole and octupole phonons in the Zr targets.

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I. INTRODUCTION

Recent experiments on heavy-ion fusion near the barrier, using radioactive beams [1], have given renewed strength to the studies of this very complex phenomenon that provides valuable information on the interplay between nuclear structure and reaction dynamics (see Ref. [2] for a recent overview). The results of such experiments involving exotic nuclides, should be compared to theoretical models able to reproduce, as well, the evidence obtained with stable beams.

On one side, it is well accepted that fusion cross sections are strongly influenced by couplings of the relative motion to nuclear shape deformations and vibrations, but the role of the nucleon-transfer degrees of freedom continues to be a matter of discussion, despite several relevant experiments and some theoretical advances. That role should be clarified, in order to place on more solid bases theoretical predictions for heavy-ion reactions where very neutron-rich exotic beams are used, thus naïvely expecting large effects on sub-barrier fusion cross sections. Consequently, from the experimental point of view, detailed systematic investigations of isotopic effects are necessary, in carefully selected cases, using stable beams that allow fusion excitations functions near and below the barrier to be measured with high accuracy, and fusion barrier distributions to be extracted.

In this context, different combinations of Ca and Zr isotopes may be of great help. The two cases ^{40}Ca+^{90,96}Zr were studied a few years ago [3]. ^{40}Ca has high-lying 2^+ and 3^- vibrational states, where the dominant excitation is the well-known octupole state. The quadrupole vibrations in both ^{90,96}Zr are weak and lie at comparable energies, but the octupole state of ^{96}Zr is significantly stronger and lower in energy than in ^{90}Zr. Neutron-transfer channels (pickup) with positive Q-values exist only for the ^{40}Ca+^{96}Zr reaction (Table I).

Striking differences were observed in the behavior of the two systems. The different low-energy slopes of the excitation functions and the shapes of the fusion barrier distributions, were qualitatively attributed to neutron-transfer couplings [3], which should be very different for the two Zr isotopes. Subsequent analyses [4] suggested, though, that these experimental observations could be a consequence of the strong octupole vibration in ^{96}Zr. This latter argument is not supported by more recent data obtained using a ^{48}Ca beam on the same two zirconium targets [5]. In this case, the large difference between the sub-barrier cross sections disappears despite the differences in octupole strengths in the two targets. What has changed, however, is that for a ^{48}Ca beam there are no positive Q-value neutron-transfer channels with either Zr isotope.

In order to consolidate any possible conclusions arising from these observations, we have decided to measure near- and sub-barrier fusion cross sections in the intermediate case ^{40}Ca+^{94}Zr. The underlying motivation is that the Q-values for few-neutron pick-up channels in ^{40}Ca+^{94}Zr are very similar (positive) to those in ^{40}Ca+^{96}Zr. On the other hand, the octupole state in ^{94}Zr is significantly weaker than in ^{96}Zr, so the difference in the interplay of collective excitations and transfers should be reflected in the results. Indeed we shall see that a purely experimental comparison of the behavior of all five systems is very instructive, and the present data provide stringent constraints on attempts to disentangle this interplay of nuclear structure and nucleon-transfer effects within a coupled-channels framework.

II. EXPERIMENT AND DISCUSSION

Fusion-evaporation cross sections have been measured for ^{40}Ca+^{94}Zr from well below to well above the Coulomb barrier

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TABLE I. Q-values (MeV) for g.s. → g.s. neutron pick-up transfer channels for various Ca+Zr systems. Neutron stripping Q-values are negative in all cases.

System	$+1n$	$+2n$	$+3n$	$+4n$	$+5n$	$+6n$
^{40}Ca+^{90}Zr	−3.61	−1.44	−5.86	−4.17	−9.65	−9.05
^{40}Ca+^{94}Zr	+0.14	+4.89	+4.19	+8.12	+3.57	+4.65
^{40}Ca+^{96}Zr	+0.51	+5.53	+5.24	+9.64	+8.42	+11.62
^{48}Ca+^{90}Zr	−6.82	−9.79	−17.73	−22.67	−31.93	−37.60
^{48}Ca+^{96}Zr	−2.71	−2.82	−6.63	−8.69	−13.87	−17.00

($E_{\rm lab}$ = 126 MeV to 162 MeV), using the ^{40}Ca beams of the XTU Tandem accelerator of LNL. The beam intensity was $\simeq$ 2–3 pnA, and the targets were ^{94}Zr evaporations (98.58% enriched in mass 94), 50 μg/cm^2 thick, on C-backings 15 μg/cm^2. Evaporation residues were detected at 0° by an energy time-of-flight telescope following beam rejection with an electrostatic deflector (see Refs. [5–7] for details).

The present ^{40}Ca+^{94}Zr data are shown in the $E\sigma_{\rm fus}$ vs energy plot of Fig. 1 (top left), together with the other four systems ^{40,48}Ca+^{90,96}Zr. The excitation functions are linear above the barrier as expected from the classical formula $E\sigma = \pi R_b^2(E - V_b)$. Here and in the following, E is the center-of-mass energy. Statistical uncertainties are smaller than the symbol size for most points, whereas the absolute cross section

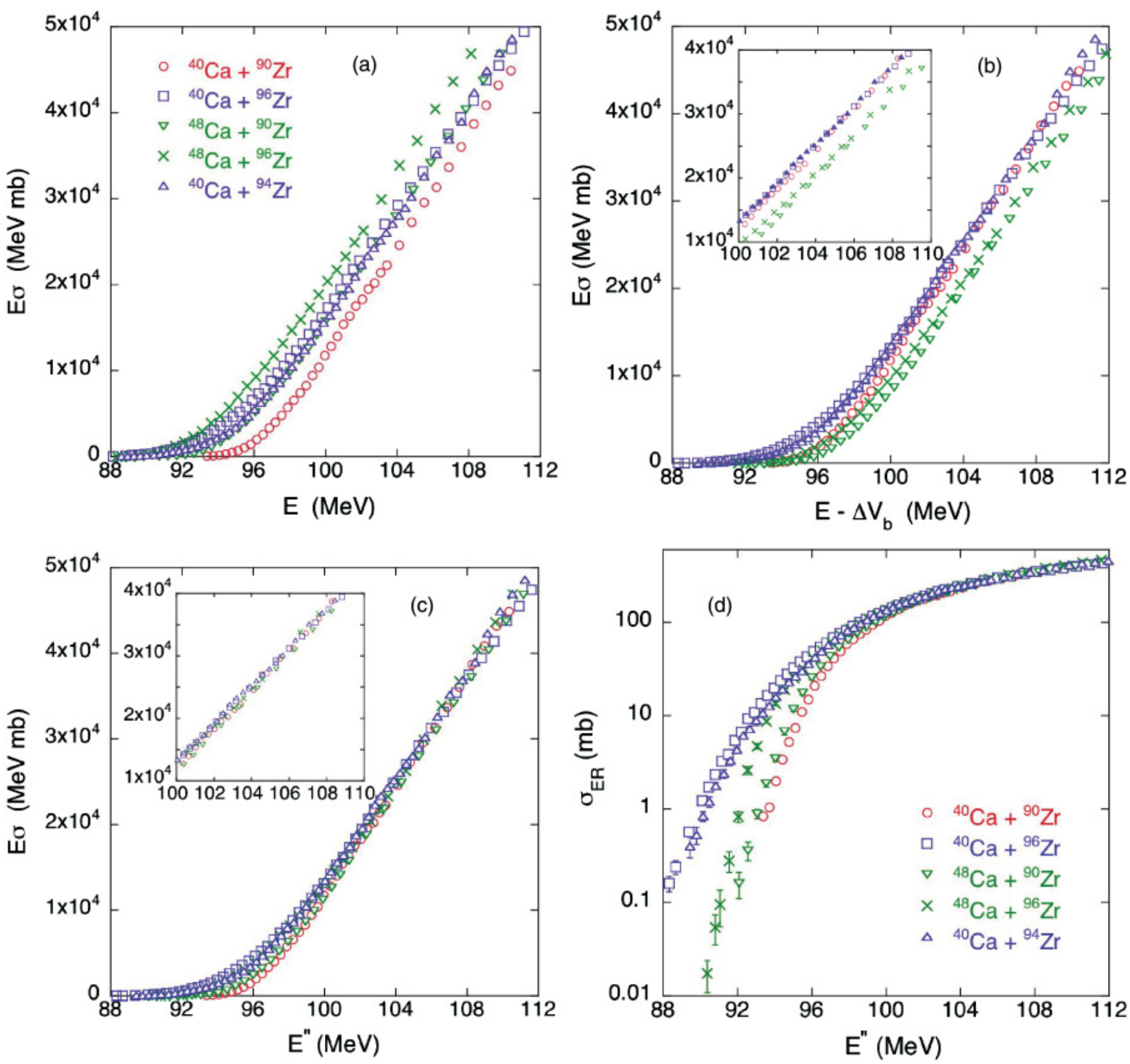

FIG. 1. (Color online) (top left) Linear plot of E × $\sigma_{\rm fus}$ vs energy for several Ca+Zr systems; (top right and bottom left) the same plot with adjusted energy scales (see text); (bottom right) fusion excitation functions on a logarithmic scale vs energy.

scale is accurate to within $\simeq \pm 15\%$ [6]. In order to compare the various systems, we should take account of their different Coulomb barriers. To this end, we use the Akyüz-Winther (AW) potential [8] (the Bass potential [9] gives almost identical barriers) and adjust the energy scales relative to the case of ^{40}Ca+^{90}Zr which remains untouched. The new abscissa in Fig. 1 (top right) is $E - \Delta V_b$, where, for each system, ΔV_b is the difference of the Coulomb barrier with respect to the case of ^{40}Ca+^{90}Zr.

In the new energy scale we see two clear-cut groups, that is, the three systems with ^{40}Ca fall on top of one another, and the two ^{48}Ca systems also nearly coincide, but shifted in energy, in the $E\sigma$ range of 1–4 × 10^4 (see the expanded view in the insert). This shift is due to the different strengths of the octupole mode in the two calcium isotopes; the stronger high-energy vibration of ^{40}Ca gives a larger renormalization of the potential [10], producing a lower Coulomb barrier. Indeed, the AW and Bass parametrizations are designed to reproduce the average behavior of the nuclear potential with varying $A_{1,2}$ and $Z_{1,2}$. One should not, however, expect them to reproduce local isotopic variations associated to strong phonons, as in the present case, and the separation into two distinct groups demonstrates that these parametrizations work rather well. The slopes of the five excitation functions in Fig. 1 are very similar, implying that the variation of barrier radius R_b is of little importance in this context.

The energy difference between the two groups of systems is ≈1.25 MeV. In the lower-left panel of Fig. 1 the energy scale of the two cases with ^{48}Ca has been shifted further, so that all excitation functions now approximately coincide above the barrier. In other words, we compensate for the different phonon couplings in ^{40}Ca and ^{48}Ca (that is, the difference in polarization potentials). Finally, all fusion excitation functions are reported in the lower-right panel of Fig. 1 on a logarithmic scale, where the energy scale E'' is the shifted one of the lower-left panel. The overall shifts $E'' - E$ are +0.84, +1.25, +1.39, and +2.46 MeV for ^{40}Ca+^{94,96}Zr, ^{48}Ca+^{90,96}Zr, respectively.

In the limit that the phonons in the Ca projectiles simply give a renormalised potential (and that negative Q-value transfer channels are relatively unimportant), the systems ^{40,48}Ca+^{90}Zr should now be identical, and indeed they are very similar in reality. ^{48}Ca+^{96}Zr has larger cross sections, as expected, due to the stronger coupling to the octupole state of ^{96}Zr. The two remaining systems ^{40}Ca+^{94,96}Zr are, however, greatly enhanced at low energies, and remarkably similar to each other. This can only be understood if one introduces an additional coupling mode for these two systems, and, based on the purely experimental systematics of Fig. 1, one is strongly inclined to identify this mode with neutron transfers with positive Q-values, which are available only in these two systems.

Next we compare the various fusion barrier distributions, in Fig. 2, using the adjusted energy scale of the lower-left panel of Fig. 1, that compensates for the different behaviors above the barriers. The distribution for ^{40}Ca+^{94}Zr has been obtained by double differentiation of $E\sigma_{\rm fus}$ vs energy, using the three-point difference formula [3,12] with an energy step $\Delta E = 1.4$ MeV (2.1 MeV above $E = 99$ MeV). It shows two main peaks at $E'' \simeq 96$ MeV and 99 MeV, and a low-energy tail extending down to the lowest energies.

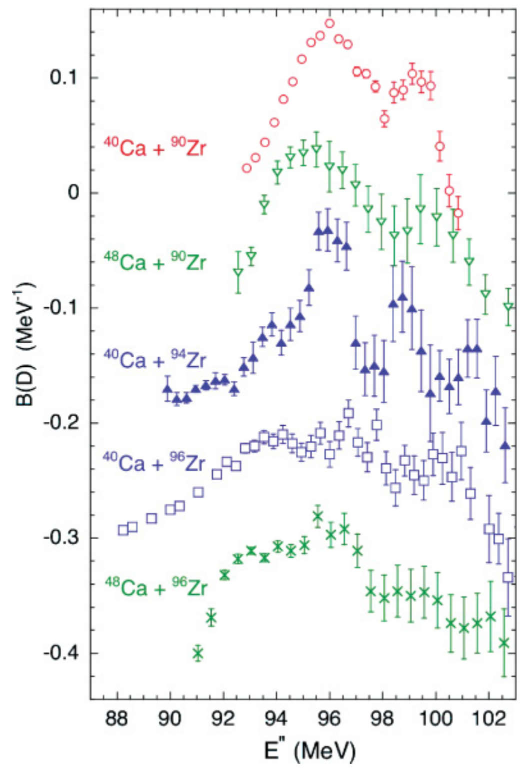

FIG. 2. (Color online) Fusion barrier distributions, where the ordinates for the various systems are diminished by successive 0.1 MeV^{-1} steps with respect to the case of ^{40}Ca+^{90}Zr.

The three distributions of ^{40}Ca+^{94}Zr and of ^{40,48}Ca+^{90}Zr are remarkably similar near the barrier, with two main separated peaks, the lower-energy one being more intense. This is interesting evidence in itself, and indicates the dominant influence of couplings to low-lying inelastic excitations in the Zr isotopes in that energy range. However, the low-energy tail of ^{40}Ca+^{94}Zr is not observed in the other two systems. This is analogous to the case of ^{40}Ca+^{96}Zr, and is responsible for the very similar behavior of the two corresponding excitation functions at sub-barrier energies (Fig. 1).

The strong octupole vibration in ^{96}Zr, contributes to making the barrier distributions of ^{40,48}Ca+^{96}Zr rather structureless [4], and these two distributions can be almost perfectly superimposed on one another, near the barrier. However, no low-energy tail shows up in ^{48}Ca+^{96}Zr, whose distribution sharply vanishes below $E'' \simeq 91$ MeV. Clearly additional couplings are available in ^{40}Ca+^{94,96}Zr, that generate barriers at low energies, below the main structure. This is only possible when *positive* Q-value channels are considered [13,14], since no static deformation is associated to the zirconium isotopes.

III. COUPLED-CHANNELS CALCULATIONS

The excitation function of ^{40}Ca+^{94}Zr has been compared with the results of coupled-channels (CC) calculations performed with the CCFULL code [15] using the Woods-Saxon parametrization of the nuclear potential. Table II shows the experimental information on the lowest collective excitations in ^{40,48}Ca and ^{A}Zr. The quadrupole vibration of ^{94}Zr is rather

TABLE II. Excitation energies E_{λ^π} and deformation parameters β_λ [16], for collective states of spin and parity λ^π.

	^{40}Ca	^{48}Ca	^{90}Zr	^{92}Zr	^{94}Zr	^{96}Zr
E_{2^+}(MeV)	3.904	3.832	2.186	0.934	0.919	1.751
β_2	0.12	0.11	0.09	0.10	0.09	0.08
E_{3^-}(MeV)	3.737	4.507	2.748	2.340	2.058	1.897
β_3	0.43	0.23	0.22	0.17	0.20	0.27

low in energy, but weak. The octupole state is above 2 MeV, and weaker than in ^{96}Zr. As for ^{40}Ca, only the 3^- state was included in the coupling scheme. We have chosen to use a diffuseness parameter $a = 0.90$ fm, as in the analysis performed in Ref. [3] for ^{40}Ca+^{90,96}Zr. This fixes the depth of the potential well to 116.2 MeV when the radius parameter is given the value r_o=1.05 fm [17]. The resulting "bare" barrier is V_b = 99.8 MeV, that is 1.2 MeV higher than the standard AW Coulomb barrier. This potential gives an excellent fit to the data above the barrier.

Figure 3 shows that a considerable part of the sub-barrier fusion enhancement is due to the high-energy octupole vibration of ^{40}Ca. One- and two-phonon excitations in ^{94}Zr, of both quadrupole *and* octupole nature, bring additional enhancements. The calculated enhancement due to the octupole mode largely exceeds the effect of the quadrupole one. Additionally, we have tried to include the $(3^-)^3$ and $(2^+)^3$ excitations in the coupling scheme, and the result is marked "three-phonon". One sees no further significant effect, that is, convergence of the results has been essentially reached. A large discrepancy with respect to experiment develops with decreasing energy, below ≈95 MeV. Additional couplings in ^{40}Ca+^{94}Zr, which might give rise to lower-energy barriers, are simply not present in the coupling scheme.

IV. SUMMARY

In summary, the present results of near- and sub-barrier fusion cross section measurements in ^{40}Ca+^{94}Zr have allowed a detailed, and purely experimental, comparison with the existing data for ^{40,48}Ca+^{90,96}Zr. In order to achieve the appropriate comparisons, it was necessary to introduce energy scales adjusted according to the average Coulomb barriers of the different systems. To this end we used the Akyüz-Winther barriers but also needed to account for the different polarization potentials arising from the highly collective, high-lying ^{40,48}Ca phonons. We believe that this technique will prove useful in other similar studies.

We observe that (1) the two systems with ^{90}Zr have very similar sub-barrier cross sections in the adjusted energy scale, and fusion of ^{48}Ca+^{96}Zr is almost a factor 10 relatively enhanced; (2) the fusion cross sections for ^{40}Ca+^{94,96}Zr are up to another factor 100 larger at the lowest energies, where

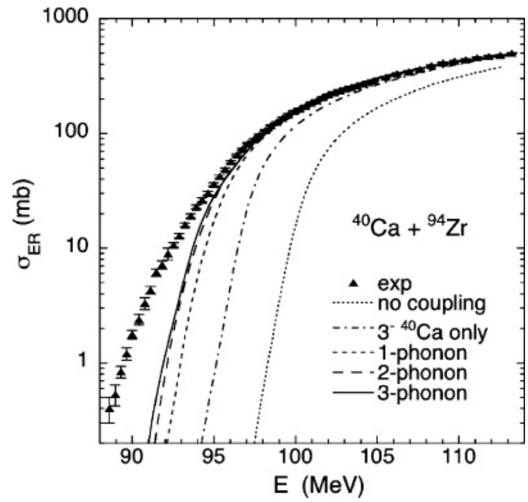

FIG. 3. Fusion excitation function of ^{40}Ca+^{94}Zr.

these two excitation functions almost coincide. Analogously, when comparing the fusion barrier distributions for ^{40}Ca+^{94}Zr and the other Ca+Zr systems, a low-energy tail appears only in the distributions for ^{40}Ca+^{94,96}Zr. All this indicates that the underlying fusion dynamics goes beyond couplings to low-lying vibrational states of the two nuclei, and, indeed, the near- and sub-barrier fusion cross sections in ^{40}Ca+^{94}Zr are certainly not reproduced by CC calculations where only those vibrational modes are taken into account.

In an early model [11] the presence of a neutron pair-transfer channel with positive Q was simulated by the introduction of a low-energy fusion barrier below the centroid of the barrier distribution. Sequential single-neutron transfers dominate in the ^{40}Ca+^{96}Zr system [18], and the $+2n$ channel with large positive Q (g.s.→g.s.) is a part of that set of channels even if not populated by direct pair transfer. We shall attempt elsewhere to include these neutron transfers directly into our CC calculations, in order to check the validity of that attractive, although qualitative, argument proposed by Broglia *et al.*

Independent of CC calculations, anyway, the systematic study of systems having the same $Z_{1,2}$ but different isotopic components, as shown in this paper, strongly supports the original suggestion that positive Q-value neutron-transfer channels do enhance sub-barrier fusion cross sections, in particular at very low energies.

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