Fusion-evaporation cross-sections for $^{48}$Ca + $^{154}$Sm near the Coulomb barrier

Evidence for fusion enhancement and hindrance


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Abstract. Measurements of fusion-evaporation cross-sections for the system $^{48}$Ca + $^{154}$Sm have been performed in the sub- and near-barrier energy range. Barrier-passing cross-sections have been obtained by adding recently measured capture-fission cross-sections at the same energies, and the barrier distribution for capture has been extracted. The data have been analyzed within a coupled-channel model, and a large subbarrier cross-section enhancement is observed, due to the ground-state prolate deformation of $^{154}$Sm.

The $^{48}$Ca + $^{154}$Sm capture cross-sections are compared to existing data on $^{16}$O + $^{186}$W fusion, leading to the same CN, where a few higher-energy points have also been measured. The evaporation residue cross-sections for the two systems above the barrier indicate that complete fusion is inhibited for $^{48}$Ca + $^{154}$Sm by $\approx 40\%$ in that energy region, with respect to $^{16}$O + $^{186}$W.

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1 Introduction

The experimental knowledge on fusion between light and medium-heavy nuclei at sub- and near-barrier energies has grown considerably in the last twenty years [1,2]. The theoretical models are able to reproduce and predict the main features of such processes, but properly understanding the fusion dynamics for heavy systems requires many more ingredients. The need for more experimental data to disentangle various concurrent effects, is clearly felt. A full understanding of all steps of the reaction dynamics is very important for the challenging issue of superheavy elements production.

For light or medium-heavy systems, capture inside the Coulomb barrier leads invariably to fusion, so that the capture (or barrier-passing) cross-section coincides with the total fusion cross-section. Total fusion implies the formation of the compound nucleus. However, for heavy systems capture inside the barrier, i.e. formation of a di-nucleus, is not a sufficient condition for fusion. The di-nucleus may reseparate into two fragments before that full equilibration of all degrees of freedom has been reached. Consequently, a considerable part of the total capture cross-section is “lost” into the quasi-fission channel. This phenomenon is experimentally observed as a hindrance to fusion [3,4].

Very schematically, fusion enhancements and fusion hindrance phenomena are both present in the interesting energy range near the Coulomb barrier for heavy and very heavy systems. They influence fusion cross-sections in opposite ways, but the underlying phenomena are acting at different stages of the dynamical evolution of the projectile + target system. Channel coupling effects, expected to be very strong in heavy systems, facilitate capture inside the Coulomb barrier. At a slightly later stage, when capture has taken place and the di-nucleus has been formed, its ability to form a real compound nucleus (CN) depends on different (less studied) entrance-channel properties, like energy, mass-asymmetry, nuclear deformation and shell effects.

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The dependence of fusion hindrance on mass asymmetry in the entrance channel was indicated by early experiments (see, e.g., [5]) and analyzed within the extra-push model [6–8]. In the measurements of Back et al. [9], evidence for quasi-fission was found for $^{32}$S + $^{182}$W, and it was shown that complete fusion is only a small fraction of the total reaction cross-section for $^{48}$Ti + $^{166}$Er and $^{60}$Ni + $^{154}$Sm. All three systems lead to the $^{214}$Th* CN. More recent measurements on the production of $^{216}$Ra* and $^{220}$Th* CN [10,11] have shown, in a model-independent way, that fusion is increasingly inhibited near the barrier, for $Z_1Z_2$ values as low as $\approx 700$, when entrance channels have decreasing mass asymmetry, due to the competition with quasi-fission. Those experiments demonstrated that the inhibition exists already for the low partial waves associated with a significant evaporation residue (ER) production.

The influence of nuclear static deformation on the fusion process has been the object of various investigations (see, e.g., [12]). In particular, the fusion barrier distribution of $^{16}$O + $^{154}$Sm [13] has a characteristic shape due to the prolate deformation of $^{154}$Sm. Using this nucleus as the target and a spherical projectile, heavier than $^{16}$O, should reveal stronger subbarrier fusion enhancements and a wider barrier distribution. However, one has also evidence that deformation may facilitate the onset of quasi-fission, thereby inhibiting fusion. In $^{60}$Ni + $^{154}$Sm [14], a strong hindrance to fusion was deduced from the measured subbarrier ER cross-sections. The fusion hindrance was attributed to “tip” collisions with the deformed samarium target at subbarrier energies, following previous evidence for $^{16}$O + $^{238}$U [15]; no hindrance was observed above the barrier where “side” collisions become energetically possible.

Closed-shell nuclei are usually rigid against quadrupole vibrations. Therefore, couplings with such inelastic states have a small effect on subbarrier fusion probabilities. But couplings to octupole deformations may be strong even in magic nuclei (e.g. in $^{40}$Ca or in $^{209}$Pb), so leading to large cross-section enhancements [16–18]. The case of $^{48}$Ca is interesting, since it is very stiff both for quadrupole and for octupole vibrations. Fusion hindrance itself may be affected as well by shell effects in the entrance channel [19,20].

This paper presents the results of our experimental study of fusion of the relatively heavy, magic nucleus $^{48}$Ca with the well-deformed target $^{154}$Sm. We provide experimental information on fusion dynamics of $^{48}$Ca + $^{154}$Sm in a large energy range going from well below to well above the Coulomb barrier. Fusion hindrance has been recently observed [21] in the similar, but heavier system $^{48}$Ca + $^{168}$Er. The purpose of the present work was twofold: 1) to obtain experimental confirmation to the expected large channel coupling effects in the subbarrier energy regime, and to analyze the results within the coupled-channel model; 2) to look for fusion hindrance in a system where $Z_1Z_2$ is as large as 1240, but the CN $^{202}$Pb* is relatively lighter than in previous studies [9–11,14,15,21], and where deformation is present, so to extend our knowledge on the entrance channel properties which may be relevant for the onset of fusion hindrance/quasi-fission.

We have measured the cross-sections for ER production (a clear signature for fusion) for this system. By adding recently measured capture-fission cross-sections in the same energy range, we have deduced total capture (barrier-passing) cross-sections. The barrier distribution has been extracted as the second derivative of the capture excitation function [1]. Both capture cross-sections and barrier distribution have been compared with the predictions of coupled-channel calculations where the static deformation of $^{154}$Sm has been taken into account. A relative comparison has also been done with the subbarrier fusion cross-sections of $^{16}$O + $^{186}$W [12,22]. Above the Coulomb barrier the $^{48}$Ca + $^{154}$Sm ER cross-sections have been analyzed together with the corresponding data for $^{16}$O + $^{186}$W, leading to the same CN, where we have also measured a few higher-energy points. The reduced ER cross-sections for the two systems have been compared, looking for a possible fusion hindrance in $^{48}$Ca + $^{154}$Sm. Part of the present results was presented at recent Conferences [23].

The following section 2 describes the experimental set-up and presents the results. Section 3 is dedicated to the analysis of the capture cross-sections for $^{48}$Ca + $^{154}$Sm within the coupled-channel model, and to a comparison of capture cross-sections for $^{48}$Ca + $^{154}$Sm with respect to fusion cross-sections of $^{16}$O + $^{186}$W. Section 4 shows the ER cross-sections for $^{48}$Ca + $^{154}$Sm and $^{16}$O + $^{186}$W in a reduced scale where fusion hindrance effects can be readily put into evidence, in a model-independent way. A summary and the conclusions of the paper are presented in sect. 5.

2 The experiments

2.1 Set-up and procedures

Heavy-ion beams from the XTU Tandem-ALPI accelerator complex of the Laboratori Nazionali di Legnaro of INFN have been used for the experiments reported here. The $^{48}$Ca beams were produced by the sputter ion source where a metallic calcium sample, enriched to 50% in mass 48, was sprayed with ammonia and the resulting CaH$_2$ ions were injected into the accelerator. Beam intensities on targets were $\approx 2-5$ pA, depending on the experimental conditions. The energy range for measurements was 163–220 MeV (roughly from 11% below to 20% above the nominal Coulomb barrier). The $^{16}$O beams had energies in the range 105–121 MeV with intensities around 10 pA.

The targets, placed in the center of a $\varphi = 100$ cm scattering chamber, were evaporations of metallic $^{154}$Sm (50–200 $\mu$g/cm$^2$) and of $^{186}$WO$_3$ (50 $\mu$g/cm$^2$) on carbon backings (15–20 $\mu$g/cm$^2$) facing the beam, with isotopic enrichments 98.7% and 97.5%, respectively. The beam energy losses in the carbon backings were $\approx 400$ keV and $\approx 70$ keV for $^{48}$Ca and for $^{16}$O, respectively, and they were taken into account in the data analysis.