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Fusion hindrance and quasi-fission in ^{48}Ca induced reactions

Implications for super-heavy element production

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Abstract. Recent experimental data on relatively mass-asymmetric collisions show that fusion hindrance can be explained in terms of the onset of quasi-fission reactions. The influence of mass-asymmetry, shell effects and target deformation on such phenomena is presented and possible implications for super-heavy element production are discussed.

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1 Introduction

The search for super-heavy elements (SHE) started in the late sixties as a consequence of the predictions of closed spherical nuclear shells at $Z = 114$ and $N = 184$ [1,2]. Nuclei with these "magic" proton and neutron numbers and their neighbours were predicted to be stabilized against spontaneous fission by large shell correction energies. By then many efforts have been devoted to the search for SHE.

Experimentally, the SHE production is an extremely challenging issue since many different parameters have to be optimized. Soon, it was realized that in order to favour the formation of very heavy elements from rather mass-symmetric entrance channels, another process had to be minimized besides spontaneous fission. This process, called quasi-fission (QF) [3], competes with complete fusion at near barrier energies and can lead to a large hindrance for fusion, therefore affecting the probability of producing SHE. Namely, the fusion of two massive nuclei leads to superheavies only when the combined system is captured inside the attractive potential pocket, survives quasi-fission and approaches a compact shape; the resulting compound nucleus (CN) has then to survive fission, leading to an evaporation residue (ER) with a finite half-life. The survival to fission can be optimized by minimizing the excitation energy and the angular momentum of the compound nucleus. Therefore, in order to optimize the SHE production rate, the challenge is to understand what are the conditions influencing QF.

In the last few years, exciting results have been obtained by both "cold fusion" reactions on Pb and Bi targets and "hot fusion" reactions with ^{48}Ca beams on actinide targets [4,5]. However, the very low cross-sections (a few pb) for production of SHE do not allow to make detailed experimental studies on the parameters influencing their formation.

Recently, it has been shown that QF reactions may be present even for relatively light combined systems [6,7] and rather mass-asymmetric combinations, where non negligible ER cross-sections are found. Therefore, studies on lighter nuclei can help to understand how entrance channel properties influence the dynamical evolution of the combined system from capture to scission.

Many factors may potentially affect ER survival and QF competition. With the purpose of studying the influence of mass-asymmetry, shell effects and target deformation on QF, the following reactions were chosen:

- ^{48}Ca + ^{168}Er, ^{12}C + ^{204}Pb → ^{216}Ra*,
- ^{48}Ca + ^{154}Sm, ^{16}O + ^{186}W → ^{202}Pb*,
- ^{48}Ca + ^{144}Sm → ^{192}Pb*,
- ^{40}Ca + ^{154}Sm → ^{194}Pb*.

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2 The experiments

The experiments were carried out at INFN-Laboratori Nazionali di Legnaro, using the stable beams delivered by the XTU-Tandem-Alpi accelerator facility. Highly enriched metallic ^{154,144}Sm, ^{168}Er (50–200 μg/cm^2) and ^{186}WO$_3$ (50 μg/cm^2) targets evaporated onto carbon backings (15–20 μg/cm^2) were used. The experimental set-up was a combination of an electrostatic deflector with a time-of-flight (TOF) spectrometer. The electrostatic deflector [8] allowed to separate ER from the incident beam, and residual beam-like particles were further discriminated by an additional Energy-TOF telescope based on a silicon and on a micro-channel plate detector. The double-arm TOF spectrometer CORSET [9], based on position-sensitive micro-channel plates, allowed to detect fission fragments (FF) in coincidence. Position and velocity of FF were used to deduce their mass and total kinetic energy (TKE). Four silicon detectors detected Rutherford yields from the targets, which were used for normalization purposes and for a precise determination of the beam position. Angular distributions for both ER and FF were measured at different energies spanning the Coulomb barrier.

3 Results and discussion

It is known that collisions between rather mass symmetric heavy nuclei are characterized by a noticeable contribution of QF events [10]. Recently, the presence of QF was put in evidence even for mass-asymmetric combinations [6]. Three reactions were studied: ^{12}C + ^{204}Pb, ^{19}F + ^{197}Au and ^{30}Si + ^{186}W, all leading to ^{216}Ra*.

Different entrance channels leading to the same compound nucleus are expected to give the same reduced ER cross-sections $k^2\sigma_{\rm ER}/\pi$ at sufficiently high excitation energies, where the transmission coefficients T_ℓ are approximately 1 for all the low angular momenta leading to ER [6,7]. However, the comparison of the reduced ER cross-sections for the three above mentioned systems showed a fusion hindrance effect for the ^{30}Si and ^{19}F induced reactions in comparison with ^{12}C + ^{204}Pb. Such effect was interpreted as due to an unexpected onset of the QF mechanism, as suggested by an increasing width of the FF mass distribution.

We extended such studies by populating ^{216}Ra* using a ^{48}Ca beam on a ^{168}Er target to move further towards a more symmetric reaction; and we looked for a clear signature of QF events. ER and FF were measured for both ^{48}Ca + ^{168}Er and ^{12}C + ^{204}Pb. Our data confirm the presence of a large fusion hindrance effect for ^{48}Ca + ^{168}Er in comparison with ^{12}C + ^{204}Pb [11]. Such fusion hindrance is consistent with a noticeable contribution of asymmetric fission found in the mass-TKE distributions of fission fragments [12]. This contribution was ascribed to the QF process and its mass-asymmetry explained in terms of shell effects manifested in the exit channel [13], favouring the formation of closed shell FF. The large anisotropy observed in the angular distribution of mass-asymmetric FF [13,14] provided a clear signature of QF events.

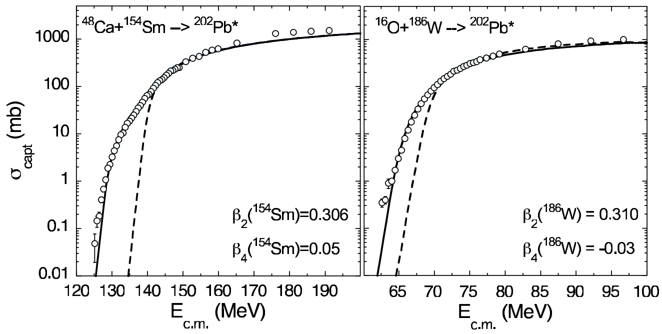

Fig. 1. Capture cross-sections for ^{48}Ca + ^{154}Sm (left panel) and ^{16}O + ^{186}W (right panel). Experimental data (points) are compared with coupled-channels calculations (lines).

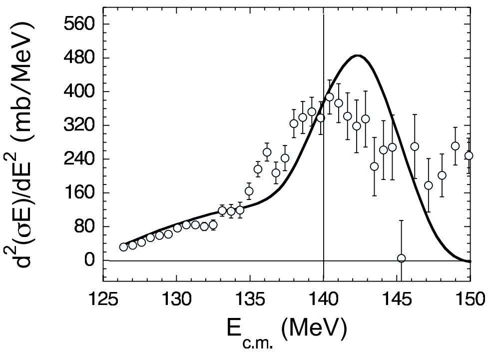

Fig. 2. Distribution of barrier energies for ^{48}Ca + ^{154}Sm.

We then studied the fusion of the magic ^{48}Ca with the well deformed target ^{154}Sm. The main purpose of this work was to look for experimental evidence of fusion hindrance in a system where Z_1Z_2 is as large as 1240 but the CN is relatively light (^{202}Pb*), and where deformation is present, so to give us information on the effect of target deformation on QF. To this aim we also extended to higher energies previous measurements on ^{16}O + ^{186}W [15,16], also leading to ^{202}Pb*. The ^{48}Ca + ^{154}Sm system is on the other hand interesting because it offers the opportunity to study the competition between possible fusion hindrance effects due to QF and fusion enhancement below the barrier due to the strong channel couplings in a reaction between a relatively heavy projectile and a well deformed target [17].

In fig. 1 the total capture (evaporation + fission) cross-sections (points) are compared for both systems to the corresponding barrier-passing cross-sections calculated with and without channel couplings. The dashed curves correspond to the no-coupling limit, while the solid curves are coupled-channels (CC) calculations performed using the CCFULL code [18] and including rotational couplings up to the 12^+ level, with the indicated β_2 and β_4 deformation parameters. A good agreement is obtained in the CC approach for the total capture cross-sections of both systems.

The experimental distribution of barrier energies for ^{48}Ca + ^{154}Sm was extracted from the second energy derivative of the fusion excitation function [19,20] and is shown in fig. 2 (points) together with CC predictions. It can be noticed that such barrier distribution is about

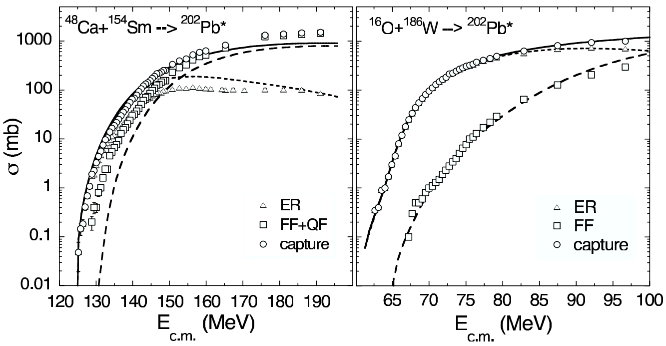

Fig. 3. Experimental ER (triangles), FF (squares) and total capture (circles) cross-sections for both ^{48}Ca + ^{154}Sm (left panel) and ^{16}O + ^{186}W (right panel) are compared with statistical model calculations (lines).

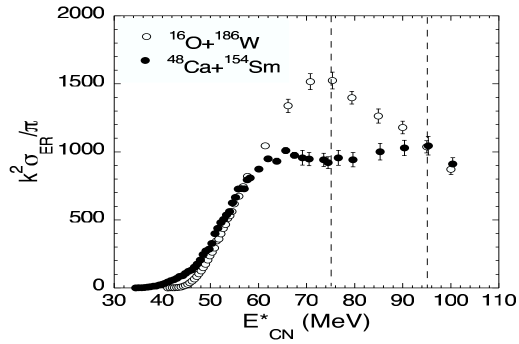

Fig. 4. Reduced ER cross-sections for ^{48}Ca + ^{154}Sm (solid circles) and ^{16}O + ^{186}W (open circles).

25 MeV wide and it clearly shows the presence of barriers lower than the average Bass [21] value (vertical line). Collisions between nuclei producing wide barrier distributions lead to enhanced sub-barrier capture cross-sections; therefore, it may be expected that such collisions may favour the production of heavy elements at low energies. Anyway, such qualitative deduction may change somehow when the QF process comes into play and the reaction dynamics leading to the compact CN is considered.

Statistical model calculations were performed by means of the HIVAP code [22] to predict both ER and FF cross-sections for ^{48}Ca + ^{154}Sm and ^{16}O + ^{186}W. Details on similar calculations performed for ^{48}Ca + ^{168}Er and ^{12}C + ^{204}Pb have been already described [11]. We just mention here that the main parameters of these calculations are the potential barrier fluctuations $\sigma(r_0)/r_0$ around the average reduced radius, which simulate the deformation effects and can be different for the two systems. The second important parameter is the k_f, which is a correction to the liquid drop fission barrier and according to the Bohr hyphothesis should depend only on the compound nucleus. We have determined such k_f by making a best-fit to the cross-sections for ^{16}O + ^{186}W, where QF is not expected. The overall reproduction of data (fig. 3, right panel) is quite satisfactory. But if we use the same k_f parameter for ^{48}Ca + ^{154}Sm (fig. 3, left panel), we overestimate the ER cross-sections and underestimate the cross-section for FF which may contain contributions from QF. Although the capture cross-sections are rather well reproduced for both systems, it seems that something (QF?) is missing from the evaporation channel in ^{48}Ca + ^{154}Sm, causing an hindrance effect.

An alternative and preferable approach to establish if a fusion hindrance effect is really present comes from the comparison of the so-called reduced ER cross-sections [6]. For this purpose, we have to determine which is the threshold CN excitation energy above which the transmission coefficients T_ℓ are close to unity for all partial waves leading to ER. We performed different calculations [14] and established that for our systems such threshold excitation energy is around 75 MeV, as the saturation of the ER yield in ^{16}O + ^{186}W confirms in a model-independent way (see fig. 4).

The experimental reduced ER cross-sections for ^{48}Ca + ^{154}Sm and ^{16}O + ^{186}W are shown in fig. 4. We see that fusion is strongly hindered for ^{48}Ca + ^{154}Sm in comparison with ^{16}O + ^{186}W in the energy range between 75 and 95 MeV, where similar reduced cross-sections are expected. Thus, it is evident that a fusion hindrance effect is present also for a relatively light CN such as ^{202}Pb* if we choose a rather mass-symmetric reaction; and it is confirmed that QF competes with complete fusion even at the low ℓ leading to ER survival.

Even more surprising is the fact that going up to excitation energies $\approx$ 100 MeV this hindrance effect seems to disappear. This could mean that QF at the low ℓ contributing to ER production is no more present and that other processes, such as pre-compound or fast fission, compete with fusion-fission at high ℓ but without affecting the fusion-evaporation mechanism and consequently also the ER cross-sections. It would be interesting if the possible reduction of fusion hindrance effects could be extrapolated to the fusion of very heavy systems. Indeed, if slightly higher excitation energies would really imply a reduction of QF at low ℓ, we could hope to gain some factor in the beamtime needed for observing SHE by increasing the excitation energy, finding a reasonable compromise as far as fusion-fission competition is concerned.

In the representation of the so-called reduced ER cross-sections nothing can be said at low E^*, since below a certain threshold energy the approximation $T_\ell \approx 1$ is no longer valid. Nevertheless, this does not mean that QF is not present at low energies.

A complementary information is given by the FF mass-energy distributions. The onset of QF for ^{48}Ca + ^{154}Sm is indeed confirmed by the presence of an asymmetric component of fission in the FF mass-energy distributions (see fig. 5, right panel). As previously found for ^{48}Ca + ^{168}Er, the results for the ^{48}Ca + ^{154}Sm reaction confirm that the relative yield of the asymmetric component of fission is increasing with the decreasing excitation energy. Therefore, although at low energies we get an enhanced capture cross-section due to the target deformation, the corresponding elongated configuration at capture leads also (and maybe predominantly) to QF and not only to ER formation, in agreement with results previously found for ^{16}O + ^{238}U [23,24].

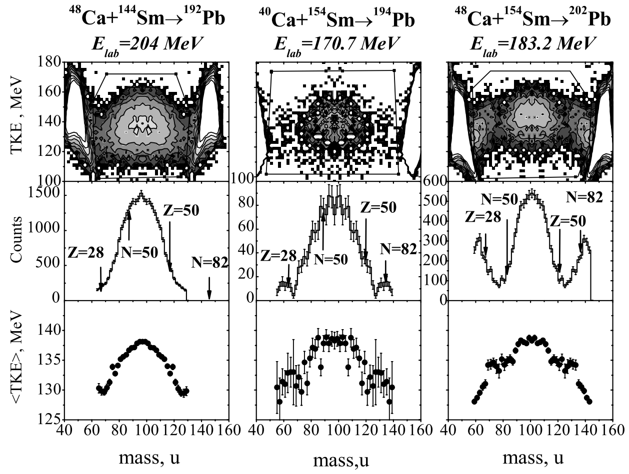

Fig. 5. TKE-mass distribution, mass yield and average TKE *vs.* FF mass for ^{48}Ca + ^{144}Sm, ^{40}Ca + ^{154}Sm and ^{48}Ca + ^{154}Sm at the same excitation energy $E^* = 50$ MeV. QF and fusion-fission events (contours in the upper panels) are distinguishable from deep inelastic and quasi-elastic events ("white wings" on the left and the right, not included in the middle and lower panels). The position of closed shells is indicated by the arrows.

The effect of the target deformation on QF was further investigated by measuring fission fragments in the reactions ^{48}Ca + ^{144}Sm and ^{40}Ca + ^{154}Sm, to be compared with ^{48}Ca + ^{154}Sm. For the two ^{48}Ca induced reactions, a major difference consists in the use of a spherical or deformed target. However, the influence of shell effects is also different for the two reactions: because of the different number of neutrons in the CN, only the population of the lighter fission fragment is affected in the case of ^{48}Ca + ^{144}Sm, instead of both light and heavy fragments as in the case of ^{48}Ca + ^{154}Sm. For ^{48}Ca + ^{144}Sm and ^{40}Ca + ^{154}Sm, leading to near-by CN, shell effects play the same role. Therefore, the main difference between ^{48}Ca + ^{144}Sm and ^{40}Ca + ^{154}Sm lies in the target deformation. For ^{48}Ca + ^{144}Sm we got no evidence of an asymmetric component of fission at any energy [14]. For ^{40}Ca + ^{154}Sm very preliminary results from a partial set of data seem to indicate that an asymmetric component of fission is present. In fig. 5 mass-TKE distributions of FF corresponding to the same excitation energy $E^* = 50$ MeV for the three systems are presented. The results indicate that the target deformation favours the onset of QF.

4 Conclusions

We studied the influence of mass-asymmetry, shell effects and target deformation on the onset of the QF that competes with complete fusion at near-barrier energies and reduces the probability of producing super-heavy elements. The results presented here lead us to the following main conclusions:

– moving towards a relatively light CN characterized by a low fissility such as ^{202}Pb*, we still have evidence of fusion hindrance effects due to QF even at low ℓ populating ER, if a relatively mass-symmetric system like ^{48}Ca + ^{154}Sm is used;
– shell effects play a role in the onset of QF (for a complete discussion on shell effects in heavy and super-heavy elements, see [13]);
– although deformed targets lead to wide barrier distributions, which should favour the production of heavy elements by increasing the sub-barrier capture cross-sections, the target deformation favours the onset of QF.

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