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HEAVY ION PHYSICS

Influence of entrance channel on fusion hindrance and quasi-fission

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Abstract. Recent experimental data showing the interplay between fusion hindrance effects and the onset of the quasi-fission mechanism are presented. The aim of such investigations is understanding the role of entrance channel properties on the competing fusion-fission and quasi-fission processes, also in connection with the possible implications for superheavy element production. In this context, the role of mass asymmetry, nuclear deformation and shell effects is discussed.

Keywords: Fusion hindrance; quasi-fission; entrance channel properties; reaction mechanism features.
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1. Motivation

The recent discovery of new superheavy elements (SHE) [1, 2] has allowed to successfully extend the limits of known elements in the periodic table. In order to push further such limits and to study the chemical properties of SHE, it is crucial to optimize the SHE production rate. This can only be achieved through a deep understanding of the fusion reaction mechanism, and, in particular, of the competition between fusion and quasi-fission (QF) (reseparation before compound nucleus formation [3]) which may inhibit fusion by many orders of magnitude. In this context, it is important to study the dependence of QF on entrance channel properties. Different theoretical approaches have been developed; however, due to the extreme complexity of the process, it is quite difficult to model it in a realistic way.

From an experimental point of view, a systematic study on reactions leading to SHE is of course not feasible. However, reactions leading to heavy nuclei where fusion-fission/quasi-fission competition is already active may be of help. Separating fusion-fission from quasi-fission is a difficult task, since the final reaction products have rather similar properties. Therefore, it is important to collect as many observables as possible to gain insight into the reaction dynamics. Some of the experimental signatures of the QF process are fragment mass distributions broader and angular anisotropies significantly larger than those originating from the statistical fission decay. Complementary information on the presence of QF may be extracted by comparing evaporation residue (ER) yields at sufficiently high excitation energies using entrance channels leading to the same composite system: lower yields in the less asymmetric reaction can be attributed to the fact that the dinuclear system reseparates before the full shape equilibration has been attained.

In this framework, we have started a research program aimed at studying which are the main parameters playing a role in the onset of QF, focusing on the importance of mass asymmetry, nuclear deformation and shell effects (in the exit channel). For this purpose, we populated Pb, Ra and Rn nuclei at comparable excitation energies, using different entrance channels and (in most cases) detecting simultaneously both ER and fission (or fission-like) fragments (FF). Most of the results on reactions studied within this program have already been published [4–10]. In this paper, after a sampling of the main conclusions already drawn from previous studies, we report on the most recent findings.

2. The experiments

Heavy-ion beams (^{12}C, ^{16}O, ^{34}S, ^{40,48}Ca) delivered from the Tandem-ALPI accelerator complex of Laboratori Nazionali di Legnaro were used to bombard highly enriched metallic ^{154,144}Sm, ^{168,170}Er, ^{176}Yb, ^{194}Pt, ^{204,206,208}Pb (50-200 $\mu g/cm^2$) and $^{186}WO_3$ (50 $\mu g/cm^2$) targets. ER and FF were simultaneously detected using an electrostatic deflector [11] coupled to an energy-time of flight (E-TOF) telescope, in conjunction with the double-arm TOF spectrometer CORSET [12]. Details on the experimental setup and procedures can be found in previous works [4–9].

3. Previous findings

Recently, an unexpected inhibition of fusion was observed in relatively light and mass asymmetric entrance channels such as ^{19}F+^{197}Au and ^{30}Si+^{186}W leading to the same composite system ^{216}Ra* [13]. The fusion hindrance, deduced from the comparison at high excitation energies of the reduced ER cross sections $k^2\sigma_{ER}/\pi$ for the two above reactions with those corresponding to ^{12}C+^{204}Pb, was attributed to the onset of QF, as broader FF mass distributions suggested. Our data on ^{12}C+^{204}Pb and ^{48}Ca+^{168}Er [4], also leading to ^{216}Ra*, besides confirming the increase of the fusion hindrance factor with the decreasing entrance channel mass asymmetry, put in evidence the importance of shell effects in the decay of the composite system [10], favoring the formation of closed shell asymmetric fragments which could be observed as "shoulders" in FF mass-TKE distributions [5]. A signature of the onset of QF was obtained from the angular distributions of asymmetric fragments, which presented a much larger anisotropy compared to symmetric fission fragments.

With the aim of studying the onset of QF while moving towards a relatively light compound nucles, we measured fusion-evaporation and fusion-fission cross sections in the ^{48}Ca+^{154}Sm reaction from well below to well above the Coulomb barrier. The comparison of the reduced ER cross sections for ^{48}Ca+^{154}Sm and ^{16}O+^{186}W, both populating ^{202}Pb*, confirmed the presence of a large fusion hindrance effect for the ^{48}Ca induced reaction. A discussion on the interesting competition between the sub-barrier fusion enhancement, due to strong couplings related to the ^{154}Sm deformation, and the above-barrier suppression attributed to QF (at that time on the basis of the presence at all measured energies of an asymmetric component in the FF mass-TKE distributions), may be found in recent papers [8, 9].

4. Recent results

As previously mentioned, the understanding of the reaction dynamics governing a complex process such as quasi-fission requires the collection of many experimental observables. Therefore, in order to look for a further signature of quasi-fission, we recently measured fission fragment angular distributions at different energies for the ^{48}Ca+^{154}Sm reaction. In Fig. 1 the angular distributions of fission-like fragments measured at E_{lab}= 182 MeV (left panel) and 202 MeV (right panel) are reported for selected mass bins. The solid lines correspond to a best-fit to the data (points) obtained using the expression:

$$d\sigma/d\theta = 2\pi sin\theta(a + be^{\beta(\theta-\pi/2)})W(\theta) \qquad (1)$$

where $W(\theta)$ is the angular distribution of fission fragments coming from the compound nucleus decay, β is a slope parameter in an exponential decay function introduced to reproduce the forward-backward asymmetry and a and b are two normalization factors corresponding, respectively, to the symmetric and asymmetric com-

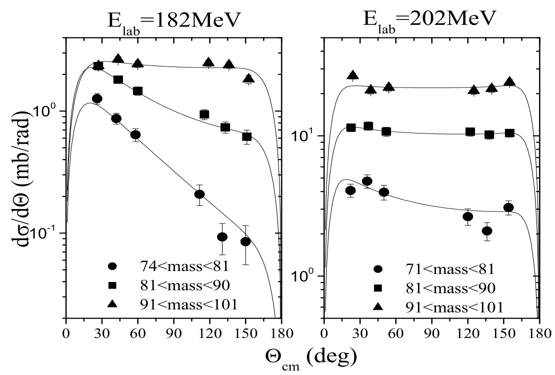

Fig. 1. Angular distribution of fission-like fragments measured for the ^{48}Ca+^{154}Sm reaction in selected fragment mass bins.

ponents of the angular distributions. One can notice that fragments corresponding to a symmetric splitting of the composite system (masses around 90-100) have angular distributions that are symmetric around 90°, as it is to be expected from the compound nucleus decay. At variance, fragments with masses 70-80 present an evident forward-backward asymmetry which is particularly pronounced at lower energies. We notice that at low energies no information about the presence of QF can be inferred from the fusion-evaporation data, since similar reduced ER cross sections for different entrance channels leading to the same compound nucleus are expected only at sufficiently high excitation energies where the transmission coefficients are ≈ 1 for all partial waves leading to ER [13].

With the aim of understanding the influence of nuclear deformation on QF we measured fission cross sections and mass-energy distributions for the two systems ^{48}Ca+^{144}Sm and ^{40}Ca+^{154}Sm, to be compared with ^{48}Ca+^{154}Sm. The choice of ^{48}Ca+^{144}Sm was made in order to "switch out" the nuclear deformation, therefore using a spherical target while keeping the same projectile. However, because of the rather different number of neutrons in the composite system (^{192}Pb vs. ^{202}Pb), shell effects may play a different role for the two reactions. Nevertheless, shell effects may be "singled out" in a comparison of ^{48}Ca+^{144}Sm and ^{40}Ca+^{154}Sm, leading to nearby compound nuclei. Therefore, a comparison of the features of fission-like fragments coming from the three above mentioned reactions may help elucidating the role of nuclear deformation on the onset of QF. In Fig. 2 the mass-TKE distributions, the yields and the average TKE are shown as a function of the fragment mass for the three Ca+Sm reactions, all leading to a composite system with 50 MeV of excitation energy. The arrows indicate the position of the closed shell fragments with Z=28, 50 and N=50,82 in the simple assumption of charge/mass equilibration. Although the ^{40}Ca+^{154}Sm data suffer from poor statistics, it can be noticed that the mass-asymmetric components appear only when the deformed ^{154}Sm target is involved. Therefore, these results suggest that the target deformation favors the onset of QF.

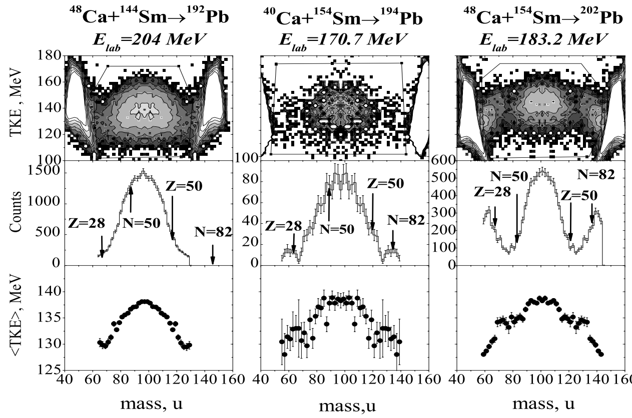

Fig. 2. Mass-TKE distributions, mass yields and average TKE vs. mass of fission-like fragments measured for the ^{48}Ca+^{144}Sm, ^{40}Ca+^{154}Sm and ^{48}Ca+^{144}Sm reactions at the same excitation energy E*=50 MeV.

We notice that, because of the difficulties in separating fusion-fission from QF (and deep inelastic collisions), the most reliable indication of compound nucleus formation is based on the observation of ER. However, if one wants to infer quantitatively the fusion hindrance factor, great attention must be payed. Indeed, at high excitation energies the emission of pre-equilibrium charged particles, by reducing the fissility of the composite system, may increase of orders of magnitude the yields of the final residues. Since part of these residues are coming from processes leading to a composite system with a lower mass, quantitative estimations of fusion hindrance factors (which are meaningful only as far as the same compound nucleus populated via different entrance channels is considered) may not be reliable if deduced from inclusive ER measurements.

One way to overcome this problem is to look at neutron evaporation channels. Such approach has been recently applied to a systematic study of fusion probabilities for Th isotopes produced through many different reactions [14]. It turned out that the fusion probability is strongly affected by the mass asymmetry while the nuclear structure of the colliding nuclei plays a minor role.

Following this line, we recently studied the evaporative decay of ^{210}Rn* produced in ^{34}S+^{176}Yb and ^{16}O+^{194}Pt reactions. We measured both the inclusive ER cross sections with the usual E-TOF technique and the single xn-channels by detecting the characteristic alpha particles emitted. Preliminary results from the E-TOF measurements (see Fig. 3) confirm the presence of fusion hindrance in the entrance channel with lower mass asymmetry. Data analysis is in progress to extract absolute cross sections for individual xn channels.

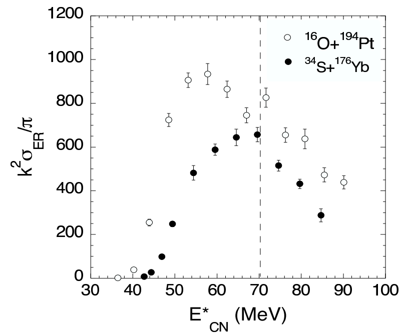

Fig. 3. Reduced ER cross sections for the ^{34}S+^{176}Yb and ^{16}O+^{194}Pt reactions, both leading to ^{210}Rn*, as a function of the compound nucleus excitation energy .

5. Conclusions

We studied the influence of entrance channel properties on QF and fusion hindrance by looking at different experimental observables in reactions populating Pb, Ra and Rn nuclei around the Coulomb barrier. Our results show that the mass asymmetry strongly influences the reaction dynamics, causing an inhibition of fusion in relatively light CN if an entrance channel with a rather low mass asymmetry is chosen. The target deformation seems to favor the onset of QF and the FF mass yields are strongly influenced by shell effects in the exit channel.

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