Cold Valleys in Fusion and Fission

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Abstract

The cold fission configuration after the preformation of the fragments resembles a short-lived dinuclear or quasi-molecular system. The most conceivable scission configuration is given by two fission fragments in touching with the symmetry axes aligned (pole-pole orientation). This conclusion was based on the simple argument that this configuration offers the optimal tunneling time, i.e. the difference between the Coulomb barrier and the decay energy Q is minimal. Other orientations are apparently precluded in cold spontaneous fission and should be regarded as quasi-fission doorways in the synthesis of superheavy elements by cold fusion.

1 Introduction

Since almost three decades it is known that the experimental sub-barrier fusion cross-sections show a substantial enhancement over cross-sections obtained in calculations based on the assumption of a spherical shape for both projectile and target, and a corresponding one-dimensional barrier. Many authors devoted their efforts to the case when the target is deformed and the projectile spherical (see [1] and references therein). Naturally, in the case when the nuclear deformations are switched-on, it is necessary to account for the relative orientation of the projectile and the target in the calculation of the fusion barrier. As concluded in [2] the orientation of the colliding nuclei has a significant effect not only on the fusion barrier height but also on the compactness of the touching configuration.

To characterize the fusion-fission valleys we introduce the driving potential as the difference between the interaction potential and the decay energy $Q = B_{\mathrm{CN}} - B_1 - B_2$ of the reaction

$$V_{\mathrm{driv}} = V(R, \theta_1, \phi_1, \theta_2, \phi_2) - Q \tag{1}$$

B_1, B_2 and B_{CN} are the binding energies of the projectile, target and compound superheavy nucleus. The heavy-ion interaction potential is calculated in the double-folding method and depends on the distance R between the centres of the two nuclei and the angles ϕ_i, θ_i $(i = 1, 2)$ which are specifing the orientation in space of the nuclei.

Next the driving potential of a given compound nucleus is calculated for all possible projectile-target combinations as a function of the mass and charge asymmetries, $\eta = (A_1 - A_2)/(A_1 + A_2)$ and $\eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2)$ at the barrier distance $R_{\rm bar}$. The charges of the target and the projectile are determined by requiring for a fixed η that the driving potential $V_{\rm driv}(R, \eta, \eta_Z)$ attains a minimum in the η_Z direction, i.e. for every fixed mass pair (A_1, A_2) a single pair of charges is determined among all possible combinations. Next, minimas of the potential in the two-dimensional (R, η) landscape are searched. In ref. [3] it was inferred a criterion for cold fusion, i.e. the deep minima of the driving potential are corresponding to the projectile-target combinations where the compound nucleus has a minimum of excitation and will de-excite to the ground-state with the emission of a couple of neutrons. The occurence of the mass-asymmetry valleys is due to the shell effects. It was advocated in ref. [4], using the frame of the fragmentation theory, that due to the existence of different mass-asymmetry valleys for the same compound system, a new, highly asymmetric fission mode appears in which one of the fragments is close to the double magic nucleus ^{208}Pb. This new type of decay was later on confirmed experimentally and is known in the literature as cluster radioactivity [5].

The possible formation of superheavy nuclei with $Z = 102 - 122$ in reactions with ^{22}Ne, ^{26}Mg, ^{48}Ca, ^{58}Fe and ^{86}Kr ions at energies near and below the Coulomb barrier has been studied at FLNR-JINR Dubna [6]. Along with other relevant quantities the mass distributions of fission fragments was determined. The nuclei ^{256}No, ^{286}112, ^{292}114 and ^{296}116 have been produced in reactions with ^{48}Ca at the same excitation energy E^*=33 MeV. The main pecularity of the data is that the quasi-fission mechanism is dominating in the case of the decay of the nuclei ^{286}112, ^{292}114 and ^{296}116. The mass distribution of quasi-fission products was found to be asymmetric with the peak of the lighter fragment located at $A_1 \approx 80$ for the superheavy nucleus ^{286}112, $\approx$ 84 for the superheavy nucleus ^{292}114 and $\approx$ 86 for ^{296}116. The authors also claimed that despite the dominating contribution of the quasi-fission process, in the symmetric region of fission fragment masses ($A_{CN}/2\pm20$) the process of compound nucleus(CN) fission is prevailing. Indeed in the light fragment mass-distribution a small and weakly asymmetric bump occurs (see Fig.1 of [6]). For all three superheavy nuclei the light fragment mass is centered around $A_1 = 132 - 134$. The nucleus ^{296}116 presents another pecularity : an additional bump centered on $A_1 = A_{CN}/2$, i.e. a totally symmetric distribution of decay products.

2 Cold Valleys of ^{286}112 and ^{296}116.

In Fig.2 a cut along the mass-asymmetry coordinate of the driving potential of the superheavy nucleus ^{112}286 is given. From the inspection of this figure we remark the differences in the driving potential when the target and the projectile are colliding with different orientations. The Ca-valley (with heavy partner U) is more pronounced when the fragments are coming in contact in $e-e$ or $e-c$ orientations. The valleys corresponding to the cluster radioactivity (superasymmetric valleys) are occuring with some differences: for $p-p$, the most pronounced are centered on ^{14}C, ^{22}Ne and ^{28}Mg, whereas for $e-c$ we remark ^{24}Ne, ^{30}Mg and ^{34}Si.

For $p-p$ oriented fragments the valley centered on ^{62}Cr is separated by a high barrier from what we call the Pb-valley, centered on ^{76}Zn and ^{80}Ge, and obviously for such configurations the tendency of the initial cold strong asymmetric system to move in the symmetric direction, before undergoing quasi-fission, is hindered.

The $p-e$ orientation presents features common to the $p-p$ but also to the $e-e$ and $e-c$ orientations. Similar to the $p-p$ case, the valley for Ca is less pronounced and the Mo-valley is broader and the target ^{96}Sr will give a minimum in the potential for this orientation.

For the $e-e$ orientation we deal with three important valleys: the Ca-valley, the Pb-valley,centered on ^{80}Ge and the Sn-valley centered mainly on ^{134}Te. As can be seen in Fig.2 this last valley is common also to the $p-p$ orientation and is assigned in the FLNR-Dubna experiment to events emerging from the fusion-fission process. On the other hand between the Pb-valley and the Sn-valley a huge barrier is showing up which determines an even stronger hindrance to symmetric quasi-fission compared to $p-p$ orientation. The Pb-valley, which is very pronounced, is centered on the same light fragment mass numbers as the mass distribution reported in [6] and assigned to quasi-fission.

Making the association $p-p$ *deepest valley* → *maximum cold fission yield*, which seems to be valide in the case of ^{252}Cf, we infer that the occurence of light fragments with masses around A_1=132-134 can be due also to the fission of the compound superheavy nucleus ^{286}112. On the other hand the quasi-fission mass distribution seems to be explained by means of the prevailance of an orientation close to the $e-e$ one. In the entrance channel we have a stable Ca-valley in the $e-e$ scenario. Since the closest valley from this one is the Pb-valley, then we expect the highest quasi-fission yields to correspond to a region around $A_1 \approx 80$. Since the excitation energy produced in the reaction ($E^* \approx 33$ MeV) is large enough such that a part of the flux moving in the symmetric region reaches the weak asymmetric valley of Sn and subsequently decay, we do not exclude that a part of the bump recorded in experiment, and assigned to the fusion-fission, is contaminated to a certain extent with quasi-fission events.

In the case of the superheavy nucleus $^{296}116$ the driving potential is qualitatively very similar to the one corresponding to $^{286}112$ (see Fig.3). There are however some differences. the minimas of the velleys are shifted towards higher values of the mass. in the $e-e$ orientation the Pb-valley is centered around $A_1 \approx 86$ whereas the Sn-valley remains almost unchanged. Instead the deepest $p-p$ valley is now centered on the symmetric region and the fragmentations with light mass number 132-134 are contributing, at least for low excitation energy, with yields smaller than in the preceeding case.

The additional bump recorded in experiment for $^{296}116$ and centered on the symmetric region is, in the light of our calculations, a good candidate for fusion-fission signature. However the weak asymmetric yields centered on $A_1 \approx$132-134 could be , like in the case of $^{286}112$, an admixture of quasi-fission and fusion-fission events.

3 Conclusions

Binary cold spontaneous fission is a rearrangement process of the mother nucleus in two fragments with a minimum of energy dissipation. The decaying system tends to choose an optimum path in which the emerging fragments are oriented pole to pole. Only for such a configuration the mass distribution observed in experiment can be understand. The Fragmentation Theory used in the past to obtain the best projectile-target combinations in order to synthesise superheavy elements is also able to give the qualitative mass distribution in cold fission.

The $p-p$ orientation produces no valley in the mass region where high quasi-fission yields are observed, confirming thus the conclusion of the authors of [6]. On the other hand the bumps observed in the weak asymmetric region with light fragment masses $A_1 \approx$132-134 are not necessarily entirely due to the decay of the CN, a contamination with quasi-fission fragments being possible according to our opinion.

We conclude that the inclusion of excitation energy around 33 MeV, as occurs in the synthesis reactions with ^{48}Ca, is not diminishing the importance of the main $p-p$ cold valley in favor of other valleys. Obviously, at a comparable excitation energy the fission mass distribution obtained in the experiment [6] does not follow the pattern of the $p-p$ valleys. For the moment it is difficult to draw firm conclusions about the apparent unimportance of the $p-p$ configurations but only to make speculations. A possible answer to this puzzle would be that the claimed fusion-fission events in the symmetric mass region are belonging, at least partially, to the quasi-fisson process, when configurations others than the $p-p$ one are important. Then, if nuclei like Mo and Zr would be recorded in the mass distribution yields, and actually a small bump of Mo is measured following the synthesis reaction with ^{48}Ca [7], this could indicate in our opinion the recording of compound nucleus fission events. The small bump observed in the mass-symmetric region for ^{296}116 is likely to be due to the fission of the compound nucleus.

Acknowledgement

The author would like to acknowledge the financial support from the European Community through a Marie Curie fellowship.

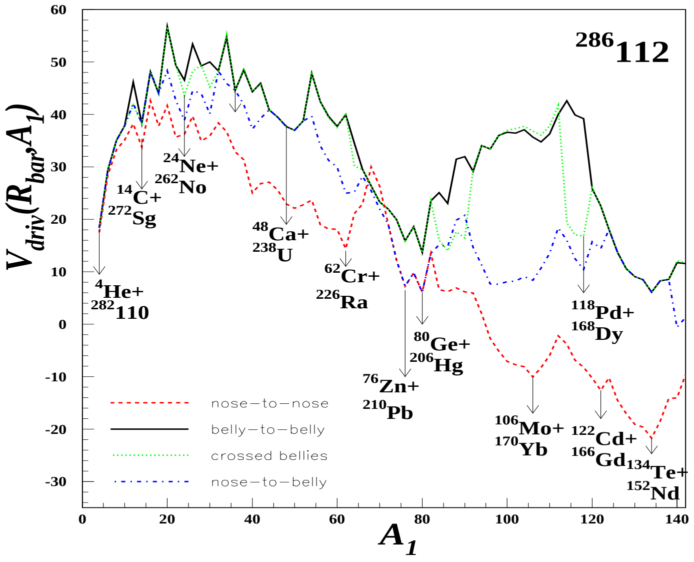

Fig. 2: Driving potential as a function of the projectile mass A_1 for the superheavy nucleus ^{286}112. The driving potential along the A_1-coordinate at $R = R_{\text{barier}}$ is represented for spherical fragments (full line), for deformed fragments oriented in nose-to-nose configuration (full line), belly-to-belly (full line), crossed bellies (dotted lines) and nose-to-belly(dot-dashed).

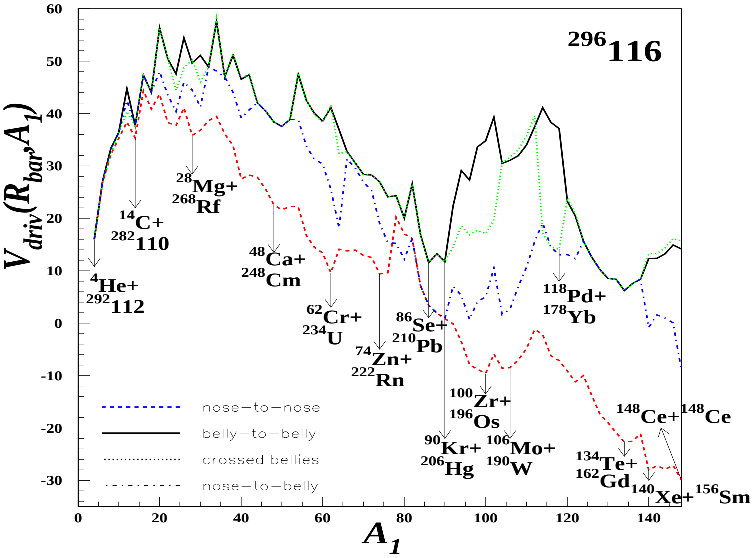

Fig. 3: Same as in previous figure for the superheavy nucleus ^{296}116.

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