Fission barriers in the quasi-molecular shape path

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The fission barriers standing in the quasi-molecular shape path have been determined within a generalized liquid drop model taking into account the nuclear proximity energy, the mass and charge asymmetry and an accurate nuclear radius. The barrier heights agree with the experimental symmetric and asymmetric fission barrier heights. The half-lives of the alpha and light nucleus decay and cluster radioactivity are reproduced within a tunneling process through these barriers. Rotating highly deformed states exist in this path. The entrance and exit channels governing the superheavy nucleus formation and decay have been investigated.

1. Quasi-molecular shape path

New observed phenomena like asymmetric fission of intermediate mass nuclei, nuclear molecules in light nuclei, super and hyperdeformations, cluster radioactivity, fast-fission of heavy systems and fragmentation have renewed interest in investigating the fusion-like fission valley and quasi-molecular shapes. Furthermore, rotating super and hyperdeformed nuclear states and superheavy nuclei can be formed only in heavy-ion collisions for which the initial configuration is two close quasi-spherical nuclei. The selected shape sequence, two joined elliptic lemniscatoids, is displayed in figure 1. Analytical formulae are available for the main shape-dependent functions.

2. Generalized Liquid Drop Model

For these shapes the balance between the Coulomb forces and surface tension forces does not allow to link the sheets of the potential energy surface

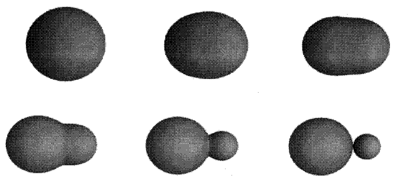

Figure 1. Selected shape sequence to simulate the fission, the cluster and alpha decay paths. The nuclei are spherical when they are separated.

corresponding respectively to one-body shapes and to two separated fragments. It is necessary to add another term called proximity energy reproducing the finite-range effects of the nuclear force in the neck or the gap between the nascent fission fragments.

A Generalized Liquid Drop Model has been developped to take into account both this nuclear proximity energy, the mass and charge asymmetry, an accurate nuclear radius and the temperature effects[1]. The initial value of the surface energy coefficient has been kept. Microscopic corrections have been determined within the asymmetric two center shell model or simpler algebraic approximations[2].

3. Symmetric and asymmetric fission barriers

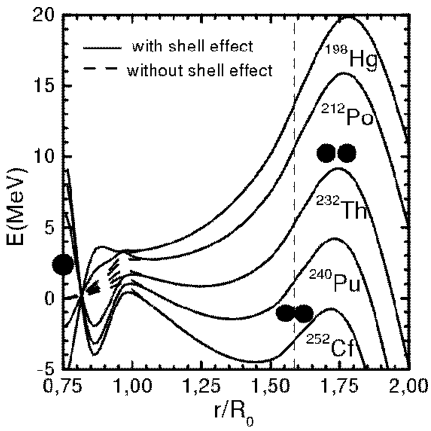

Figure 2. Potential barriers with and without shell effects for the symmetric fission of ^{198}Hg, ^{212}Po, ^{232}Th, ^{240}Pu and ^{252}Cf versus the mass center distance.

In this deformation valley the barrier top corresponds to two separated fragments maintained in unstable equilibrium by the balance between the repulsive Coulomb forces and the attractive nuclear proximity forces. With increasing mass the proximity forces induce progressively an inflexion in the curve and double-humped barriers appear naturally for actinides (see figures 2 and 3). The heights of the potential barriers[3] agree with the experimental fission barrier heights, in particular for the asymmetric fission of $^{70,76}Se$, ^{75}Br, $^{90,94,98}Mo$, $^{110,112}In$, ^{149}Tb and ^{194}Hg.

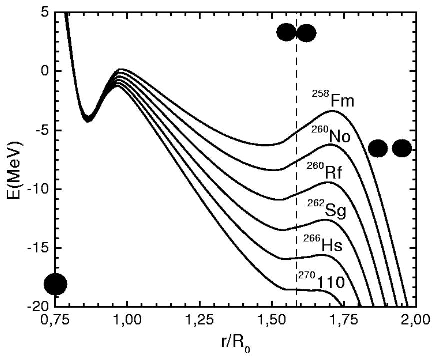

Figure 3. Potential barriers including shell effects for the symmetric fission of ^{258}Fm, ^{260}No, ^{260}Rf, ^{262}Sg, ^{266}Hs and $^{270}110$.

4. Half-lives of the alpha decay and light nucleus emission

The partial half-lives for the α and light nucleus emission have been determined from the WKB barrier penetration probability as for a spontaneous asymmetric fission, without adjustable preformation factor[4,5]. The barriers have been adjusted to reproduce the experimental Q value (see figures 4 and 5). The agreement between the theoretical and experimental data of $Log_{10}[T_{1/2}(s)]$ for 373 α emitters is very good as for the emission of ^{14}C, ^{20}O, ^{23}F, $^{24,26}Ne$, $^{28,30}Mg$ and ^{32}Si by isotopes of Fr, Ra, Ac, Pa, Th, U and Pu. Analytic formulae are proposed for the partial half-lives and predictions for the α decay of superheavy elements have been proposed[6].

5. Super and hyperdeformed rotating nuclei

Within this GLDM, the two-center shell model and the Strutinsky method or the algebraic droplet model shell corrections, normal, super and highly deformed minima appear in different angular momentum ranges. The first

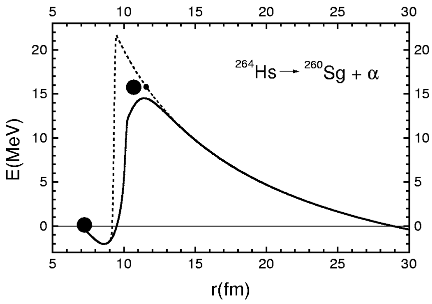

Figure 4. Potential barrier including empirical microscopic corrections against emission of α from the ^{264}Hs parent nucleus. The dashed and solid lines correspond respectively to the deformation energy without and with a nuclear proximity energy term.

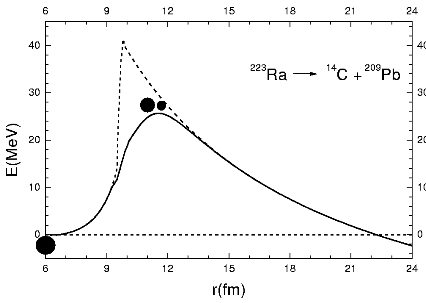

Figure 5. Potential barrier against emission of ^{14}C from the ^{223}Ra parent nucleus.

minimum has a pure microscopic origin. At intermediate spins, both the shell corrections and the proximity energy contribute to form the second potential pocket while, for the highest angular momenta, the persistence of a highly deformed minimum is mainly due to the proximity forces that prevent the negotiating of the scission barrier. The results for the quadrupole moment, the moment of inertia and the excitation energy[7] agree roughly with the data obtained recently on the superdeformed bands in ^{40}Ca, ^{44}Ti, ^{48}Cr, ^{56}Ni, ^{84}Zr, ^{132}Ce, ^{152}Dy and ^{192}Hg. Predictions are given for the ^{126}Ba nucleus presently under investigation (see figure 6).

6. Very heavy elements

The heaviest elements decay via α emission and the predictions of the half-lives given by the formulas derived from the GLDM agree well with the data when the selected theoretical Q_α is the one proposed by a recent version

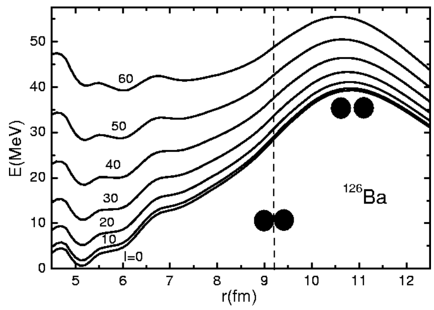

Figure 6. Sum of the deformation and rotational energies for ^{126}Ba as functions of the angular momentum ($\hbar$ unit) and the distance r between the mass centers. The vertical dashed line indicates the transition from one-body to two body shapes (r=9.2 fm).

of the Thomas-Fermi model[6]. The fission barriers are one-humped barriers since the nuclear proximity forces can no more compensate for the high repulsive Coulomb forces. Due only to shell effects the barrier height can still reach 5 MeV, the value of the next proton magic number playing a major role (see figure 7).

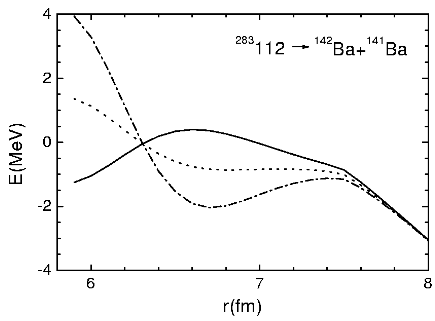

Figure 7. Symmetric fission barriers for ^{283}112. The full line, dotted curve and dashed and dotted curve include the shell effects given by the Droplet Model assuming respectively a proton magic number of 114, 120 and 126.

The potential barriers governing the entrance channel leading possibly to superheavy elements have been investigated with this model. For moderately asymmetric reactions (cold fusion reactions : ^{64}Ni, ^{70}Zn, ^{76}Ge, ^{82}Se, ^{86}Kr on ^{208}Pb) double-hump potential barriers stand and fast fission of compact shapes in the outer well is the main exit channel. Very asymmetric reactions (warm fusion reactions : ^{48}Ca on ^{238}U, ^{244}Pu or ^{248}Cm) lead to one hump barriers which can be passed only with an energy much higher than the ground state energy of the superheavy element. Then, only emission of several neutrons or an α particle can stabilize the nuclear system and allows to reach a ground state. The formation of superheavy elements via almost symmetric reactions is hardly likely (see figure 8).

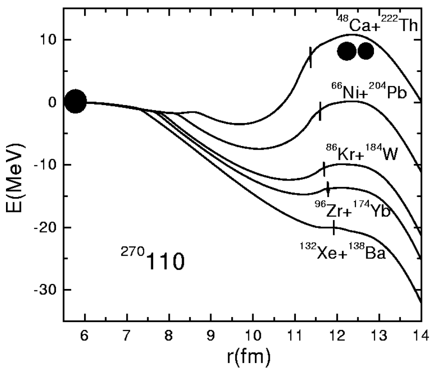

Figure 8. Potential barriers for different reactions leading to the $^{270}110$ nucleus. r is the distance between mass centres. The vertical bar corresponds to the contact point.

7. Conclusion

The potential barriers appearing in the quasi-molecular shape path have been investigated within both a Generalized Liquid Drop Model taking into account the interaction energy between the close nucleons when a deep neck or a gap exists and the shell corrections. The main characteristics of the symmetric and asymmetric fission, the light nucleus and α emissions, the highly deformed rotating states and the superheavy formation and decay can be described in this fusion-like deformation path.

References

1. G. Royer and B. Remaud, *J. Phys. G: Nucl. Phys* **10**, 1057 (1984).
2. R. A. Gherghescu and G. Royer, *Phys. Rev.* **C68**, 014315 (2003).
3. G. Royer and K. Zbiri, *Nucl. Phys.* **A697**, 630 (2002).
4. G. Royer, *J. Phys. G: Nucl. Part Phys* **26**, 1149 (2000).
5. G. Royer and R. Moustabchir, *Nucl. Phys.* **A683**, 182 (2001).
6. G. Royer and R. A. Gherghescu, *Nucl. Phys.* **A699**, 479 (2002).
7. G. Royer, C. Bonilla and R. A. Gherghescu, *Phys. Rev.* **C67**, 34315 (2003).