ELSEVIER

Nuclear Physics A734 (2004) 164–167

NUCLEAR PHYSICS A

www.elsevier.com/locate/npe

Fusion-fission dynamics of super-heavy element formation and decay

V.I. Zagrebaev[a]

[a]Flerov Laboratory of Nuclear Reaction, JINR, Dubna, 141980, Moscow region, Russia

Formation dynamics of very heavy compound nuclei taking place in strong competition with the process of quasi-fission is discussed. For the first time a common driving potential is defined in the whole configuration space and used for simultaneous description of the whole evolution process starting from approaching of two heavy nuclei and ending in compound nucleus configuration of the system and/or in fission channels (normal and fast) with formation of fission fragments. Theoretical analysis of available experimental data on the "cold" and "hot" fusion-fission reactions was performed and the corresponding cross sections of super-heavy element formation were calculated up to $Z_{CN} = 120$.

1. CAPTURE, FUSION, AND EvR FORMATION CROSS SECTIONS

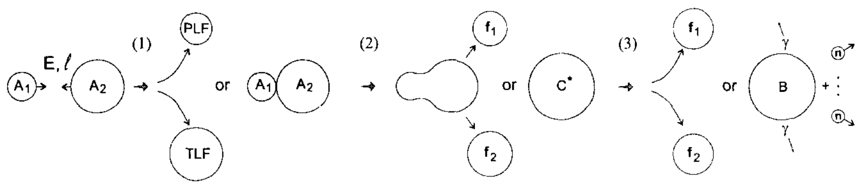

Figure 1. Schematic picture of super-heavy nucleus formation.

The process of a cold residual nucleus formation is shown schematically in Fig. 1. A whole process can be divided into three reaction stages. At the first stage, colliding nuclei overcome the Coulomb barrier and approach the point of contact. Quasi-elastic and deep-inelastic reaction channels dominate at this stage leading to formation of projectile-like and target-like fragments (PLF and TLF) in the exit channel. Denote the corresponding probability as $P_{cont}(l, E)$. At the second reaction stage touching nuclei evolve into the configuration of an almost spherical compound mono-nucleus. After dynamic deformation and exchange by several nucleons, two touching heavy nuclei may re-separate into PLF and TLF or may go directly to fission channels without formation of compound nucleus. The later process is usually called quasi-fission. Denote a probability for two touching nuclei to form the compound nucleus as $P_{CN}(l, E)$. At the third reaction stage the compound nucleus emits neutrons and γ rays lowering its excitation energy and forming finally the residual nucleus in its ground state. This process takes place in strong competition with a regular fission, and the corresponding survival probability $P_{xn}(l, E^*)$ is usually much less than unity even for a low-excited super-heavy nucleus.

doi:10.1016/j.nuclphysa.2004.01.025

The formation cross section of a cold residual nucleus B, which is the product of neutron evaporation and γ emission from an excited compound nucleus C, formed in the fusion process of two heavy nuclei $A_1 + A_2 \to C \to B + xn + N\gamma$ at c.m. energy E close to the Coulomb barrier in the entrance channel, can be decomposed over partial waves and written as

$$\sigma_{ER}^{xn}(E) \approx \frac{\pi\hbar^2}{2\mu E}\sum_{l=0}^{\infty}(2l+1)P_{cont}(E,l)\cdot P_{CN}(A_1+A_2\to C;E,l)\cdot P_{xn}(C\to B;E^*,l). \quad (1)$$

Semi-empirical [1] and/or channel coupling approaches [2,3] may be used to calculate rather accurately a penetrability of the multi-dimensional Coulomb barrier $P_{cont}(l,E)$ and the corresponding capture cross section. The survival probability $P_{xn}(l,E^*)$ of an excited compound nucleus can be also calculated rather accurately within a statistical model [4,1]. The most uncertain parameter here is the height of the fission barrier. Unfortunately, the fission barriers of super-heavy nuclei calculated within the different approaches differ greatly (by several MeV). However, experimental estimation of these barriers is still possible [5] The processes of the compound nucleus formation and quasi-fission are the least studied stages of heavy ion fusion reaction. Today there is no consensus for the mechanism of the compound nucleus formation itself, and quite different, sometimes opposite in their physics sense, models are used for its description.

2. TWO-CORE MODEL

In [6,7] a new approach was proposed for description of fusion-fission dynamics based on a semi-empirical version of the two-center shell model idea [8]. It is assumed that on a path from the initial configuration of two touching nuclei to the compound nucleus configuration and on a reverse path to the fission channels the nuclear system consists of two cores (Z_1, N_1) and (Z_2, N_2) surrounded with a certain number of common (shared) nucleons $\Delta A = A_{CN} - A_1 - A_2$ moving in the whole volume occupied by the two cores. The processes of compound nucleus formation, fission and quasi-fission take place in the space $(Z_1, N_1, \delta_1; Z_2, N_2, \delta_2)$, where δ_1 and δ_2 are the dynamic deformations of the cores. The compound nucleus is finally formed when the elongation of the system becomes shorter than a saddle point elongation of CN.

Within this two-core model the corresponding fusion-fission driving potential $V_{fus-fis}(R, Z_1, N_1, \delta_1; Z_2, N_2, \delta_2)$ was derived and was found to be close to the two-center shell model potential energy at $R < R_{cont}$ [6]. Nevertheless, there are several advantages of the proposed approach. The driving potential is derived basing on experimental binding energies of two cores, which means that the "true" shell structure is taken into account and, thus, for well separated nuclei (large values of R) $V_{fus-fis}$ gives an *explicit* values of nucleus-nucleus interaction. For the first time the fusion-fission driving potential is defined in the whole region $R_{CN} < R < \infty$, it is a continuous function at $R = R_{cont}$, it gives the realistic Coulomb barrier at $R = R_B > R_{cont}$ and may be used for simultaneous description of the whole fusion-fission process. At last, along with using the variables $(Z_1, N_1; Z_2, N_2)$, one may easily recalculate the driving potential as a function of mass asymmetry $(A_1 - A_2)/(A_1 + A_2)$ and elongation $R_{12} = r_0(A_1^{1/3} + A_2^{1/3})$ (at $R > R_{cont}$, $R_{12} = R = s + R_1 + R_2$, where s is the distance between nuclear surfaces). These variables along with deformations δ_1 and δ_2 are commonly used for description of fission process.

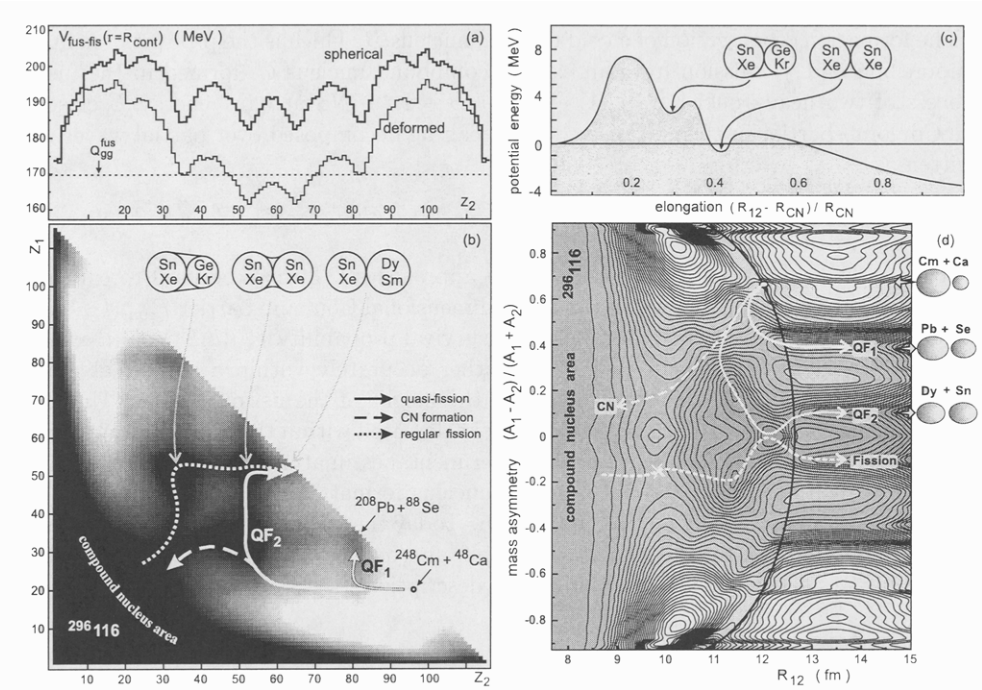

Figure 2. Driving potential $V_{fus-fis}$ of the nuclear system consisting of 116 protons and 180 neutrons. (a) Potential energy of two touching nuclei at $A_1 + A_2 = A_{CN}$, $\Delta A = 0$, i.e., along the diagonal of the lower figure, which corresponds to the black solid curve on the right-bottom panel. Topographical landscape of the driving potential on the plane $(Z_1 - Z_2)$ (b) and on the (mass asymmetry - elongation) plane (d). The dark regions correspond to the lower potential energies. The dashed, solid, and dotted curves with arrows show fusion, quasi-fission, and regular fission paths, respectively. (c) Three humped fission barrier calculated along the fission path (dotted curve).

As can be seen from Fig. 2, the shell structure, clearly revealing itself in the contact of two nuclei, is also retained at $R < R_{cont}$ (see the deep minima in the regions of $Z_{1,2} \sim 50$ and $Z_{1,2} \sim 82$ in Fig. 2b). Following the fission path (dotted curves in Fig. 2b,d) the system overcomes the multi-humped fission barrier (Fig. 2c). The intermediate minima correspond to the shape isomer states. From analysis of the driving potential (see Fig. 2b) we may definitely conclude now that these isomeric states are nothing else but two-cluster configurations with magic or semi-magic cores.

Using the driving potential $V_{fus-fis}$ one may determine the probability of the compound nucleus formation P_{CN}. It can be done, for example, by solving the master equation for the distribution function $F(Z_1, N_1, Z_2, N_2, \delta_1, \delta_2; t)$ [6,7]. The probability of the compound nucleus formation is defined as an integral of the distribution function over the region $R < R_{saddle}$. Similarly one can define the probabilities of finding the system in different quasi-fission channels, i.e., the charge and mass distributions of the fission fragments.

3. CROSS SECTIONS OF SHE FORMATION

Calculated in that way the capture, fusion, and SHE formation cross sections for the "cold" and "hot" fusion reactions leading to EvRs with $Z \geq 102$ can be found in [9]. In Fig. 3 the calculated excitation functions for production of super-heavy nuclei in reactions induced by ^{48}Ca are shown for 2n÷5n channels. In the calculations the shell corrections to the ground state energies of super-heavy nuclei proposed by P. Möller *et al.* [10] were used to estimate the corresponding fission barriers. From obtained results one may conclude that the "hot" fusion reactions can be successfully used at existing facilities for a synthesis of super-heavy nuclei with Z up to 120. The preferable beam energy corresponds to about 40 MeV of CN excitation energy with detection of 3n and/or 4n evaporation products, i.e. it should be slightly higher than those used in the previous experiments [11].

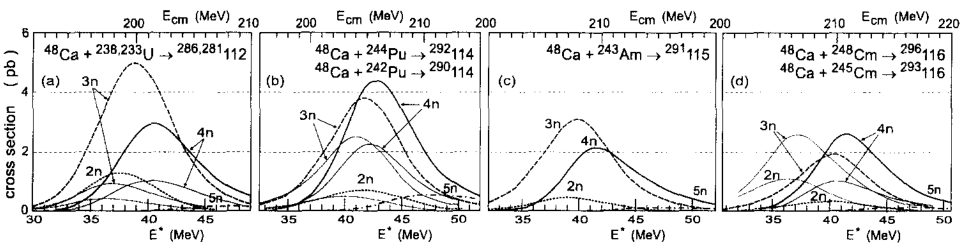

Figure 3. Calculated excitation functions of super-heavy element formation in the fusion reactions induced by ^{48}Ca. Thin curves correspond to lighter isotopes (lower energy scale).

REFERENCES

1. V.I. Zagrebaev, Y. Aritomo, M.G. Itkis, Yu.Ts. Oganessian, and M. Ohta, Phys.Rev. C **65** (2002) 014607.
2. K. Hagino, N. Rowley, A.T. Kruppa, Comp. Phys. Commun., **123** (1999) 143.
3. V.I. Zagrebaev and V.V. Samarin, JINR report No. P7-2003-32, Dubna, 2003; CC fusion code of the NRV: http://nrv.jinr.ru/nrv.
4. A.V. Ignatyuk, *Statistical properties of excited atomic nuclei*, Energoatomizdat, Moscow, 1983.
5. M.G. Itkis, Yu.Ts. Oganessian, and V.I. Zagrebaev, Phys.Rev. C **65**, 044602 (2002).
6. V.I. Zagrebaev, Phys.Rev. C **64** (2001) 034606.
7. V.I. Zagrebaev, J.Nucl.Radiochem.Sci. **3**, No. 1 (2002) 13.
8. U. Mosel, J. Maruhn, and W. Greiner, Phys.Lett. B **34** (1971) 587; J. Maruhn and W. Greiner, Z.Physik, **251** (1972) 431.
9. V.I. Zagrebaev, M.G. Itkis, and Yu.Ts. Oganessian, Yad. Fiz., **66**, No.6 (2003) 1069 [Phys. At. Nucl., **66**, No.6 (2003) 1033].
10. P. Möller, J.R. Nix, W.D. Myers, W.J. Swiatecki, At.Data Nucl.Data Tables **59** (1995) 185.
11. Yu.Ts. Oganessian et al., Phys.Rev. C **62** (2000) 041604(R); Phys.Rev. C **63** (2001) 011301(R).