SCIENTIFIC REPORT

Project PCE_2011-3-0050 Contract 43/05.10.2011

concerning the project implementation during the period January–December 2015

Spontaneous fission of superheavy nuclei

In a fiision process a parent nucleus deforms becoming longer, then a neck appears and it breaks up into two fragments, usually with different masses. In a "static" approach one would expect that fission "trajectory (or path)" is determined by the minima of deformation energy, E_{def}.

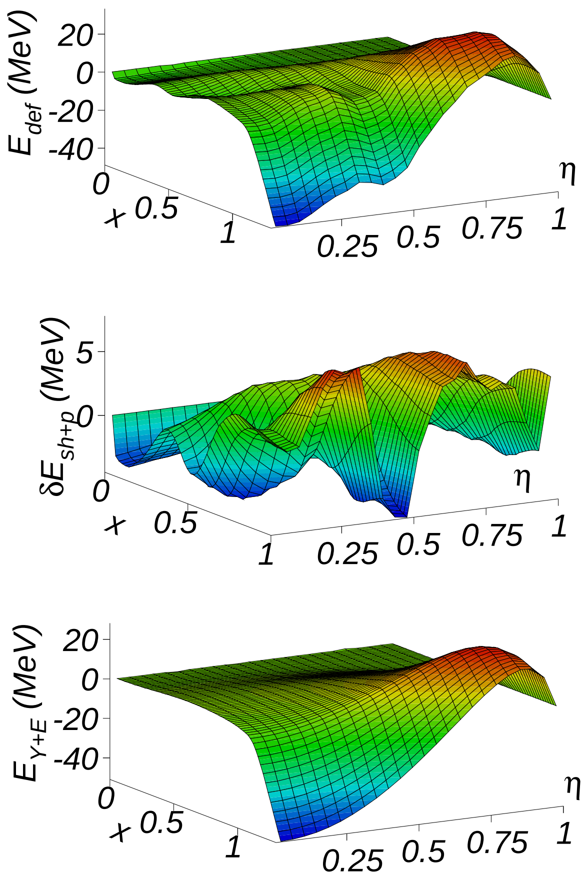

Figure 1: PES of ^{286}Fl vs $(R-R_i)/(R_t-R_i) \geq 0$ and $\eta = (A_1 - A_2)/(A_1 + A_2)$. Y+EM (bottom), Shell + Pairing corrections (center), and total deformation energy (top).

Strutinsky introduced his macroscopic-microscopic method in 1967 by adding to the macroscopic deformation energy (e.g. given by Yukawa plus Exponential model (Y+EM), shell and pairing corrections calculated based on the proton and neutron energy levels of a single-particle shell model (e.g. the asymmetric two center shell model (ATCSM) [1])

$$E_{def} = E_{Y+E} + \delta E \ ; \quad \delta E = (\delta U + \delta P)_p + (\delta U + \delta P)_n \qquad (1)$$

An example for fission of ^{286}Fl is given in figure 1. For pairing corrections, δP, we find solutions λ and Δ of a system of two BCS (Bardeen, Cooper, Schrieffer) equations.

A typical potential barrier shape of heavy and superheavy nuclei with two humps is given in figure 2. Barrier tunnelling was for the first time studied by G. Gamow in 1928 for α decay. We

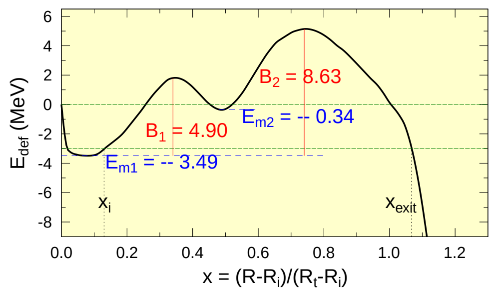

Figure 2: Deformation energy of ^{286}Fl symmetrical fission. Important characteristics of the two humped barrier: first and second minima, E_{m1}, E_{m2}, first and second barrier height, B_1, B_2, and the two turning points, x_i, x_{exit}.

have to study the dynamics of fission process, in which one have not only the deformation energy E_{def} but also the nuclear inertia tensor B.

Within WKB (Wentzel–Kramers–Brillouin) quasiclassical approximation the half-life of a parent nucleus AZ against the split into a light fragment A_2Z_2 and a heavy fragment A_1Z_1 is given by

$$T = [(h \ln 2)/(2E_v)]exp(K_{ov} + K_s) \quad (2)$$

where the action integral is expressed as

$$K = \frac{2\sqrt{2m}}{\hbar} \int_{R_a}^{R_b} \{[(B(R)/m)][E_{def}(R) - E_{def}(R_a)]\}^{1/2} dR \quad (3)$$

with $B =$ the cranking inertia, $K = K_{ov} + K_s$, and the $E(R) = E_{def}$ potential energy of deformation. R_a and R_b are the turning points of the WKB integral where $E_{def} = E_{def}(R_a) = E_{def}(R_b)$. The two terms of the action integral K, correspond to the overlapping (K_{ov}) and separated (K_s) fragments.

The least action trajectory is the one along which the action integral has a minimum value. We studied two kinds of parametrization of ^{286}Fl nucleus: *1) twodimensional* (R, η) with R separation distance of the fragments and $\eta = (A1 - A2)/A$ the mass asymmetry. In this case the radius of the light fragment R_2 decreases exponentially towards the final value $R_2f = 1.16A_2^{1/3}$ and *2) onedimensional*, in which $R_2 = R_2f =$ constant.

According to the cranking model, introduced by Inglis, the components B_{ij} of the inertia tensor ar given by

$$B_{ij} = 2\hbar^2 \sum_{\nu\mu} \frac{\langle\nu|\partial H/\partial\beta_i|\mu\rangle\langle\mu|\partial H/\partial\beta_j|\nu\rangle}{(E_\nu + E_\mu)^3} (u_\nu v_\mu + u_\mu v_\nu)^2 \quad (4)$$

where H is the single-particle Hamiltonian allowing to determine the energy levels and the wave functions $|\nu\rangle$, u_ν, v_ν are the BCS occupation probabilities, E_ν is the quasiparticle energy and β_i, β_j are the independent shape coordinates. Again we follow the procedure for proton and neutron levels and the final result is obtained by adding the two contributions. For two independent shape coordinates we have

$$B(R) = B_{RR}(R, R_2) + 2B_{RR_2}\frac{dR_2}{dR} + B_{R_2R_2}\left(\frac{dR_2}{dR}\right)^2 = B_{11} + B_{12} + B_{22} \quad (5)$$

where $B_{11} = B_{RR}$, $B_{12} = 2B_{RR_2}\frac{dR_2}{dR}$, $B_{22} = B_{R_2R_2}\left(\frac{dR_2}{dR}\right)^2$.

Calculating the cranking inertia tensor

An example of variation with $x = (R - R_i)/(R_t - R_i)$ and η is given in figure 3. For only one deformation parameter, R, $B(R) = B_{RR}(R)$.

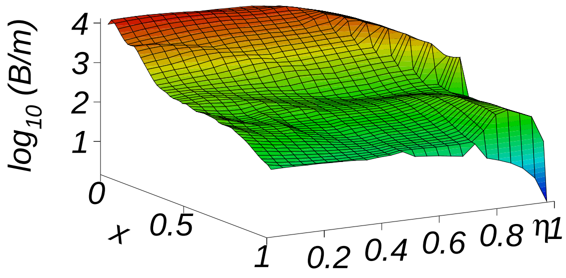

Figure 3: Decimal logarithm of inertia tensor, $\log_{10}(B/m)$, for fission of ^{286}Fl.

A comparison between nuclear inertia for two kinds of shape parametrization is given in figure 4. There are very large values of inertia when R_2 decreases exponentially. At the peak we compare $B/m = 13000$ with 2000.

Least action trajectory

As input data in the FORTRAN minimization programme we use a matrix with 61 rows for every one of the 24 mass asymmetries. In every row we give the following quantities $R, R_2, E_{def}, B_{RR}, B_{R2R}, B_{R2R2}, x, \eta$.

For the most probable mass assymetry 0.0870 or 0.0430 we found necessary quite large zero point vibration energies $E_v = 4.2678, 4.3774$ MeV in order to reproduce experimental half-lives.

Much smaller values of E_v (1.3370, 1.4052, 1.4544, 1.5438, 2.0780 MeV) are needed when $R_2 =$ constant for fission of ^{286}Fl with light fragments ^{132}Sn, ^{130}Te, ^{134}Sn, ^{134}Te and ^{136}Xe, respectively.

Half-lives against spontaneous fission of already measured nuclei ^{282,284}Cn si ^{286}Fl

The experimental values are $\log_{10} T_f^{exp}(s) = -0.523, -3.086, -0.980$ for ^{286}Fl and ^{282,284}Cn respectively. Other calculation examples may be also found [2, 3, 4, 5, 6, 7, 8]. The results are, generally speaking, very different from the experimental ones. Previously [9, 10] we reported calculations for ^{282,284}Cn. We realized that the Werner-Wheeler inertia tensor [9] is too small, and the cranking inertia [10] is more realistic.

An exponential variation similar with cranking inertia allowed us to reproduce the experimental half-life for ^{284}Cn with a parameter $E_v = 0.5$ MeV [9]. For ^{282}Cn we used cranking inertia; in this

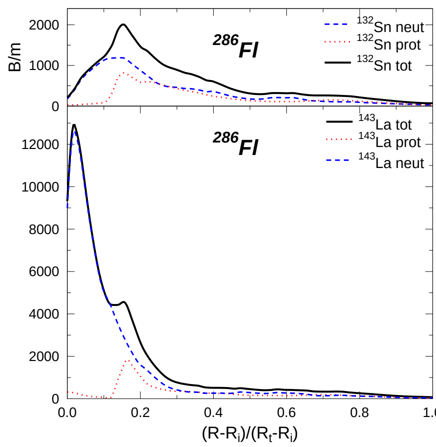

Figure 4: Cranking inertia for symmetrical fission of ^{286}Fl within parametrization with variable R_2 (BOTTOM) and for fission of ^{286}Fl with light fragment ^{132}Sn for $R_2 =$ constant (TOP).

case $\log_{10} T_f^{exp}(s) = -0.523$ was reproduced by using $E_v = 0.4368, 0.60289, 1.9662$ MeV for light fragments ^{130}Pd, ^{134}Cd and ^{132}Sn, respectively.

In conclusion, with our method of calculating the spontaneous fission half-life including macroscopic-microscopic method for deformation energy based on asymmetric two-center shell model, and the cranking inertia for the dynamical part, we may find a sequence of several trajectories one of which gives the least action. The shape parametrization with one deformation coordinate (R) and R_2 =constant is more suitable to describe the fission process of SHs in comparison with that of two deformation coordinates (R, η) in which at a given mass asymmetry, η, the radius of the light fragment, R_2, decreases exponentially toward the final value R_{2f} which remainds us about the alpha or cluster preformation at the nuclear surface [11, 12].

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Publications and Presentations at Conferences in 2015

Articles

1. D.N. Poenaru, R.A. Gherghescu, Fission approach to cluster radioactivity, Pramana Journal of Physics, 85 (2015) 415-421.
2. R. A. Gherghescu, D. N. Poenaru, Spontaneous fission of superheavy nuclei, Pramana Journal of Physics, 85 (2015) 439-446.
3. D. N. Poenaru, 75 ani de fisiune nucleara, Revista de Politica Stiintei si Scientometrie Serie Noua, 4 (1) (2015) 50-54.
4. D. N. Poenaru, Subfinantarea cercetarii stiintifice din Romania, Revista de Politica Stiintei si Scientometrie Serie Noua, 4 (2) (2015) 145-148.
5. D. N. Poenaru, Savantul de renume international, necunoscut in Romania, Revista de Politica Stiintei si Scientometrie Serie Noua, 4 (3) (2015) 224-230.

6. D. N. Poenaru, La aniversare ... (80 ani acad. D.R. Popescu) Crisana, LXX (2015) nr 7440, p. 11.

E-print

7. D. N. Poenaru, R. A. Gherghescu, W. Greiner, Anti-cluster Decay and Anti-alpha Decay of Antimatter nuclei, E-print, arXiv:1501.06792v1 [nucl-th] 2015.

Invited Presentation published in Proceedings

8. D. N. Poenaru, R. A. Gherghescu, W. Greiner, N. S. Shakib, How rare is cluster decay of superheavy nuclei, in Nuclear Physics: Present and Future (FIAS Interdisciplinary Science Series), (Springer International Publishing Switzerland, 2015) Ed W. Greiner, pp. 131-140,
9. D.N. Poenaru, R.A. Gherghescu, Newest developments in Cluster Radioactivity, Proc. of the International Workshop on "Collectivity in Relativistic Heavy Ion Collisions", held in Kolymbari, Crete, Greece, 2014 (Barcelona, 2015) Eds. L. Bravina, V.K. Magas, A. Feijoo, pp. 168-177.

Invited Presentations at International Conferences

10. D.N. Poenaru, R.A. Gherghescu, W. Greiner, Anti-cluster decay and anti-alpha decay of antimatter nuclei, 34th Workshop on Nuclear Theory, Goverdatsi, Rila Mountain, Bulgaria, 2015.
11. R.A. Gherghescu, D.N. Poenaru, Influence of cranking inertia on binary nuclear processes, 34th Workshop on Nuclear Theory, Goverdatsi, Rila Mountain, Bulgaria, 2015.

Invited Presentations at National Conferences

12. D.N. Poenaru, Completari cu noi elemente ale tabelului lui Mendeleev, Masa rotunda "Colaborarea stiintifica Horia Hulubei - Yvette Cauchois si spiritualitatea maramureseana", Manastirea Barsana, 2015.
13. D.N. Poenaru, Personalitatea marelui savant Alexandru Proca, Seminar de Istoria Electrotehnicii Romanesti, INCDIE ICPE-CA, Bucuresti, 2015.

Referee, 2015

1. Physical Review Letters (SRI=8.688) 1 referee report
2. Physics Letters B (SRI=3.608) 2 referee reports
3. Journal of Physics G: Nucl Part Phys (SRI=1.849) 1 referee report
4. Physical Review C (SRI=1.308) 3 referee reports
5. European Physical Journal A (SRI=1.130) 1 referee report
6. Nuclear Physics A (SRI=0.880) 2 referee reports
7. International J. Mod. Phys. E (SRI=0.301) 1 referee report
8. Mod. Phys. Letters A (SRI=0.557) 1 referee report

Diploma Outstanding Contribution in Reviewing, Nuclear Physics A for 2014 awarded in May 2015.

Citations, Hirsch index, i10 index, factor G

With more than 144 citation in 2015 we had in November 2015 3184 citations by others, H=29, i10=50, G=53.

In 2015 I found 4 PhD thesis citing my works hence until now I know about 43 such PhD thesis. Link to my Google Scholar Profile http://scholar.google.com/citations?hl=ro&user=SH1MaoIAAAAJ Link to Gherghescu's Scholar Profile http://scholar.google.ro/citations?user=4ckbd0gAAAAJ&hl=en

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