SCIENTIFIC REPORT

Project PCE_2011-3-0049 Contract 42/05.10.2011

concerning the project implementation during the period January–December 2015

Cross-sections in sub-barrier fusion for superheavy nuclei

Pairing interaction influence on transmission coefficient of fusion cross-section

Activities

1.1. Calculation of BCS pairing corrections using the asymmetric two center shell model (ATCSM).

1.2. Calculation of cranking mass parameters in binary nuclear systems.

1.3. Calculation of transmission coefficient of fusion cross-section. Pairing influence on deformation enery and mass parameters.

1.4. Calculation of cranking nuclear inertia tensor along an arbitrary fusion path specified by a relationship between R and η.

Pairing interaction and its influence on deformation enery

The investigation of binary nuclear systems aims to predict the most favorables projectile-target nuclides for sub-barrier fusion, or the most probable fission fragments for spontaneous fission. We are using the macroscopic-microscopic method according to which the deformation energy

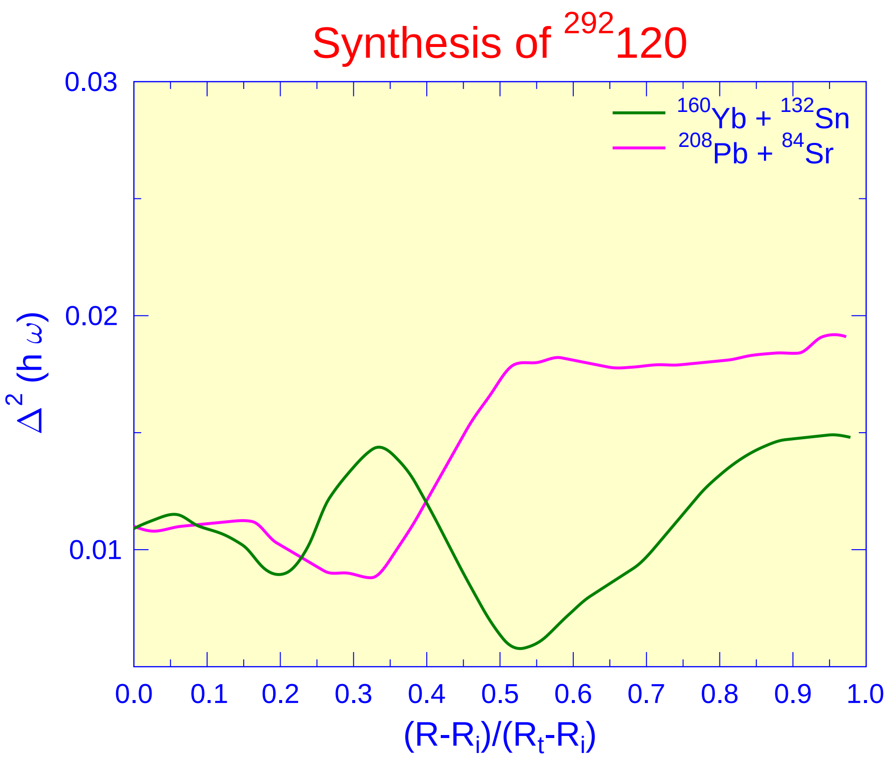

Figura 1: Variation of pairing energy gap with normalized separation distance for the following reactions ^{160}Yb+^{132}Sn and ^{208}Pb+^{84}Sr producing ^{292}120 superheavy nucleus.

is a sum of two quantities: the macroscopic energy of a deformed charged liquid drop, and the microscopic corrections due to quantum nature of the process. The last one is crucial in diging the valleys on potential energy surfaces. They became favorable trajectories for fusion or fission due to large values of the potential barriers. The total deformation energy is given by

$$E_{def} = E_{LDM} + Eshell + \delta P \tag{1}$$

where E_{LDM} is the macroscopic part calculated within Yukawa-plus-exponential model. The last two terms are microscopic corrections: $Eshell$ is the shell corrections and δP the pairing

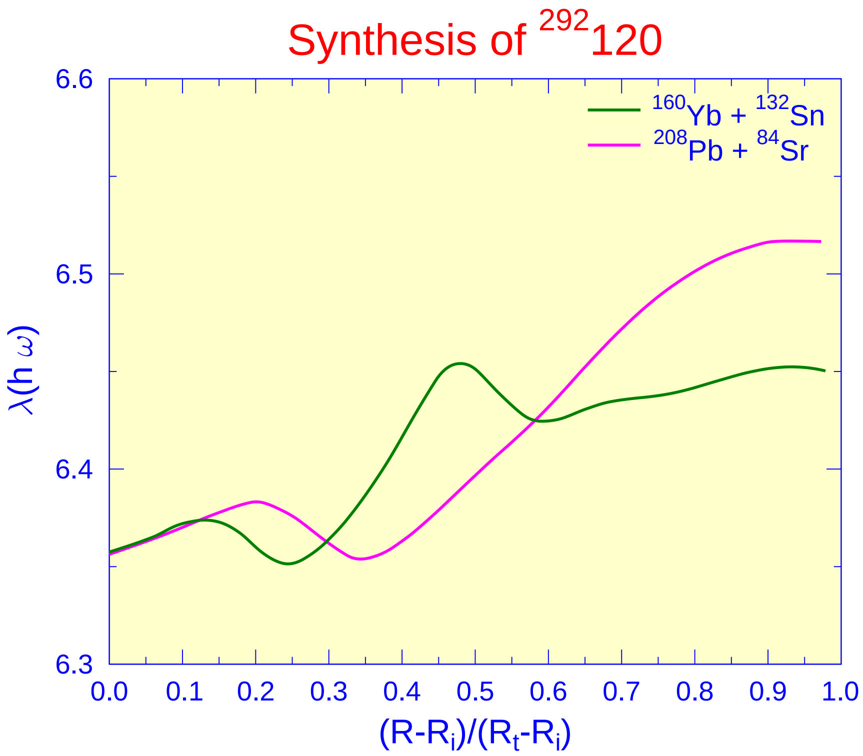

Figura 2: Fermi level variation after switching on the pairing interactions for the following reactions ^{160}Yb+^{132}Sn si ^{208}Pb+^{84}Sr, for the synthesis ofa superheavy nucleus ^{292}120.

corrections. We are using the Strutinsky's approach to calculate the shell corrections and the Bardeen-Cooper-Schrieffer (BCS) model to obtain the pairing corrections. We adapted the methods to binary systems. In the first stage we obtain an energy corresponding to a fictitial uniform distribution extracted from the total sum of nucleon pair energies:

$$\delta p = p - \tilde{p} \tag{2}$$

We need to know the pairing gap Δ and the fermi level λ. These are solutions of the nonlinear BCS system of two equations

$$n' - n = \sum_{k=k_i}^{k_f} \frac{\epsilon_k - \lambda}{\sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}} \tag{3}$$

$$\frac{2}{G} = \sum_{k=k_i}^{k_f} \frac{1}{\sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}} \tag{4}$$

We particularized this system for a binary system: two similar systems with different pairing strengths G have been solved. G_1 corresponds to the heavy fragment or target nuceus and G_2 to

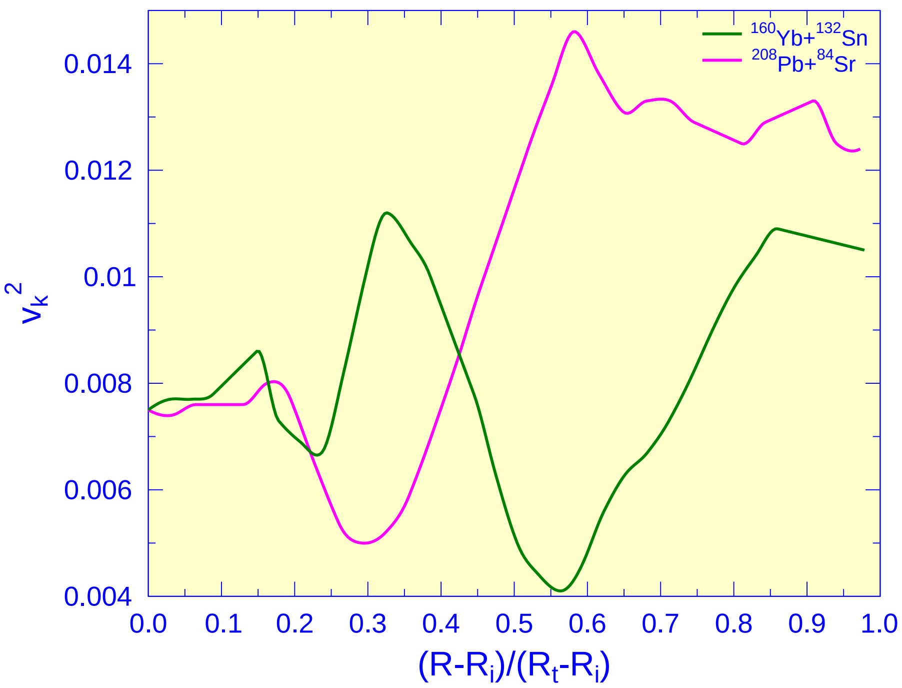

Figura 3: Occupation probabilities of quasi-particles under pairing correlations for the reactions ^{160}Yb+^{132}Sn si ^{208}Pb+^{84}Sr producing ^{292}120 superheavy nucleus.

the light fragment or the projectile. The two quantities are dependent on mass asymmetry, as can be seen from the two figures implying two almost symmetrical and two asymmetrical fragments.

One can see how strongly depends the Fermi energy on the mass asymmetry. Its value is very large at the touching point for the asymmetric channel (with Pb), due to a large energy difference between the shells.

The pairing gap follows almost the same trend starting from the compound nucleus value (the same for the two channels) and leading to a much larger Δ for the asymmetric channel.

For each energy level these quantities will determine the occupation probabilities of quasi-particles under pairing correlations, u_k^2, and of the similar quantity for the holes, v_k^2 with $u_k^2 = 1 - v_k^2$.

Influence of pairing interaction on inertia tensor

In order to obtain the transmission probability we used the idea of sub-barierr fusion reactions leading to a compound nucleus in its ground state. This concept is based on obtaining a final state as stable as possible against α decay which is usually a very fast process in a superheavy nucleus. In the ground state the compound nucleus will have zero excitation hence the maximum surviving probability.

The action integral is calculated within WKB (Wentzel-Kramers-Brillouin) approximation. The potential barrier penetrability is give by

$$P = \exp(-K_{ov}) \tag{5}$$

wher the action integral K_{ov} is

$$K_{ov}(b_P, \kappa_T, \kappa_P; R) = \frac{2}{\hbar} \int_{(fus)} [2B(R)_{b_P,\kappa_T,\kappa_P} E_{def}(R)_{b_P,\kappa_T,\kappa_P}]^{1/2} dR \tag{6}$$

The components of cranking inertia tensor is calculated as

$$B_{ij} = 2\hbar^2 \sum_{kk'} \frac{\langle k'|\partial H_{DTCSM}/\partial q_i|k\rangle\langle k|\partial H_{DTCSM}/\partial q_j|k'\rangle}{(E_k + E_{k'})^3}(u_k v_{k'} + u_{k'} v_k)^2 + P_{ij} \tag{7}$$

where one can see the importance of occupation probabilities due to pairing interactions.

Cross-section

The sub-barrier fusion cross-section is given by

$$\sigma(E) = \underbrace{\pi\lambda^2} \cdot \underbrace{T(E)} \tag{8}$$

where $\pi\lambda^2$ is the area covered by de Broglie wavelength, and $T(E)$ is the transmission coefficient. For sub-barrier fusion reactions we took

$$T(E) = P(E, E_{TP} \tag{9}$$

where P is the WKB penetrability. In this way we introduced the influence of pairing interaction on transmission coefficient of the cross-section via two quantities: the microscopic part of deformation energy and the inertia tensor. We performed calculations for the synthesis of superheavy nuclei with $Z = 114, 120, 126$. The favorable partners (leading to large penetrabilities) are those with at least one proton and/or neutron magic number, as could be Pb or Sn target nucleus.

The project objectiv of this year was fulfilled. The results have been submitted for publication.

Publications and Presentations at Conferences in 2015

Articles

1. R. A. Gherghescu, D. N. Poenaru, Spontaneous fission of superheavy nuclei, Pramana Journal of Physics, 85 (2015) 439-446.

2. D.N. Poenaru, R.A. Gherghescu, Fission approach to cluster radioactivity, Pramana Journal of Physics, 85 (2015) 415-421.

3. D. N. Poenaru, R. A. Gherghescu, W. Greiner, Anti-cluster Decay and Anti-alpha Decay of Antimatter nuclei, Romanian Reports in Physics, to be published.

Invited Presentation published in Proceedings

4. 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,

5. 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

6. R.A. Gherghescu, D.N. Poenaru, Influence of cranking inertia on binary nuclear processes, 34th Workshop on Nuclear Theory, Goverdatsi, Rila Mountain, Bulgaria, 2015.

7. 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.

Referee, 2015

1. Physical Review Letters (SRI=8.688) 1 referee report
2. Journal of Physics G: Nucl Part Phys (SRI=1.849) 3 referee reports
3. Physical Review C (SRI=1.308) 3 referee reports
4. International J. Mod. Phys. E (SRI=0.301) 1 referee report

Citations, Hirsch index, i10 index

In November 2015 I had a total of 1059 citations, H=17, i10=27.

Link to my Google Scholar Profile http://scholar.google.ro/citations?user=4ckbd0gAAAAJ&hl=en

Project Director: Dr. Radu A. Poenariu-Gherghescu