Production of super heavy elements by inverse fission

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Introduction

- In order to achieve fusion of light and medium system it is sufficient to provide a radial energy equal to the Bass barrier
- Complete fusion cross section could be approximate with sharp cutoff model:

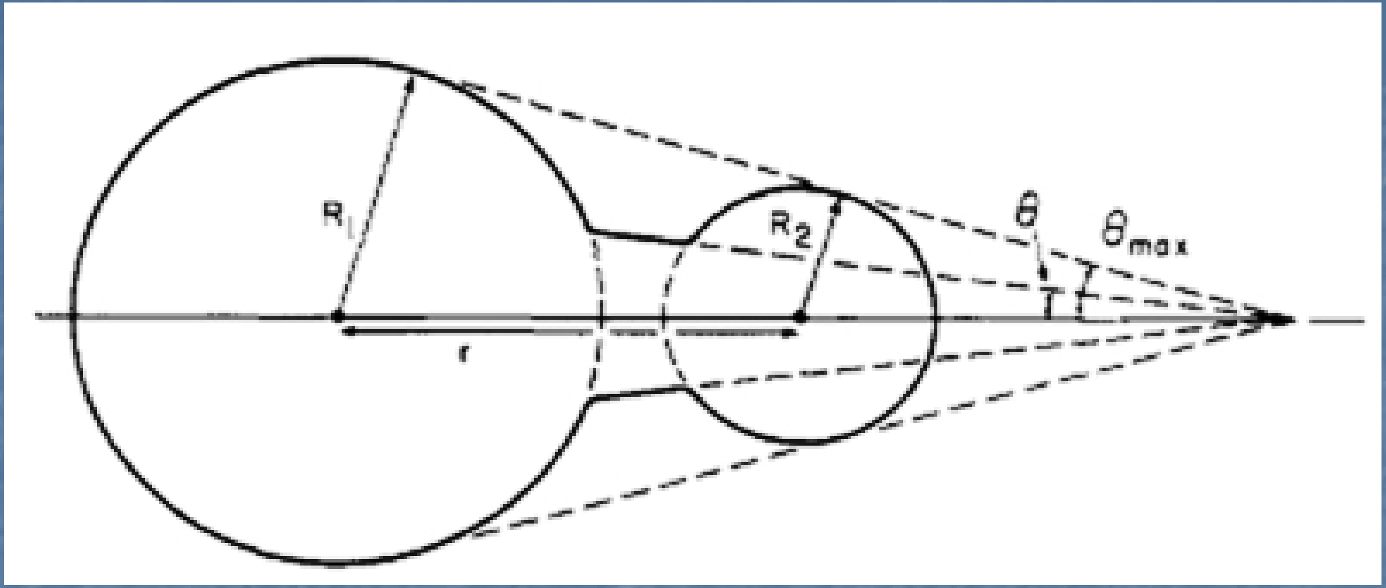
$$\sigma_{fu} = \pi r_{fu}^2 \left(1 - \frac{V_{fu}}{E_{cm}}\right)$$

- For fusion of heavier systems, a clear cross section deficiency is observed ("fusion hindrance")
- Fusion takes place only at energies much higher than Bass barrier
- Swiatecki model

Swiatecki model

- Macroscopic theory of dynamics of nucleus-nucleus collisions :
    - Macroscopic potential energy (liquid drop potential)
    - Macroscopic dissipation function
        - Wall formula – resistance against deformation
        - Wall and Window formula – resistance against particle exchange
    - 3 degrees of freedom
        - asymmetry variable
        - distance variable
        - window opening variable

Swiatecki model



$$\Delta = \frac{R_1 - R_2}{R_1 + R_2}, \quad \rho = \frac{r}{R_1 + R_2}, \quad \alpha = \left(\frac{\sin \theta}{\sin \theta_{\max}} \right)^2$$

$$\begin{cases} \alpha < \dfrac{1}{2}: \text{ dinuclear regime} \\ \alpha \geq \dfrac{1}{2}: \text{ mononuclear regime} \end{cases}$$

Equations of motion in dinuclear regime

$$\mu\frac{d^2\sigma}{d\tau^2}+\nu^2\frac{d\sigma}{d\tau}+\nu-X_{eff}=0$$

$$\frac{d\nu}{d\tau}=\frac{2\nu-3\nu^2-\sigma}{4\nu\left(\sigma+\nu^2\right)}$$

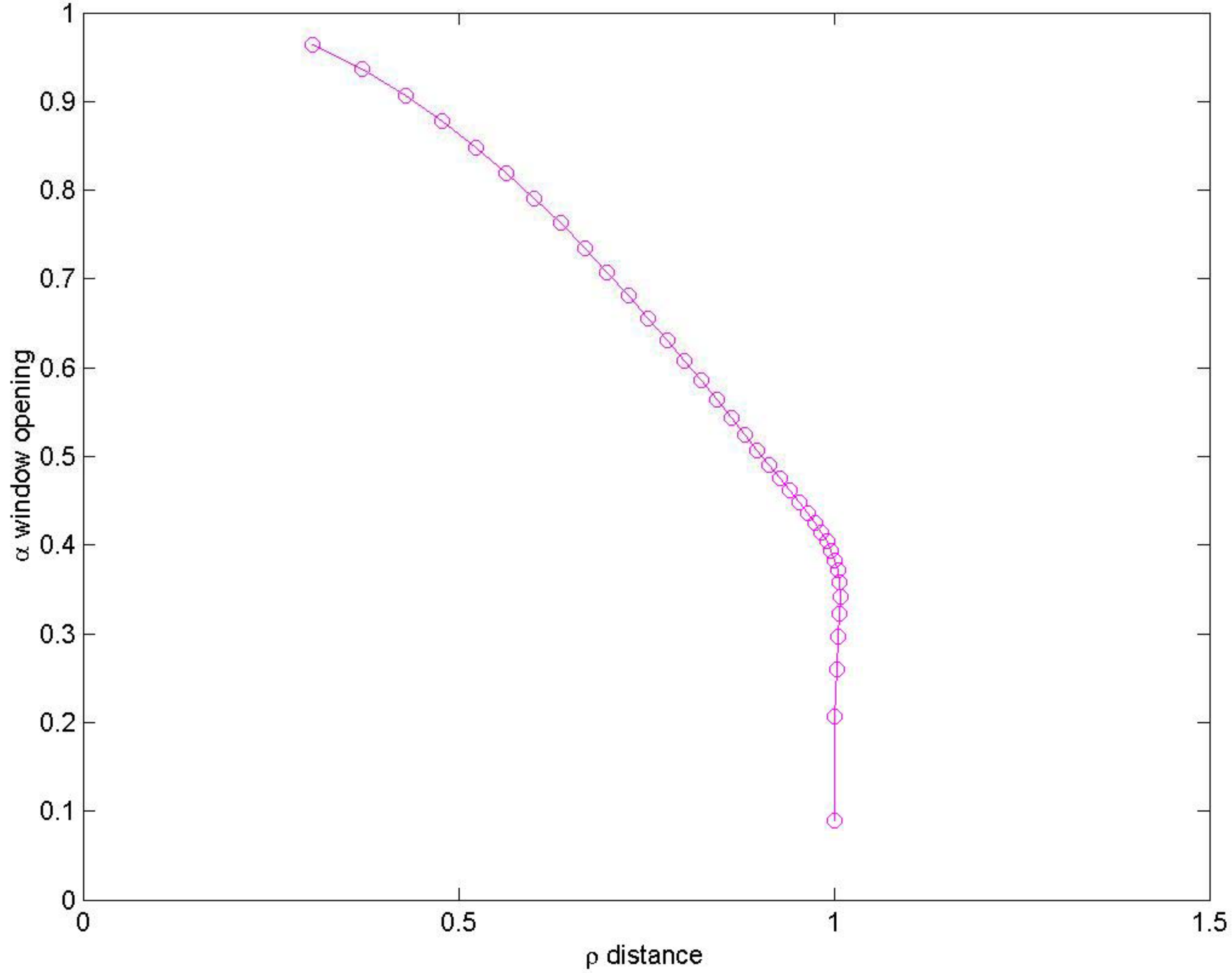
- X_{eff} – effective fissility parameter, measure of repulsive electric force compared to attractive surface-tension force
- $X_{eff} < X_{th}$ system automatically goes into conditional saddle
- $X_{eff} > X_{th}$ additional energy needed E_x (extra push)

$$E_x=E_{ch}*a^2\left(x_{eff}-x_{th}+f^2\left(\frac{L}{L_{ch}}\right)^2\right)^2$$

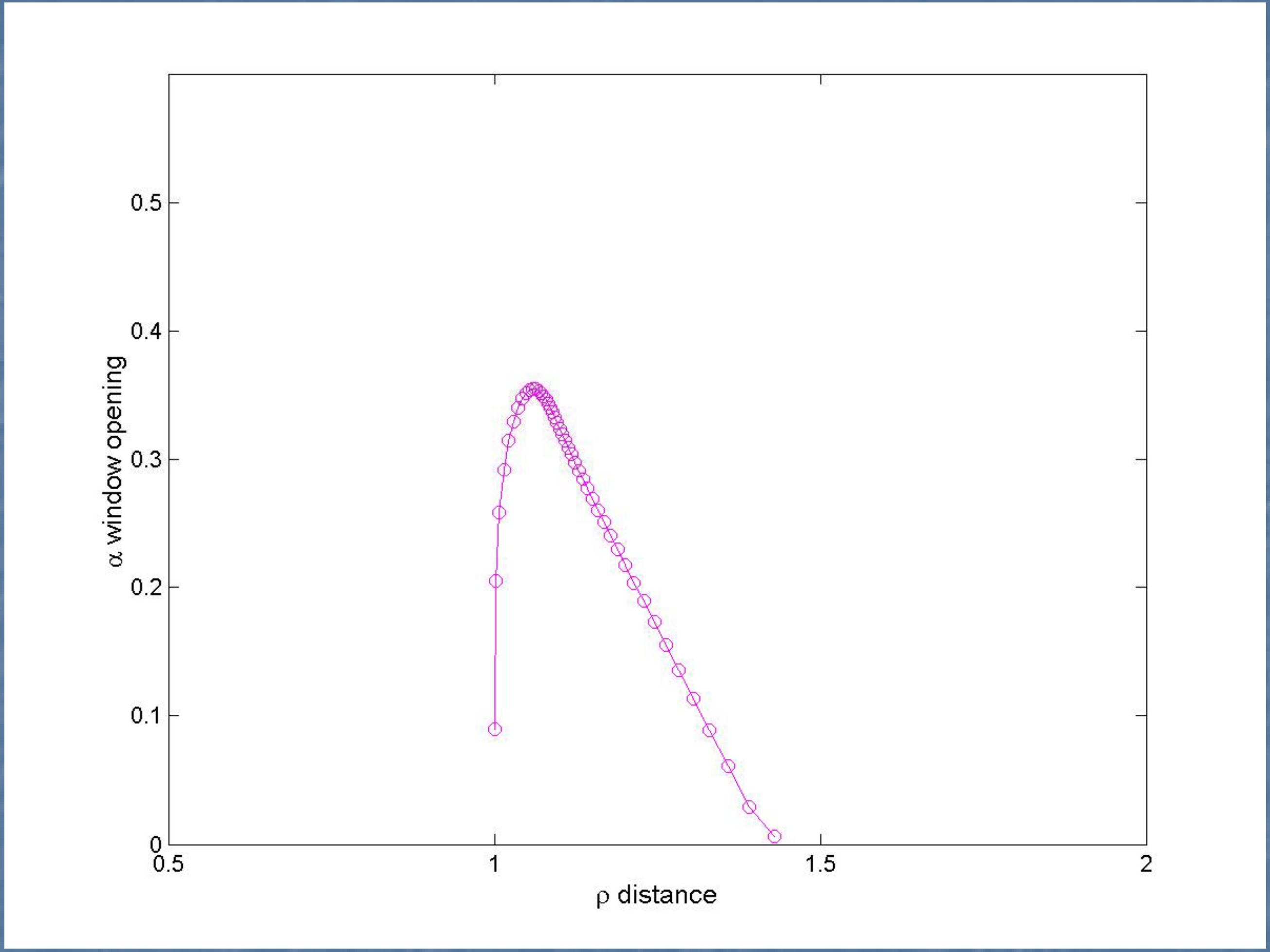
Estimated parameters

- $x_{th} = 0.7 \pm 0.02$
- $a=12 \pm 2$
- $f=0.75 \pm 10\%$ (for non central collisions)

$^{58}Fe + ^{124}Sn \longrightarrow ^{182}Os$



$^{86}Kr+^{124}Sn \longrightarrow ^{210}Rn$

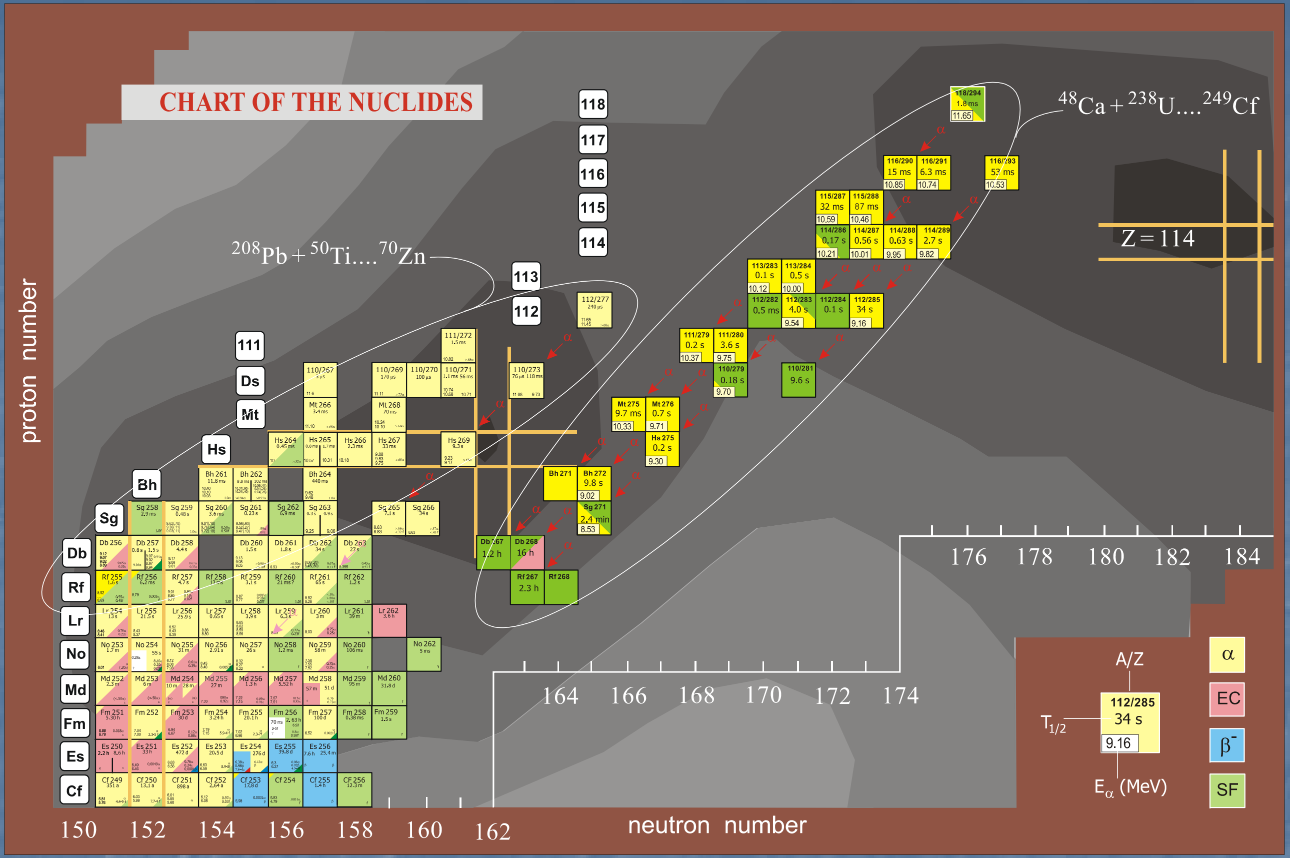


$X_{eff}=0.726$

$E_x=1.61$ MeV

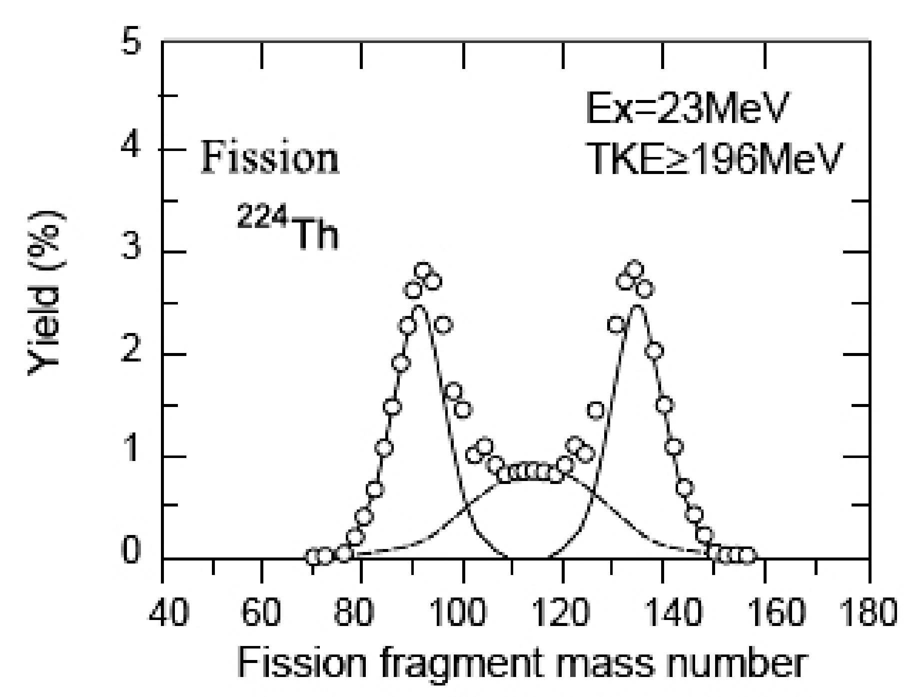
Extra push energy needed to compensate dissipated energy lost in overcoming the barrier heats the compound system and thus for SHE synthesis significantly reduce survival probability

Island of stability of SHE i inverse fission



- The only way to synthesize the isotopes of super heavy elements in the center of the island of SHE stability is to use the projectile-target combinations of isotopes with highest neutron excess,
- Fission fragment originating from “cold fission” have large neutron excess
- Maximal yields of “cold fission” are at ”magic number nuclei”

Fission fragment distribution from the compound nucleus ^{224}Th (^{16}O + ^{208}Pb, E_{lab}=196 MeV, E_x=23MeV)

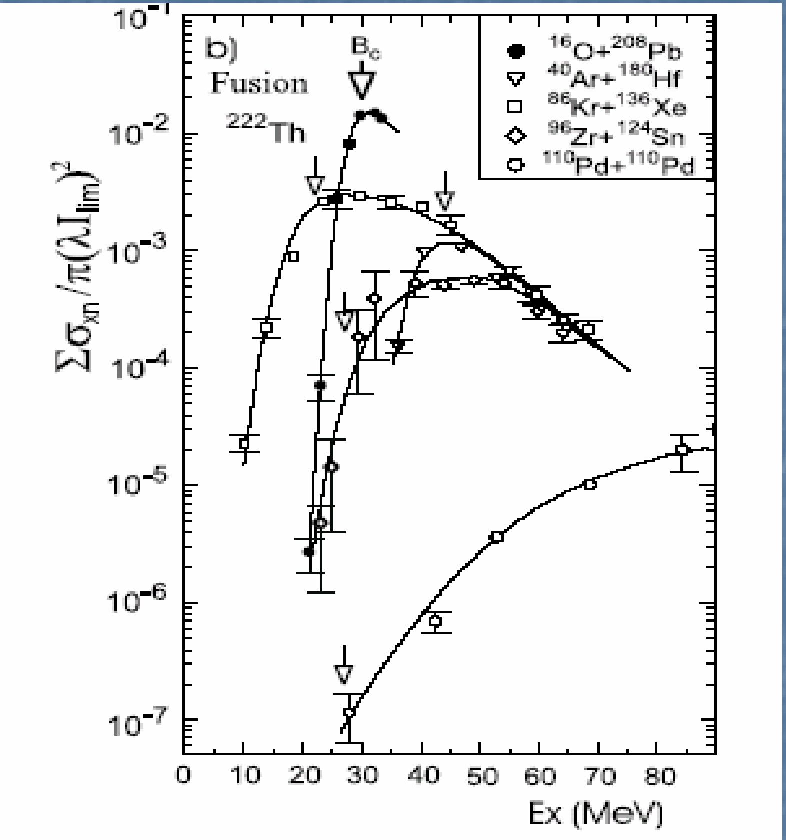


(Oganessian, EPJ2002)

- Asymmetric mass distribution of cold fission fragmenats with maximum yield at A~88 i A~136
- Charge distribution: maximum yield at Z~36 i Z~54

⟹ maximal yield of cold fission fragments at N~52 i N~82

Cross-section for formation of the EVRs 220-224Th for various reactions



- 3 orders of magnitude higher cross section for fusion ^{86}Kr+^{136}Xe (fragments of asymmetric cold fission)

- Changing target ^{136}Xe into ^{130}Xe, causes a decrease of EVR cross section by almost 3 orders of magnitude

- Collective nuclear motion from the contact configuration of ^{86}Kr and ^{136}Xe to the saddle point of ^{222}Th follows a shorter path compared to the case of ^{216}Th which undergoes mainly symmetric fission.

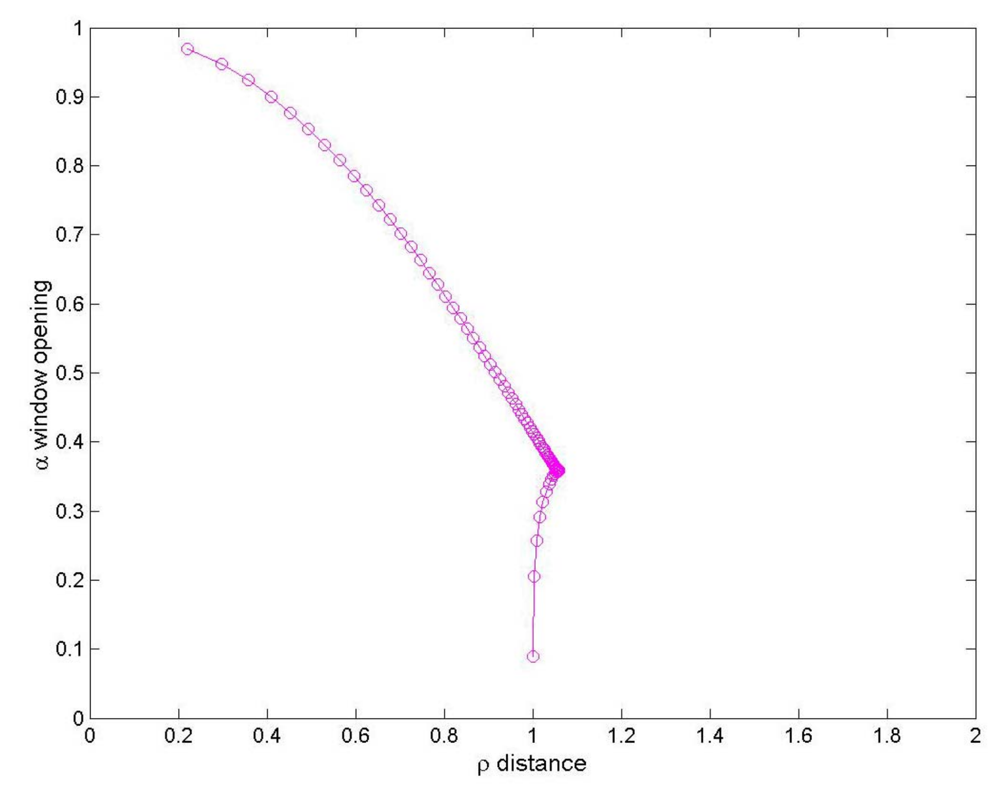
Conclusion and future perspectives

- Nuclei close in charge and mass to the most probable cold fission fragments of the SHE may have enhanced fusion caused by shell structure properties.

- The systems with magic number of nucleons (^{86}Kr, ^{136}Xe) and low excitation energy <20 MeV reduces dissipative losses better then liquid drop model predicts
- Extra push energy should be decreased by some correction factor taking into account shell effects.

Double magic nucleus ^{132}Sn (Intensity ~10^{12} pps)

proposed reaction $160Gd(132Sn,n)^{291}114$ $X_{eff}=0.953$



HIVAP calculation:

Cross section 1 pb for $X_{th}=0.82$ and extra push energy $E_x= 43$ MeV

Needed E_x increases the excitation of CN, causes evaporation of additional number of neutrons.

If assumed shell enhancements are able to reduce the effective system fissility X_{eff} from 0.953 to 0.7, the system may enter the mononuclear regime without any E_x needed and EVR could be detected at cross section values of the order of 1 pb.