

Correspondence between cluster radioactivity of actinides and asymmetric fission of super heavy nuclei

Michał Warda

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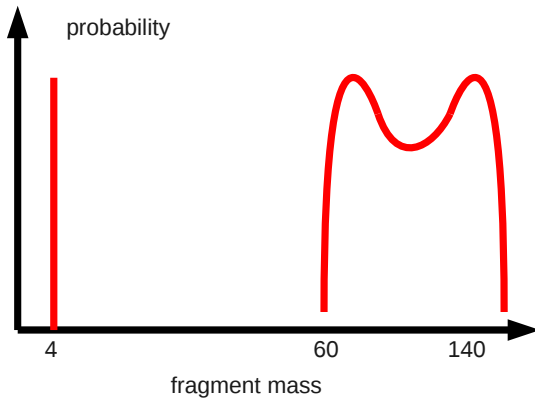
Trento, 9-13.04.2018

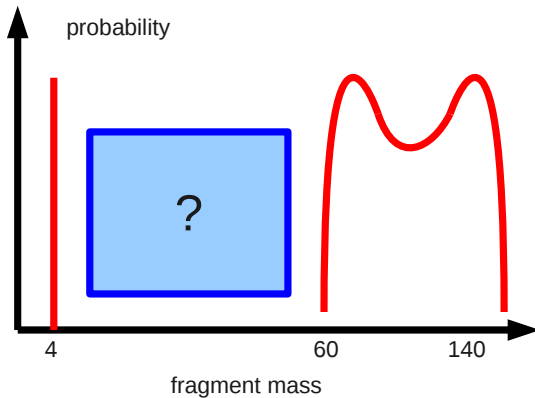


Collaboration:

- J.L. Egido, UAM, Madrid
- L.M. Robledo, UAM, Madrid
- A. Zdeb, UMCS, Lublin









Discovery of cluster radioactivity

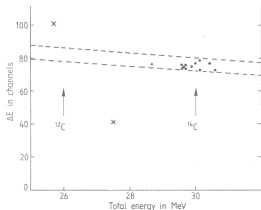
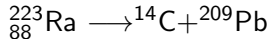


Fig. 1 Contents of the two-dimensional array ΔE versus E_{total} after a run of 189 days. The dotted line indicates the allowed region for carbon ions and the arrows indicate the total energies expected for ^{12}C and ^{14}C emissions in the decay of ^{223}Ra . The lower of the two crosses represents a quadruple pile-up. Below the total energy displayed, large numbers of triple and double α -pile-ups were recorded. Single α -events (and, in part, even double α -pile-ups) were biased out on the analogue side to avoid deadline problems on the digital side. The upper cross is an event which was recorded during a thunderstorm which affected the mains badly. A run of 194 days was made before this one, yielding 8 events and, in addition, a run of approximately half a year was performed to investigate possible cosmic ray-induced events. Channel 77 in $\Delta E = 6.7$ MeV, which is exactly as expected for 30 MeV ^{14}C . Detector characteristics: The dead layer of the ΔE detector (200 mm^2 active area, $8.2\text{ }\mu\text{m}$ sensitive thickness) was determined to lie between 0.3 and $0.8\text{ }\mu\text{m}$. In addition a protective layer of gold of thickness $20\text{ }\mu\text{g cm}^{-2}$ was evaporated on the source and $15\text{ }\mu\text{g cm}^{-2}$ carbon film inserted between the source and the ΔE detector. An extra $30\text{--}40\text{ }\mu\text{g cm}^{-2}$ of gold is present on the E -detector (300 mm^2 active area). This gives a total of $150\text{--}250\text{ }\mu\text{g cm}^{-2}$ of effective dead layer (Si equivalent) and an energy loss of ^{14}C ions of $0.5\text{--}0.8$ MeV. The source of strength $3.3\text{ }\mu\text{Ci}$ gave a counting rate of $\approx 4,000\text{ s}^{-1}$, corresponding to an effective solid angle of detection of $\approx 1/3$ sr.



H.J. Rose and G.A. Jones, *Nature* **307**, 245 (1984)

Sandulescu, Poenaru and Greiner, *Sov. J. Part Nucl.* **11**, 528 (1980)

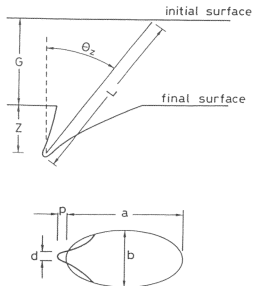


Fig. 1. Geometry of a track etched until the end of the particle range, L . G is the thickness of the material etched away, d the tip diameter, a and b the major and minor axes, p the overhang, θ_z the zenith angle, z the track depth.

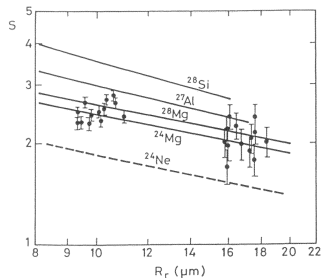


Fig. 6. Comparison of the sensitivity S measured at two stages of the etching process for the 15 events from the decay of ^{236}Pu with accelerator calibrations. Reprinted with permission from M. Hussonnois et al., "Cluster decay of ^{236}Pu and correlations of the probabilities of α decay, cluster decay and spontaneous fission of heavy nuclei" JETP Letters 62 (1995) p 701. Copyright 1995 American Institute of Physics.

R. Bonetti, A. Guglielmetti, in *Heavy Elements and Related New Phenomena Vol II*, ed. W. Greiner and R.K. Gupta, p.634, Word Scientific, 1999



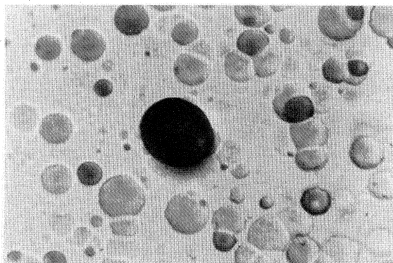


FIG. 1. Photomicrograph showing one etch pit due to a 56 MeV ^{24}Ne ion striking a Cronar detector nearly head on. About 3×10^6 alpha particles passed through this field of view.

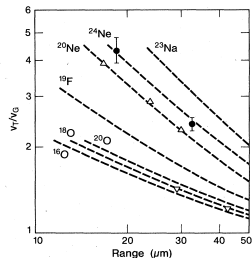


FIG. 2. Comparison of average signal of ^{24}Ne nuclei (●) emitted from ^{232}U with calibrations (dashed lines) obtained with ^{18}O (▽) and ^{20}Ne (Δ) ions at Lawrence Berkeley Laboratory accelerators. Ratio of etching rate along track to general etching rate v_T/v_G , is plotted as a function of residual range.

Barwick et al., PRC 31, 1984 (1985)



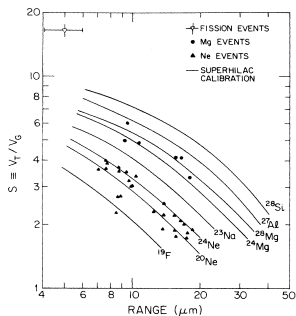


FIG. 1. Identification of ions emitted from ^{234}U as Ne and Mg. The curves are based on calibrations obtained with ^{28}Si , ^{24}Mg , and ^{20}Ne ions at Lawrence Berkeley Laboratory SuperHilac.

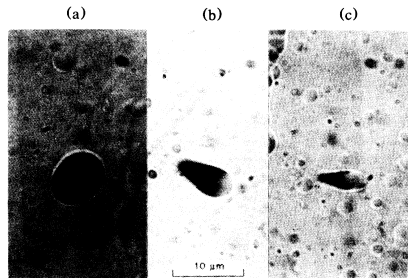


FIG. 2. Photomicrographs showing etch pits due to (a) spontaneous fission, (b) Mg emission, and (c) Ne emission from ^{234}U source.

Wang et al., PRC **36**, 2717 (1987)



Cluster radioactivity: key facts

- Emitters: $^{221}_{87}\text{Fr}$ — $^{242}_{96}\text{Cm}$
experimental evidence in 12 even-even, 9 odd nuclei
- Clusters: ^{14}C — ^{34}Si
- Heavy mass residue: doubly magic $^{208}\text{Pb} \pm 4$ nucleons
"Lead radioactivity"
- Half lives: $10^{11} \text{ s} - 10^{26} \text{ s}$
- α branching ratio: $10^{-9} - 10^{-16}$



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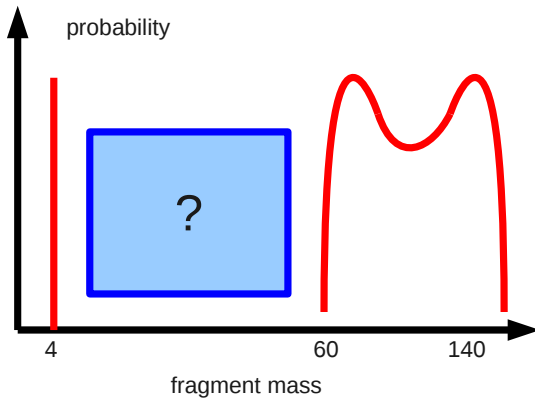
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Theoretical description

- Extrapolation of Gamov model of alpha emission
Modified Geiger-Nuttall formula for half-lives



$$\log_{10} T_{1/2}^{AZ} = \frac{aA_2\eta + bZ_2\eta_z}{\sqrt{Q}} + c.$$

$$a=10.603, b=78.027, \text{ and } c=-80.66$$

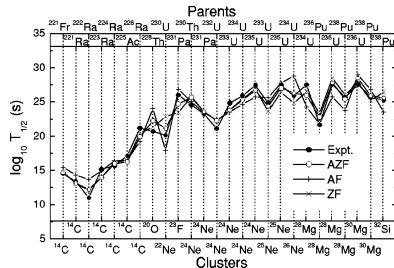


FIG. 1. $\log_{10} T_{1/2}$ (s) for different clusters emitted from various radioactive parents, calculated by using the AZ formula (AZF) and compared with experimental data. Also, the results of calculations for AF ($b=0$) and ZF ($a=0$) truncations of AZF are shown for comparisons.

Balasubramaniam et al., PRC **70**, 017301 (2004)

$$\log_{10} T_{1/2} = a\sqrt{\mu}Z_cZ_dQ^{-1/2} + b\sqrt{\mu}(Z_cZ_d)^{1/2} + c$$

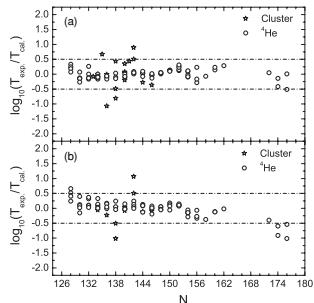


FIG. 4. Deviations between the logarithms of the experimental data and of the calculated values for even-even nuclei (a) when we use two sets of parameters to describe α decay and cluster radioactivity respectively and (b) when we use one set of parameters to describe both α decay and cluster radioactivity at the same time.

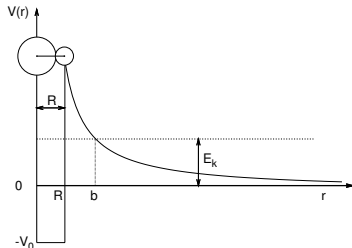
Ni et al., PRC **78**, 044310 (2008)



$$V(r) = \begin{cases} -V_0 & 0 \leq r \leq R \\ \frac{Z_1 Z_2 e^2}{r} & r > R \end{cases}$$

$$R = r_0(A_1^{1/3} + A_2^{1/3})$$

$$b = \frac{Z_1 Z_2 e^2}{E_k}$$

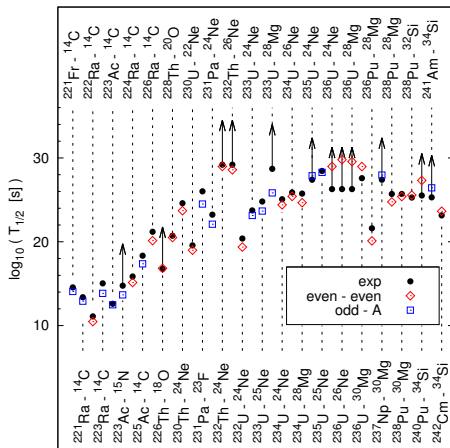


$$P = \exp \left[-\frac{2}{\hbar} \int_R^b \sqrt{2\mu(V(x) - E_k)} dx \right]$$

$$P = \exp \left\{ -\frac{2}{\hbar} \sqrt{2\mu Z_1 Z_2 e^2 b} \left[\arccos \sqrt{\frac{R}{b}} - \sqrt{\frac{R}{b} - \left(\frac{R}{b}\right)^2} \right] \right\}$$

A. Zdeb, M. Warda, K. Pomorski, Phys. Rev. C87 024308 (2013)



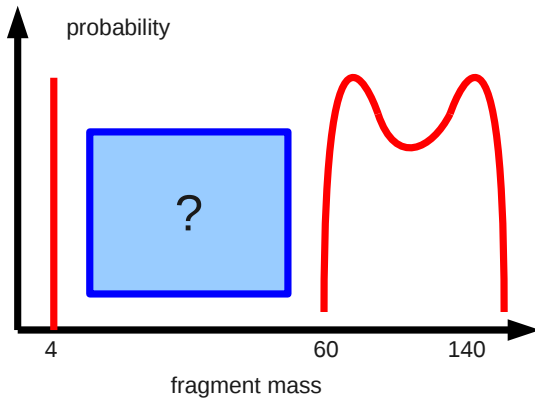


$$T_{1/2} = \frac{\ln 2}{P_\nu} \cdot 10^h$$

$$P_\nu = \frac{\pi \hbar}{2\mu R^2}$$

$$r_0 = 1.21 \text{ fm}$$

$$h = 1.973$$



Theoretical description

- Very asymmetric fission
- Potential energy surfaces are determined in the self-consistent procedure in HFB theory with Gogny D1S force

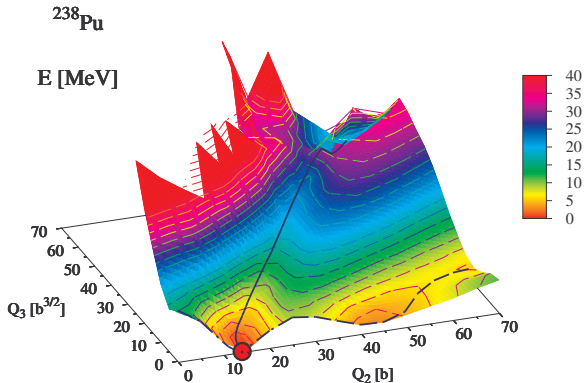
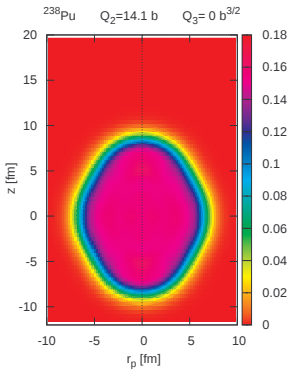


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Shape evolution: ^{238}Pu

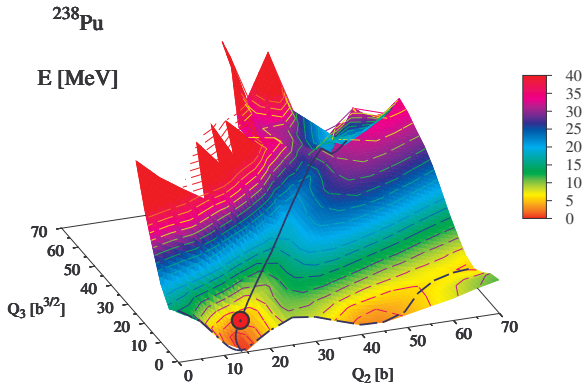
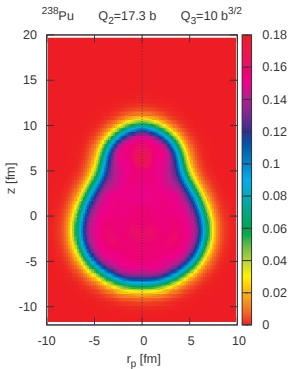


M. Warda and L. M. Robledo, Phys. Rev. C 84, 044608 (2011).

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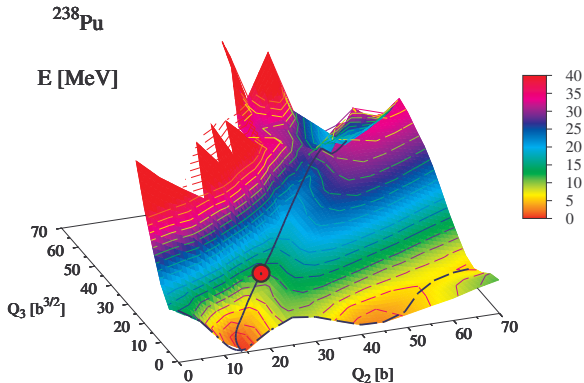
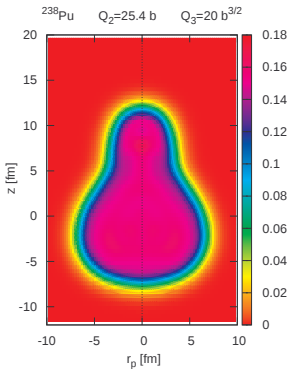


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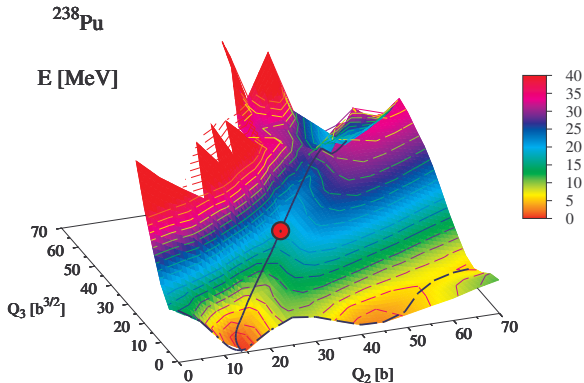
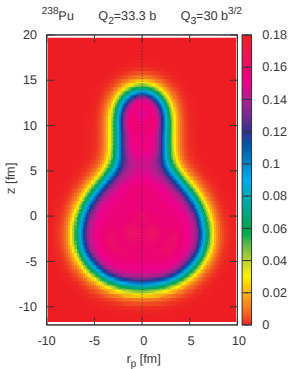


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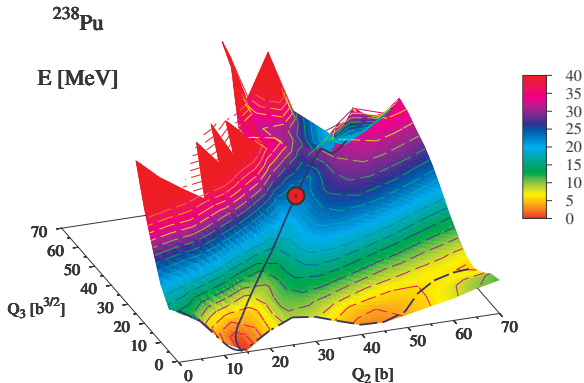
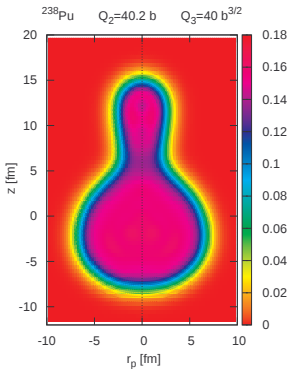


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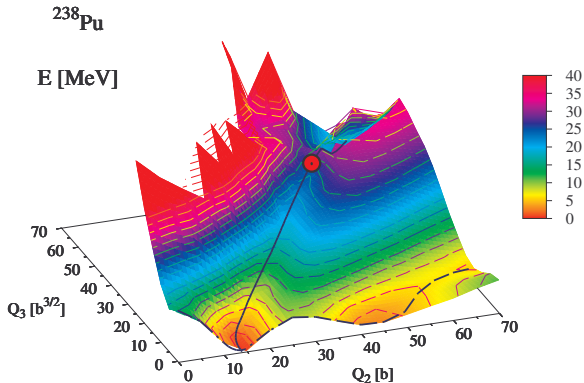
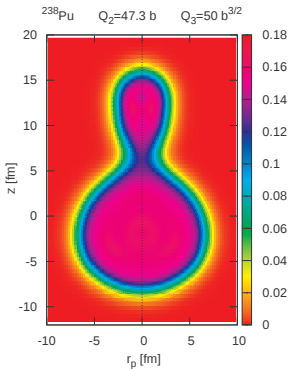


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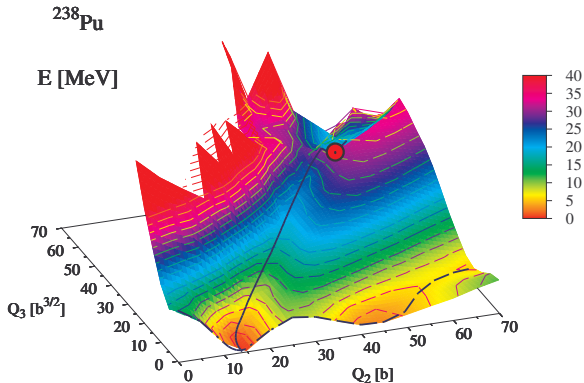
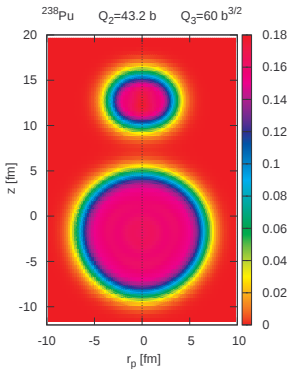


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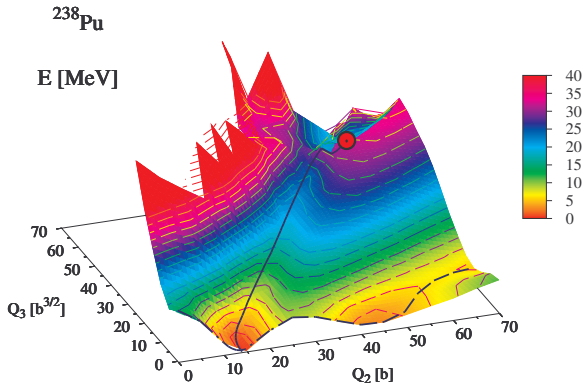
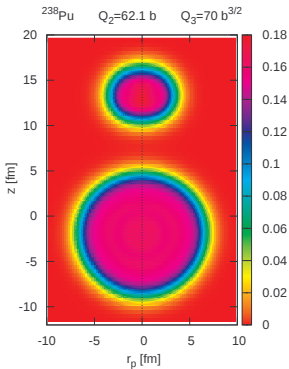


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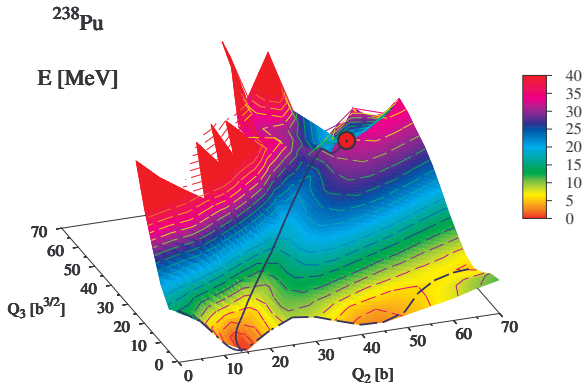
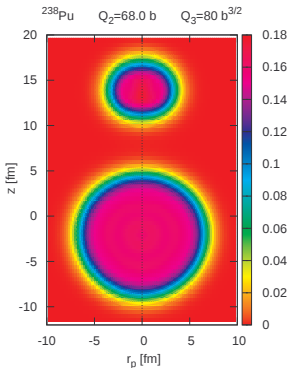


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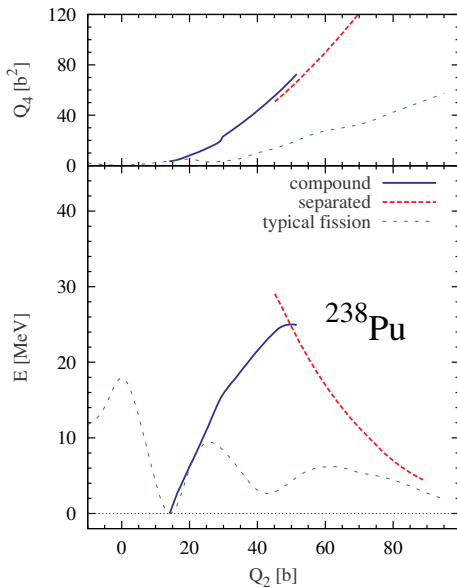
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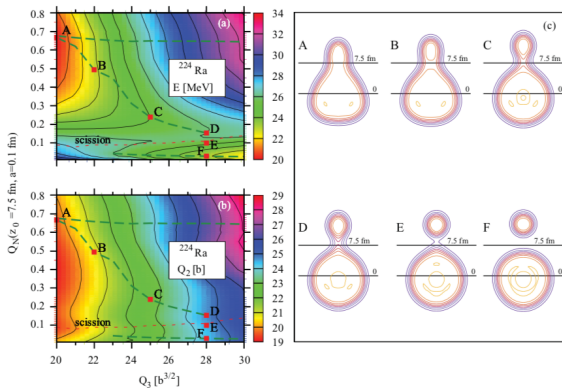
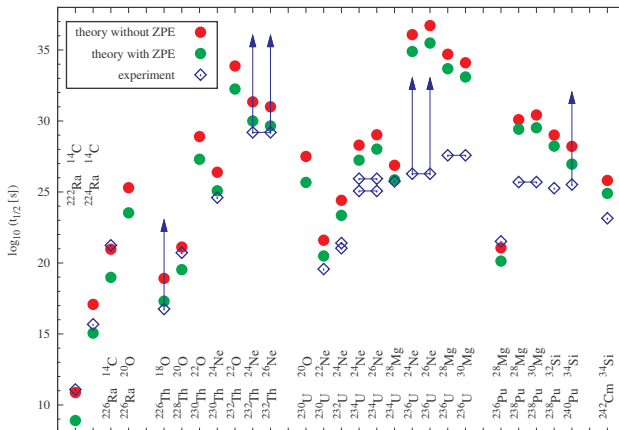
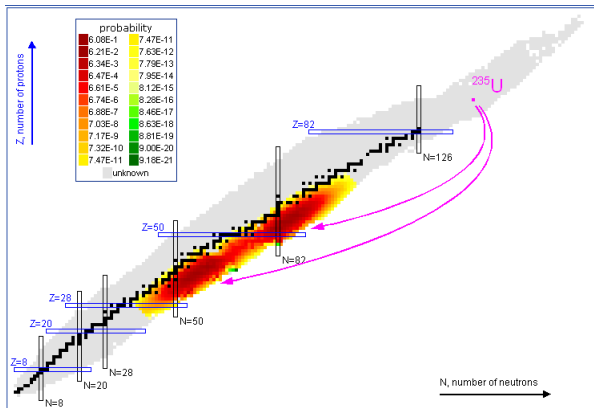


FIG. 8. (Color online) (a) Saddle region of the PES and (b) quadrupole moment Q_2 plotted as a function of octupole moment Q_3 and neck parameter Q_N in ^{224}Ra . Green dashed lines are fission paths and the red short-dashed line is the scission line. (c) Contour plots of density distributions for some deformations marked in panel (a). Equidensity lines are plotted every 0.02 fm^{-3} .





Fission fragments - N/Z ratio

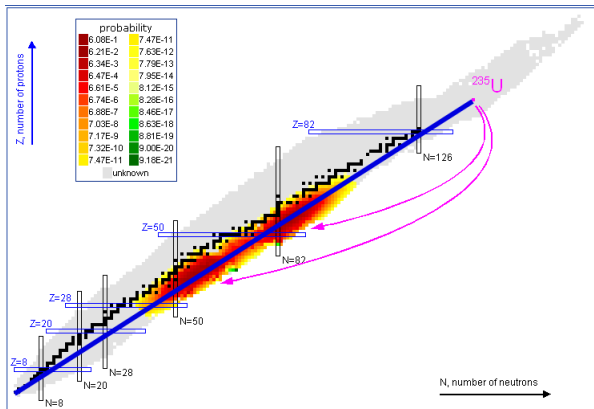


<http://lablemminglounge.blogspot.com/2011/03/why-fuel-rods-are-radioactive.html>

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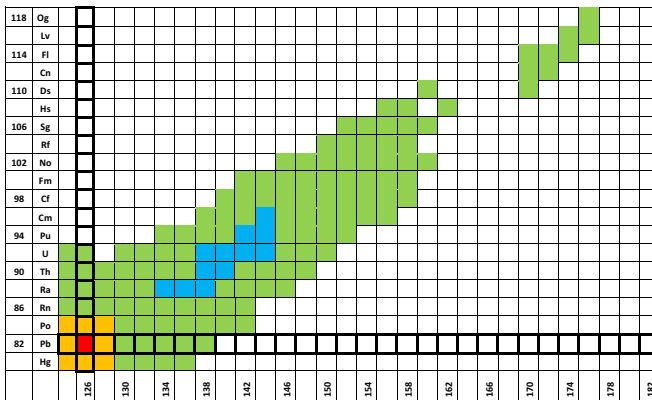
Fission fragments - N/Z ratio



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Cluster radioactivity - chart of nuclides





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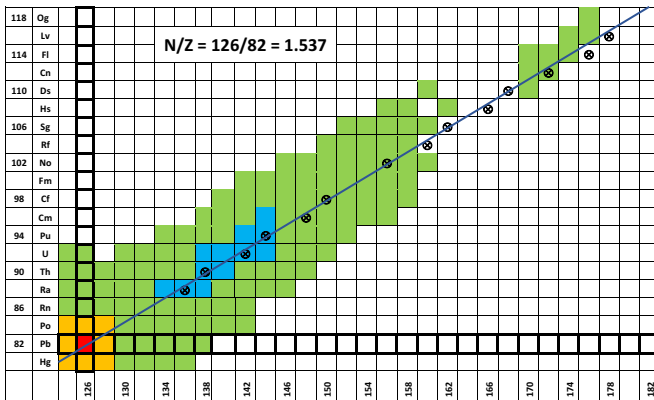
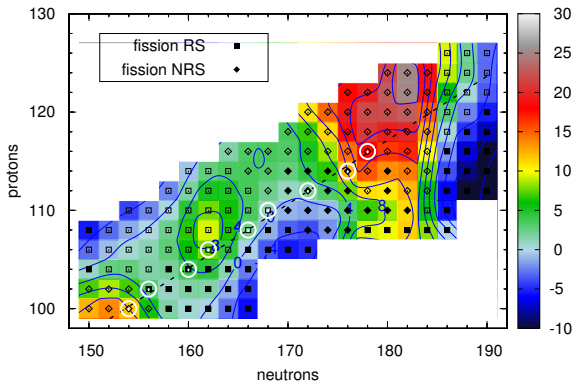


Chart of SH nuclides



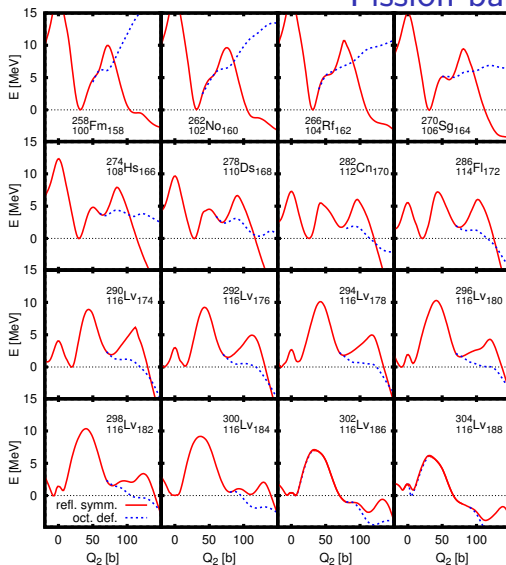
M. Warda, J.L. Egido, Phys. Rev. C 86 (2012) 014322

A. Baran, M. Kowal, P.G. Reinhard, L.M. Robledo, A. Staszczak, M. Warda, Nucl. Phys. A 944 (2015) 442

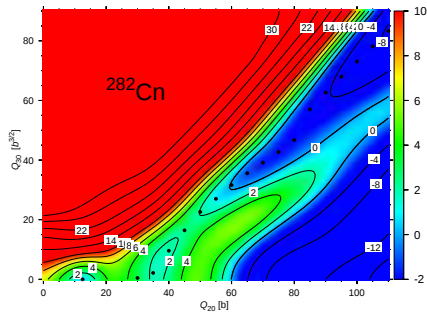
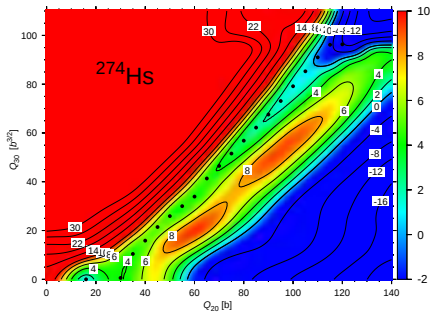
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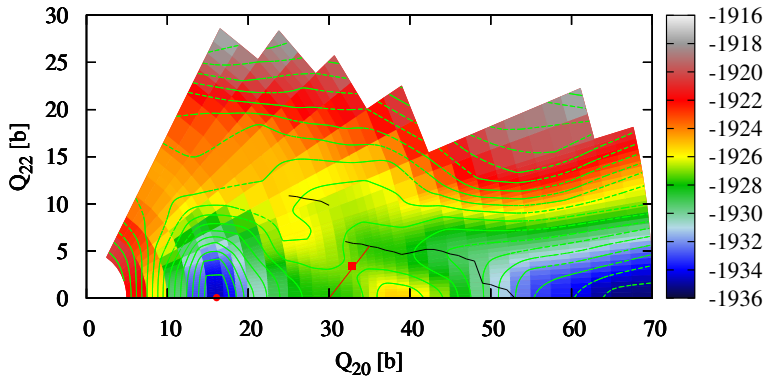
Fission barriers



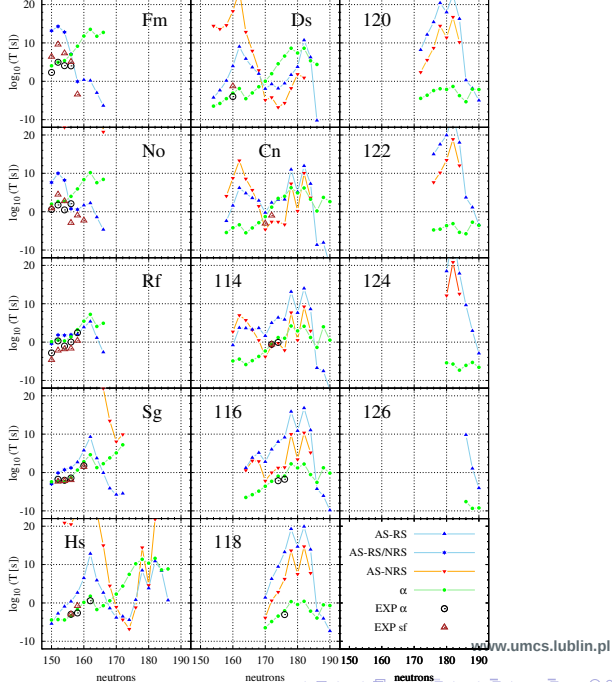
Fission barriers in ^{274}Hs and ^{282}Cn



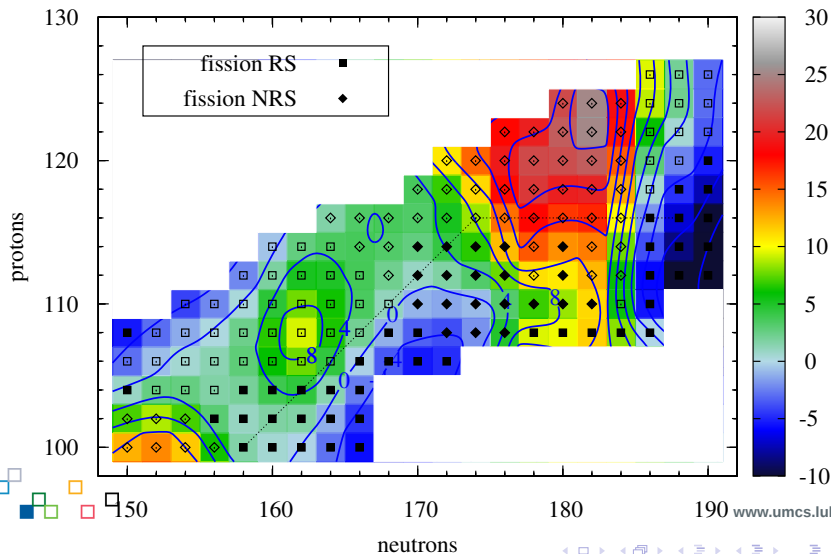
Triaxial potential energy surface



Fission and α -decay half-lives



Fission half-lives



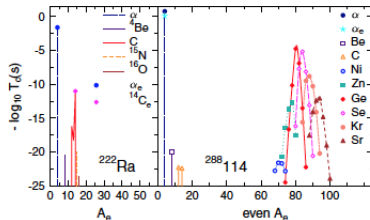
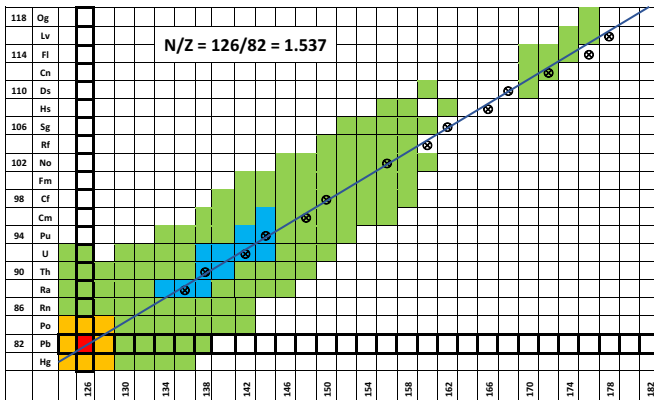


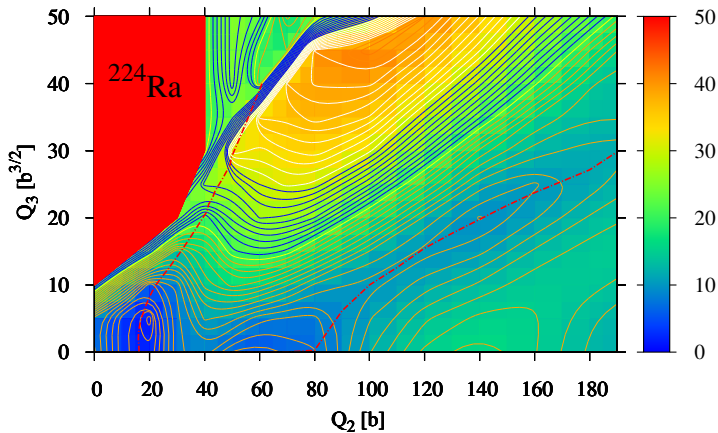
FIG. 1 (color online). Time spectra of different cluster emissions from ^{222}Ra (left panel) and from the superheavy nucleus $^{288}114$ (right panel). The most probable emitted clusters from ^{222}Ra and $^{288}114$ are ^{14}C and ^{80}Ge , respectively, both leading to ^{208}Pb daughter nucleus.

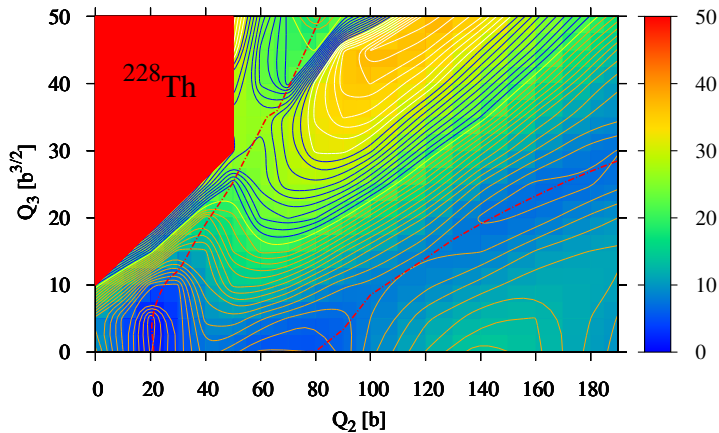
D. N. Poenaru, R. A. Gherghescu, and W. Greiner
 Phys. Rev. Lett. 107, 062503 (2011); Phys. Rev. C 85, 034615 (2012)

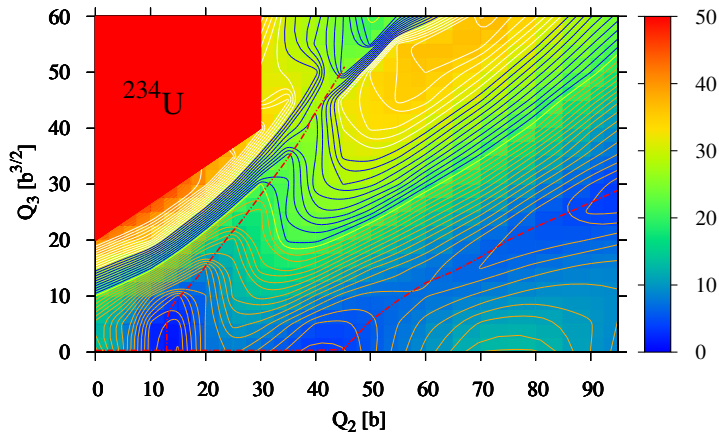


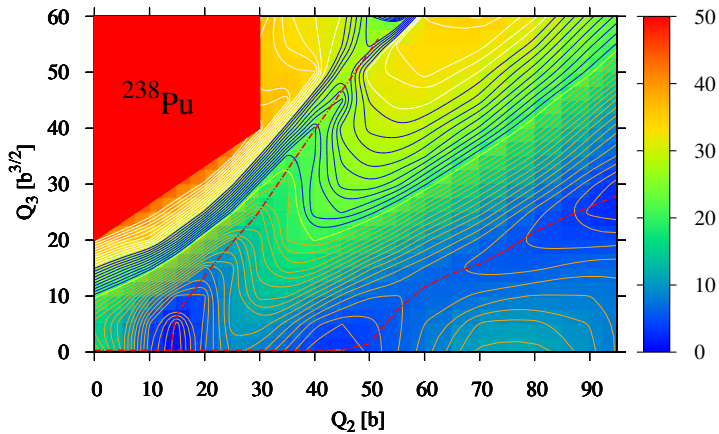
Cluster radioactivity - chart of nuclides

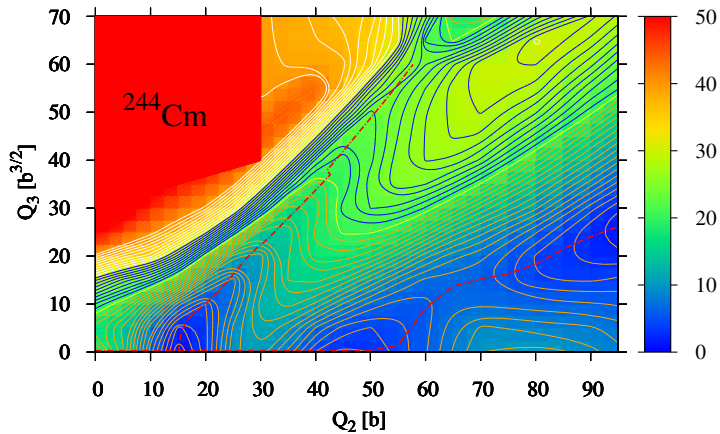


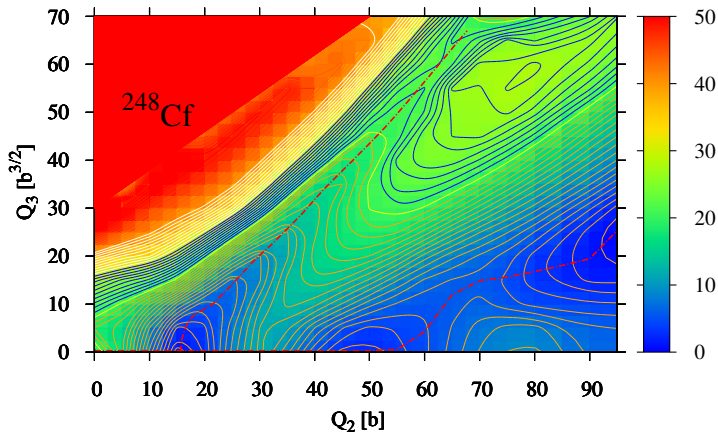


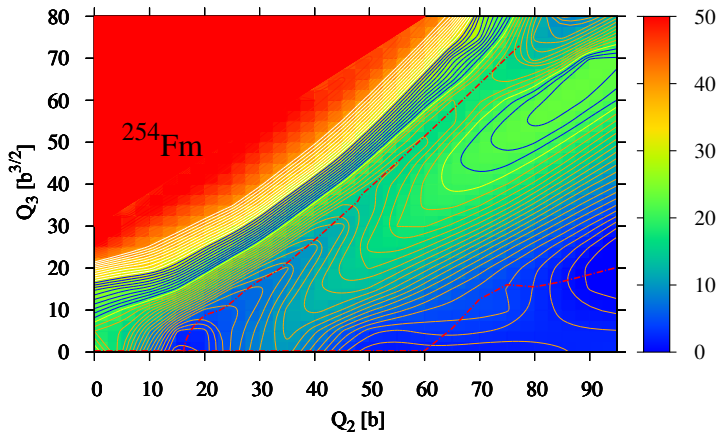


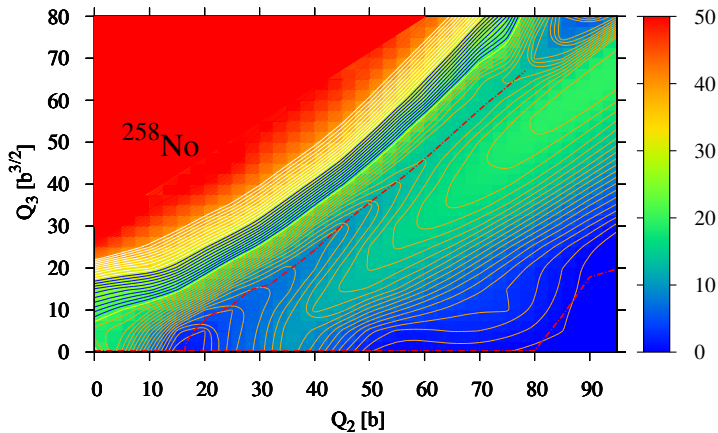


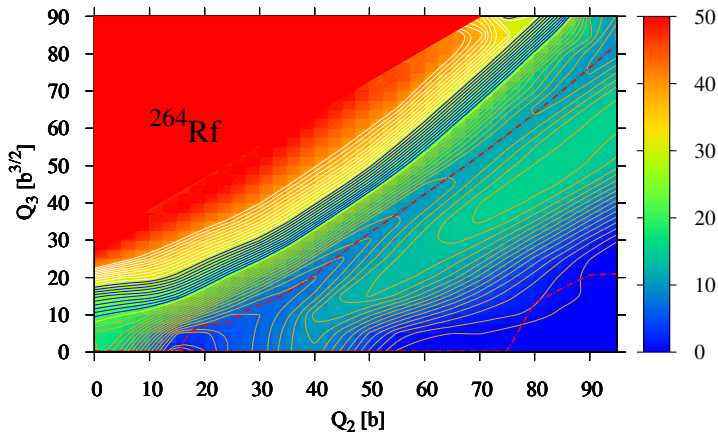


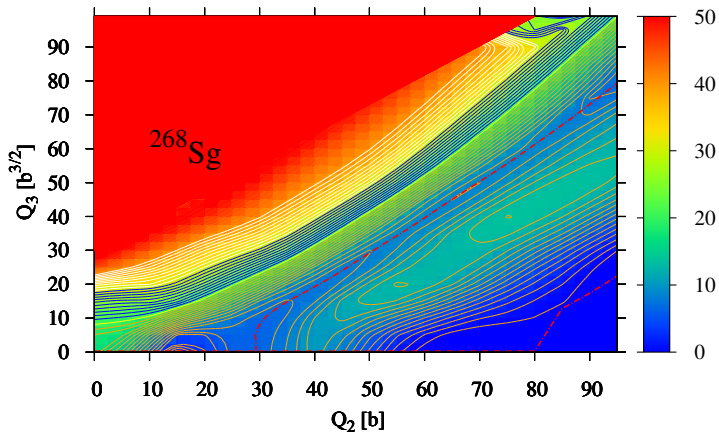


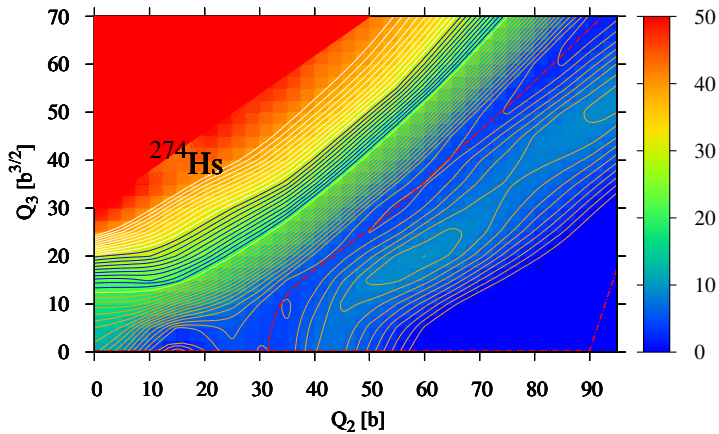


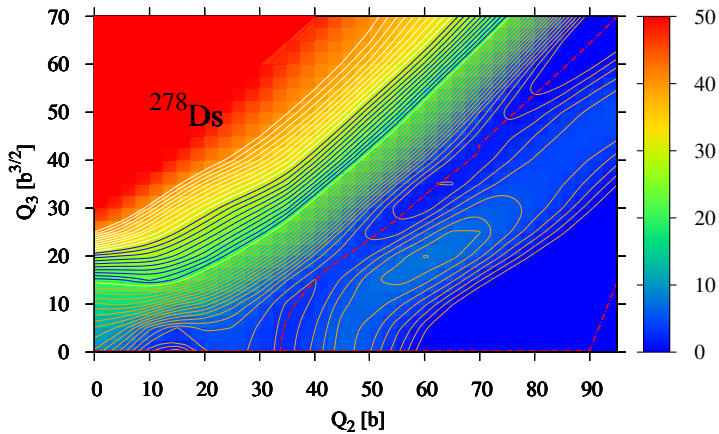


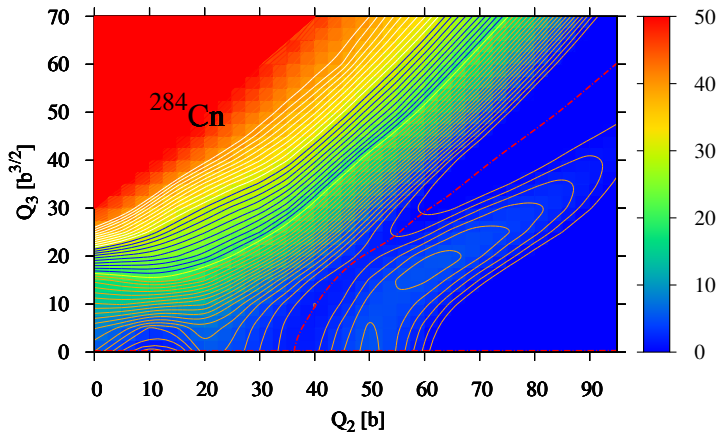


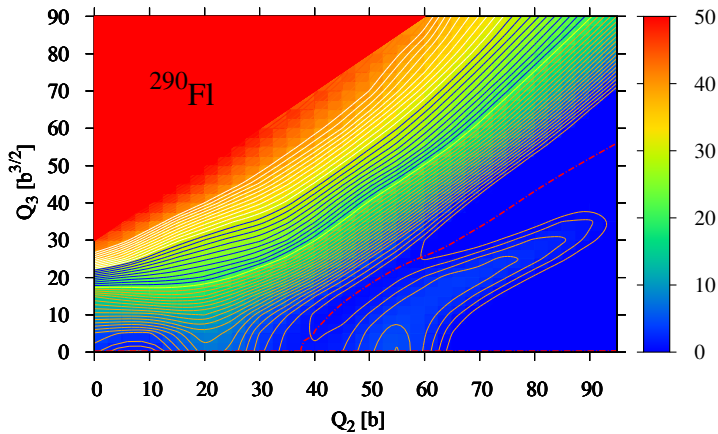


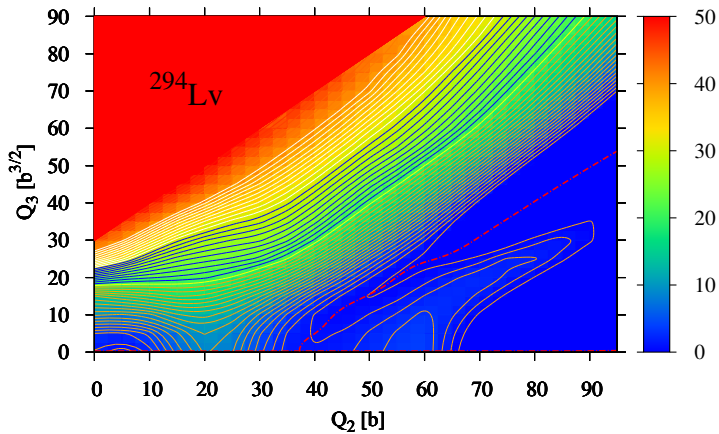






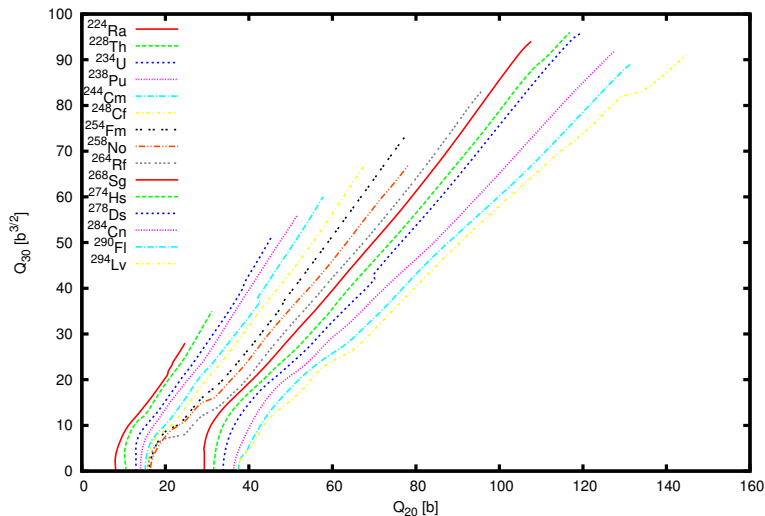


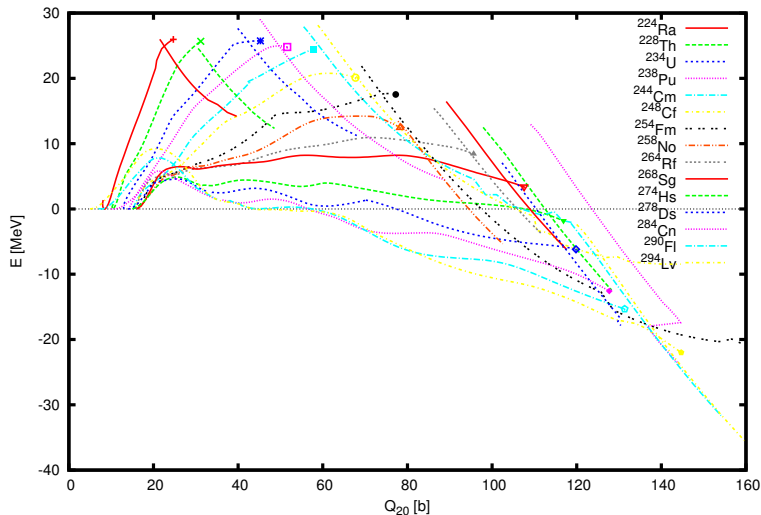






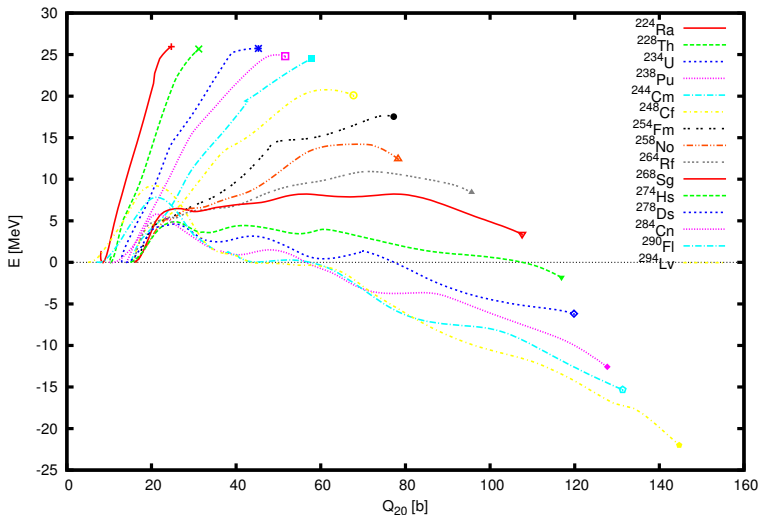
Cluster barriers



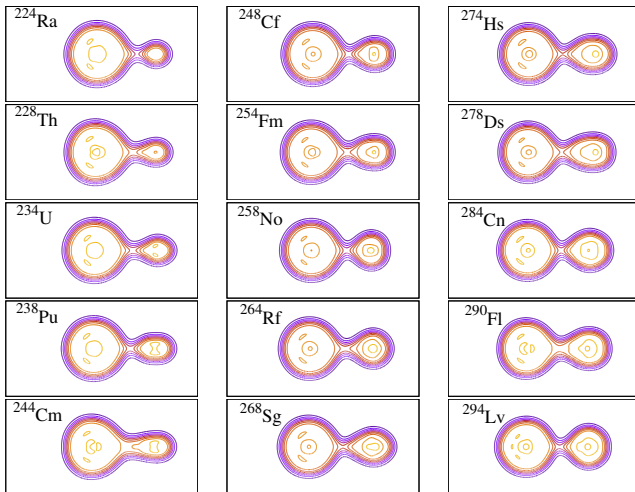




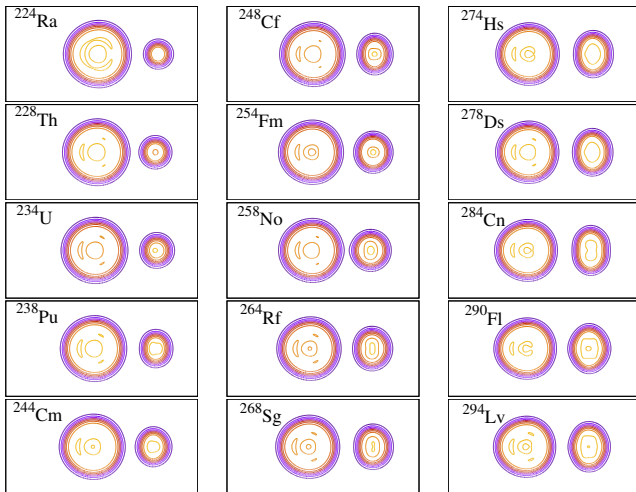
Cluster barriers

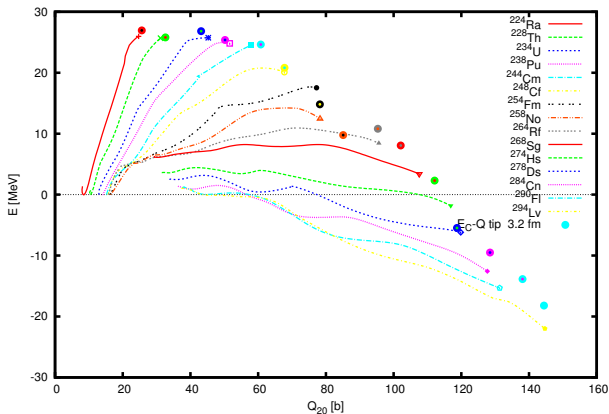


Pre-scission shapes

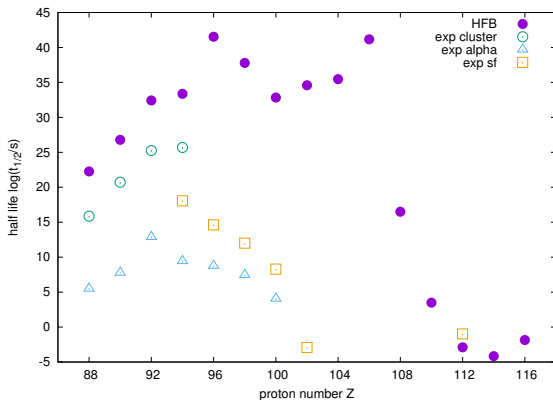


Post-scission shapes





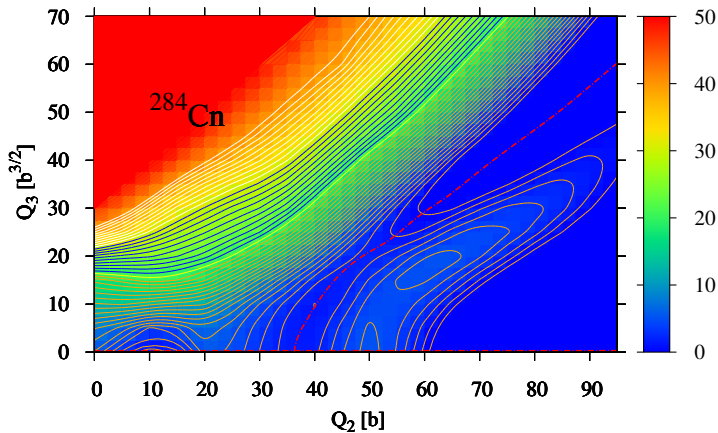
$$E = k \frac{82(Z - 82)e^2}{r_{208} + r_{A-208} + d} - Q$$

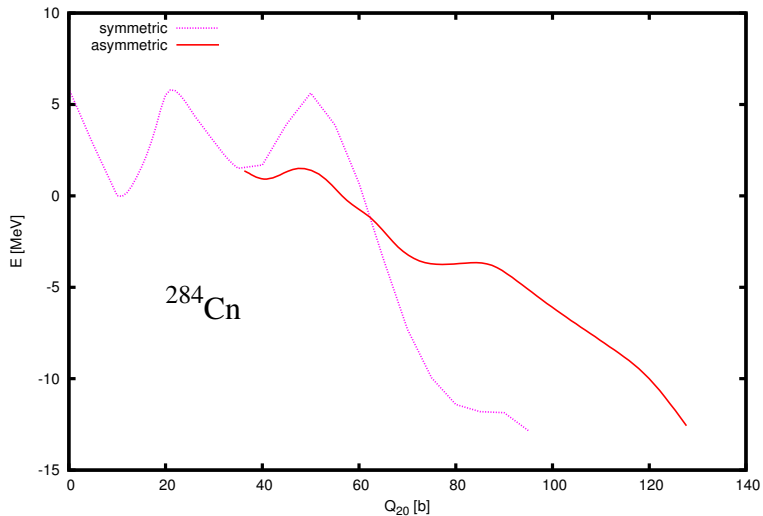


Experimental evidence in ^{284}Cn :

- GSI: 9 events
Ch. Düllmann, et al., Phys.Rev.Lett. 104, 252701 (2010)
- Dubna: 19 events
Yu. Oganessian, Radiochim.Acta 99, 429 (2011)
- lifetimes: 30 ms - 400 ms







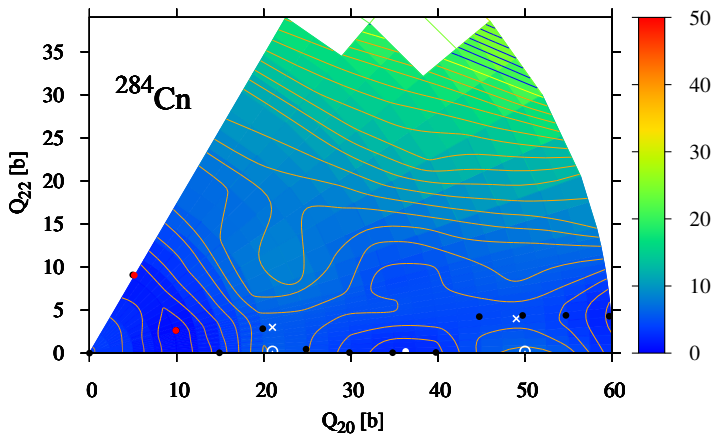
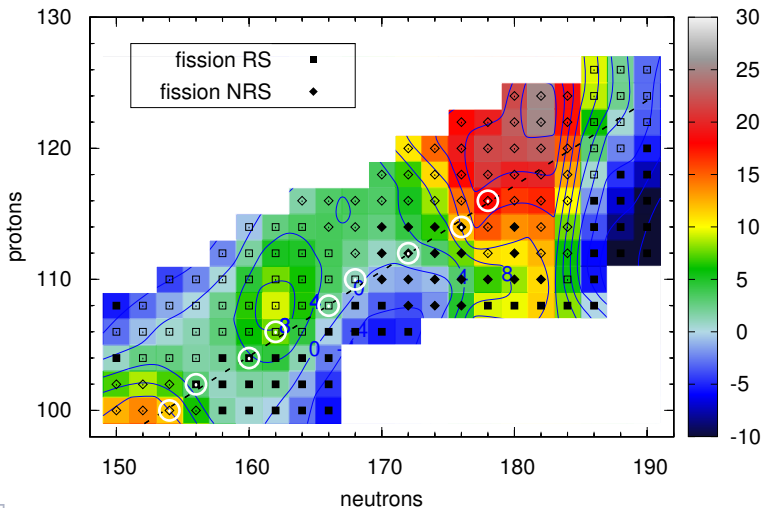
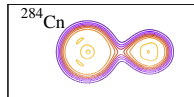
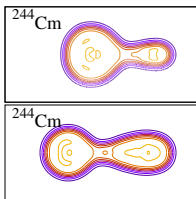
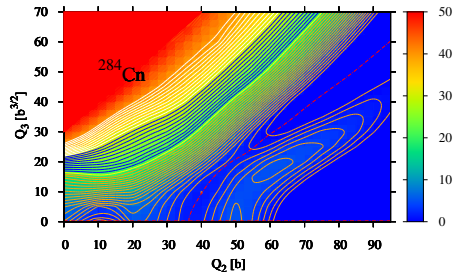
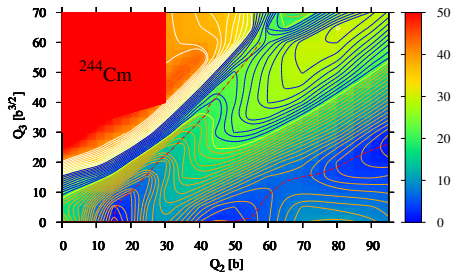


Chart of SH nuclides



Actinides and superheavies



- Asymmetric fission in super heavy nuclei region has the same nature as cluster radioactivity in actinides
- This decay may be dominant in some super heavy nuclei
- Sharp fragment mass distribution with ^{208}Pb fragment is predicted



