

Cluster radioactivity in heavy and super-heavy nuclei

Michał Warda

Uniwersytet Marii Curie-Skłodowskiej
Lublin, Poland

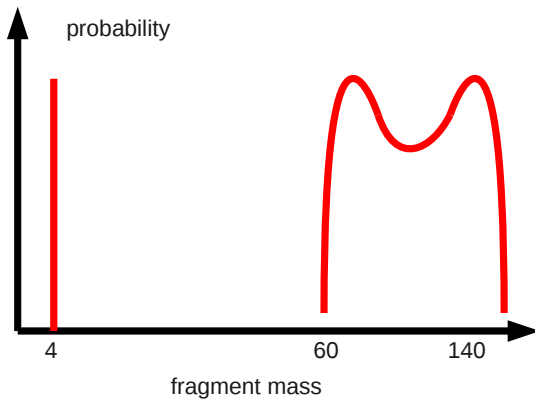
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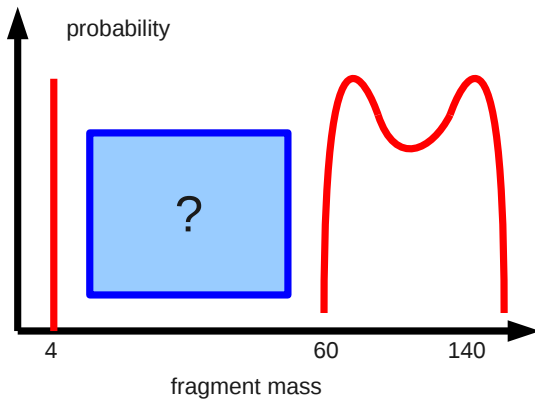
2nd Symposium on Intermediate-energy Heavy Ion Collisions
Beijing, 15.07.2024



- Luis M. Robledo, UAM, Madrid
- Rayner Rodriguez Guzman, NU, Astana
- Anna Zdeb, UMCS, Lublin
- Krzysztof Pomorski, UMCS, Lublin









Discovery of cluster radioactivity

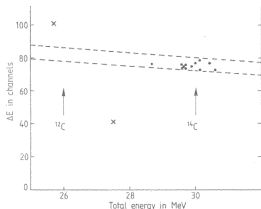
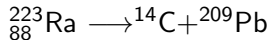


Fig. 1 Contents of the two-dimensional array ΔE versus E_{total} after a run of 189 days. The dotted line indicates the allowed region for carbon ions and the arrows indicate the total energies expected for ^{12}C and ^{14}C emissions in the decay of ^{223}Ra . The lower of the two crosses represents 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 mm² active area, 8.2 μm sensitive thickness) was determined to lie between 0.3 and 0.8 μm . In addition a protective layer of gold of thickness 20 $\mu\text{g cm}^{-2}$ was evaporated on the source and 15 $\mu\text{g cm}^{-2}$ carbon film inserted between the source and the ΔE detector. An extra 30–40 $\mu\text{g cm}^{-2}$ of gold is present on the E -detector (300 mm² active area). This gives a total of 150–250 $\mu\text{g cm}^{-2}$ of effective dead layer (Si equivalent) and an energy loss of ^{14}C ions of 0.5–0.8 MeV. The source of strength 3.3 μCi gave a counting rate of $\approx 4,000 \text{ s}^{-1}$, corresponding to an effective solid angle of detection of $\approx 1/3 \text{ sr}$.

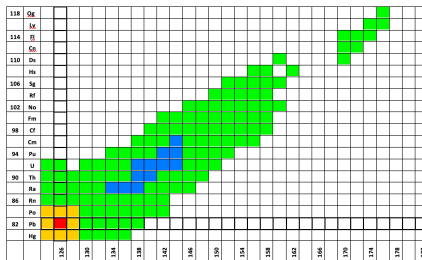


H.J. Rose and G.A. Jones, *Nature* **307**, 245 (1984)

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

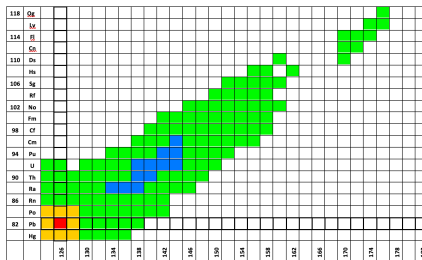
Cluster radioactivity: key facts

- Emitters: $^{221}_{87}\text{Fr}$ — $^{242}_{96}\text{Cm}$
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} s — 10^{26} s
- α branching ratio: 10^{-9} — 10^{-16}



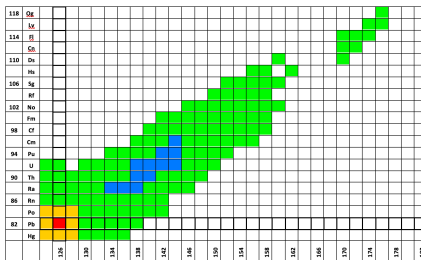
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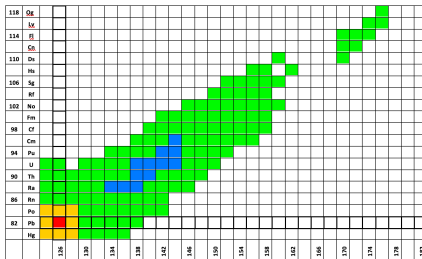
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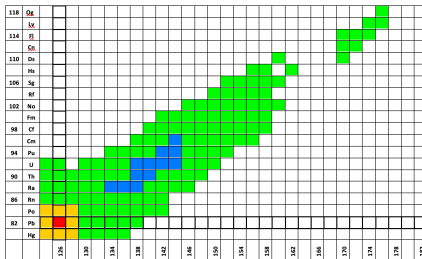
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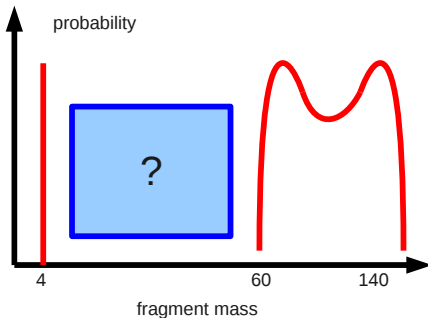


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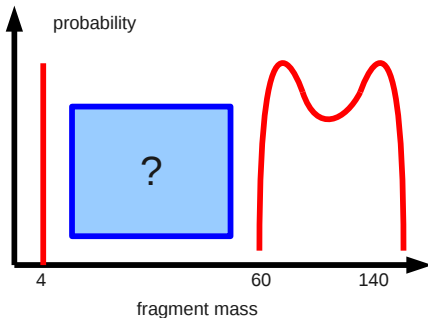
Theoretical description



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



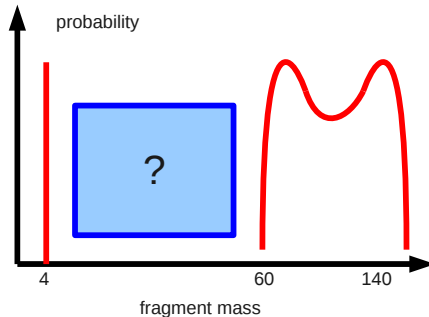
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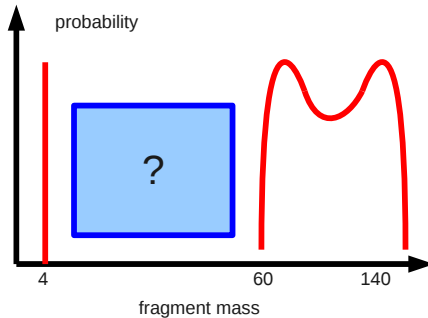
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Potential energy surface in fission

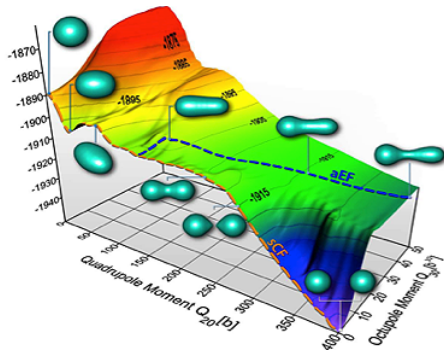
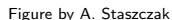
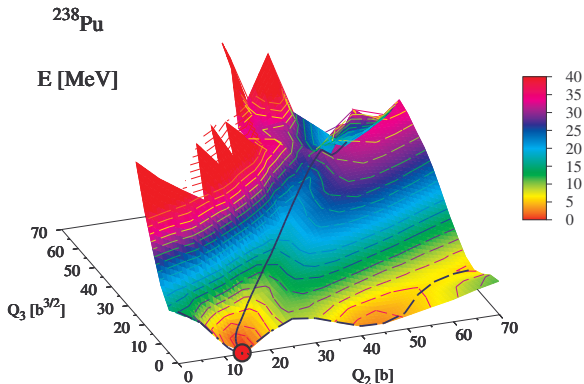
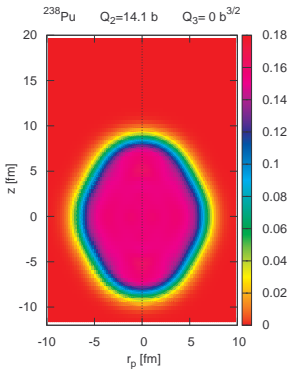


Figure by A. Staszczak



- Next slides show potential energy surfaces determined in the self-consistent method in HFB theory with Gogny D1S force

Shape evolution: ^{238}Pu



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

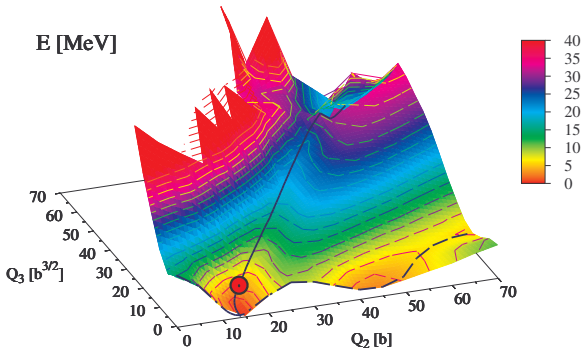
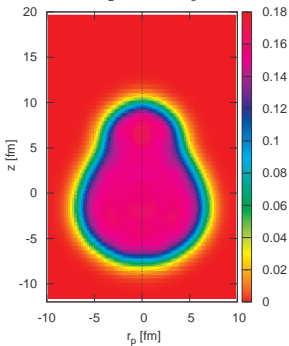
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Shape evolution: ^{238}Pu

^{238}Pu

^{238}Pu $Q_2=17.3 \text{ b}$ $Q_3=10 \text{ b}^{3/2}$



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

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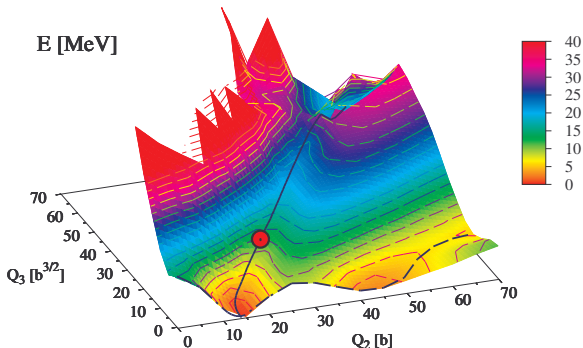
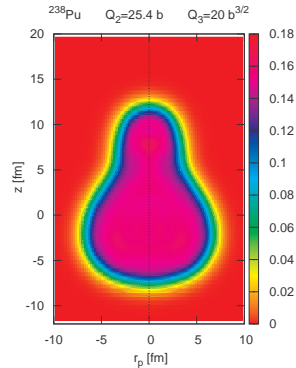
Shape evolution: ^{238}Pu

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E [MeV]

Q_3 [$\text{b}^{3/2}$]

Q_2 [b]



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

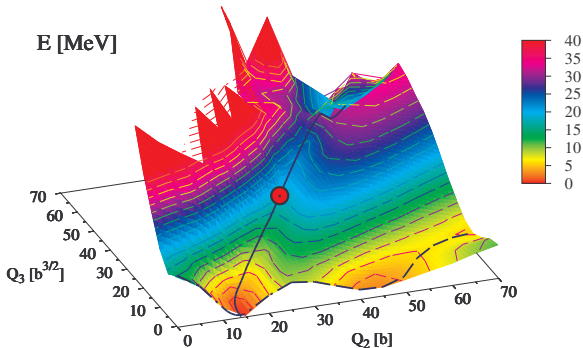
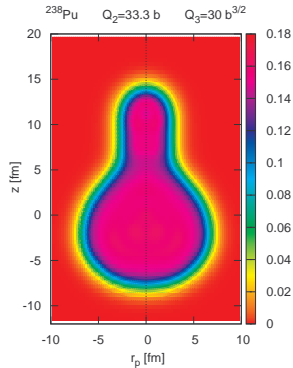
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Shape evolution: ^{238}Pu

^{238}Pu

E [MeV]

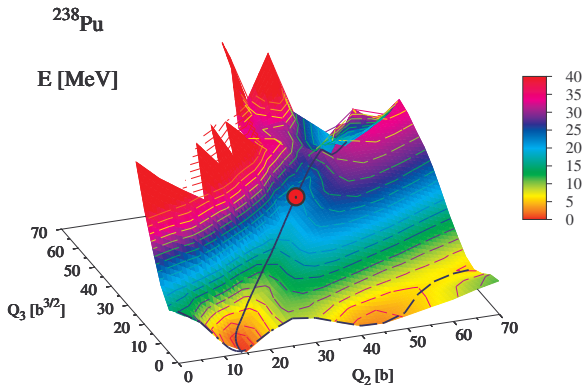
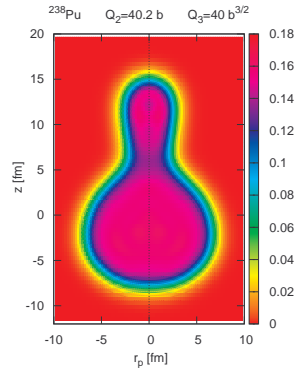


M. Warda and L. M. Robledo, Phys. Rev. C 84, 044608 (2011)

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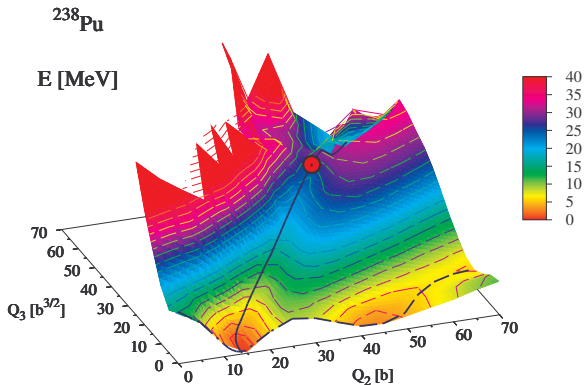
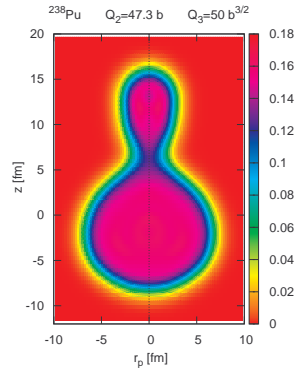
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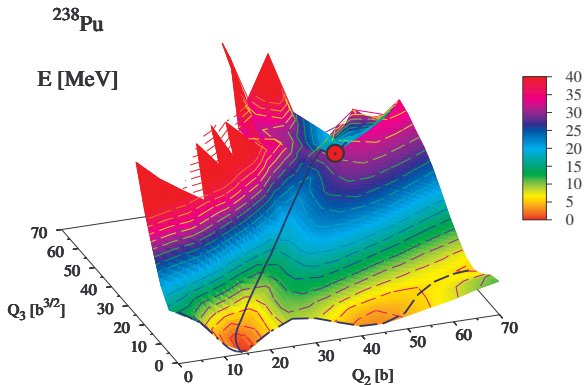
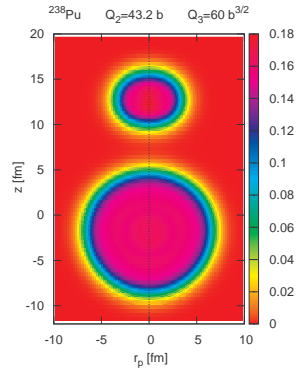
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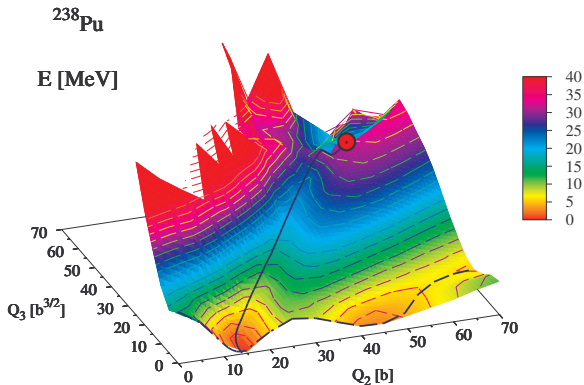
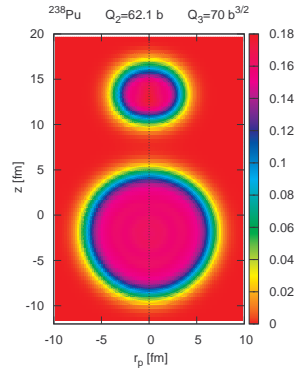


M. Warda and L. M. Robledo, Phys. Rev. C 84, 044608 (2011)

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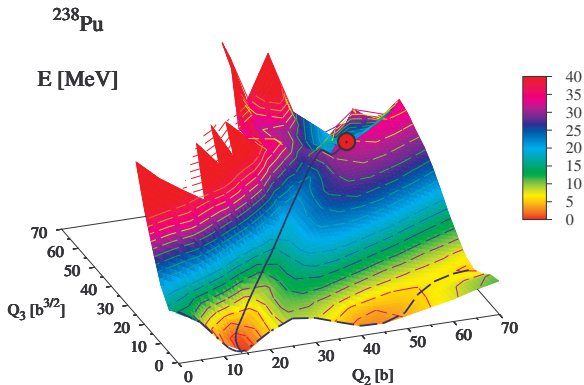
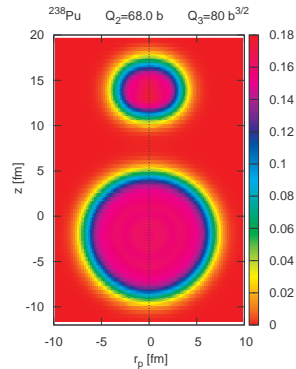


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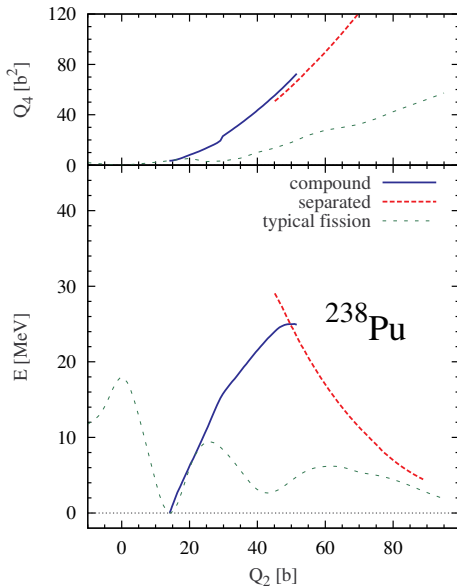
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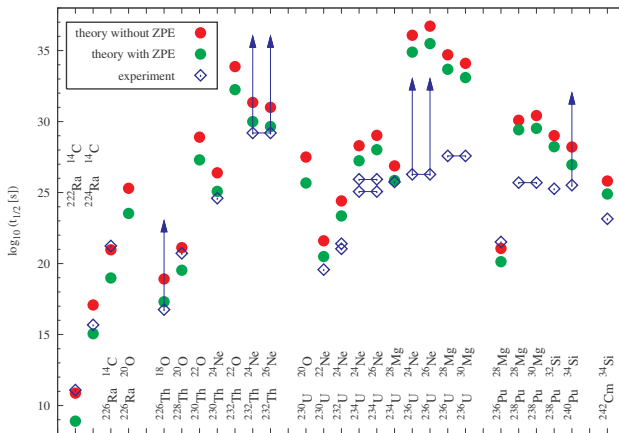
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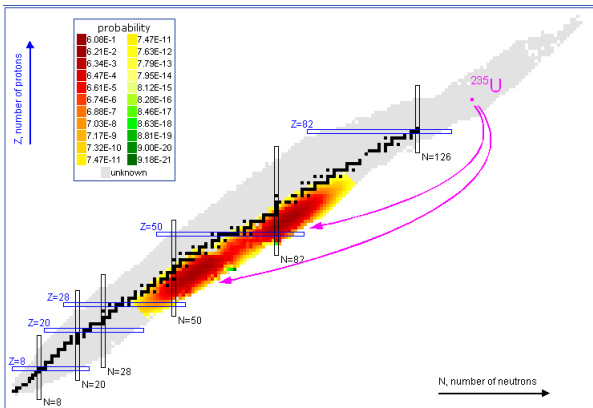
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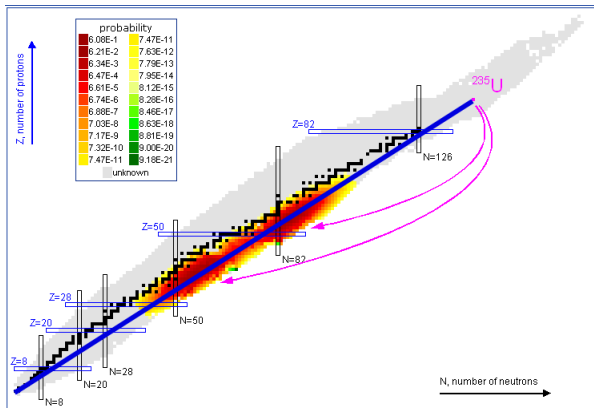


Fission fragments - N/Z ratio



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

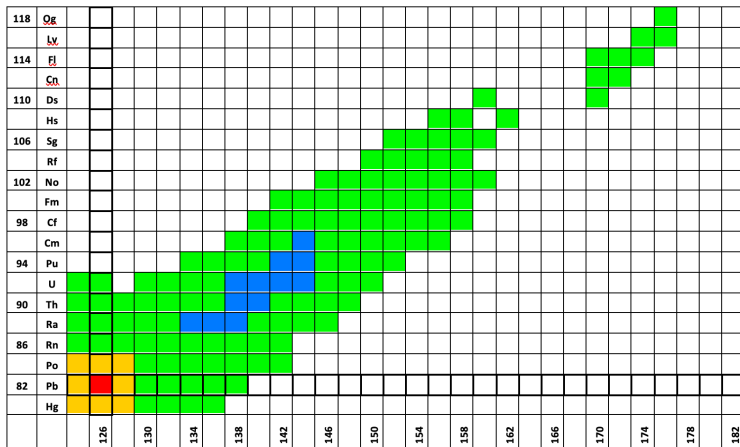
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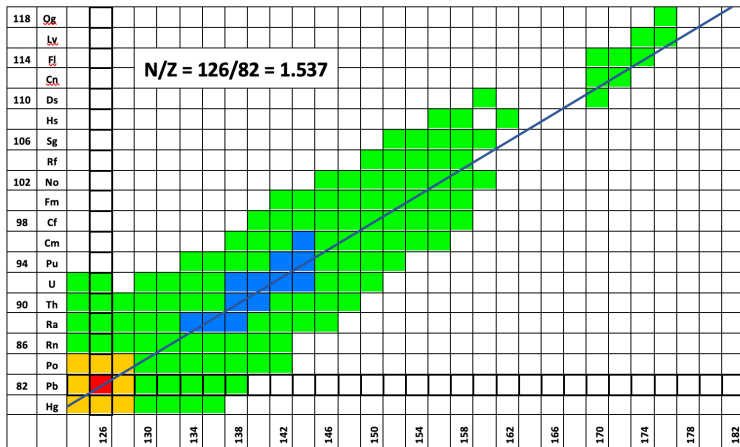


Cluster radioactivity - chart of nuclides





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Cluster radioactivity - chart of nuclides

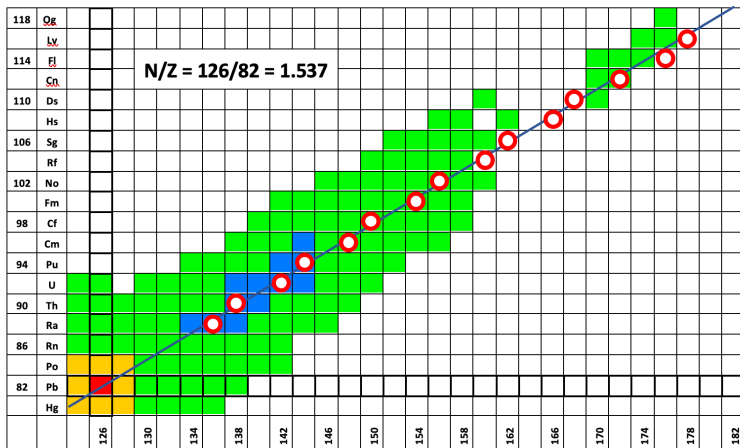
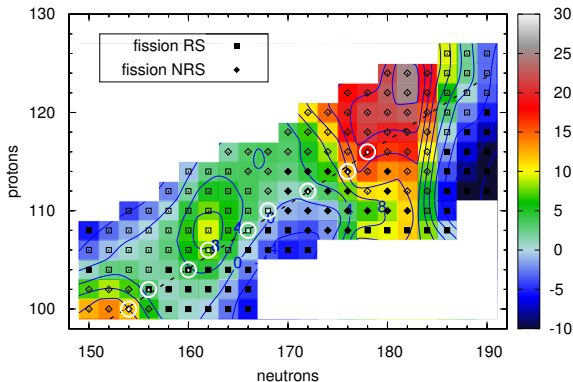


Chart of SH nuclides



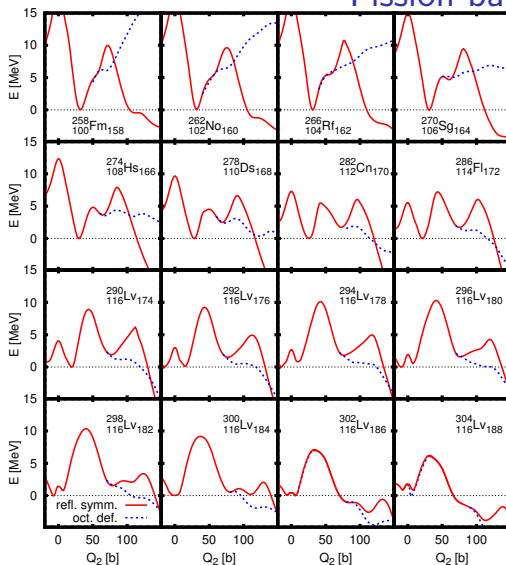
M. Warda, J.L. Egido, Phys. Rev. C 86 (2012) 014322

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



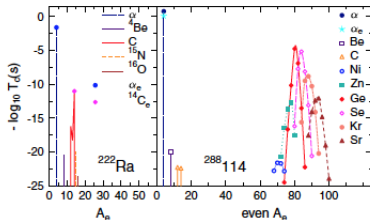
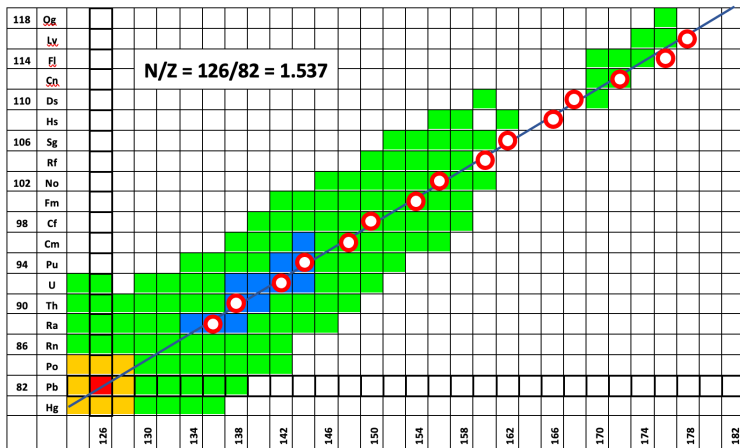


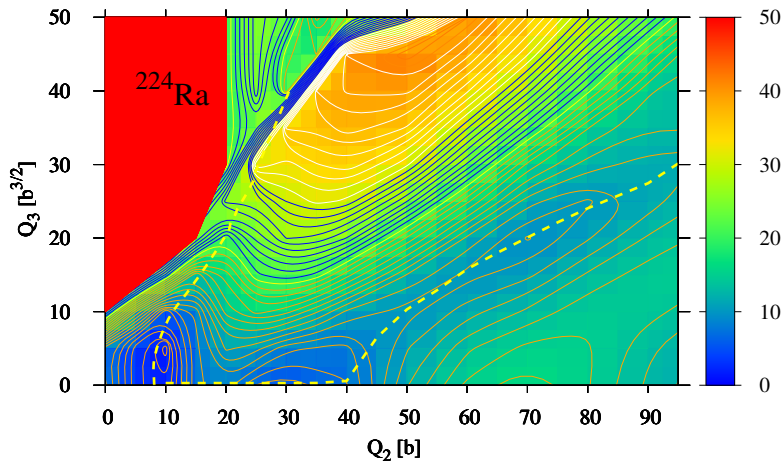
FIG. 1 (color online). Time spectra of different cluster emissions from ^{222}Ra (left panel) and from the superheavy nucleus $^{288}114$ (right panel). The most probable emitted clusters from ^{222}Ra and $^{288}114$ are ^{14}C and ^{80}Ge , respectively, both leading to ^{208}Pb daughter nucleus.

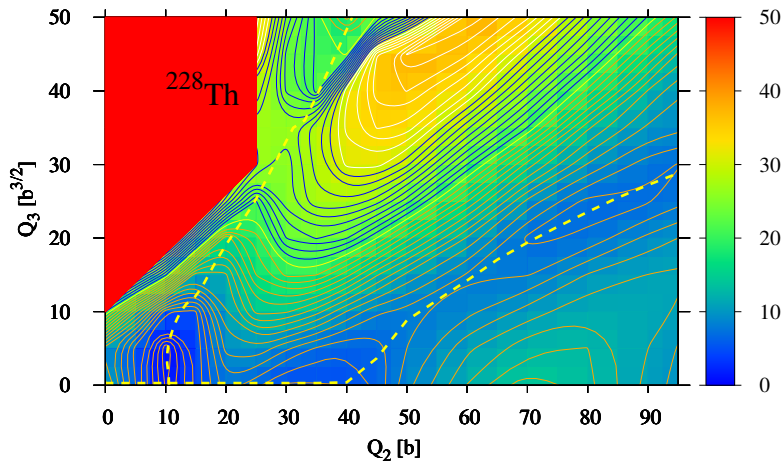
D. N. Poenaru, R. A. Gherghescu, and W. Greiner
 Phys. Rev. Lett. 107, 062503 (2011); Phys. Rev. C 85, 034615 (2012)

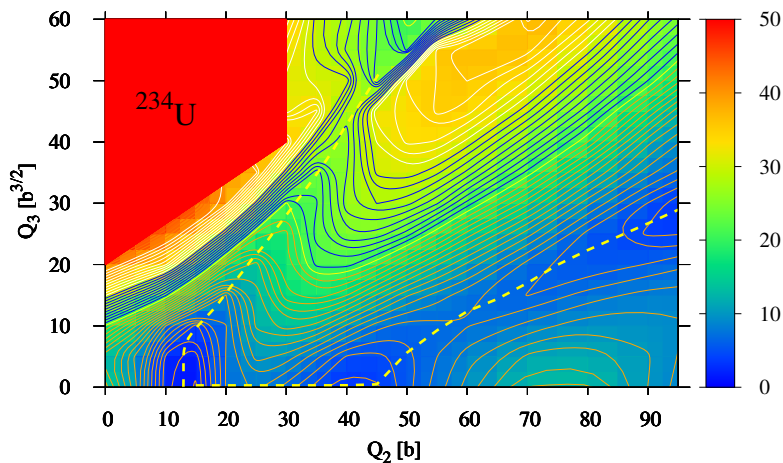


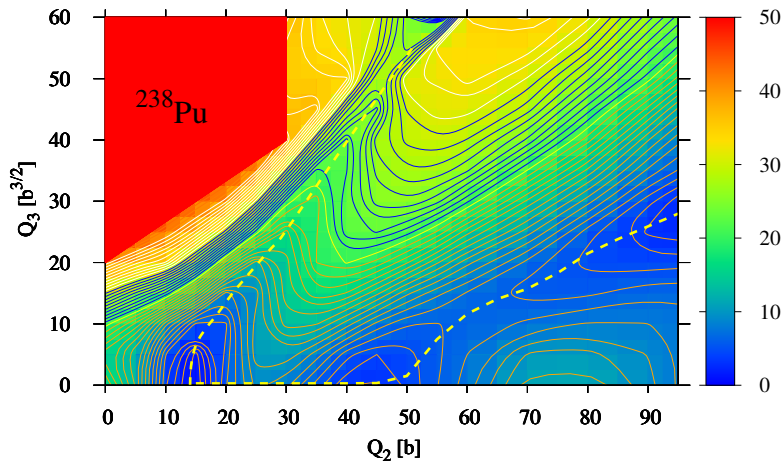
Cluster radioactivity - chart of nuclides

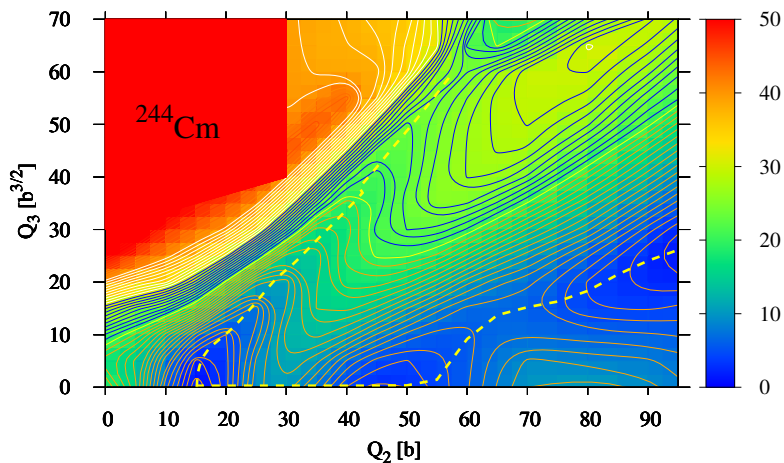


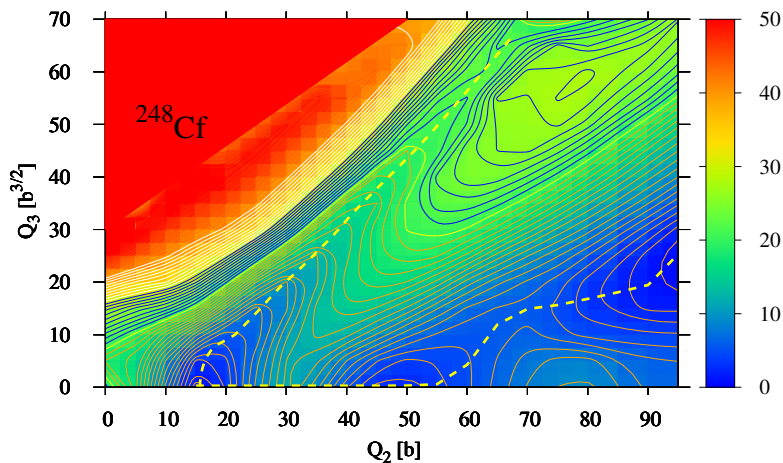


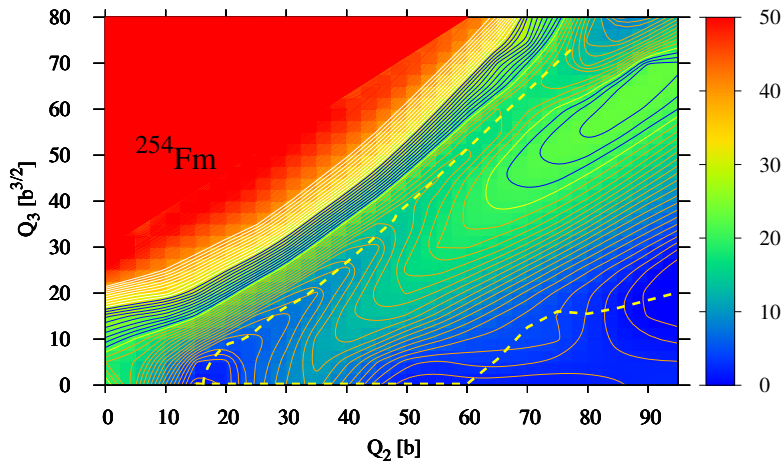


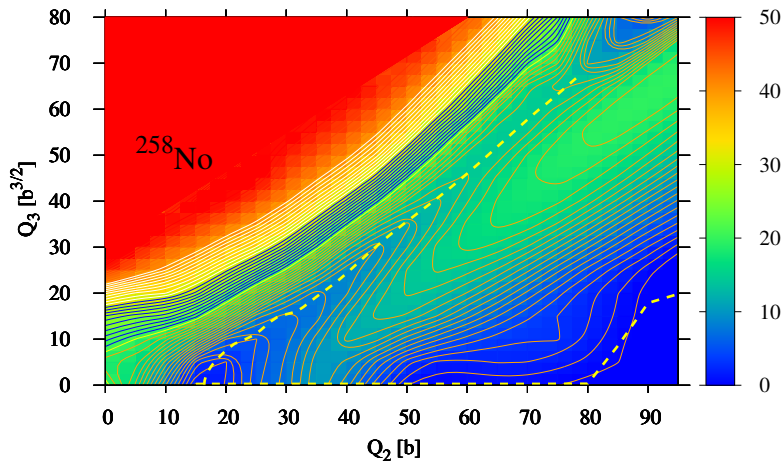


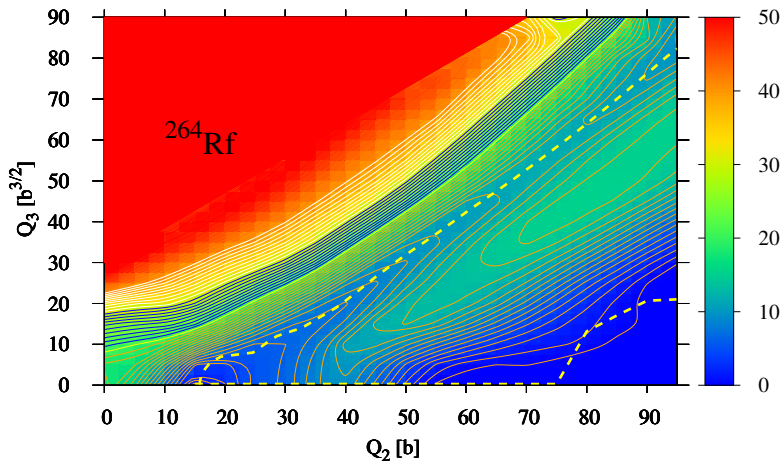


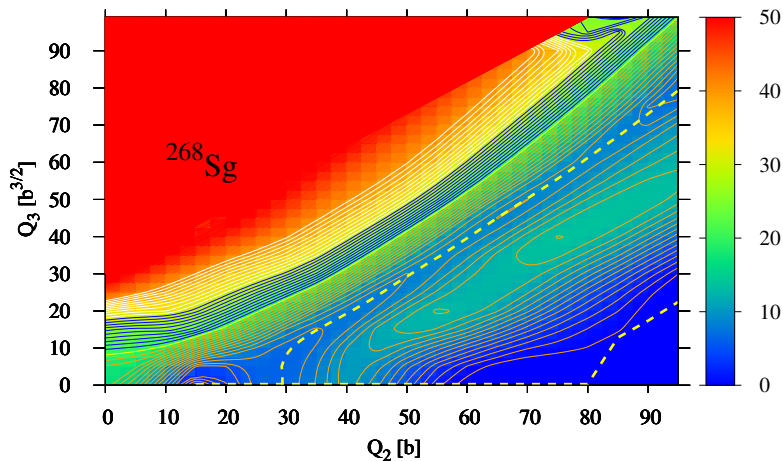


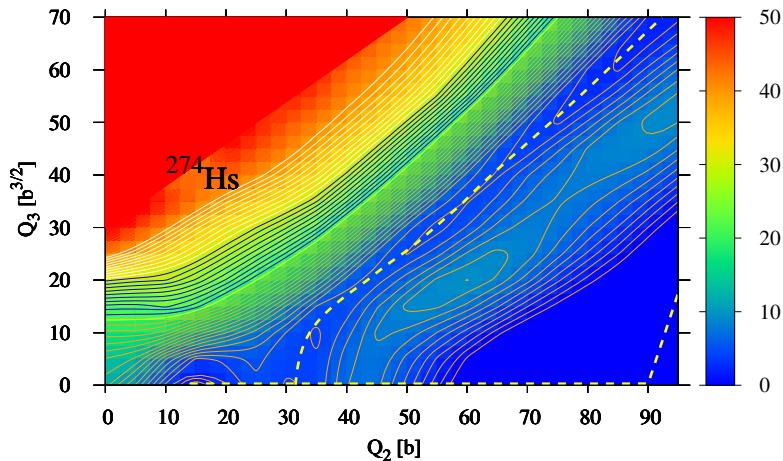


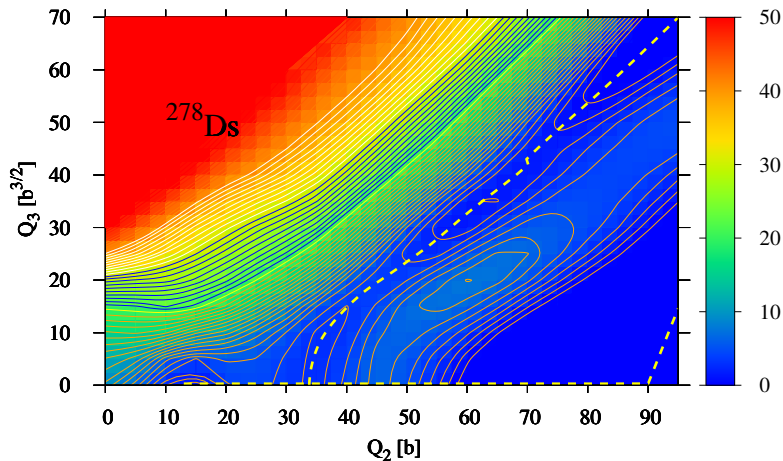


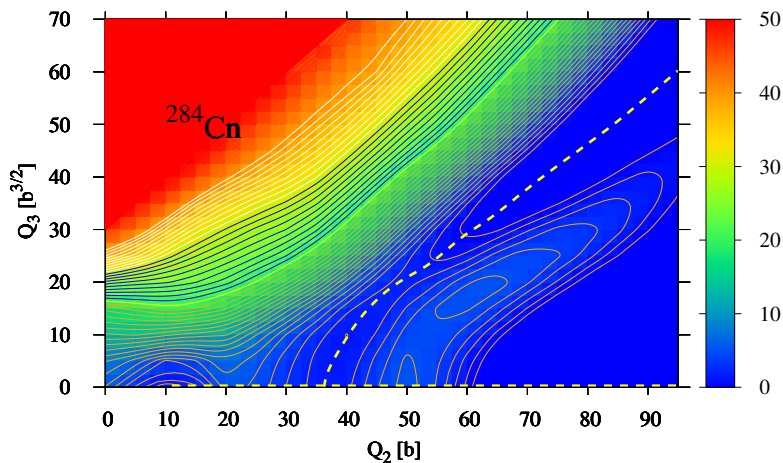


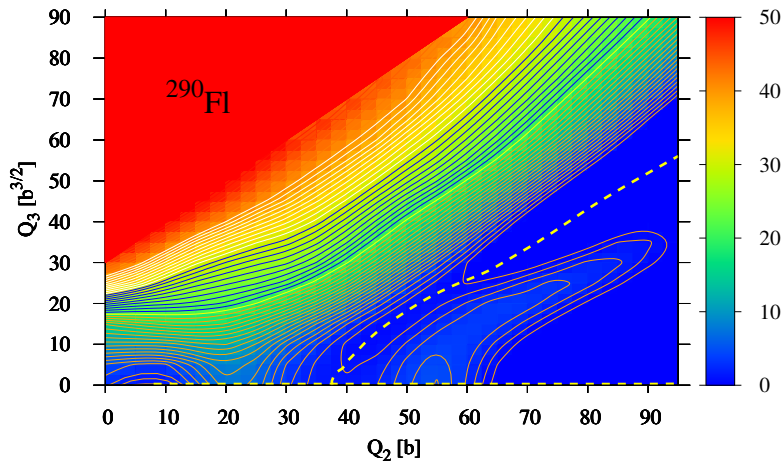


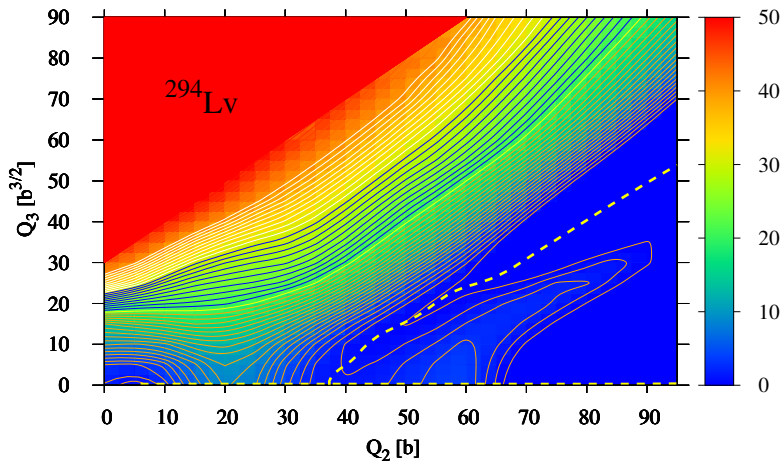






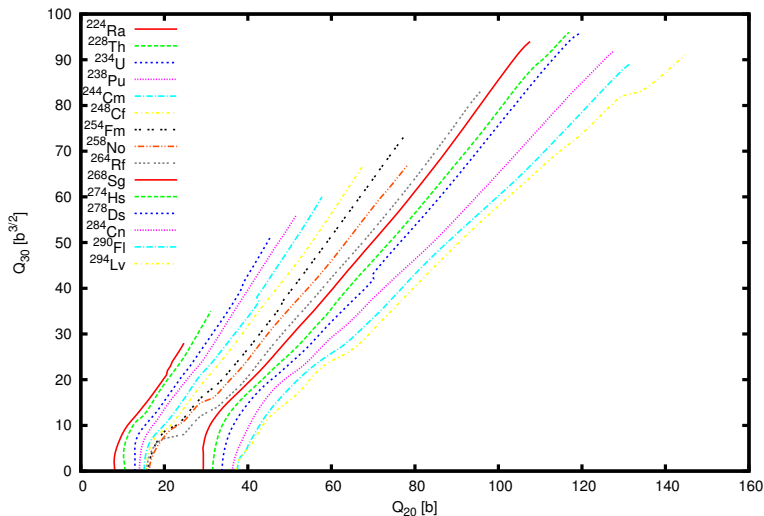


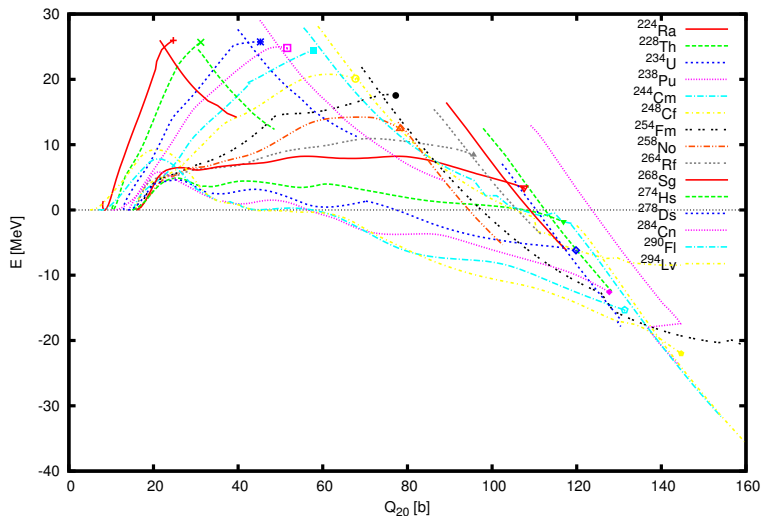






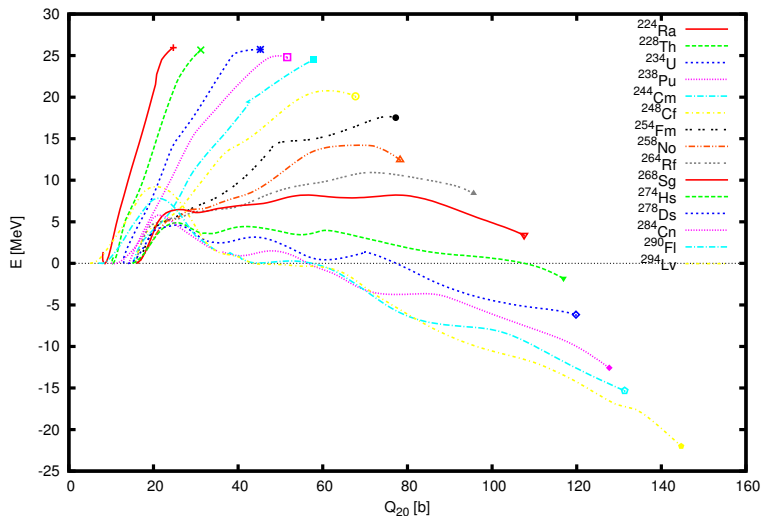
Cluster barriers



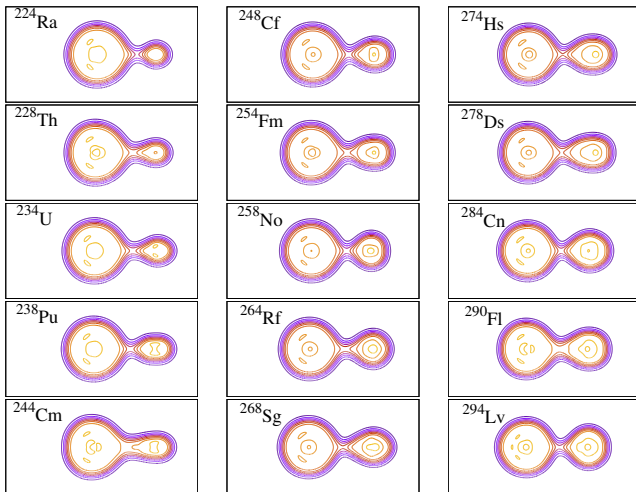




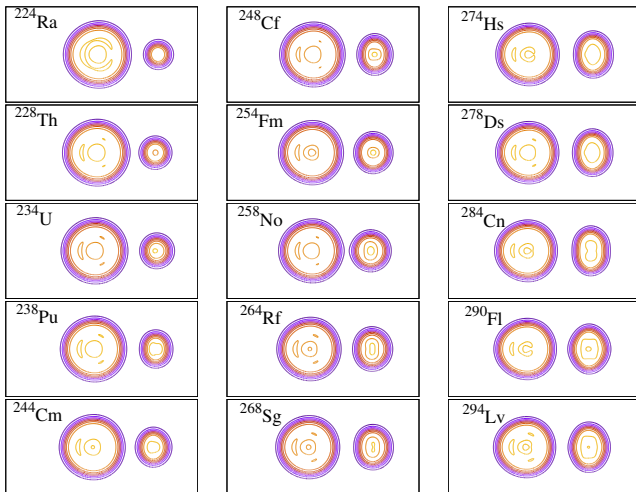
Cluster barriers

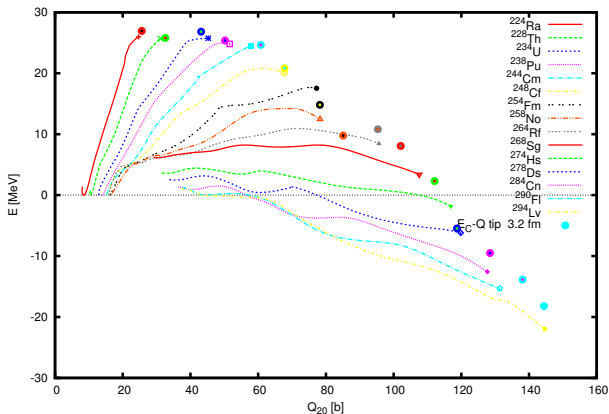


Pre-scission shapes

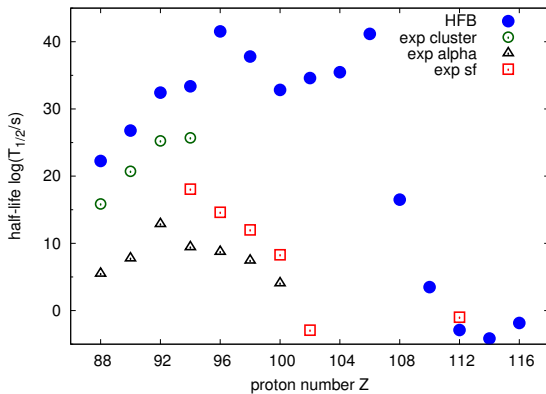


Post-scission shapes





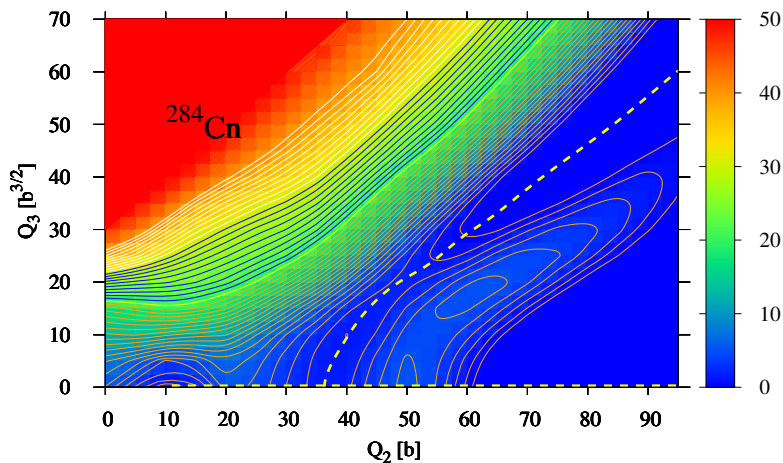
$$E = k \frac{82(Z - 82)e^2}{r_{208} + r_{A-208} + d} - Q$$



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





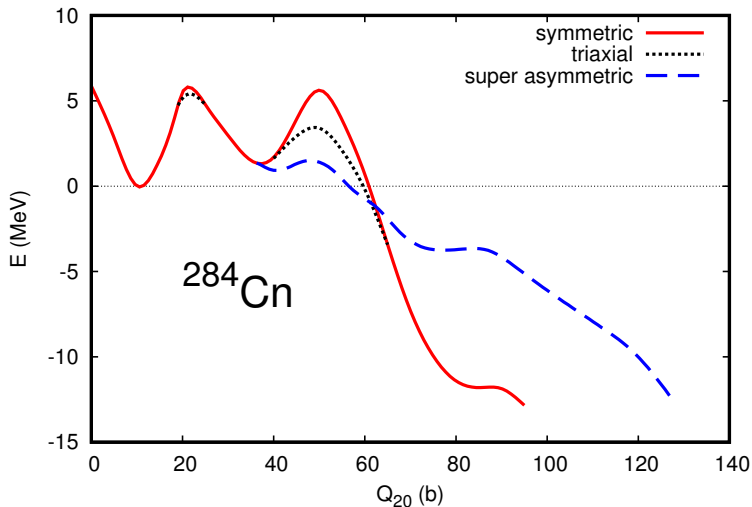
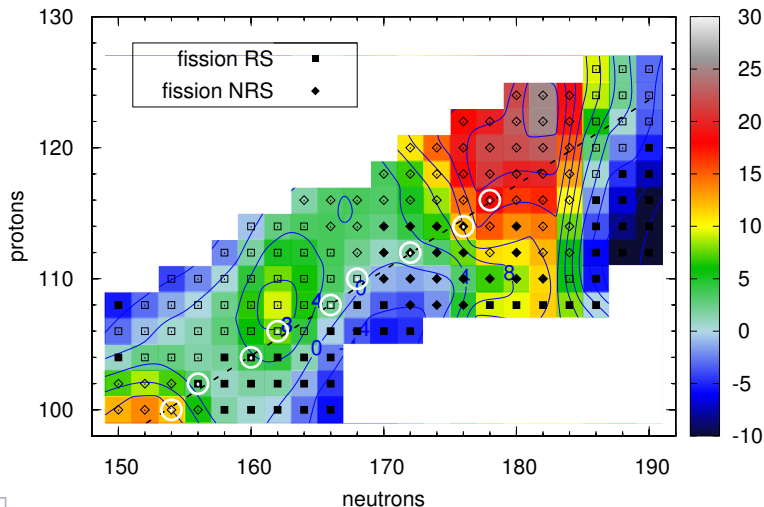
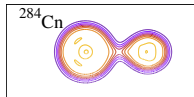
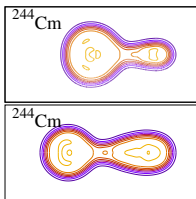
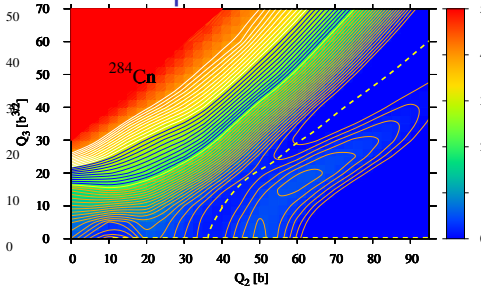
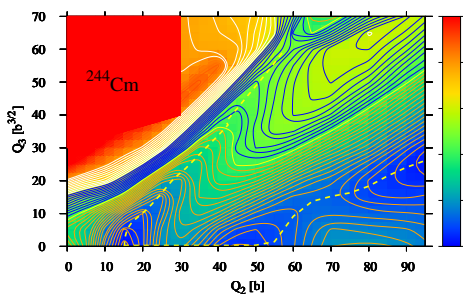


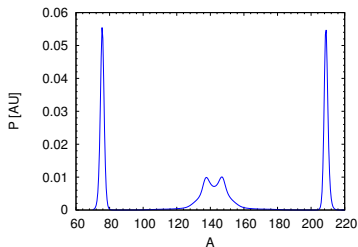
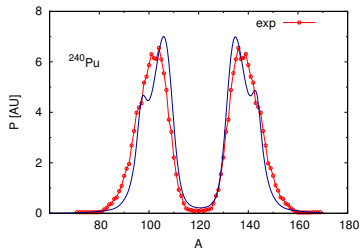
Chart of SH nuclides



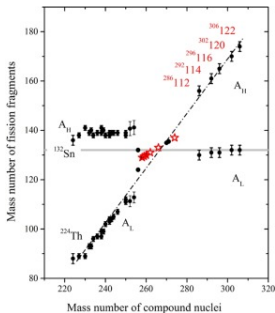
Actinides and superheavies



Fragment mass distribution



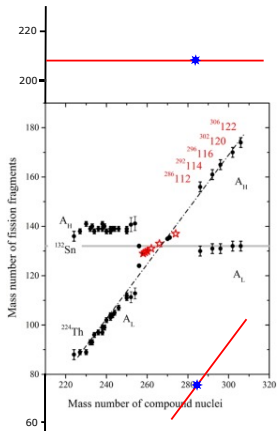
Mean fission fragment mass



M.G.Itkis, E.Vardaci, I.M.Itkis, G.N.Knyazheva, E.M.Kozulin, Nuclear Physics A944 (2015) 204



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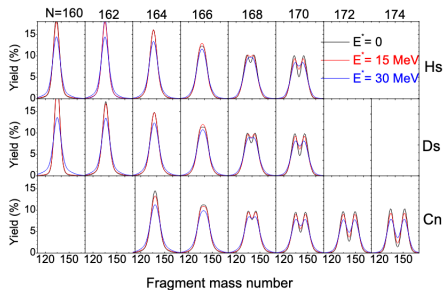


FIG. 3. The calculated fragment mass distributions for isotopes of Hs, Ds, and Cn for which spontaneous fission has been detected. Three values of the excitation energy E^* have been considered. $T_{\text{coll}} = 2$ MeV, $E_d = 40$ MeV.

N. Carjan, F. A. Ivanyuk, and Yu. Ts. Oganessian Phys. Rev. C 99, 064606 (2019)



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

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