Cluster radioactivity fission valleys along isotopic and isotonic chains of heavy and super-heavy nuclei.

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Collaboration:

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- A. Zdeb, UMCS, Lublin
- R. Rodriguez-Guzman, Nazarbayev University, Astana

Cluster radioactivity: key facts

Cluster radioactivity is a type of radioactive decay in which an atomic nucleus emits a light nucleus (heavier than α particle) – cluster of protons and neutrons.

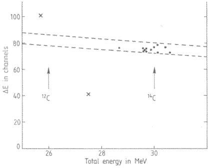


Fig. 1 Contents of the two-dimensional array ΔE versus E_{total} after a run of 189 days. The dotted line indicates the allowed region for carbon ions and the arrows indicate the total energies expected for ^{12}C and ^{14}C emissions in the decay of ^{223}Ra. The lower of the two crosses represents 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 deadtime 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 $\Delta E \equiv 6.7$ 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 µm sensitive thickness) was determined to lie between 0.3 and 0.8 µm. In addition a protective layer of gold of thickness 20 µg cm^{-2} was evaporated on the source and 15 µg cm^{-2} carbon film inserted between the source and the ΔE detector. An extra 30–40 µg cm^{-2} of gold is present on the E-detector (300 mm^2 active area). This gives a total of 150–250 µg 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 s^{-1}, corresponding to an effective solid angle of detection of $\approx 1/3$ sr.

$$^{223}_{88}\mathrm{Ra} \longrightarrow {}^{14}\mathrm{C} + {}^{209}\mathrm{Pb}$$

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

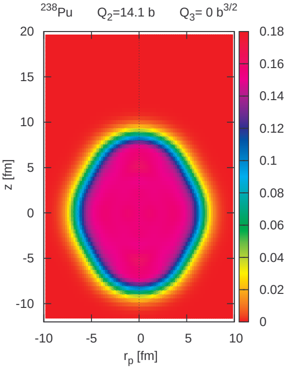
Theoretical description

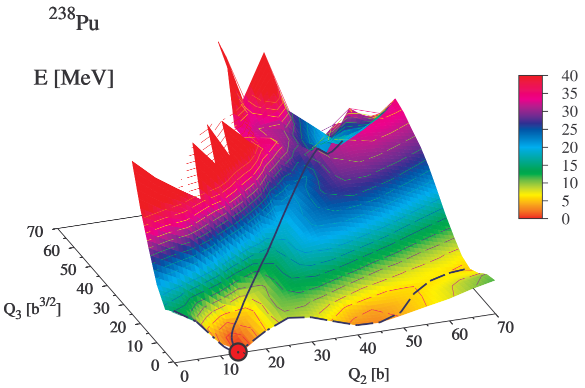
- Extrapolation of Gamov model of α emission
- Modified Geiger-Nuttall formula for half-lives

or

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

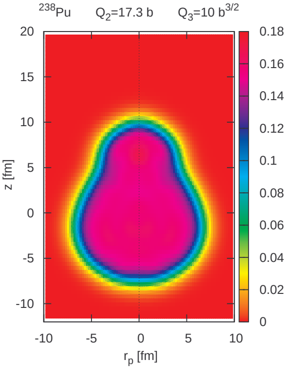
Shape evolution: ^{238}Pu

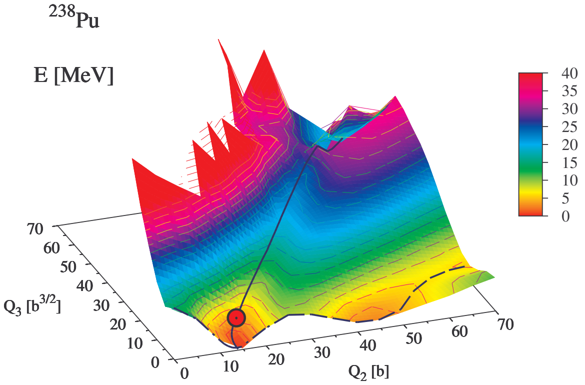




M. Warda and L. M. Robledo, Phys. Rev. C 84, 044608 (2011).

Shape evolution: ^{238}Pu





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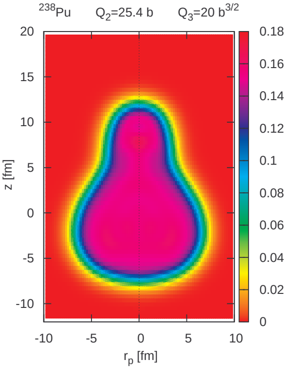

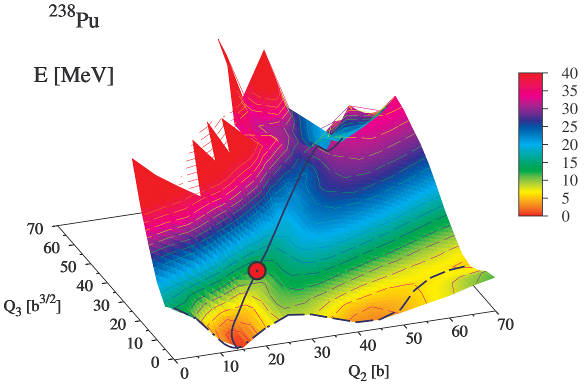

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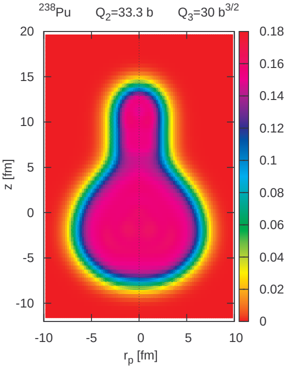

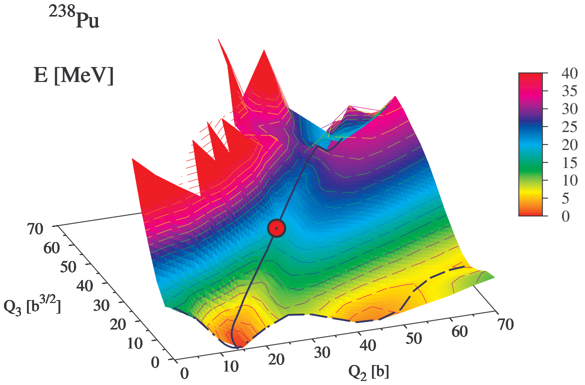

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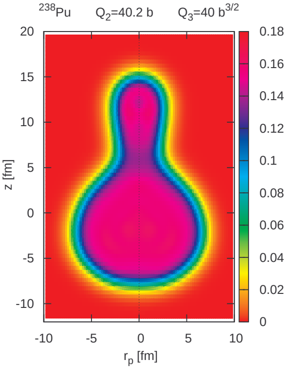

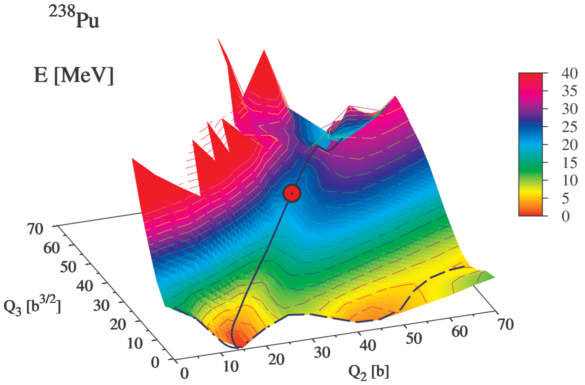

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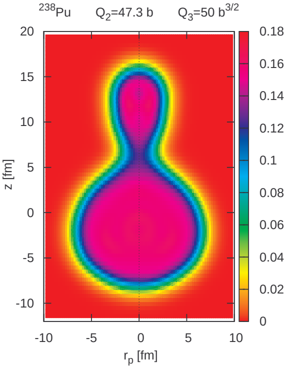

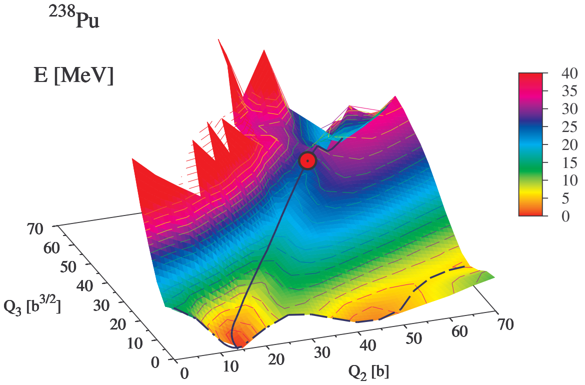

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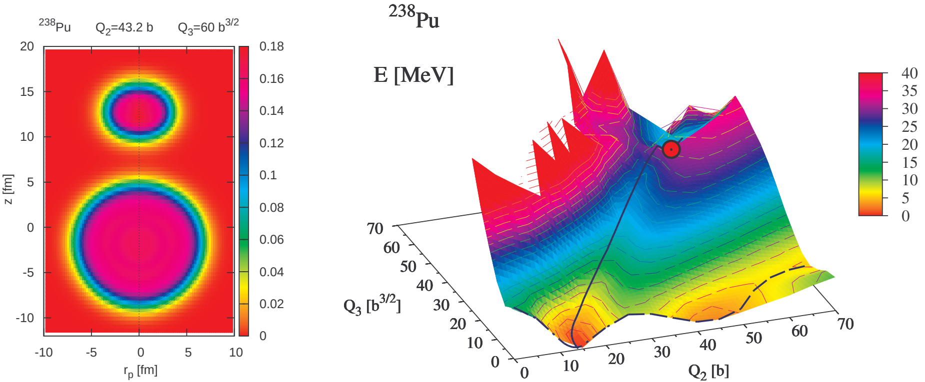
Shape evolution: ^{238}Pu



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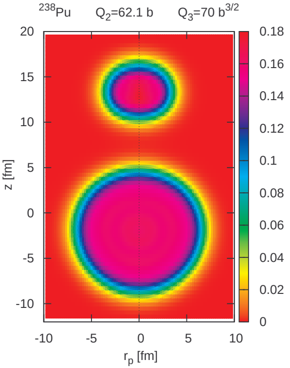

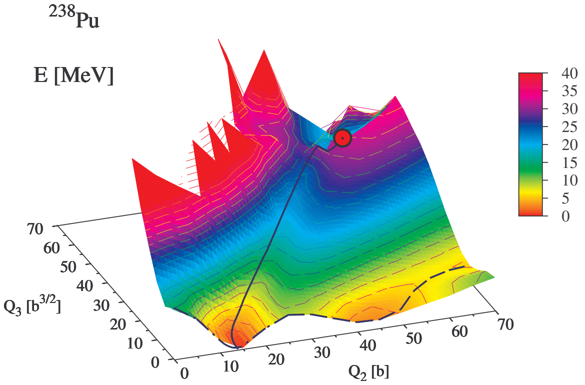

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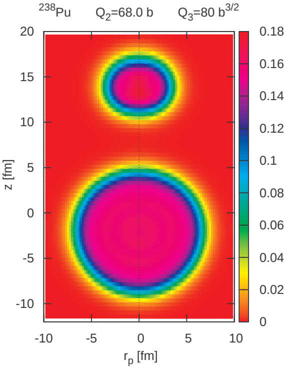

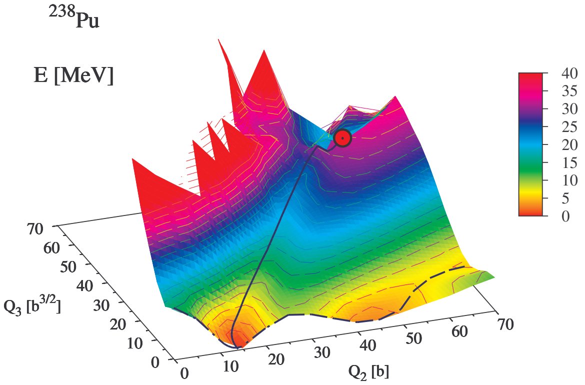

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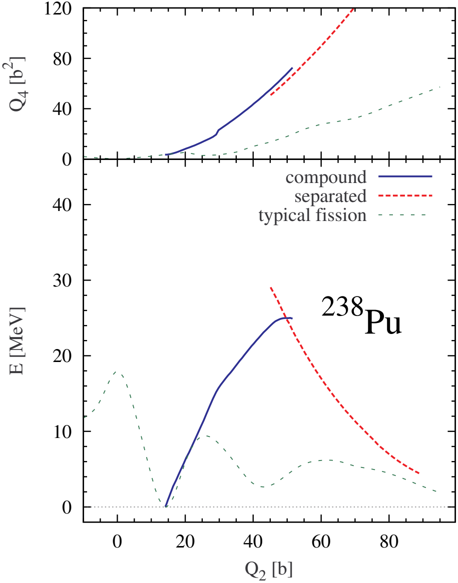
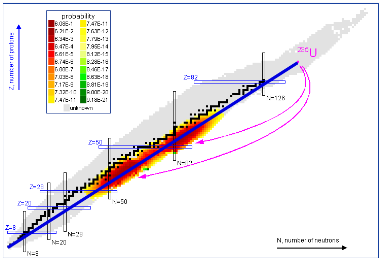
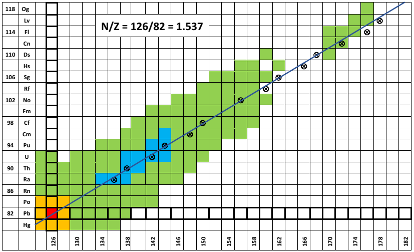


120
80
40
0
Q_4 [b^2]
compound
separated
typical fission
40
30
20
10
0
E [MeV]
^{238}Pu
0
20
40
60
80
Q_2 [b]

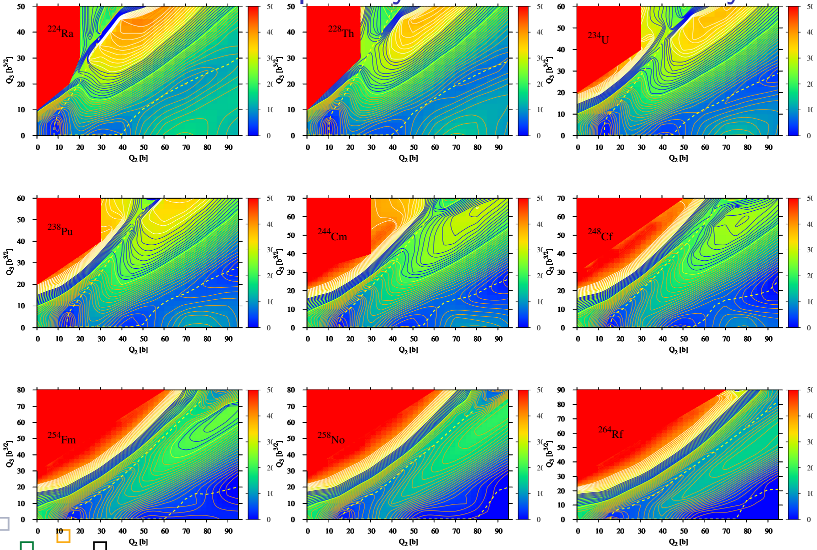
Fission fragments - N/Z ratio





M. Warda, A. Zdeb, and L. M. Robledo, Phys. Rev. C 98, 041602 (2018).

Super asymmetric fission valley



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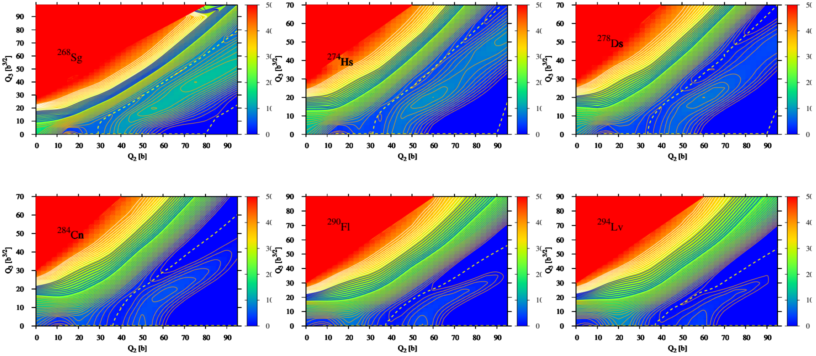
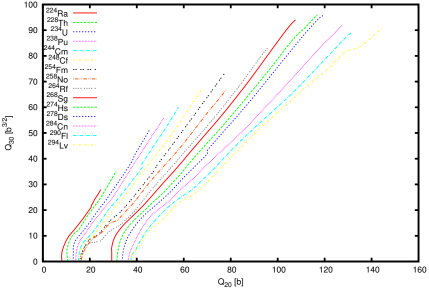
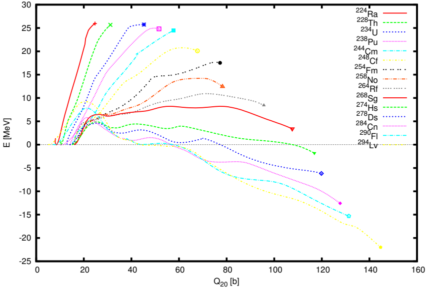
Super asymmetric fission valley



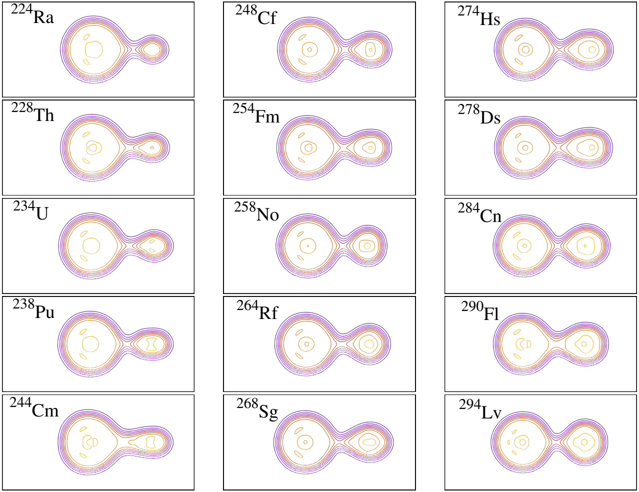
Cluster barriers



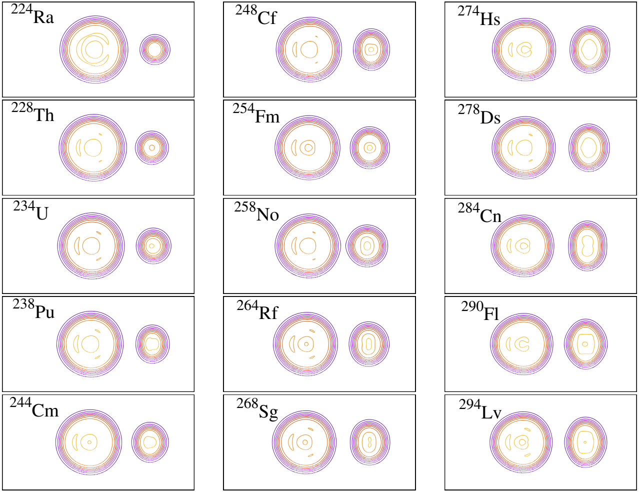


$$E = k\frac{82(Z-82)e^2}{r_{208} + r_{A-208} + d} - Q$$

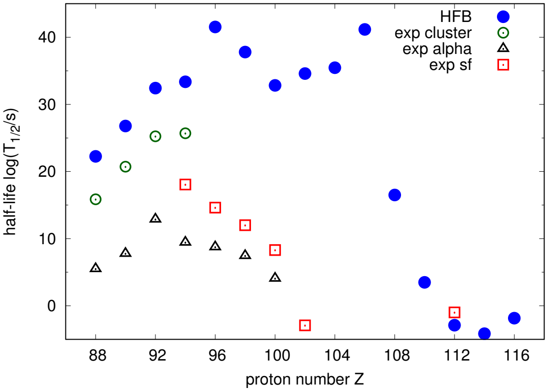
Pre-scission shapes



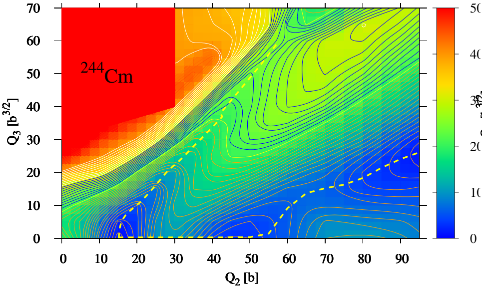
Post-scission shapes

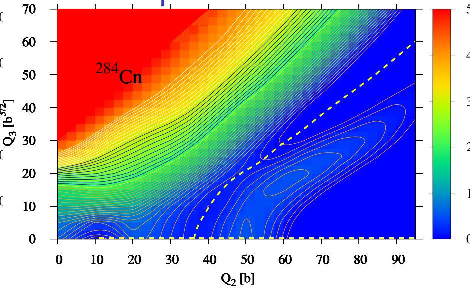


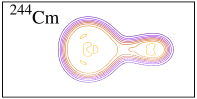
Half-llives

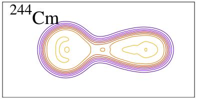

HFB
exp cluster
exp alpha
exp sf
half-life log($T_{1/2}$/s)
40
30
20
10
0
88
92
96
100
104
108
112
116
proton number Z

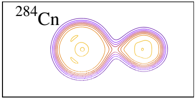
Actinides and superheavies



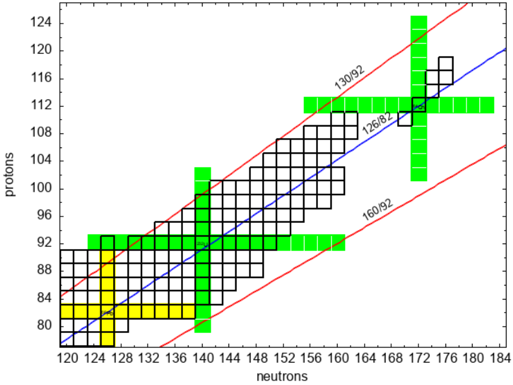




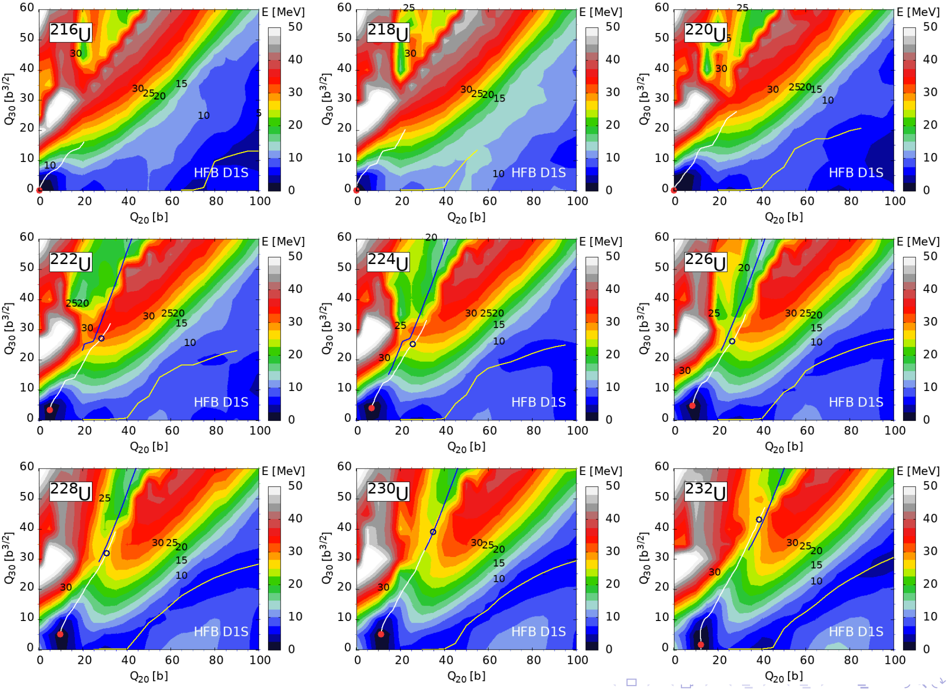




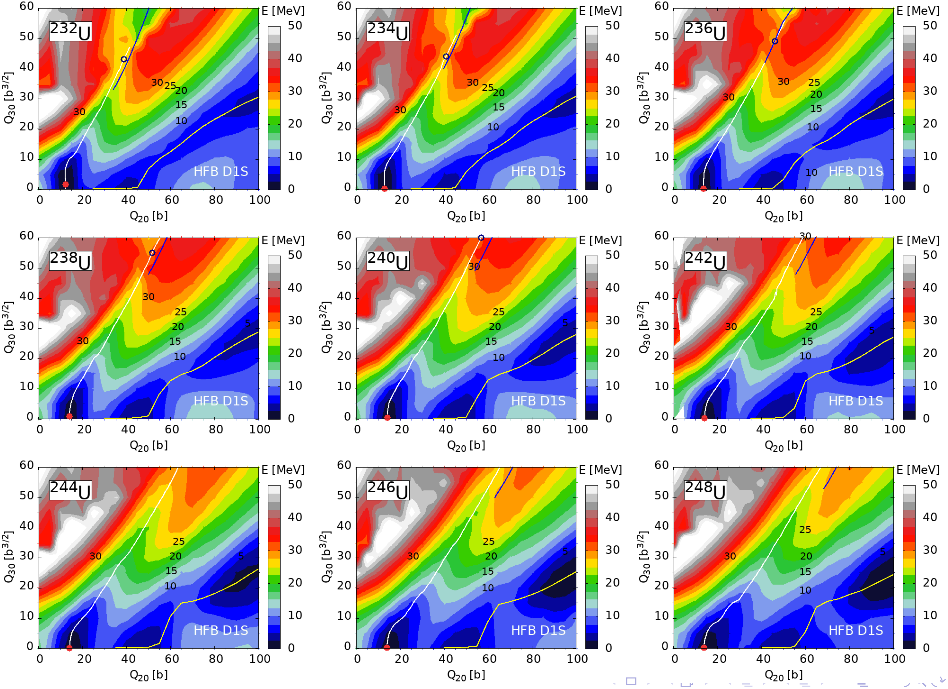
Isotopes and isobars



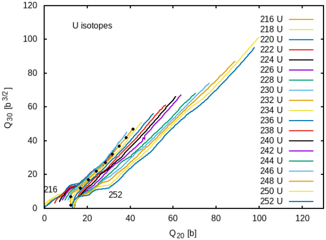
M. Warda, A. Zdeb, and R. Rodrguez-Guzmn, arXiv:2603.03519, Phys. Rev. C accepted

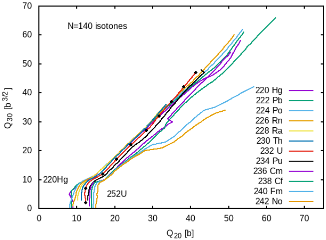


216U
218U
220U
222U
224U
226U
228U
230U
232U
HFB D1S
E [MeV]
Q30 [b3/2]
Q20 [b]

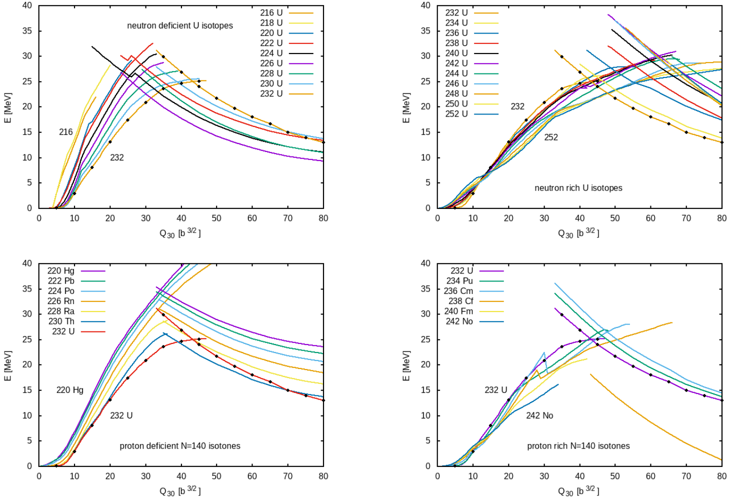

232U
234U
236U
238U
240U
242U
244U
246U
248U
HFB D1S
E [MeV]
Q30 [b3/2]
Q20 [b]

Fission paths around ^{232}U





Fission paths around ^{232}U



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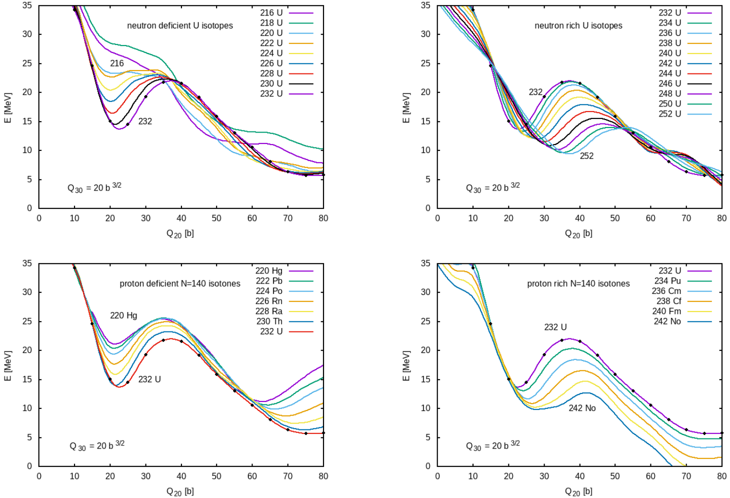
Fission paths around ^{232}U



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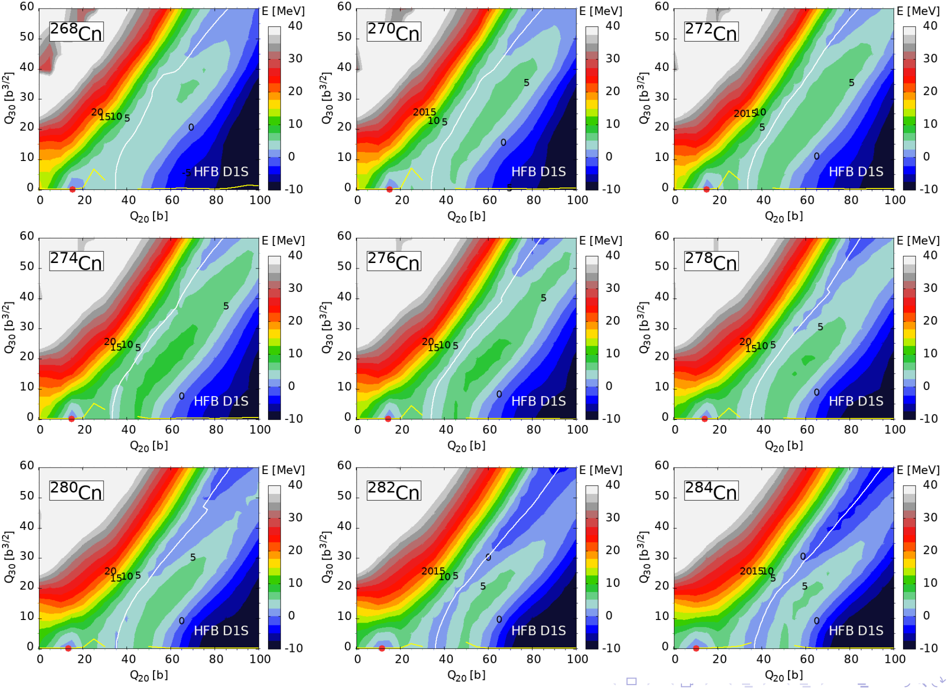
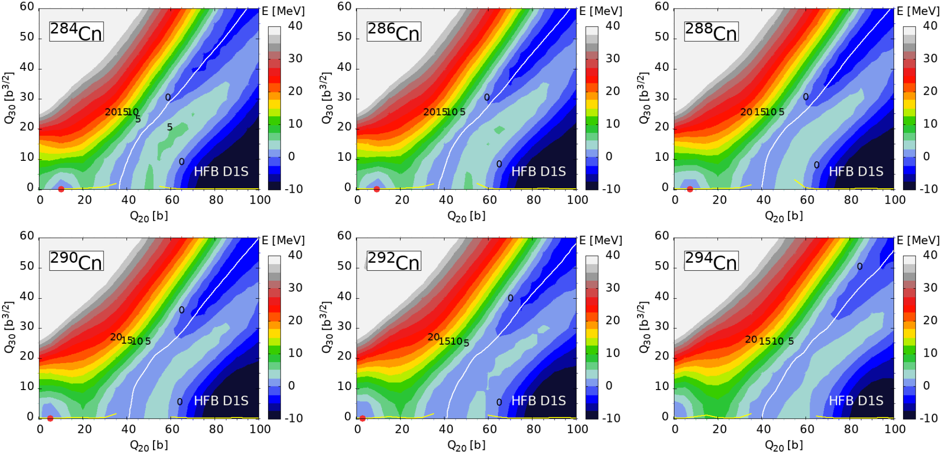


268Cn
270Cn
272Cn
274Cn
276Cn
278Cn
280Cn
282Cn
284Cn
HFB D1S
E [MeV]
Q_{30} [$b^{3/2}$]
Q_{20} [b]



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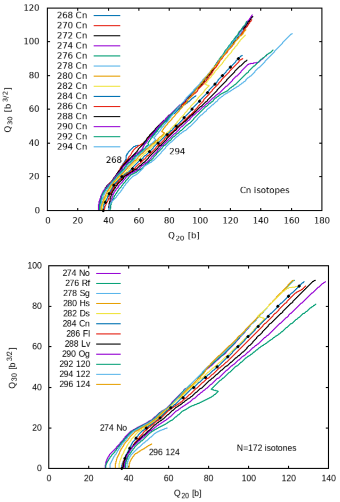
Fission paths around ^{284}Cn



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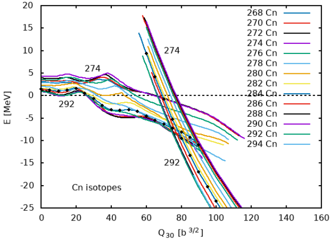
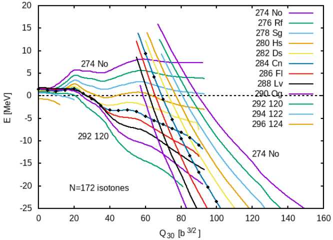
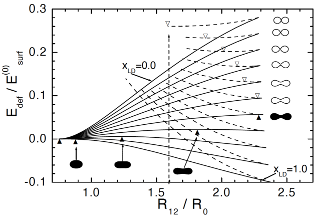
Fission paths around ^{284}Cn

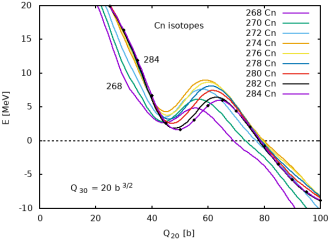


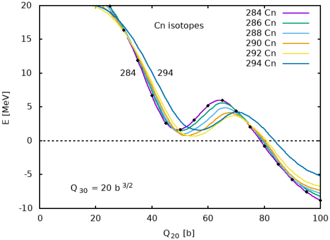


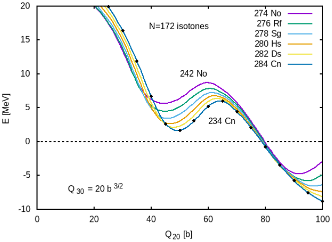


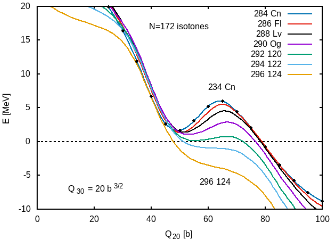
F. Ivanyuk, K. Pomorski, Phys. Rev. C 79, 054327 (2009).
F. Ivanyuk, K. Pomorski, Int. J. Mod. Phys E 19, 514 (2010).

Fission paths around ^{284}Cn

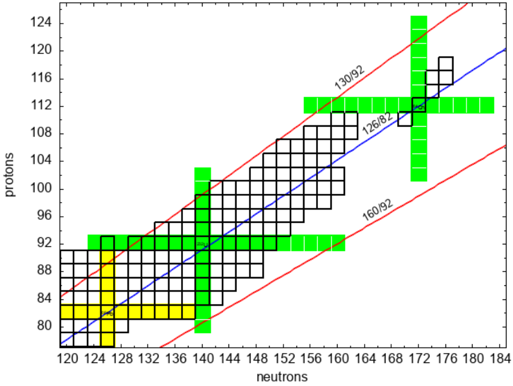








Isotopes and isobars



Conclusions

- Cluster radioactivity described as super-asymmetric fission in actinides and super-heavy nuclei
- This decay may be dominant decay channel in some super-heavy nuclei
- Shell correction of doubly-magic ^{208}Pb and symmetry energy (N/Z ratio) play the crucial role in the enhancement of this decay channel

Further investigations

- Shapes and sizes of pre-fragments
- Influence on magic numbers on mass asymmetry
- Half-lives in the cluster radioactivity channel

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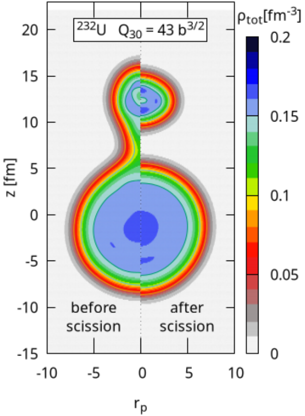

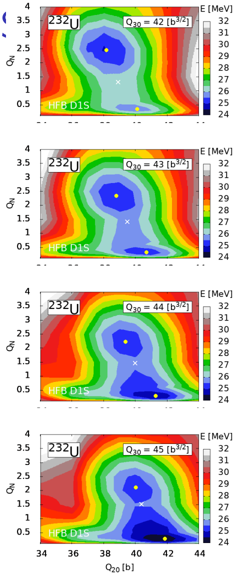

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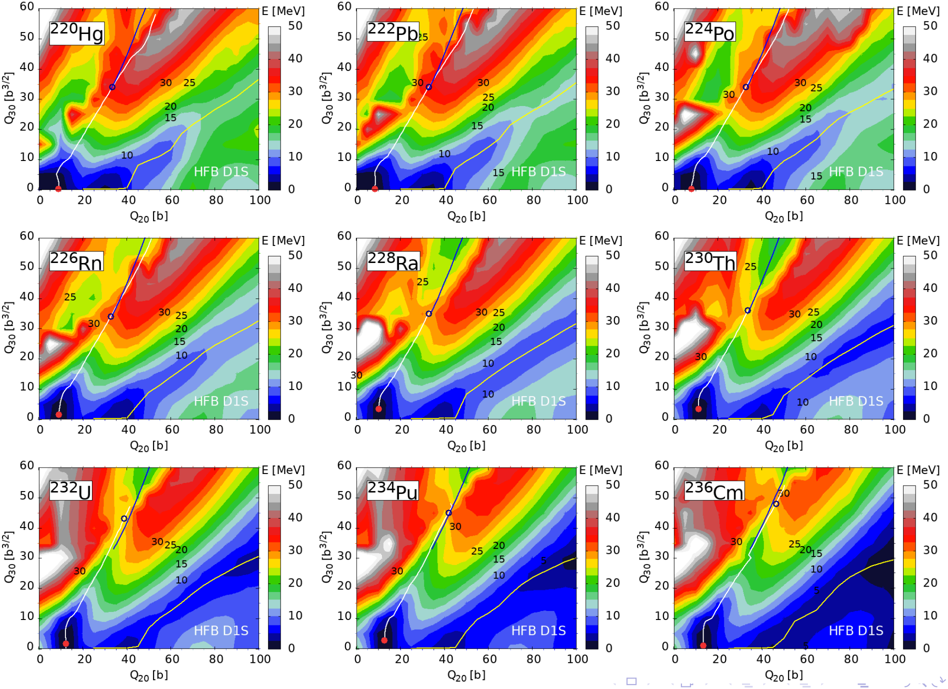
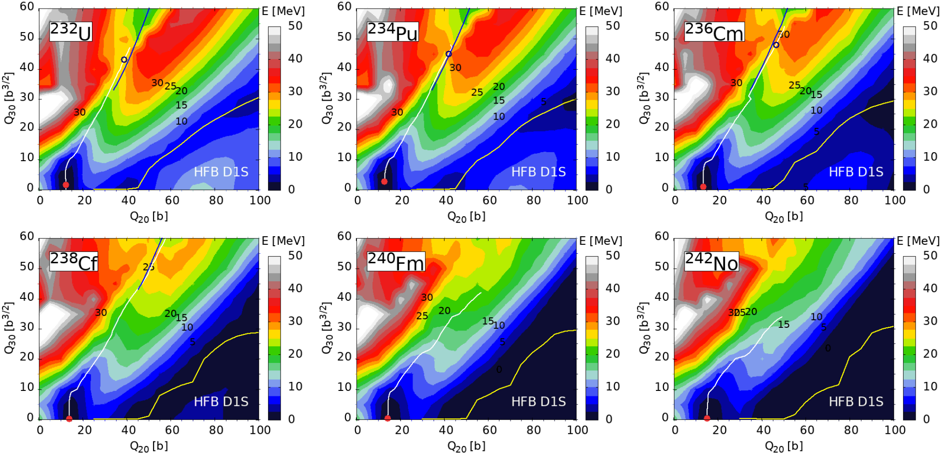


220Hg
222Pb
224Po
226Rn
228Ra
230Th
232U
234Pu
236Cm
E [MeV]
Q30 [b3/2]
Q20 [b]
HFB D1S



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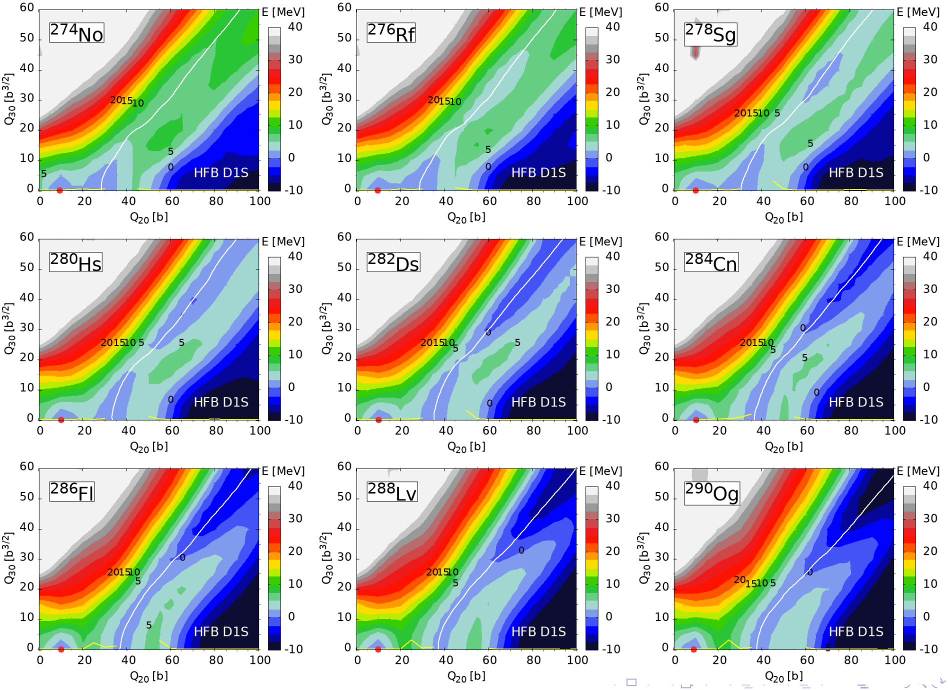
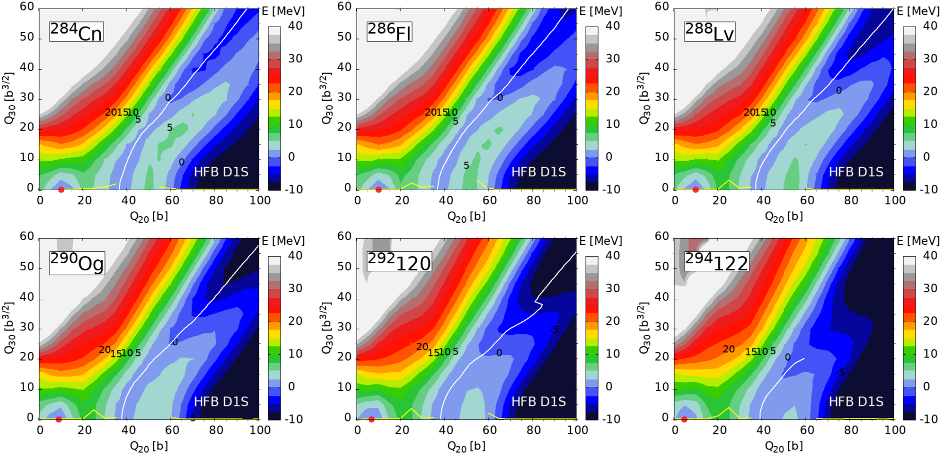


^{274}No
^{276}Rf
^{278}Sg
^{280}Hs
^{282}Ds
^{284}Cn
^{286}Fl
^{288}Lv
^{290}Og
HFB D1S
E [MeV]
Q_{30} [b$^{3/2}$]
Q_{20} [b]



284Cn
286Fl
288Lv
290Og
292120
294122
HFB D1S
E [MeV]
Q20 [b]
Q30 [b3/2]