Super asymmetric fission in super heavy nuclei

Michał Warda

Uniwersytet Marii Curie-Skłodowskiej
Lublin, Poland

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Collaboration:

- L.M. Robledo, UAM, Madrid
- A. Zdeb, UMCS, Lublin / CEA, Bruyères-le-Châtel

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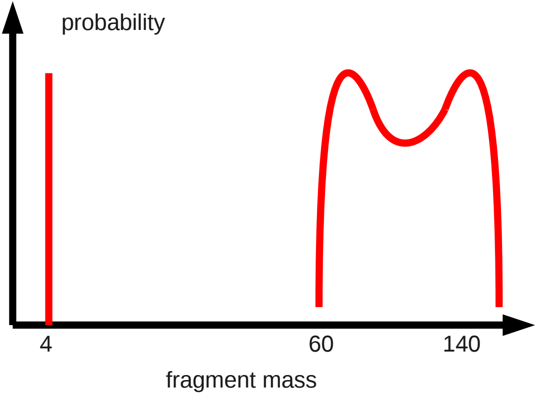
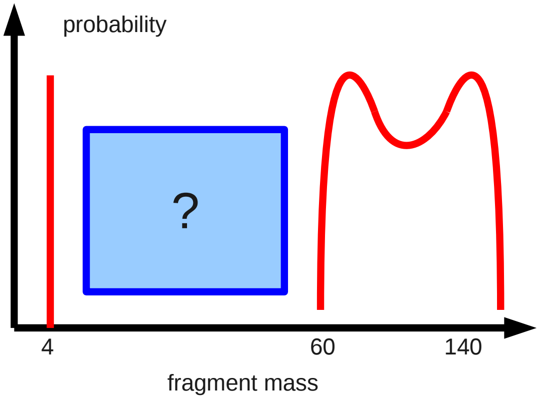

probability
4
60
140
fragment mass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Discovery of cluster radioactivity

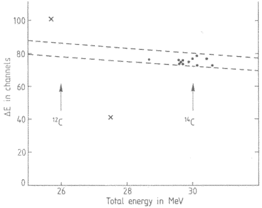

Fig. 1 Contents of the two-dimensional array ΔE versus E_{total} after a run of 189 days. The dotted line indicates the allowed region for carbon ions and the arrows indicate the total energies expected for ^{12}C and ^{14}C emissions in the decay of ^{223}Ra. The lower of the two crosses represents 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 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 $\Delta E \cong 6.7$ 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)

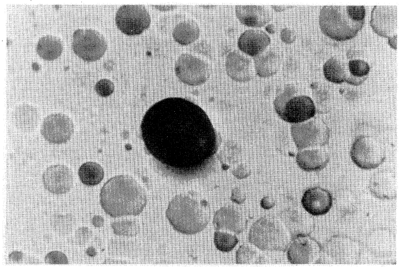

FIG. 1. Photomicrograph showing one etch pit due to a 56 MeV ^{24}Ne ion striking a Cronar detector nearly head on. About 3×10^6 alpha particles passed through this field of view.

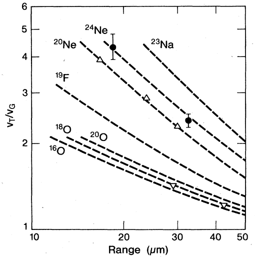

FIG. 2. Comparison of average signal of ^{24}Ne nuclei (●) emitted from ^{232}U with calibrations (dashed lines) obtained with ^{18}O (▽) and ^{20}Ne (Δ) ions at Lawrence Berkeley Laboratory accelerators. Ratio of etching rate along track to general etching rate v_T/v_G, is plotted as a function of residual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

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

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"
- Half lives: 10^{11} s – 10^{26} s
- α branching ratio: 10^{-9} – 10^{-16}

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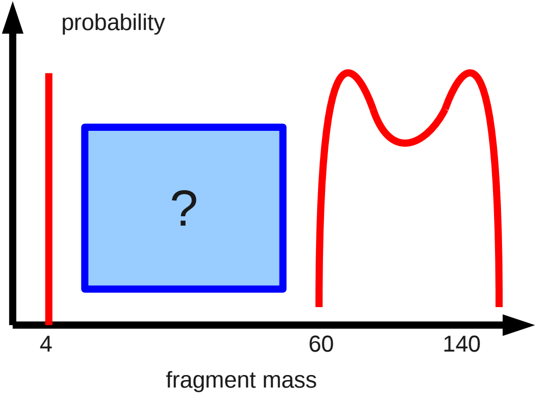
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?
4
60
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Theoretical description

- Extrapolation of Gamov model of alpha emission
- Modified Geiger-Nuttall formula for half-lives
- Very asymmetric fission
- Potential energy surfaces are determined in the self-consistent procedure in HFB theory with Gogny D1S force

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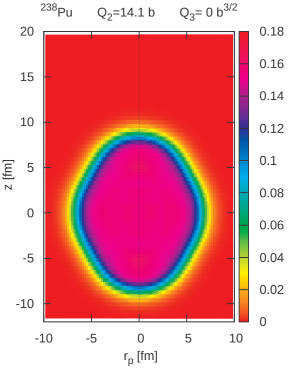
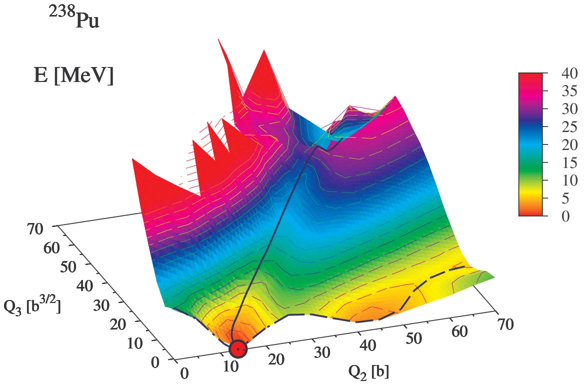
Shape evolution: ^{238}Pu





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

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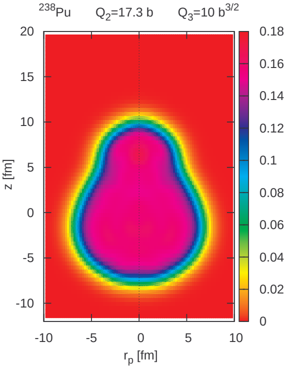

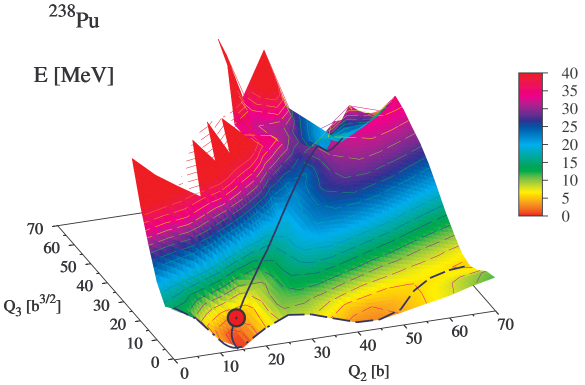

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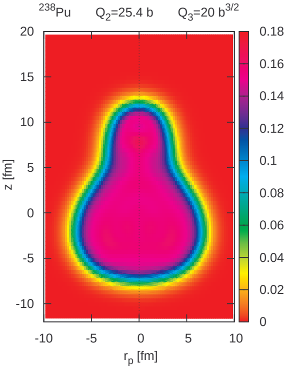

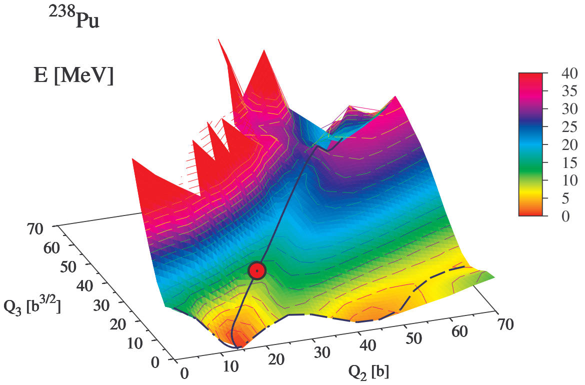

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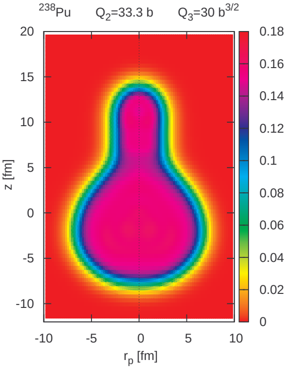

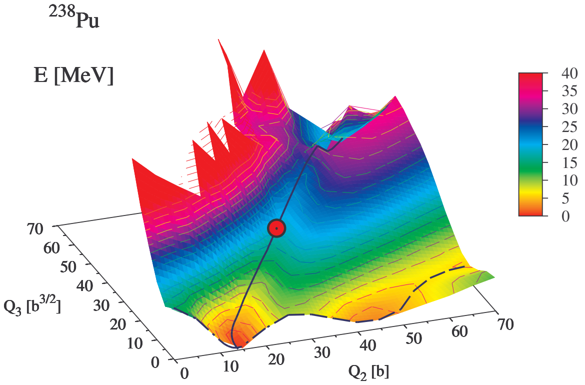

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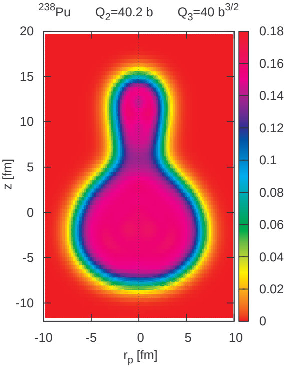

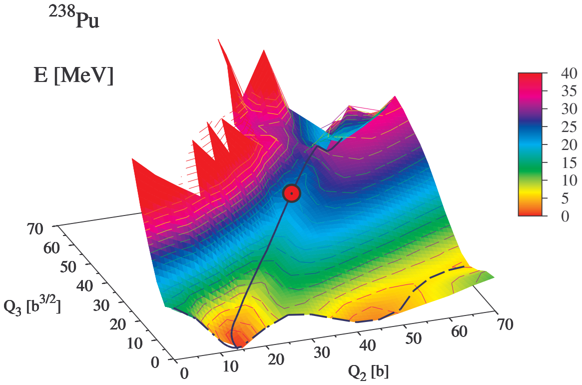

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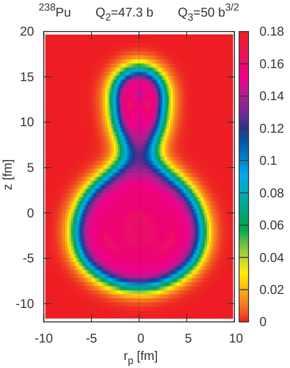

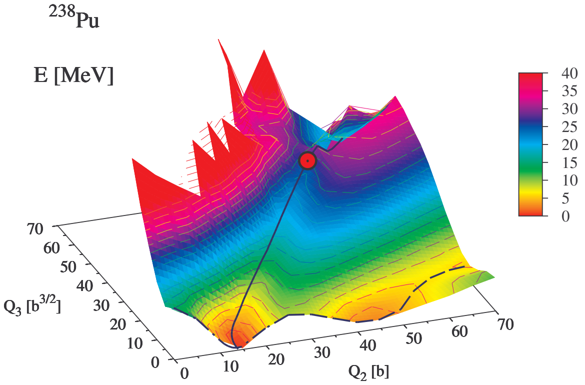

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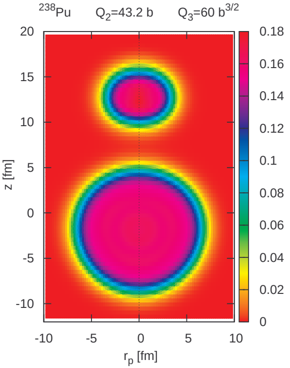

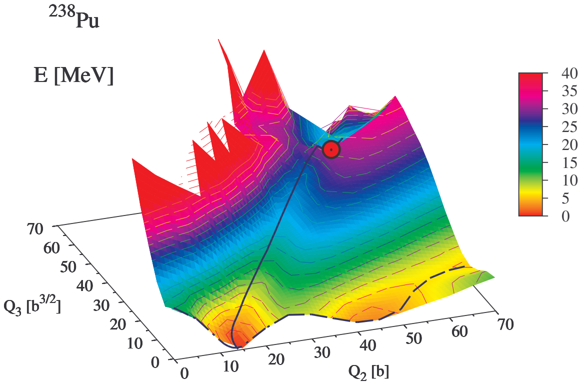

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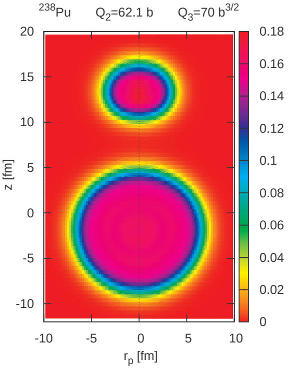

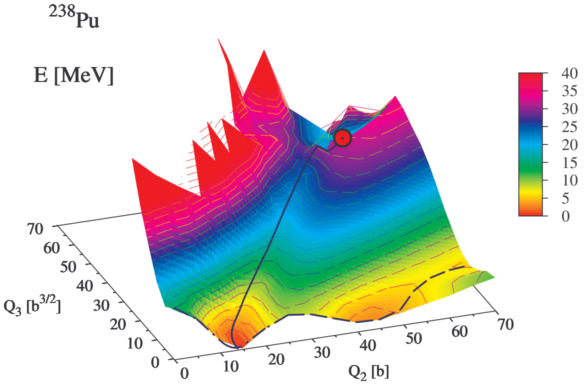

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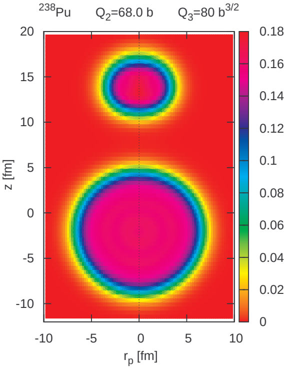

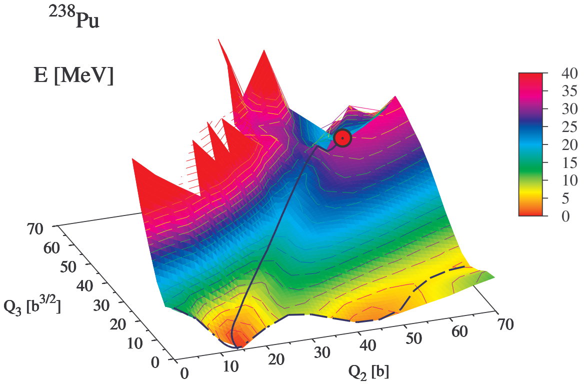

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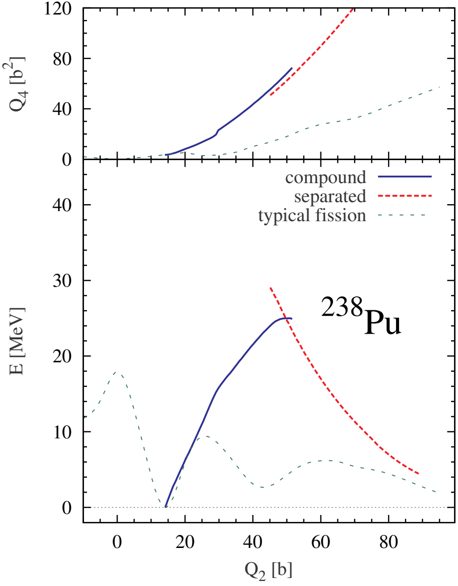

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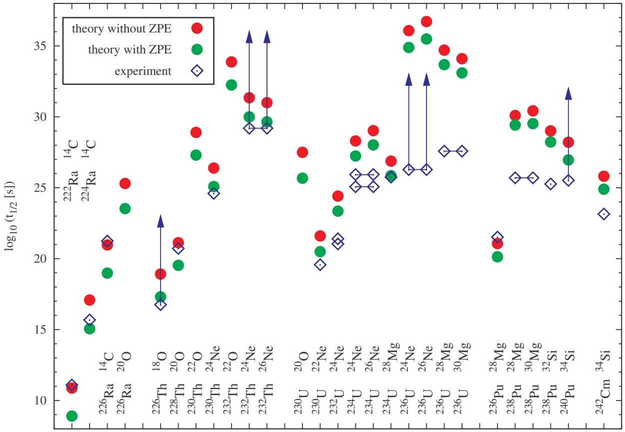
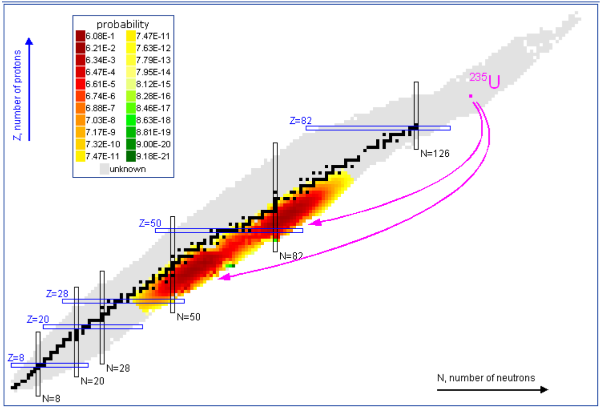
Half-lives


theory without ZPE
theory with ZPE
experiment
$\log_{10}(t_{1/2}\,[s])$
10
15
20
25
30
35
^{222}Ra ^{14}C
^{224}Ra ^{14}C
^{226}Ra ^{14}C
^{226}Ra ^{20}O
^{226}Th ^{18}O
^{228}Th ^{20}O
^{230}Th ^{22}O
^{230}Th ^{24}Ne
^{232}Th ^{22}O
^{232}Th ^{24}Ne
^{232}Th ^{26}Ne
^{230}U ^{20}O
^{230}U ^{22}Ne
^{232}U ^{24}Ne
^{234}U ^{24}Ne
^{234}U ^{26}Ne
^{234}U ^{28}Mg
^{236}U ^{24}Ne
^{236}U ^{26}Ne
^{236}U ^{28}Mg
^{236}U ^{30}Mg
^{236}Pu ^{28}Mg
^{238}Pu ^{28}Mg
^{238}Pu ^{30}Mg
^{238}Pu ^{32}Si
^{240}Pu ^{34}Si
^{242}Cm ^{34}Si

Fission fragments - N/Z ratio



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

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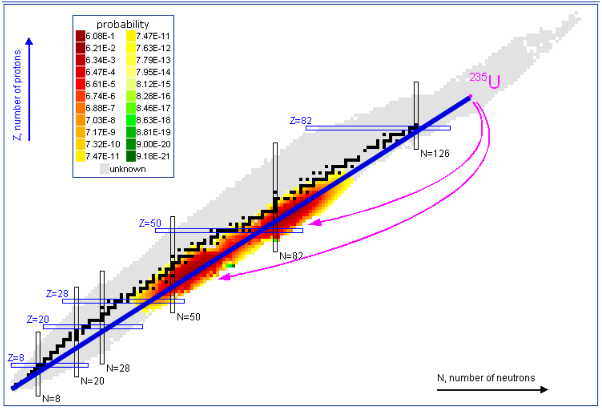

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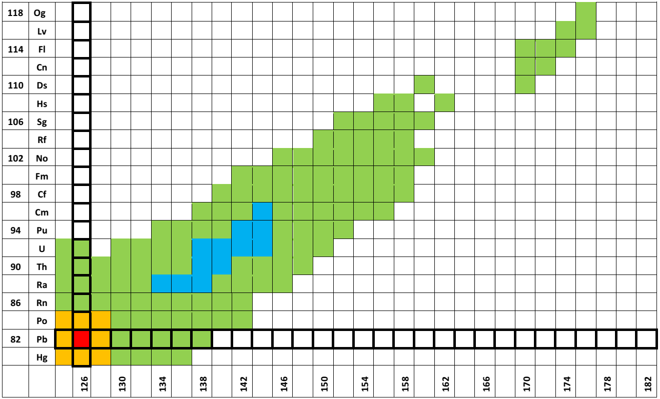
Cluster radioactivity - chart of nuclides



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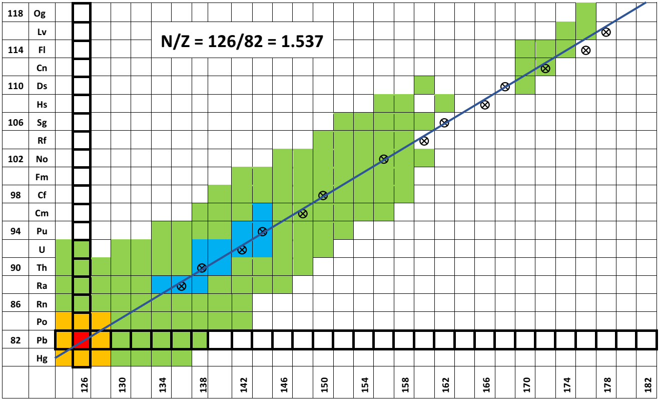
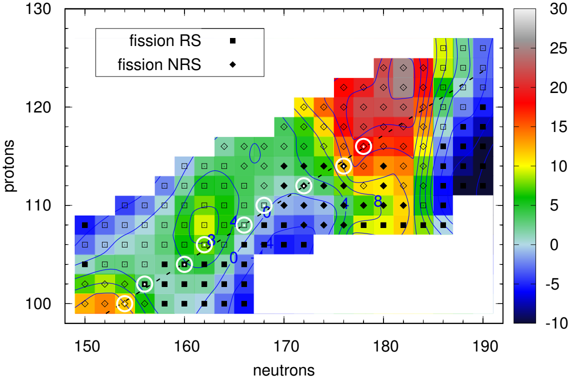
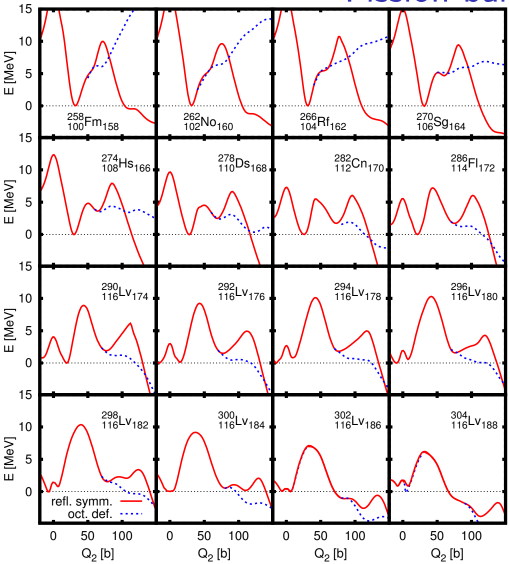


Chart of SH nuclides



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

Fission barriers



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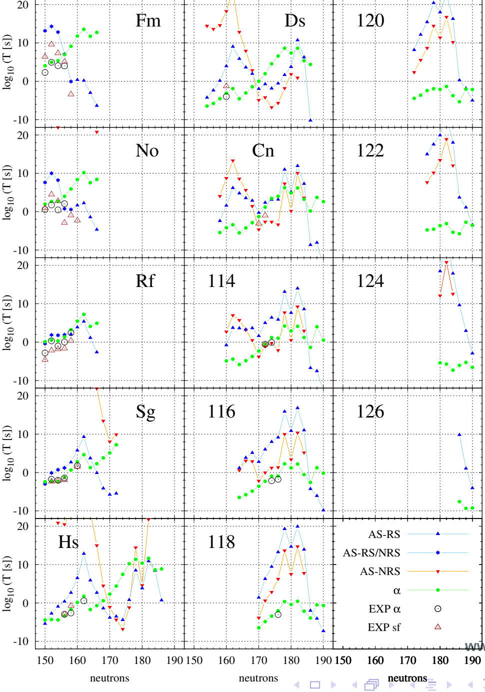
Fission and α-decay half-lives



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Previous approach

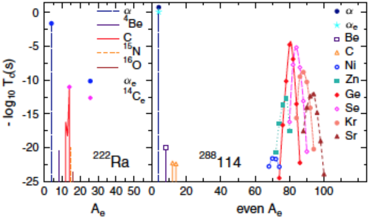
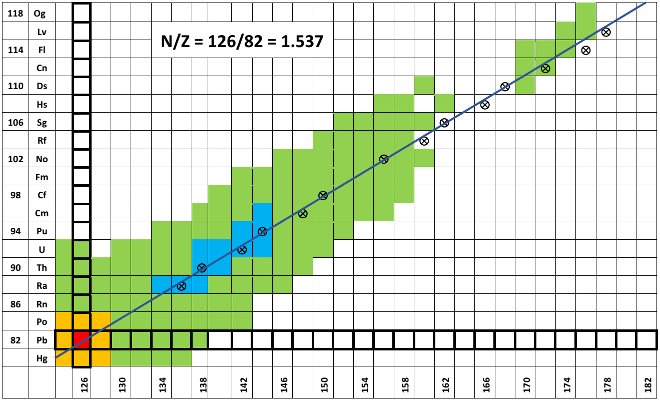


FIG. 1 (color online). Time spectra of different cluster emissions from ^{222}Ra (left panel) and from the superheavy nucleus ^{288}114 (right panel). The most probable emitted clusters from ^{222}Ra and ^{288}114 are ^{14}C and ^{80}Ge, respectively, both leading to ^{208}Pb daughter nucleus.

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



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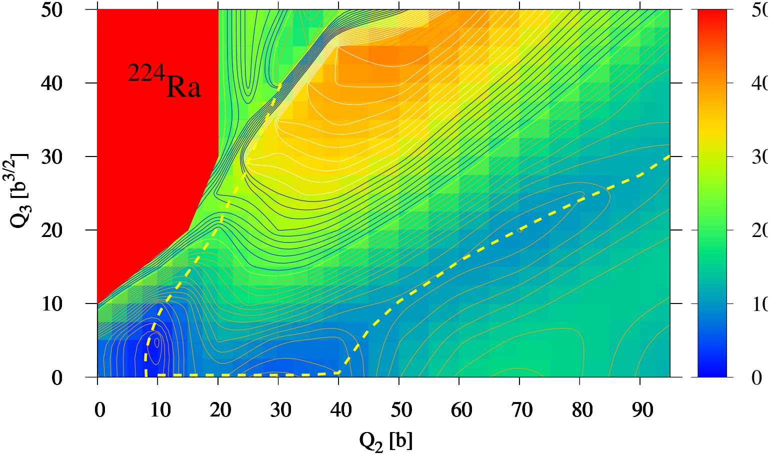
^{224}Ra



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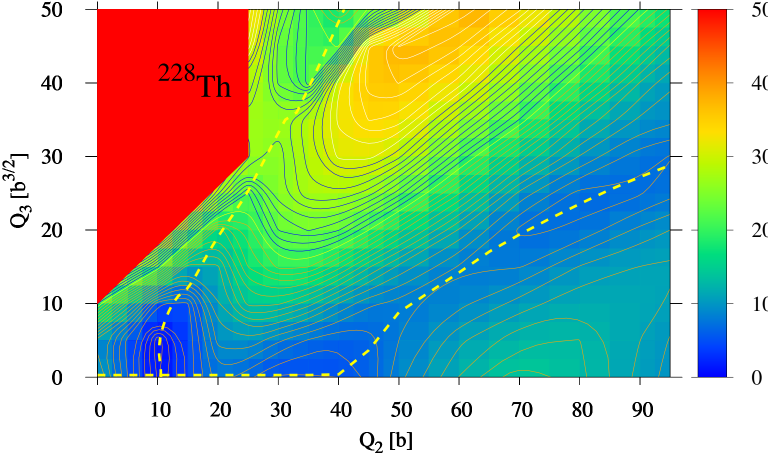
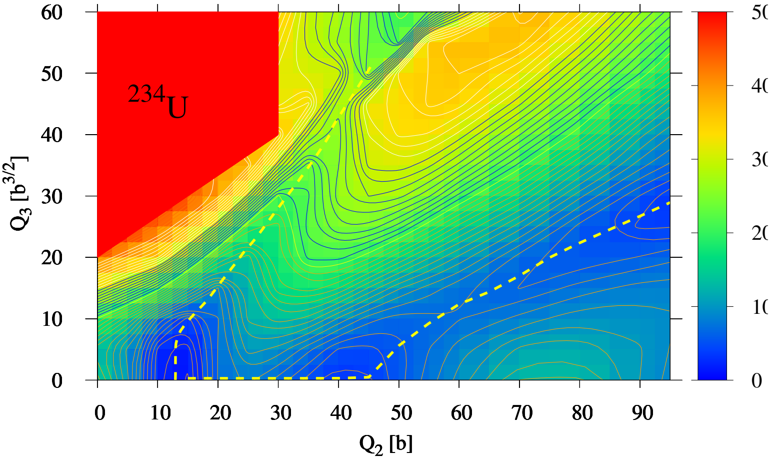
^{228}Th



^{234}U



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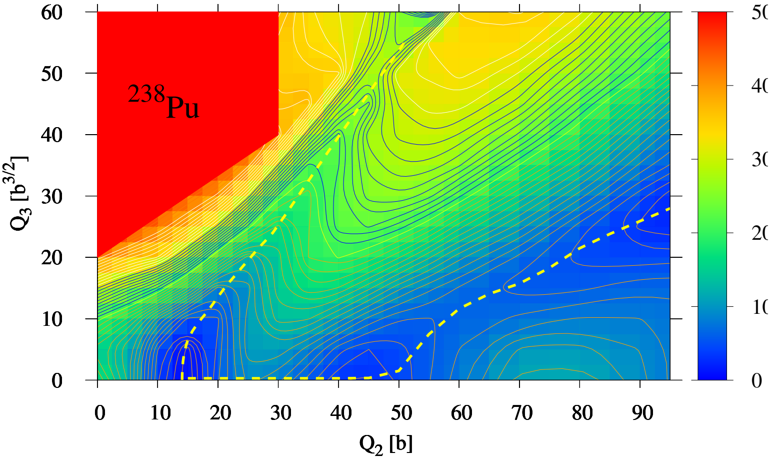
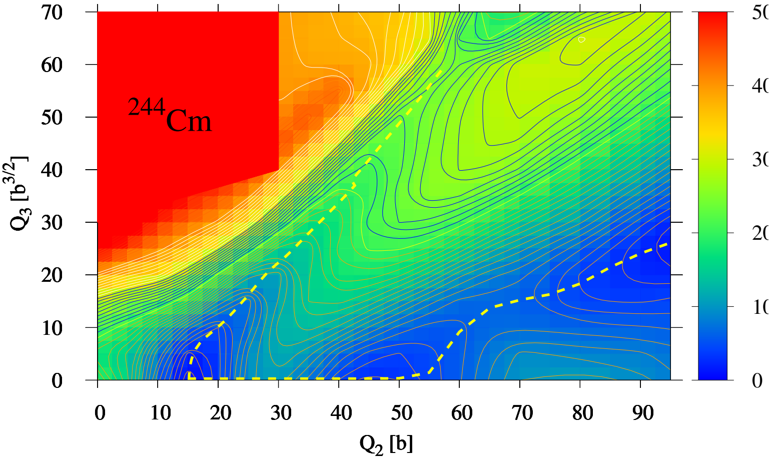
^{238}Pu

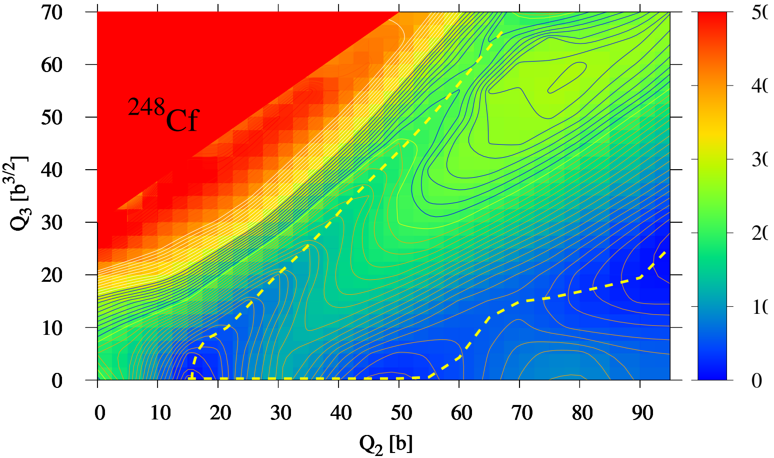


^{244}Cm

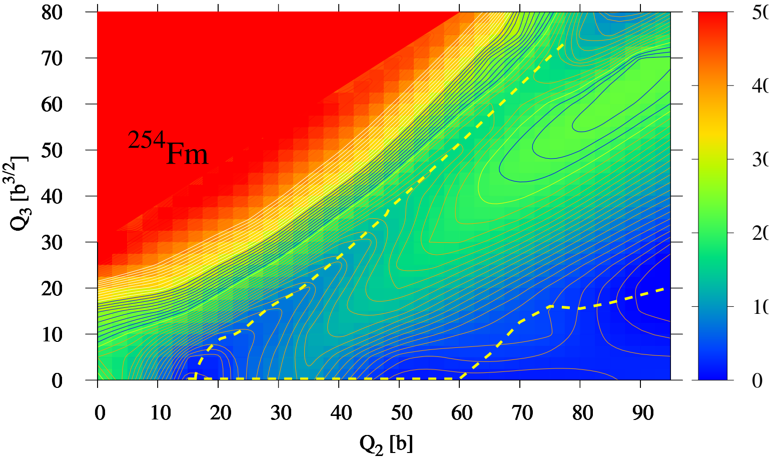


244Cm
Q3 [b3/2]
Q2 [b]
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
5(
4(
3(
2(
1(
0

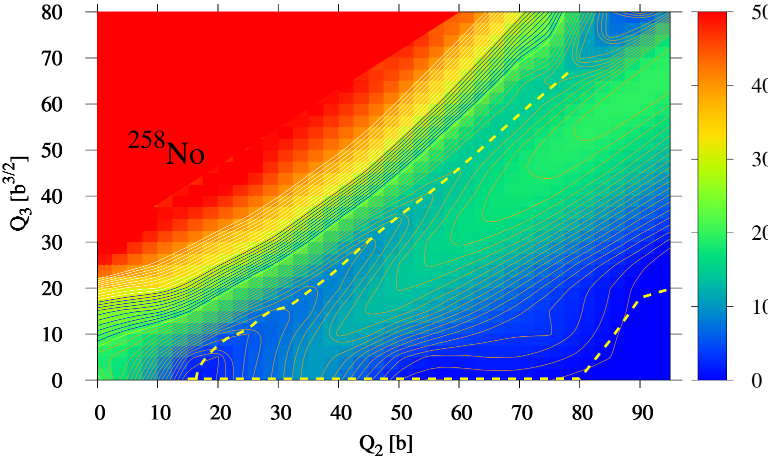
^{248}Cf



^{254}Fm

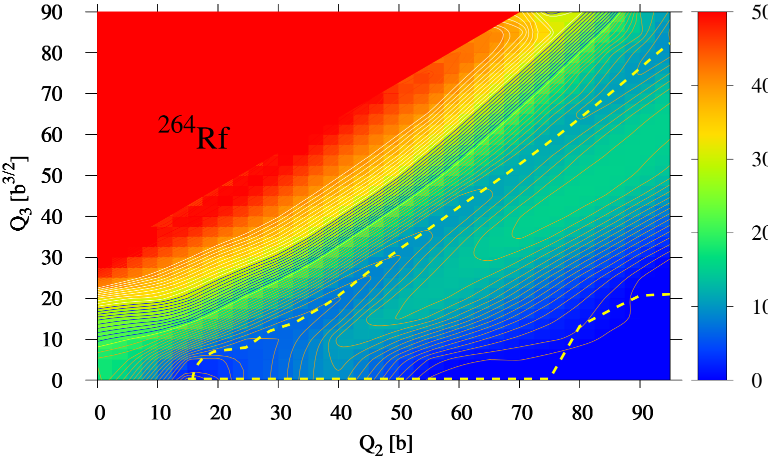


^{258}No

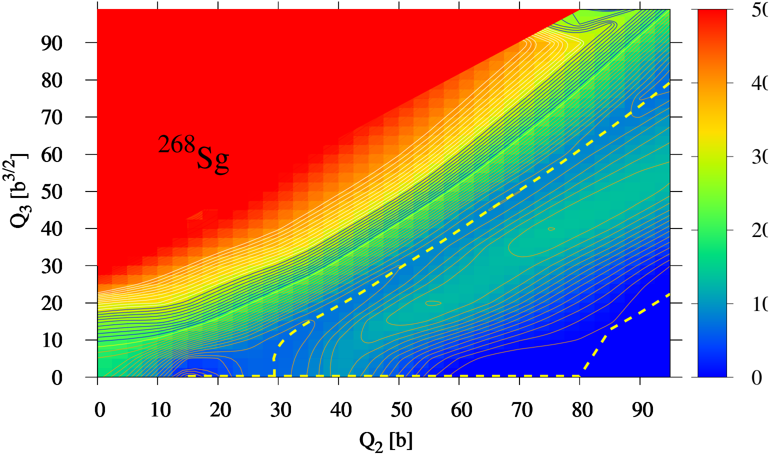


^{258}No
Q_3 [$b^{3/2}$]
Q_2 [b]
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
5(
4(
3(
2(
1(
0

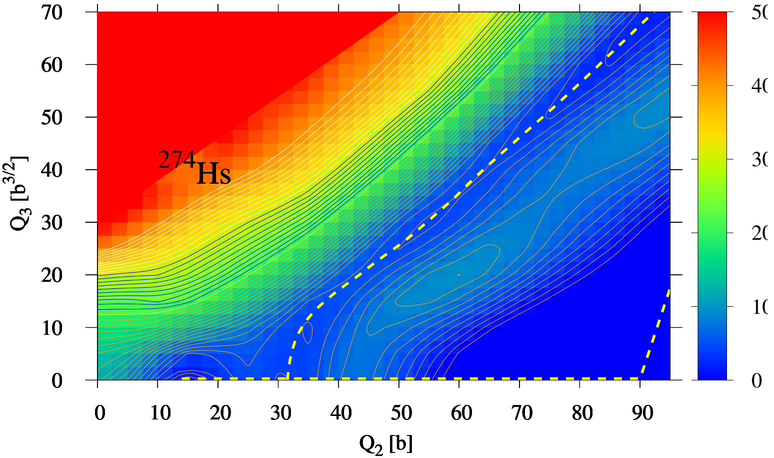
^{264}Rf



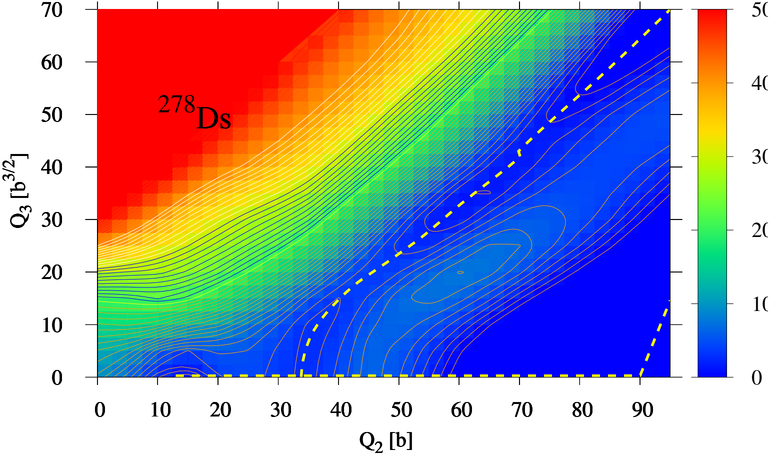
^{268}Sg


268Sg
Q3 [b3/2]
Q2 [b]
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90

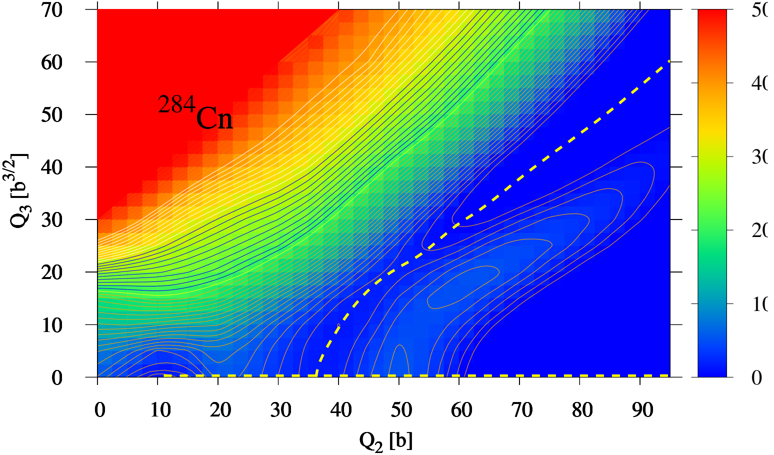
^{274}Hs


70
60
50
40
30
20
10
0
Q_3 [$b^{3/2}$]
^{274}Hs
0
10
20
30
40
50
60
70
80
90
Q_2 [b]
5(
4(
3(
2(
1(
0

^{278}Ds



^{284}Cn



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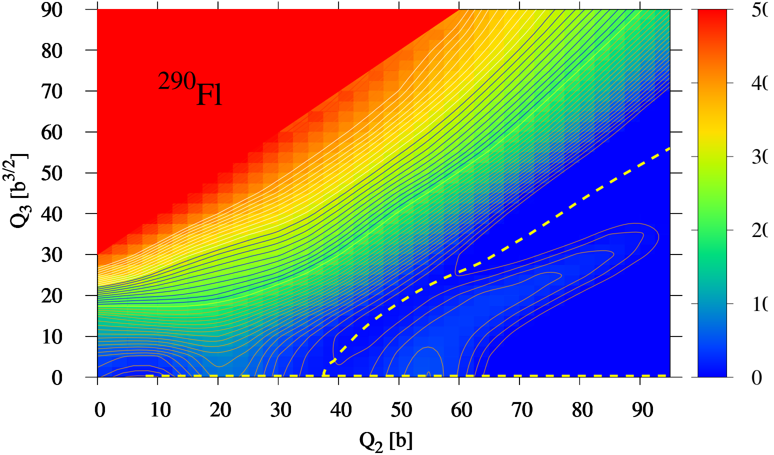
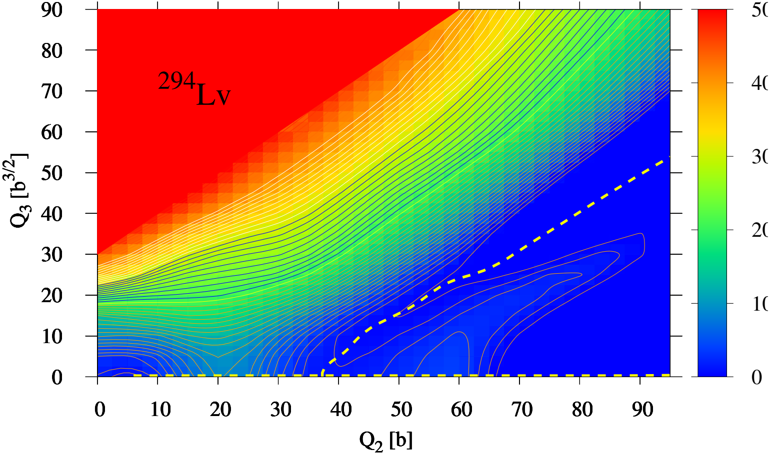
^{290}Fl

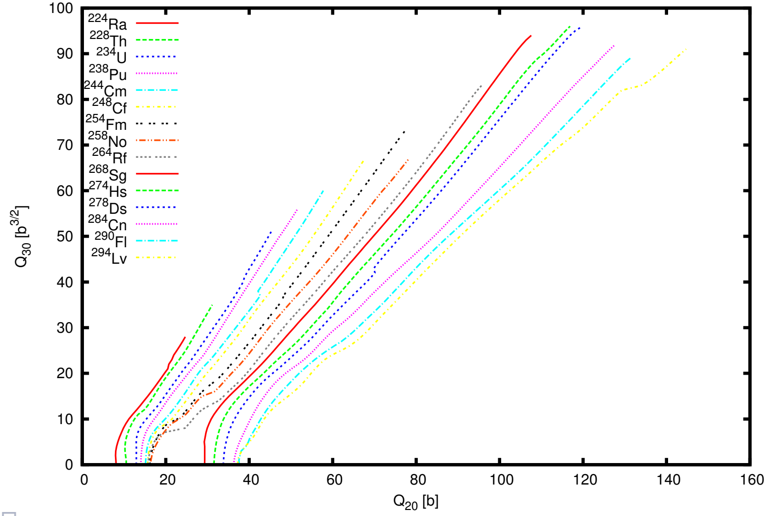


^{294}Lv



^{294}Lv
Q_3 [b$^{3/2}$]
Q_2 [b]
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90

Cluster barriers



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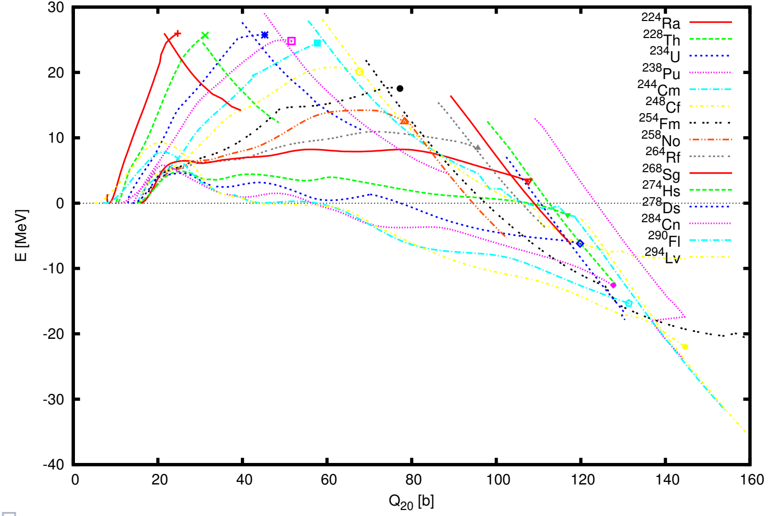
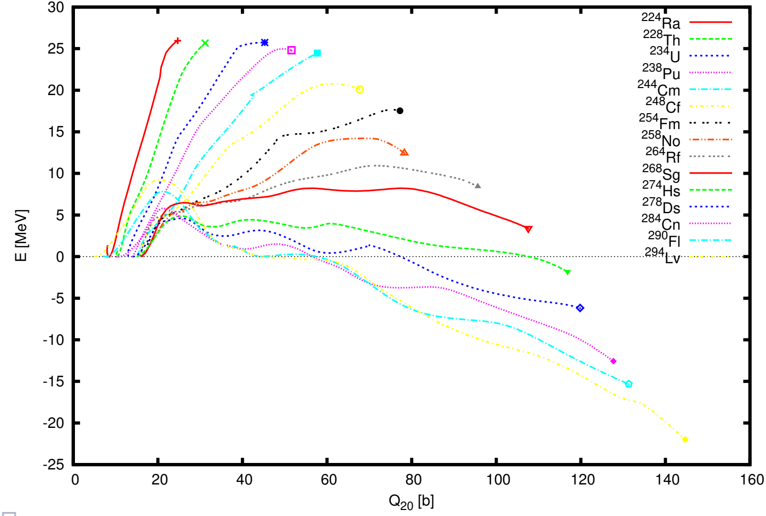
Cluster barriers



Cluster barriers



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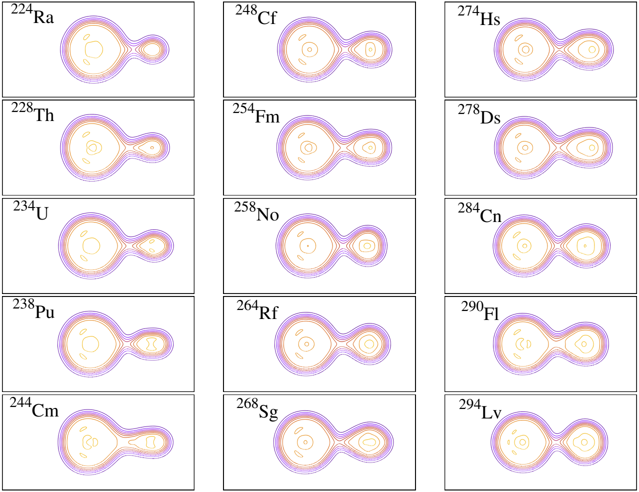
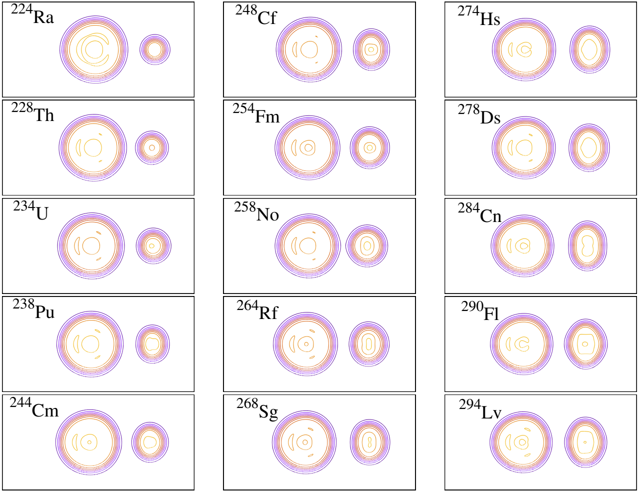
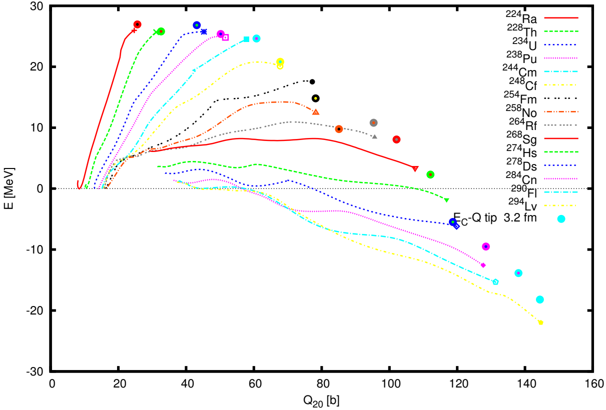
Pre-scission shapes



Post-scission shapes

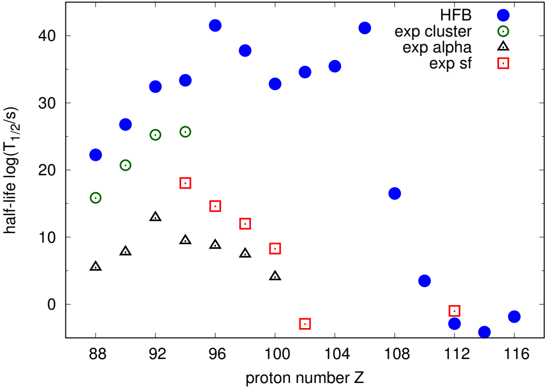


Cluster barriers



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

Half-llives

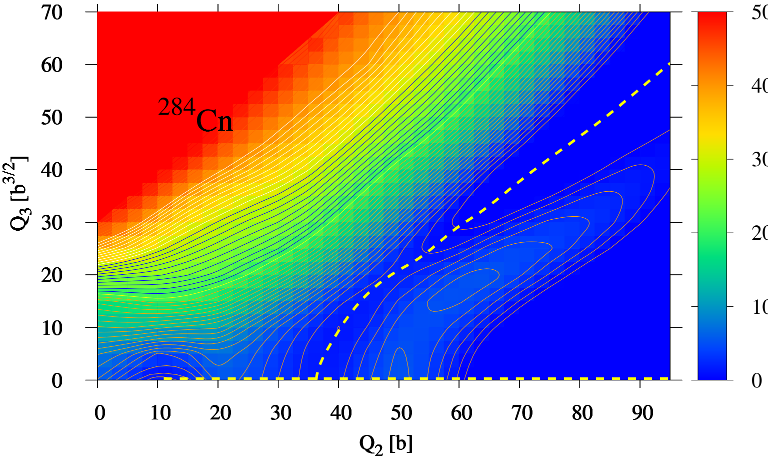


HFB
exp cluster
exp alpha
exp sf
half-life log($T_{1/2}$/s)
proton number Z
0
10
20
30
40
88
92
96
100
104
108
112
116

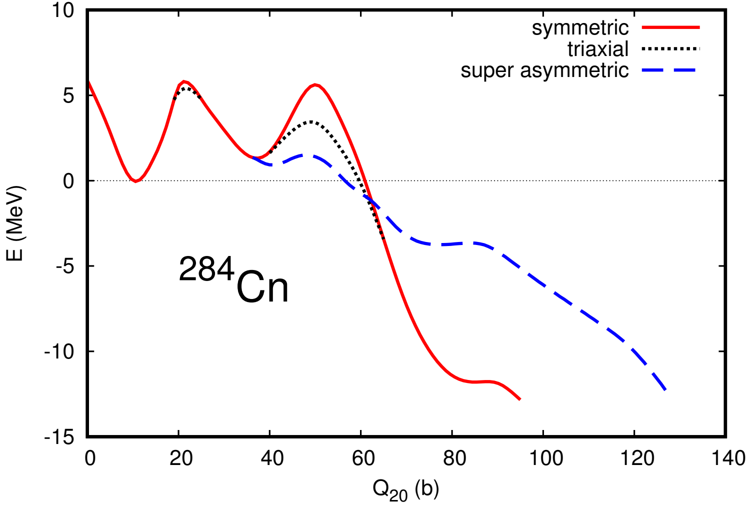
Experimental evidence in ^{284}Cn:

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

^{284}Cn

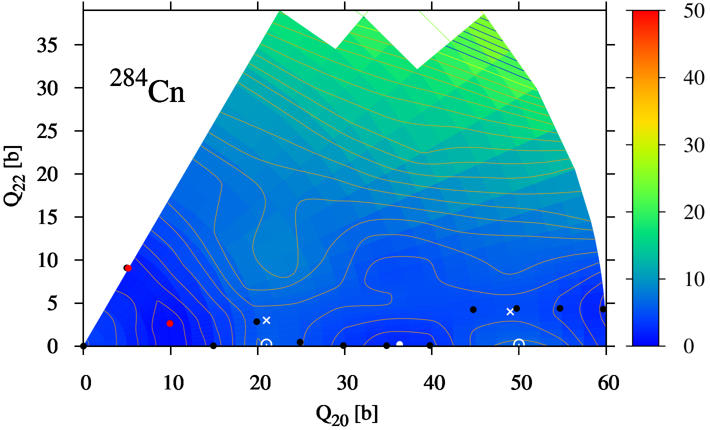


^{284}Cn



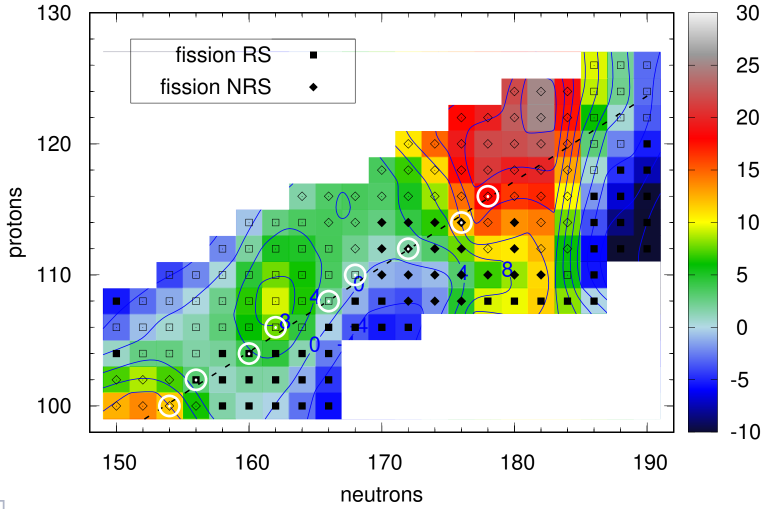
symmetric
triaxial
super asymmetric
284Cn
E (MeV)
Q20 (b)
10
5
0
-5
-10
-15
0
20
40
60
80
100
120
140

^{284}Cn

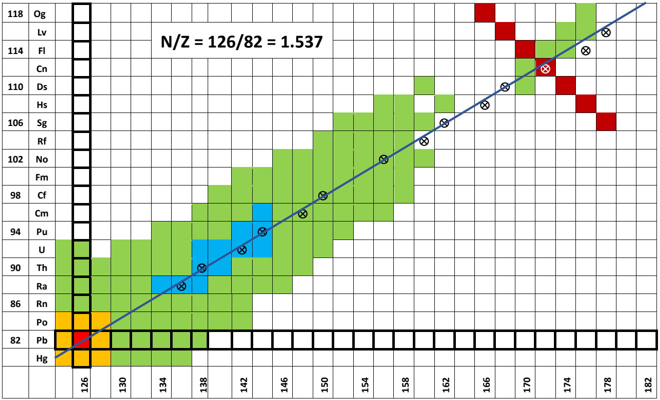


284Cn
Q22 [b]
Q20 [b]
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
0
10
20
30
40
50

Chart of SH nuclides

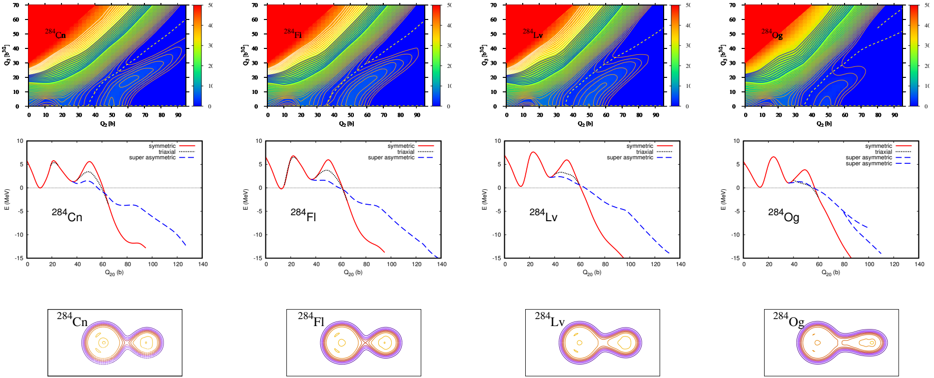


Isobars 284


N/Z = 126/82 = 1.537
118 Og
Lv
114 Fl
Cn
110 Ds
Hs
106 Sg
Rf
102 No
Fm
98 Cf
Cm
94 Pu
U
90 Th
Ra
86 Rn
Po
82 Pb
Hg
126
130
134
138
142
146
150
154
158
162
166
170
174
178
182

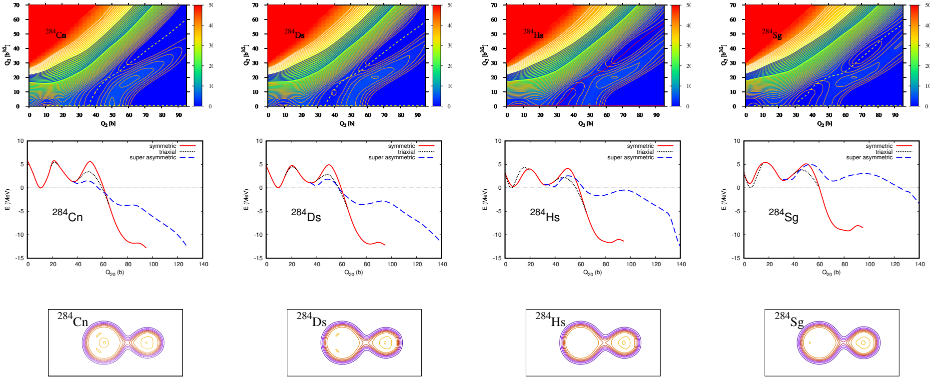
UMCS

Isobars 284



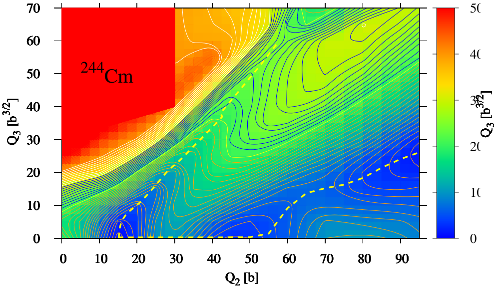
Z_H =82	Z_H =82	Z_H =83	Z_H =86
N_H =126	N_H =124	N_H =122	N_H =123
N/Z=1.535	N/Z=1.491,	N/Z=1.448	N/Z=1.407
N_H/Z_H = 1.537	N_H/Z_H = 1.512	N_H/Z_H = 1.470	N_H/Z_H = 1.430

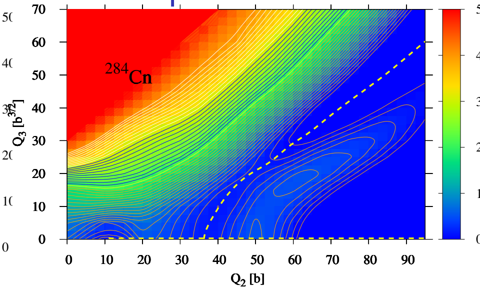
Isobars 284

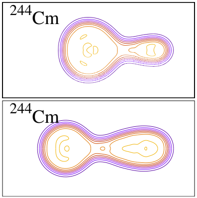


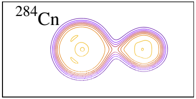
$Z_H = 82$	$Z_H = 80$	$Z_H = 78$	$Z_H = 75$
$N_H = 126$	$N_H = 126$	$N_H = 127$	$N_H = 127$
N/Z=1.535	N/Z=1.581	N/Z=1.630	N/Z=1.679
$N_H/Z_H = 1.537$	$N_H/Z_H = 1.575$	$N_H/Z_H = 1.628$	$N_H/Z_H = 1.693$

Actinides and superheavies

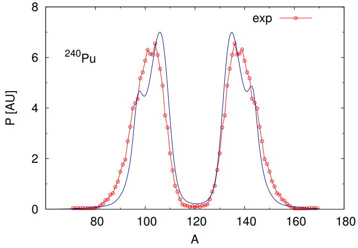


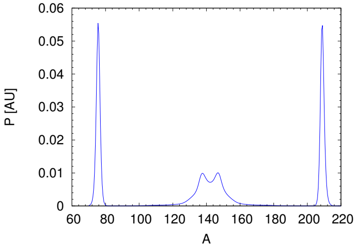






Fragment mass distribution - preliminary





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Conclusions

- 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

M. Warda, A. Zdeb, L.M. Robledo
Cluster Radioactivity in Super Heavy Nuclei
Phys. Rev. **C 98** 041602(R) (2018)