Mean-field description of fission in light Hg isotopes

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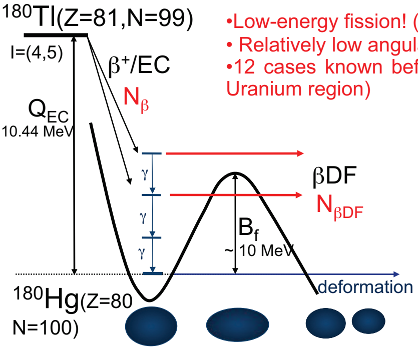
Kazimierz Dolny, 26-30.09.2012

Electron capture delayed fission

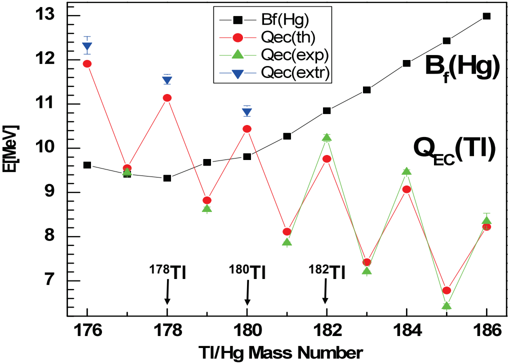


- Low-energy fission! (E^*~3-12 MeV, limited by Q_{EC})
- Relatively low angular momentum of the state
- 12 cases known before our work (neutron-deficient Uranium region)

βDF branch

$$P_{\beta DF} = \frac{N_{\beta DF}}{N_{\beta}}$$

A.N. Andreyev, *Recent results on fission in the lightest Hg-Rn isotopes*, FUSTIPEN 2012, Seminar



Masses/Q_{EC} and B_f values from FRLDM

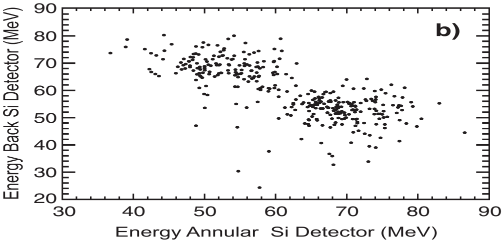


FIG. 2. (a) Singles α-decay energy spectrum from both Si detectors; (b) Si-Si coincidence spectrum in the fission-energy region. The two-peaked structure in (b) originates because the two fission fragments have different energies, a direct result of the asymmetric mass distribution.

A.N. Andreyev, et al. *New Type of Asymmetric Fission in Proton-Rich Nuclei*, Phys. Rev. Lett. **105**, 252502 (2010).

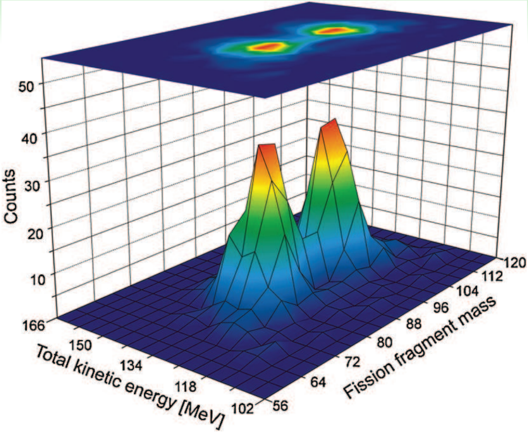


FIG. 4 (color online). The derived fission-fragment distribution of ^{180}Hg as a function of the fragment mass and the total kinetic energy.

$$A_H/A_L = 100/80$$

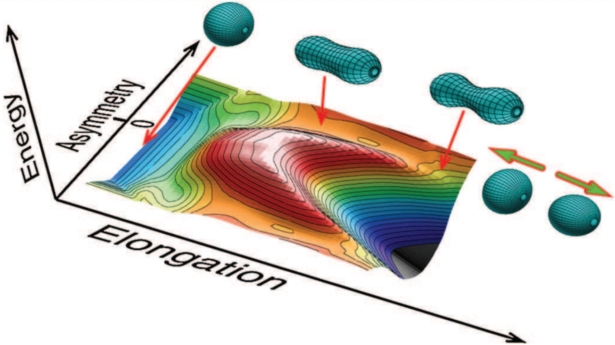
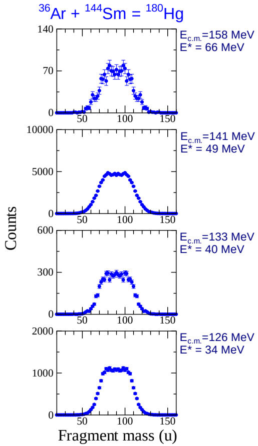


FIG. 5 (color online). A schematic representation of the potential-energy surface for ^{180}Hg in two dimensions (elongation and asymmetry) resulting from a five-dimensional analysis. The shapes shown, connected by arrows to their locations, are the ground state, the saddle point, and the point where the asymmetric valley disappears.

Asymmetric fission of ^{180}Hg for large exitation energies



A. Andreyev, K. Nishio et al., Jan 2010: JAEA,Tokai,Japan

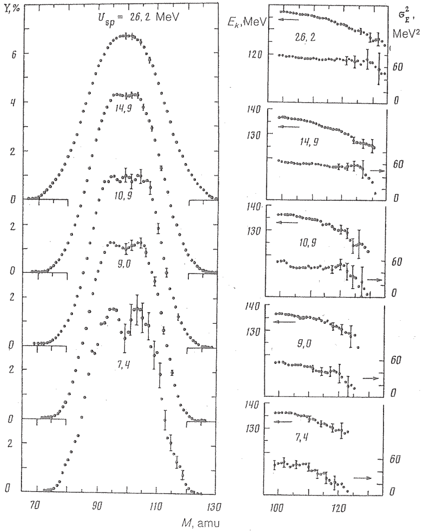


FIG. 3. Mass yields Y, total kinetic energy E_k, and its dispersion σ_E^2 as functions of fragment mass M and excitation energy for the compound nucleus ^{198}Hg.

M.G. Itkis, et al. *Mass asymmetry of symmetric fission of nuclei with* $A \sim 200$, Yad. Fiz. **52**, 944 (1990).

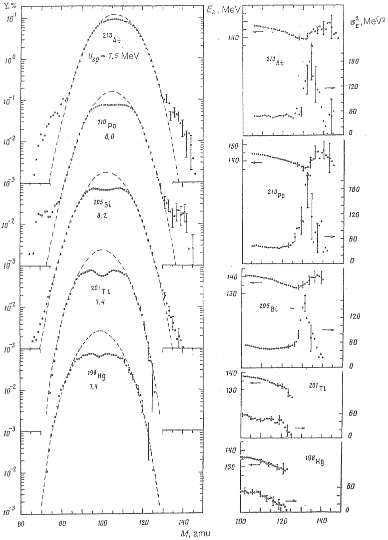


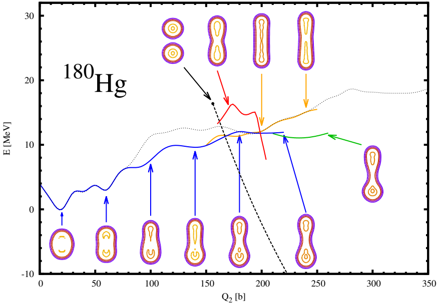
FIG. 5. Mass and energy distribution of fragments from fission of ^{198}Hg–^{213}At for $U_{sp} \simeq 7$–8 MeV. At the left are the mass yields $Y(M)$ (the dashed curves are a calculation of $\tilde{Y}(M)$ in accordance with Eq. (4)), and at the right is the dependence of the total kinetic energy E_k and its dispersion σ_E^2 on the heavy-fragment mass.

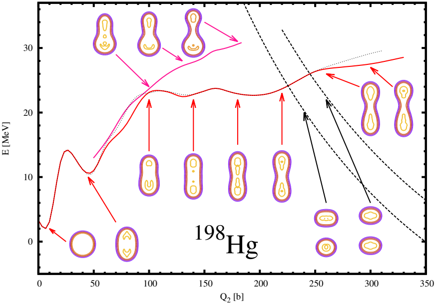
$$A_H/A_L = 103/95$$

Calculations of potential energy surfaces

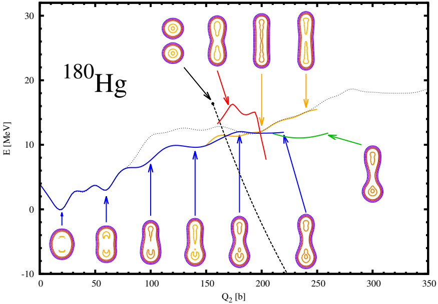
- Hartree-Focka-Bogolubov theory
- Gogny D1S and Skyrme SkM* parameter sets
- Constrains on quadrupole and octupole moments as well as on the neck parameter
- Excitations of nuclei were not taken into account

Fission barriers in ^{180}Hg and ^{198}Hg

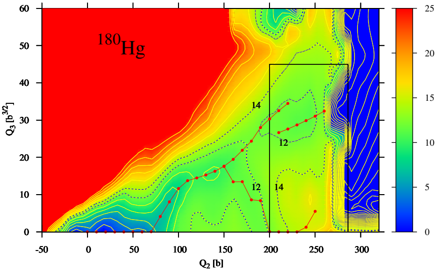




^{180}Hg

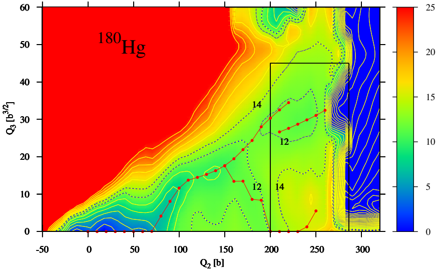


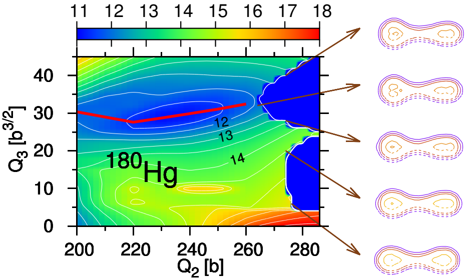
180Hg
E [MeV]
Q2 [b]
30
20
10
0
-10
0
50
100
150
200
250
300
350



180Hg
Q3 [b3/2]
Q2 [b]
14
12
12
14
60
50
40
30
20
10
0
-50
0
50
100
150
200
250
300
25
20
15
10
5
0

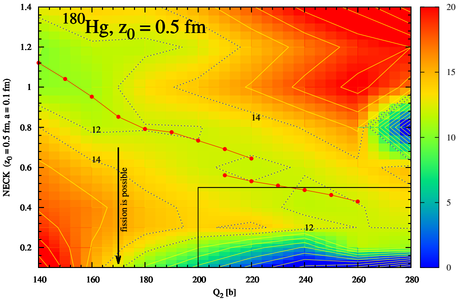
^{180}Hg

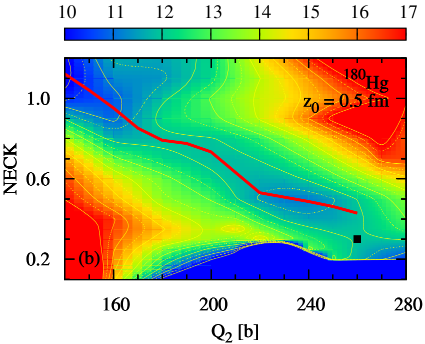




$$A_H/A_L = 101/79$$

^{180}Hg – neck parameter

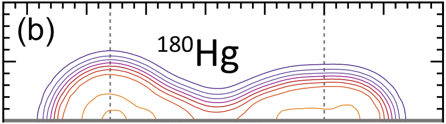




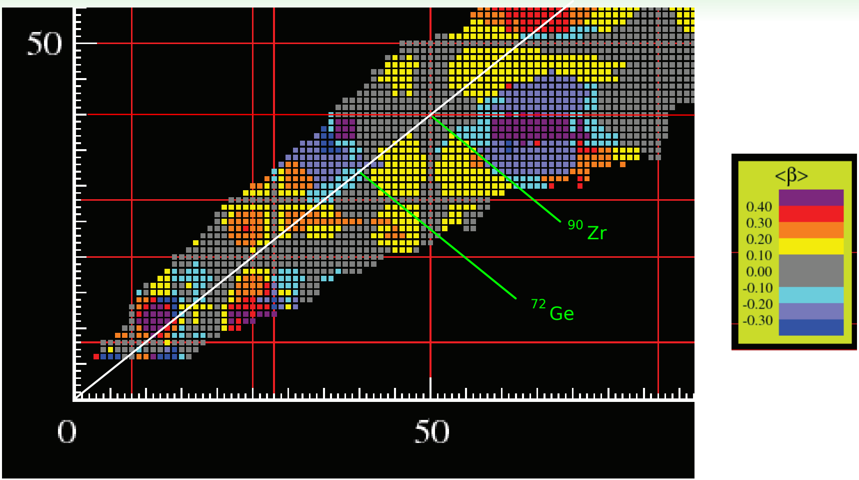
$$\hat{Q}_N = exp\left(-\frac{(z-z_0)^2}{a^2}\right)$$

Fragments before scission should have:

- the same N/Z ratio as the parent system
- mass numbers that reproduce the doubled mass of the outer part of the fragment
- density distributions that match those of the fragments

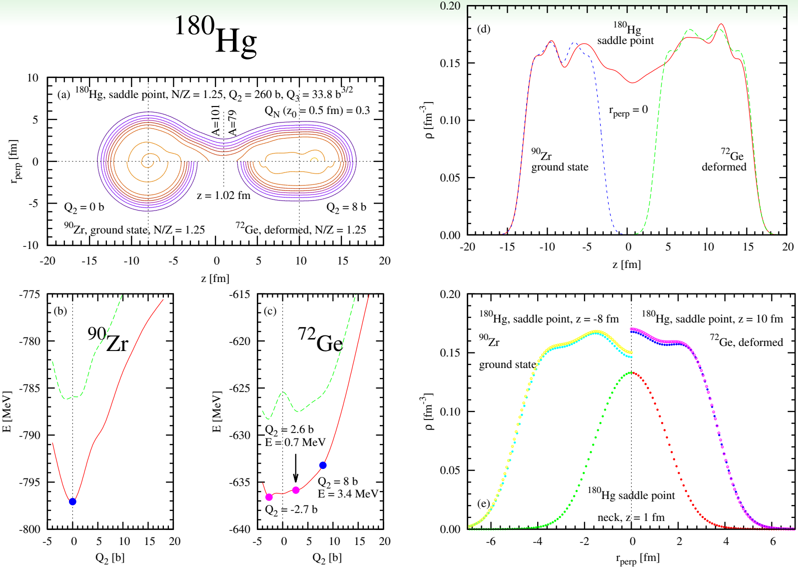


^{180}Hg, $N/Z = 1.25$



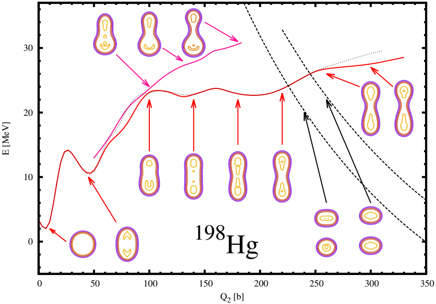
http://www-phynu.cea.fr/

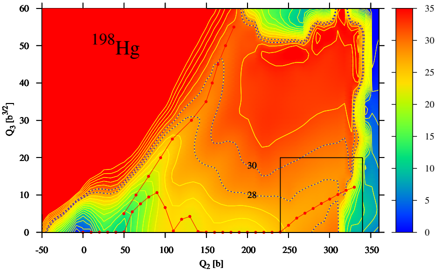
^{180}Hg



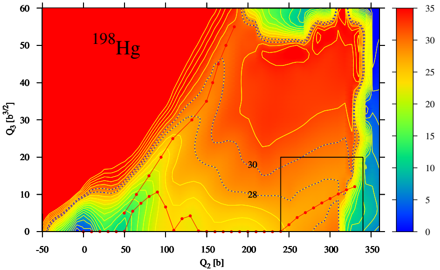
(a) 180Hg, saddle point, N/Z = 1.25, Q2 = 260 b, Q3 = 33.8 b3/2
QN (z0 = 0.5 fm) = 0.3
A=101
A=79
z = 1.02 fm
Q2 = 0 b
Q2 = 8 b
90Zr, ground state, N/Z = 1.25
72Ge, deformed, N/Z = 1.25
rperp [fm]
z [fm]
(d)
180Hg
saddle point
rperp = 0
90Zr
ground state
72Ge
deformed
ρ [fm-3]
z [fm]
(b)
90Zr
E [MeV]
Q2 [b]
(c)
72Ge
Q2 = 2.6 b
E = 0.7 MeV
Q2 = 8 b
E = 3.4 MeV
Q2 = -2.7 b
E [MeV]
Q2 [b]
180Hg, saddle point, z = -8 fm
180Hg, saddle point, z = 10 fm
90Zr
ground state
72Ge, deformed
180Hg saddle point
neck, z = 1 fm
(e)
ρ [fm-3]
rperp [fm]

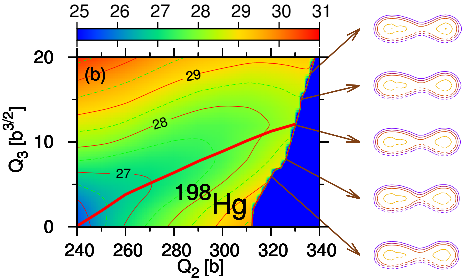
^{198}Hg





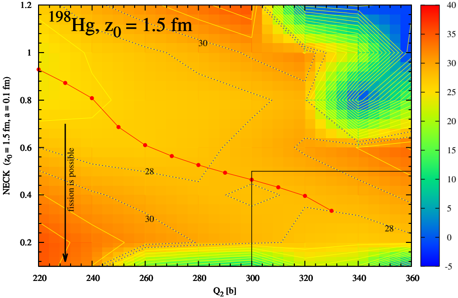
^{198}Hg

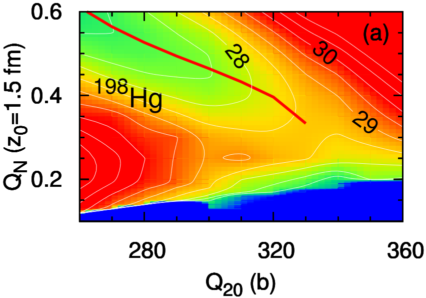




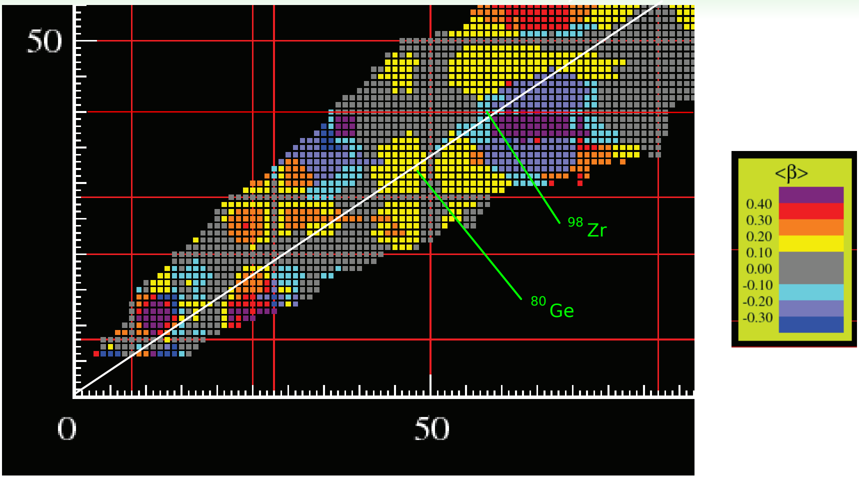
$$A_H/A_L = 108/80$$

^{198}Hg – neck parameter

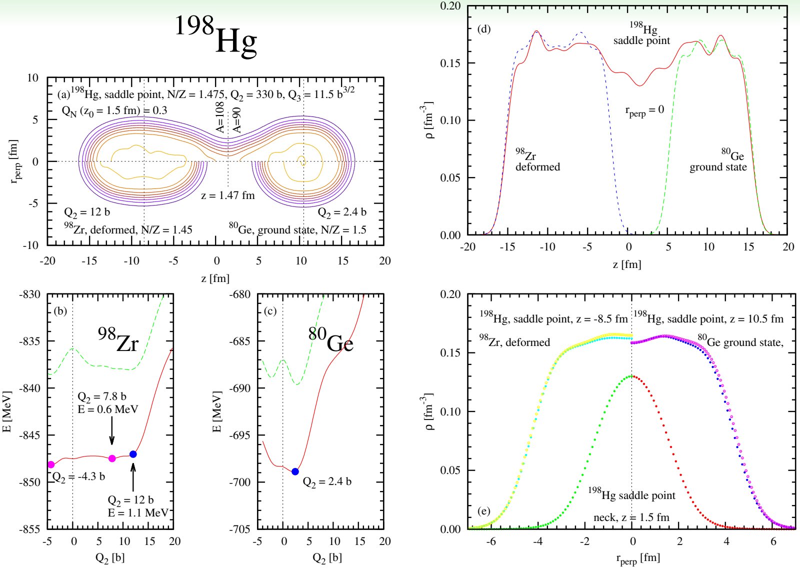




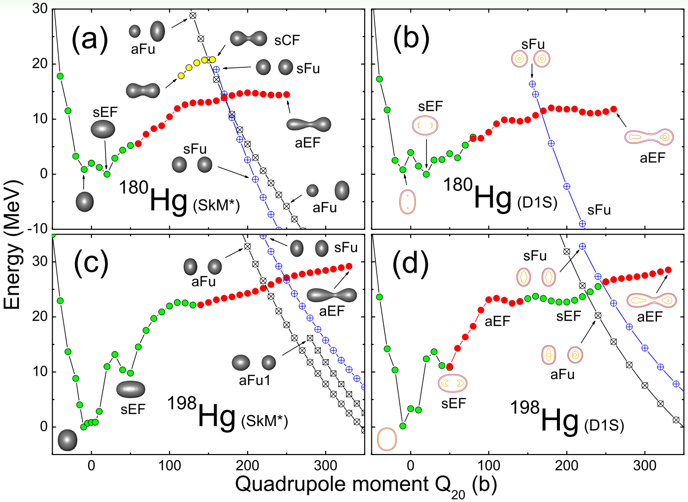
^{198}Hg, $N/Z = 1.475$



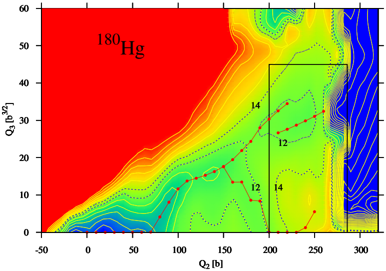
http://www-phynu.cea.fr/

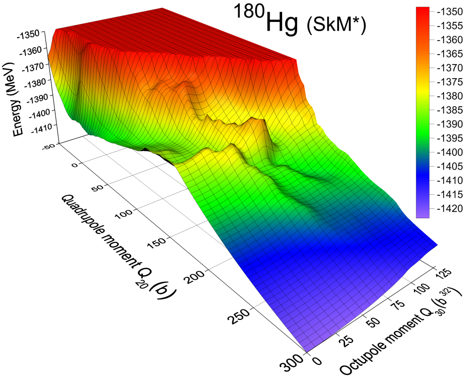

198Hg
(a) 198Hg, saddle point, N/Z = 1.475, Q2 = 330 b, Q3 = 11.5 b3/2
QN (z0 = 1.5 fm) = 0.3
A=108
A=90
z = 1.47 fm
Q2 = 12 b
98Zr, deformed, N/Z = 1.45
Q2 = 2.4 b
80Ge, ground state, N/Z = 1.5
rperp [fm]
z [fm]
(d)
198Hg
saddle point
rperp = 0
98Zr
deformed
80Ge
ground state
ρ [fm-3]
z [fm]
(b)
98Zr
Q2 = 7.8 b
E = 0.6 MeV
Q2 = -4.3 b
Q2 = 12 b
E = 1.1 MeV
E [MeV]
Q2 [b]
(c)
80Ge
Q2 = 2.4 b
E [MeV]
Q2 [b]
198Hg, saddle point, z = -8.5 fm
198Hg, saddle point, z = 10.5 fm
98Zr, deformed
80Ge ground state,
198Hg saddle point
neck, z = 1.5 fm
(e)
ρ [fm-3]
rperp [fm]

Gogny D1S i Skyrme SkM*

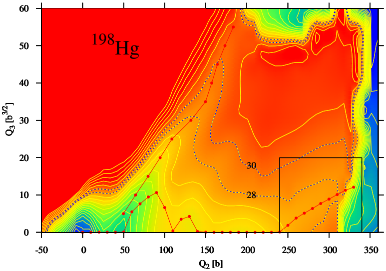


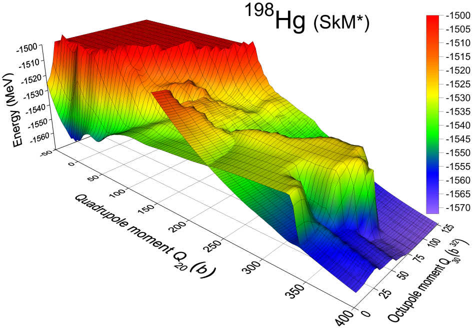
^{180}Hg, Gogny D1S i Skyrme SkM*

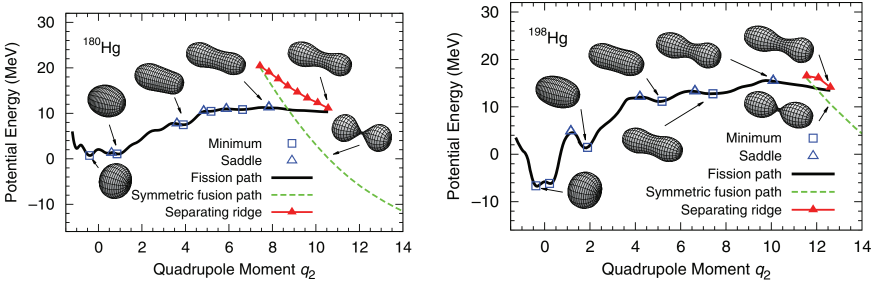




^{198}Hg, Gogny D1S i Skyrme SkM*

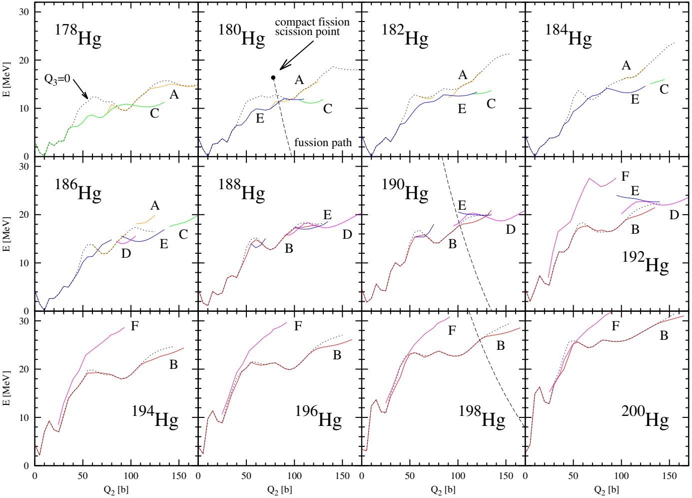






T.Ichikawa, et al. Phys Rev. C86, 024610 (2012).

^{178}Hg – ^{200}Hg

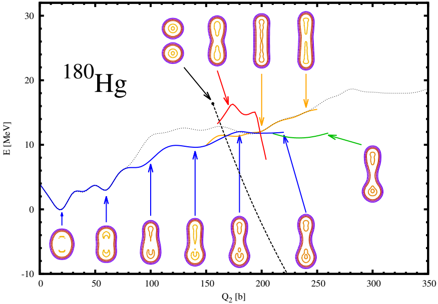


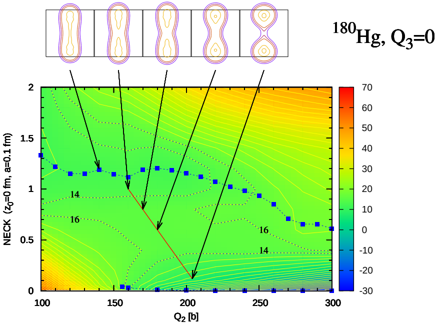
178Hg
180Hg
182Hg
184Hg
186Hg
188Hg
190Hg
192Hg
194Hg
196Hg
198Hg
200Hg
compact fission
scission point
fusion path
Q3=0
A
B
C
D
E
F
E [MeV]
Q2 [b]

Conclusions:

- Potential energy surfaces of ^{180}Hg and ^{198}Hg were determined
- Reflection asymmetric fission paths were found
- Fragment mass asymmetry of ^{180}Hg is reproduced properly
- Asymmetry of fission fragments of ^{198}Hg is predicted less precisely
- Masses of fragments before scission are explained

M. Warda, A. Staszczak, W. Nazarewicz,
Phys. Rev. C86, 024601 (2012).


180Hg
E [MeV]
Q2 [b]
30
20
10
0
-10
0
50
100
150
200
250
300
350


180Hg, Q3=0
NECK (z0=0 fm, a=0.1 fm)
Q2 [b]
14
16
16
14
2
1.5
1
0.5
0
100
150
200
250
300
70
60
50
40
30
20
10
0
-10
-20
-30

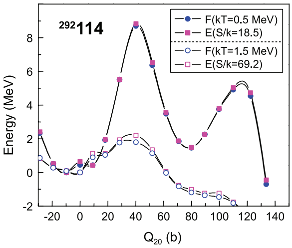


FIG. 1 (color online). Calculated isothermal (F at constant T) and isentropic (E at constant S) axial symmetric fission pathways for $^{292}114$ as a function of the total quadrupole moment Q_{20}. The isothermal calculations were carried out at $kT = 0.5$ and 1.5 MeV. In the isentropic description, S was fixed at the free energy minimum, i.e., $S/k = 18.5(69.2)$ at $kT = 0.5(1.5)$ MeV.

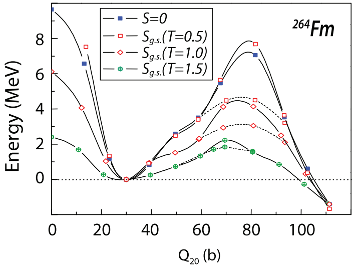


FIG. 3 (color online). Symmetric isentropic fission pathways of ^{264}Fm at the values of S corresponding to $kT_{\mathrm{g.s.}} = 0, 0.5, 1.0,$ and 1.5 MeV The energy has been normalized to zero at the ground-state minimum. The effect of triaxial degrees of freedom on the first barrier is marked by dashed lines.

J.C. Pei et al., *Fission Barriers of Compound Superheavy Nuclei*, Phys. Rev. Lett. **102**, 192501 (2009).

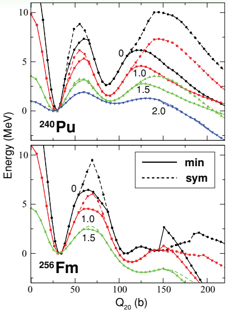


FIG. 1. (Color online) Fission pathways of ^{240}Pu (top) and ^{256}Fm (bottom) as functions of the mass quadrupole moment Q_{20} at different values of the ground-state temperature $kT_{\rm g.s.}$ (marked by numbers, in MeV). Along the minimum-energy pathways ("min"; solid lines), all self-consistent mean-field symmetries can be broken. To illustrate the corresponding energy gain, the axial, reflection-symmetric energy curves are also shown ("sym"; dashed lines). The energy curves have been normalized to zero at the ground-state minimum. The values of $kT_{\rm g.s.} = 1$, 1.5, and 2 MeV correspond to excitation energies of 13.82, 36.79, and 70.88 MeV for ^{240}Pu and 14.93, 39.20, and 75.16 MeV (not shown) for ^{256}Fm.

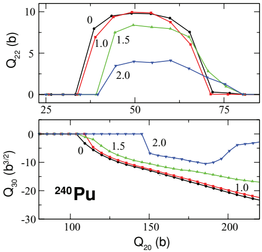


FIG. 2. (Color online) Variation of nonaxial (Q_{22}, top) and reflection asymmetric (Q_{30}, bottom) mass moments as a function of Q_{20} and temperature (indicated in MeV) for ^{240}Pu. It is seen that triaxiality and reflection asymmetry persist to $kT_{\rm g.s.} = 2$ MeV. However, as indicated in Fig. 1, their impact on the total energy is negligible at the largest temperatures considered.

J.A. Sheikh et al., *Systematic study of fission barriers of excited superheavy nuclei*, Phys. Rev. C **80**, 011302(R) (2009).