Two decades of collaboration with Peter Möller

Akira Iwamoto, JAEA and Juntendo Univ.

At the start of our collaboration

In 1991–1992, my nuclear physics laboratory in JAERI (now JAEA) invited Peter Möller for several months and we started the first collaboration work.

In 1993, the laboratory was reorganized into "Advanced Science Research Center". The laboratory survived up to now as the basic nuclear physics group in the Center.

First collaboration paper with Peter Möller appeared in 1994, from which 2-decades passed.

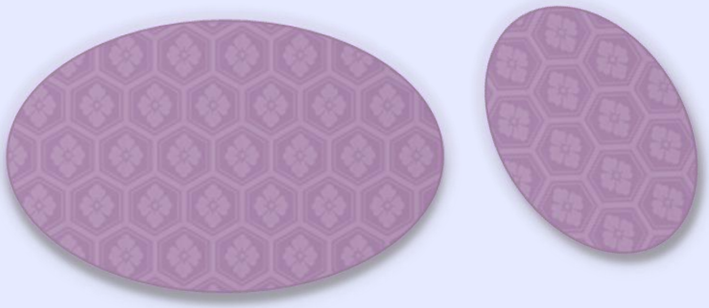
Talk is organized along the following 3 streams

1. First collaboration paper and following works
2. Fission barrier calculus
3. ^{180}Hg and new type of asymmetric fission

Oklo natural reactor

1. First collaboration paper and following works

The first target of our collaboration : develop a general purpose code to calculate the nucleus-nucleus potential



The model was based on the double-folding model where the folding integral was calculated with Yukawa-plus-exponential folding function. The original six-dimensional integral for both volumes of nuclei can be reduced to four-dimensional integral over both surfaces of nuclei, assuming constant density sharp-surface nuclei.

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NUCLEAR PHYSICS A

Nuclear Physics A 575 (1994) 381–411

Macroscopic potential-energy surfaces for arbitrarily oriented, deformed heavy ions

Peter Möller [a,b,1], Akira Iwamoto [b]

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Received 28 February 1994

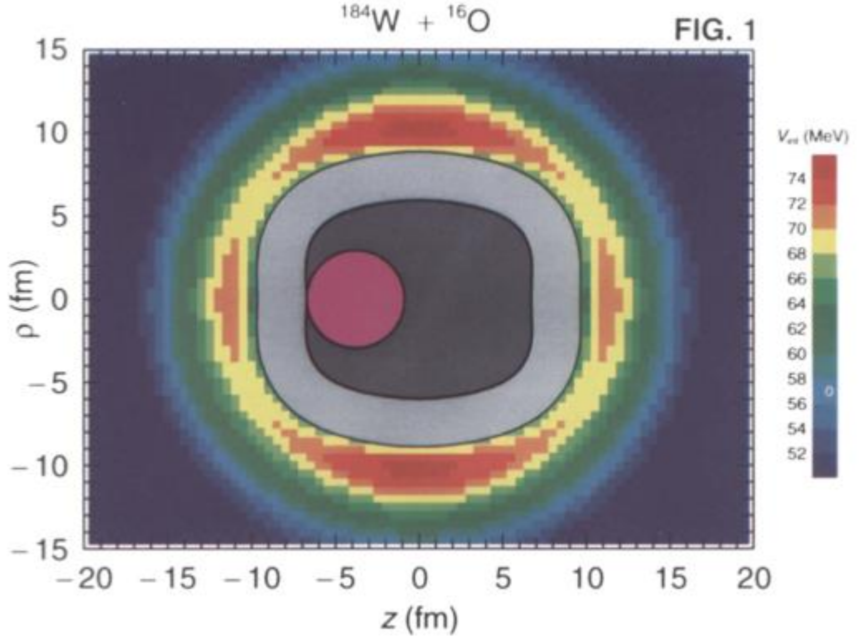

$^{184}W + ^{16}O$
15
10
5
0
−5
−10
−15
ρ (fm)
−20 −15 −10 −5 0 5 10 15 20
z (fm)
V_{ee} (MeV)
74
72
70
68
66
64
62
60
58
56
54
52

FIG. 1

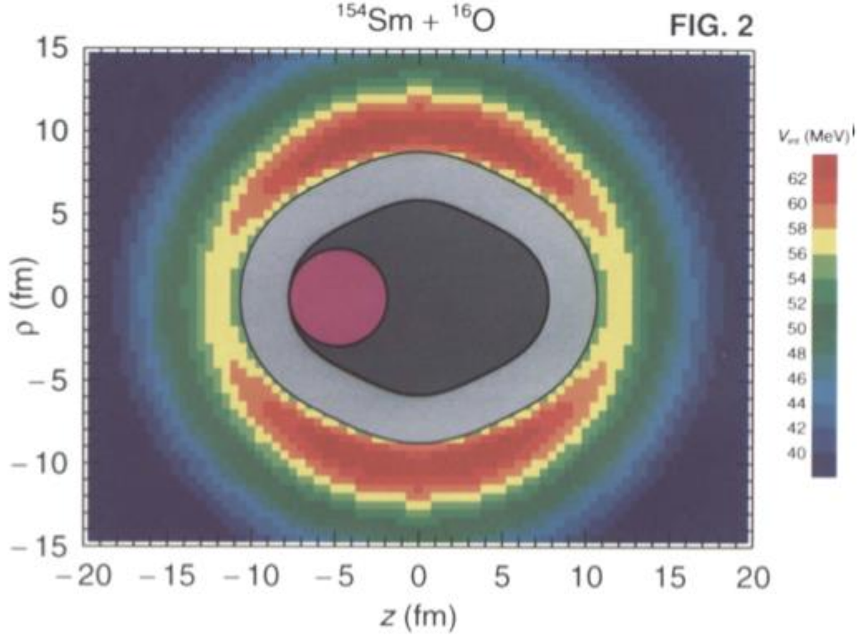
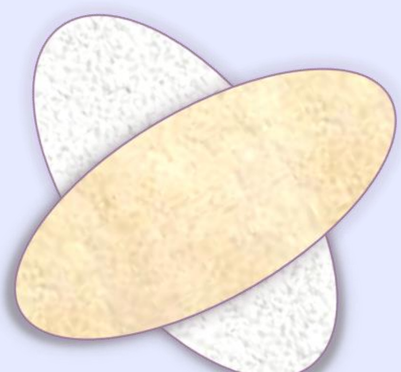
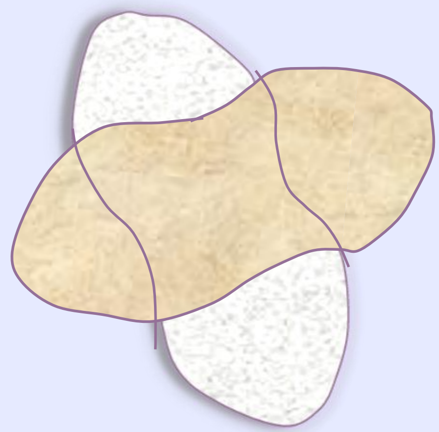

$^{154}Sm + ^{16}O$
15
10
5
0
−5
−10
−15
ρ (fm)
−20 −15 −10 −5 0 5 10 15 20
z (fm)
V_{ee} (MeV)
62
60
58
56
54
52
50
48
46
44
42
40

FIG. 2

This model is used everywhere when we calculate the macroscopic ion-ion potential energy

- For example, in searching of the candidate reactions for SHE production, we proposed "Hugging Fusion" concept.
- It is very effective for getting the strong nuclear force between two ions but because of the offset of it's configuration, the relative Coulomb force is not so strong.





ELSEVIER

Nuclear Physics A 596 (1996) 329–354

NUCLEAR PHYSICS A

Collisions of deformed nuclei: A path to the far side of the superheavy island

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Received 21 June 1995; revised 18 August 1995

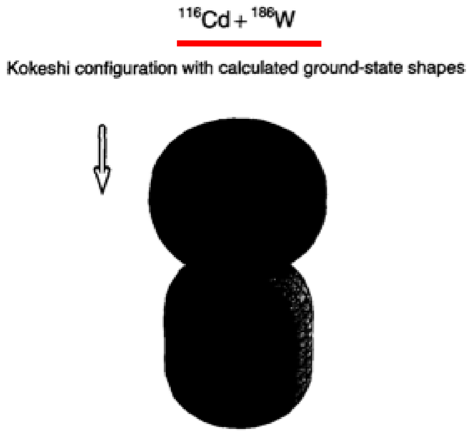


Fig. 19. Polar-parallel Kokeshi configuration of ^{116}Cd + ^{186}W for shapes corresponding to calculated ground-state deformation parameters; that is, the configuration is [o, p⁻, ¦]. The arrow gives the direction of the incident beam. Fusion-barrier parameters for this configuration/direction are given on line 16 of Table 1.

4.2. *Oblate fusion configurations*

We showed above that the sign of ϵ_4 significantly influenced fusion-barrier properties of colliding heavy ions. Correspondingly, one anticipates that the sign of ϵ_2 has a large effect on the fusion barrier, so in Figs. 19 and 20 we give two examples of fusion configurations corresponding to an oblate projectile and a prolate target for the reaction

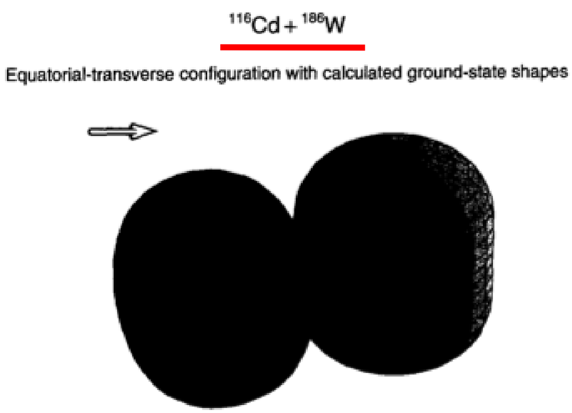
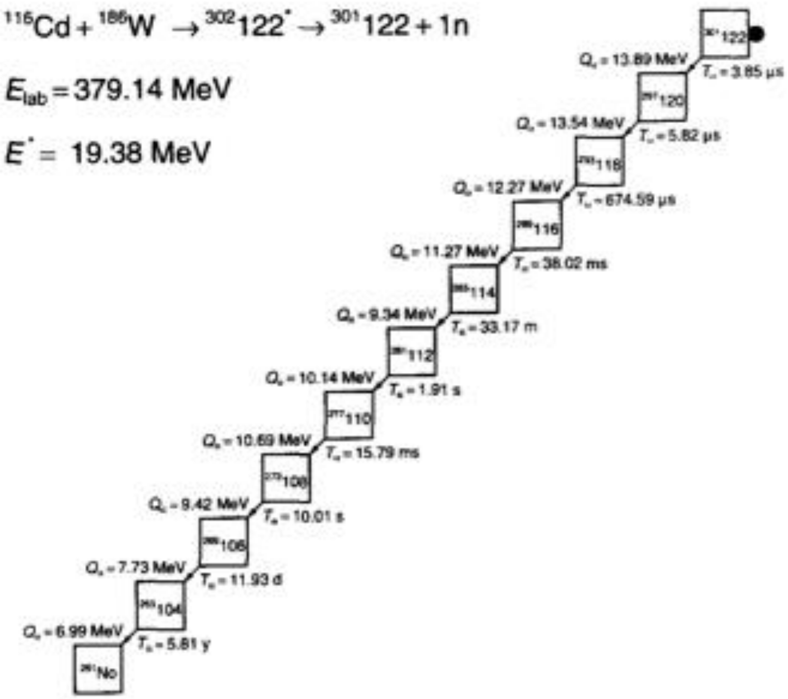


Fig. 20. Equatorial-transverse configuration of ^{116}Cd+^{186}W for shapes corresponding to calculated ground-state deformation parameters; that is, the configuration is [o, p⁻, ⊣]. The arrow gives the direction of the incident beam. Fusion-barrier parameters for this configuration/direction are given on line 17 of Table 1.

$^{116}Cd + ^{186}W \rightarrow {}^{302}122^* \rightarrow {}^{301}122 + 1n$

$E_{lab} = 379.14$ MeV

$E^* = 19.38$ MeV



PHYSICAL REVIEW C 71, 044608 (2005)

Barrier for cold-fusion production of superheavy elements

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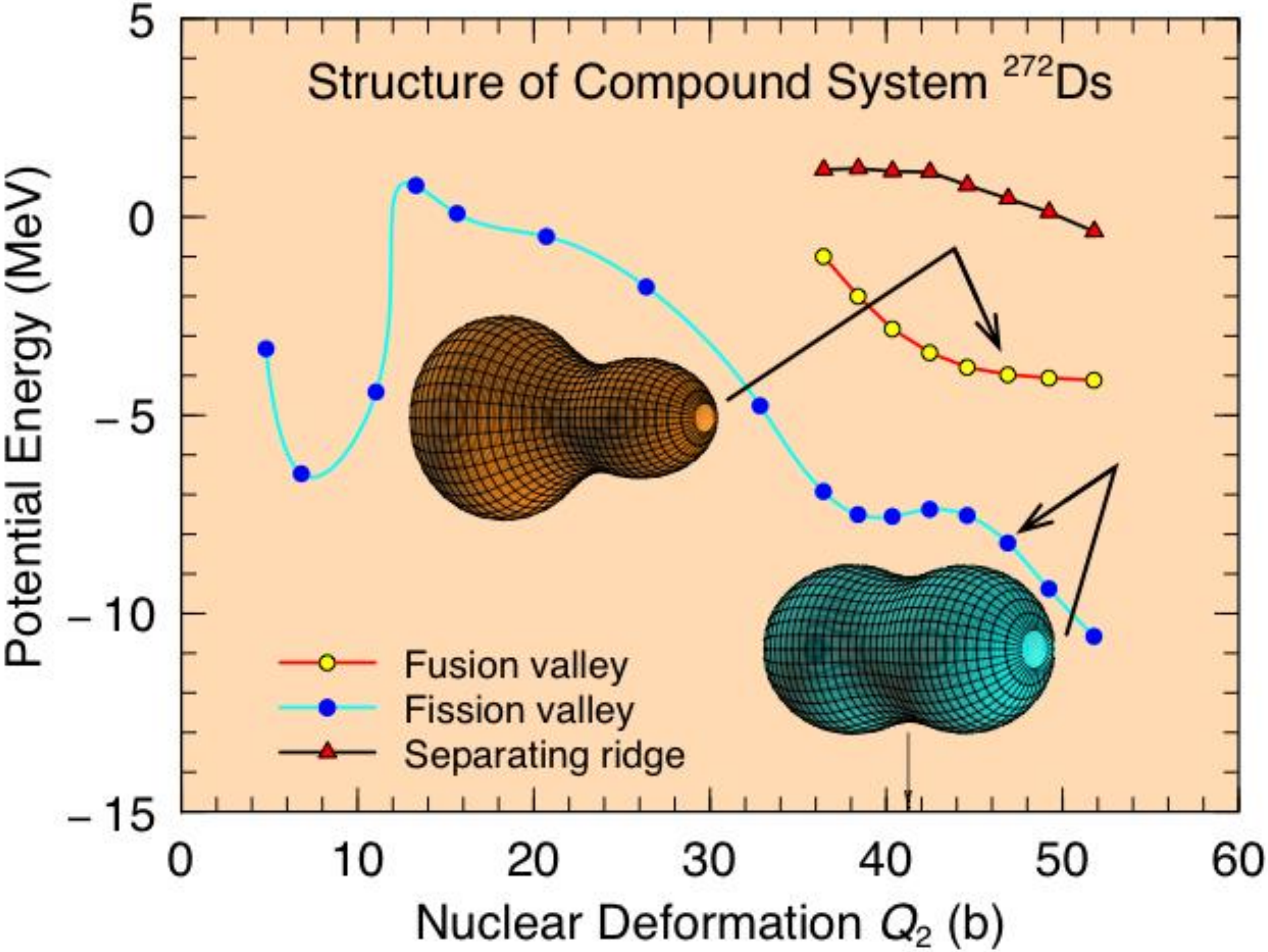
(Received 5 November 2004; published 28 April 2005)

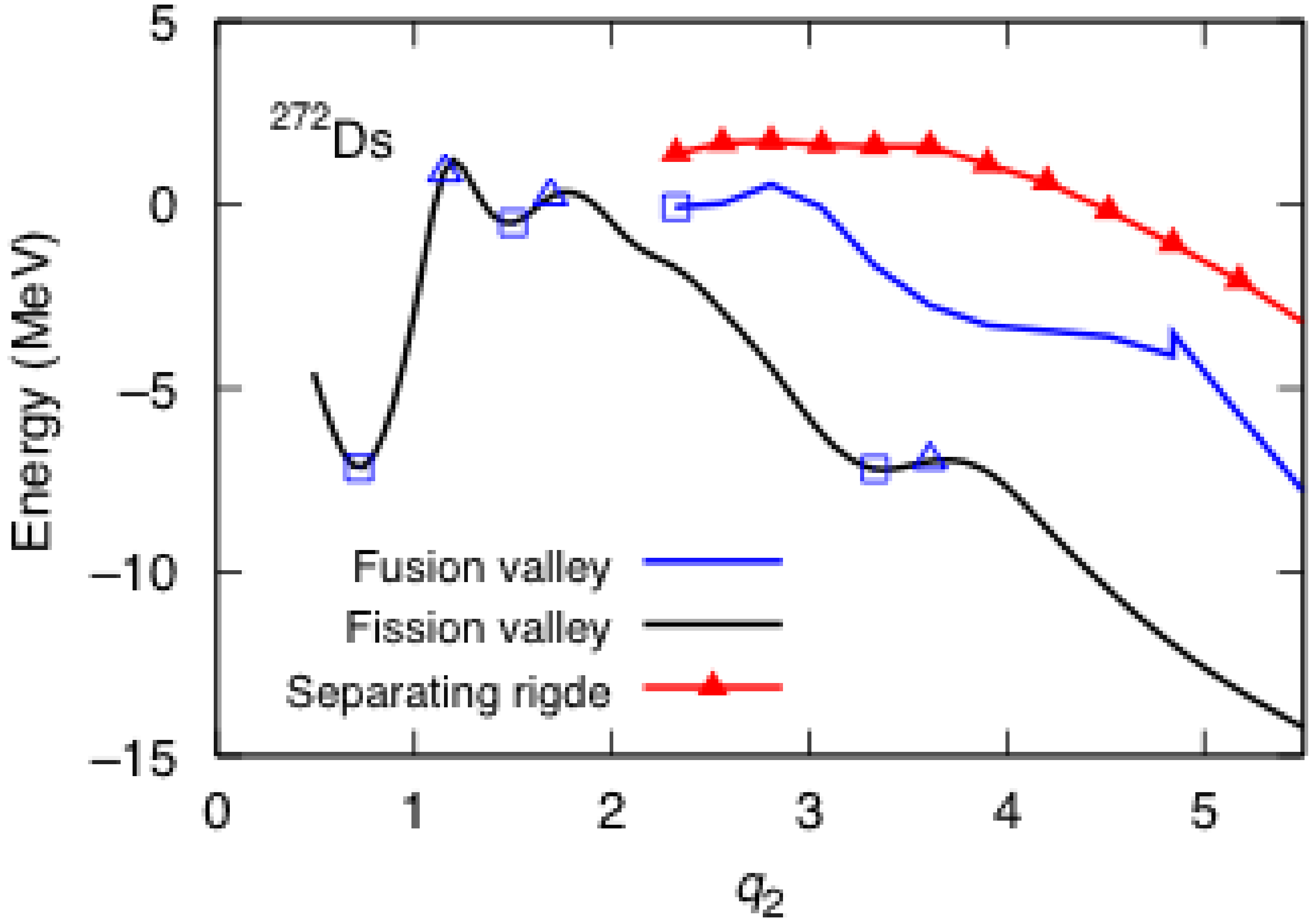
In the incident channel of cold fusion reaction, projectile is expected to be highly deformed near the fusion barrier.

In addition, what's interesting is that we always find, in the one-body fission configuration, there exists a fission valley with almost spherical Pb(Bi)-like plus highly deformed projectile-like configuration!!



Structure of Compound System ^{272}Ds
Potential Energy (MeV)
Nuclear Deformation Q_2 (b)
5
0
−5
−10
−15
0
10
20
30
40
50
60
Fusion valley
Fission valley
Separating ridge

Extended calculation of potential for ^{272}Ds

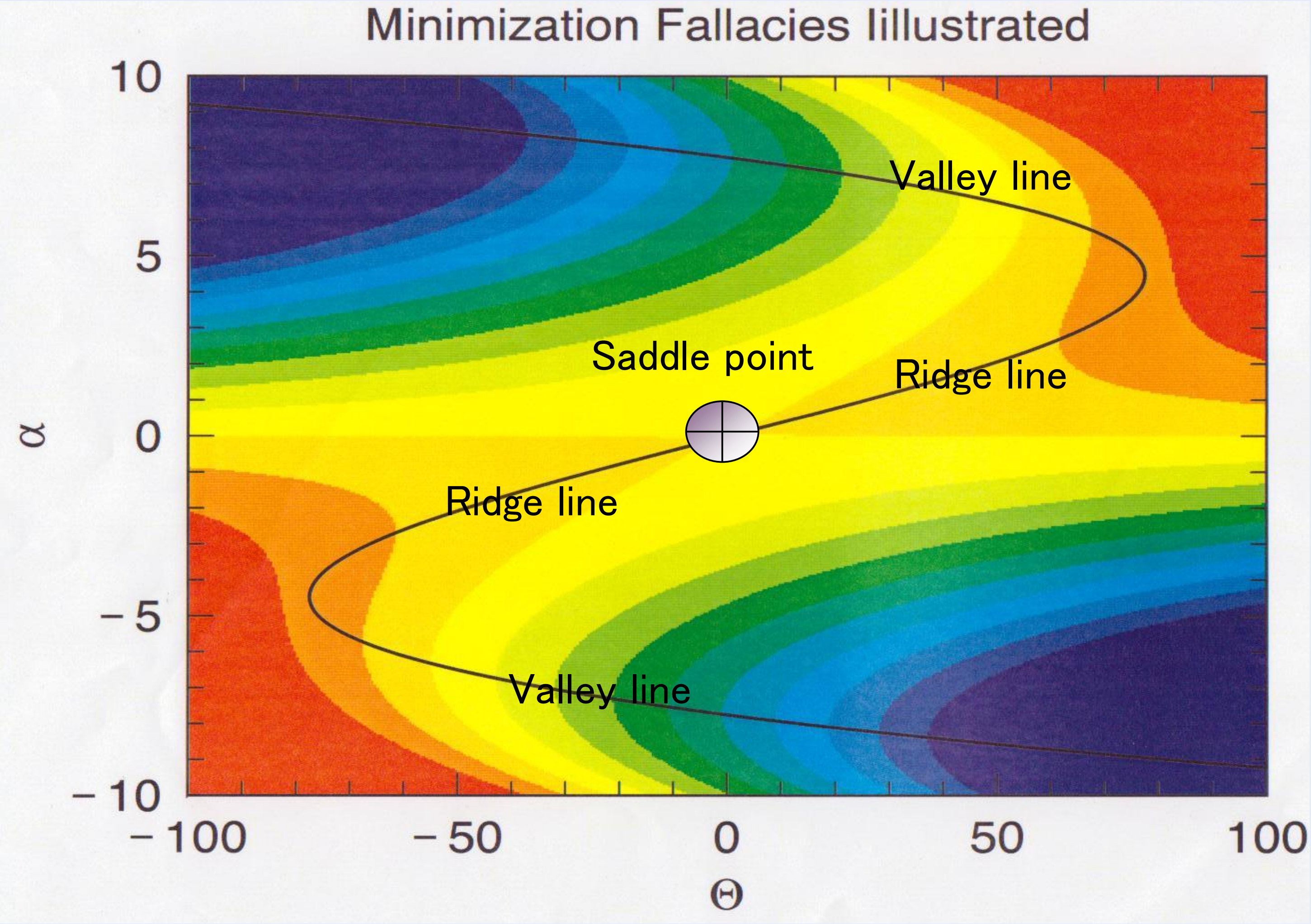


2. Fission barrier calculus

- When we need many shape parameters to specify the fissioning nucleus, there exist many saddle points. (We use macroscopic-microscopic model)
- The lowest and some of near lowest ones are important for low energy fission.
- How to fix them is an important and not an easy task.

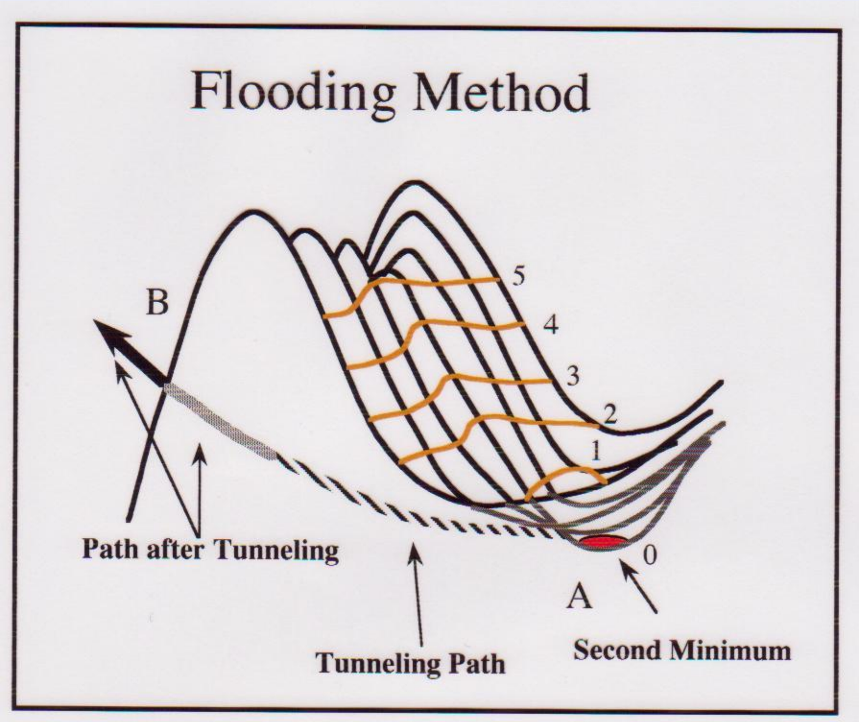
- At first glance, constrained HF, HFB models looks more feasible to attack this problem, but it isn't!!
- For example, how to fix the second lowest and third lowest ones? Is the lowest one obtained is really lowest? (If there isn't the way to fix the second lowest, no one can say yes.)

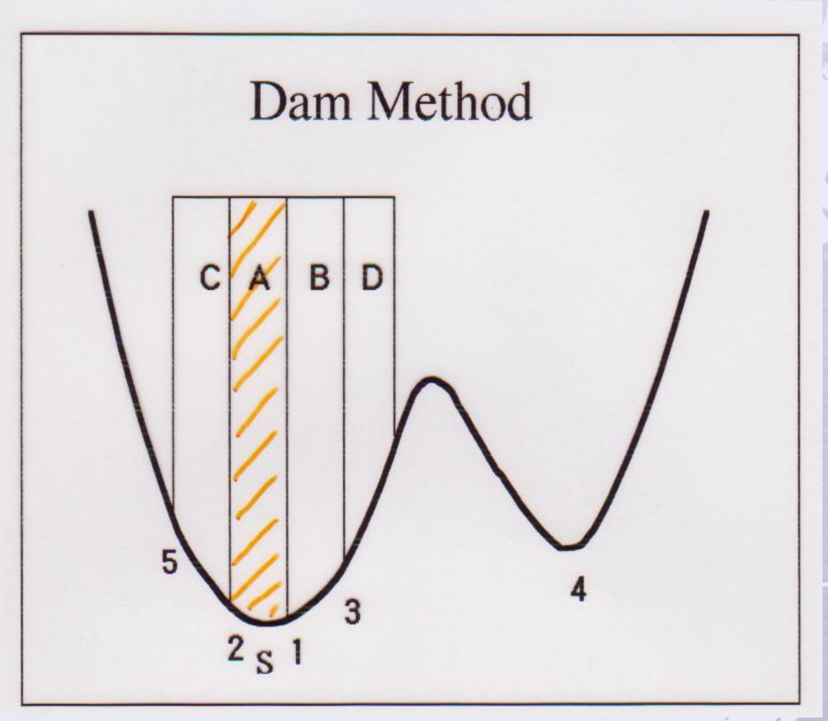
Real saddle point is a point of minimum after the minimization with respect to theta



Techniques for fixing multiple saddles heights and locations

- Water immersion (flooding) method, dam method.





Mystery of bimodal fission

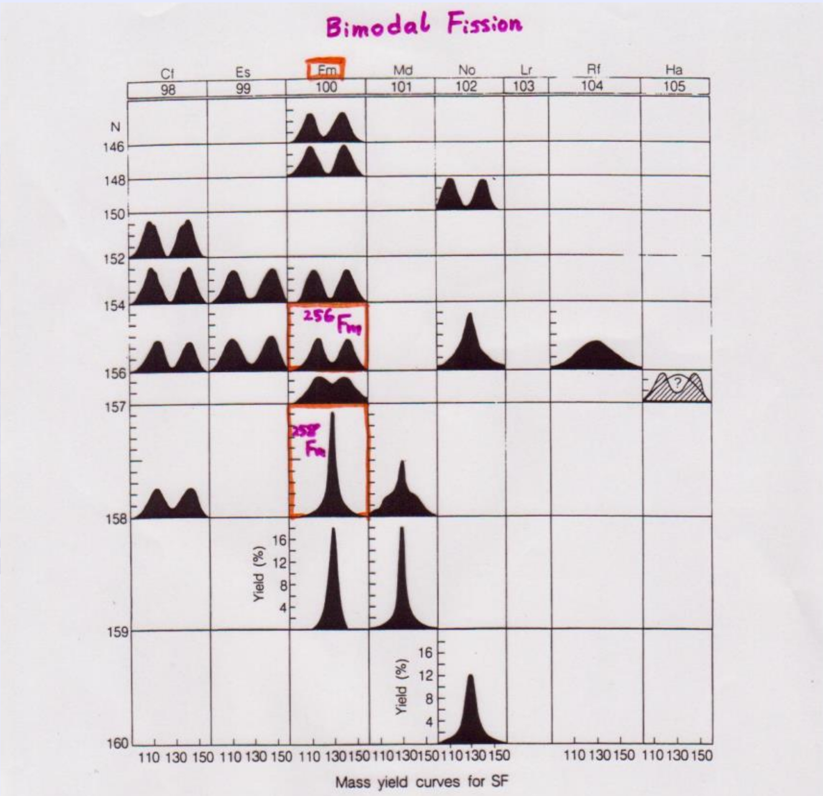
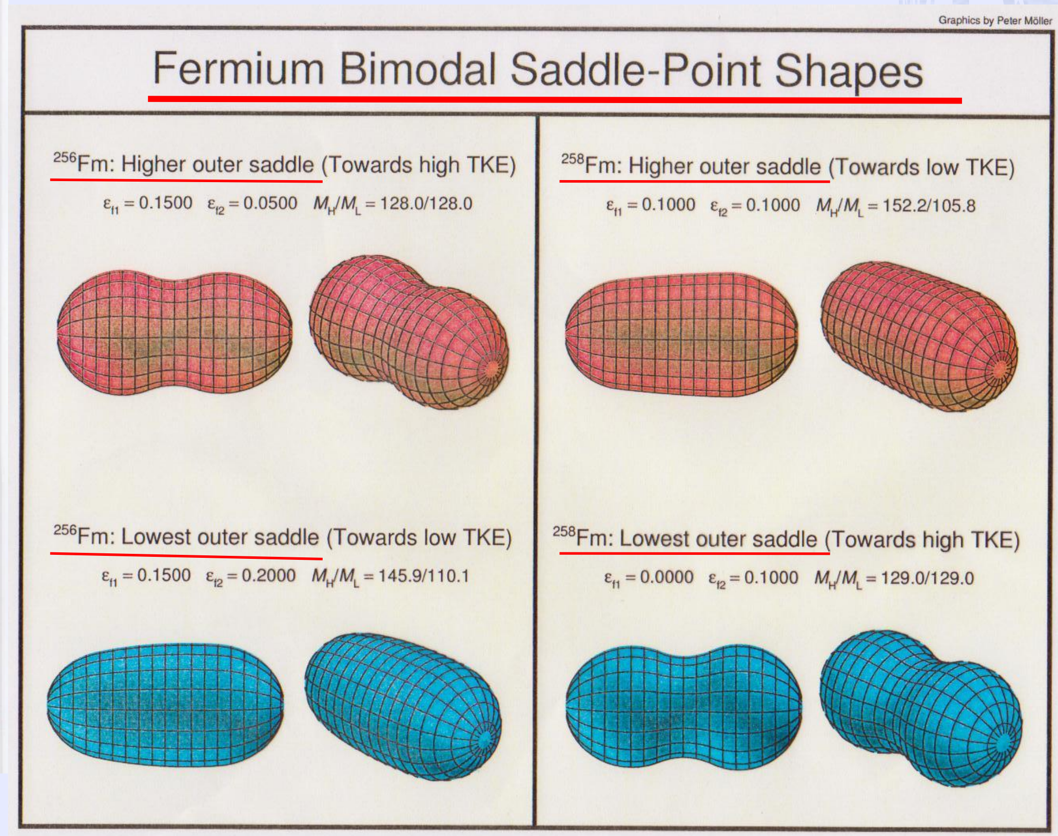
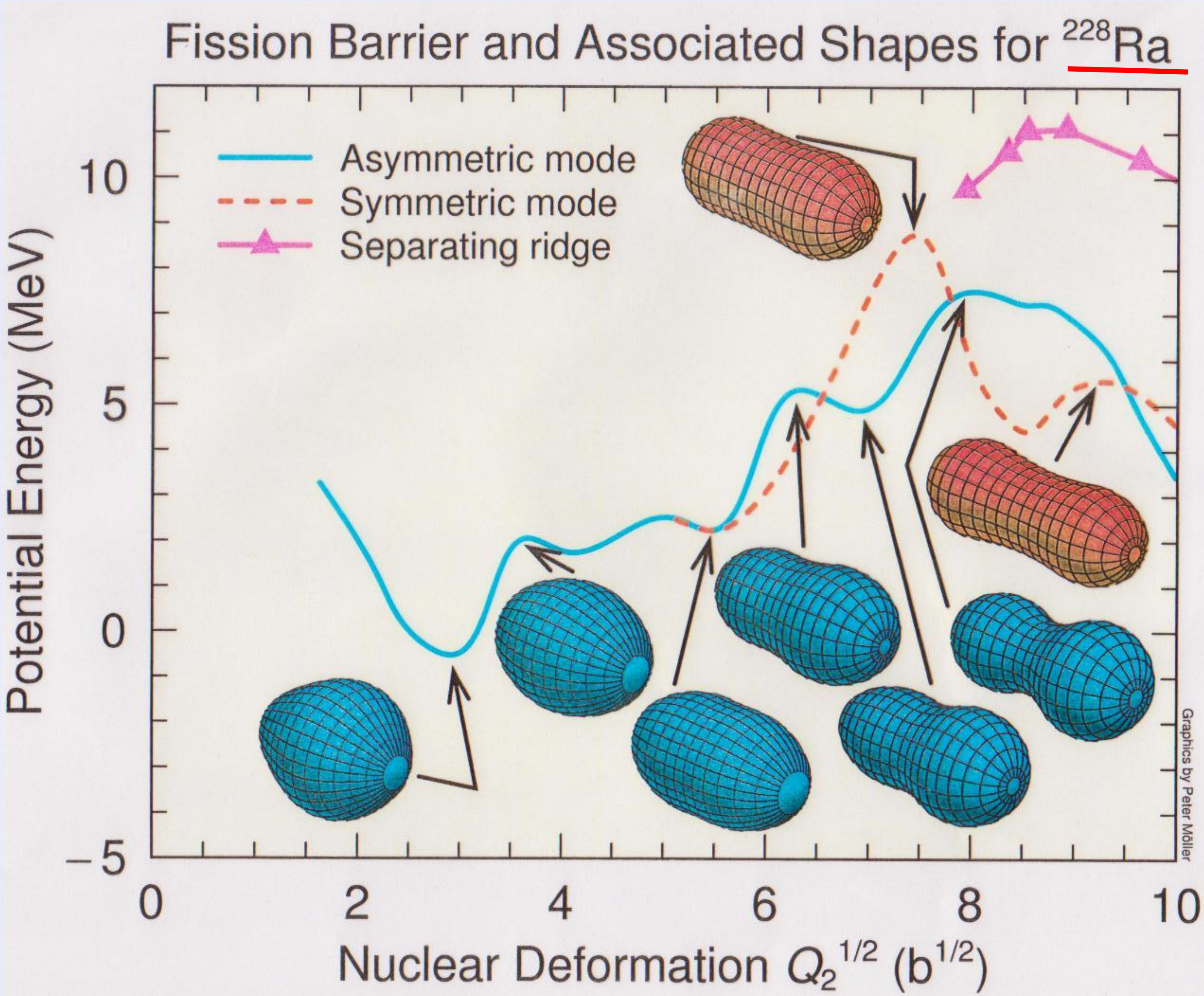


FIGURE 6
c of mass-yield distributions (normalized to 200% fission fr
or SF of trans-Bk isotopes, 1989.

We thought we have understood it but the whole understanding of life-time is yet out of our reach




Fission Barrier and Associated Shapes for 228Ra
Asymmetric mode
Symmetric mode
Separating ridge
Potential Energy (MeV)
10
5
0
−5
0
2
4
6
8
10
Nuclear Deformation Q2 1/2 (b1/2)
Graphics by Peter Möller

Nature ***409*, *785–790 (15 February 2001)***

articles

Nuclear fission modes and fragment mass asymmetries in a five-dimensional deformation space

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Established a method of fixing the multiple saddle points systematically in full 5-dimensional parameter space

Transition of mass asymmetric to symmetric fission of ^{256}Fm to ^{258}Fm was reproduced

Peak mass asymmetry was reproduced systematically well

Root 66


OFFICIAL SCENIC HISTORIC MARKER
CONTINENTAL DIVIDE
Elevation 7245 ft.
Rainfall divides at this point. To the west it drains into the Pacific Ocean, to the east, into the Atlantic.

3. ^{180}Hg and new type of asymmetric fission

- A very exotic process of β–delayed (e–capture) fission of ^{180}Ti was studied at ISOLDE
- In contrast to traditional expectation, the low–energy fission of $^{180}Hg_{100}$ showed an asymmetric fission (A_H/A_L ~ 100/80), not symmetric two $^{90}Zr_{50}$’s

PRL **105**, 252502 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

New Type of Asymmetric Fission in Proton-Rich Nuclei

A. N. Andreyev,[1,2] J. Elseviers,[1] M. Huyse,[1] P. Van Duppen,[1] S. Antalic,[3] A. Barzakh,[4] N. Bree,[1] T. E. Cocolios,[1] V. F. Comas,[5] J. Diriken,[1] D. Fedorov,[4] V. Fedosseev,[6] S. Franchoo,[7] J. A. Heredia,[5] O. Ivanov,[1] U. Köster,[8] B. A. Marsh,[6] K. Nishio,[9] R. D. Page,[10] N. Patronis,[1,11] M. Seliverstov,[1,4] I. Tsekhanovich,[12,17] P. Van den Bergh,[1] J. Van De Walle,[6] M. Venhart,[1,3] S. Vermote,[13] M. Veselsky,[14] C. Wagemans,[13] T. Ichikawa,[15] A. Iwamoto,[9] P. Möller,[16] and A. J. Sierk[16]

PHYSICAL REVIEW C **86**, 024610 (2012)

Contrasting fission potential-energy structure of actinides and mercury isotopes

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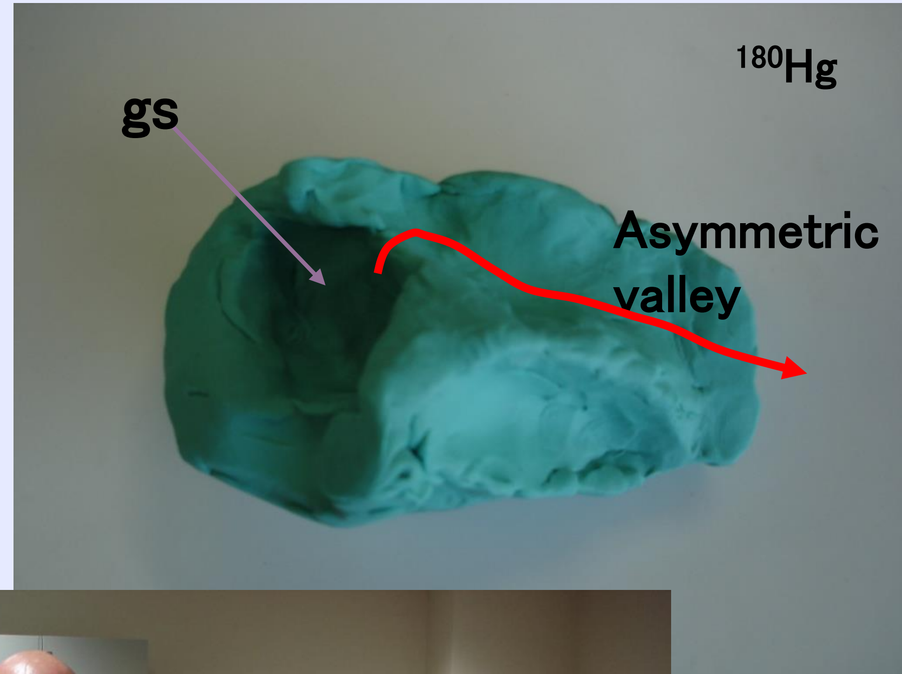
(Received 9 March 2012; revised manuscript received 15 June 2012; published 27 August 2012)

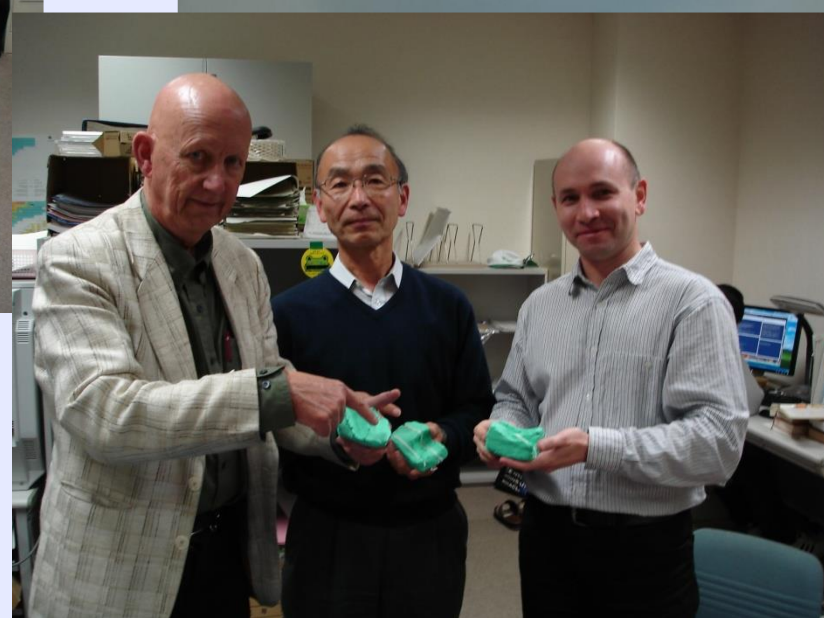
- It is a new type of fission in mass lighter than ~200 region, where the mass asymmetric fission is not an exceptional phenomenon but expected to appear quite commonly.
- A new era of fission search was started!!

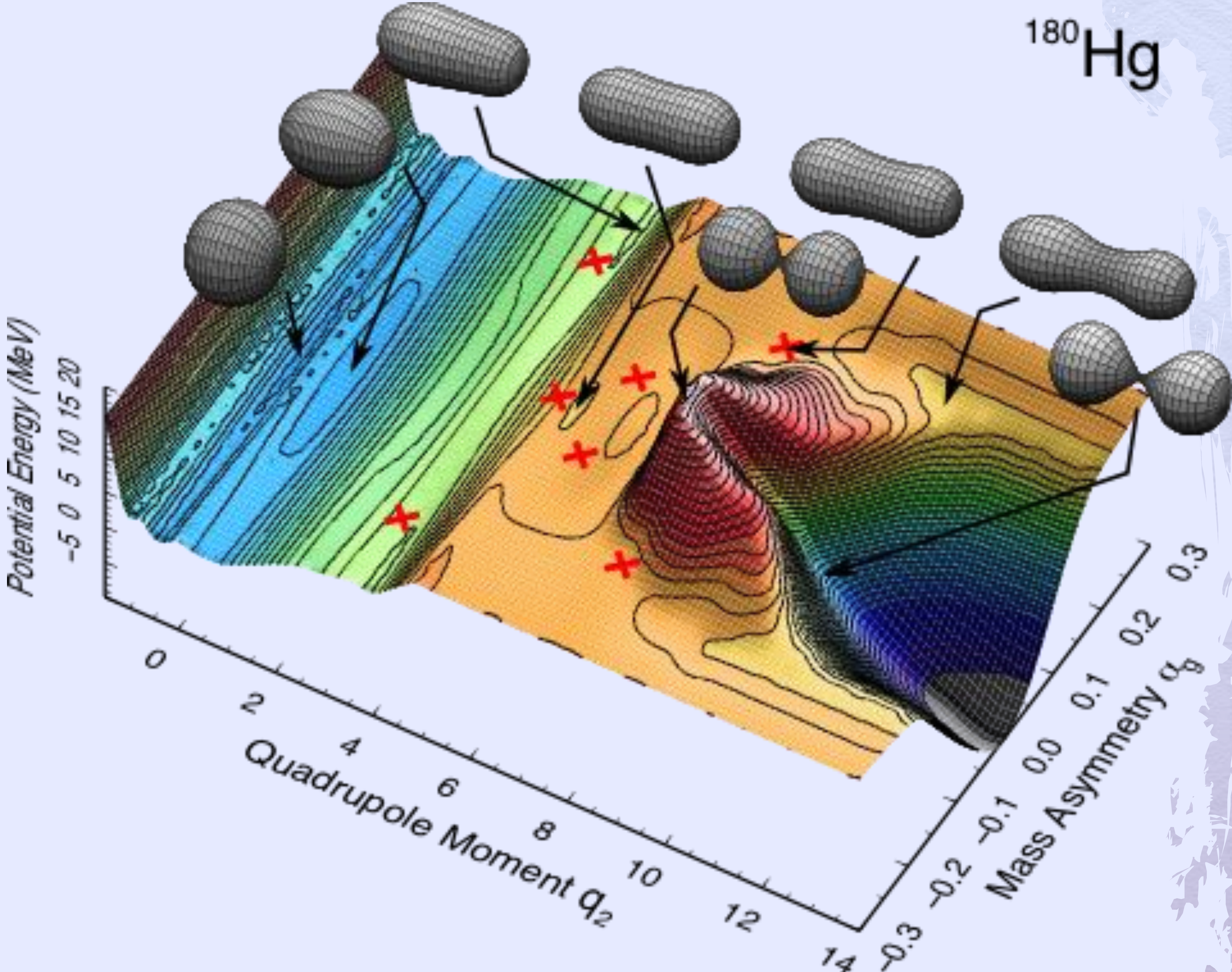
PM: So, do you need a PES for 180Hg?

CLDM: Clay Liquid Drop Model (~2008, to be published yet)

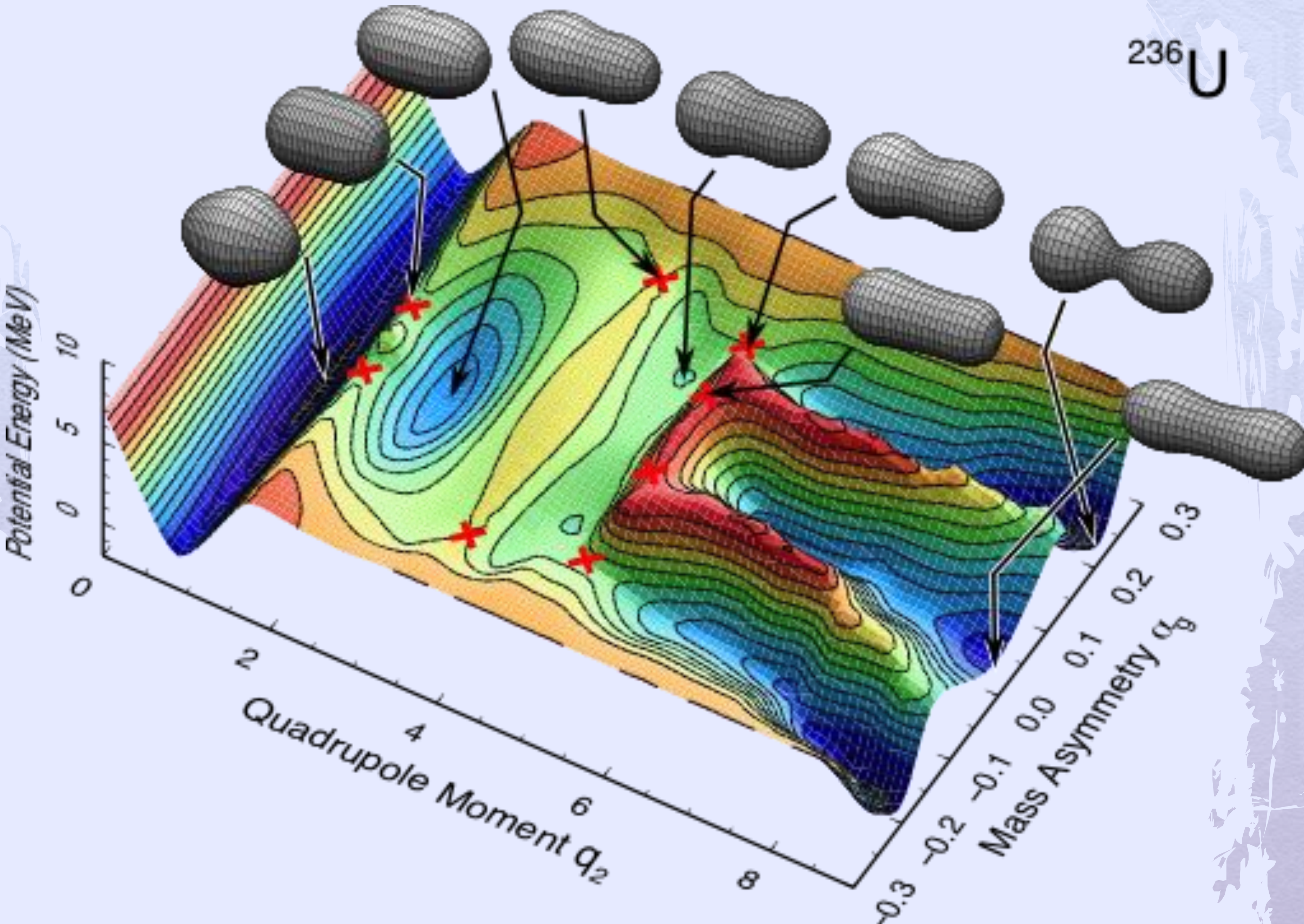

PM: “Look, it’s trivial...”





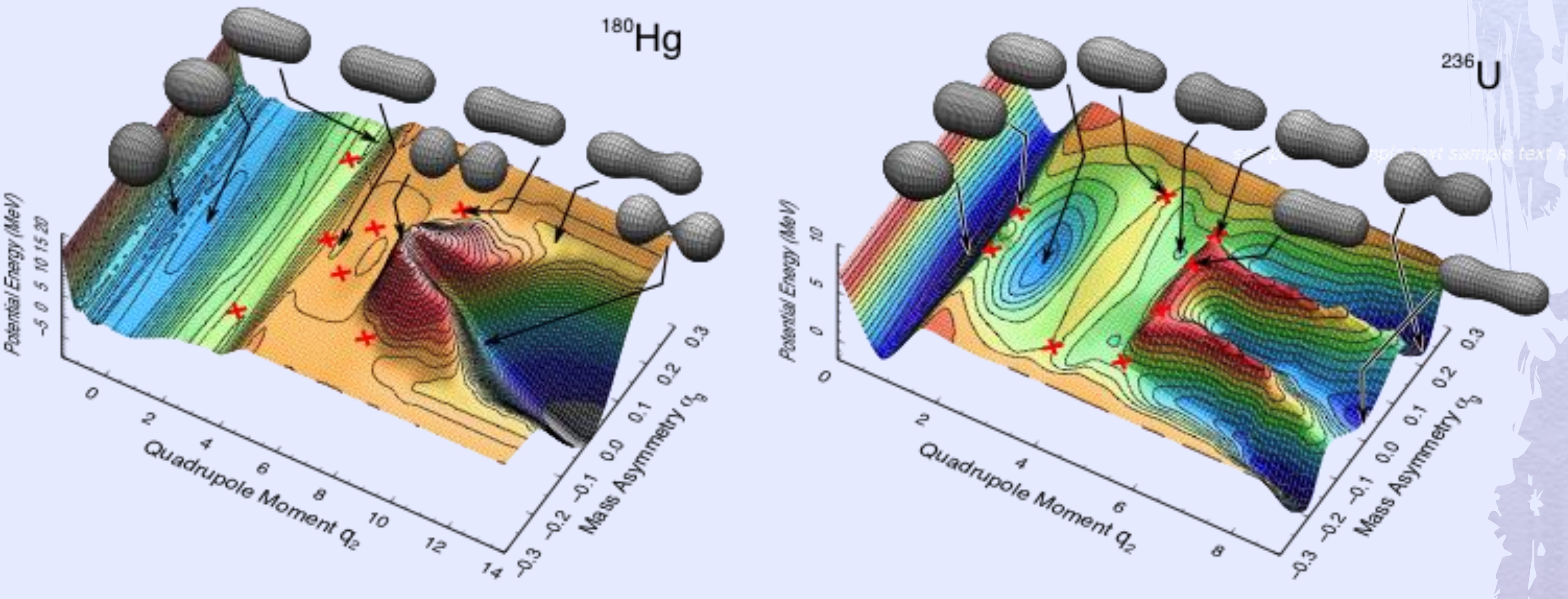


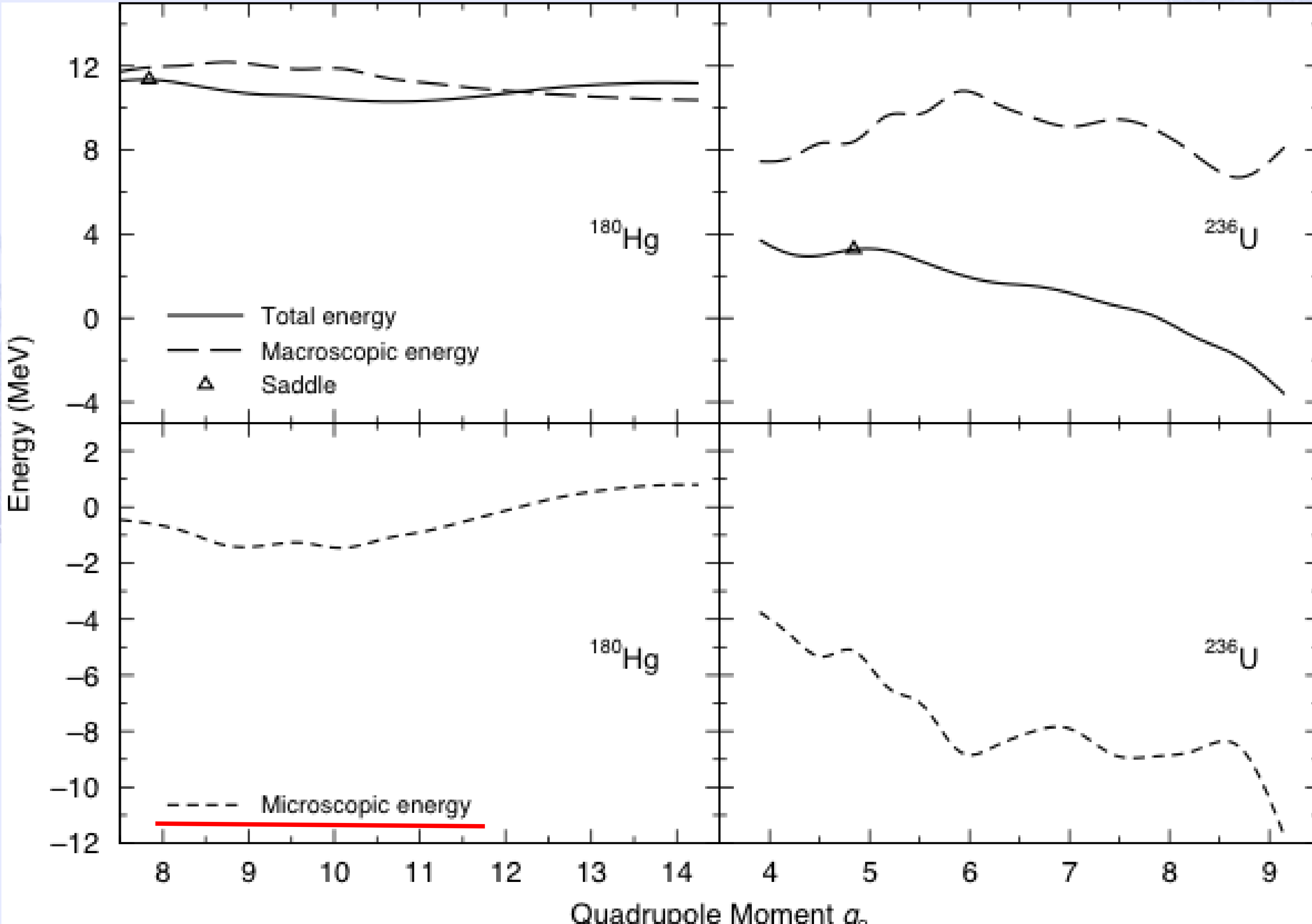
^{180}Hg
Potential Energy (MeV)
-5 0 5 10 15 20
Quadrupole Moment q_2
0 2 4 6 8 10 12 14
Mass Asymmetry α_g
-0.3 -0.2 -0.1 0.0 0.1 0.2 0.3



236U
Potential Energy (MeV)
0
5
10
Quadrupole Moment q2
0
2
4
6
8
Mass Asymmetry q3
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3

Contrasting Fission Potential-Energy Surfaces Hg↔U





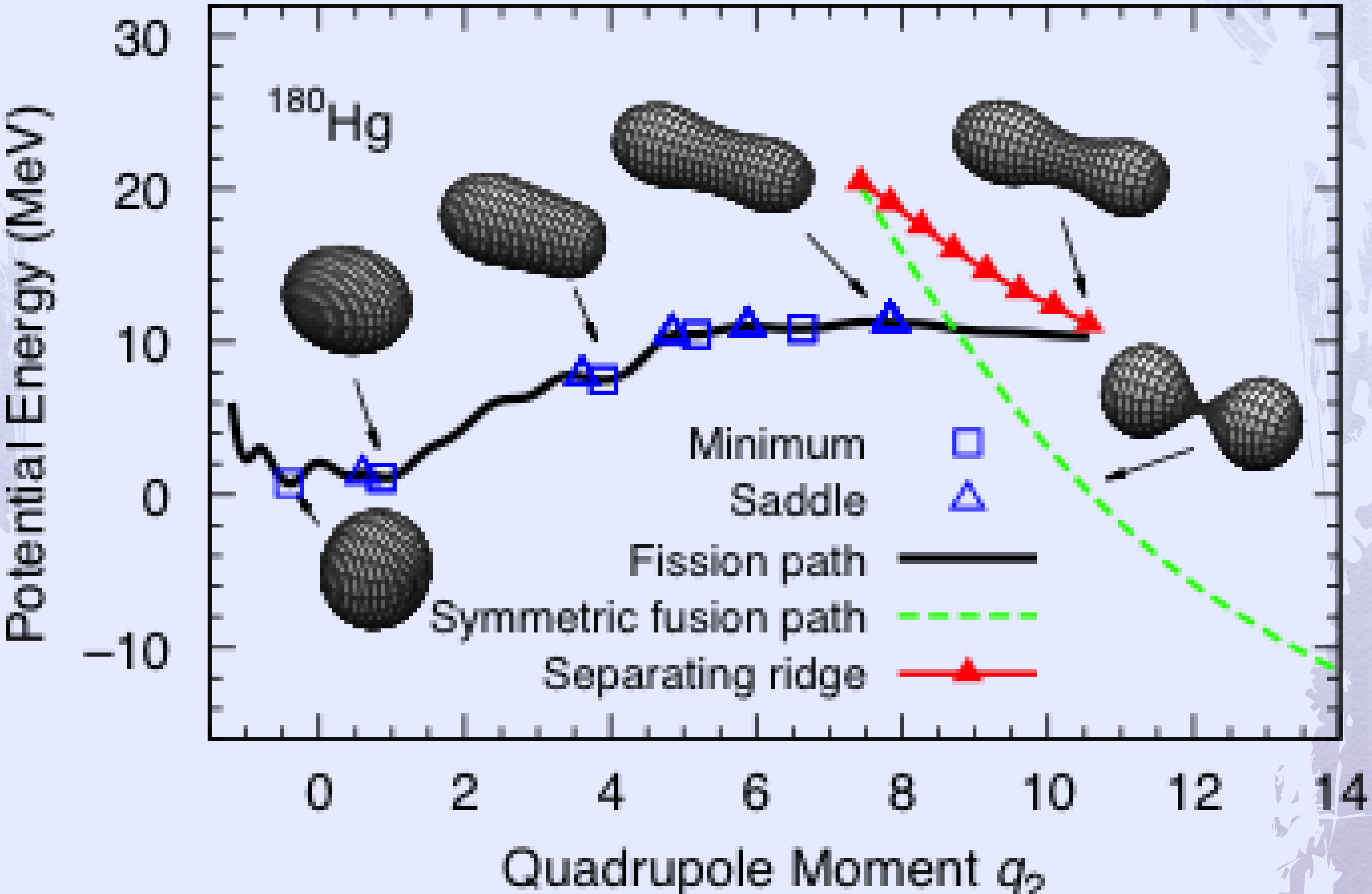
12
8
4
0
−4
2
0
−2
−4
−6
−8
−10
−12
Energy (MeV)
180Hg
236U
Total energy
Macroscopic energy
Saddle
Microscopic energy
8
9
10
11
12
13
14
4
5
6
7
8
9
Quadrupole Moment q2

New aspects of ^{180}Hg

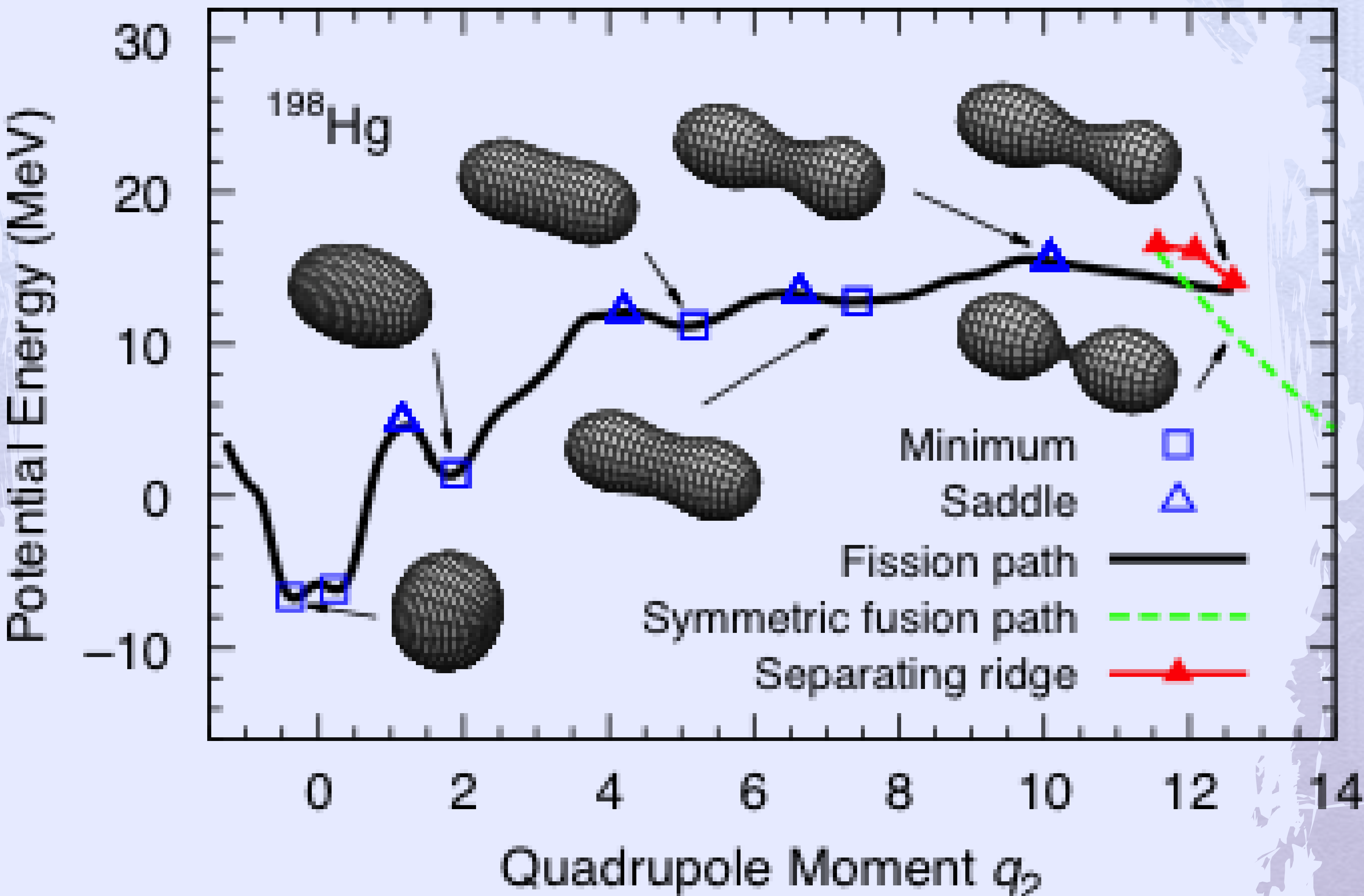
- It occurs a coexistence of fission and fusion valley between second minimum and scission region (including outer barrier).
- The asymmetric fission valley is LD dominant (small shell effect causes mass asymmetry) and fusion valley is shell + LD dominant, which feature is in sharp contrast with typical actinide nuclei. (resembling in Fm isotopes)
- Vast and flat potential energy surface in the above region necessitates a careful treatment of the (mass and) friction tensors.

Finally

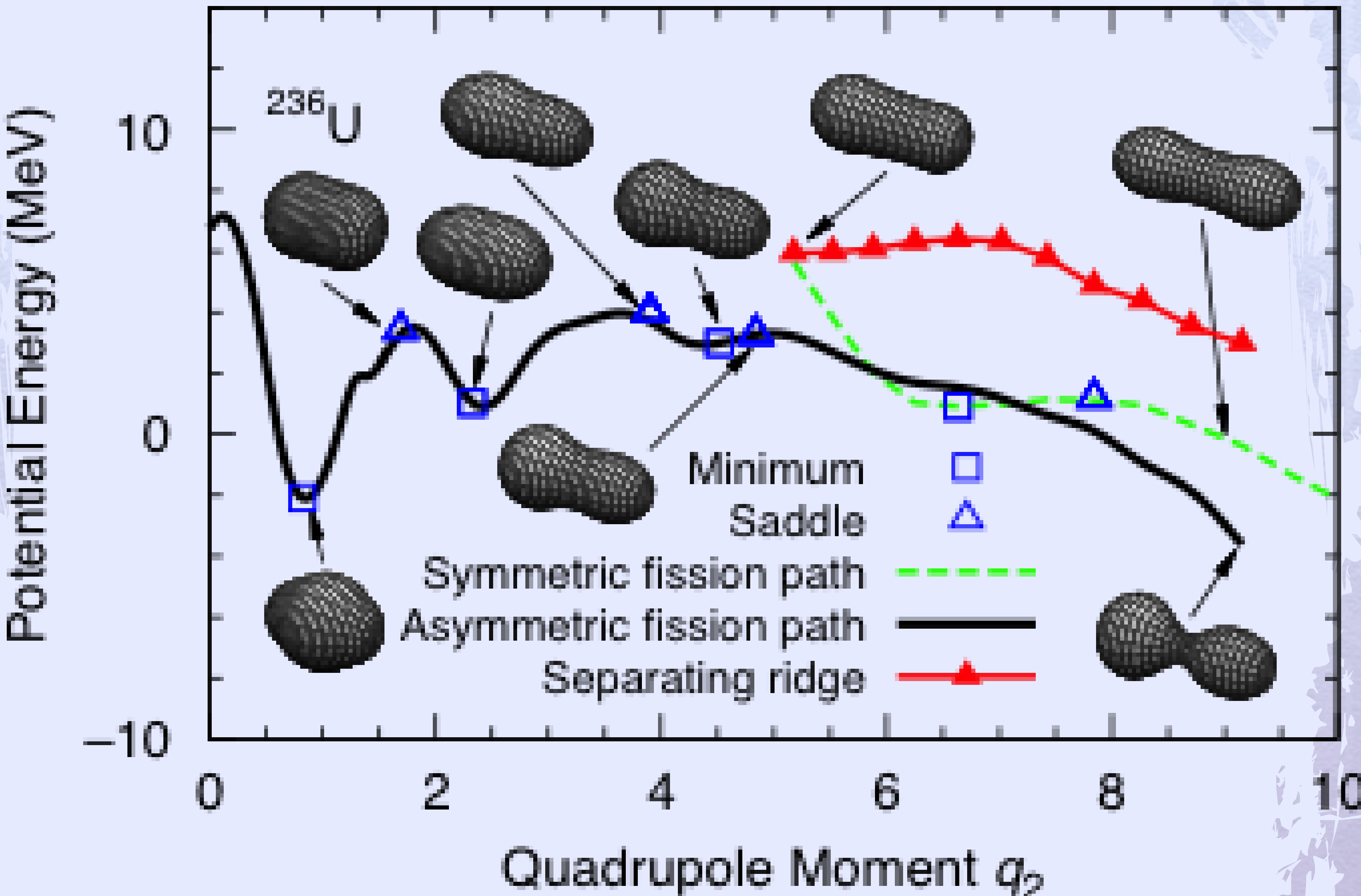
- Thank you Peter for more than two decades of interesting collaborations.
- Hoping to develop our works to get a deeper understanding of nuclear fission and related topics!

180Hg
Potential Energy (MeV)
Quadrupole Moment q_2
30
20
10
0
−10
0
2
4
6
8
10
12
14
Minimum
Saddle
Fission path
Symmetric fusion path
Separating ridge



^{198}Hg
Potential Energy (MeV)
30
20
10
0
−10
0
2
4
6
8
10
12
14
Quadrupole Moment q_2
Minimum
Saddle
Fission path
Symmetric fusion path
Separating ridge



Potential Energy (MeV)
10
0
−10
0
2
4
6
8
10
Quadrupole Moment q_2
^{236}U
Minimum
Saddle
Symmetric fission path
Asymmetric fission path
Separating ridge