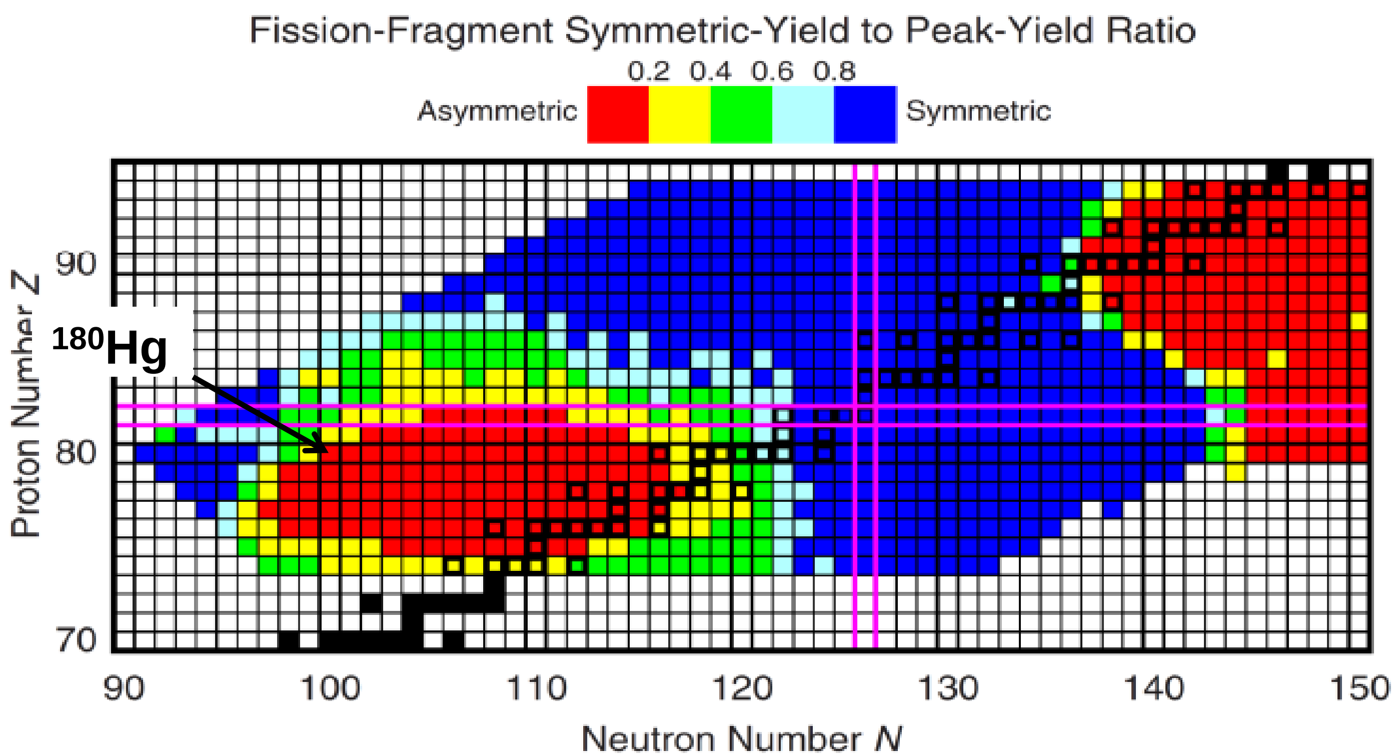
Beta-delayed fission in the lead region: mapping asymmetry-to-symmetry transition

Andrei Andreyev
University of York, UK, ISOLDE-CERN(Geneva,Switzerland)
Japan Atomic Energy Agency (JAEA), Tokai, Japan
On behalf of York-Leuven-Bratislava-Brussels-Bruyeres-le-Chatel-Bordeaux-ISOLDE-JAEA Collaboration



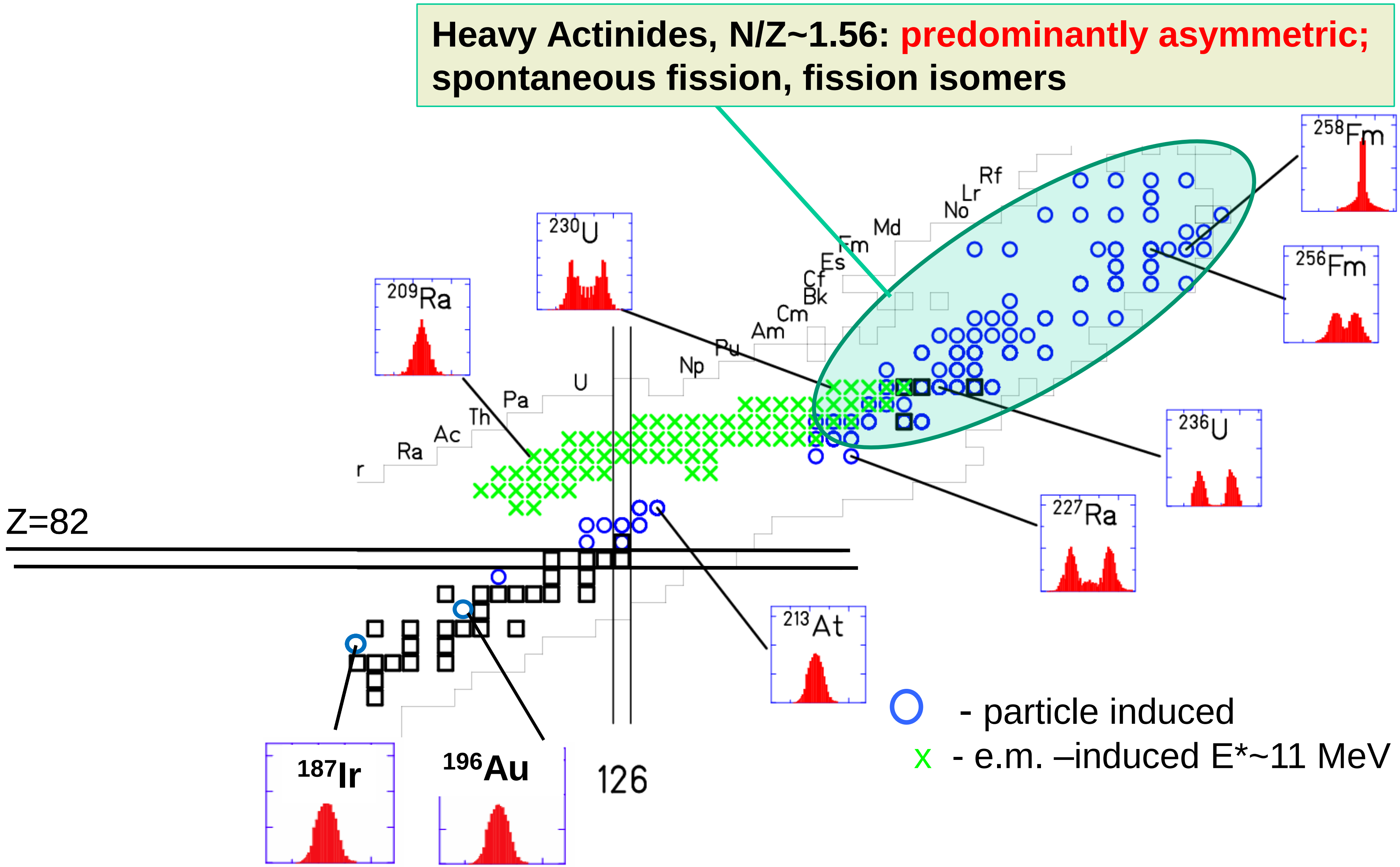
P.Moller, J. Randrup, PRC91 (2015)

JAEA, 25th March 2019

Beta-delayed fission in the lead region: mapping asymmetry-to-symmetry transition

- Low-energy fission in the "new" regions of the Nuclear Chart
- βDF of $^{178,180}Hg$, $^{194,196}At$, ^{202}Fr at ISOLDE(CERN)
- βDF of $^{188m1,m2}Bi$ – probing spin dependence of fission at low E*
- Theory efforts (see several follow-up talks)

Experimental information on low-energy fission
Nuclei with measured charge/mass split (RIPL-2 + GSI)



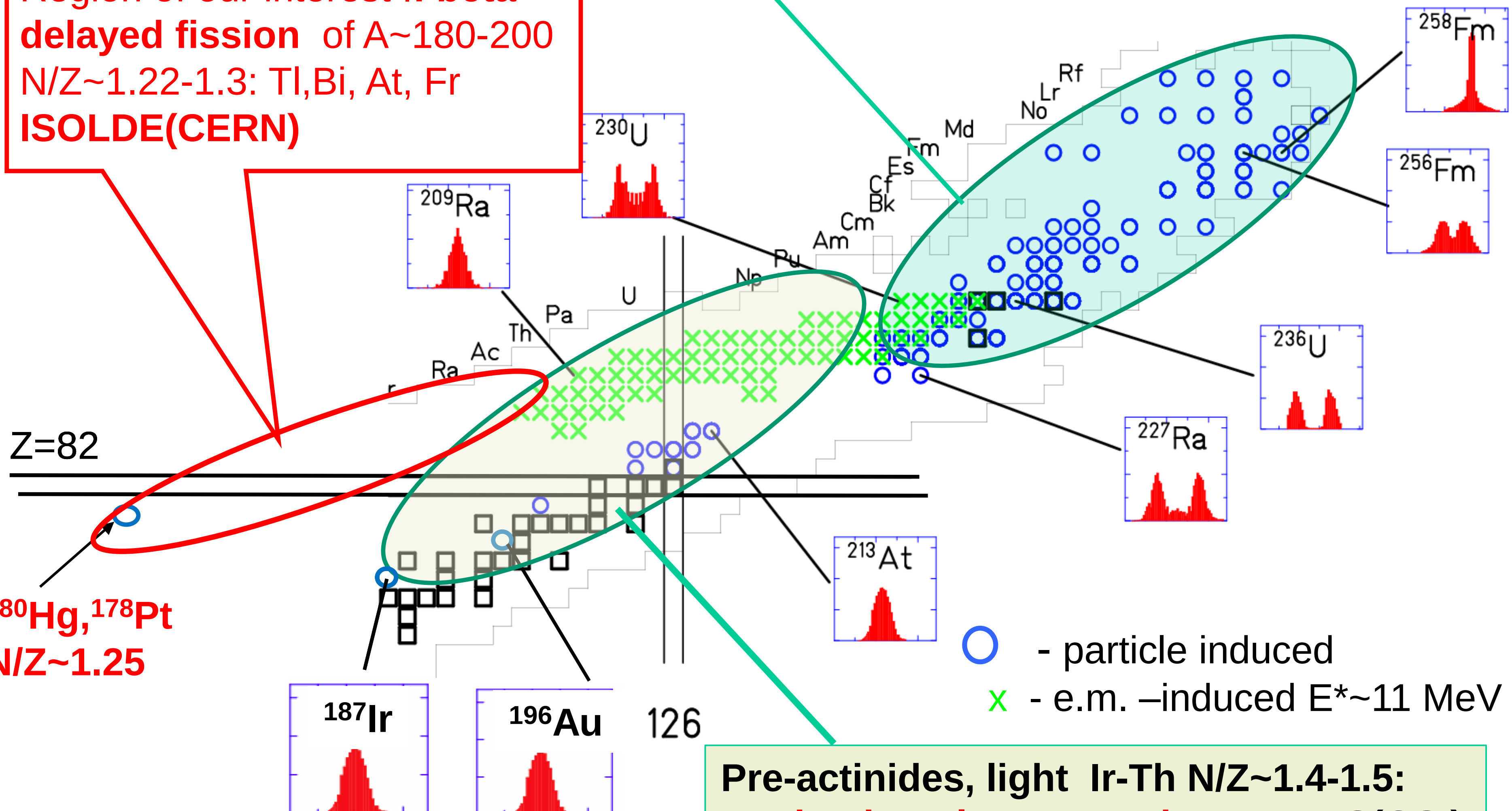
A.N. Andreyev, K.Nishio, K.-H. Schmidt, "Review on experimental progress in fission", Reports on Progress in Physics, 81, 016301 (2018)

Experimental information on low-energy fission

Nuclei with measured charge/mass split (RIPL-2 + GSI)

Heavy Actinides, N/Z~1.56: predominantly asymmetric; aneous fission, fission isomers

Region of our interest I: **beta-delayed fission** of A~180-200 N/Z~1.22-1.3: Tl,Bi, At, Fr **ISOLDE(CERN)**



^{180}Hg,^{178}Pt N/Z~1.25

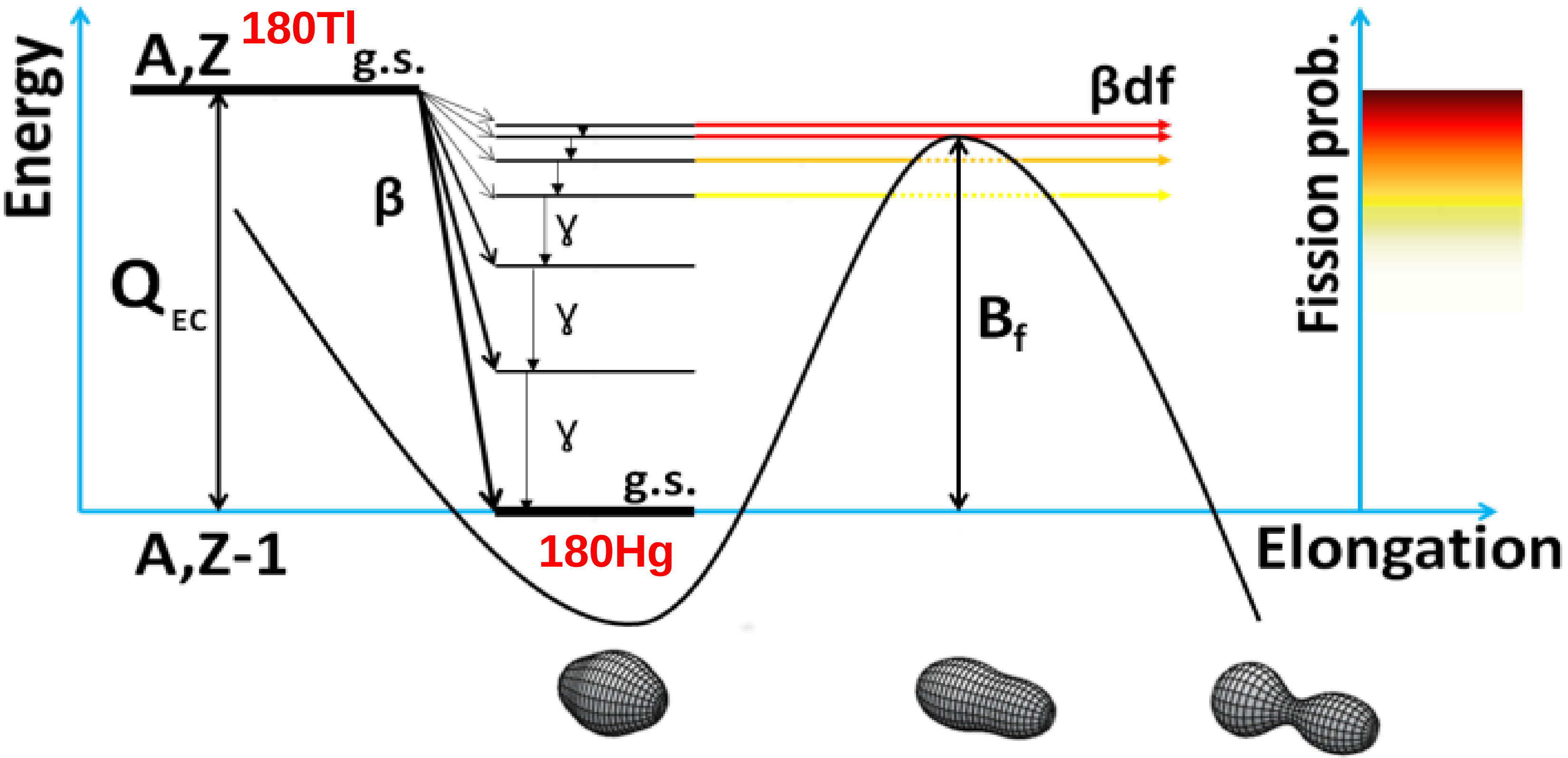
- particle induced

x - e.m. –induced E*~11 MeV

Pre-actinides, light Ir-Th N/Z~1.4-1.5: predominantly symmetric, e.g. FRS(GSI)

A.N. Andreyev, K.Nishio, K.-H. Schmidt, “Review on experimental progress

Beta-Delayed Fission



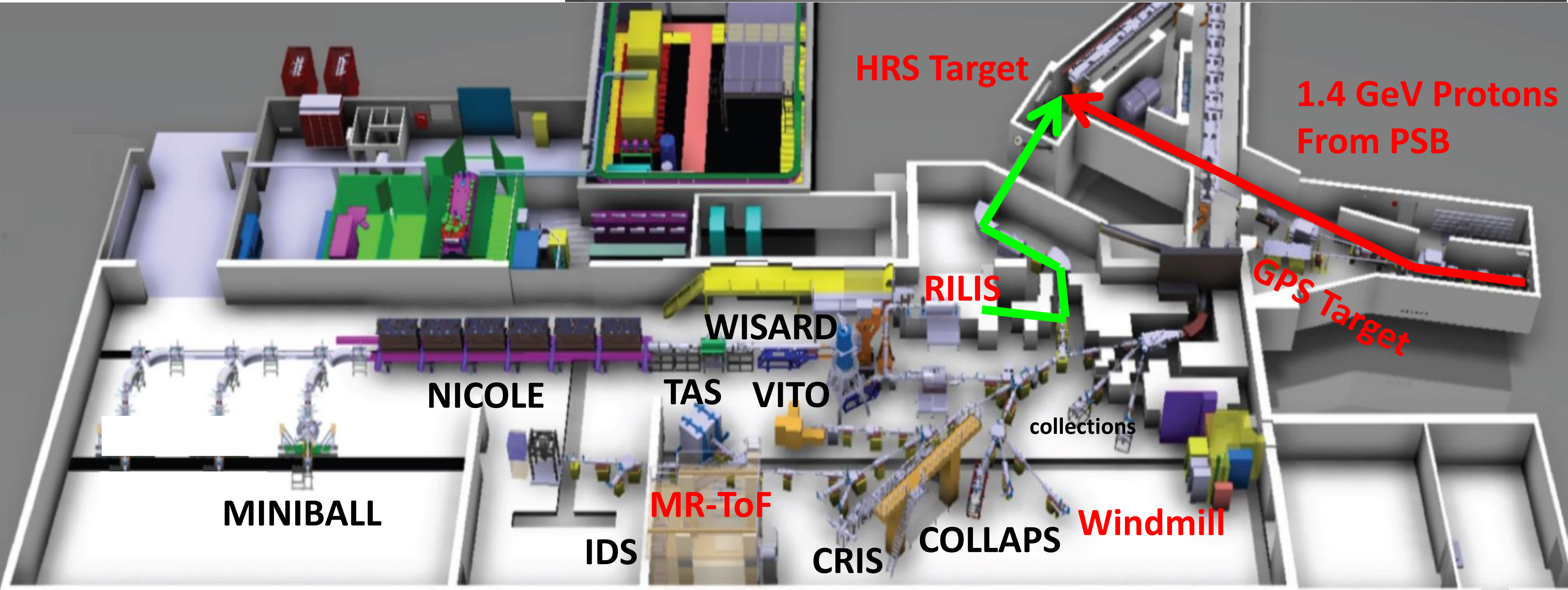
- Two step process: β decay followed by fission
- Low-energy fission (E*~3-12 MeV, limited by Q_{EC})

  e.g. ^{180}Tl: Q_{EC}=10.4 MeV, $B_{f,calc}$=9.8 MeV
- Relatively low angular momentum of the state

  e.g. ^{180}Tl: I=4 or 5 (some cases: up to 10)

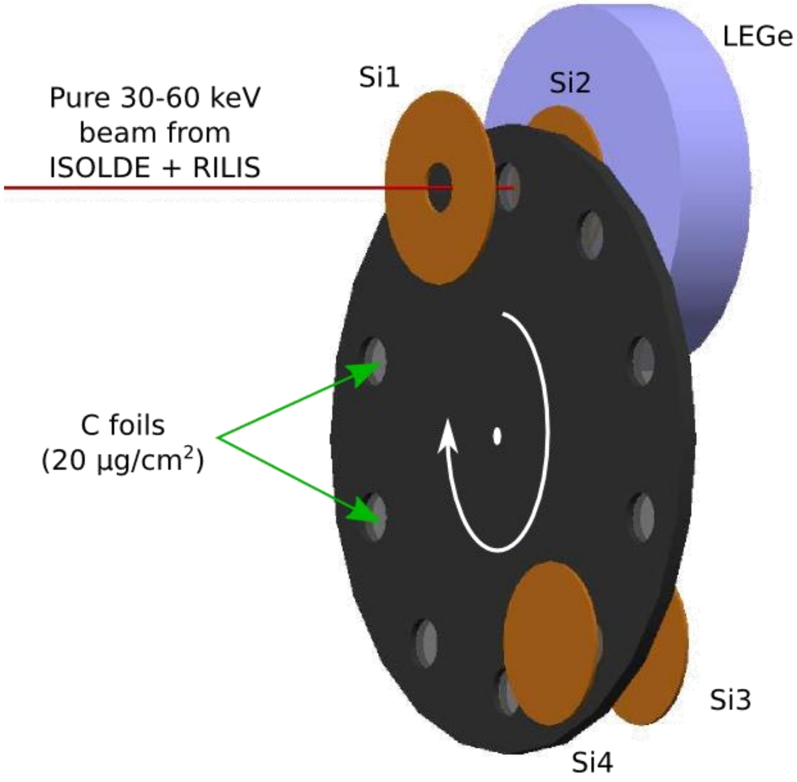
A.N. Andreyev, M. Huyse, P. Van Duppen, Reviews of Modern Physics, 85, 1541 (2013)
A.N. Andreyev, K.Nishio, K.-H. Schmitd, Reports on Progress in Physics, 81, 016301 (2018)

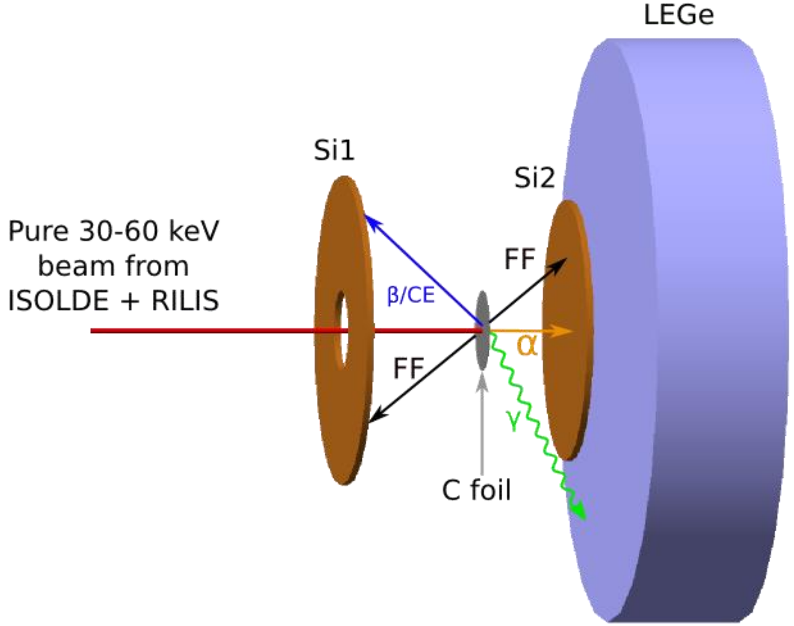
The ISOLDE facility at CERN

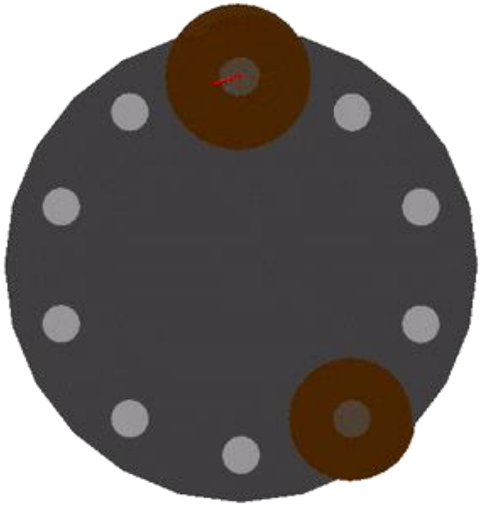


Detection system for βDF studies at ISOLDE

A.N. Andreyev et al. PRL 105 (2010)





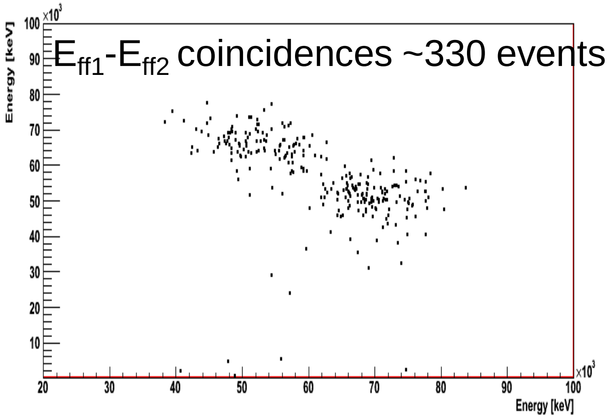


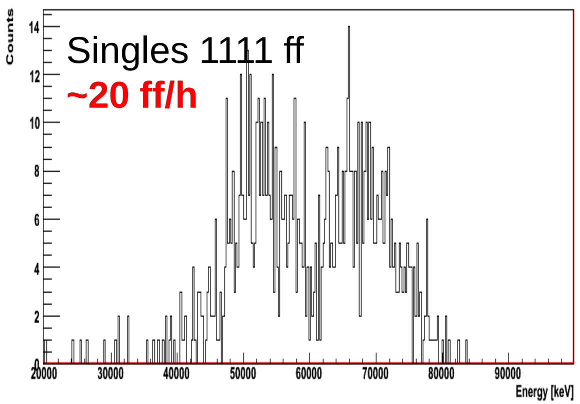
Setup: Si detectors both sides of the C-foil

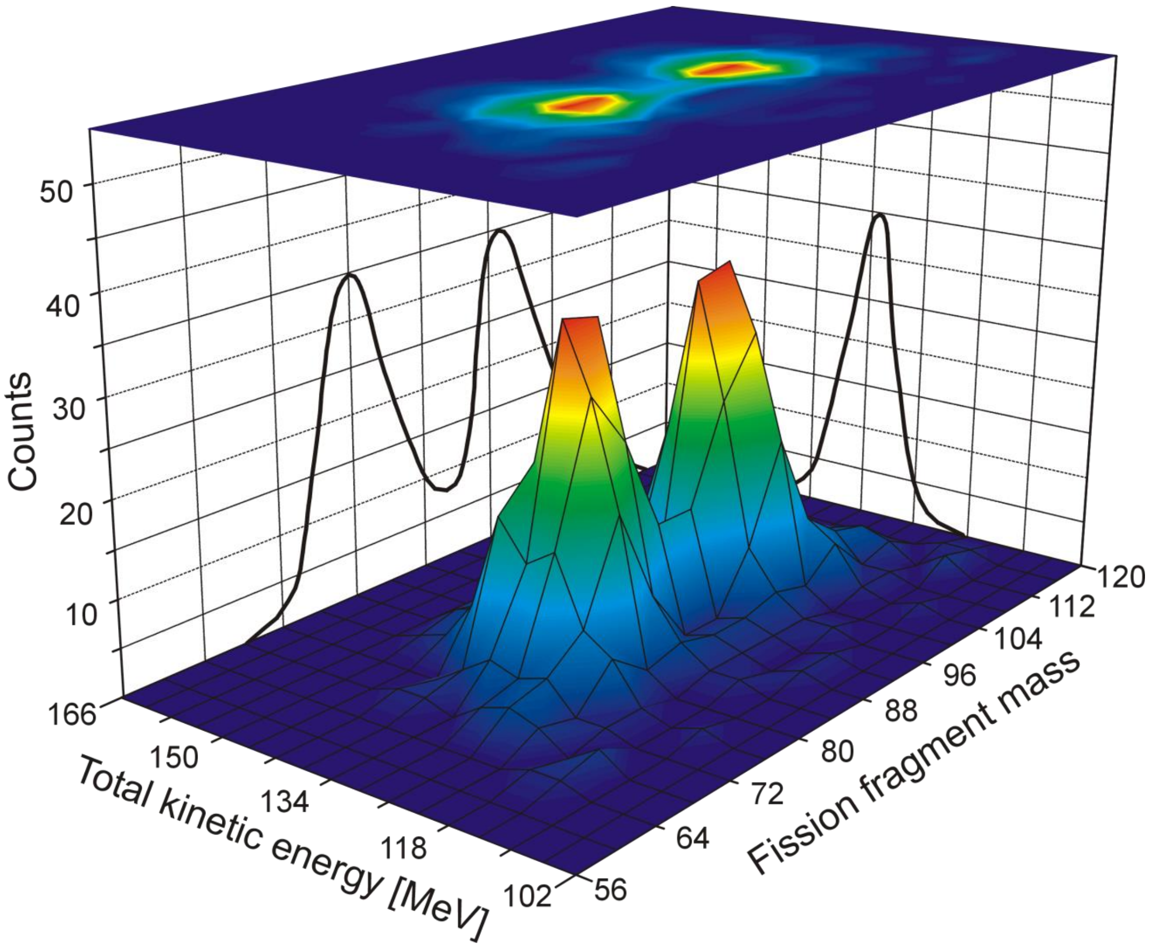
- Simple setup & DAQ: 2 Surface barrier detectors (1 of them – annular) and 2 PIPS detectors.
- 34% geometrical efficiency at implantation site.
- Fission fragments, alpha-gamma coincidences
- Digital electronics

Year 2008: Mass distribution of fission fragments in βDF of ^{180}Tl (the fission of ^{180}Hg)

ASYMMETRIC energy split! Thus asymmetric mass split: M_H=100(4) and M_L= 80(4)







A problem: "low-energy" FF's - 1 AMeV only, Z identification difficult
The most probable fission fragments are ^{100}Ru (N=56,Z=44) and ^{80}Kr (N=44,Z=36)

New Type of Asymmetric Fission in Proton-Rich Nuclei

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

New Type of Asymmetric Fission in Proton-Rich Nuclei **via βDF of ^{180}Tl**

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]

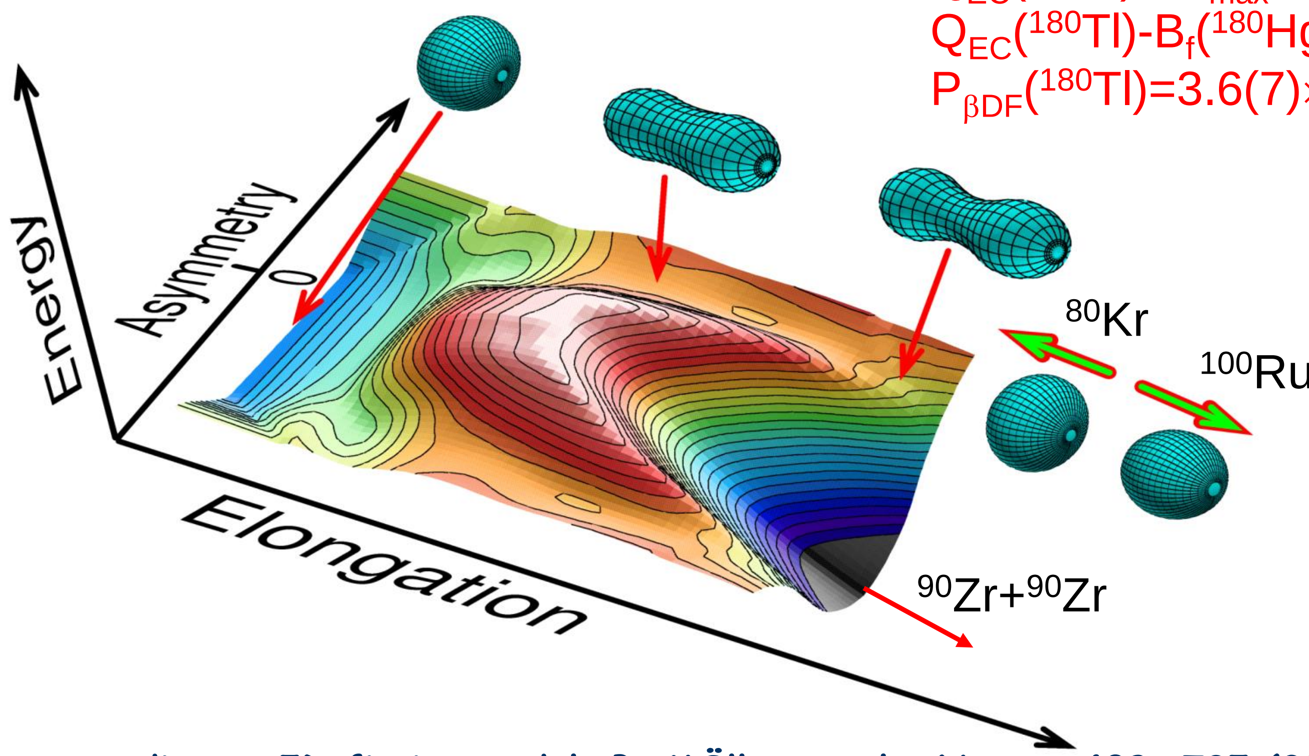
[1]*Instituut voor Kern- en Stralingsfysica, K.U. Leuven, University of Leuven, B-3001 Leuven, Belgium*

[2]*School of Engineering, University of the West of Scotland, Paisley, PA1 2BE, United Kingdom, and the Scottish Universities Physics Alliance (SUPA)*

$Q_{EC}(^{180}Tl)=E^*_{max}=10.44$ MeV

$Q_{EC}(^{180}Tl)-B_f(^{180}Hg)=0.63$ MeV

$P_{\beta DF}(^{180}Tl)=3.6(7)\times10^{-5}$



Calculations according to 5D fission model, P. MÖller et al., Nature 409, 785 (2001)

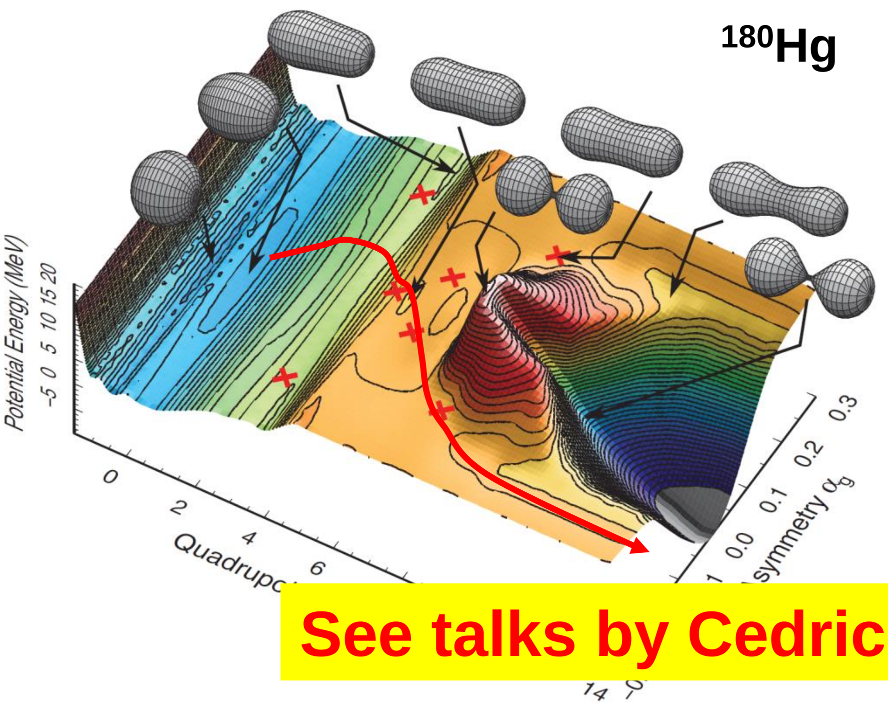
Two types of asymmetry: what's the difference?

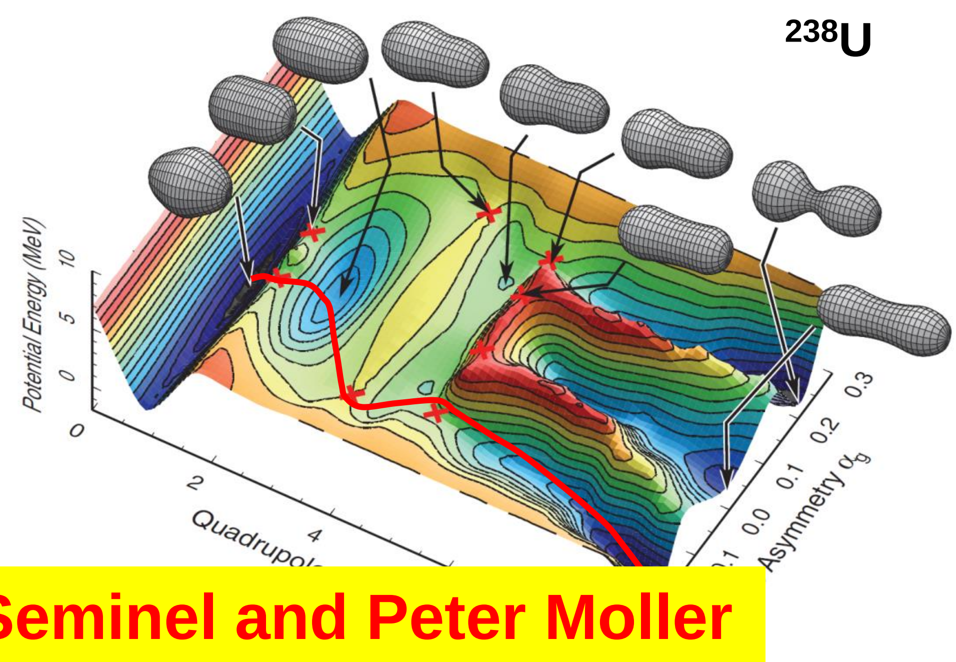
PHYSICAL REVIEW C **86**, 024610 (2012)

Contrasting fission potential-energy structure of actinides and mercury isotopes

Takatoshi Ichikawa,[1] Akira Iwamoto,[2] Peter Möller,[3] and Arnold J. Sierk[3]

Conclusions: The mechanism of asymmetric fission must be very different in the lighter proton-rich mercury isotopes compared to the actinide region and is apparently unrelated to fragment shell structure. Isotopes lighter than ^{192}Hg have the saddle point shielded from a deep symmetric valley by a significant ridge. The ridge vanishes for the heavier Hg isotopes, for which we would expect a qualitatively different asymmetry of the fragments.





See talks by Cedric Seminel and Peter Moller

Brownian Metropolis Shape Motion

based on J. Randrup and P. Moller, PRL 106, 132503 (2011)

Phys. Rev. C 85, 024306 (2012)

Calculated fission yields of neutron-deficient mercury isotopes

Peter Möller[1],* Jørgen Randrup[2], and Arnold J. Sierk[1]
[1] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Dated: November 21, 2011)

The recent unexpected discovery of asymmetric fission of ^{180}Hg following the electron-capture decay of ^{180}Tl has led to intense interest in experimentally mapping the fission-yield properties over more extended regions of the nuclear chart and compound-system energies. We present here a first calculation of fission-fragment yields for neutron-deficient Hg isotopes, using the recently developed Brownian Metropolis shape motion treatment. The results for ^{180}Hg are in approximate agreement with the experimental data. For ^{174}Hg the symmetric yield increases strongly with decreasing energy, an unusual feature, which would be interesting to verify experimentally.
PACS numbers: 25.85.-w, 24.10.Lx,24.75.+i

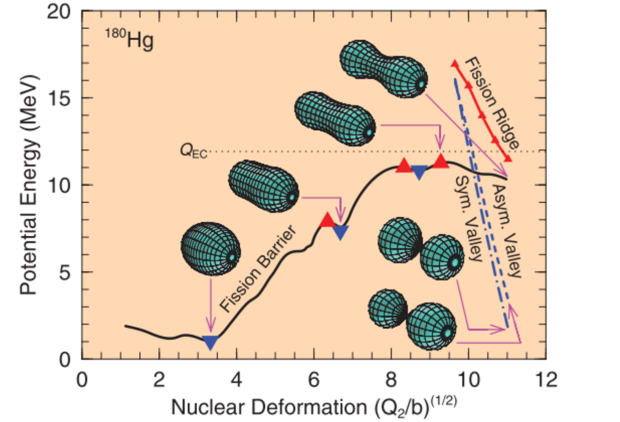
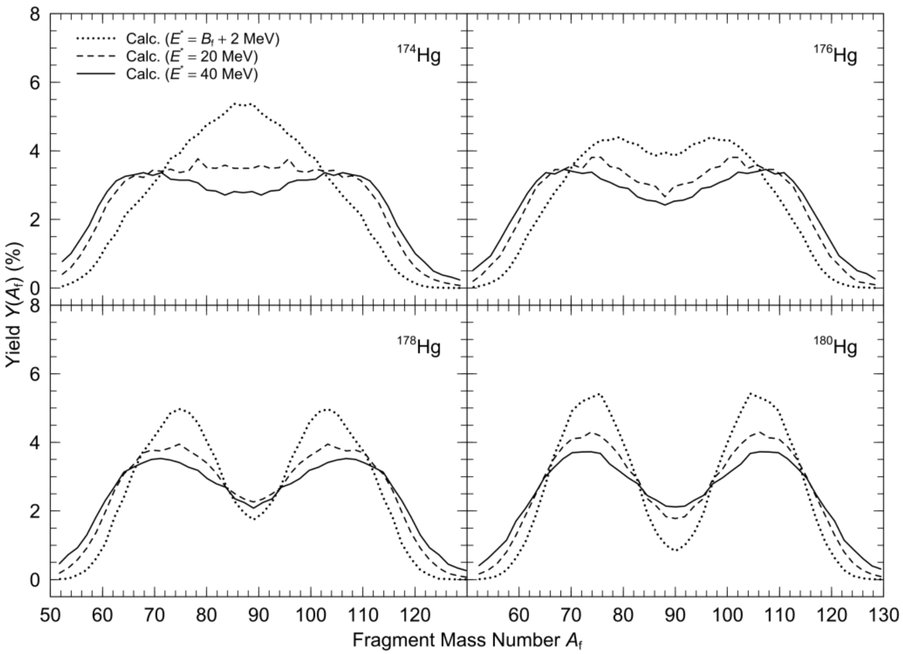
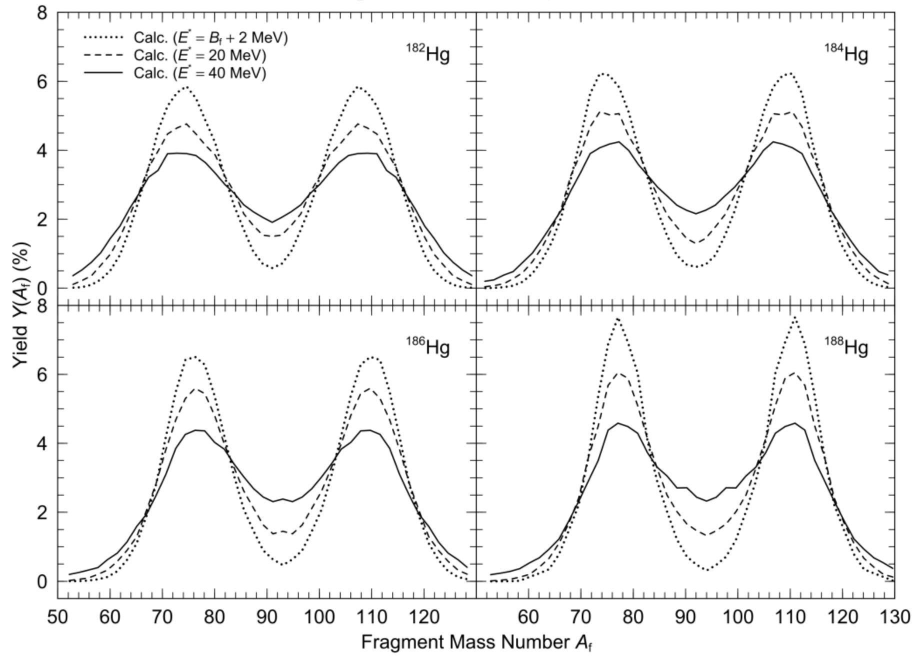


FIG. 4. (Color online) Minima, saddles, major valleys, and ridges in the 5D potential-energy surface of ^{180}Hg (see text). At the last plotted point on the fission barrier, $(Q_2/\text{b})^{(1/2)} \approx 11$, the asymmetry of the shape is $A_H/A_L = 108/72$.





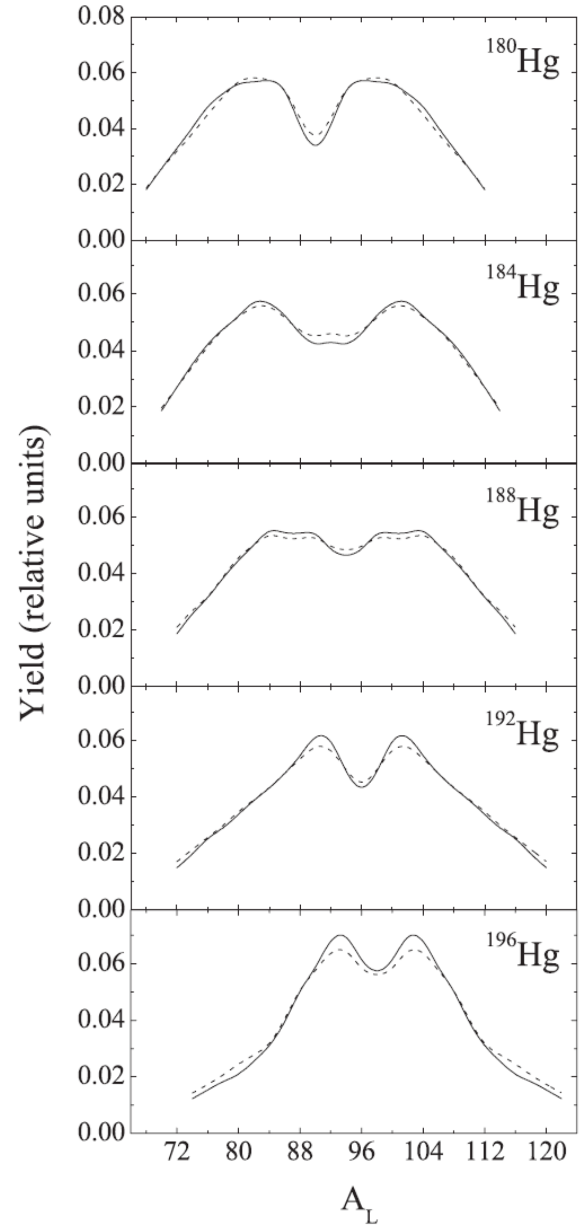
'Improved' Scission-Point Model

PHYSICAL REVIEW C **86**, 044315 (2012)

Mass distributions for induced fission of different Hg isotopes

A. V. Andreev, G. G. Adamian, and N. V. Antonenko
Joint Institute for Nuclear Research, 141980 Dubna, Russia
(Received 20 June 2012; revised manuscript received 6 September 2012; published 11 October 2012)

With the improved scission-point model mass distributions are calculated for induced fission of different Hg isotopes with even mass numbers $A = 180, 184, 188, 192, 196$, and 198. The calculated mass distribution and mean total kinetic energy of fission fragments are in good agreement with the existing experimental data. The asymmetric mass distribution of fission fragments of ^{180}Hg observed in the recent experiment is explained. The change in the shape of the mass distribution from asymmetric to more symmetric is revealed with increasing A of the fissioning ^{A}Hg nucleus, and reactions are proposed to verify this prediction experimentally.



- Inter-fragment distance is not fixed and calculated.
- values of ~0.5-1 fm result (Wilkins – fixed at 1.4 fm)

- Mass symmetry/asymmetry doesn't change as a function of E* (up to E*~60 MeV) – good for future experiments

'Self-consistent Scission-Point Model'

PHYSICAL REVIEW C **86**, 064601 (2012)

Role of deformed shell effects on the mass asymmetry in nuclear fission of mercury isotopes

Stefano Panebianco, Jean-Luc Sida, Héloise Goutte, and Jean-François Lemaître
IRFU/Service de Physique Nucleaire, CEA Centre de Saclay, F-91191 Gif-sur-Yvette, France

Noël Dubray and Stéphane Hilaire
CEA, DAM, DIF, F-91297, Arpajon, France
(Received 9 October 2012; published 3 December 2012)

$$E_{\rm av}(Z_{1,2}, N_{1,2}, \beta_{1,2}, d) = E_{\rm tot} - E_{\rm HFB}(Z_1, N_1, \beta_1) - E_{\rm HFB}(Z_2, N_2, \beta_2) - E_{\rm nucl}(Z_{1,2}, N_{1,2}, \beta_{1,2}, d) - E_{\rm Coul}(Z_{1,2}, N_{1,2}, \beta_{1,2}, d).$$

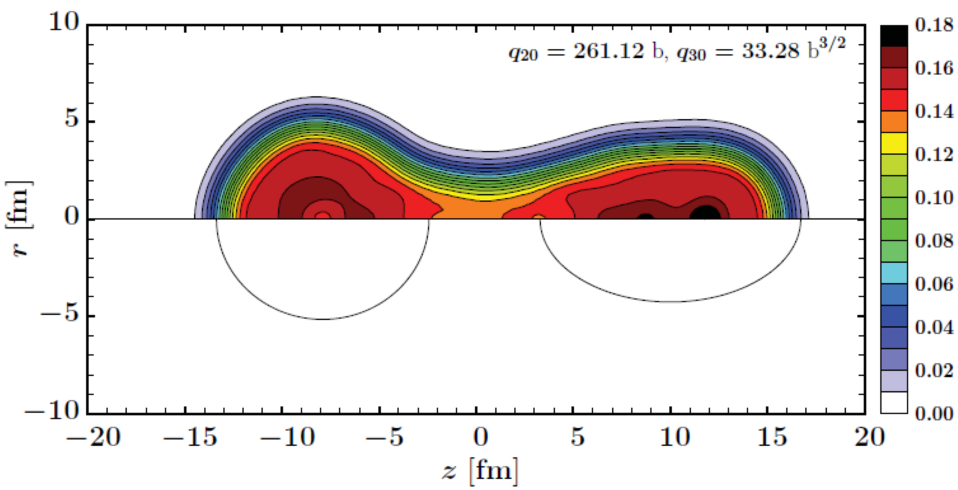


FIG. 4. (Color online) Total nuclear density for the most energetically favorable scission configuration in ^{180}Hg fission, extracted from a self-consistent HFB calculation. In the lower part of the figure, two

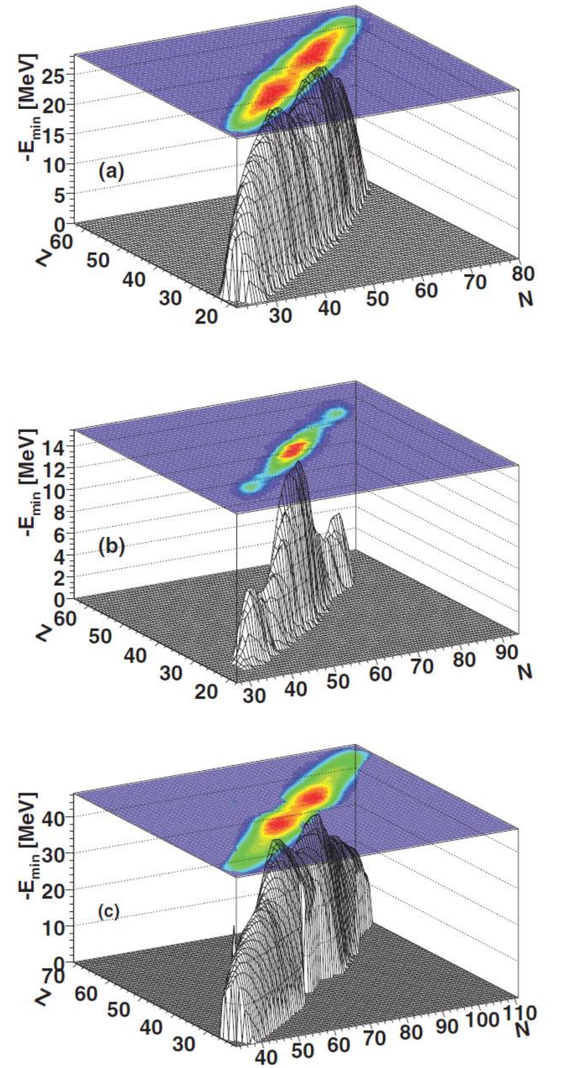


FIG. 2. (Color online) Minimum absolute available energy at scission calculated for all possible fragmentations in (a) ^{180}Hg and (b) ^{198}Hg fission at 10 MeV and in (c) the thermal n-induced fission of ^{235}U.

Mean-field HFB+Gogny D1S

PHYSICAL REVIEW C **86**, 024601 (2012)

Fission modes of mercury isotopes

M. Warda,[1] A. Staszczak,[1,2,3] and W. Nazarewicz[2,3,4]

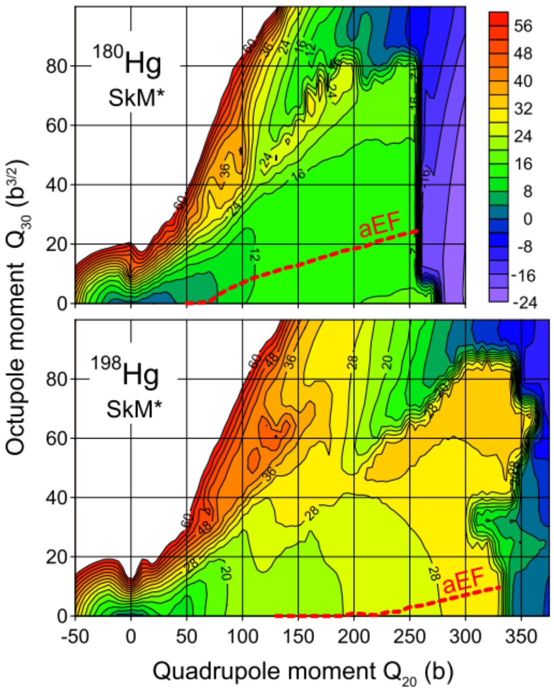


FIG. 2. (Color online) PES for ^{180}Hg (top) and ^{198}Hg (bottom) in the plane of collective coordinates $Q_{20}-Q_{30}$ in HFB-SkM*. The aEF fission pathway corresponding to asymmetric elongated fragments is marked. The difference between contour lines is 4 MeV. The effects due to triaxiality, known to impact inner fission barriers in the actinides, are negligible here.

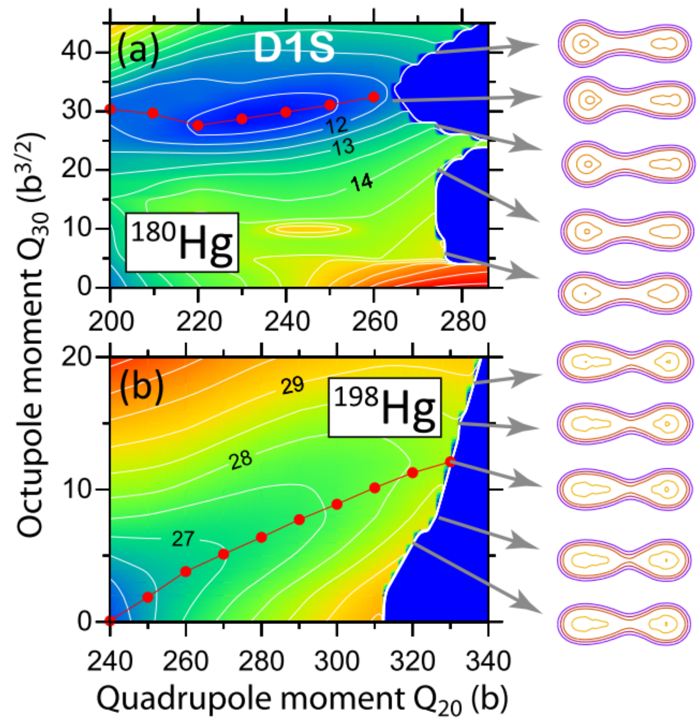
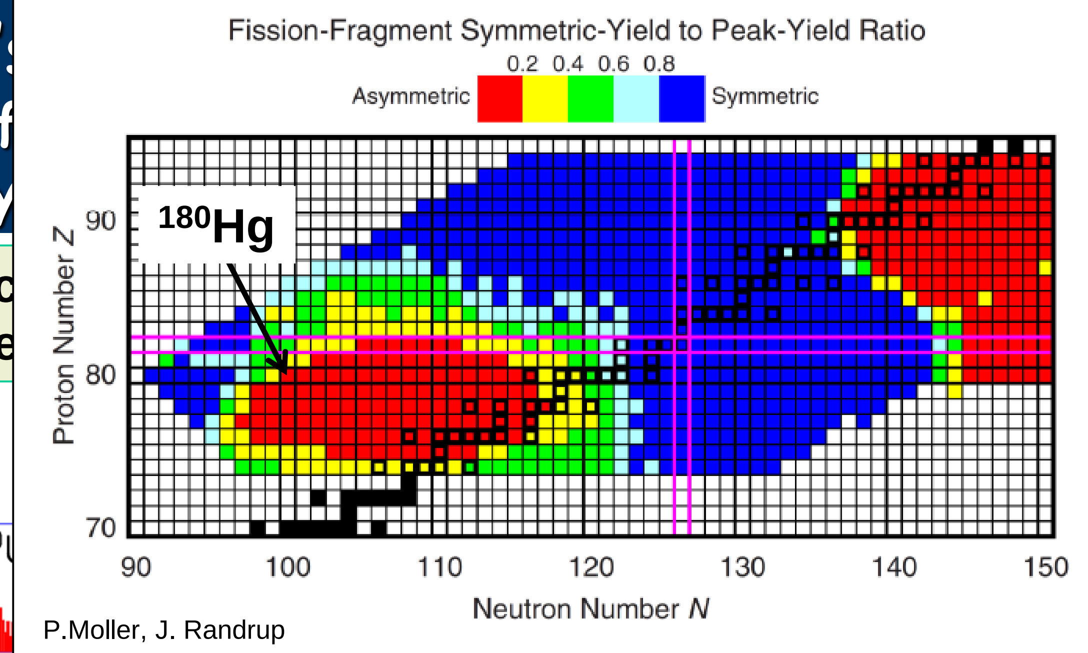


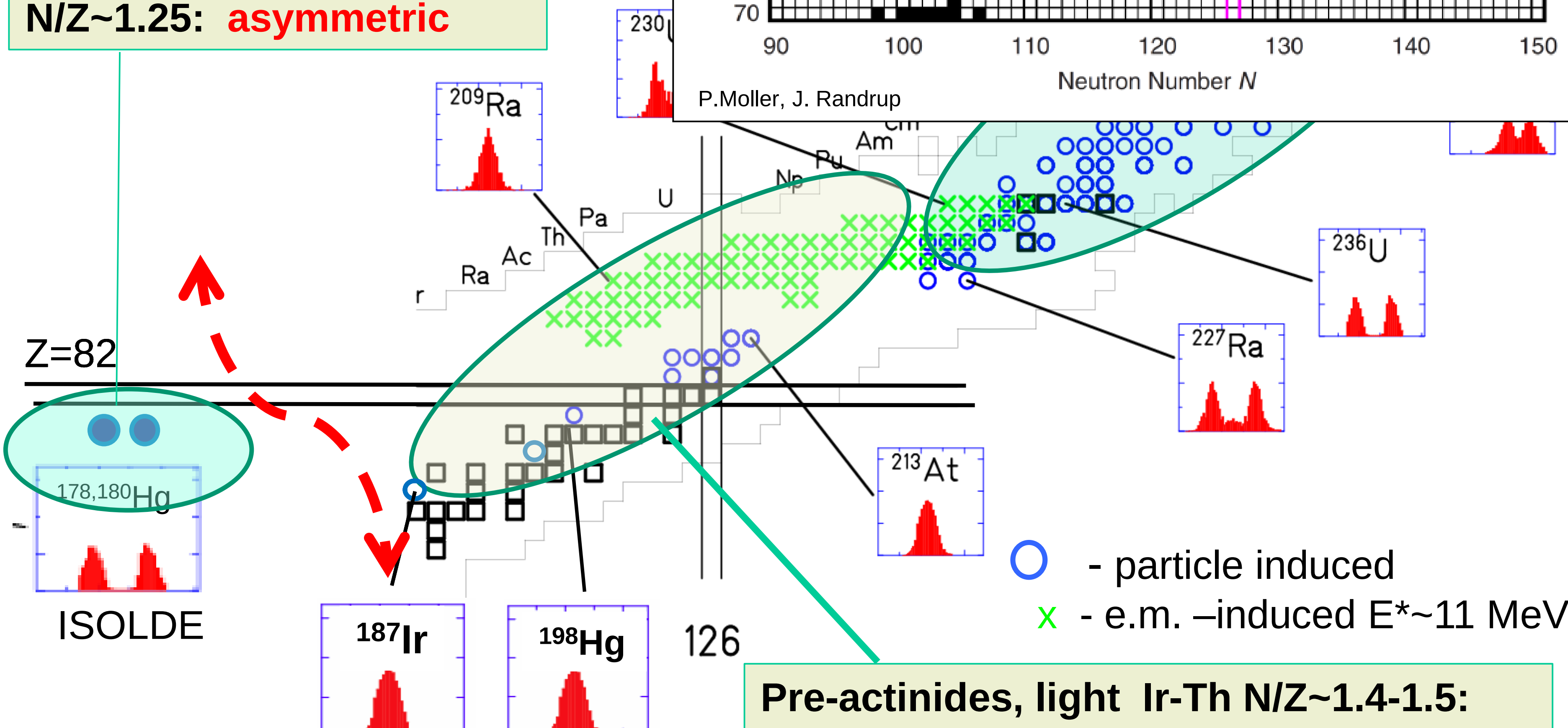
FIG. 3. (Color online) PES in HFB-D1S for ^{180}Hg (top) and ^{198}Hg (bottom) in the (Q_{20}, Q_{30}) plane in the pre-scission region of aEF valley. The symmetric limit corresponds to $Q_{30}=0$. The aEF valley and density profiles for pre-scission configurations are indicated. The difference between contour lines is 0.5 MeV. Note different Q_{30}-scales in ^{180}Hg and ^{198}Hg plots.

What's
Probing transition f
Probing excitations energy

Heavy Ac
spontane

Lightest Hg isotopes with N/Z~1.25: asymmetric

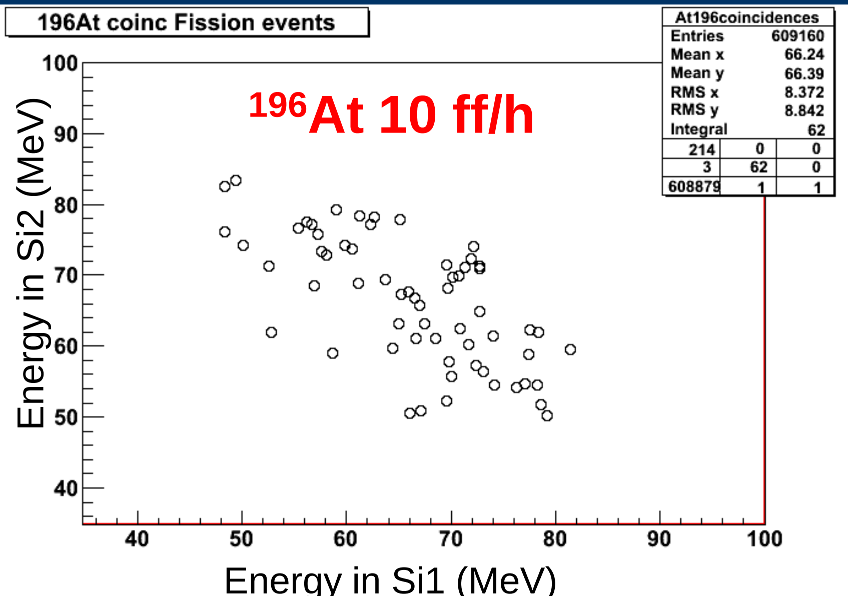


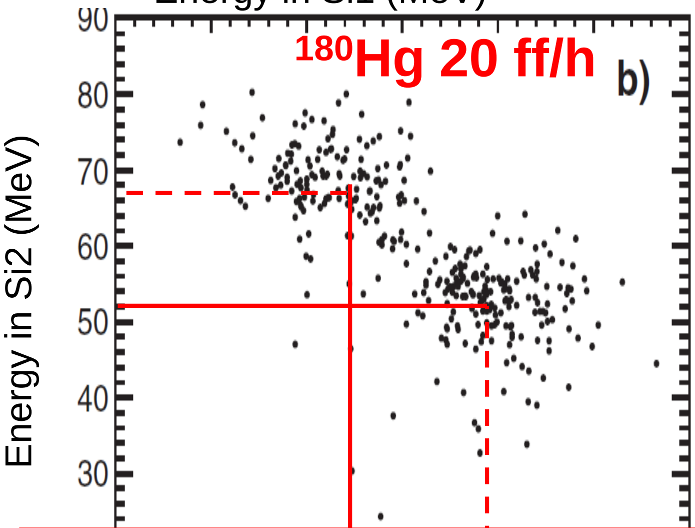


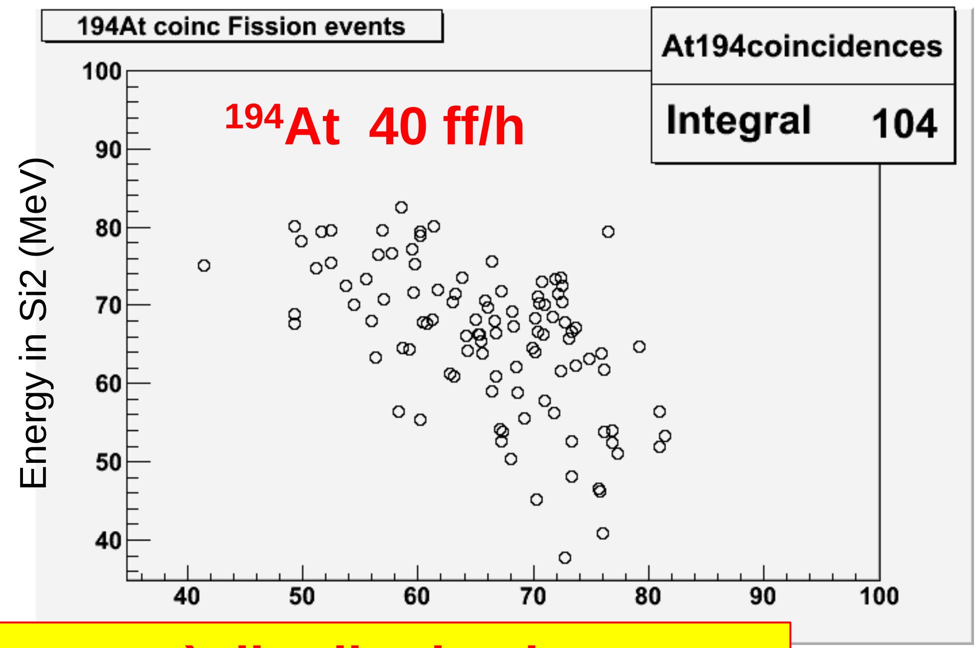
A.N. Andreyev, K.Nishio, K.-H. Schmidt, "Review on experimental progress

Pre-actinides, light Ir-Th N/Z~1.4-1.5: predominantly symmetric, e.g. FRS(GSI)

Mass Distributions of ^{194,196}Po via βDF of ^{194,196}At at ISOLDE



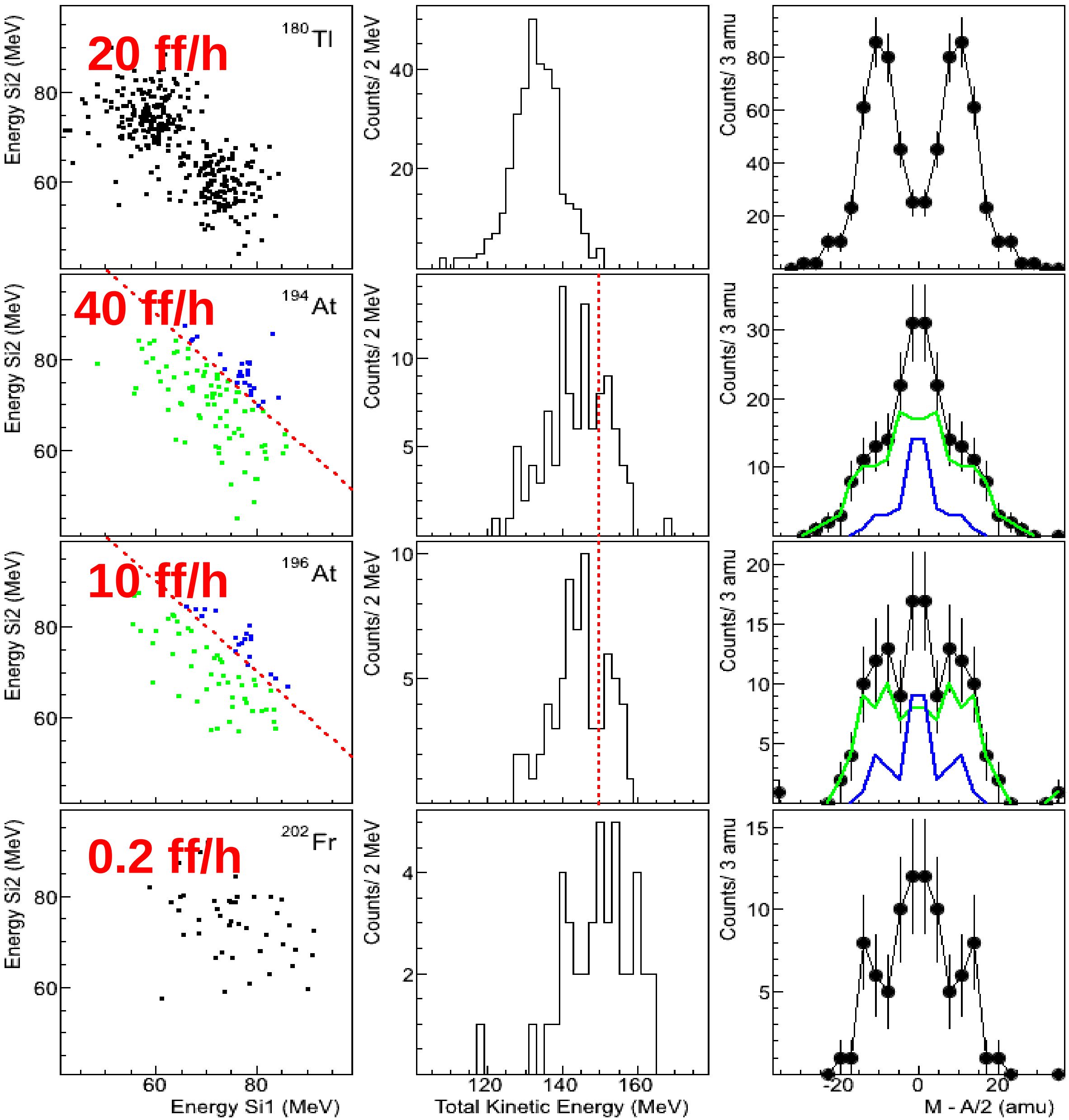




Clear difference in energy (thus, mass) distribution between 2-peaked fission of ^{180}Hg and a broad distribution in ^{194,196}Po

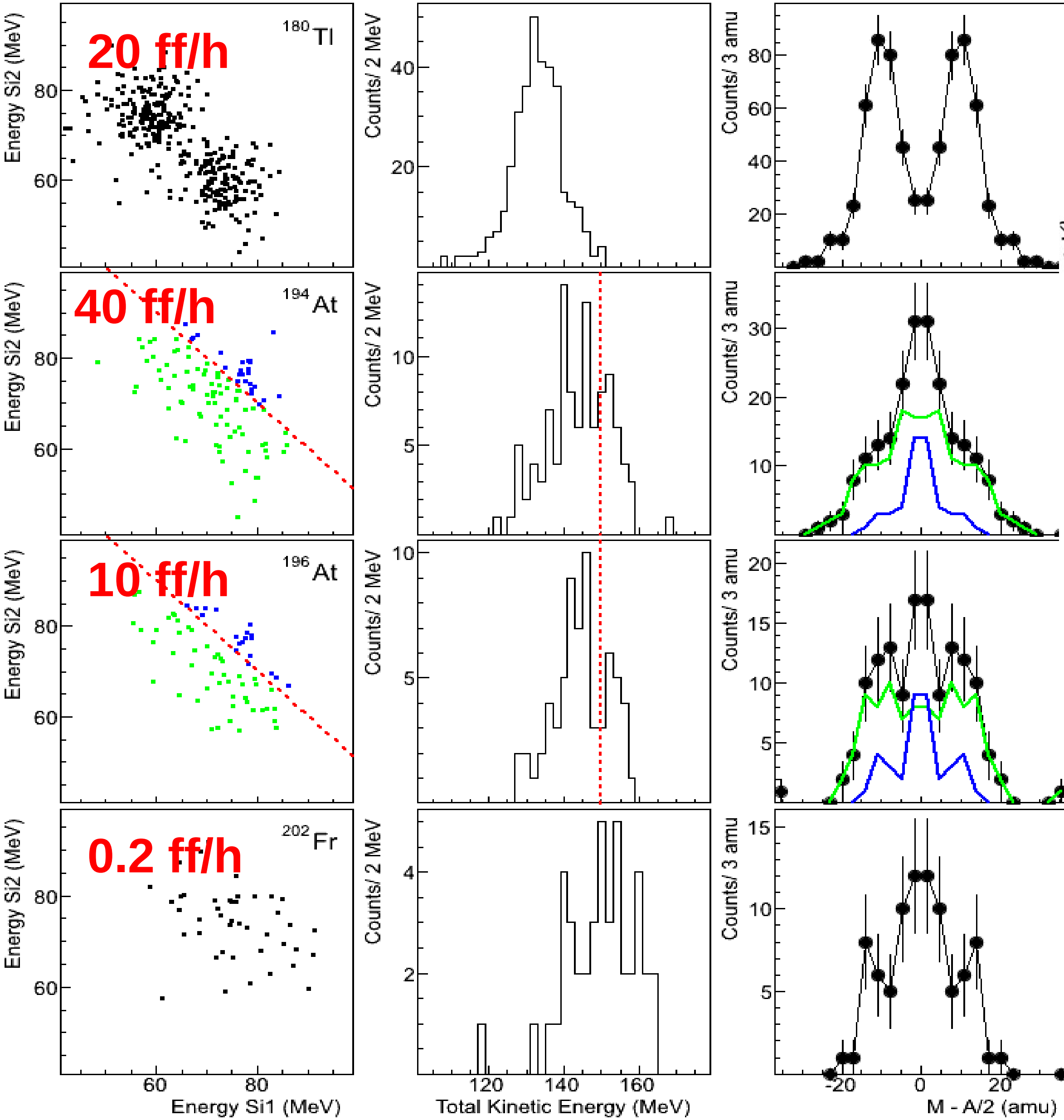
Multimodal Mass Distributions in βDF of ^{194,196}At and ^{200,202}Fr

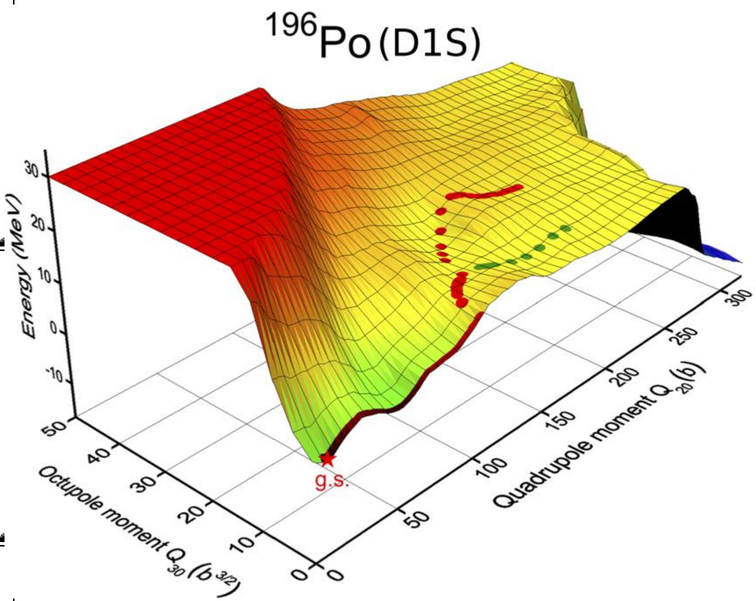
L.Ghys et al., Phys. Rev. C 90, 044305 (2014)



Multimodal Mass Distributions in βDF of ^{194,196}At and ^{200,202}Fr

L.Ghys et al., Phys. Rev. C 90, 044305 (2014)



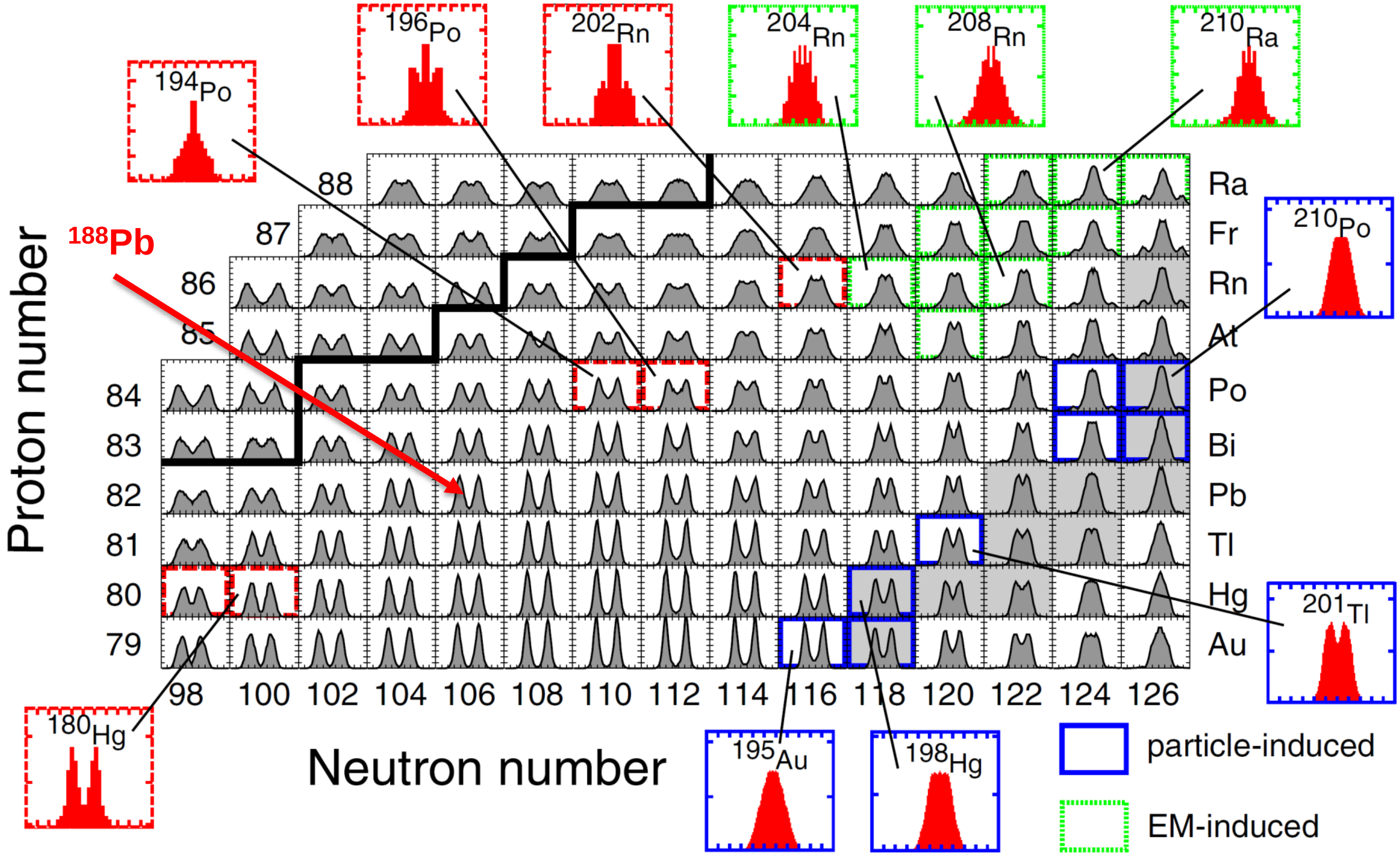


J. D. McDonnell et al., PRC90, 021302(2014)

See also talk by I. Tsekhanovich on fusion-fission in the lead region **(probing excitation energy dependence of FFMD's)**

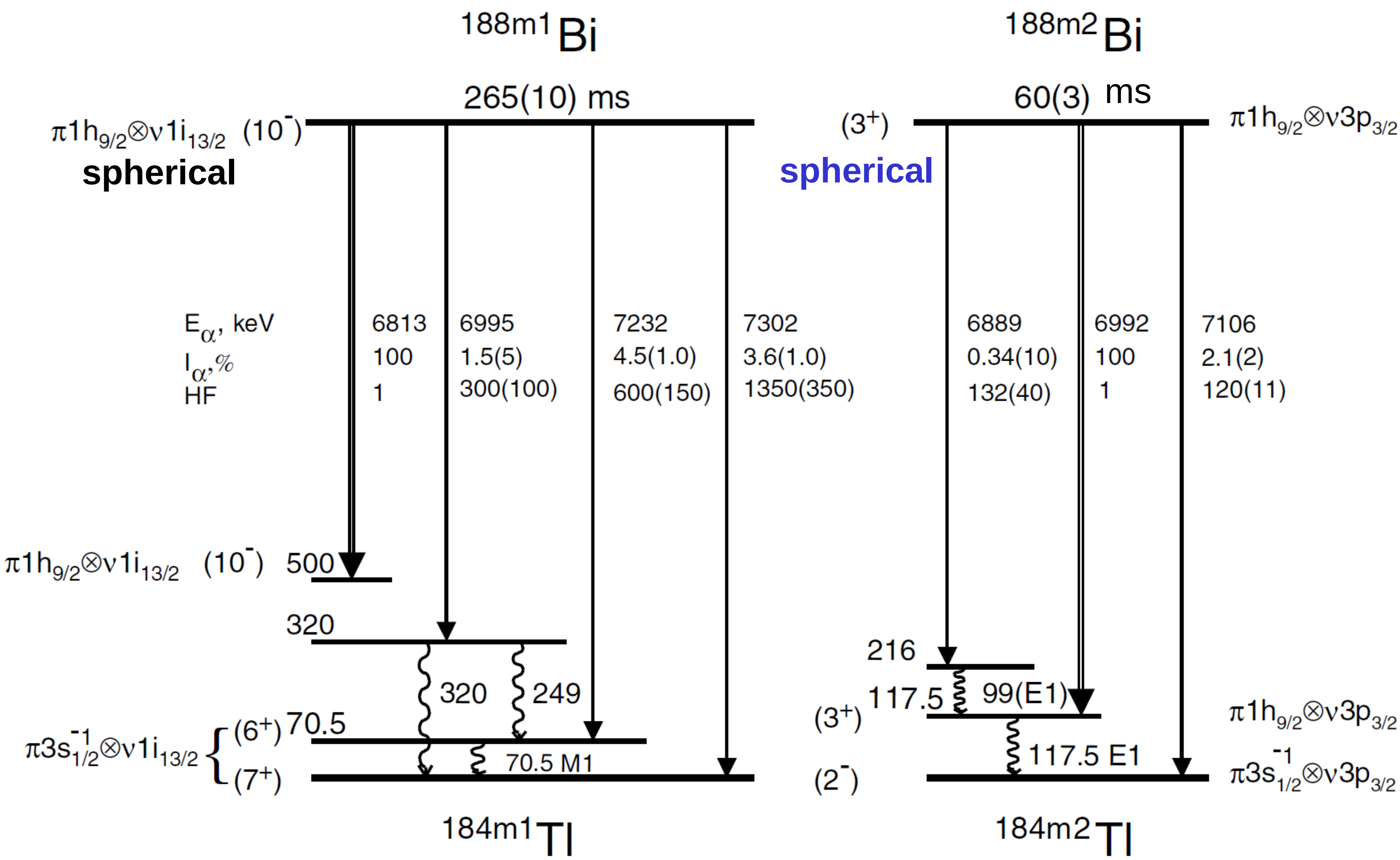
FFMDs in the Lead Region: Experiment vs Theory

L.Ghys et al., Phys. Rev. C 90, 044305 (2014)



Calculated FFMDs: P. Moller and J.Randrup

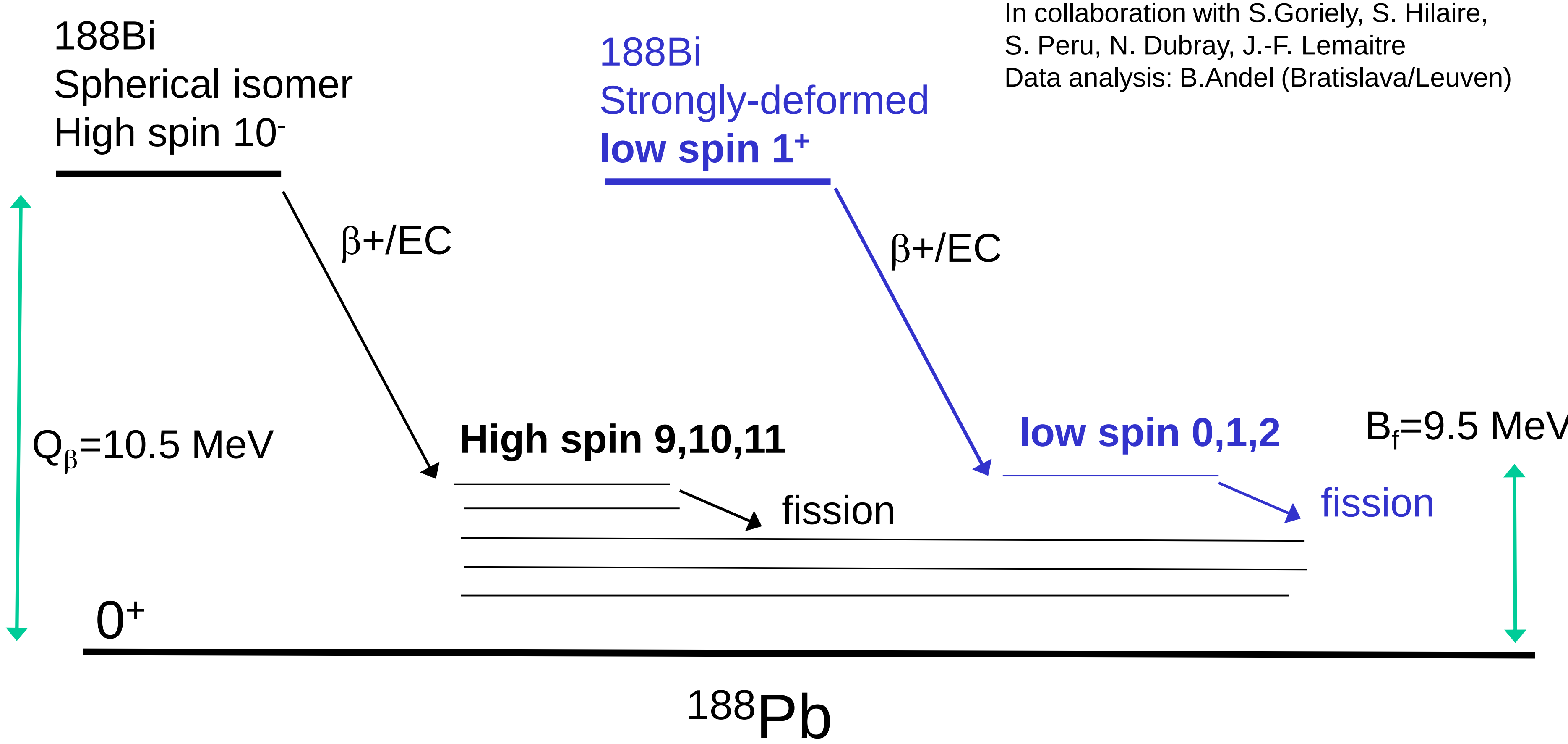
Beta-Delayed Fission of two isomers in ^{188}Bi (fission of ^{188}Pb): probing spin dependence of fission?



A.Andreyev et al, EPJA18,39(2003) -alpha decay; J.Lane et al, Phys. Rev.C87 (2013) – βdf at SHIP

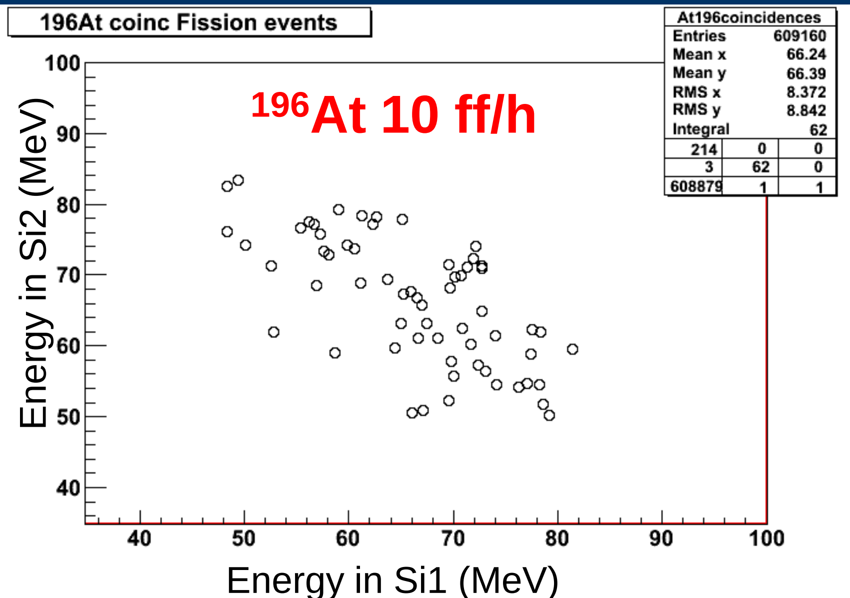
Very schematically: βDF of two isomers in ^{188}Bi:

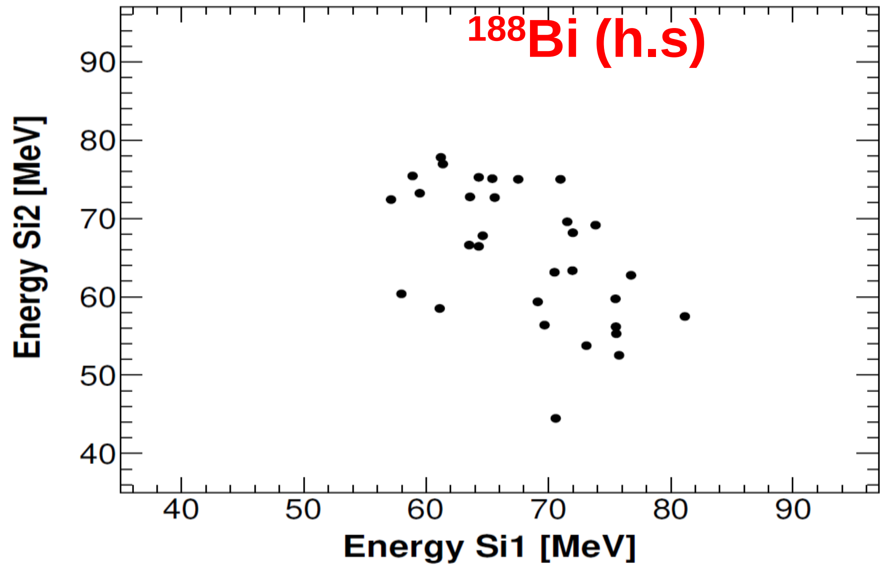
In collaboration with S.Goriely, S. Hilaire, S. Peru, N. Dubray, J.-F. Lemaitre
Data analysis: B.Andel (Bratislava/Leuven)

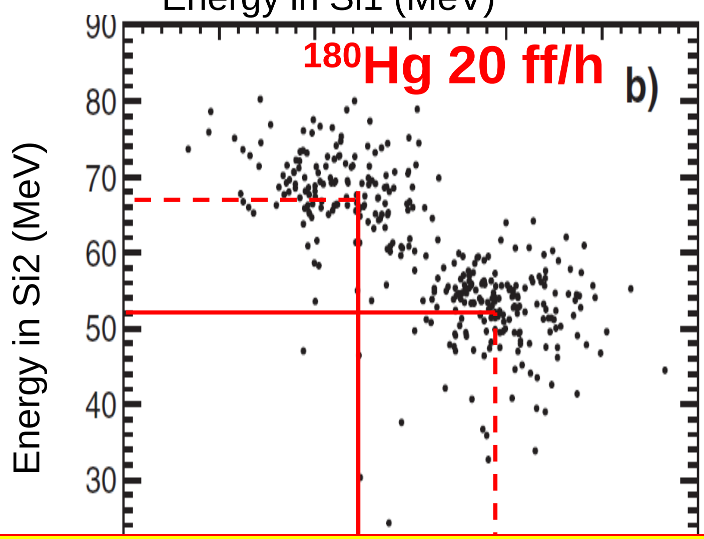


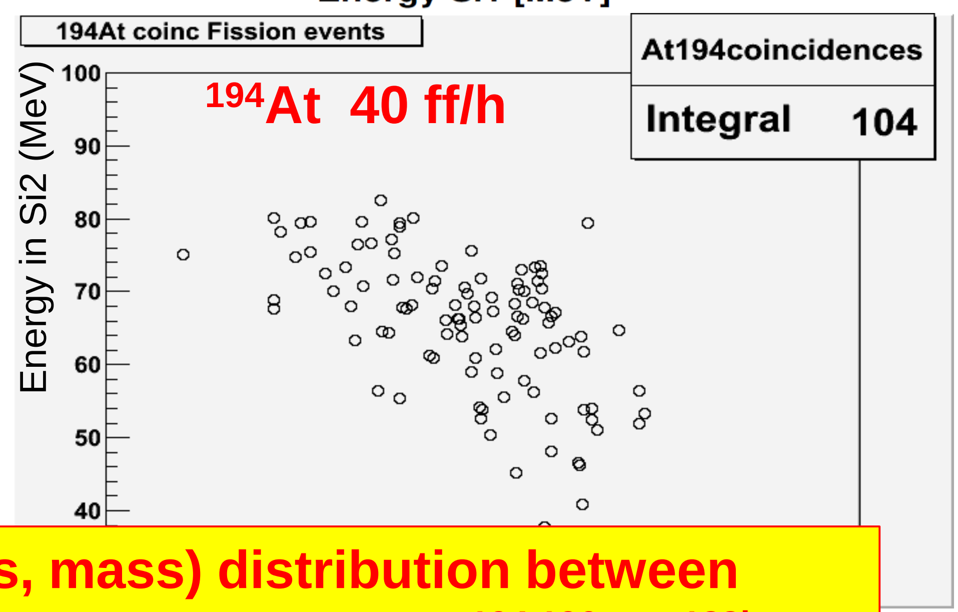
At ISOLDE, we can produce **clean (laser-separated !) beams** of both isomers in ^{188}Bi, and study whether their respective **βDF has different properties** (e.g. **different FFMDs**,**TKE's**, **fission probabilities)**

^{188}Bi (hs) in comparison to ^{194,196}Po via βDF of ^{194,196}At



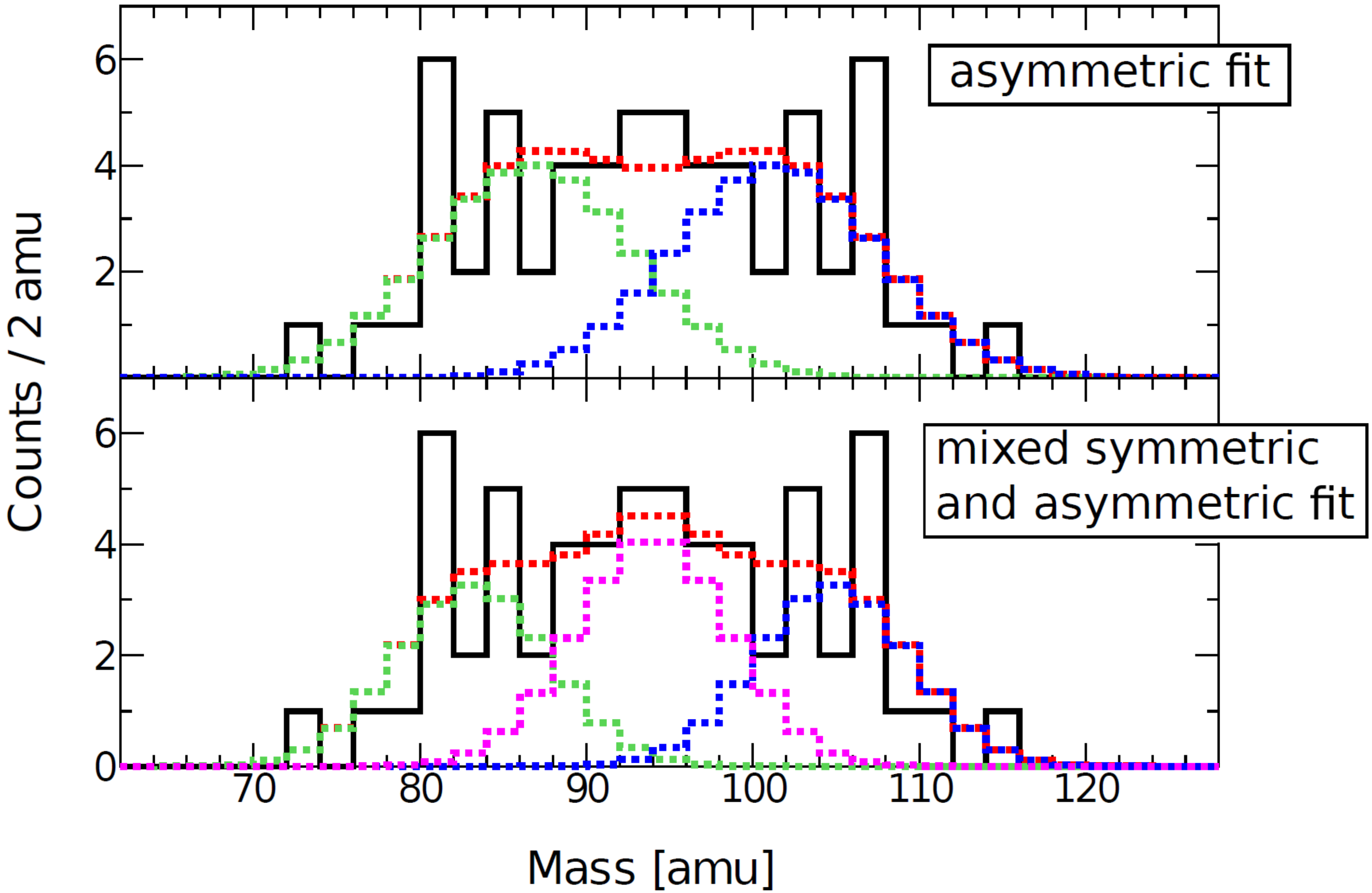






Clear difference in energy (thus, mass) distribution between 2-peaked fission of ^{180}Hg and a broad distribution in ^{194,196}Po,^{188hs}Bi

βDF of hs isomer in ^{188}Bi at ISOLDE (fission of ^{188}Pb) (preliminary data)



Either pure mass-asymmetric split or a mixture of symmetric and mass asymmetric

SOFIA@GSI: Coulex-induced fission of relativistic RIBs in inverse kinematics (J. Taieb, A. Chatillon et al)

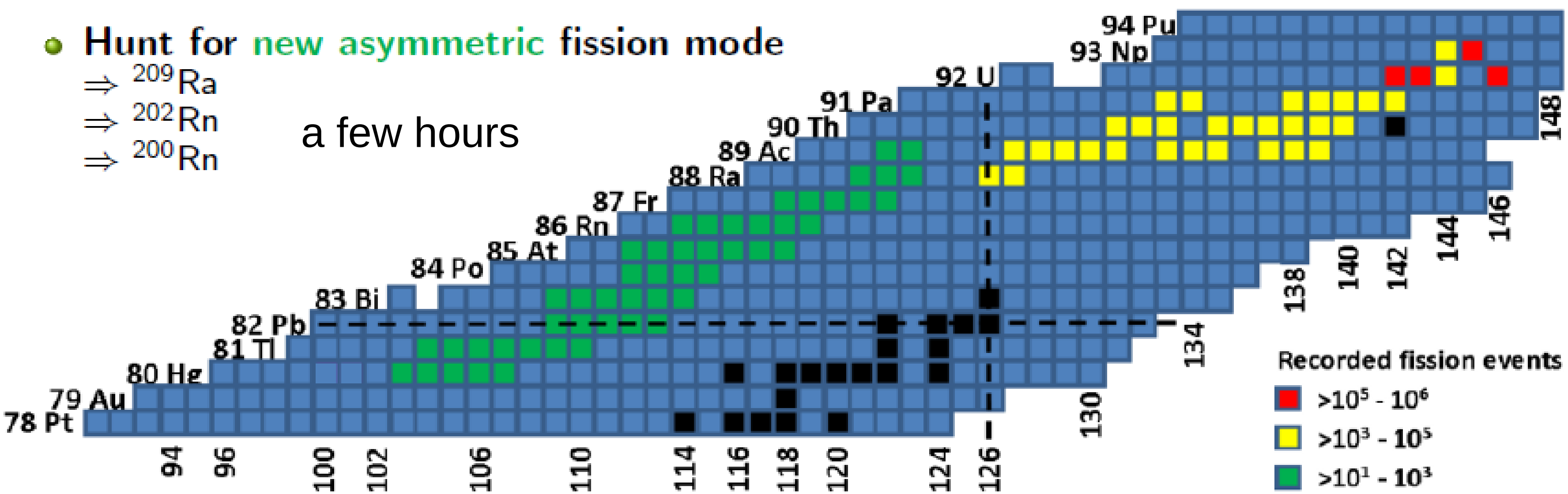
Physics cases

- Application purpose: high statistics
  - $\Rightarrow$ ^{238}U
  - $\Rightarrow$ ^{235}U-^{238}Np

~2 days

- Transition from asymmetric to symmetric fission modes
  - $\Rightarrow$ ^{230}Th
  - $\Rightarrow$ ^{226}Th
  - $\Rightarrow$ ^{222}Th
- Hunt for new asymmetric fission mode
  - $\Rightarrow$ ^{209}Ra
  - $\Rightarrow$ ^{202}Rn
  - $\Rightarrow$ ^{200}Rn

a few hours



SOFIA-1: FISSION OF 70 NUCLEI STUDIED, half of them for the first time

Conclusions

- βDF experiments at ISOLDE allow **to probe the low-energy fission in the transitional region** between the asymmetry of $^{178,180}Hg$ and symmetry around ^{210}Rn (studies by Coulex)

- **A mixture of asymmetric and symmetric FFMD's** is observed in several cases

- This inference is **in a qualitative agreement** with 'global' predictions by Moller/Randrup's model, though **some quantitative discrepancies are noted**. Many other theory approaches!

- **SOFIA-like experiments**, which can provide much better Z and A determination **are a must**.

- **Excitation energy dependence** (see talk by I. Tsekhanovich)