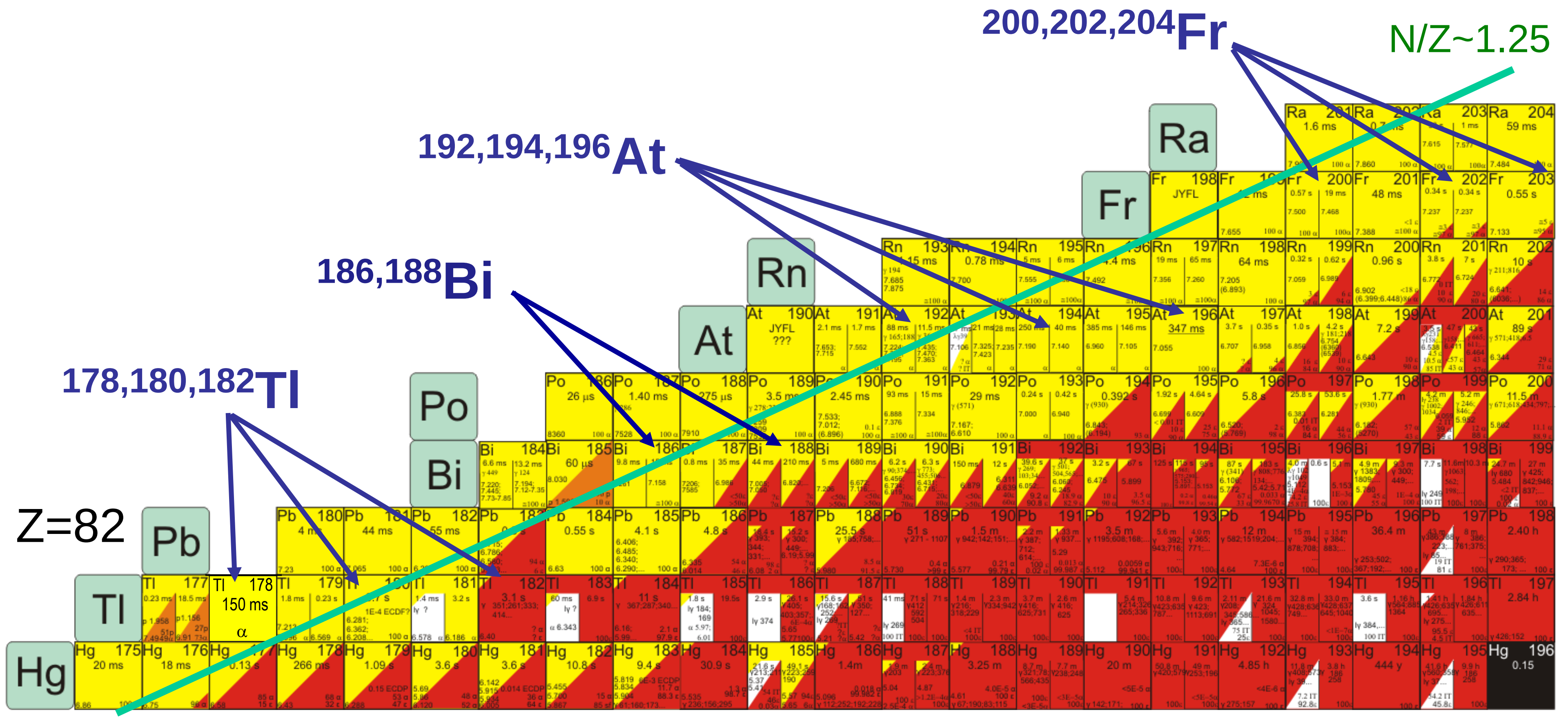
# Mapping Fission in 'Terra Incognita' in the neutron-deficient lead region


Andrei Andreyev

University of York, UK

Japan Atomic Energy Agency (JAEA, Tokai, Japan)


NN2015 Conference, 23 June 2015

# Collaboration

THE UNIVERSITY of York

**<u>A. Andreyev</u>**
V.Truesdale

ISOLDE
CERN, Geneva

**JAEA Tandem**

JAEA

**<u>K. Nishio</u>**
S.. Mitsuoka
I. Nishinaka
H. Makii
S. Chiba
A.Iwamoto
H.Koura
Y.Utsuno

Los Alamos NATIONAL LABORATORY
P. Möller, A. Sierk

**LBNL(Berkeley):** Jorgen Randrup

**Yukawa Institute (Kyoto, Japan)**
T. Ichikawa

IKS KATHOLIEKE UNIVERSITEIT LEUVEN

J. Elseviers
C. Van Beveren
L. Ghys
M. Huyse
D. Radulov
E. Rapisarda
P. Van Duppen

**J. D. McDonnell, W. Nazarewicz, A. Staszczak, A. Warda et al**.

Thomas E. Cocolios (University of Manchester)
U. Koster (*ILL, Grenoble, France*)
M. Veselský, M. Venhart (*Slovakia*)
I.Tsekhanovich  (CENBG, France)
L. Popescu, D. Pauwels, SCK•CEN, Mol, Belgium
S. Antalic et al. Comenium University, Slovakia

# Outlook

- Brief (experimental) review on low-energy fission
- Low-energy fission in "new" regions of the Nuclear Chart
- Beta Delayed Fission ($\beta$DF) – what it is and why?
- $\beta$DF of $^{178,180}$Hg, $^{194,196}$At, $^{202}$Fr at ISOLDE (CERN)
- Fusion-fission reactions at JAEA and ANU: the probe of excitation energy and N/Z dependence in Hg isotopes
- Conclusions: Future for low-energy fission with RIBs

# A reminder: Symmetric vs Asymmetric Fission

J. Phys. G: Nucl. Part. Phys. **35** (2008) 035104 A V Karpov *et al*

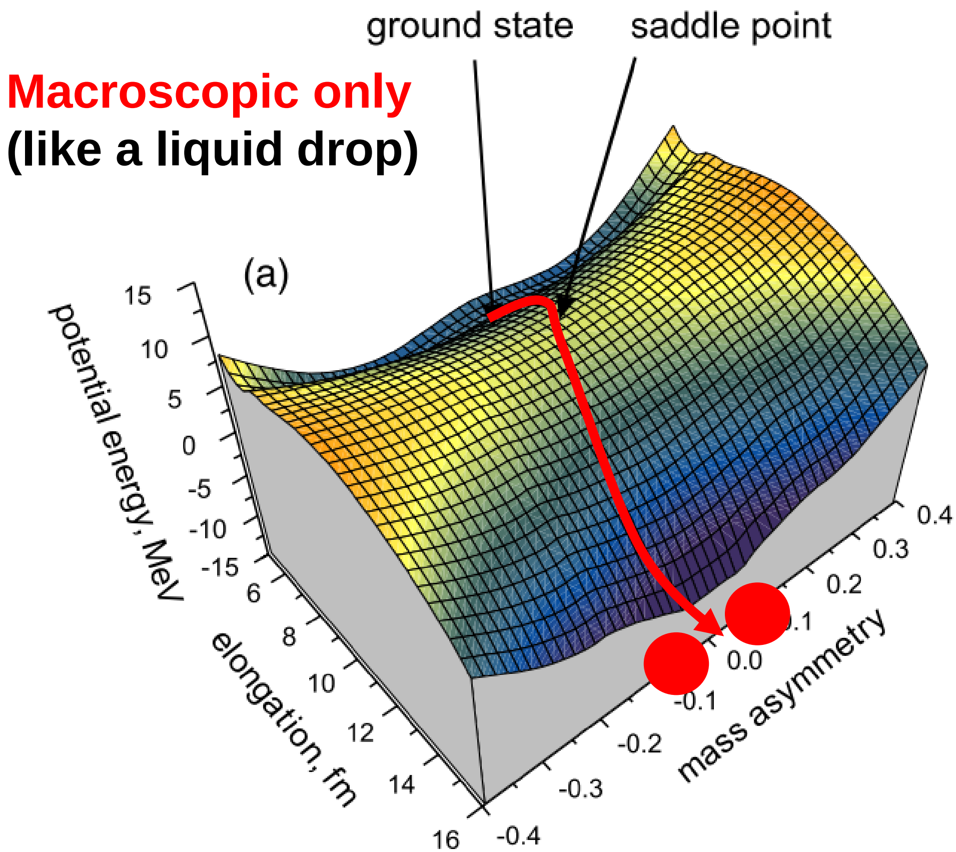



**Figure 2.** Macroscopic (a) and macro-microscopic (b) potential energy surface for the $^{238}$U nucleus in the coordinates $(R, \eta)$. The potential energy is obtained for $\delta = 0$ and $\varepsilon = 0.35$. The macroscopic part is normalized to zero for the spherical shape of the compound nucleus.

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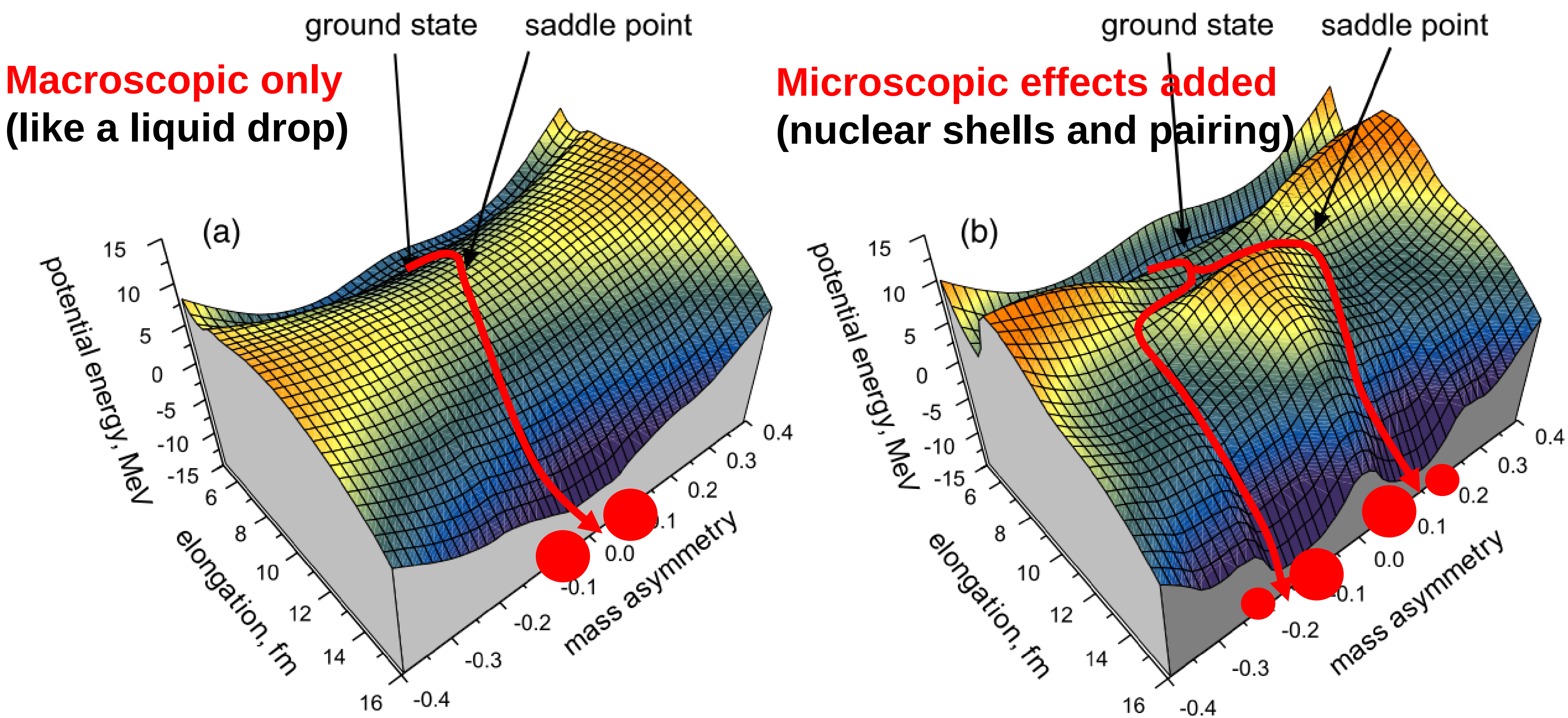
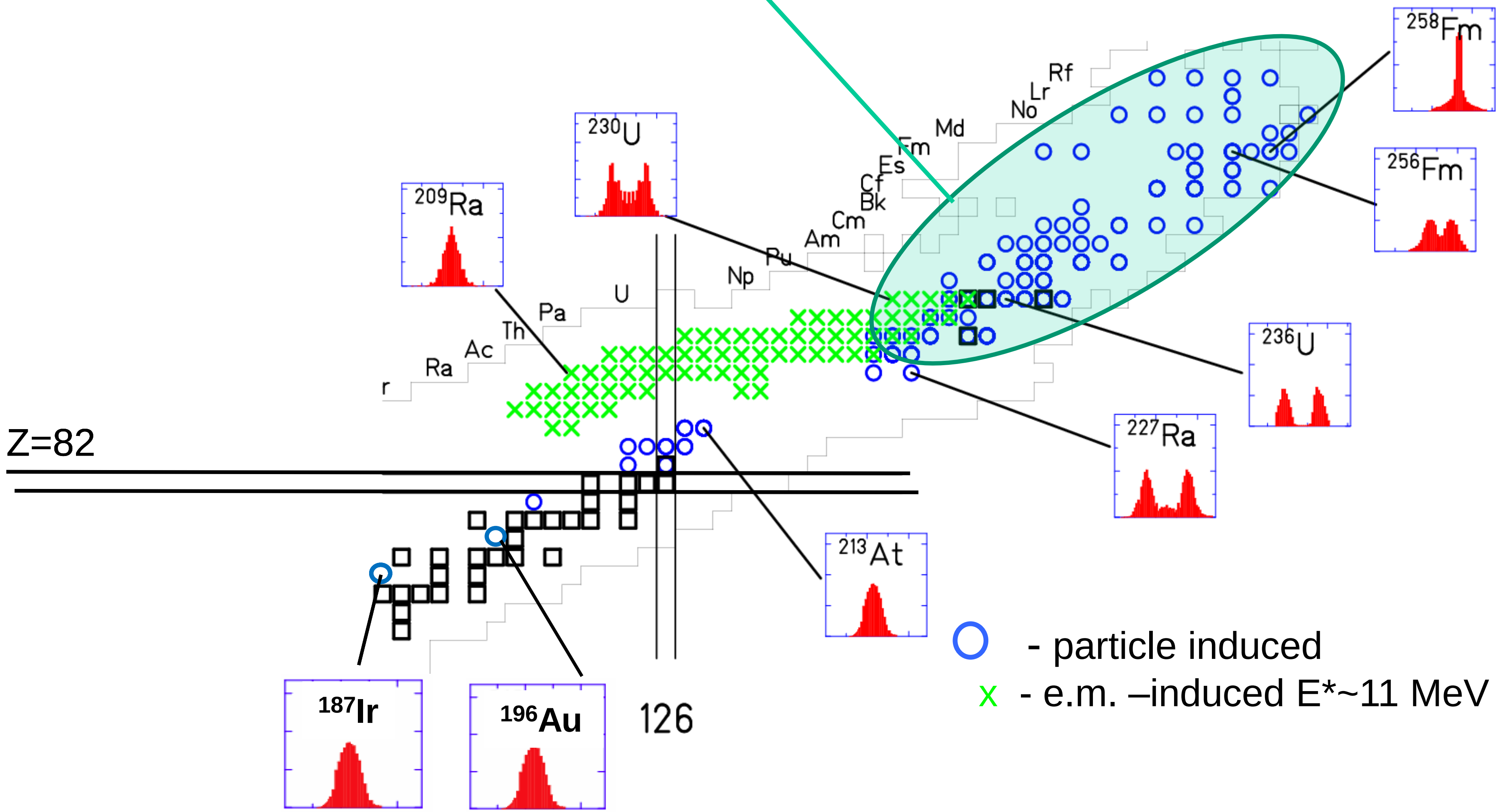



**Figure 2.** Macroscopic (a) and macro-microscopic (b) potential energy surface for the $^{238}$U nucleus in the coordinates $(R, \eta)$. The potential energy is obtained for $\delta = 0$ and $\varepsilon = 0.35$. The macroscopic part is normalized to zero for the spherical shape of the compound nucleus.

# Experimental information on low-energy fission
## (nuclei with measured charge/mass split)

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



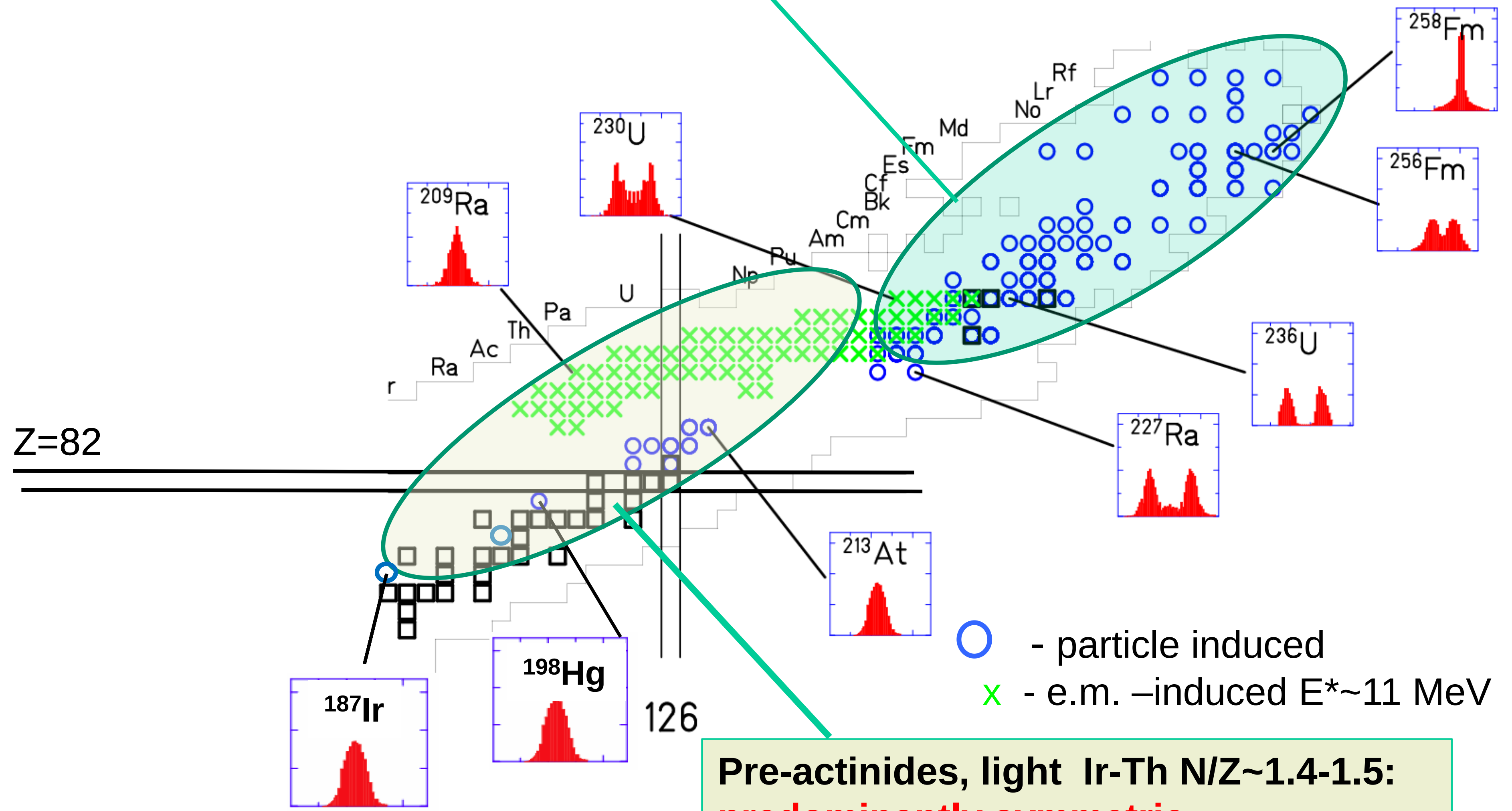

- particle induced

x - e.m. –induced E*~11 MeV

K.-H. Schmidt et al.

# Experimental information on low-energy fission
## Nuclei with measured charge/mass split

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




**Pre-actinides, light Ir-Th N/Z~1.4-1.5:**
**predominantly symmetric**

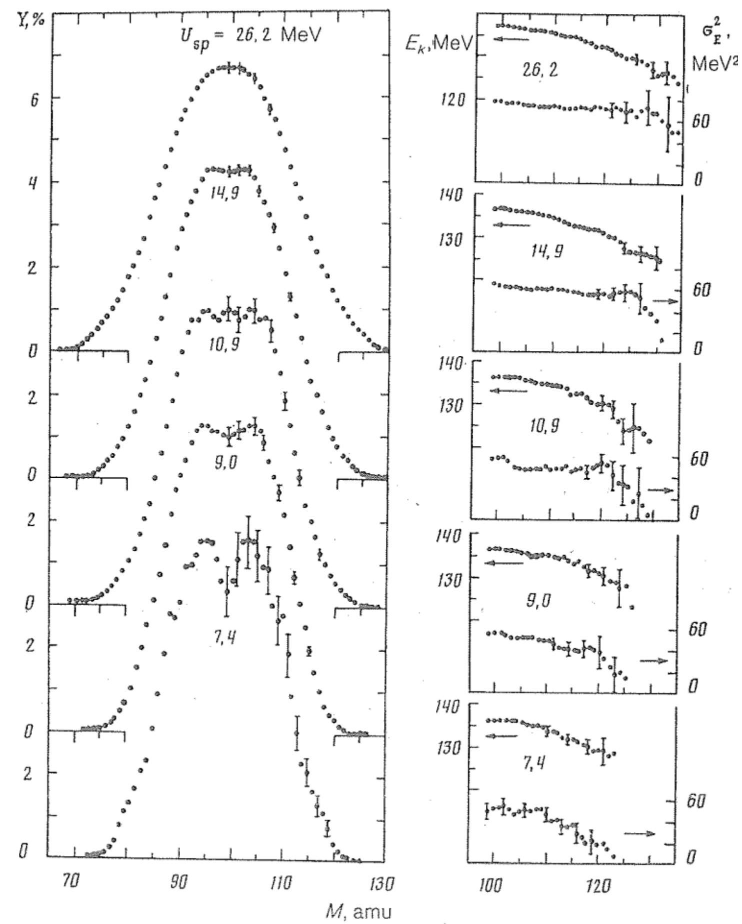
# An example of symmetry in the vicinity of $^{208}$Pb

## Mass asymmetry of symmetric fission of nuclei with $A \simeq 200$

M. G. Itkis, N. A. Kondrat'ev, S. I. Mul'gin, V. N. Okolovich, A. Ya. Rusanov, and G. N. Smirenkin[1)]

*Institute of Nuclear Physics, Kazakh Academy of Scie*

(Submitted 17 April 1990)
Yad. Fiz. 52, 944–959 (October 1990)



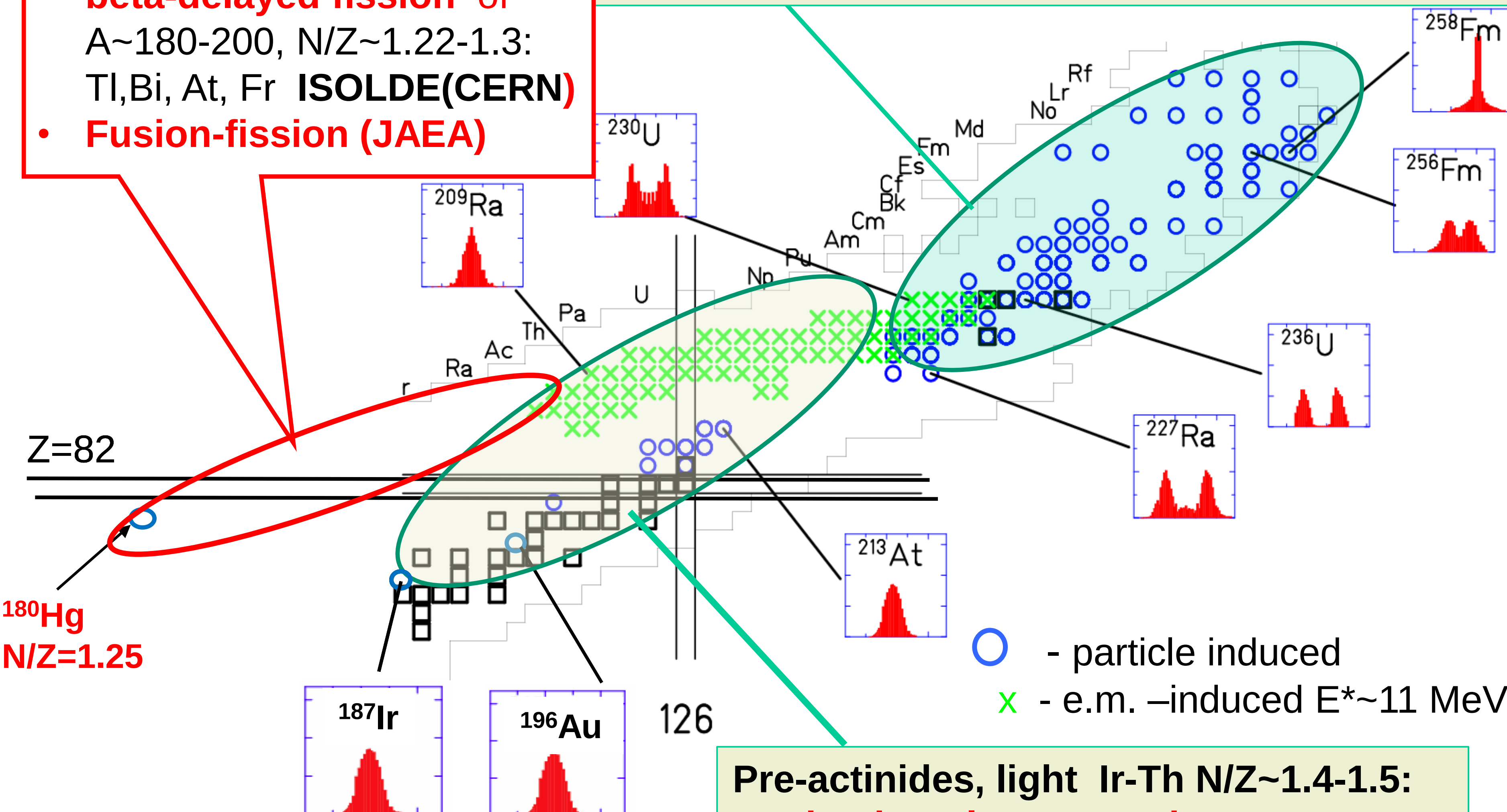



- **$^{198}$Hg – symmetric,** with a dip at symmetry at the lowest E*
- Several papers, very good data for several nuclei in this region, also as a function of E* - still needs to be explored/explained by the theory!

# Region of our interest: fission of neutron-deficient nuclei between Hg and Rn

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

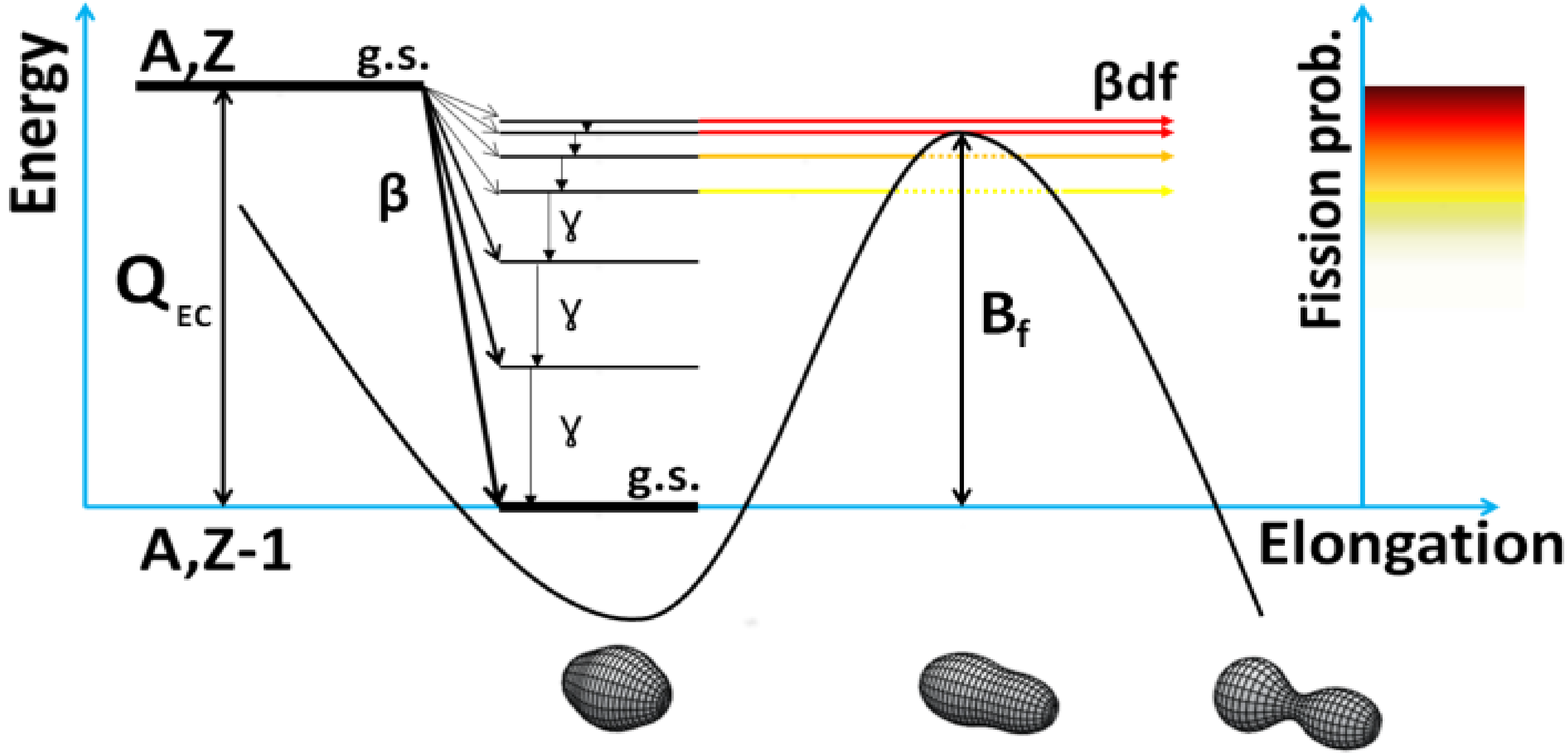
- **beta-delayed fission** of A~180-200, N/Z~1.22-1.3: Tl,Bi, At, Fr **ISOLDE(CERN)**
- **Fusion-fission (JAEA)**




**Pre-actinides, light Ir-Th N/Z~1.4-1.5:**
**predominantly symmetric**

# Beta-Delayed Fission

Discovery: $^{232,234}Am$ (1966, Dubna)

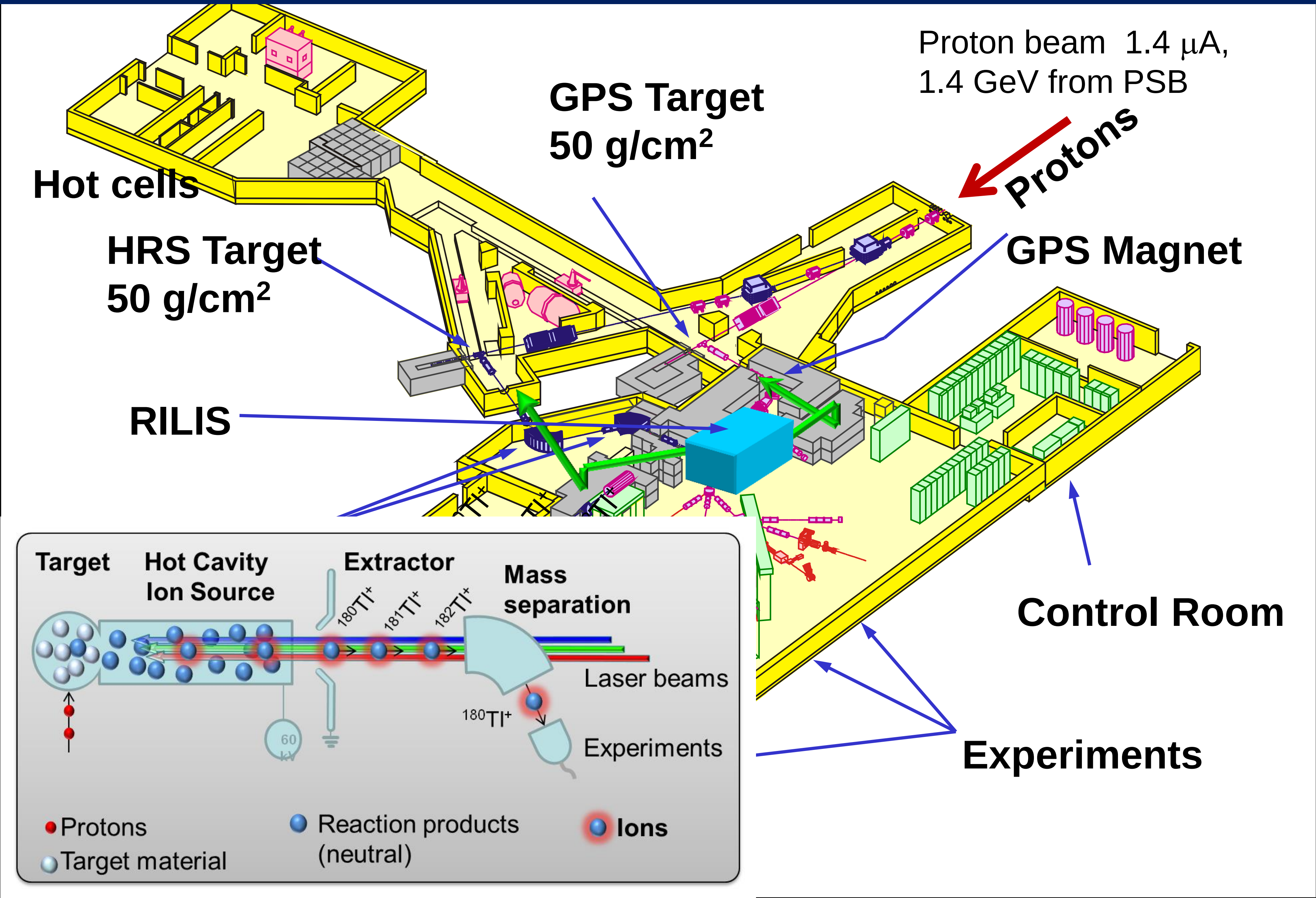



•**Two step process:** β decay of the parent (e.g. $^{180}Tl$) followed by fission of daughter ($^{180}Hg$) from excited states close to the top of the fission barrier

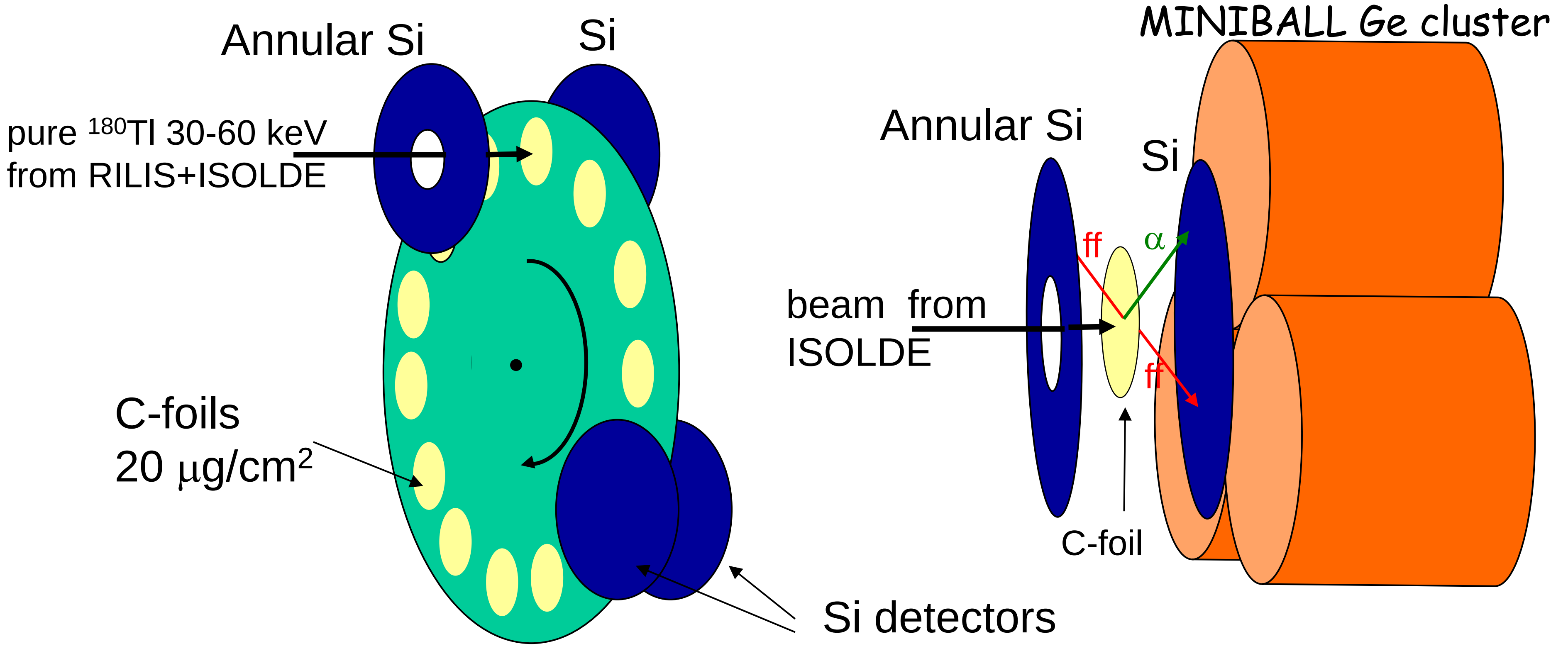
•**Low-energy fission** (E*~3-12 MeV, limited by $Q_{EC}$)
e.g. $^{180}Tl$: $Q_{EC}$=10.4 MeV, $B_{f,calc}(^{180}Hg)$=9.8 MeV

•**Low angular momentum of the fissionning state**

# Mass Separator ISOLDE (CERN)



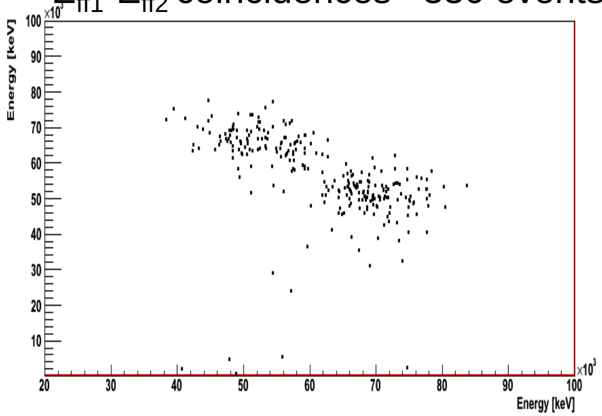
# Detection system for βDF studies at ISOLDE



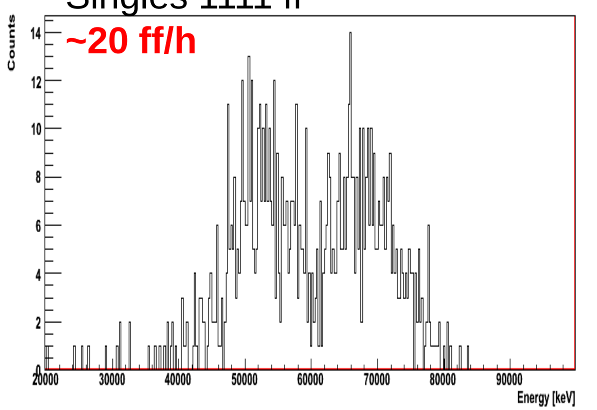

A.Andreyev et al. PRL 105 (2010)

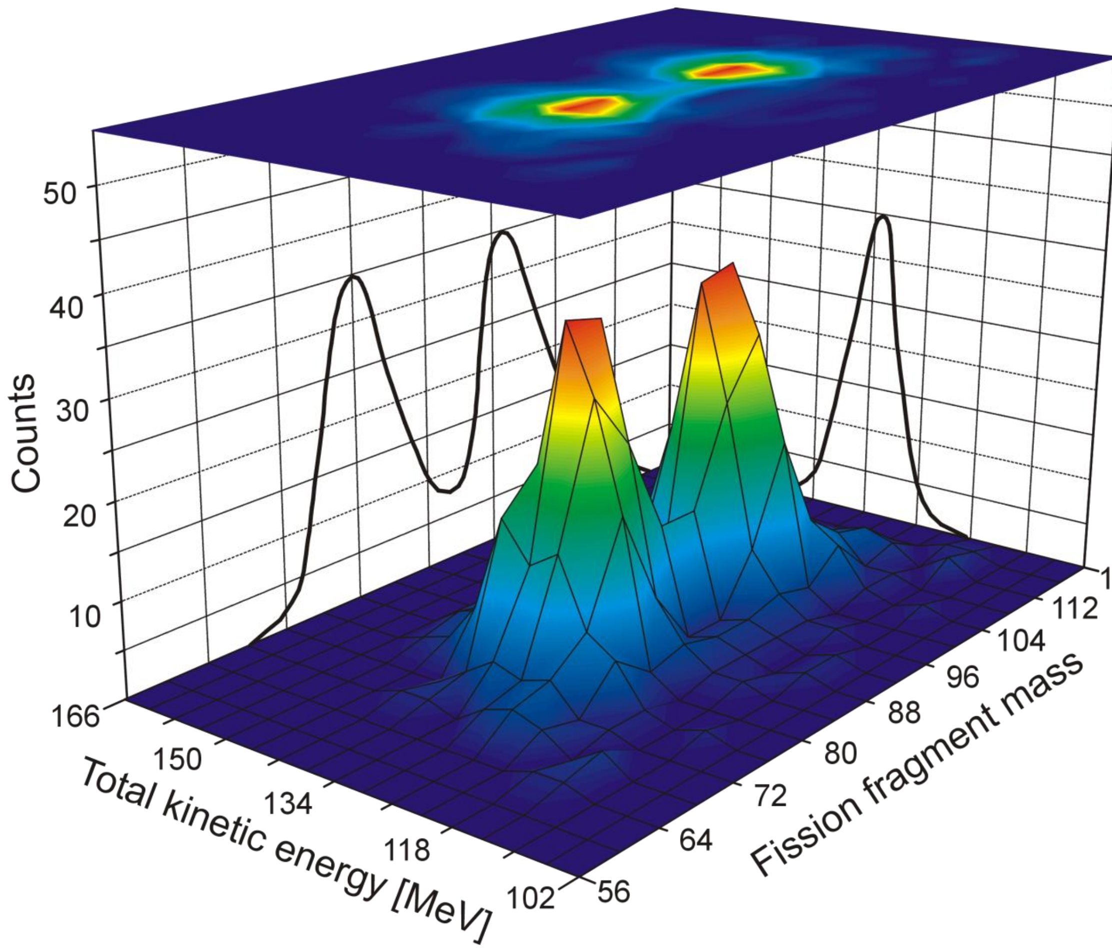
# Mass distribution of fission fragments from βDF of $^{180}$Tl
## (recall: fissionning nucleus is $^{180}$Hg, which is twice semi-magic $^{90}$Zr)

$E_{ff1}$-$E_{ff2}$ coincidences ~330 events




Singles 1111 ff




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

**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

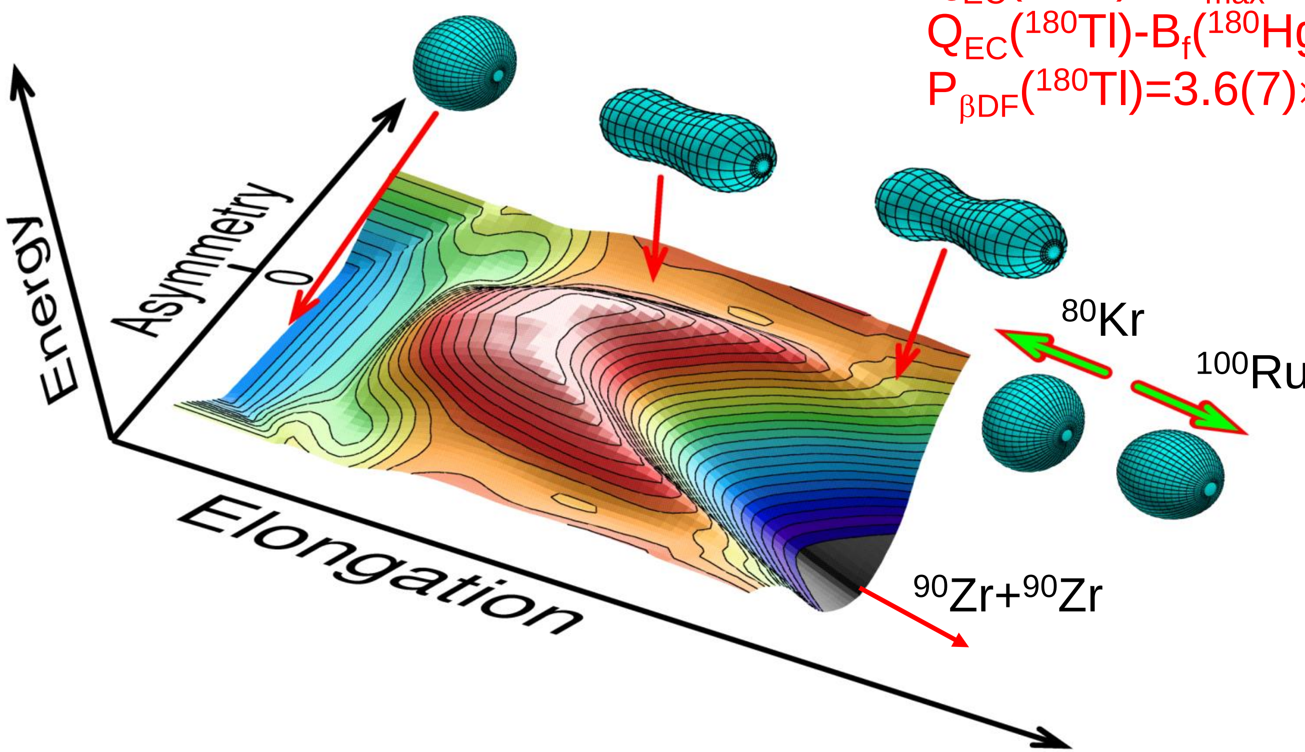
**New Type of Asymmetric Fission in Proton-Rich Nuclei**

**fission of $^{180}$Hg 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)*

$Q_{EC}(^{180}\text{Tl})=E^*_{max}=10.44$ MeV
$Q_{EC}(^{180}\text{Tl})-B_f(^{180}\text{Hg})=0.63$ MeV
$P_{\beta DF}(^{180}\text{Tl})=3.6(7)\times10^{-5}$




**5D fission model by P. Möller et al., Nature 409, 785, 2001**

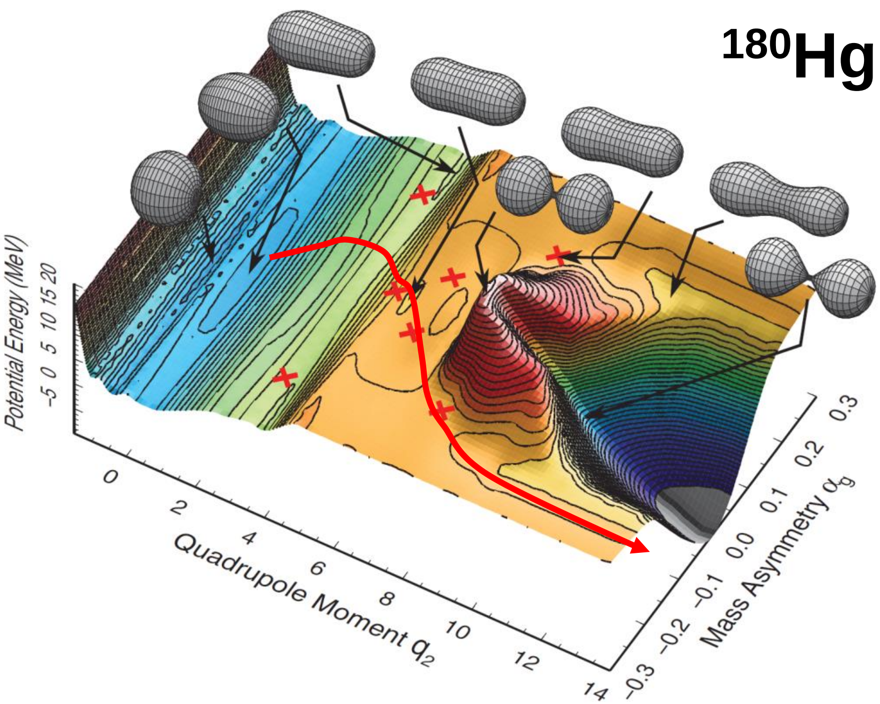
# Two types of asymmetry: what's the difference?

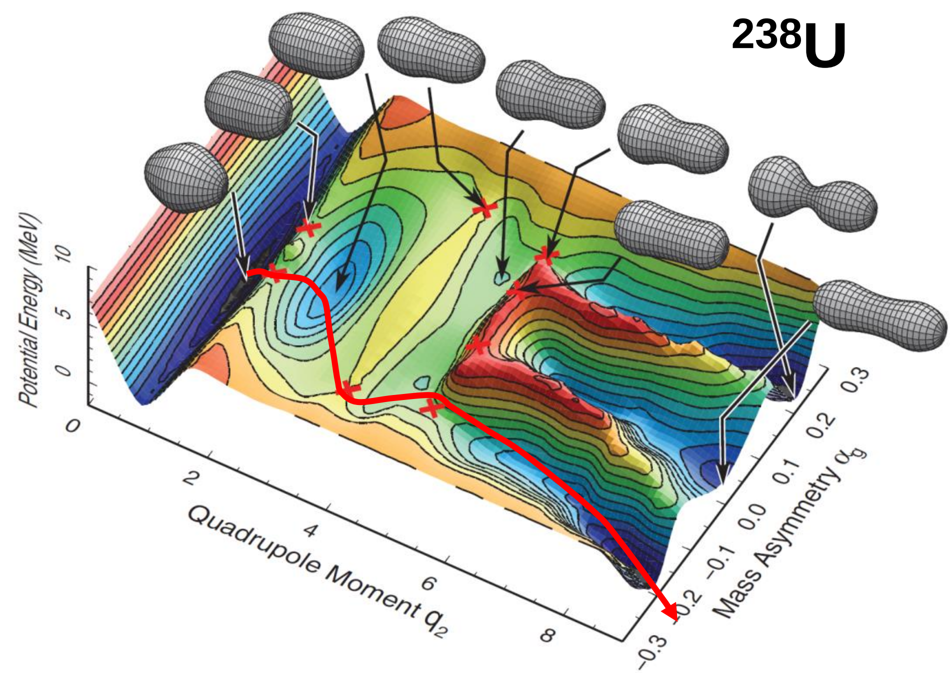
PHYSICAL REVIEW C **86**, 024610 (2012)

**Contrasting fission potential-energy structure of actinides and mercury isotopes**

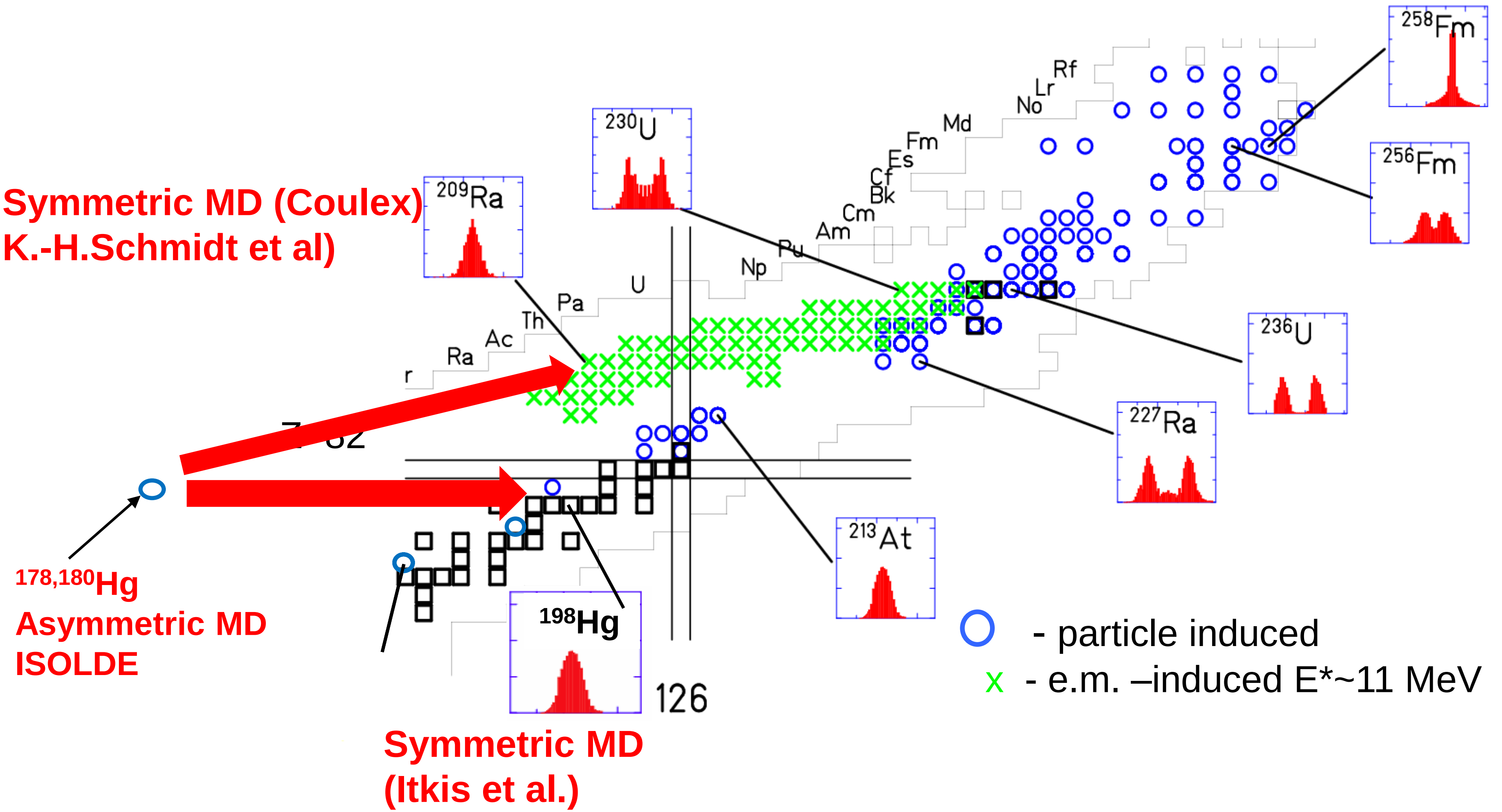
Takatoshi Ichikawa,[1] Akira Iwamoto,[2] Peter Möller,[3] and Arnold J. Sierk[3]

**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.

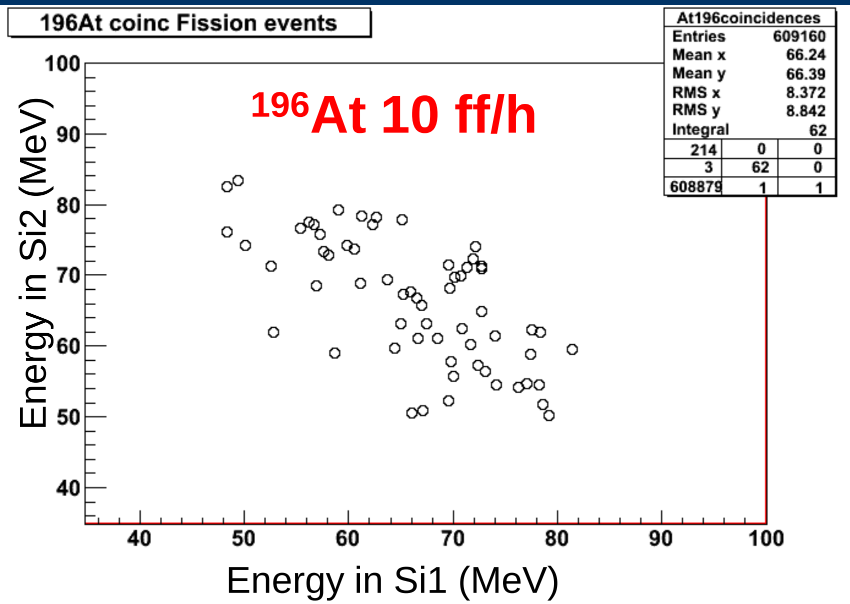


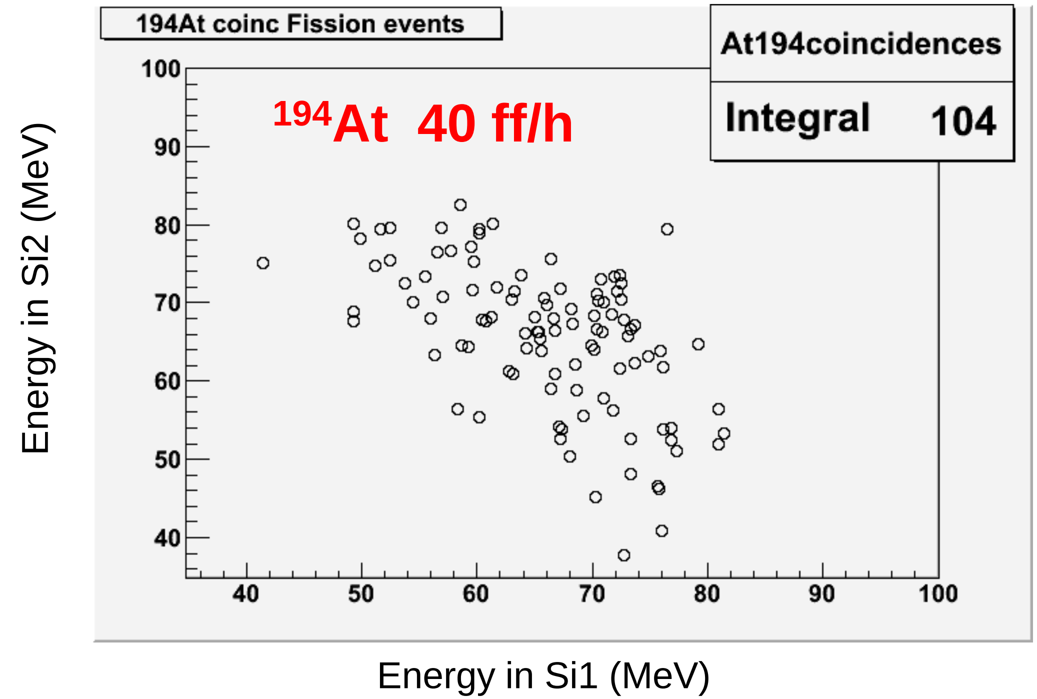



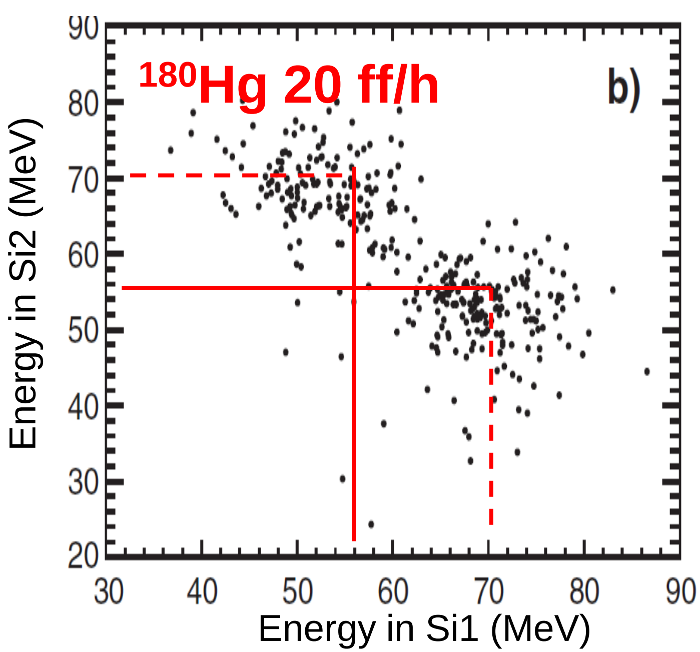
# Search for transition from asymmetry of $^{178,180}$Hg to symmetry of $^{198}$Hg (Itkis's data) and around $^{209}$Rn (Schmidt's data, Coulex)



# ISOLDE: Mass Distributions of $^{194,196}$Po via βDF of $^{194,196}$At



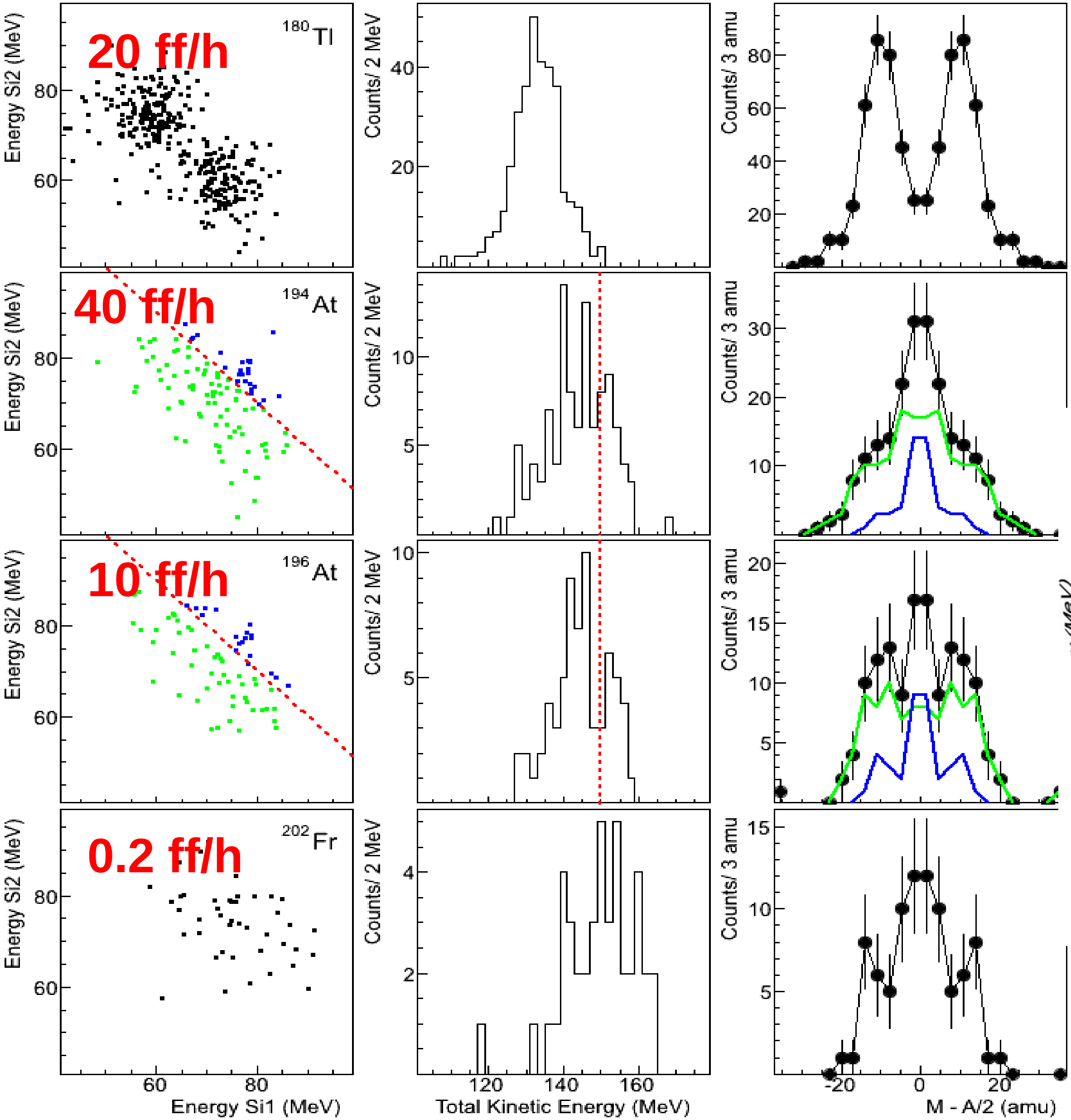



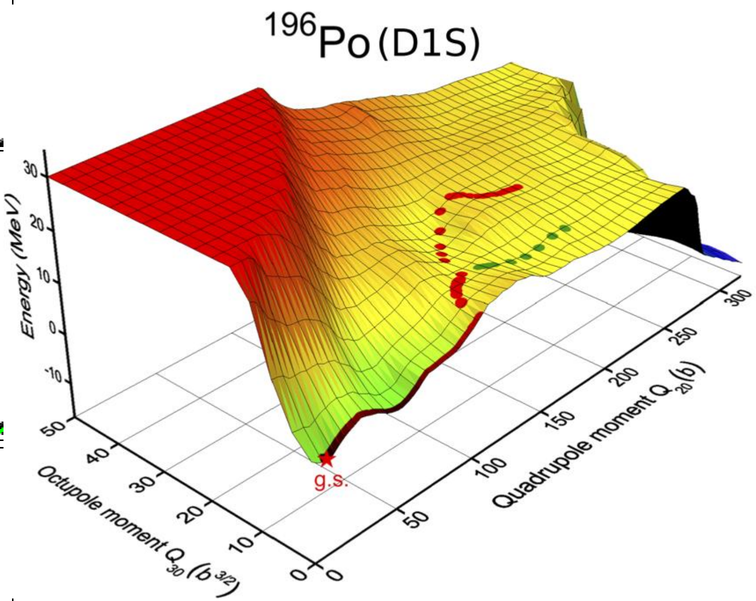




- **Clear difference in energy (thus, mass) distribution between 2-peaked fission of $^{180}$Hg and a broad distribution in $^{194,196}$Po**
- **A mixture of 2 modes in in $^{194,196}$Po?**

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

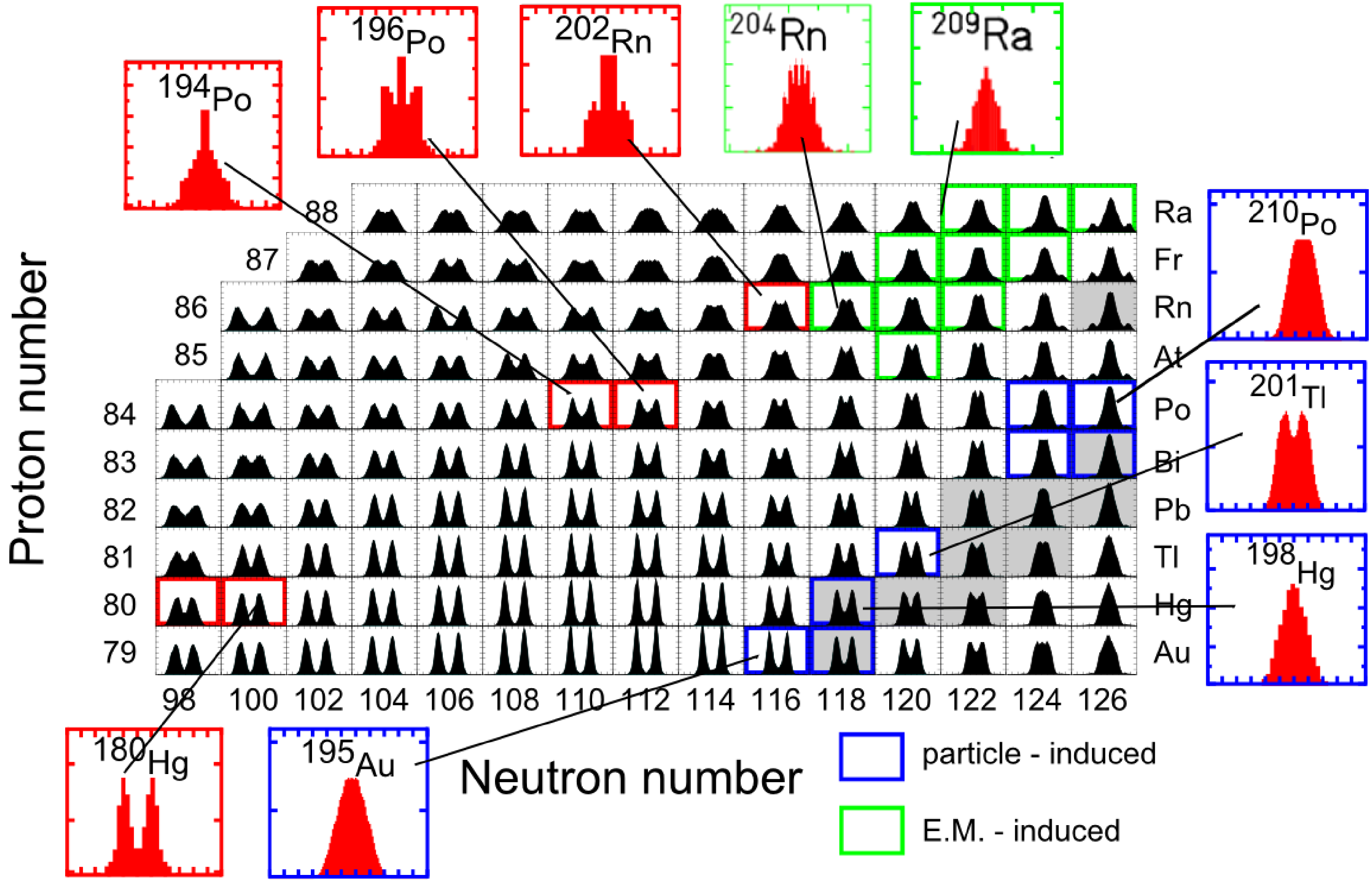
L.Ghys et al., Phys. Rev. C 90, 044305 (2014)




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

# 'Global' Calculations for MD's of proton-rich nuclei with A~180-200 (P. Moller and J. Randrup)




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

# Mapping beta-delayed fission: from neutron-deficient to neutron-rich nuclei

**Reviews of Modern Physics, 85, 1541 (2013)**

## *Colloquium:* Beta-delayed fission of atomic nuclei

Andrei N. Andreyev*

*Department of Physics,*
*University of York,*
*Heslington, York YO10 5DD,*
*United Kingdom*
*Advanced Science Research Centre (ASRC),*
*Japanese Atomic Energy Agency(JAEA), Tokai-mura,*
*Japan*

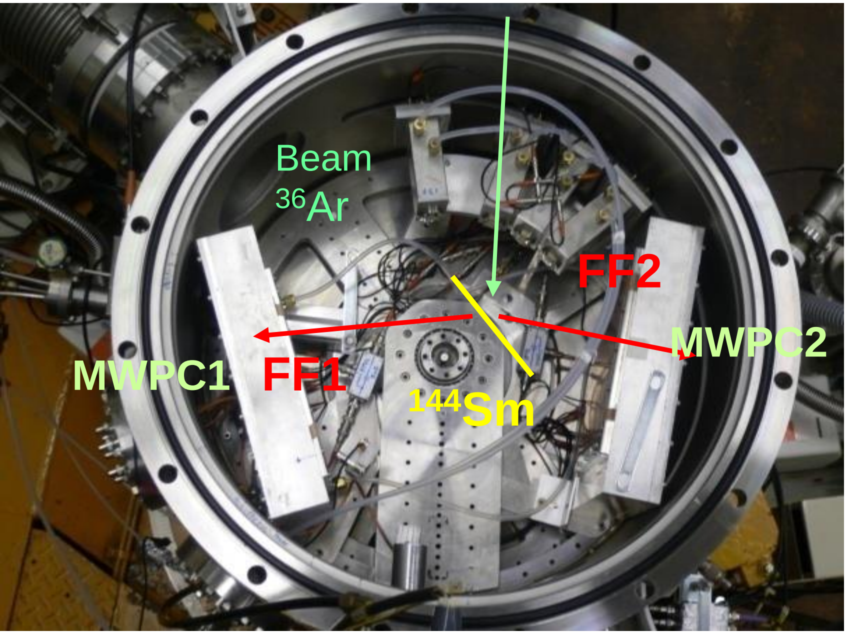
Mark Huyse, Piet Van Duppen

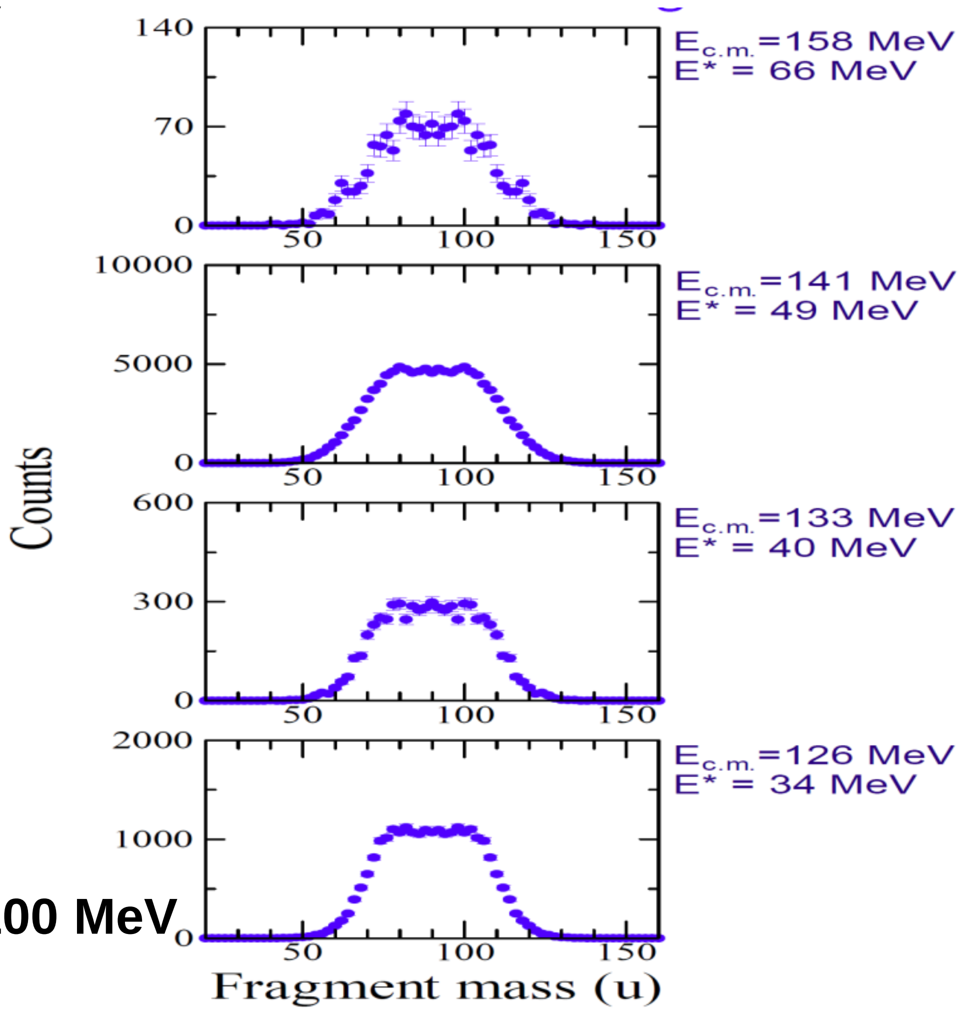
*Instituut voor Kern- en Stralingsfysica,*
*KU Leuven, University of Leuven, B-3001 Leuven,*
*Belgium*

This Colloquium reviews the studies of exotic type of low-energy nuclear fission, the $\beta$-delayed fission ($\beta$DF). Emphasis is made on the new data from very neutron-deficient nuclei in the lead region, previously scarcely studied as far as fission is concerned. These

# $^{180}$Hg: More surprises?
# How does $^{180}$Hg fission at *higher* excitation energies?

•$^{36}$Ar+$^{144}$Sm→$^{180}$Hg* E*=34-66 MeV
•2010: JAEA,Tokai



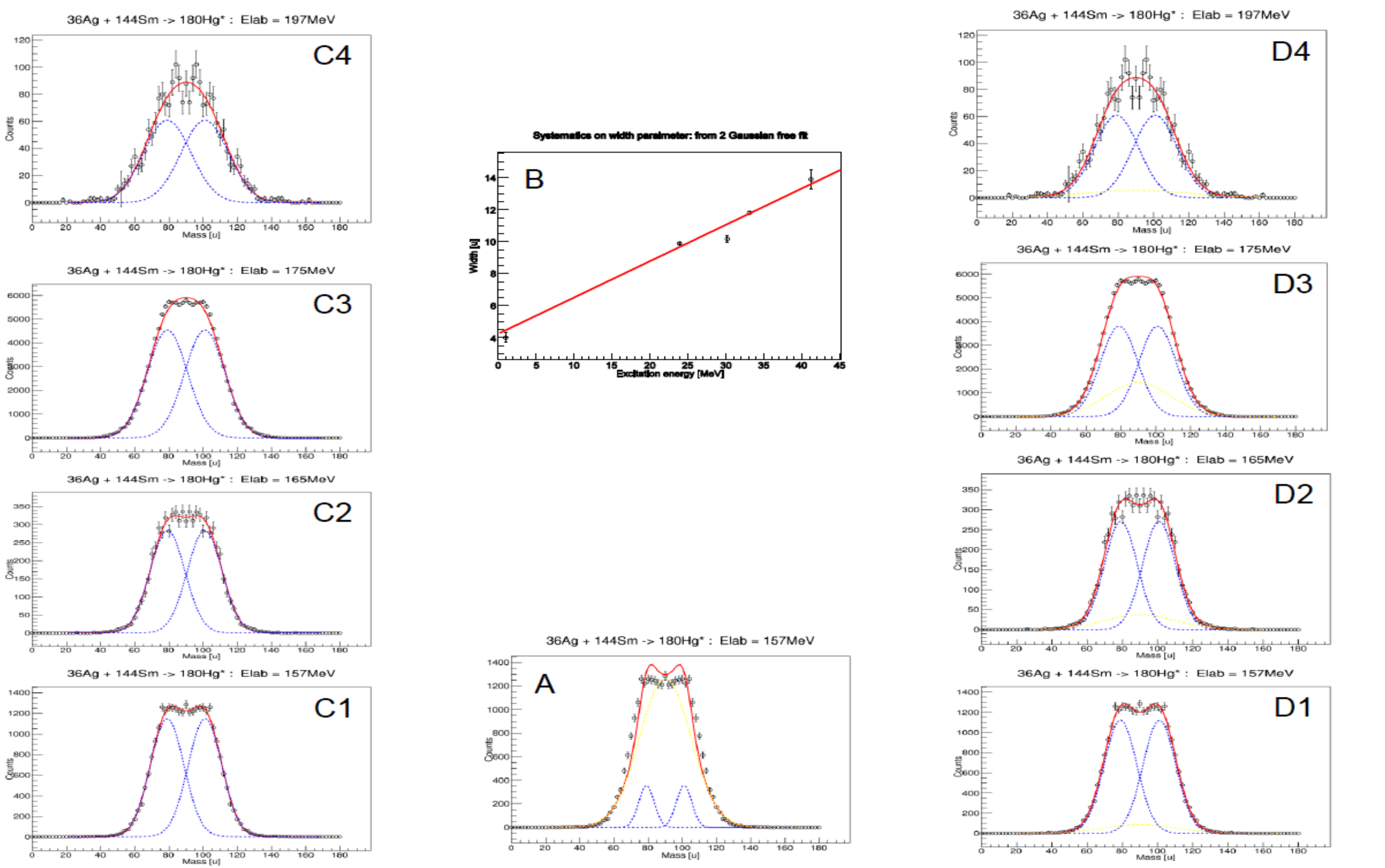

**•2010-2012, JAEA**
**•$^{36,40}$Ar+$^{144,154}$Sm→$^{180-194}$Hg* E*=30-100 MeV**

**JAEA workshops 2012-2014**
**submitted to PLB (2015)**

**Even at E*=66 MeV: asymmetric mass split with $A_1$~100, $A_2$~80**

Supported by Reimei Foundation (JAEA)

# $^{180}$Hg: One or two fission modes?



# 'Brownian Metropolis Shape Motion': Mass Split and Excitation energy dependence

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

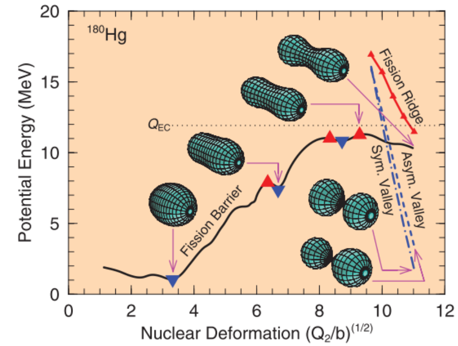
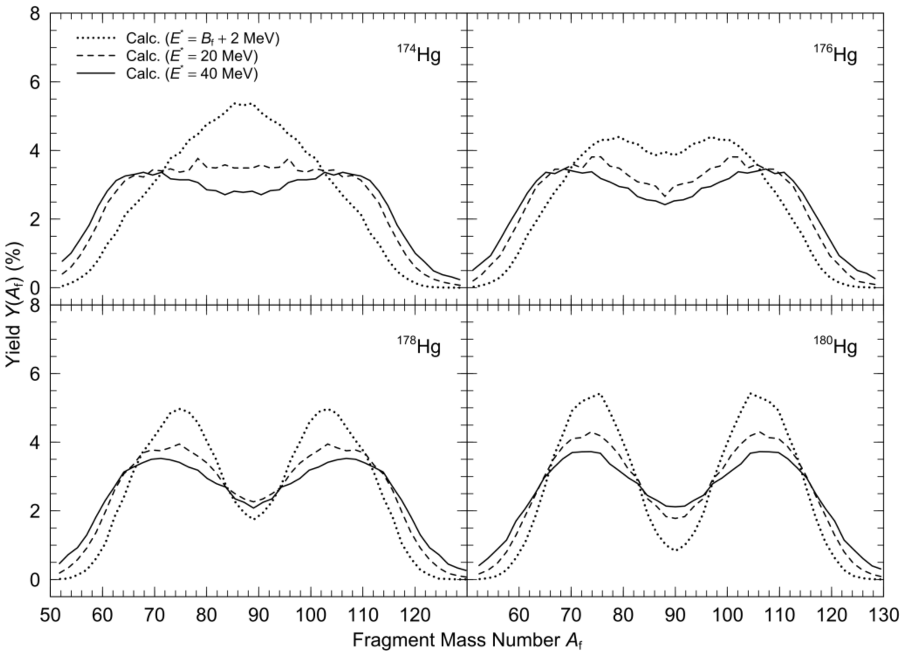
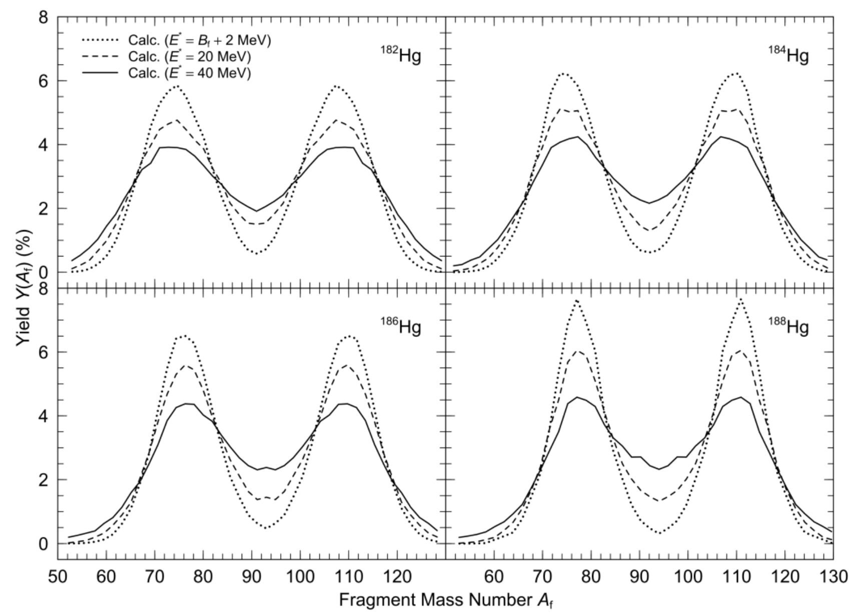



FIG. 4. (Color online) Minima, saddles, major valleys, and ridges in the 5D potential-energy surface of $^{180}$Hg (see text). At the last plotted point on the fission barrier, $(Q_2/\mathrm{b})^{(1/2)} \approx 11$, the asymmetry of the shape is $A_\mathrm{H}/A_\mathrm{L} = 108/72$.



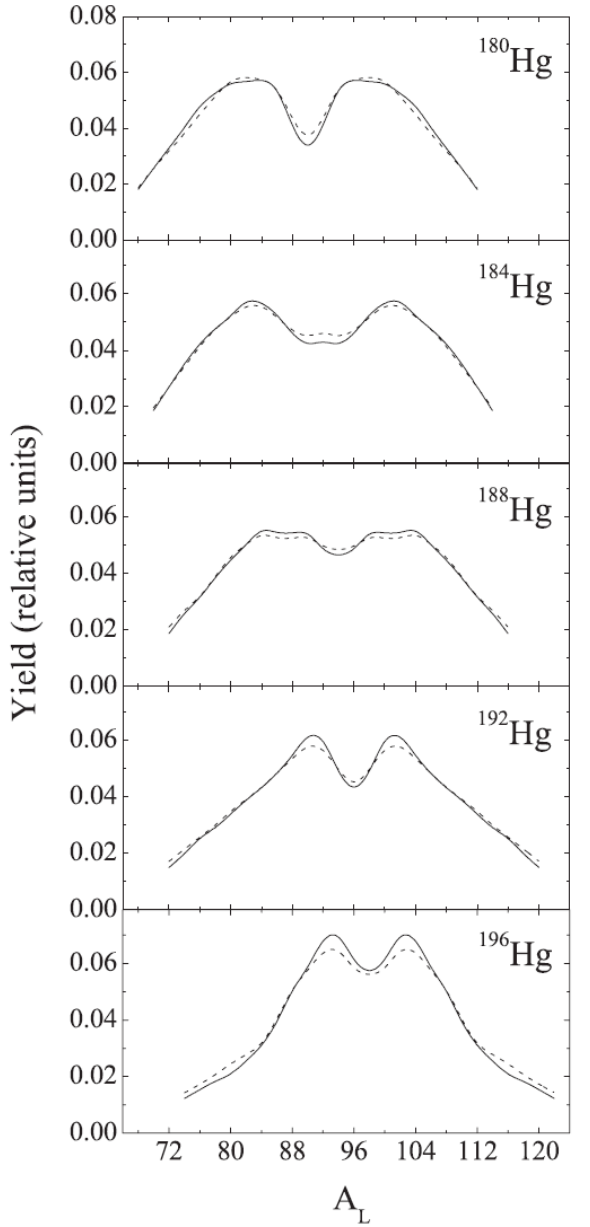
# Dubna's 'Improved Scission-Point Model'

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**

# CEA's '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)

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

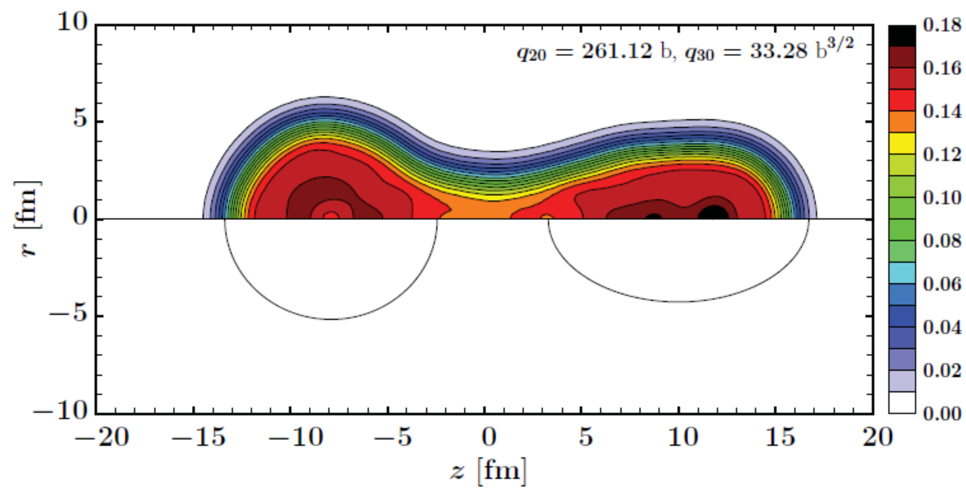



FIG. 4. (Color online) Total nuclear density for the most energetically favorable scission configuration in $^{180}$Hg fission, extracted from a self-consistent HFB calculation. In the lower part of the figure, two

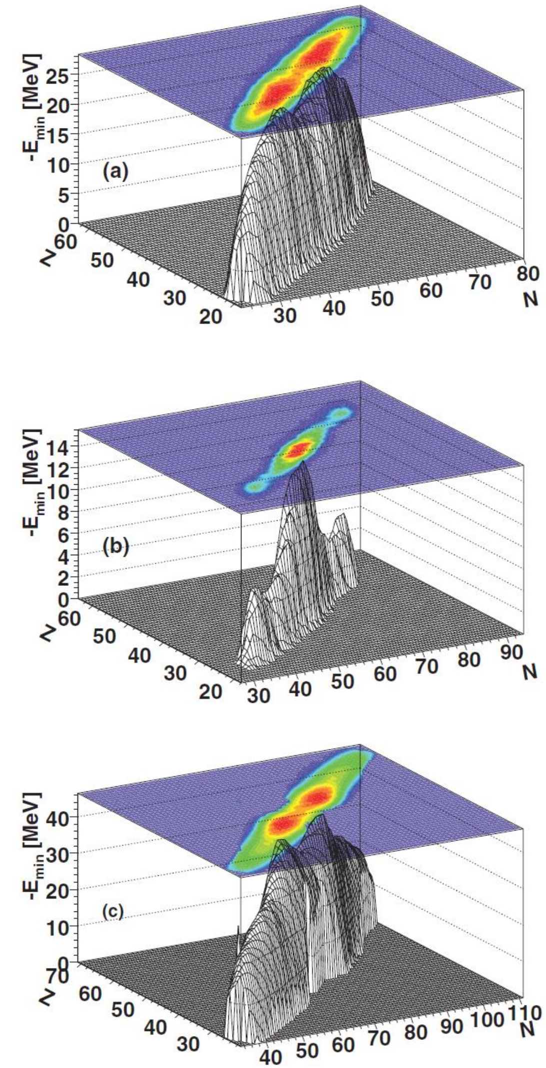



FIG. 2. (Color online) Minimum absolute available energy at scission calculated for all possible fragmentations in (a) $^{180}$Hg and (b) $^{198}$Hg fission at 10 MeV and in (c) the thermal $n$-induced fission of $^{235}$U.

# ‘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]

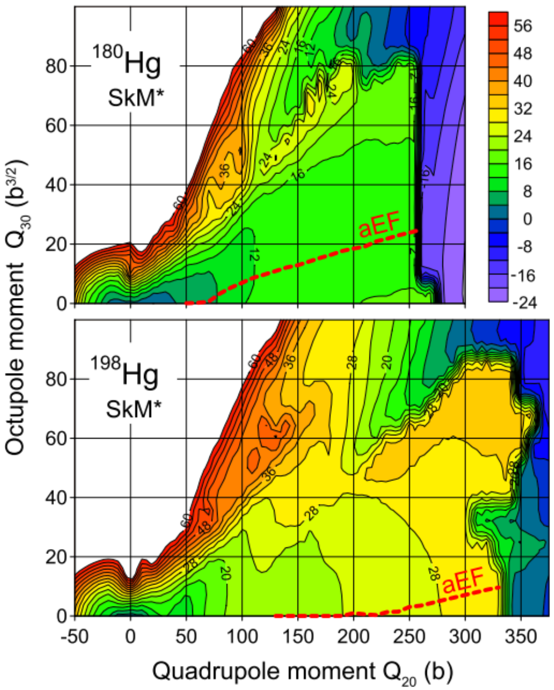



FIG. 2. (Color online) PES for $^{180}$Hg (top) and $^{198}$Hg (bottom) in the plane of collective coordinates $Q_{20} - Q_{30}$ in HFB-SkM*. The aEF fission pathway corresponding to asymmetric elongated fragments is marked. The difference between contour lines is 4 MeV. The effects due to triaxiality,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

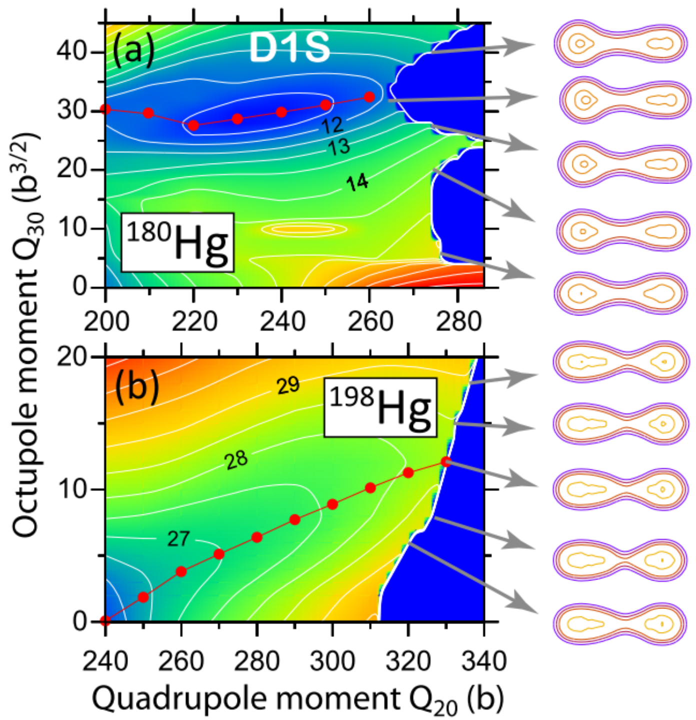


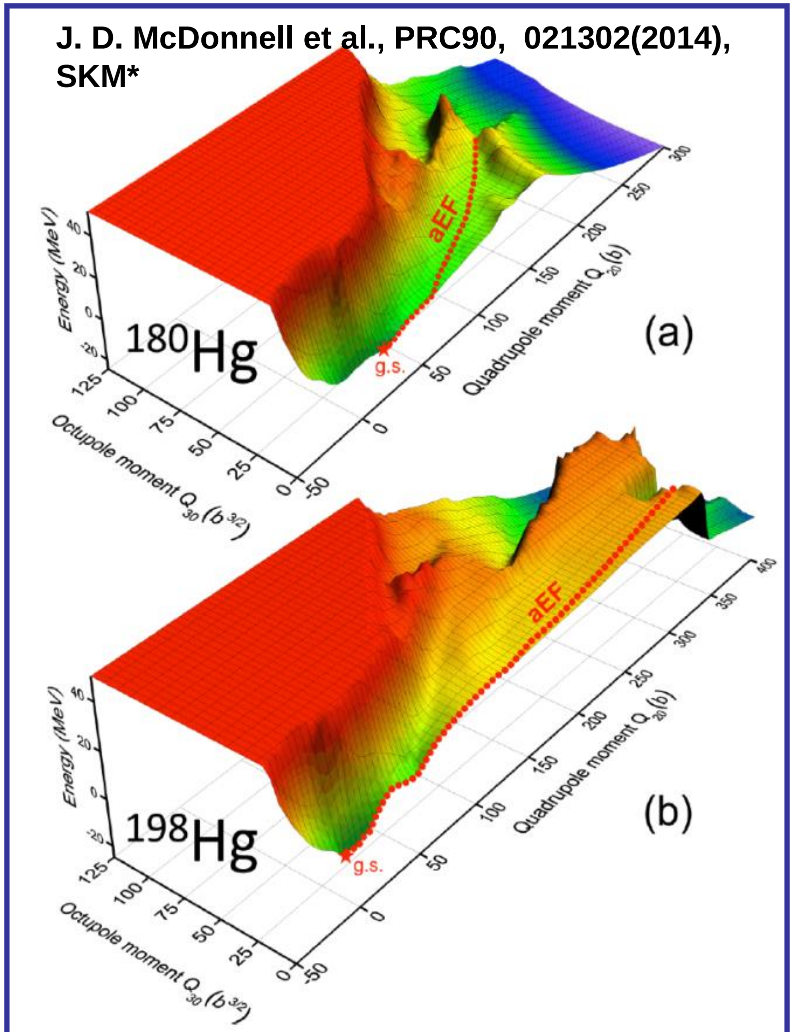

FIG. 3. (Color online) PES in HFB-D1S for $^{180}$Hg (top) and $^{198}$Hg (bottom) in the $(Q_{20}, Q_{30})$ plane in the pre-scission region of aEF valley. The symmetric limit corresponds to $Q_{30} = 0$. The aEF valley and density profiles for pre-scission configurations are indicated. The difference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

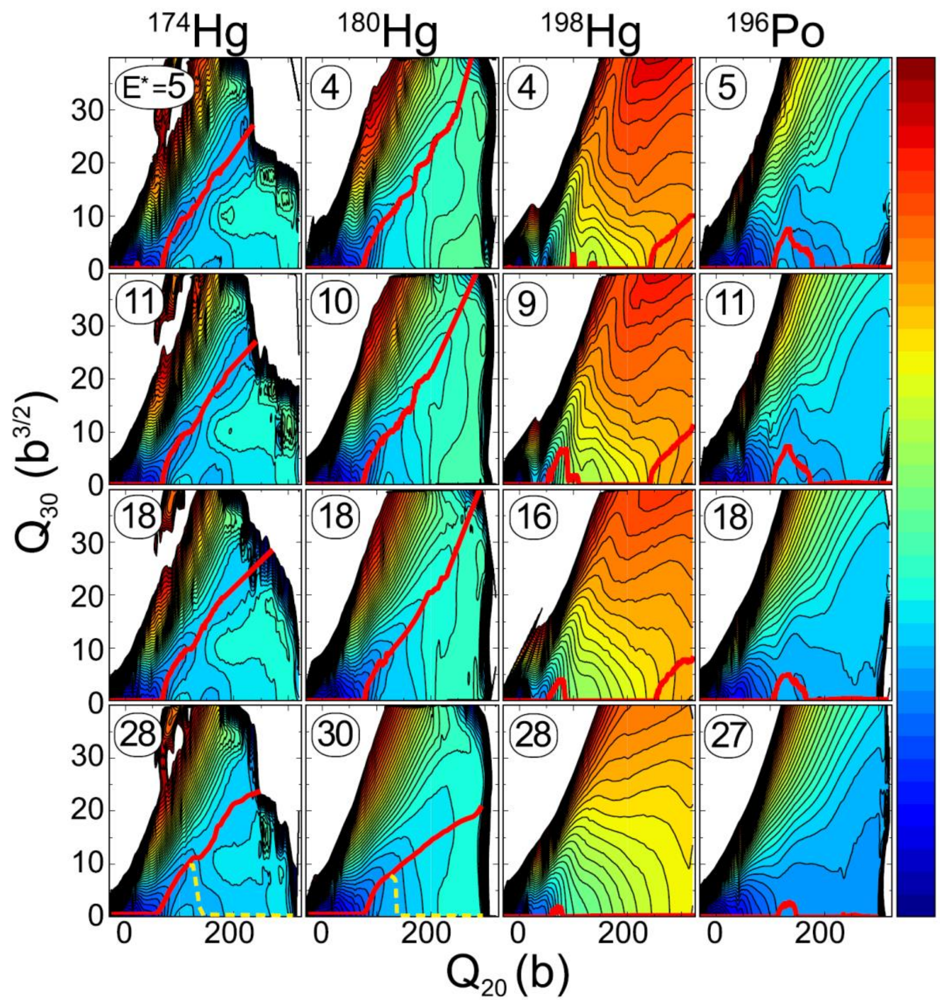
# Excitation-energy dependence of shell effects and of the fission barrier in the lead region (SKM*)

PHYSICAL REVIEW C **90**, 021302(R) (2014)

**Excitation-energy dependence of fission in the mercury region**

J. D. McDonnell,[1,2] W. Nazarewicz,[2,3,4] J. A. Sheikh,[2,3,5] A. Staszczak,[2,6] and M. W




SkM∗ and a density-dependent pairing interaction.

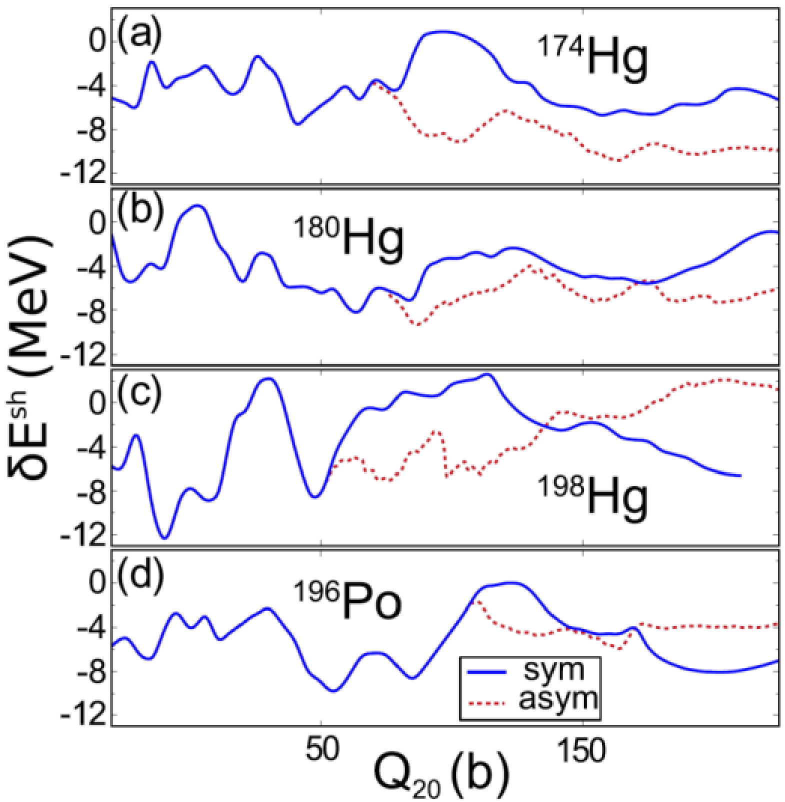
# Excitation-energy dependence of shell effects and of the fission barrier in the lead region (SKM*)

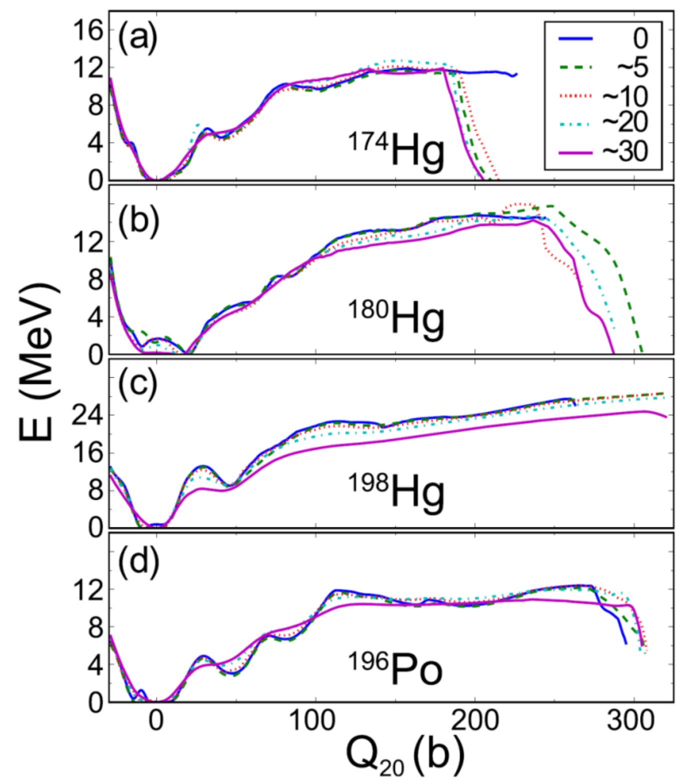
PHYSICAL REVIEW C **90**, 021302(R) (2014)

**Excitation-energy dependence of fission in the mercury region**

J. D. McDonnell,[1,2] W. Nazarewicz,[2,3,4] J. A. Sheikh,[2,3,5] A. Staszczak,[2,6] and M. Warda[6]

**Conclusions:** Our self-consistent theory suggests that excitation energy weakly affects the fission pattern of the nuclei considered. The transition from the asymmetric fission in the proton-rich nuclei to a more symmetric fission in the heavier isotopes is governed by the shell structure of pre-scission configurations.



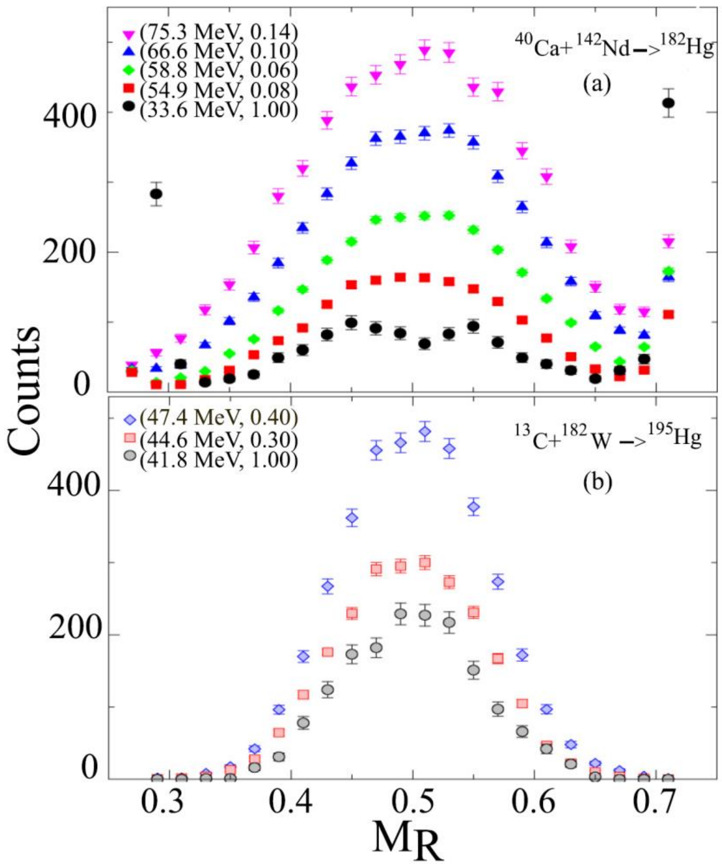



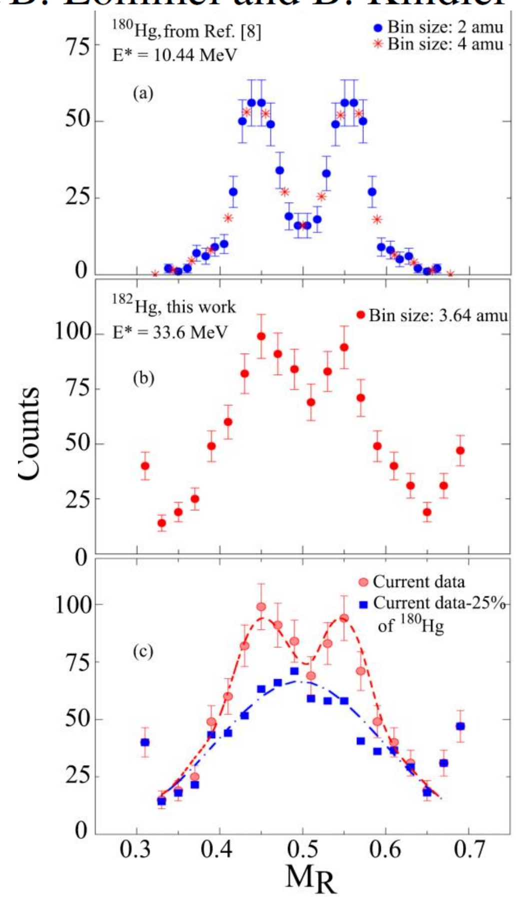
# Fusion-Fission of $^{182,195}$Hg at ANU

PHYSICAL REVIEW C **91**, 064605 (2015)

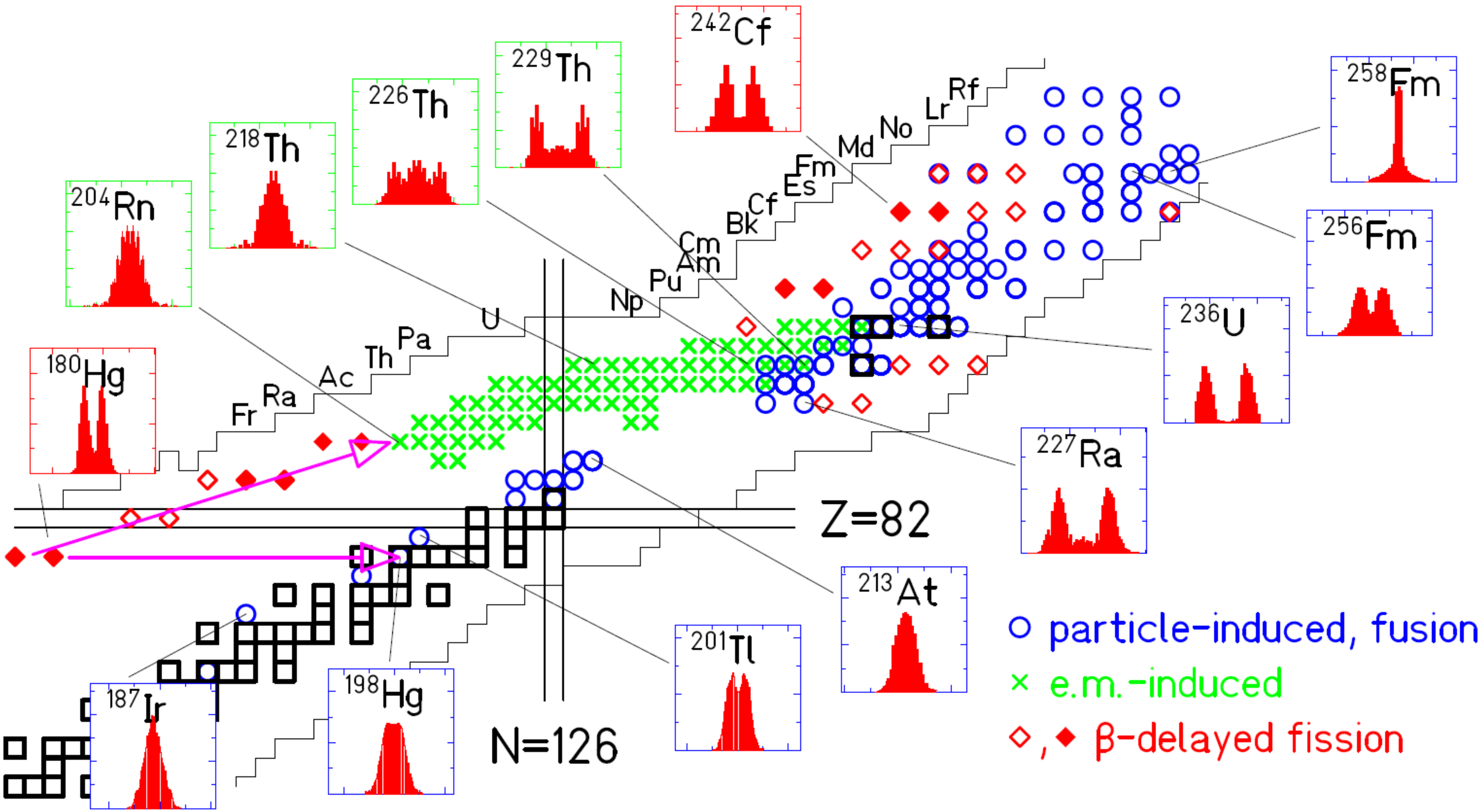
**Observation of mass-asymmetric fission of mercury nuclei in heavy ion fusion**

E. Prasad,* D. J. Hinde,† K. Ramachandran,‡ E. Williams, M. Dasgupta, I. P. Carter, K. J. Cook, D. Y. Jeung, D. H. Luong, S. McNeil, C. S. Palshetkar, D. C. Rafferty, C. Simenel, and A. Wakhle§
J. Khuyagbaatar Ch. E. Düllmann B. Lommel and B. Kindler



# Mapping Fission in 'Terra Incognita' in the Lead region




- New type of asymmetric fission in the neutron-deficient lead region ($^{178,180}$Hg)
- Multimodal fission in $^{194,196}$Po
- Unusual behaviour of shell effects and fission barriers as a function of E* in the lead region

# Conclusions:
# Bright future for fission studies with stable and RIBs

**Access to both proton- and neutron- rich nuclei**
**Un-precendented precision in Z,A determination**

- Beta Delayed Fission (βDF) at ISOLDE at 60 keV
- Fusion-fission reactions

- Transfer-induced fission at HIE-ISOLDE at 5 AMeV
- Coulex-induced fission with SOFIA@GSI at 1 AGeV
- Transfer-induced fission with SAMURAI@RIKEN at 350 AMeV
- Transfer-induced fission at VAMOS@GANIL at 6 AMeV
- Further plans (ELISe@FAIR, SCRIT@RIKEN)