Beta-delayed fission: from neutron-deficient to neutron-rich nuclei

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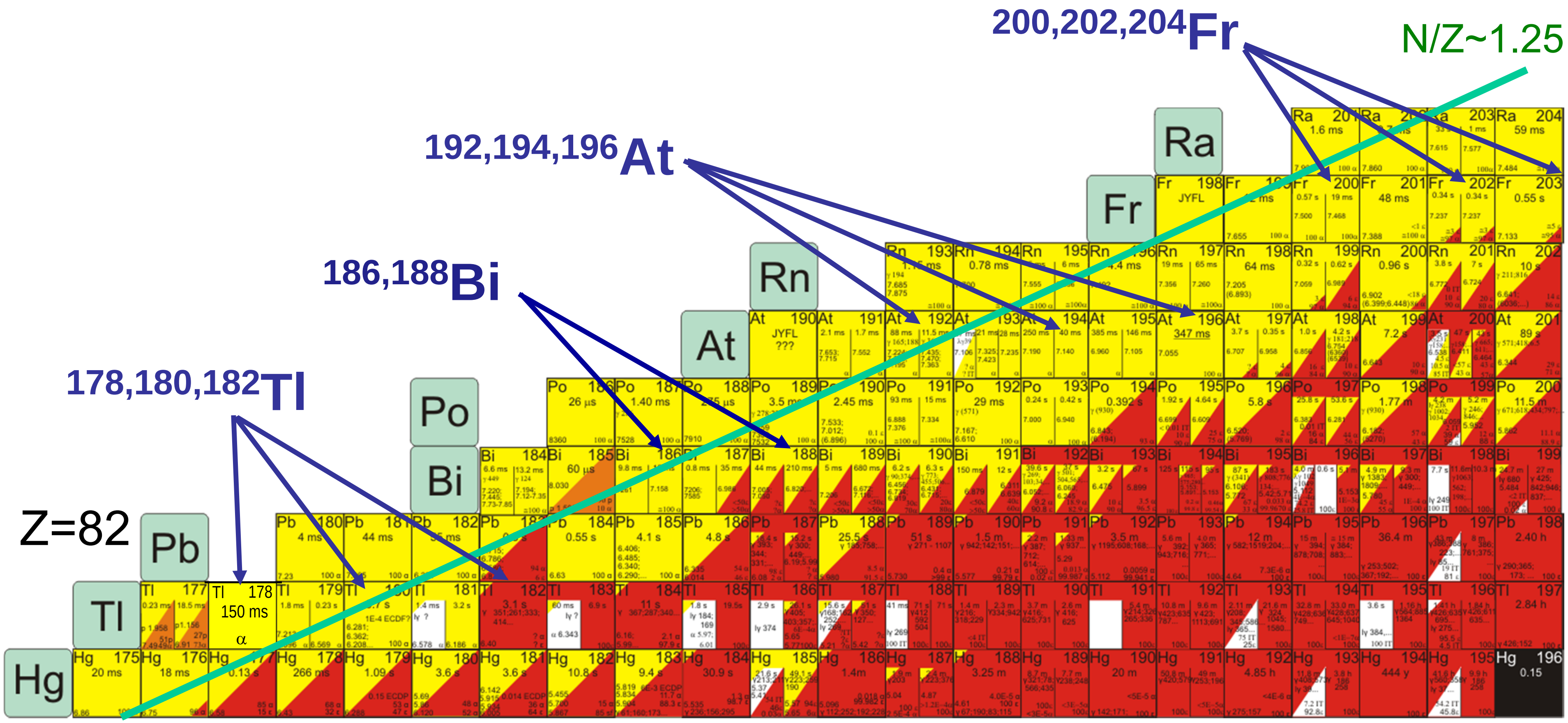
University of York, UK



10th ASRC Workshop. JAEA, 22rd March 2013

Collaboration

THE UNIVERSITY of York

A. Andreyev
V.Truesdale
R. Wadsworth
D. Jenkins
M. Vermeulen
C. Barton
M. Bentley

ISOLDE
CERN, Geneva

JAEA Tandem

JAEA

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Outlook

- Brief (experimental) review on low-energy fission
- Low-energy fission in “new” regions of the Nuclear Chart
- Beta Delayed Fission (βDF) – what it is and why?
- βDF ^{194,196}At, ^{202}Fr
- Further plans and ideas

Symmetric vs Asymmetric Fission

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

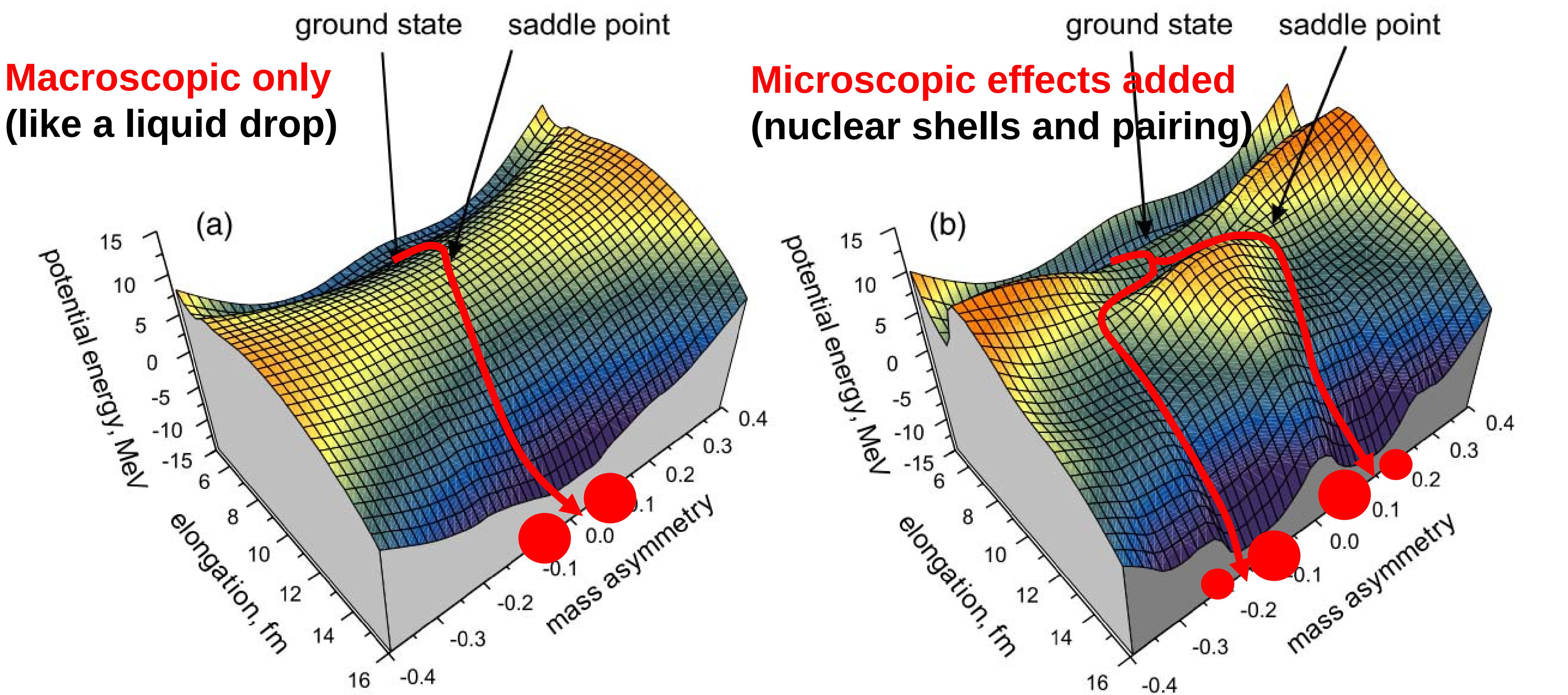
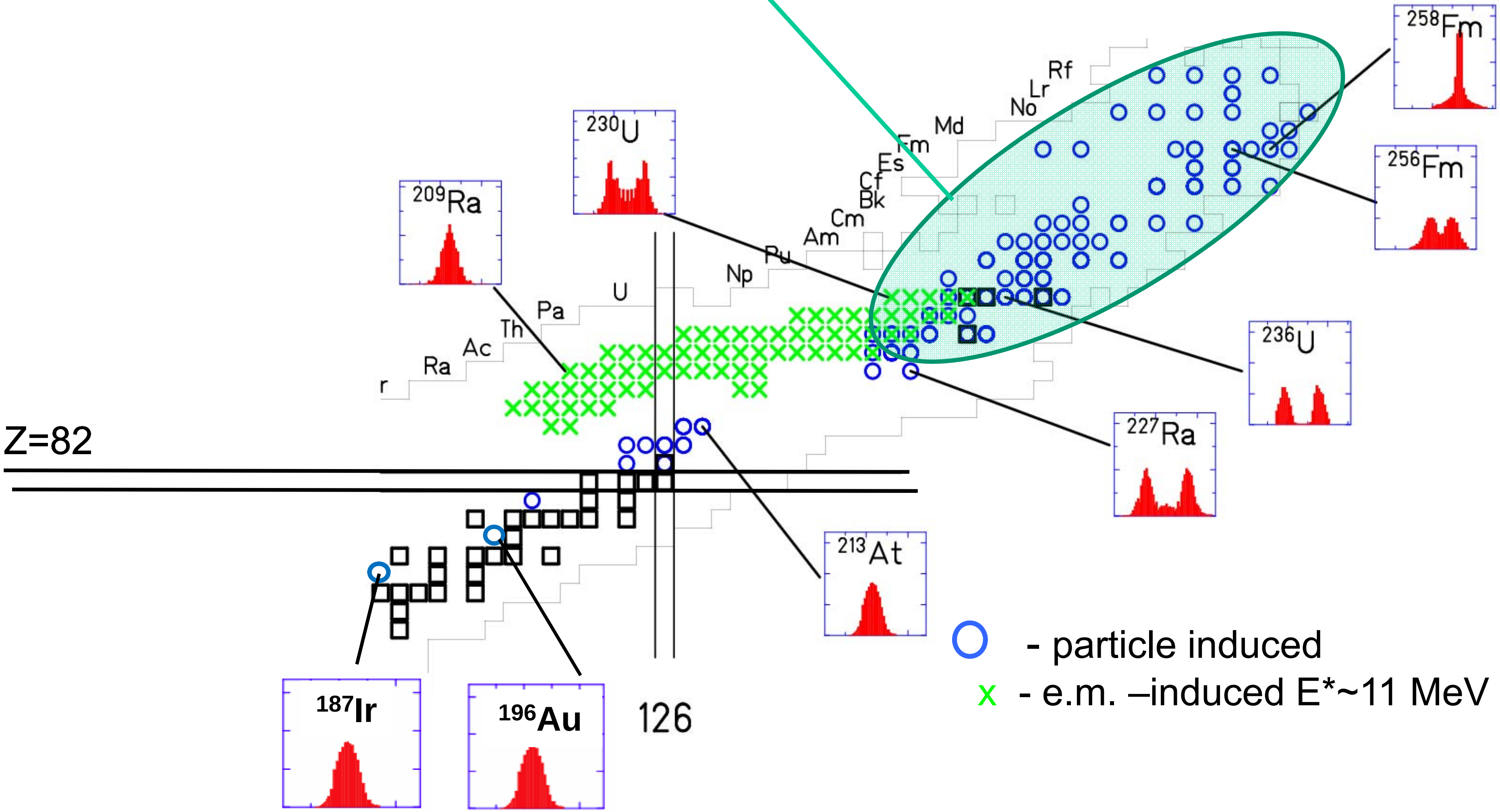


Figure 2. Macroscopic (a) and macro-microscopic (b) potential energy surface for the ^{238}U nucleus in the coordinates (R, η). The potential energy is obtained for $\delta = 0$ and $\varepsilon = 0.35$. The macroscopic part is normalized to zero for the spherical shape of the compound nucleus.

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

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



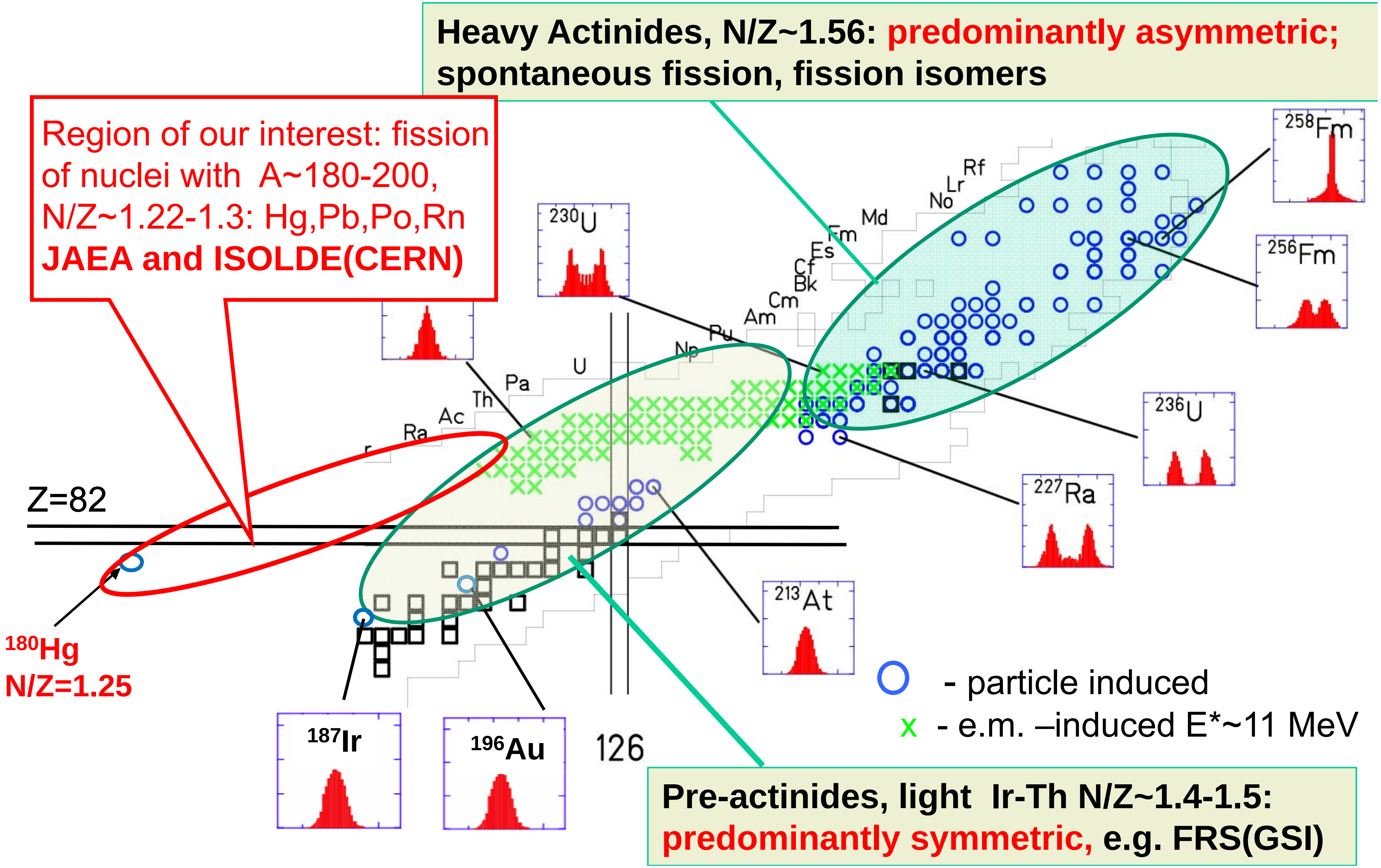
○ - particle induced

x - e.m. –induced E*~11 MeV

K.-H. Schmidt et al.

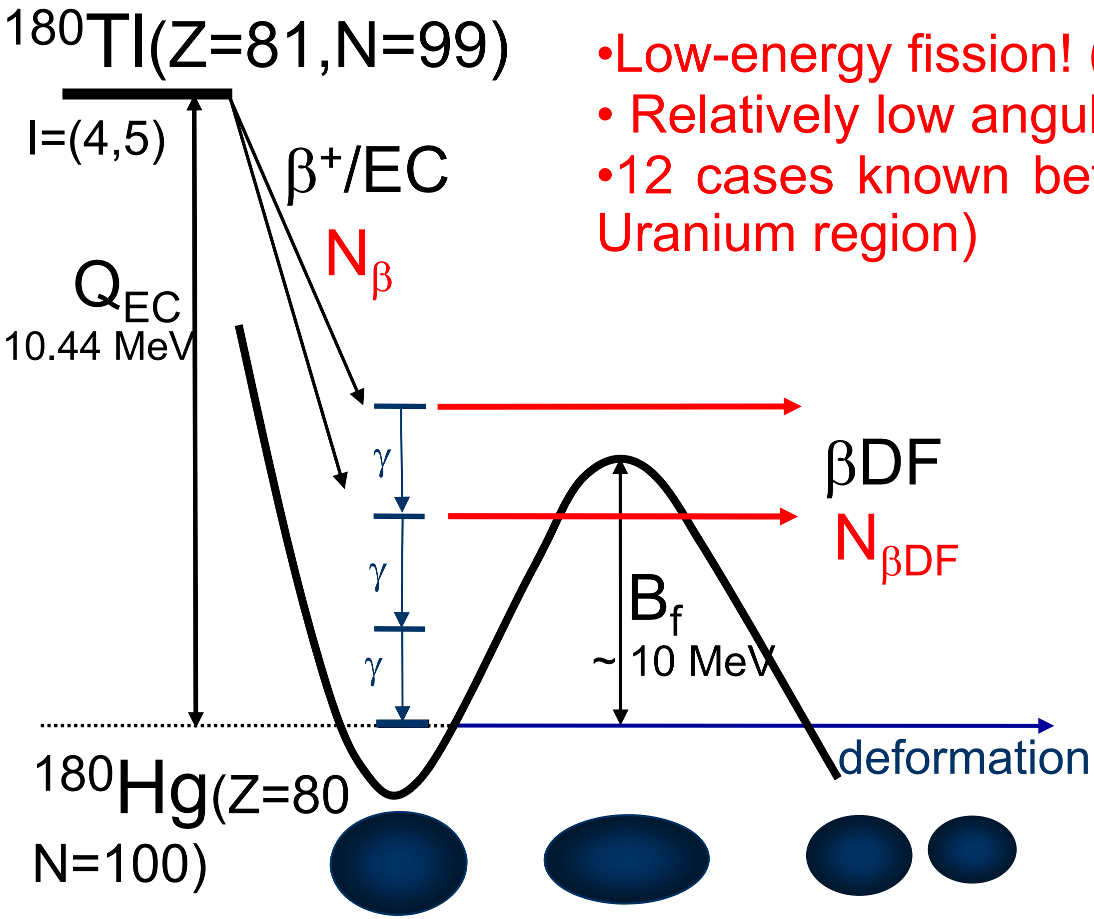
Experimental information on low-energy fission

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



Beta-Delayed Fission

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



- 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)

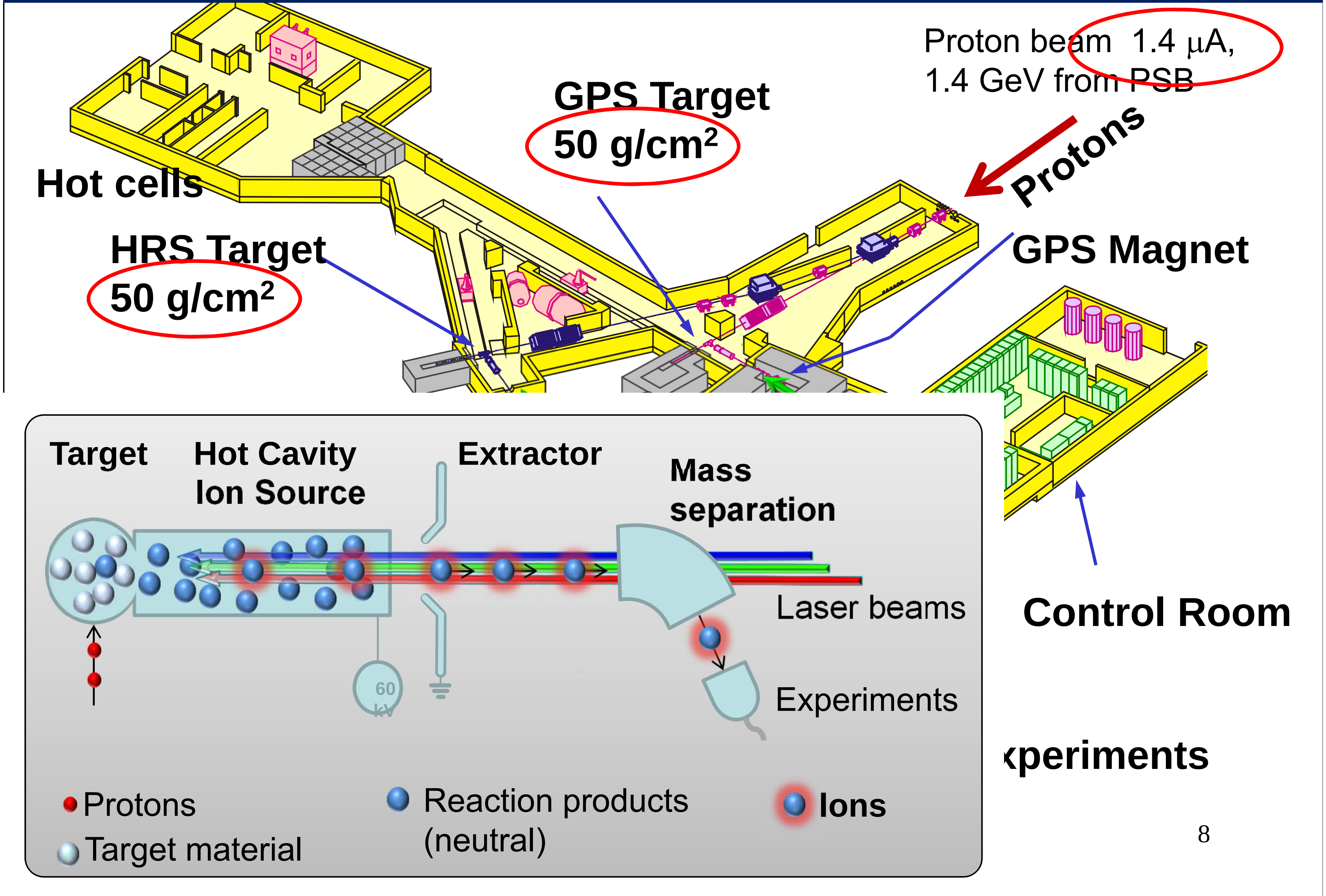
βDF branch

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

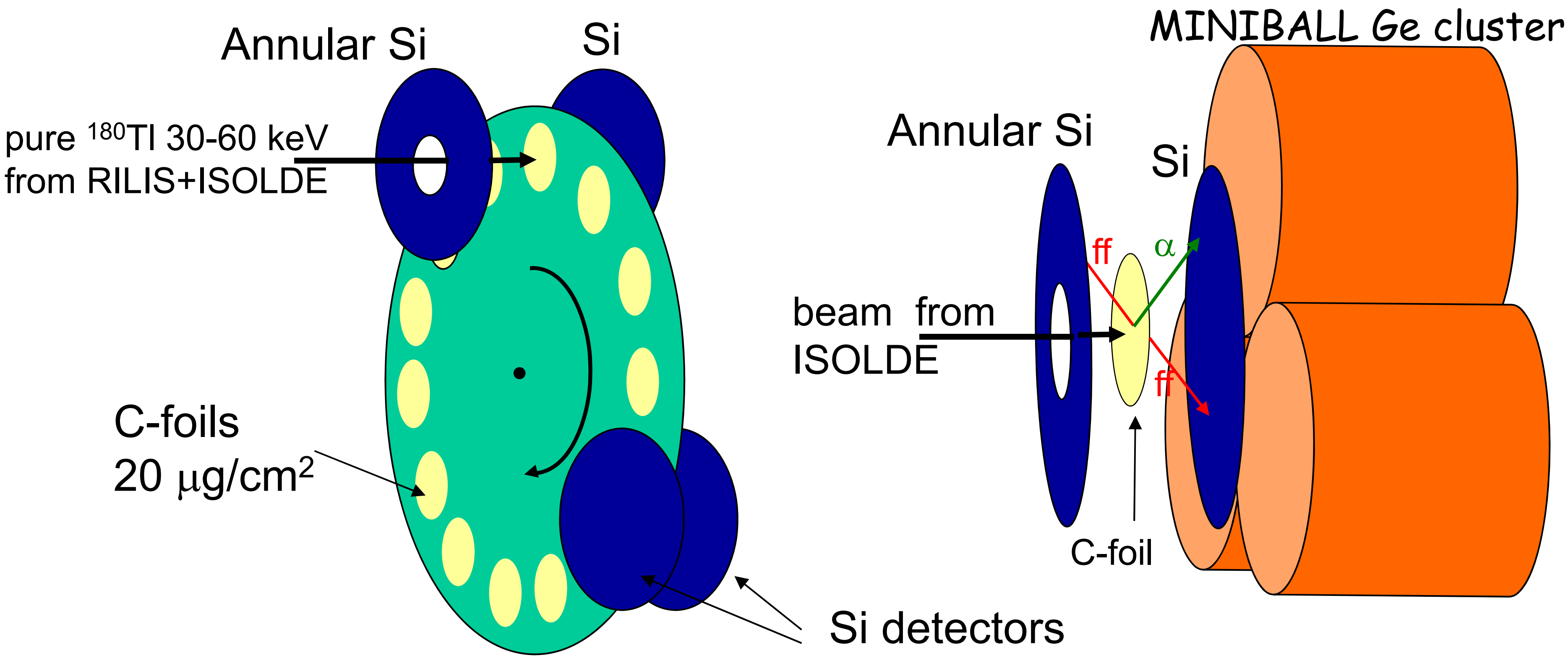
$P_{\beta DF}$ depends strongly on:

- Q_{EC} of the parent: the higher Q_{EC}, the larger the $P_{\beta DF}$
- B_f of the daughter: the lower B_f, the larger the $P_{\beta DF}$
- Actually, Q_{EC}-B_f and β-strength S_β are the most important parameters

Mass Separator ISOLDE

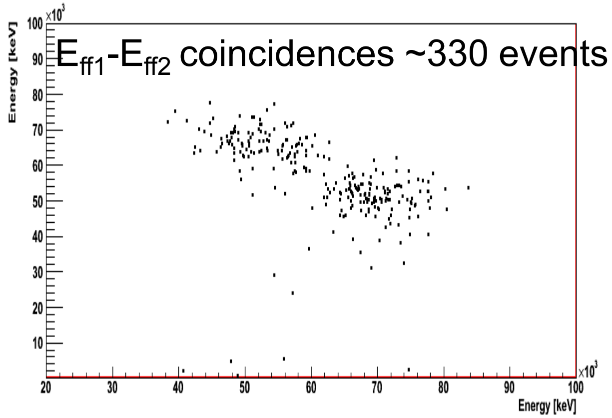


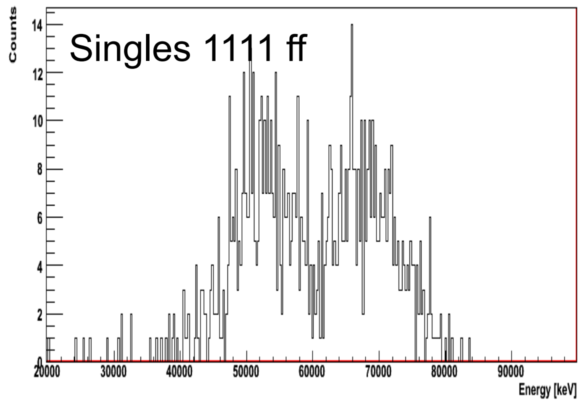
Detection system for βDF studies at ISOLDE

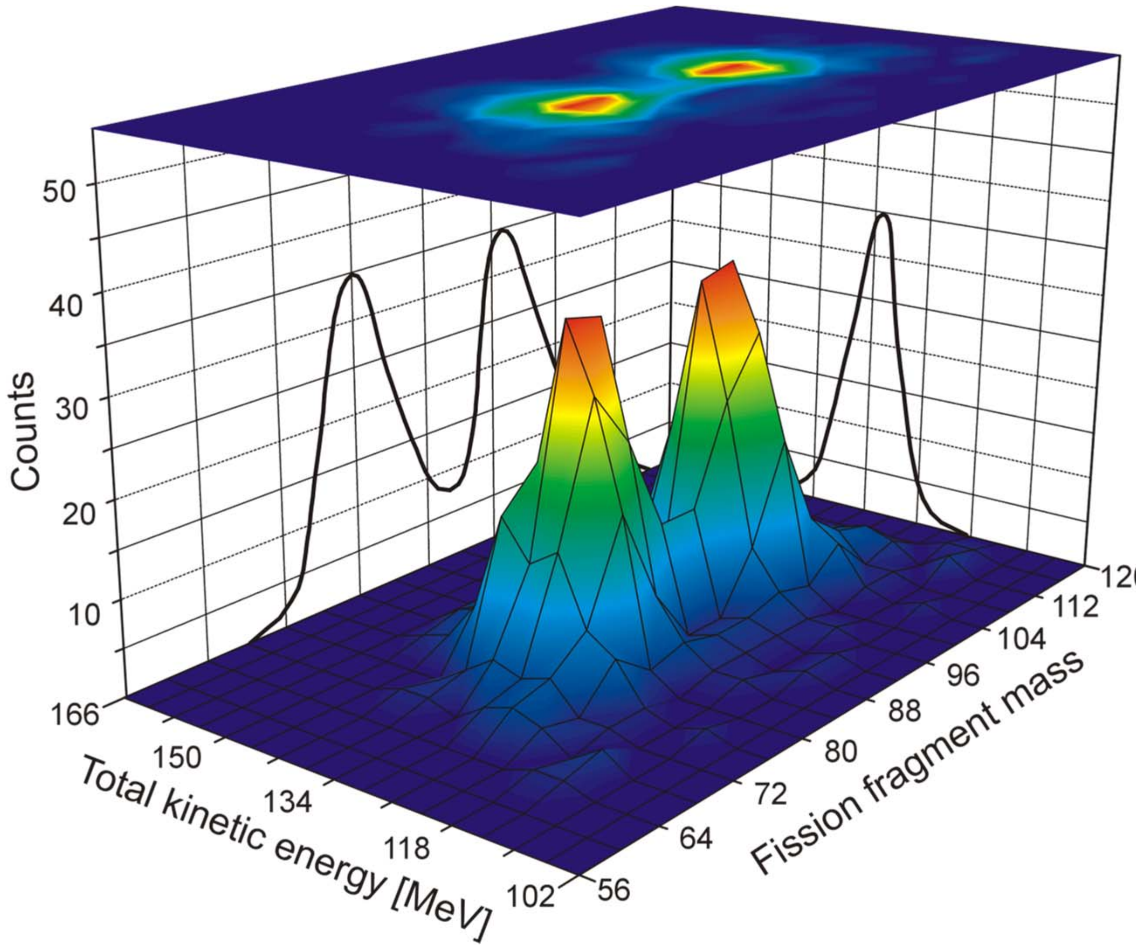


Energy/Mass distribution of fission fragments from ^{180}Hg

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



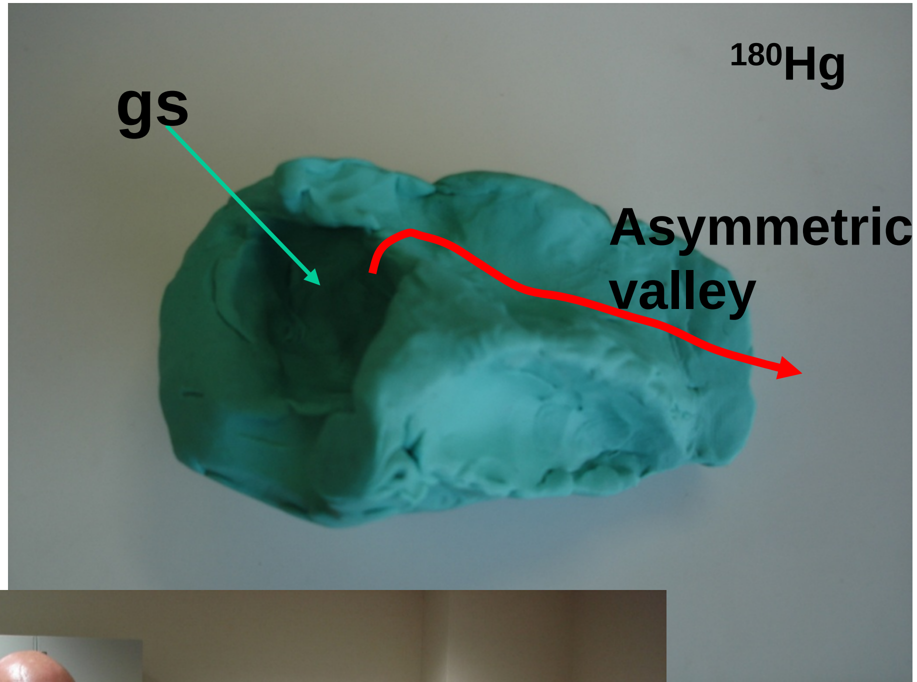


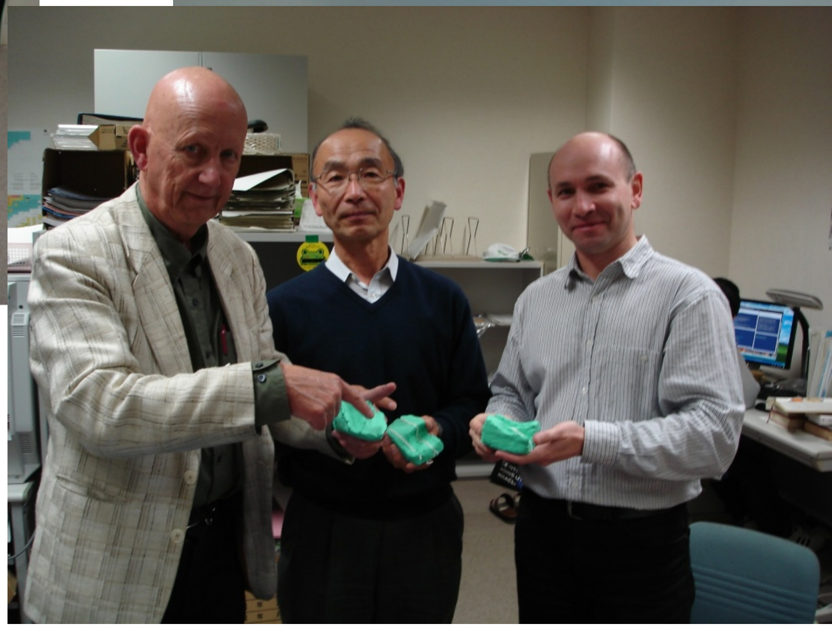


The most probable fission fragments are ^{100}Ru (N=56,Z=44) and ^{80}Kr (N=44,Z=36)

CLDM (P. Möller et al., yet unpublished)

CLDM: Clay Liquid Drop Model (circa 2008)





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]

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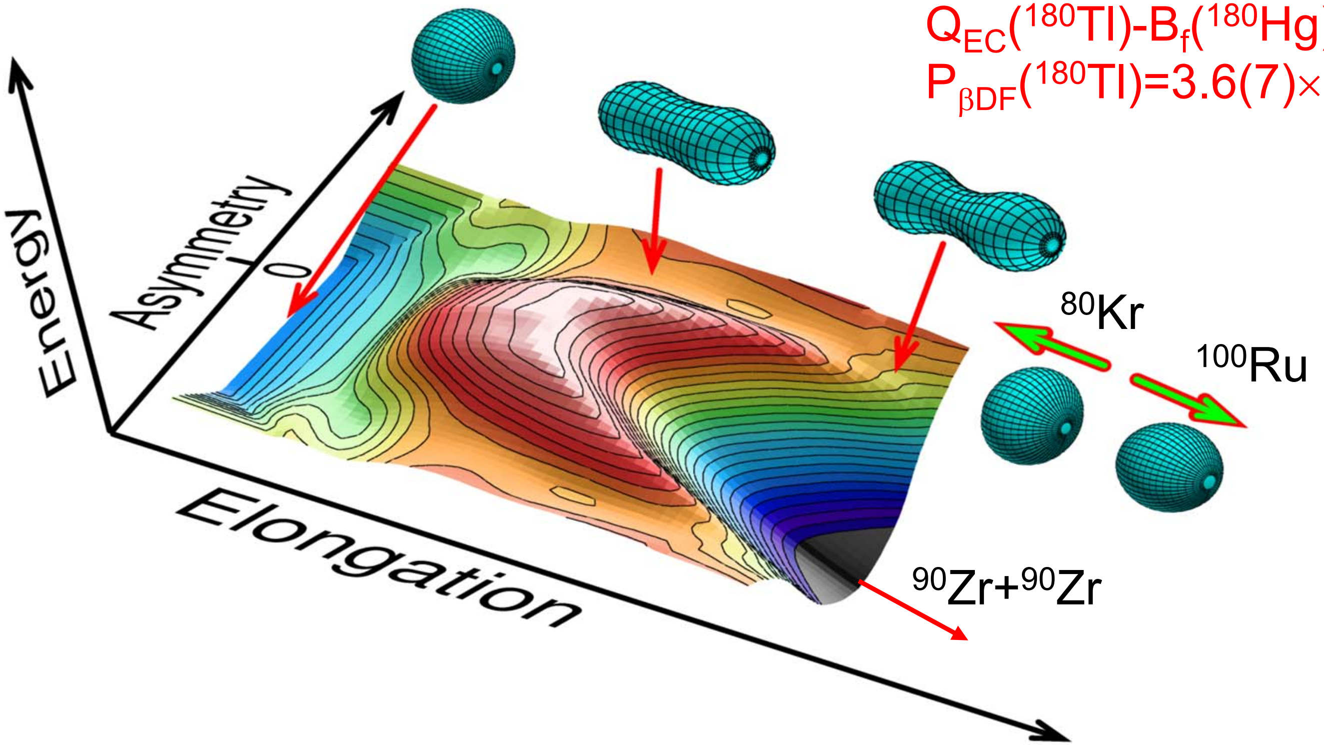
[2]*School of Engineering, University of the West of Scotland, Paisley, PA1 2BE, United Kingdom, and the Scottish Universities Physics Alliance (SUPA)*

$Q_{EC}(^{180}Tl)=E^*_{max}=10.44$ MeV
$Q_{EC}(^{180}Tl)-B_f(^{180}Hg)=0.63$ MeV
$P_{\beta DF}(^{180}Tl)=3.6(7)\times 10^{-5}$



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

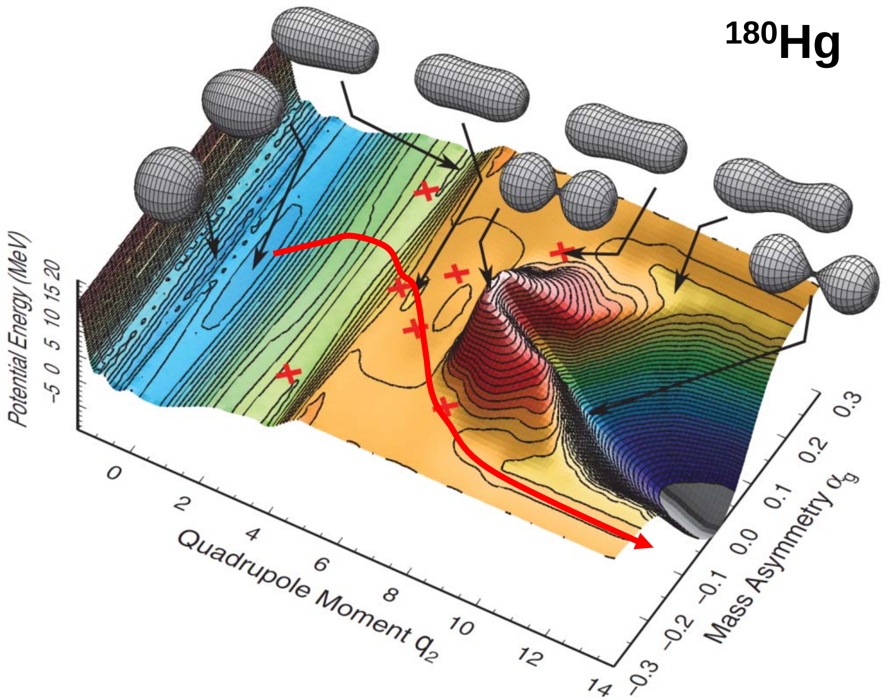
Two types of asymmetry: what's the difference?

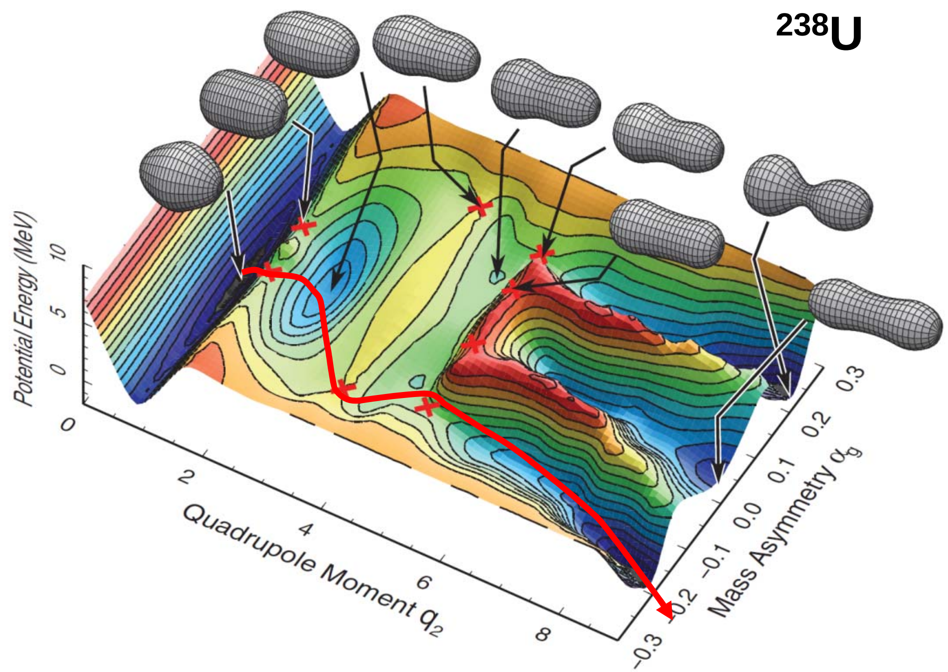
PHYSICAL REVIEW C **86**, 024610 (2012)

Contrasting fission potential-energy structure of actinides and mercury isotopes

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

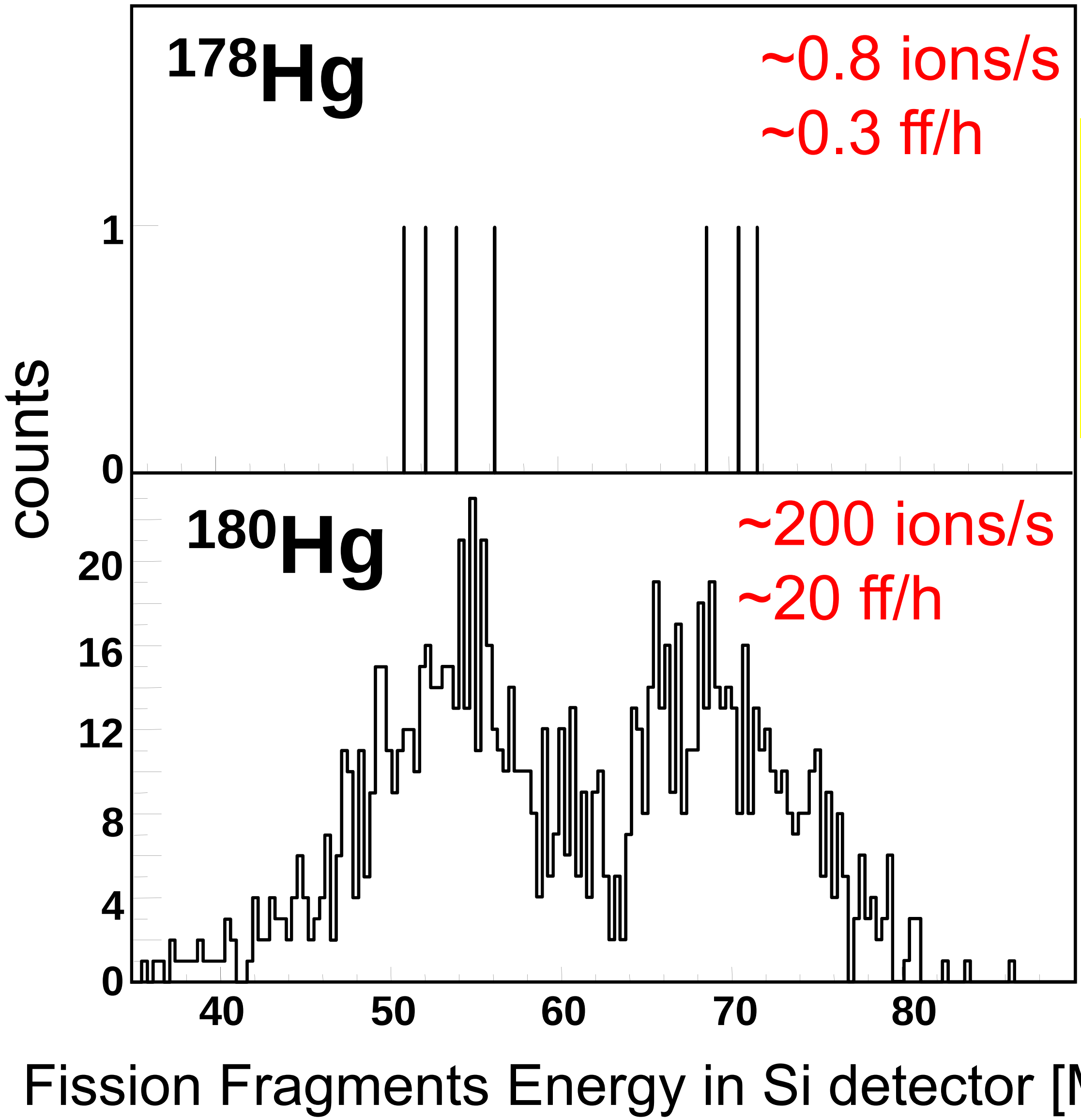
Conclusions: The mechanism of asymmetric fission must be very different in the lighter proton-rich mercury isotopes compared to the actinide region and is apparently unrelated to fragment shell structure. Isotopes lighter than ^{192}Hg have the saddle point shielded from a deep symmetric valley by a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





βDF of ^{178}Tl @ISOLDE

V. Liberati et al (submitted to PRC, 2013)



$Q_{EC}(^{178}Tl)=E^*_{max}(^{178}Hg)=11.14$ MeV

$Q_{EC}(^{178}Tl)-B_f(^{178}Hg)=1.82$ MeV

At this level of statistics: also asymmetric fission of ^{178}Hg, with mass split similar to ^{180}Hg

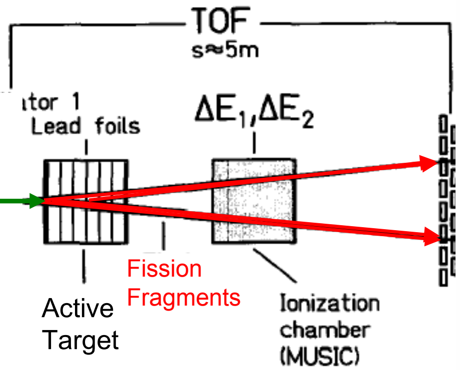
$E^*_{max}(^{180}Hg)=10.44$ MeV

Low-energy Electromagnetically-Induced Fission in-flight at FRS(GSI), K.-H. Schmidt et al.

- Primary beam ^{238}U at 1 AGeV
- 1 g/cm^2 primary target
- Separated RIBs from FRS
- Pb secondary target
- **E*~11-12 MeV (GDR)**

Identified RIB from FRS

e.g. **^{204}Rn**



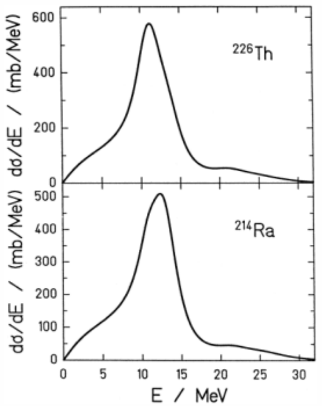


Fig. 16. Calculated excitation-energy distributions of ^{226}Th and ^{214}Ra used as secondary projectiles after electromagnetic excitations in a lead target at 430 A MeV.

K.-H. Schmidt et al. / Nuclear Physics A 665 (2000) 221–267

^{204}Rn@FRS symmetric (E*~12 MeV)

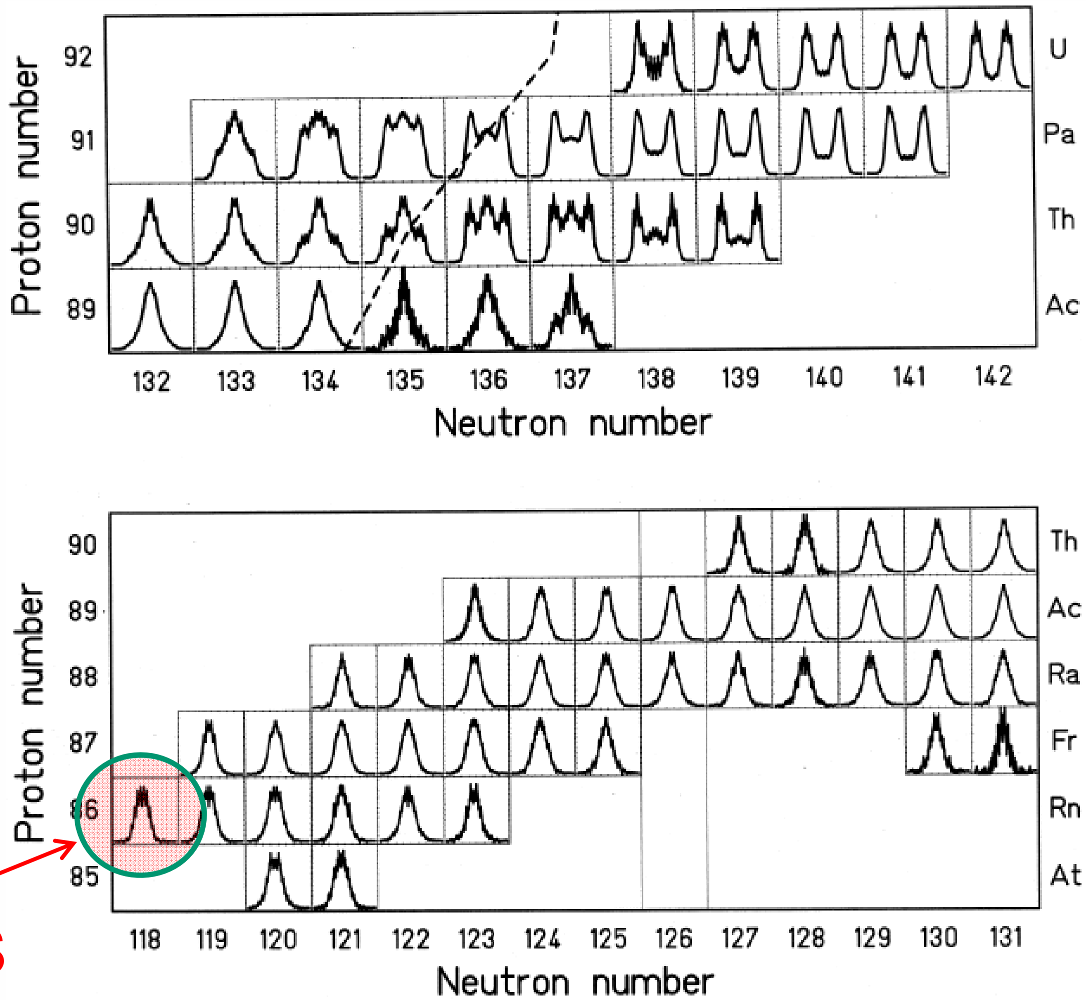
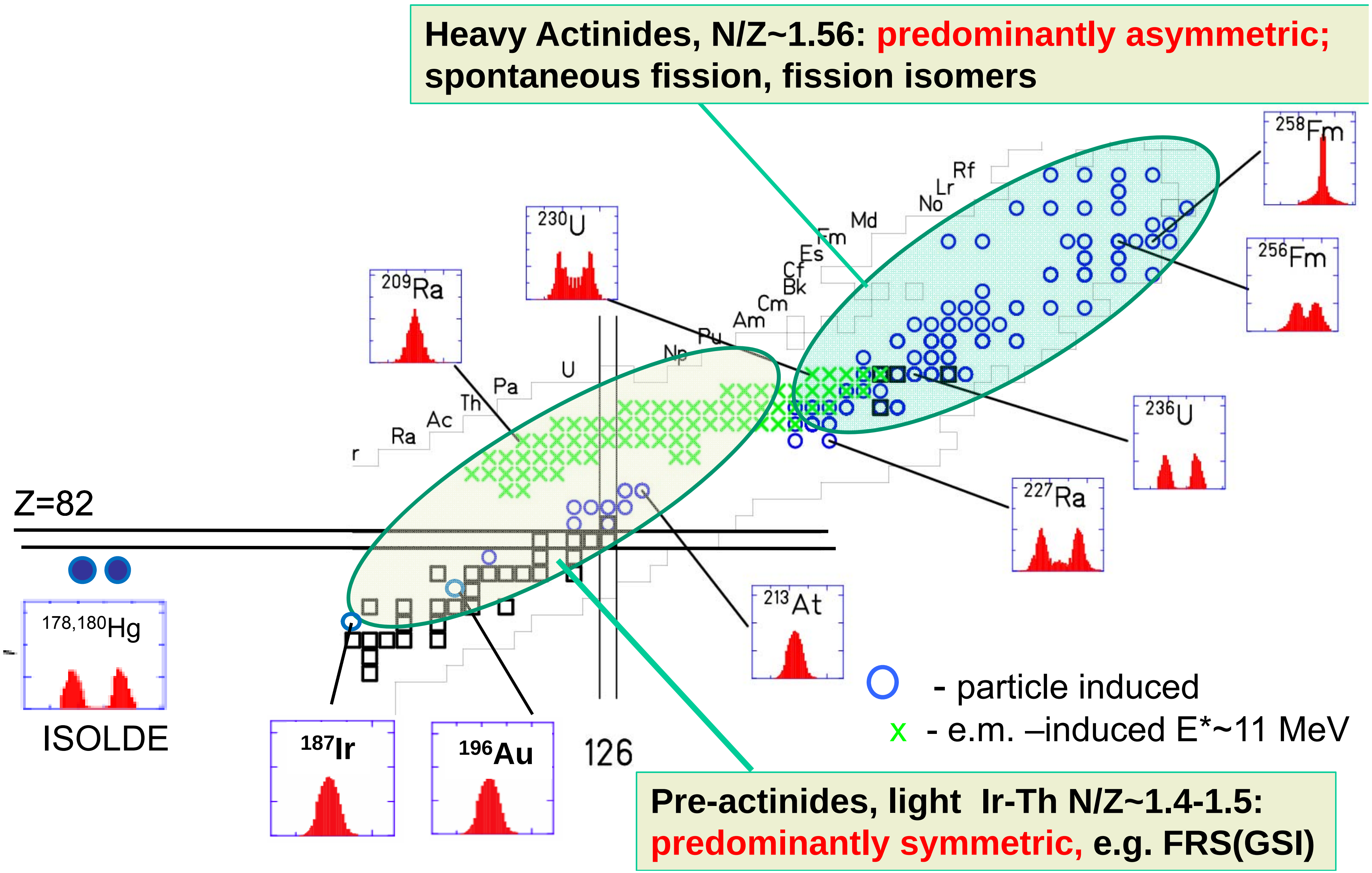
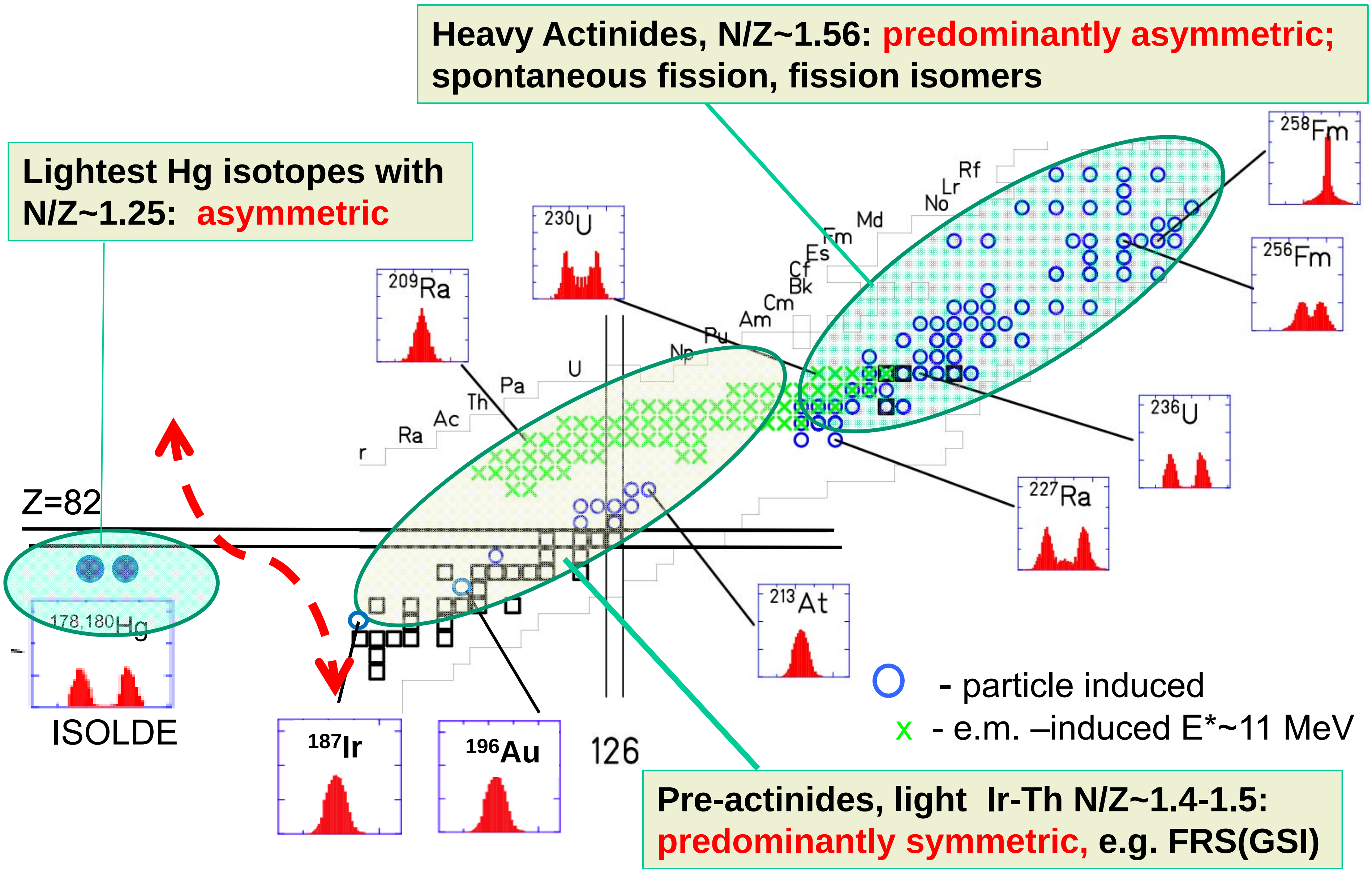


Fig. 20. Measured fission-fragment nuclear-charge distributions in the range $Z=24$ to $Z=65$ from ^{221}Ac to ^{234}U (upper part) and from ^{205}At to ^{221}Th (lower part) in electromagnetic-induced fission are shown on a chart of the nuclides. The dashed line in the upper part indicates the transition from symmetric to asymmetric fission as predicted by Möller [103] who calculated the stability of the saddle-point configuration against mass-asymmetric deformations. Nuclei on the right-hand side of this line were expected to predominantly show asymmetric fission, while nuclei on the left-hand side were expected to show symmetric fission with higher probability.

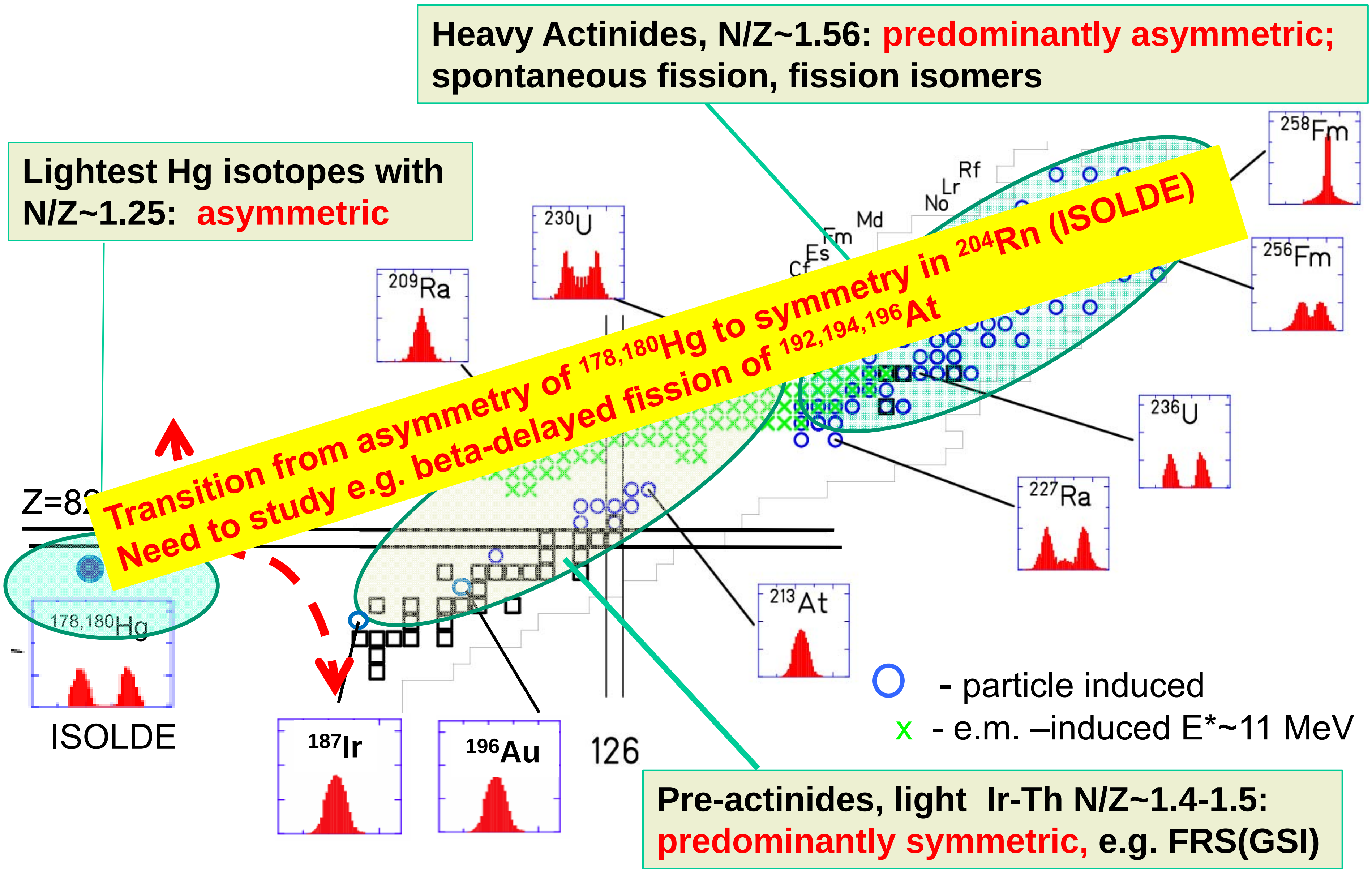
New Region of Asymmetric Fission



New Region of Asymmetric Fission



From Asymmetry to Symmetry



Fission of Proton-rich nuclei with A~180-200

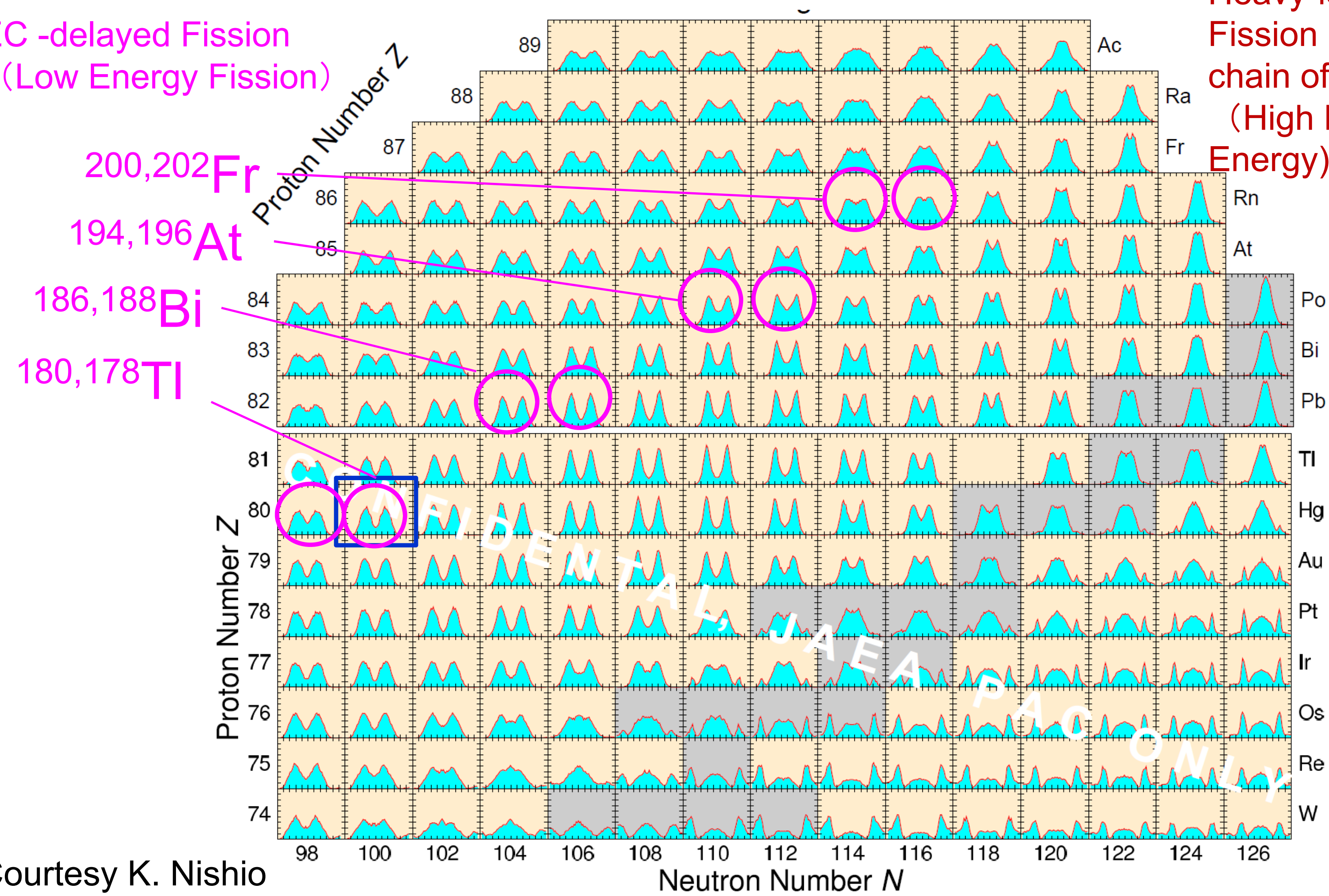
Courtesy P. Moller (LANL) and J. Randrup (LBNL), 5th ASRC workshop on Fission, Tokai 2012

CERN-ISOLDE

EC -delayed Fission
(Low Energy Fission)

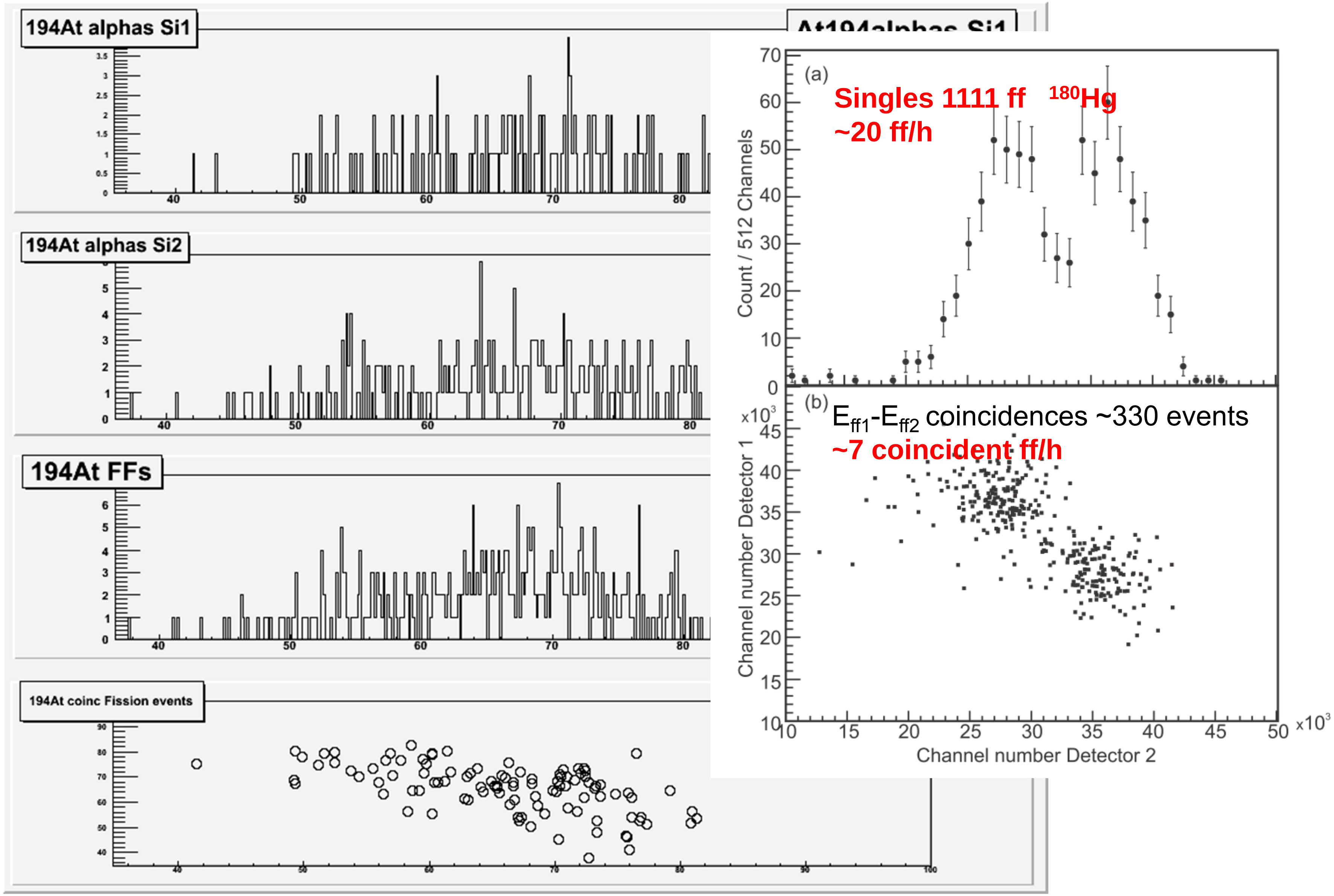
JAEA tandem

Heavy-ion induced Fission Mercury chain of isotopes
(High Excitation Energy)

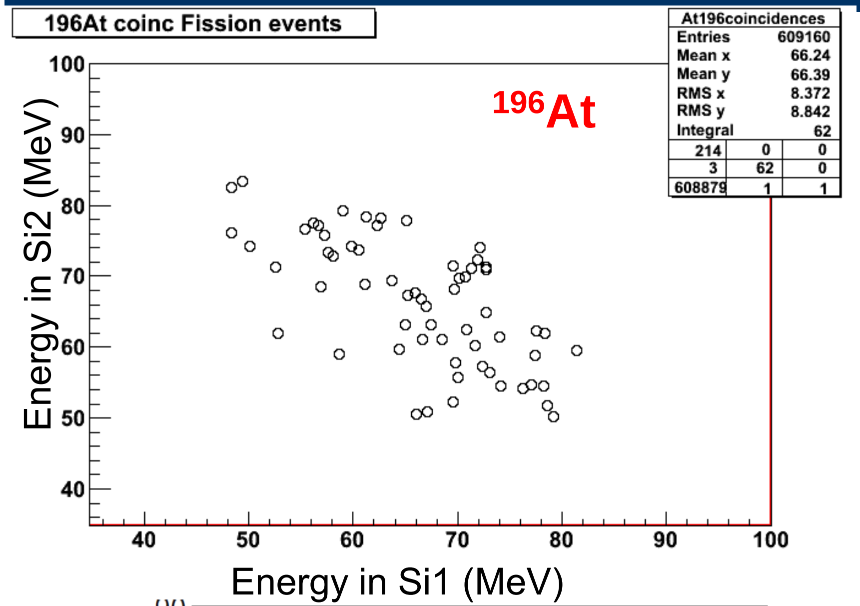


Courtesy K. Nishio

IS534, 9-14 May 2012: Mass Distributions Measurements of $^{194,196}Po$ via βDF of $^{194,196}At$



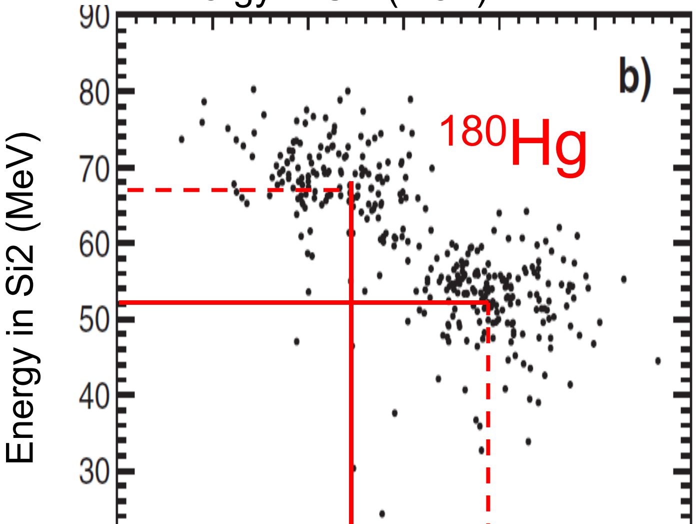
IS534, 9-14 May 2012: Mass Distributions Measurements of ^{194,196}Po via βDF of ^{194,196}At

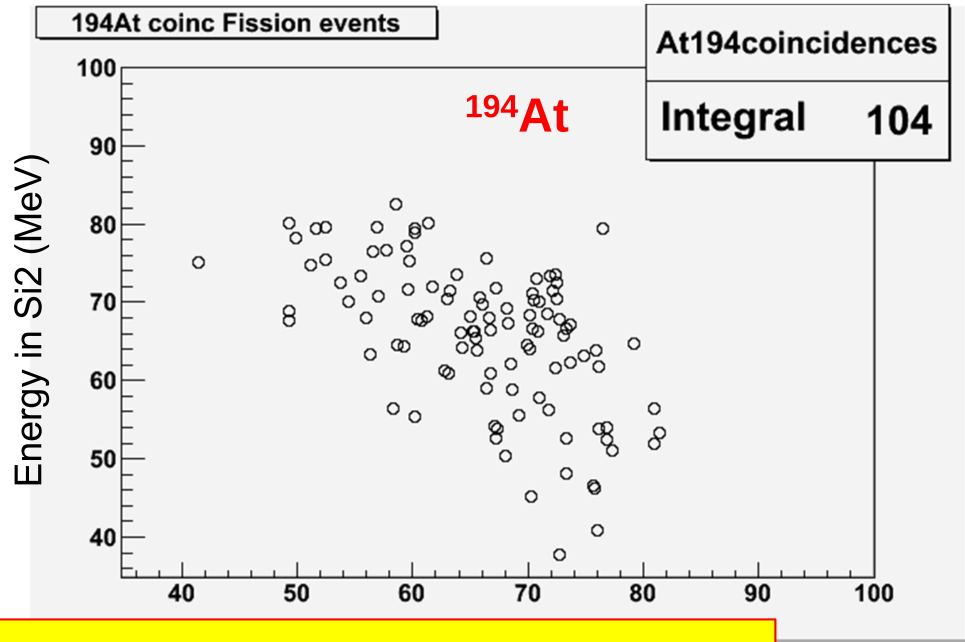


βDF of ^{194}At:

singles: 40 ff/hour

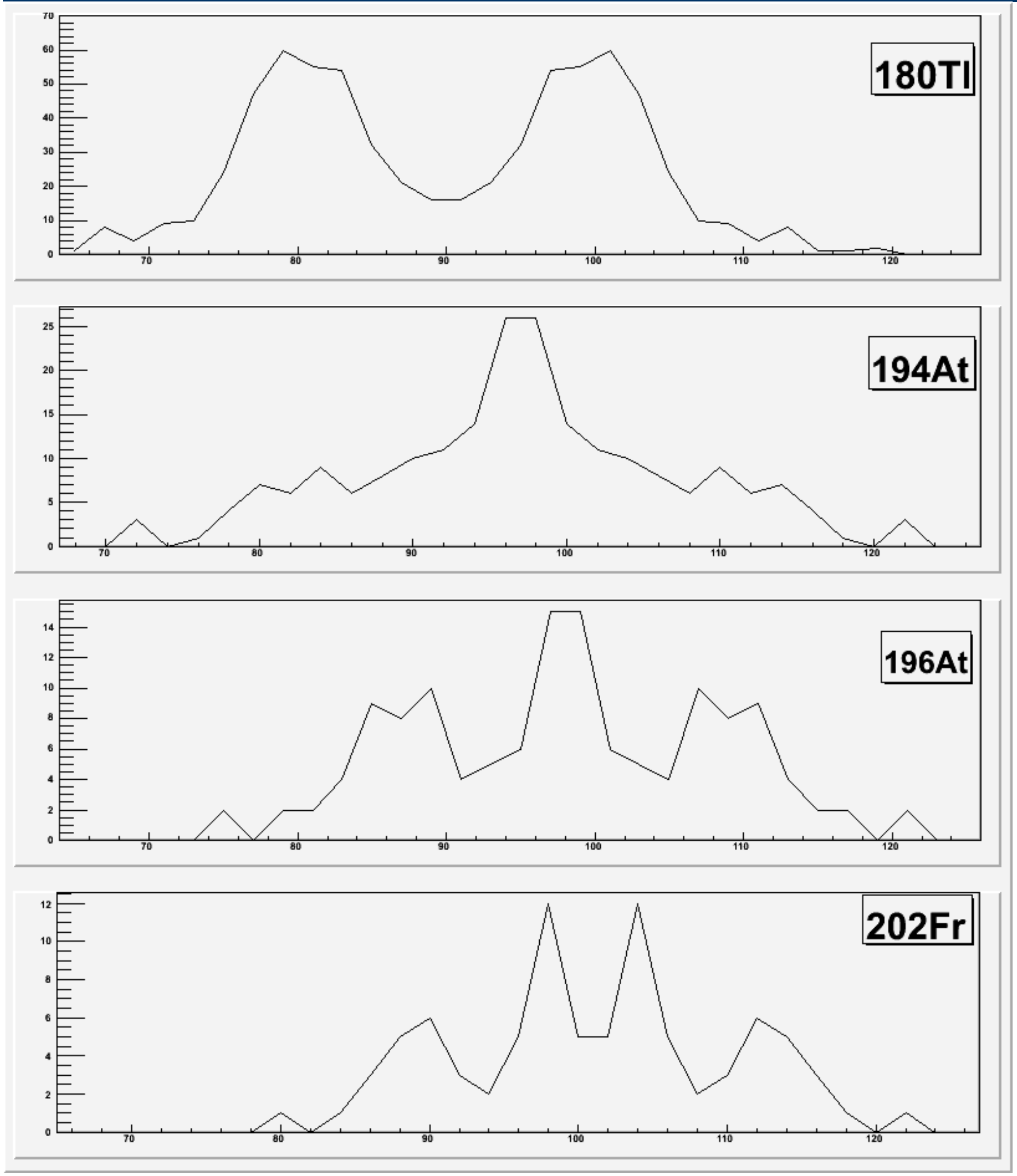
Coincidences: ~10 ff/hour





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

May and June 2012: Mass Distributions Measurements via βDF of $^{194,196}At$ and $^{200,202}Fr$



Fission Fragment Mass

Gradual transition from asymmetry in ^{180}Tl to **a mixture of symmetric and asymmetric** in ^{196}At and ^{202}Fr!

Recent Theory Efforts for the Hg's chain

•Several theory groups have initiated their calculations for the long chain of Hg isotopes

• Must account for asymmetry of $^{178,180}Hg$ (data by Andreyev et al.)

•Must account for 'apparent symmetry' of ^{198}Hg (data by Itkis et al.)

•Need excitation-energy dependence (as higher-energy data start to become available – JAEA experiments by Nishio, Andreyev et al.)

Some examples: '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

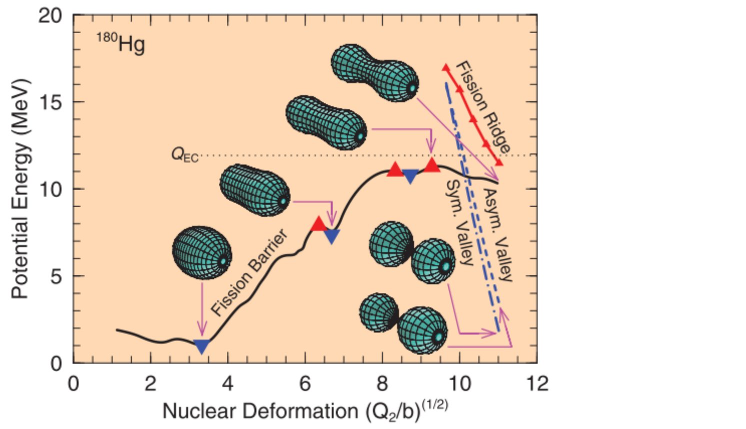
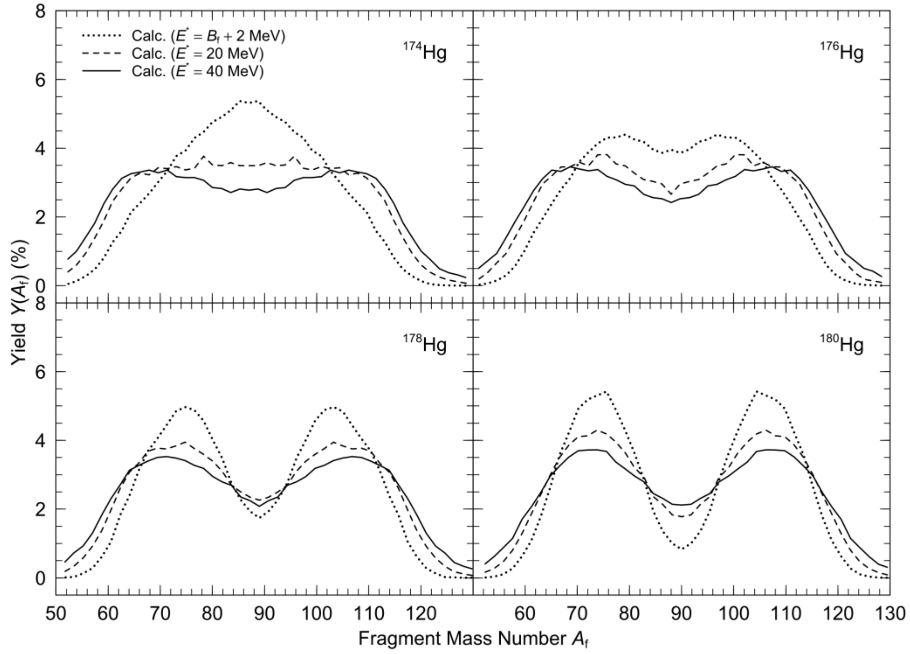
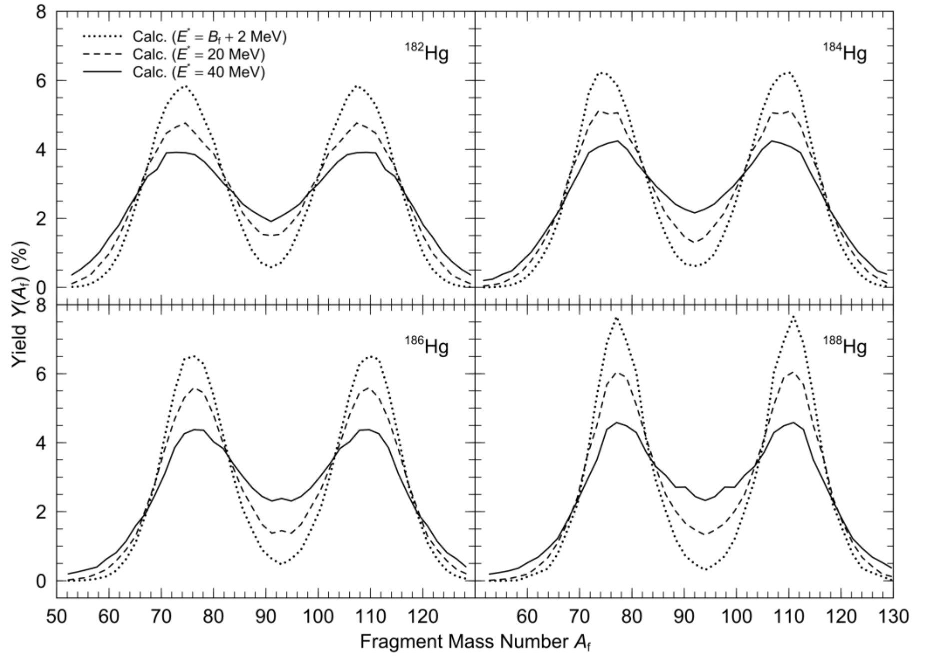


FIG. 4. (Color online) Minima, saddles, major valleys, and ridges in the 5D potential-energy surface of ^{180}Hg (see text). At the last plotted point on the fission barrier, $(Q_2/b)^{(1/2)} \approx 11$, the asymmetry of the shape is $A_H/A_L = 108/72$.





Some examples: 'Improved Scission-Point Model'

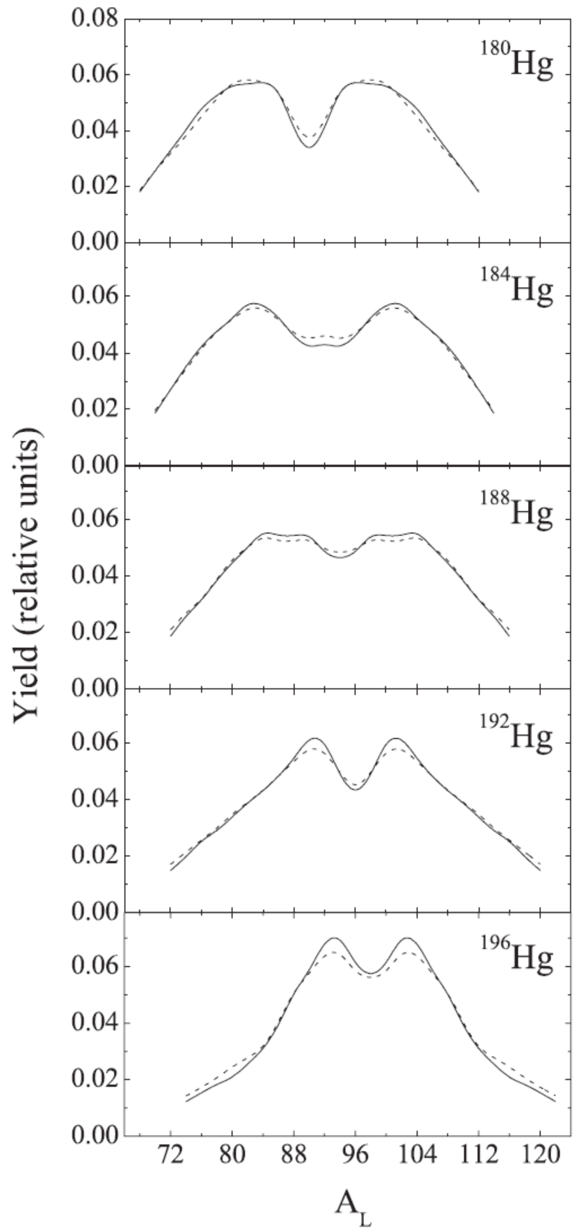
PHYSICAL REVIEW C **86**, 044315 (2012)

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

Also, J.-L. Sida et al. – private communication

Some examples: '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]

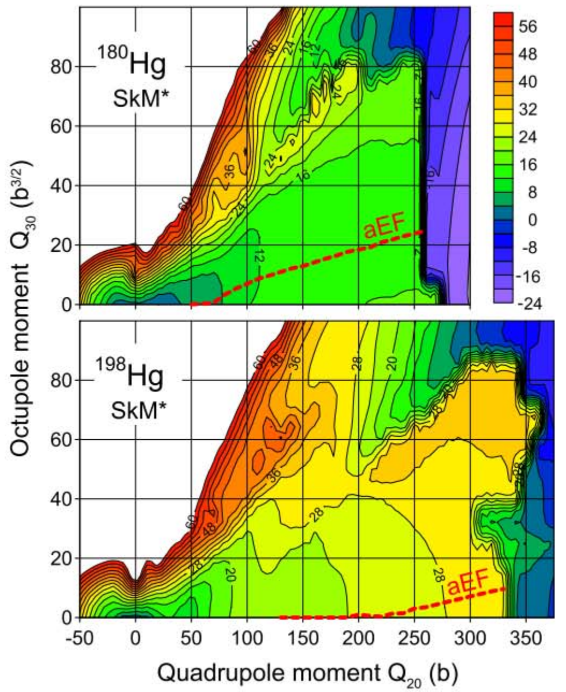


FIG. 2. (Color online) PES for ^{180}Hg (top) and ^{198}Hg (bottom) in the plane of collective coordinates $Q_{20} - Q_{30}$ in HFB-SkM*. The aEF fission pathway corresponding to asymmetric elongated fragments is marked. The difference between contour lines is 4 MeV. The effects due to triaxiality, known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

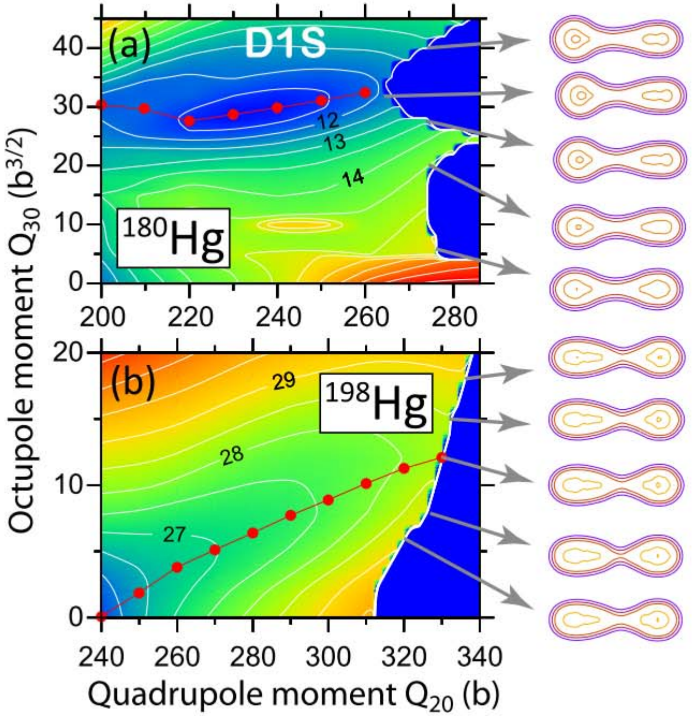


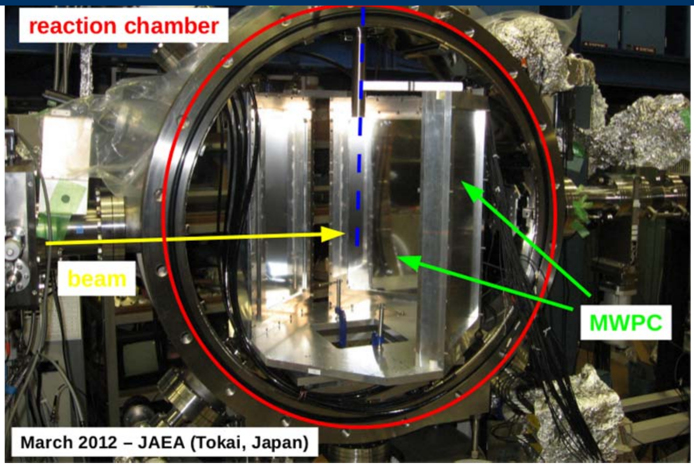
FIG. 3. (Color online) PES in HFB-D1S for ^{180}Hg (top) and ^{198}Hg (bottom) in the (Q_{20}, Q_{30}) plane in the pre-scission region of aEF valley. The symmetric limit corresponds to $Q_{30} = 0$. The aEF valley and density profiles for pre-scission configurations are indicated. The difference between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

Fusion- Fission Reactions at JAEA's tandem

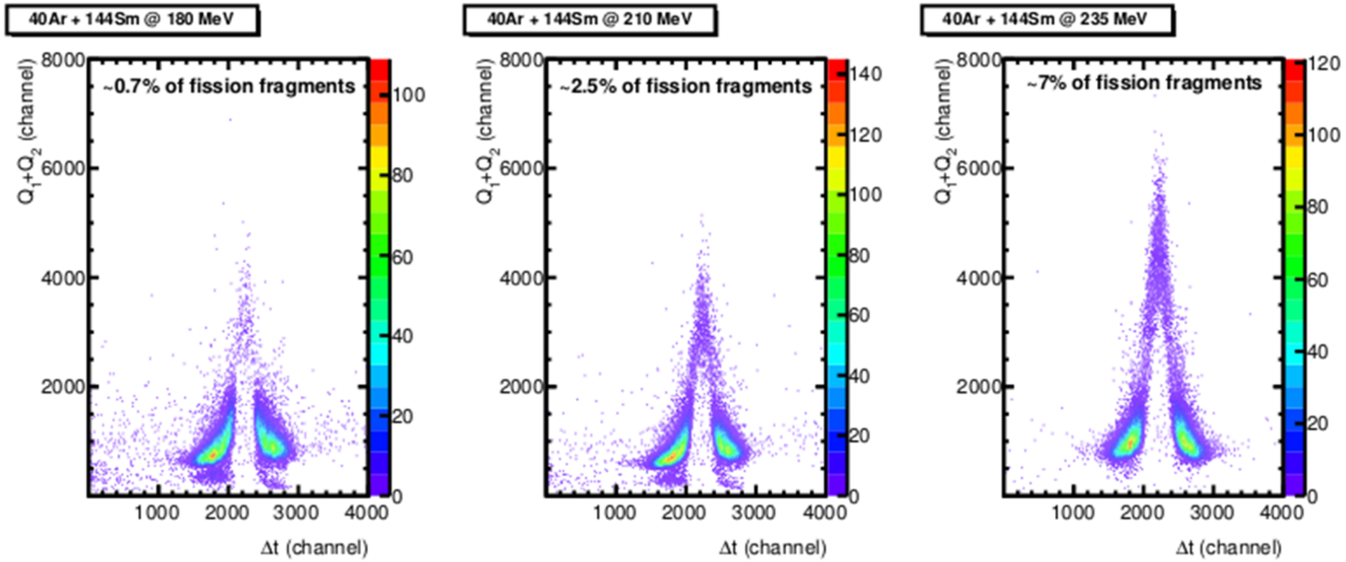
New experiment at JAEA (March-April 2012)

$^{36-40}Ar + ^{144}Sm \rightarrow ^{180-184}Hg$
$^{36-40}Ar + ^{154}Sm \rightarrow ^{190-194}Hg$
$^{36-40}Ar + ^{142}Nd \rightarrow ^{178-182}Pt$
$^{90}Zr + ^{90}Zr \rightarrow ^{180}Hg$

Ebeam from 160 to 235 MeV



New reaction chamber, larger MWPC
new electronics (time-stamping)



Analysis in progress

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

Invited review in Reviews of Modern Physics

Submitted: Jan. 2013

March 2013: got very positive referees reports

Colloquium: Beta-delayed fission of atomic nuclei

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This Colloquium reviews the studies of exotic type of low-energy nuclear fission, the β-delayed fission (βDF). 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

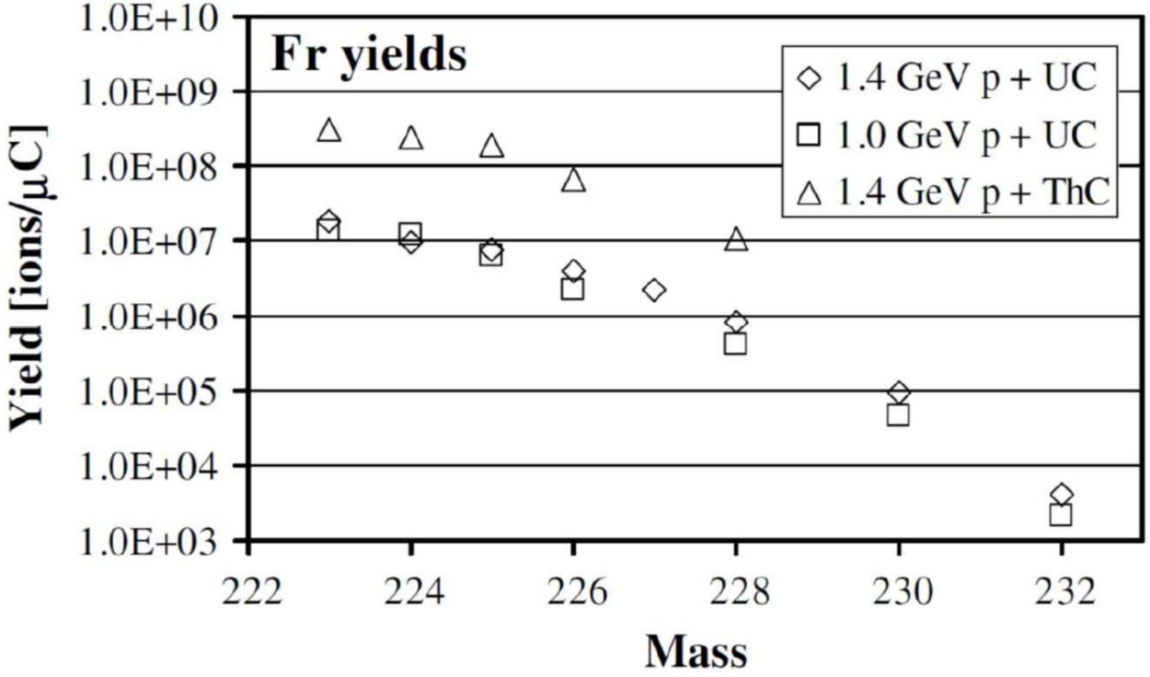
Known Beta-delayed fission nuclei

Isotope	$T_{1/2}$	$Q_{EC}-B_f$ [MeV]	Production[&], Separation, Detection	$P_{\beta DF}$	Observables*	References
β^+/EC –delayed fission in the neutron-deficient isotopes						
^{178}**Tl**	252(20) ms	1.82	SR,IS,WM	$\mathbf{1.5(6)\times10^{-3}}$	Z,A,T,KE,TKE,MD,GF	(Liberati *et al.*, 2013)
^{180}**Tl**	1.09(1) s	0.63	SR,IS,WM	$\mathbf{3.2(2)\times10^{-5}}$	Z,A,T,KE,TKE,MD,GF	(Elseviers *et al.*, 2013)
	$0.97^{+0.09}_{-0.08}$ s		FE,NS,MF	$\sim3\times10^{-(7\pm1)}$	T,EXF	(Lazarev *et al.*, 1987, 1992)
^{186m1,m2}Bi	9.8(4), 14.8(8) ms[#]	2.09	FE,RS,Si/Ge	$7.6\times10^{-2,e}$	T,EXF,KE,GF	(Lane *et al.*, 2013)
^{188m1,m2}Bi	$\sim$0.3 s[c]	0.51	FE,NS,MF	$3.4\times10^{-4,a,c}$	T,EXF	(Lazarev *et al.*, 1992)
	265(10), 60(3) ms[#]		FE,RS,Si/Ge	$(0.16-0.48)\times10^{-2,f}$	T,EXF,KE,GF	(Lane *et al.*, 2013)
^{192m1,m2}At	88(6), 11.5(6) ms[#]	2.09	FE,RS,Si/Ge	$(7-35)\times10^{-2}$	T,EXF,KE,GF	(Andreyev *et al.*, 2013)
^{194m1,m2}At	310(8), 253(10) ms[#]	-0.04	FE,RS,Si/Ge	$\sim(0.8-1.6)\times10^{-2}$	T,EXF,KE,GF	(Andreyev *et al.*, 2013)
			SR,IS,WM		Z,A,T,KE,TKE,MD,GF	(Andreyev *et al.*, 2012)
^{196}At	$0.23^{+0.05}_{-0.03}$ s	-1.19	FE,NS,MF	$8.8\times10^{-4,a}$	T,EXF	(Lazarev *et al.*, 1992)
			SR,IS,WM		Z,A,T,KE,TKE,MD,GF	(Andreyev *et al.*, 2012)
^{200}Fr	49(4) ms[#]	0.82	SR,IS,WM		Z,A,T,KE,TKE,MD,GF	(Andreyev *et al.*, 2011)
^{202m1,m2}Fr	0.30(5), 0.29(5) s[#]	-1.17	SR,IS,WM		Z,A,T,KE,TKE,MD,GF	(Andreyev *et al.*, 2011)
^{228}**Np**	61.4(14) s	-0.87	FE,RC,MG	$\mathbf{2.0(9)\times10^{-4}}$	Z,T,KE,TKE,MD,GF	(Kreek *et al.*, 1994a)
	60(5) s		FE,NS,MF		T,EXF	(Kuznetsov *et al.*, 1966)
^{232}**Am**	1.31(4) min	1.65	FE,RC,MG	$\mathbf{6.9(10)\times10^{-4}}$	Z,T,KE,TKE,MD,GF	(Hall *et al.*, 1990a)
	55(7) s		FE,NS,Si	$(1.3^{+4}_{-0.8})\times10^{-2}$	T,KE	(Habs *et al.*, 1978)
	1.40(25) min		FE,NS,MF	6.96×10^{-2}	T,EXF	(Kuznetsov *et al.*, 1967)
^{234}**Am**	2.32(8) min	0.29	FE,RC,MG	$\mathbf{6.6(18)\times10^{-5}}$	Z,T,KE,TKE,MD,GF	(Hall *et al.*, 1989a, 1990b)
	2.6(2) min		FE,NS,MF	$\sim6.95\times10^{-5}$	T,EXF	(Kuznetsov *et al.*, 1967)
^{238}**Bk**	144(5) s	-0.15	FE,RC,MG	$\mathbf{4.8(20)\times10^{-4}}$	Z,T,KE,TKE,MD,GF	(Kreek *et al.*, 1994b)
^{240}**Bk**	4.2(8) min	-1.99	FE,NS,MF	$\mathbf{(1.3^{+1.8}_{-0.7})\times10^{-5}}$	T	(Galeriu, 1983)
	5(2) min		FE,NS,MF	$1\times10^{-5,b}$	T	(Gangrsky *et al.*, 1980)
^{242}**Es**	11(3) s	-0.94	FE,RC,MG	$\mathbf{0.6(2)\times10^{-2}}$	Z,T,KE,TKE,MD	(Shaughnessy *et al.*, 2000)
	5 – 25 s		FE,RS,Si	$1.4(8)\times10^{-2}$	T,KE	(Hingmann *et al.*, 1984)
	17.8(16) s		FE,RS,Si	$(1.3^{+1.2}_{-0.7})\times10^{-2}$	T,KE	(Antalic *et al.*, 2010)
^{244}**Es**	38(11) s	-2.24	FE,RC,MG	$\mathbf{1.2(4)\times10^{-4}}$	Z,T,KE,TKE,MD	(Shaughnessy *et al.*, 2002)
			FE,NS,MF	$1\times10^{-4,b}$	T	(Gangrsky *et al.*, 1980)
^{246}**Es**	7.7(5) min	-3.47	FE,RC,MG	$\mathbf{(3.7^{+8.5}_{-3.0})\times10^{-5}}$	Z,T,KE	(Shaughnessy *et al.*, 2001)
	8 min		FE,NS,MF	$3\times10^{-5,b}$	T	(Gangrsky *et al.*, 1980)
^{248}**Es**	23(3) min	-4.26	FE,RC,MG	$\mathbf{3.5(18)\times10^{-6}}$	Z,T,KE	(Shaughnessy *et al.*, 2001)
			FE,NS,MF	$3\times10^{-7,b}$	T	(Gangrsky *et al.*, 1980)
^{246m1,m2}Md	0.9(2), 4.4(8) s	0.14	FE,RS,Si	$>1\times10^{-1}$	T,KE	(Antalic *et al.*, 2010)
	1.0(4) s[c]		FE,RS,Si	$\sim0.65\times10^{-1}$	T,KE	(Ninov *et al.*, 1996)
^{250}Md	52(6) s[#]	-2.64	FE,NS,MF	$2\times10^{-4,b}$	T	(Gangrsky *et al.*, 1980)
β^- –delayed fission in the neutron-rich isotopes						
^{228}Ac	6.15(2) h[#]	-4.45	LLP,RC,MF/Ge	$5(2)\times10^{-12}$		(Yanbing *et al.*, 2006)
^{230}Ac	122(3) s[#]	-2.73	TR,RC,MF/Ge	$1.19(40)\times10^{-8}$		(Shuanggui *et al.*, 2001)
^{256m}Es	7.6 h[#]	-3.23	TR,RC,Si/Ge	2×10^{-5}	T,KE	(Hall *et al.*, 1989b)
^{234gs}Pa	6.70(5) h[#]	-2.55	NI,NS,MF	$3\times10^{-12,d}$	T	(Gangrsky *et al.*, 1978)
^{234m}Pa	1.159(11) min[#]		LLP,RC,MF	$10^{-12,d}$	T	(Gangrsky *et al.*, 1978)
^{236}Pa	9.1(1) min[#]	-2.02	SR,RC,MF/Ge	$\sim10^{-9}$	T	(Batist *et al.*, 1977)
			FE/GI,NS,MF	$10^{-9,d}/3\times10^{-10,d}$	T	(Gangrsky *et al.*, 1978)
^{238}Pa	2.3(1) min[#]	-2.14	NI,NS,MF	$6\times10^{-7},\ 1\times10^{-8,d}$	T	(Gangrsky *et al.*, 1978)
			NI,RC,MF	$<2.6\times10^{-8}$		(Baas-May *et al.*, 1985)

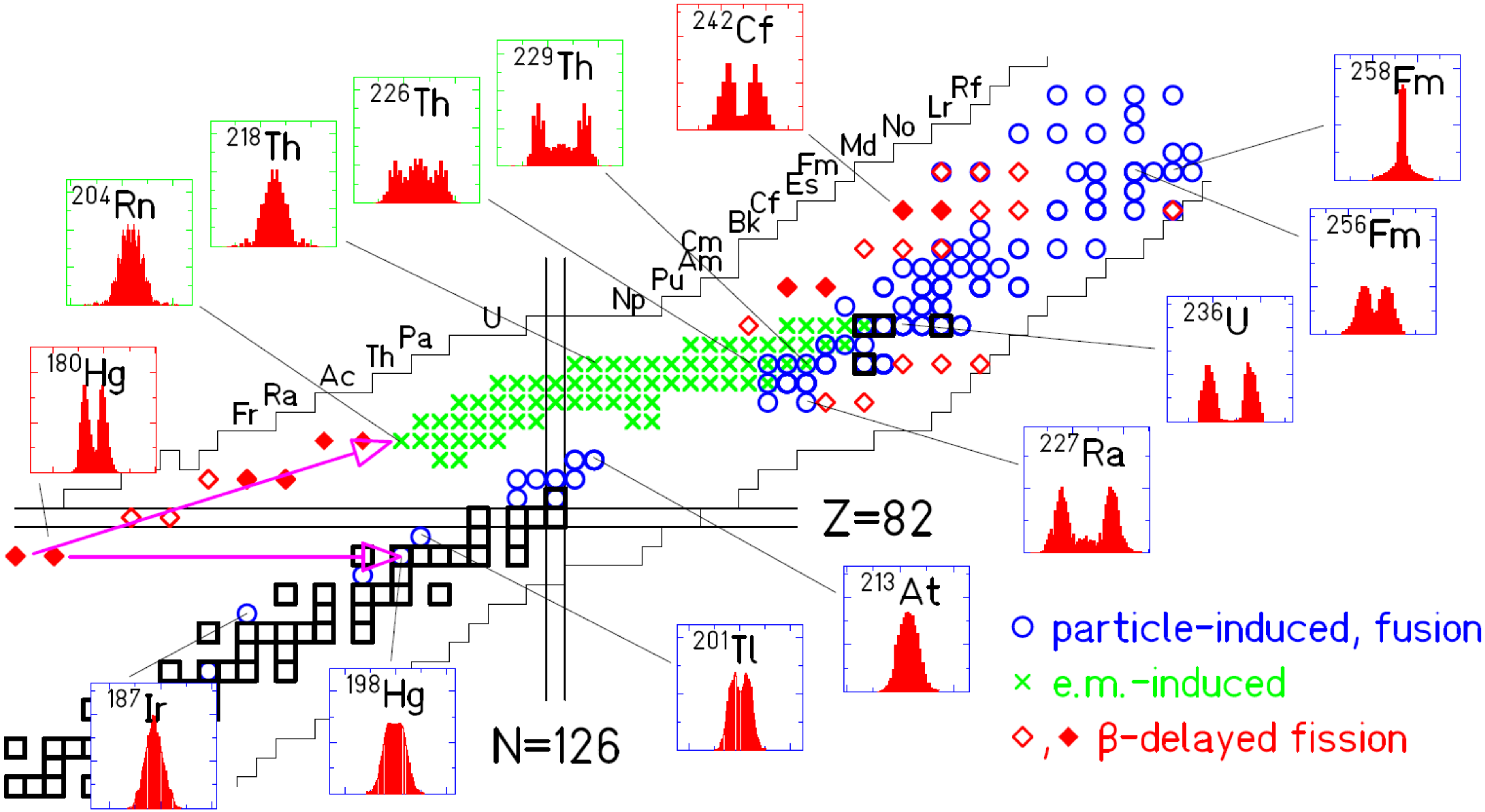
Beta-delayed fission in tne neutron-rich Fr nuclei

Isotope	$T_{1/2}$	$Q_{EC} - B_f$ [MeV]	Production Separation, Detection	$P_{\beta DF}$ Upper Limit
$^{242}Bk^a$	7.0(13) min$^{\#}$	-3.49	FE,NS,MF	$< 3 \times 10^{-7}$
$^{248}Md^a$	7(3) s$^{\#}$	-1.45	FE,NS,MF	$< 5 \times 10^{-4}$
$^{228}Fr^b$	38(1) s$^{\#}$	-3.33	SR,IS,Si/Ge	$< 2 \times 10^{-7}$
$^{230}Fr^b$	19.1(5) s$^{\#}$	-2.05	SR,IS,Si/Ge	$< 3 \times 10^{-6}$
$^{232}Fr^b$	5.5(6) s	-1.34	SR,IS,Si/Ge	$< 7 \times 10^{-4,c}$
$^{232}Ac^b$	119(5) s	-1.75	SR,IS,Si	$< 10^{-6}$

$^{\#}$ Evaluated half-life value from (ENSDF, 2013).
a) Studied by (Gangrsky *et al.*, 1978).
b) Studied by (Mezilev *et al.*, 1990).
c) Different limits for different β-γ transitions.



Mapping 'Terra Incognita' in Low-Energy Fission



To be shown in: A. N. Andreyev, M. Huyse, P. Van Duppen, "Beta-delayed Fission", Review of Modern Physics (under refereeing now)

Thank you!

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