Beta-delayed fission as a tool to study near and sub-barrier fission in extremely exotic nuclei

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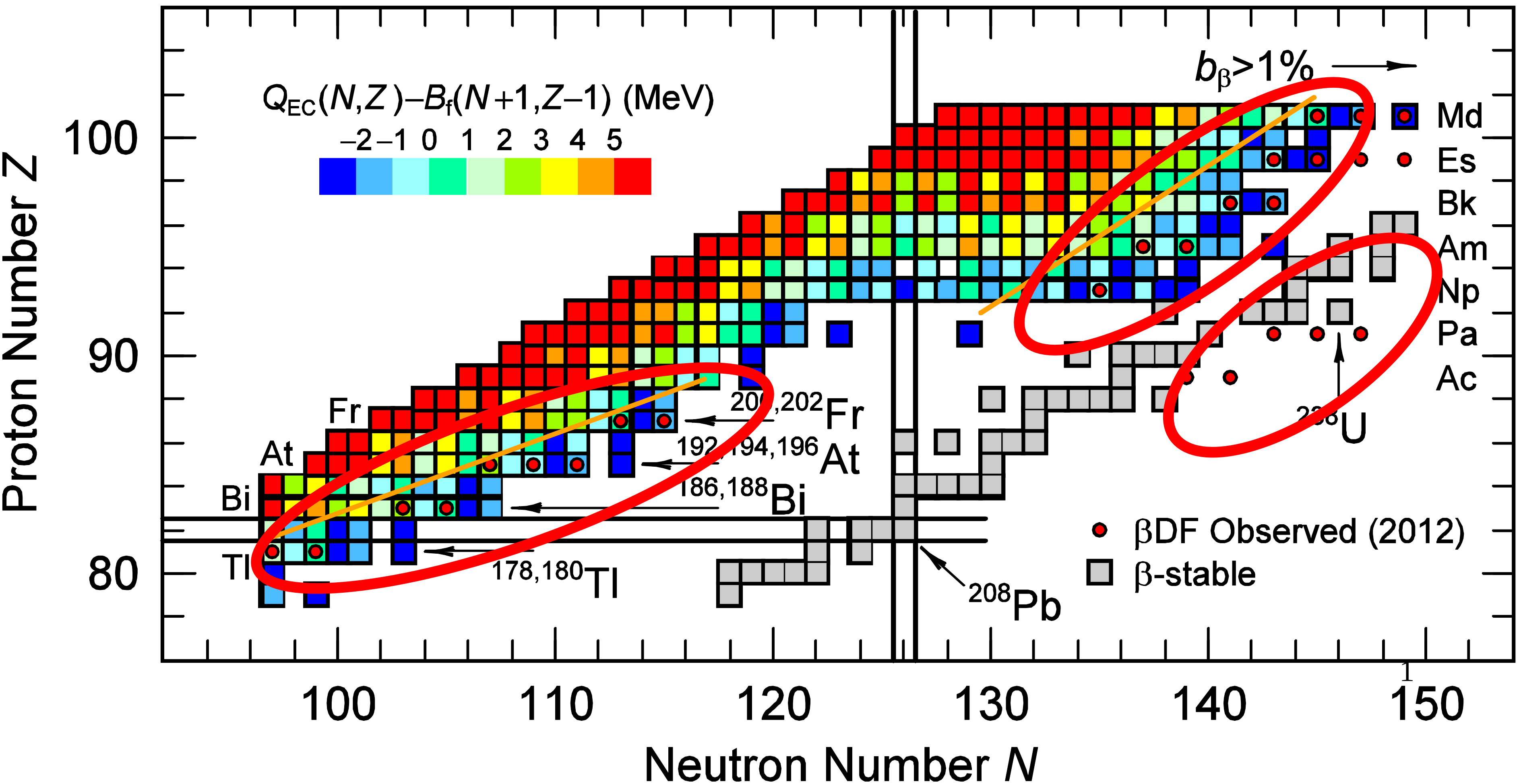

Collaboration

THE UNIVERSITY of York

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R. Wadsworth
D. Jenkins
M. Vermeulen
C. Barton
M. Bentley

ISOLDE
CERN, Geneva

JAEA Tandem

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S. Antalic, Z. Kalaninova, Comenium University, Slovakia

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 at ISOLDE (CERN)
- βDF ^{194}At at SHIP (GSI)
- Further plans

Outlook

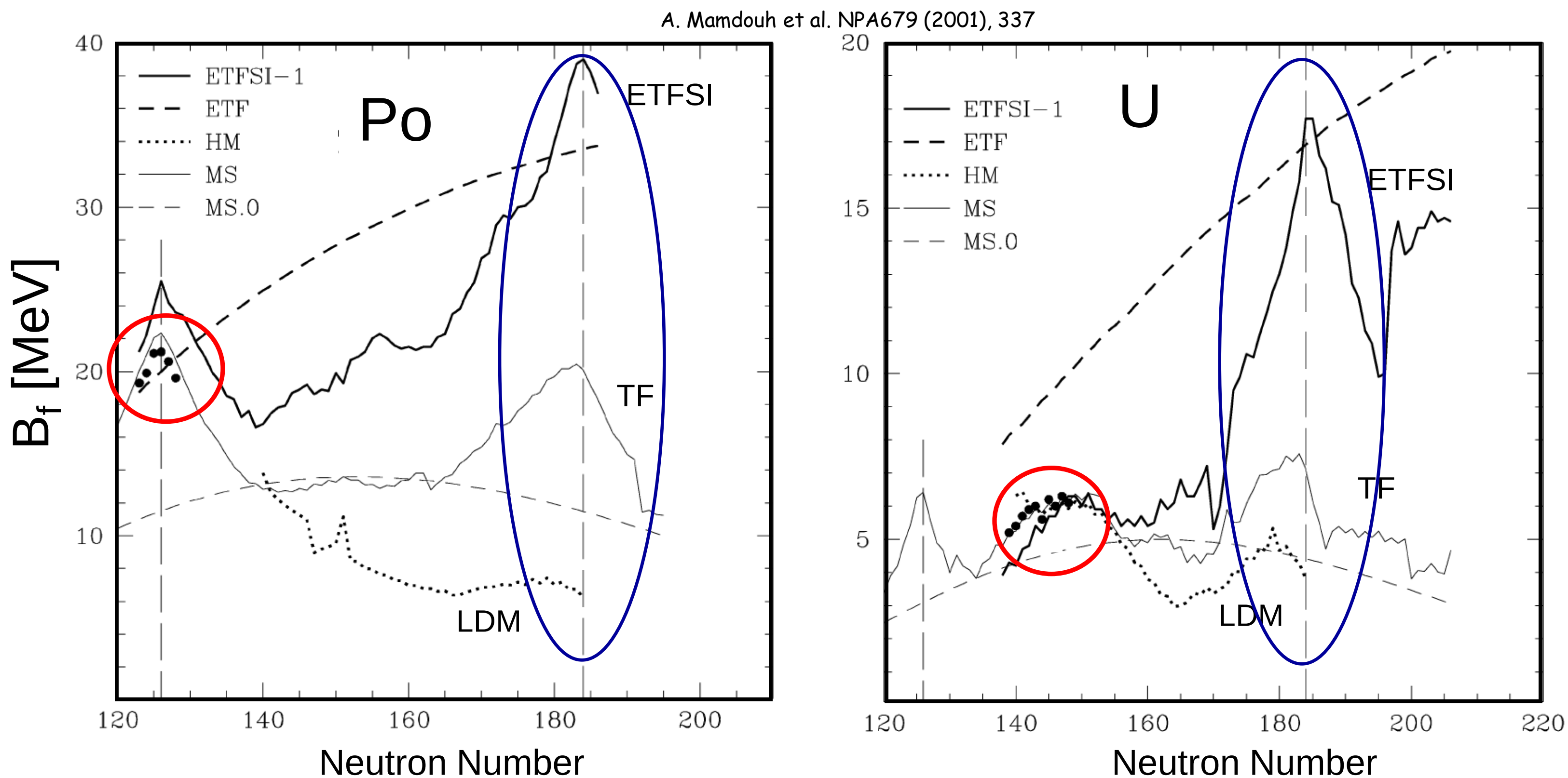
•Many nuclear properties change far from stability line (e.g. disappearance of traditional magic numbers; appearance of new shell gaps; halos, skins…

•**What happens to fission far from stability, e.g. on the extremely proton-rich or neutron-rich side (relevant for r-process)?**

•Not simple to answer, as to fission these nuclei at low excitation energy ($E^*\sim B_f$) is a very challenging task as none of them fissions from g.s.

Fission Barrier Calculations for the r-process nuclei

Full symbols – experimental data
Lines – calculations (LDM,TF, ETFSI)



- Good agreement between $B_{f,cal}$ and $B_{f,exp}$ for nuclei close to stability
- Large disagreement far of stability (especially on the n-rich sides)
- Need measured fission data far of stability to 'tune' fission models

A Detour:

What can one learn with a rate of 1 fission/h?

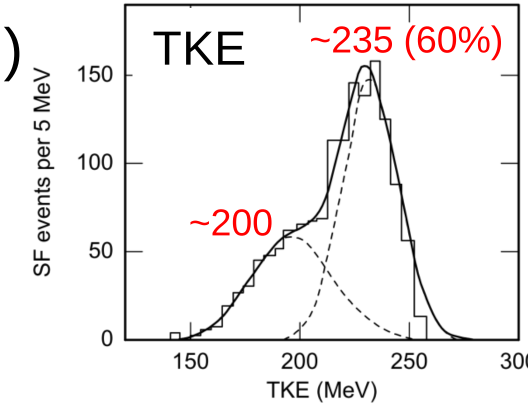
OR

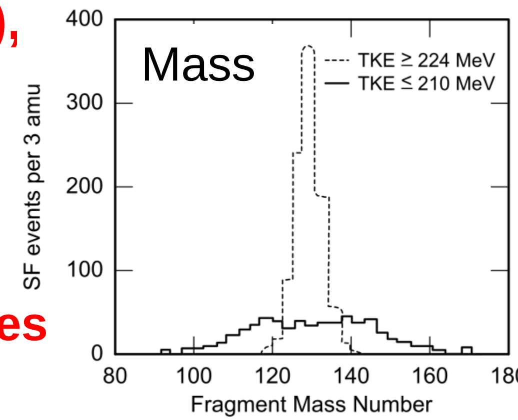
What can one learn from ~100-1000 fission events?

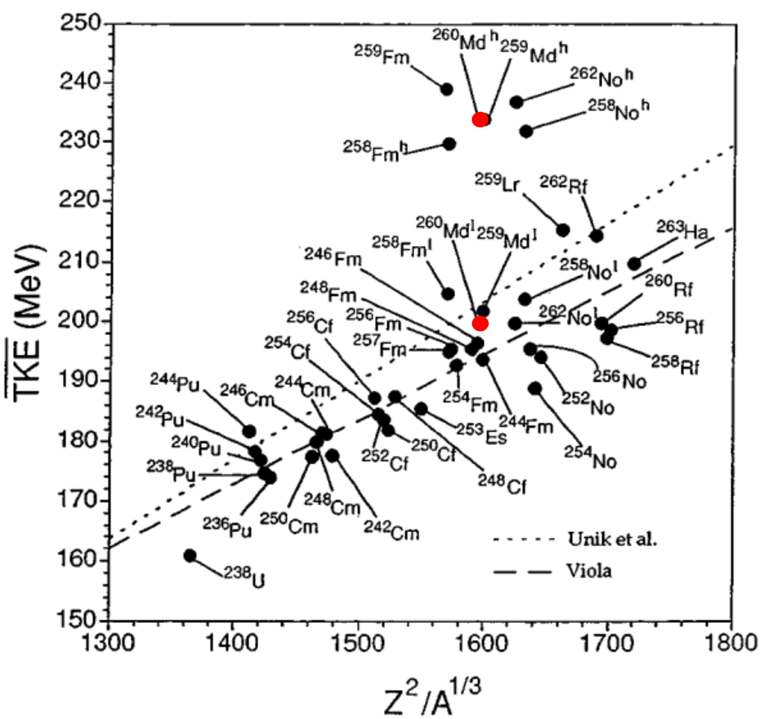
Bimodal Fission of ^{260}Md ($T_{1/2}$~32 d)

J. F. Wild et al., Phys. Rev. C4, 640, 1990

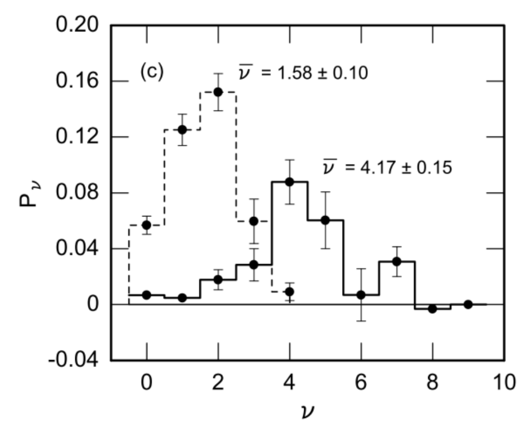
- $^{22}Ne+^{254}Es(T_{1/2}=276\ d) \rightarrow\ ^{260}Md$ (α transfer reaction)
- 34 irradiations in a **2.5 months irradiation period**
- Collection of recoils on a foil
- Radiochemical separation of **~3000 ^{260}Md atoms**
- Deposited on a very thin foil
- **98 days of counting with Si and neutron detectors**
- **1207 singles fission fragments, 905 coincident (TKE),**
- **Neutron multiplicity (as a function of TKE)**







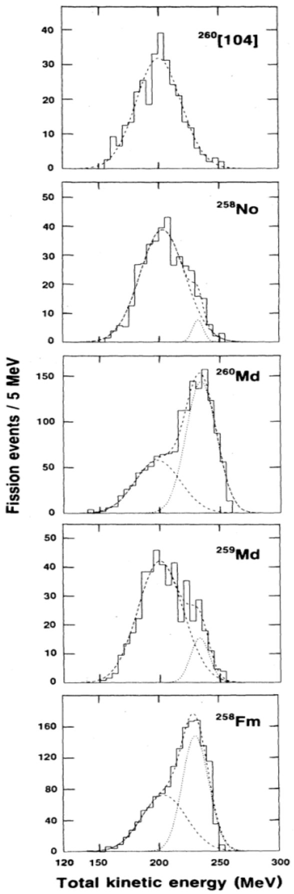
- **Two-humped TKE**
- **Two components in masses**
- **High TKE – low ν**
- **Low TKE – high ν**



Bimodal Fission

E. K. Hulet et, Phys. Rev. C40, 770 (1989)

Total Kinetic Energy (TKE)



~300 ff

382 ff

~1400 ff

~450 ff

~1400 ff

FIG. 7. Unfolding of the asymmetric TKE distributions of

Masses

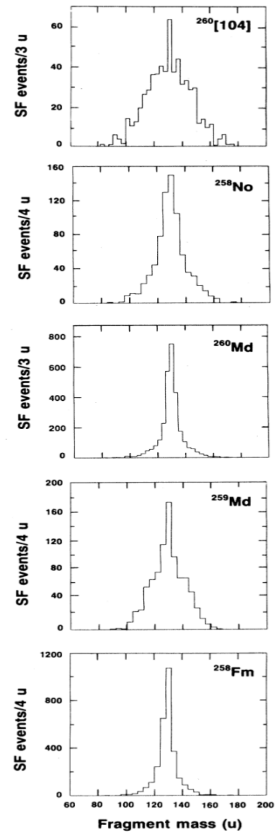


FIG. 5. Provisional mass distributions (no neutron corrections) obtained from correlated fragment energies. The mass bins have been chosen to be slightly different for each nuclide.

Mass components as a function of TKE

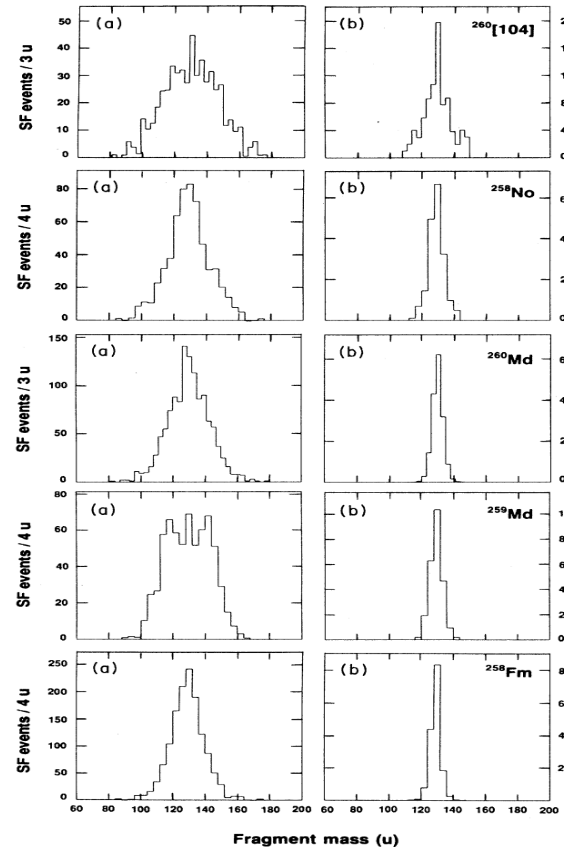


FIG. 8. Mass distributions obtained by sorting fission events according to their total kinetic energies: (a) for events with

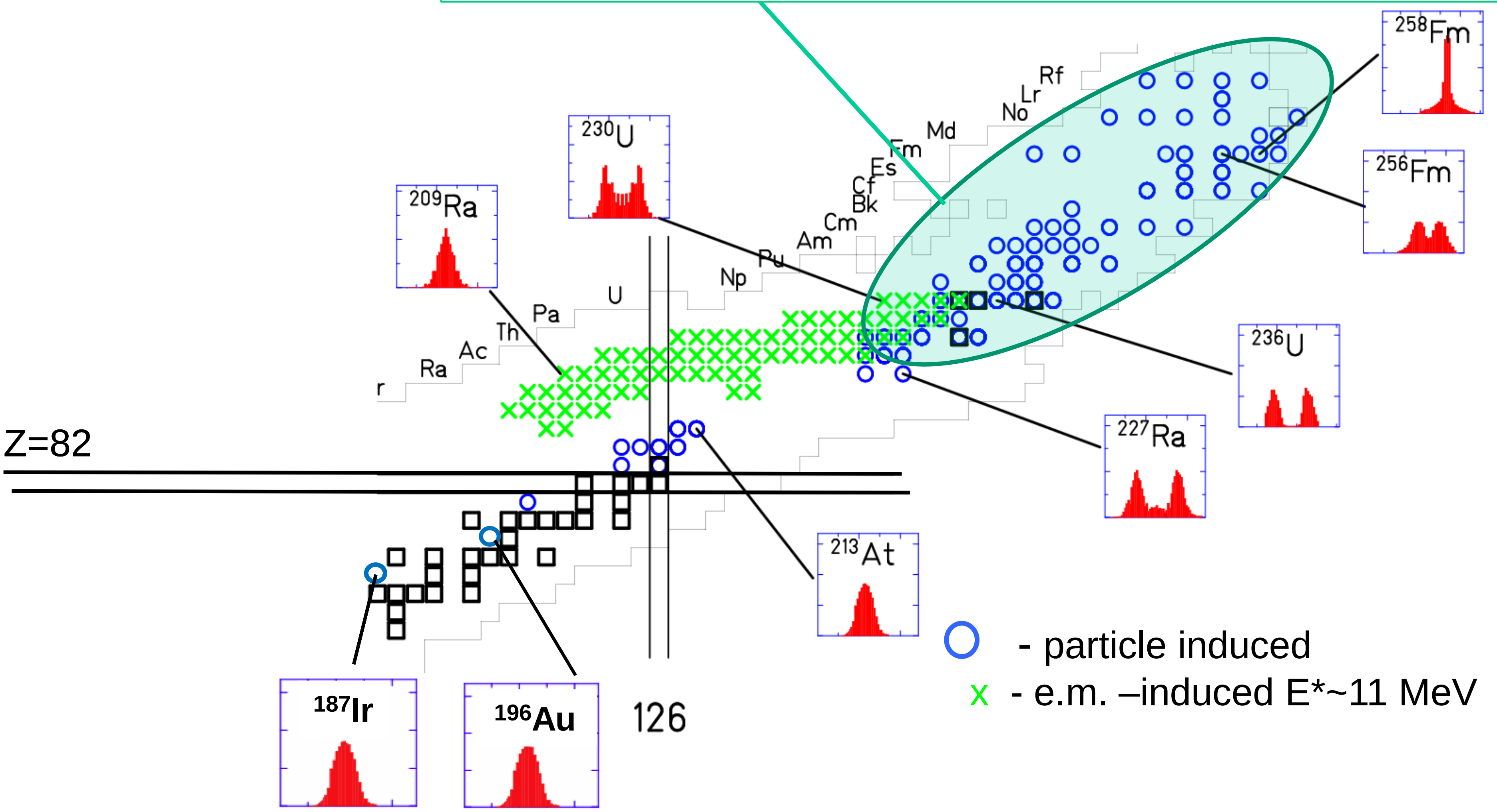
Evidence for bimodal fission: strong deviation of TKE from a single Gaussian

Detailed fission fragments energy measurements are "A MUST"

Y. Nagame and H. Nakahara, Radiochim. Acta 100, 605, 2012

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

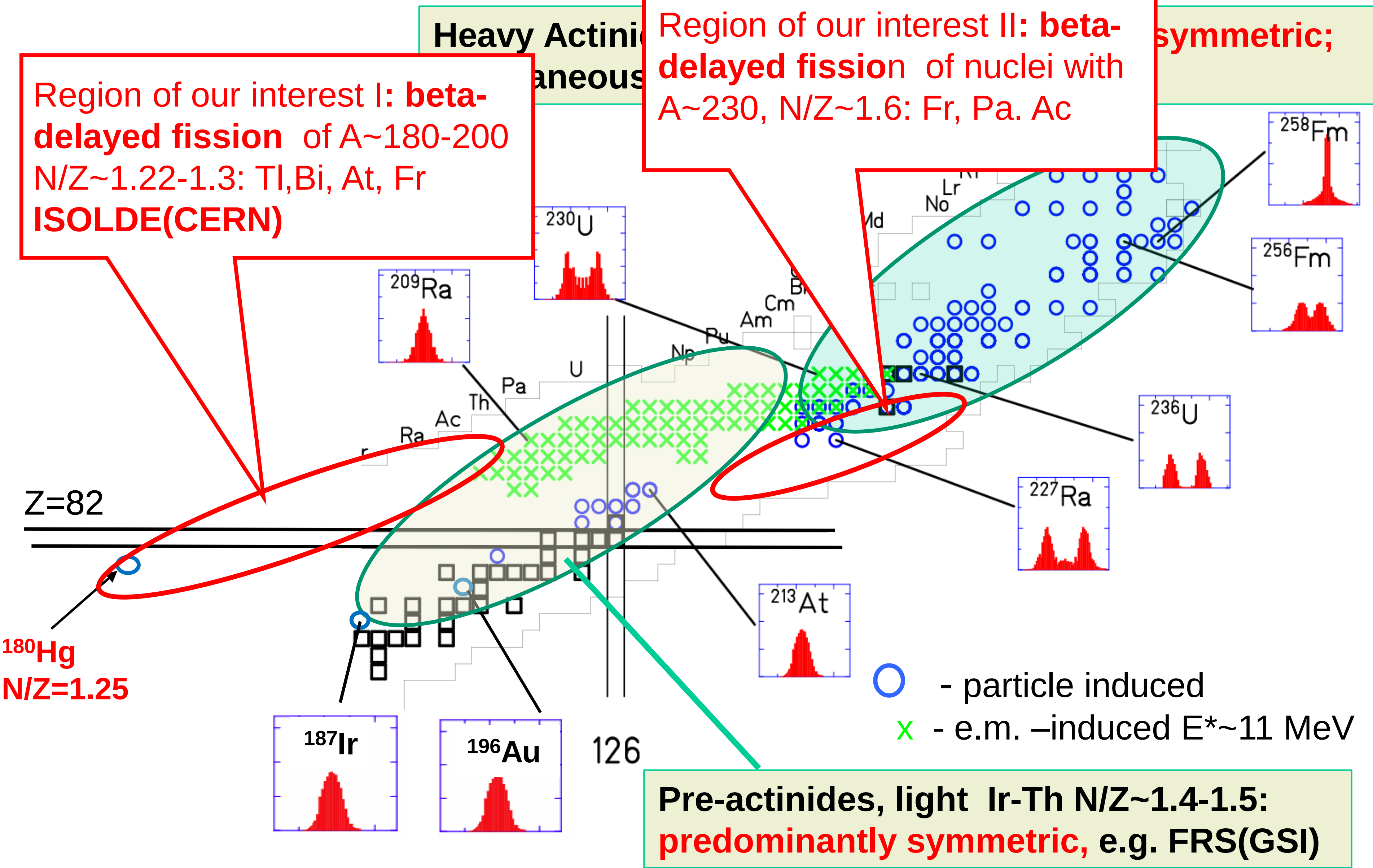
Heavy Actinides, N/Z~1.56: predominantly asymmetric; spontaneous fission, fission isomers



K.-H. Schmidt et al.

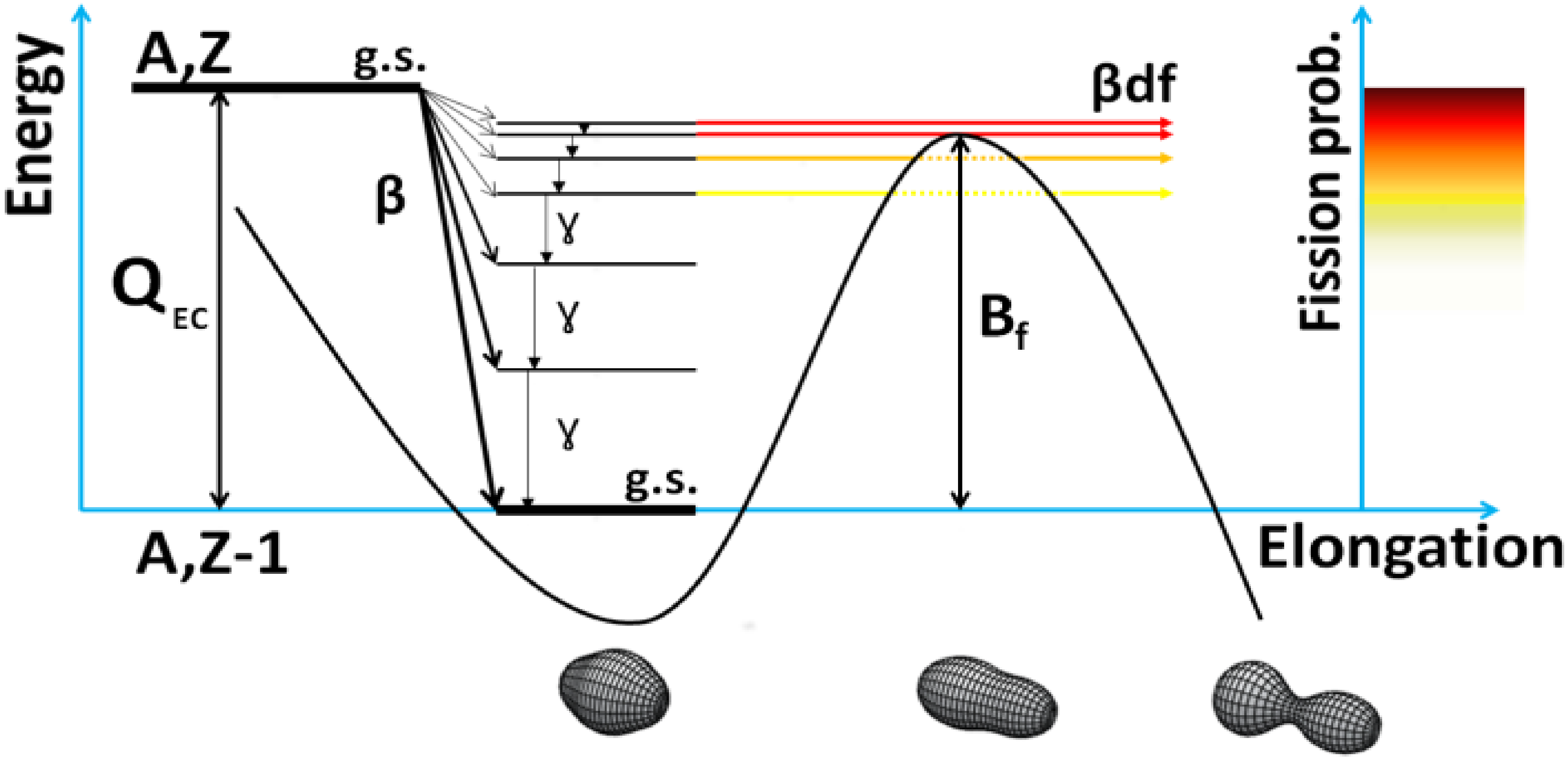
Experimental information on low-energy fission

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



Beta-Delayed Fission

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

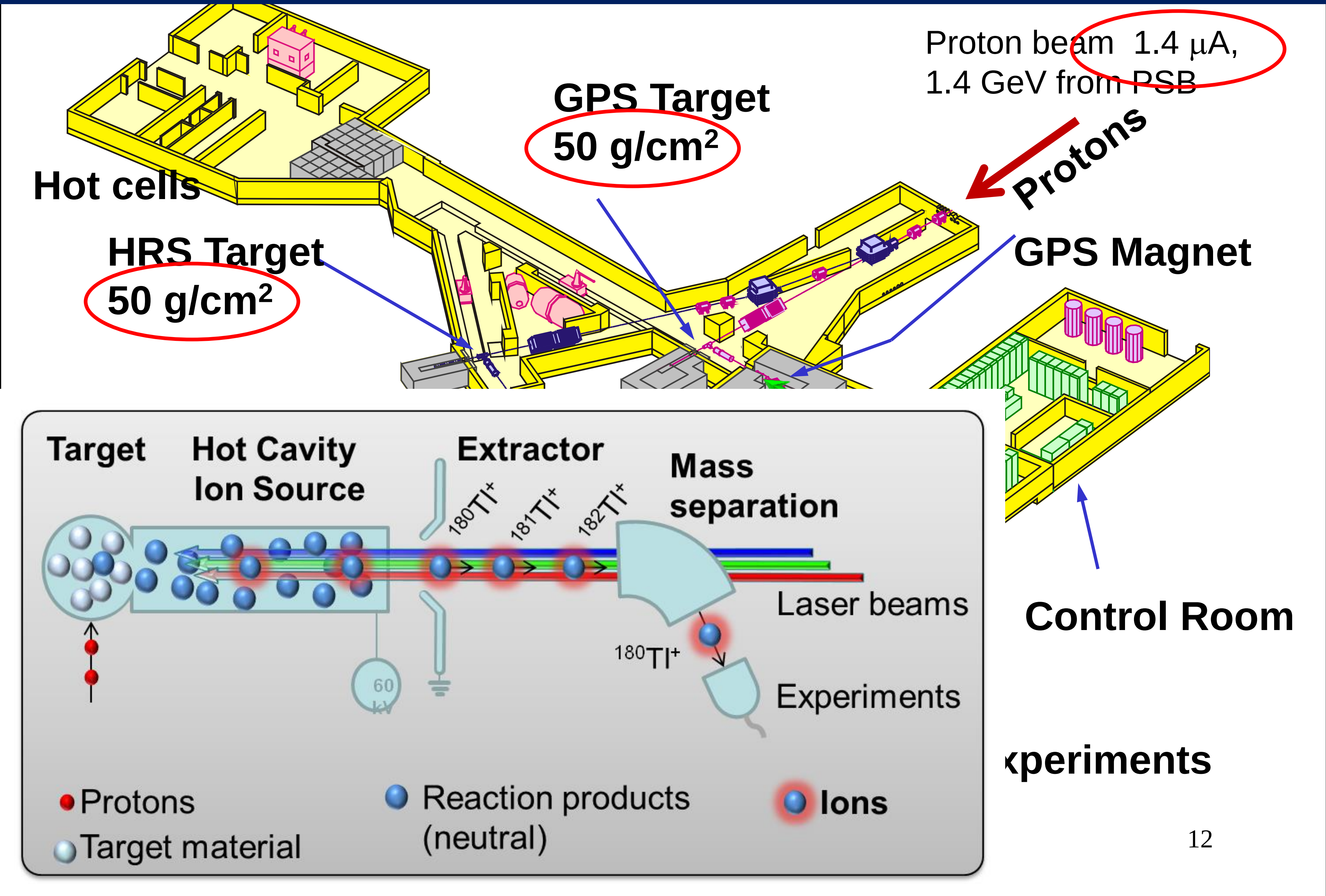


- Two step process: β decay followed by fission
- Low-energy fission (E*~3-12 MeV, limited by Q_{EC})
  e.g. ^{180}Tl: Q_{EC}=10.4 MeV, $B_{f,calc}$=9.8 MeV
- Relatively low angular momentum of the state
  e.g. ^{180}Tl: I=4 or 5 (some cases: up to 10)

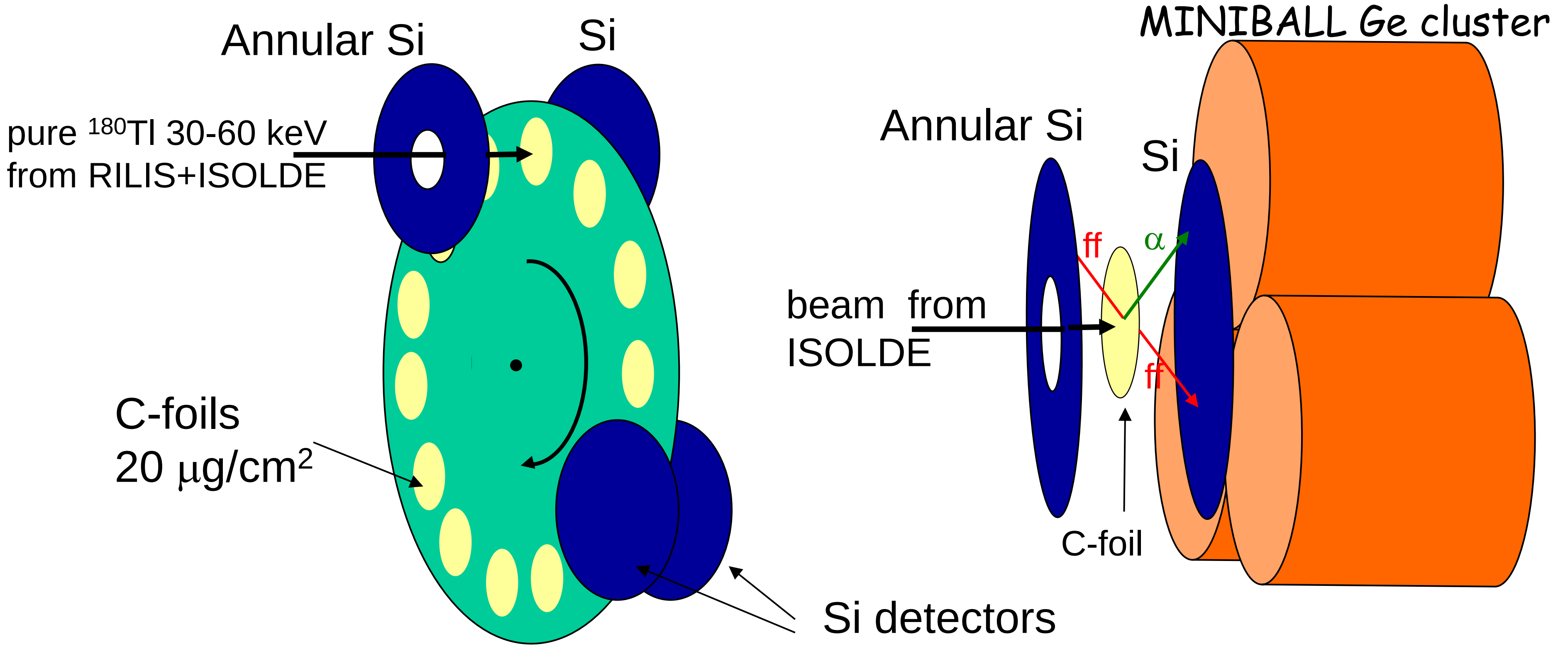
βDF branch

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

Mass Separator ISOLDE (CERN)



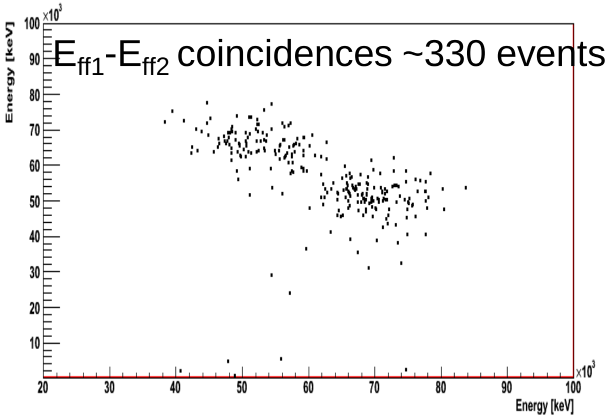
Detection system for βDF studies at ISOLDE

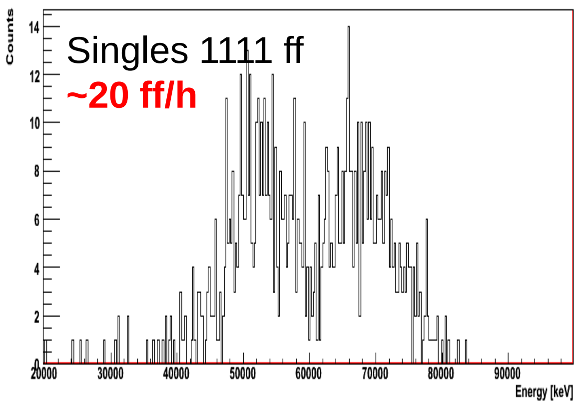


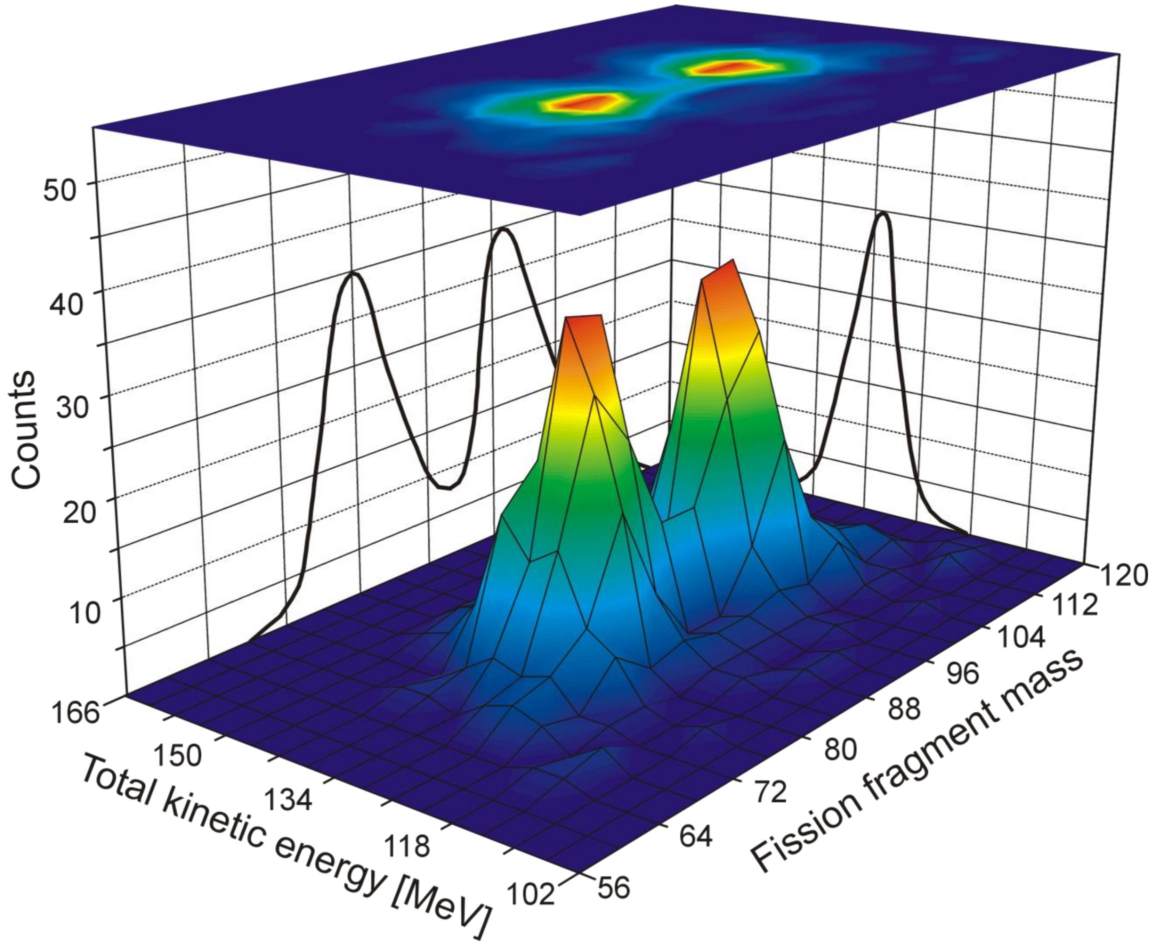
A.Andreyev et al. PRL 105 (2010)

Mass distribution of fission fragments from bDF of ^{180}Tl

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



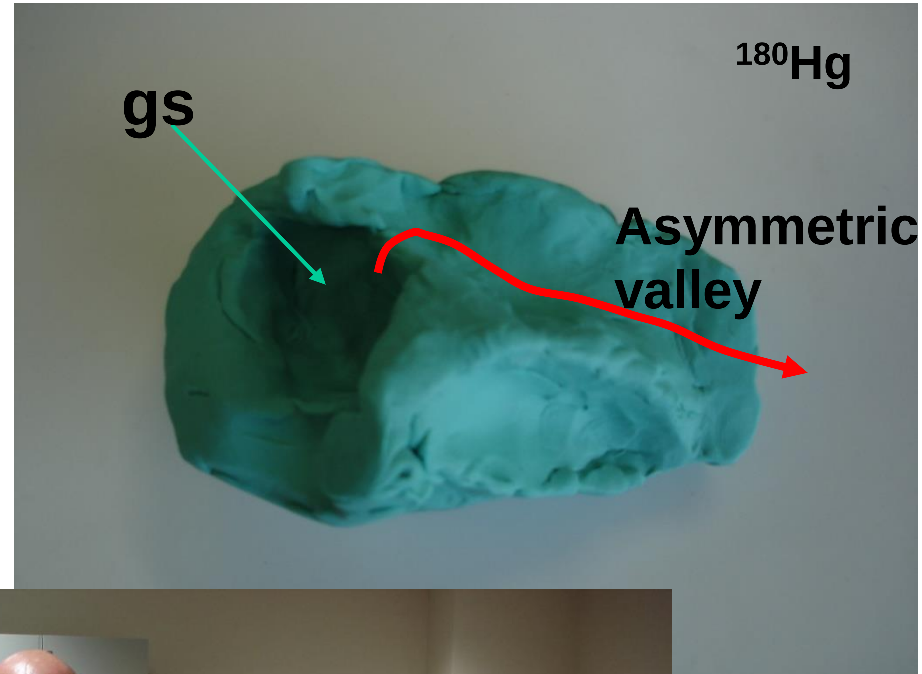


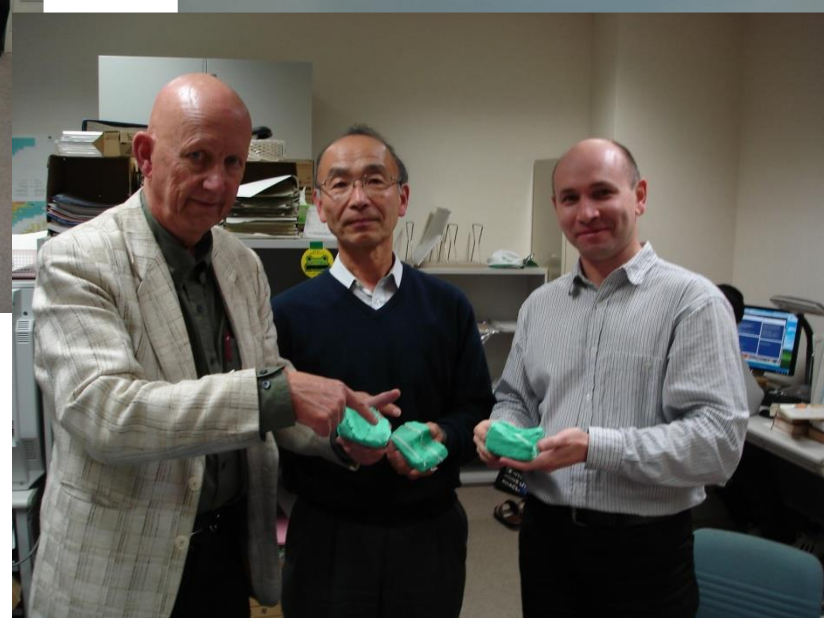


The most probable fission fragments are ^{100}Ru (N=56,Z=44) and ^{80}Kr (N=44,Z=36)

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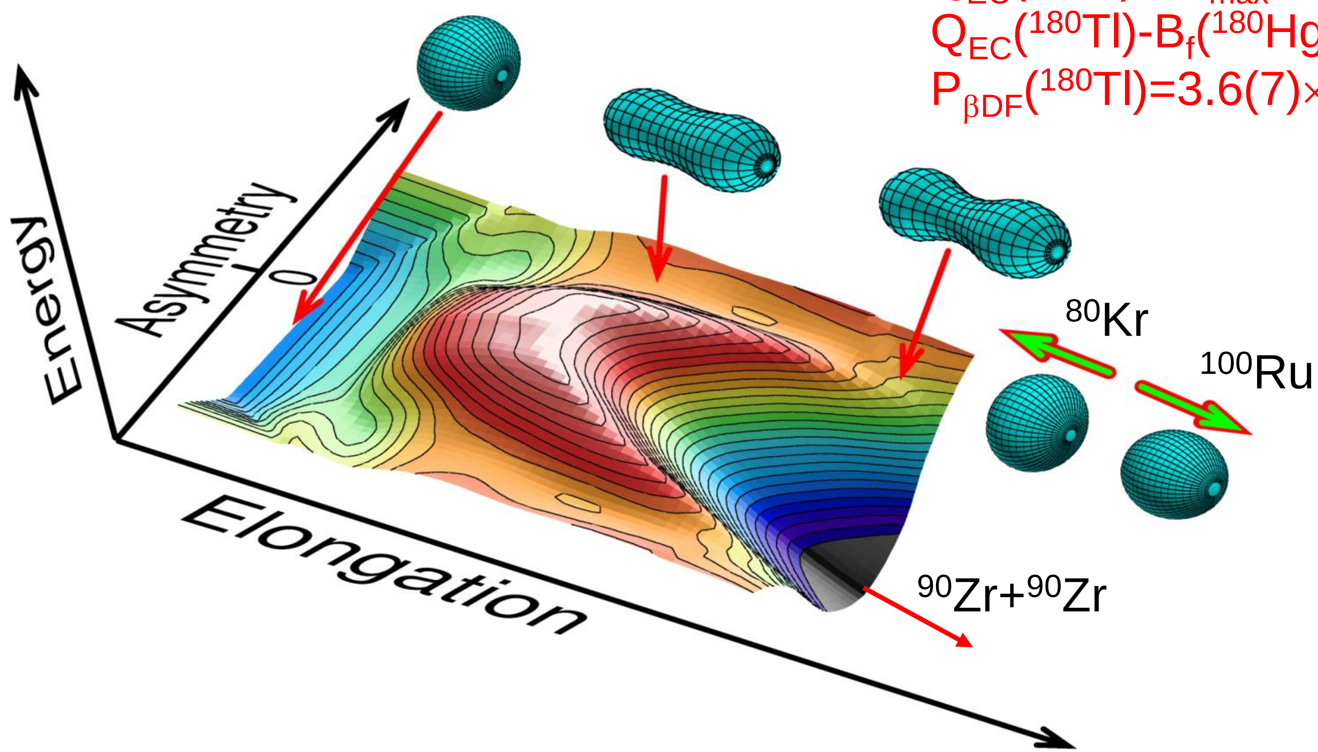
[2]*School of Engineering, University of the West of Scotland, Paisley, PA1 2BE, United Kingdom, and the Scottish Universities Physics Alliance (SUPA)*

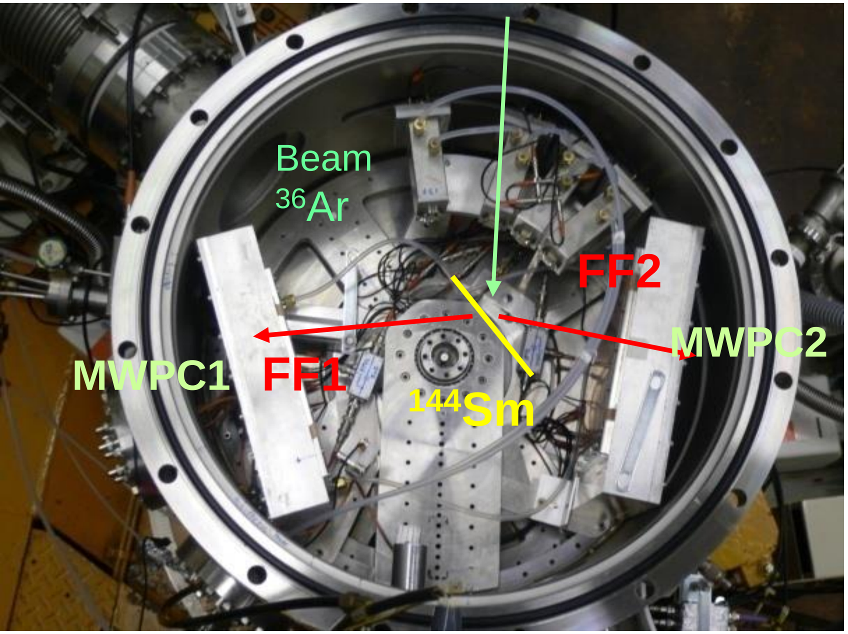
$Q_{EC}(^{180}\mathrm{Tl})=E^*_{max}=10.44$ MeV
$Q_{EC}(^{180}\mathrm{Tl})-B_f(^{180}\mathrm{Hg})=0.63$ MeV
$P_{\beta DF}(^{180}\mathrm{Tl})=3.6(7)\times10^{-5}$

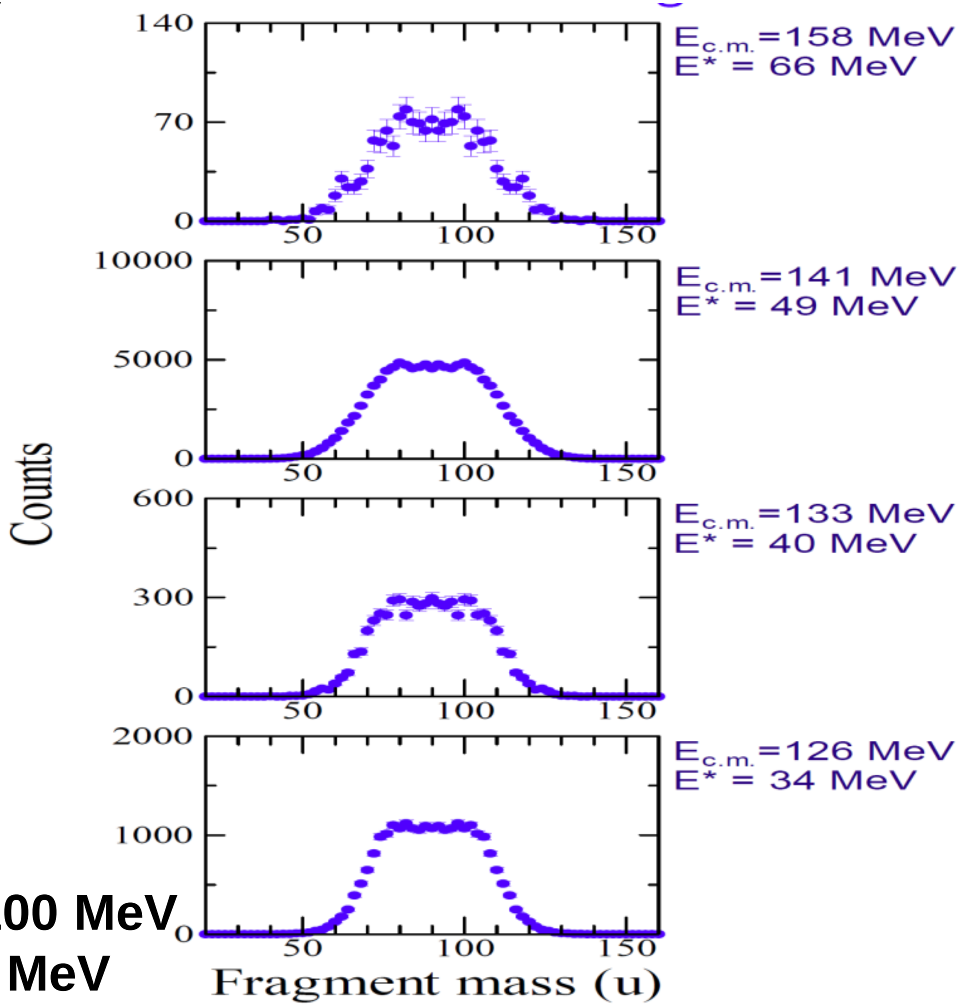


Calculations according to 5D fission model (P. Möller et al., Nature 409, 785 (2001))

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

- $^{36}Ar+^{144}Sm \rightarrow ^{180}Hg^{*}$ E*=34-66 MeV
- 2010-2012: JAEA, Tokai





- **2010-2012, JAEA**
- **$^{36,40}Ar+^{144,154}Sm \rightarrow ^{180\text{-}194}Hg^{*}$ E*=30-100 MeV**
- **$^{36,40}Ar+^{142}Nd \rightarrow ^{178,182}Pt^{*}$ E*=30-100 MeV**

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

- **Approved $^{90}Zr+^{90}Zr \rightarrow ^{180}Hg^{*}$ (E*~15 MeV)**

Courtesy K. Nishio

Supported by Reimei Foundation (JAEA)

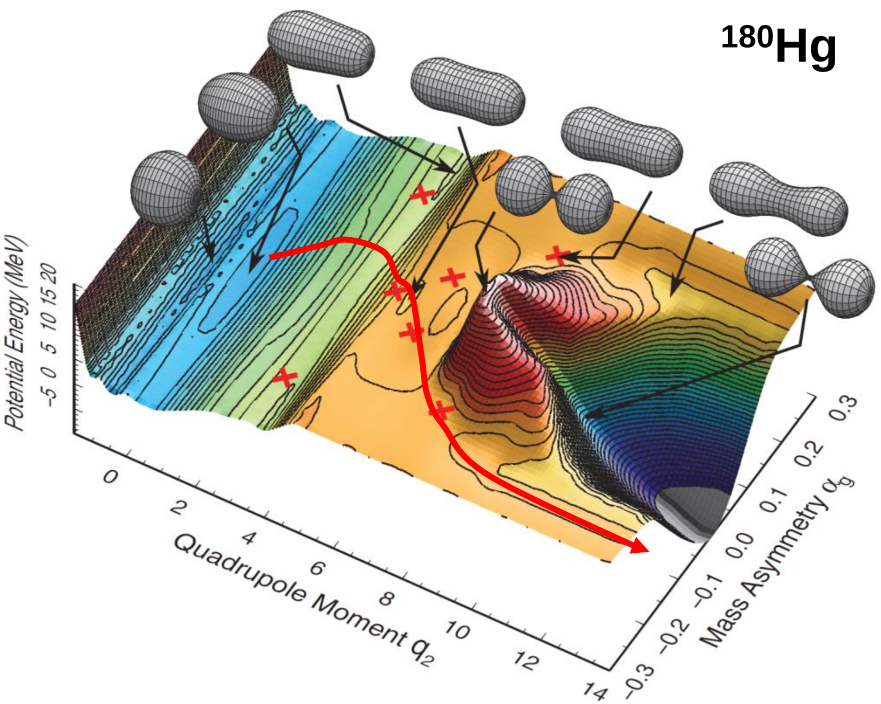
Two types of asymmetry: what's the difference?

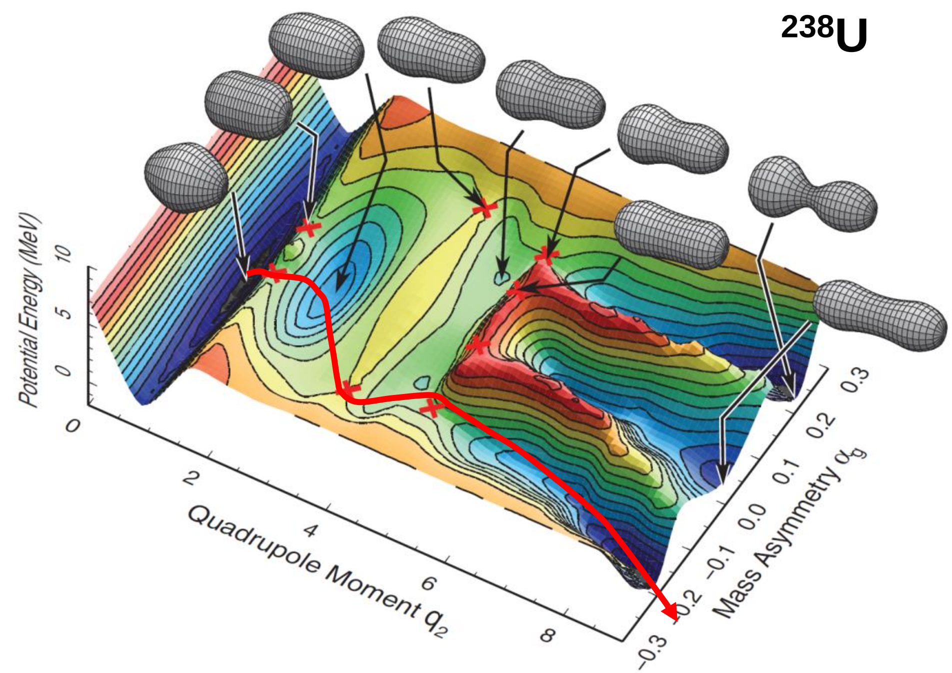
PHYSICAL REVIEW C **86**, 024610 (2012)

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.





'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, Héloïse Goutte, and Jean-François Lemaître
IRFU/Service de Physique Nucléaire, 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)

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

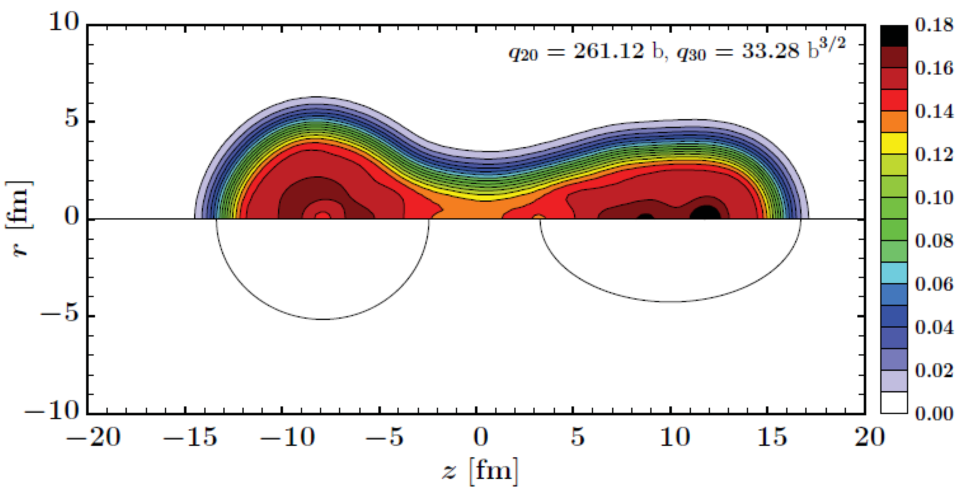


FIG. 4. (Color online) Total nuclear density for the most energetically favorable scission configuration in ^{180}Hg fission, extracted from a self-consistent HFB calculation. In the lower part of the figure, two

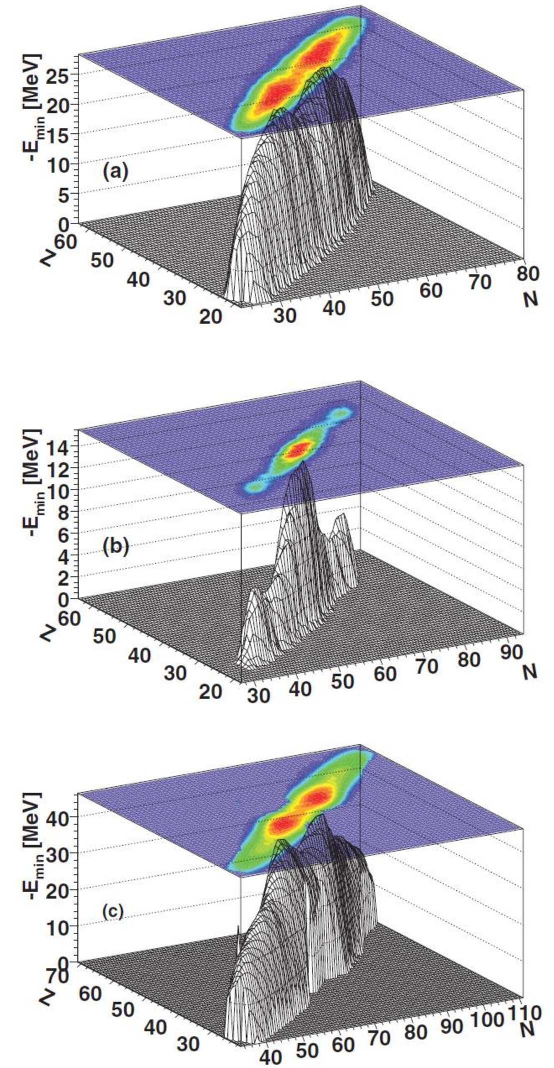


FIG. 2. (Color online) Minimum absolute available energy at scission calculated for all possible fragmentations in (a) ^{180}Hg and (b) ^{198}Hg fission at 10 MeV and in (c) the thermal n-induced fission of ^{235}U.

'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]

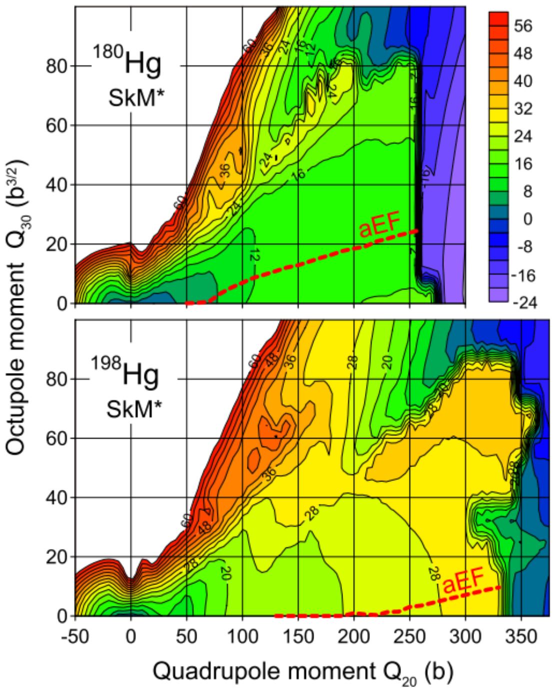


FIG. 2. (Color online) PES for ^{180}Hg (top) and ^{198}Hg (bottom) in the plane of collective coordinates $Q_{20} - Q_{30}$ in HFB-SkM*. The aEF fission pathway corresponding to asymmetric elongated fragments is marked. The difference between contour lines is 4 MeV. The effects due to triaxiality, known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

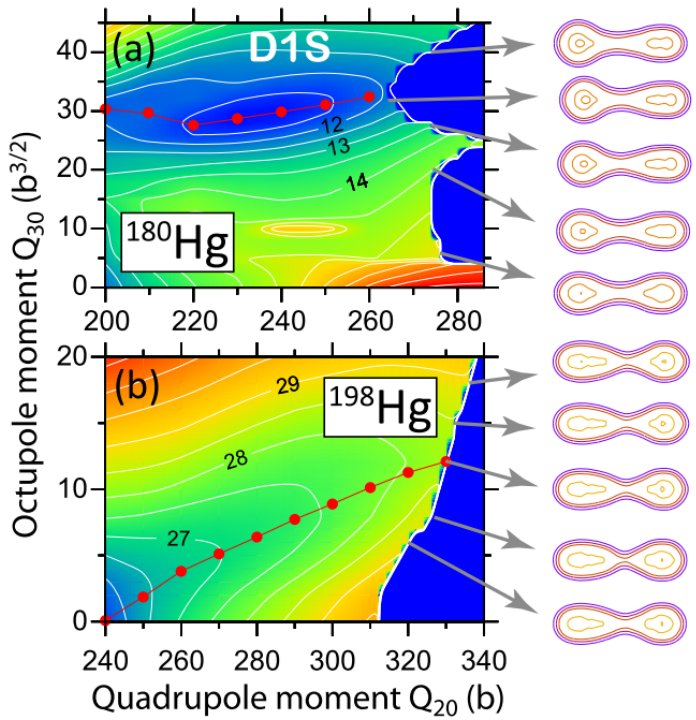


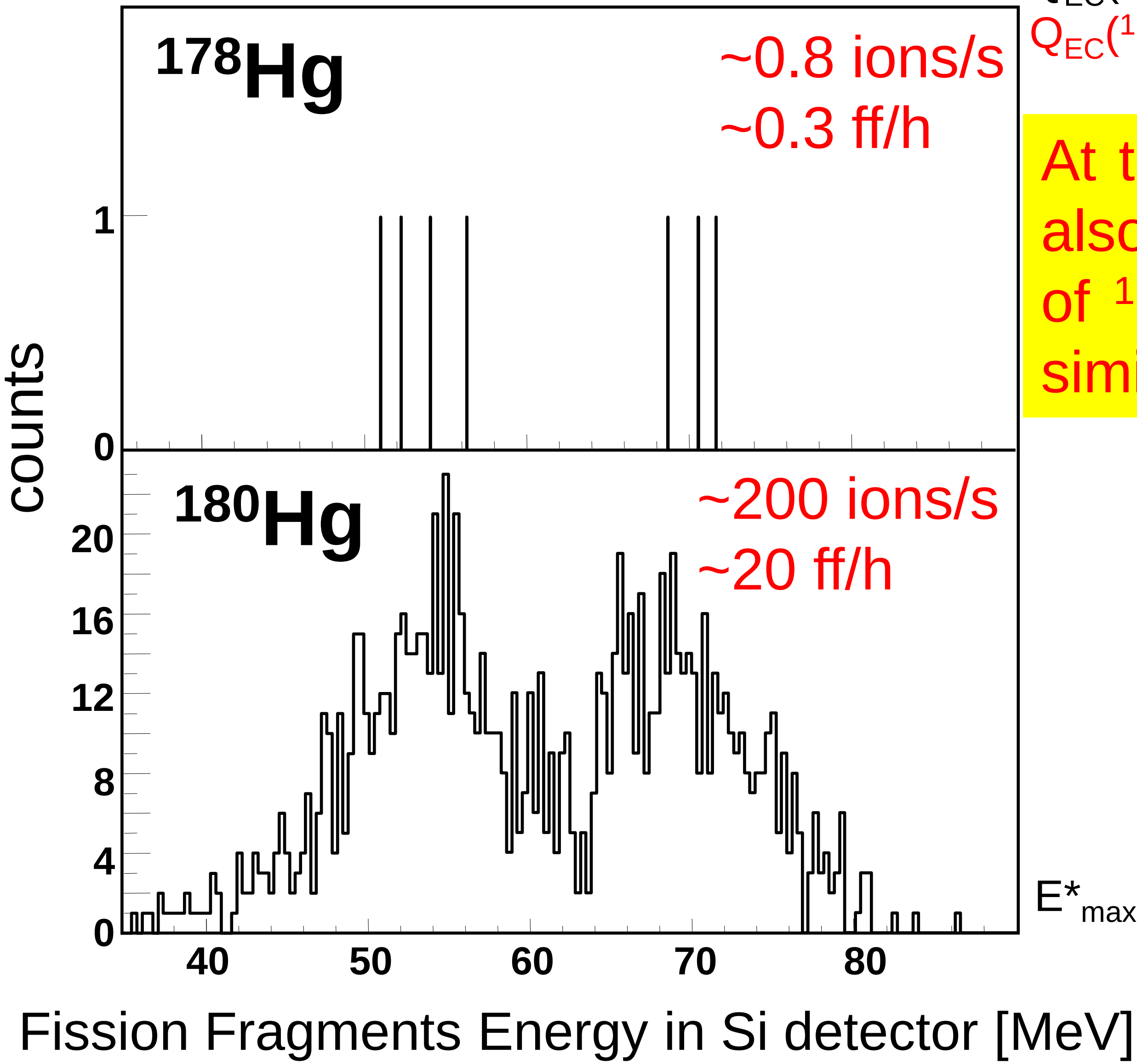
FIG. 3. (Color online) PES in HFB-D1S for ^{180}Hg (top) and ^{198}Hg (bottom) in the (Q_{20}, Q_{30}) plane in the pre-scission region of aEF valley. The symmetric limit corresponds to $Q_{30} = 0$. The aEF valley and density profiles for pre-scission configurations are indicated. The difference between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

βDF of ^{178}Tl @ISOLDE

V. Liberati et al (PRC, 2013, in print)

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

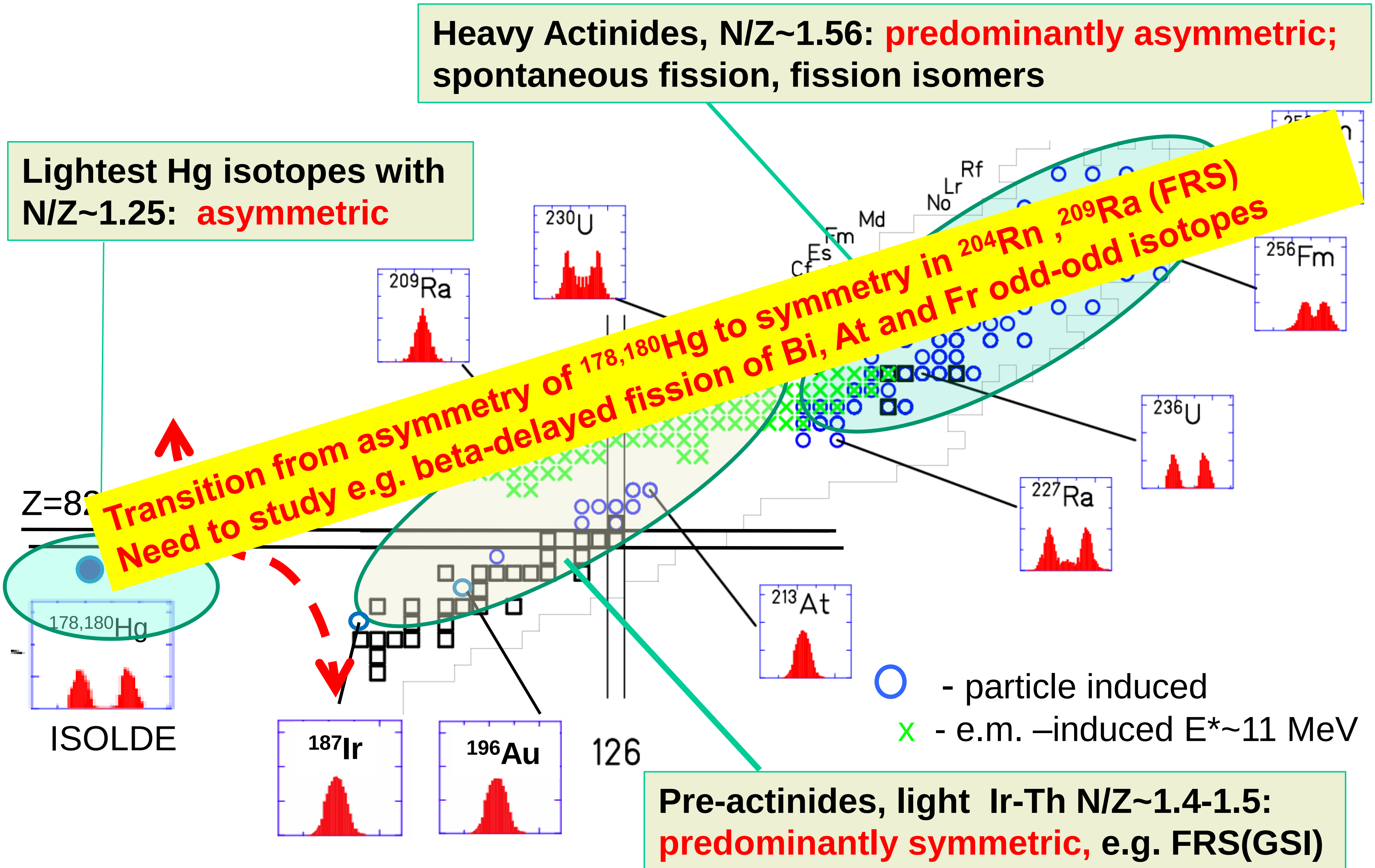
$Q_{EC}(^{178}Tl)-B_f(^{178}Hg)=1.82$ MeV



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

From Asymmetry to Symmetry



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

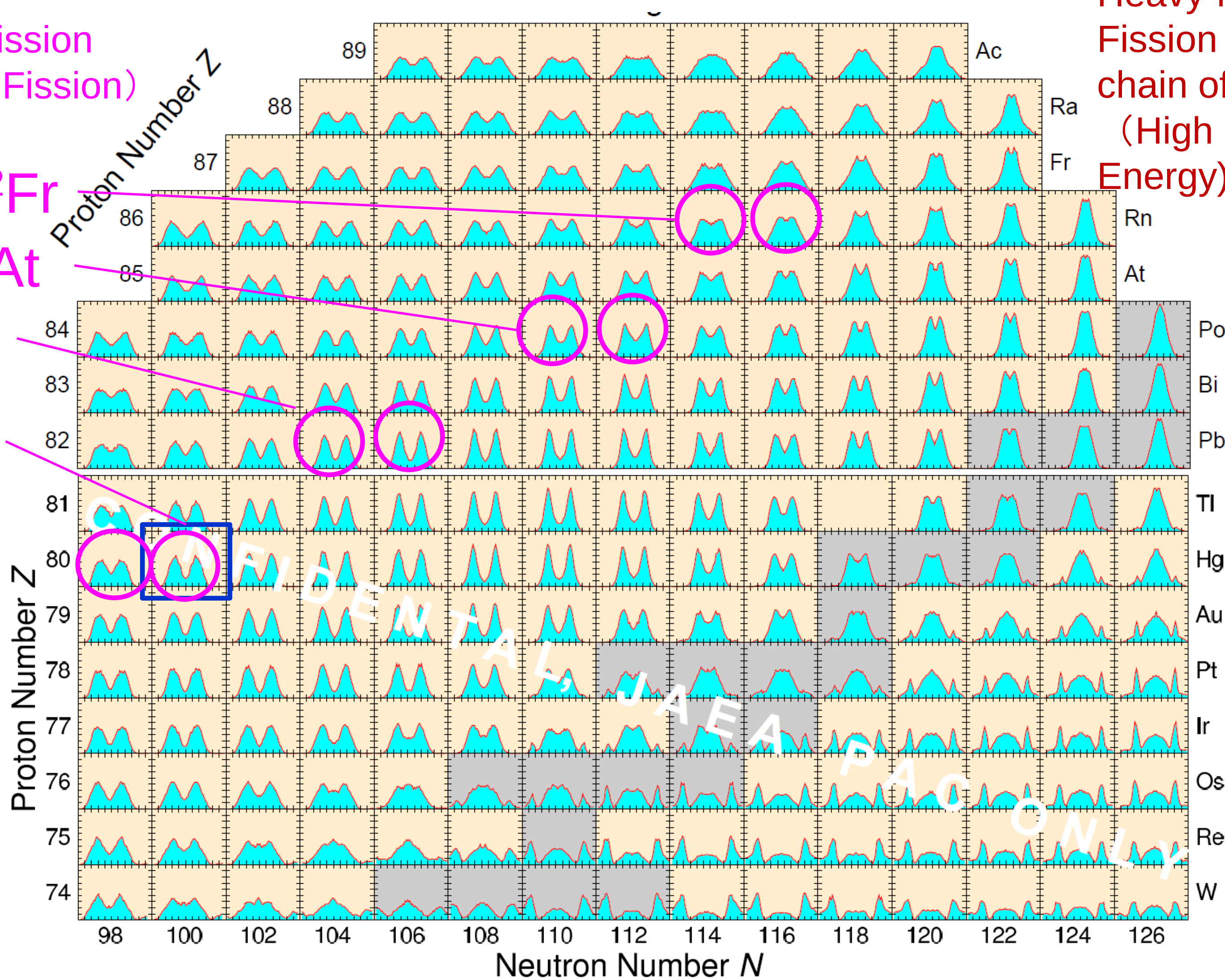
Courtesy P. Moller (LANL) and J. Randrup (LBNL), 5th ASRC workshop on Fission, Tokai 2012

CERN-ISOLDE

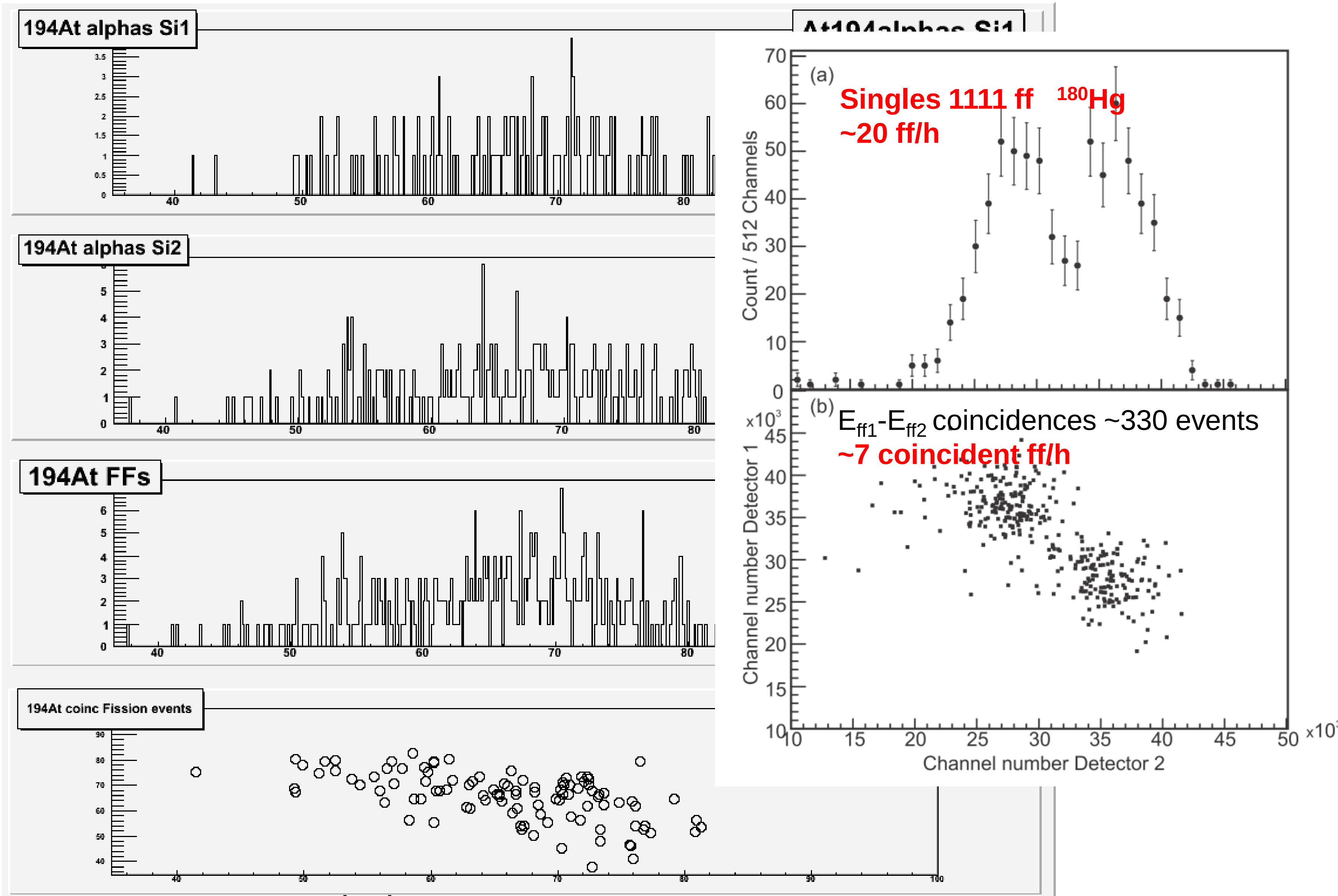
EC -delayed Fission
（Low Energy Fission）

JAEA tandem

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

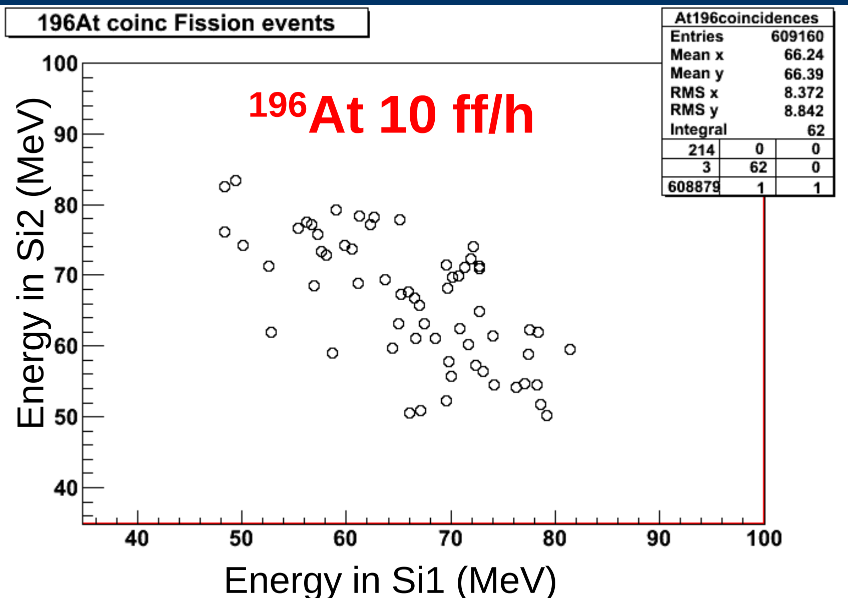


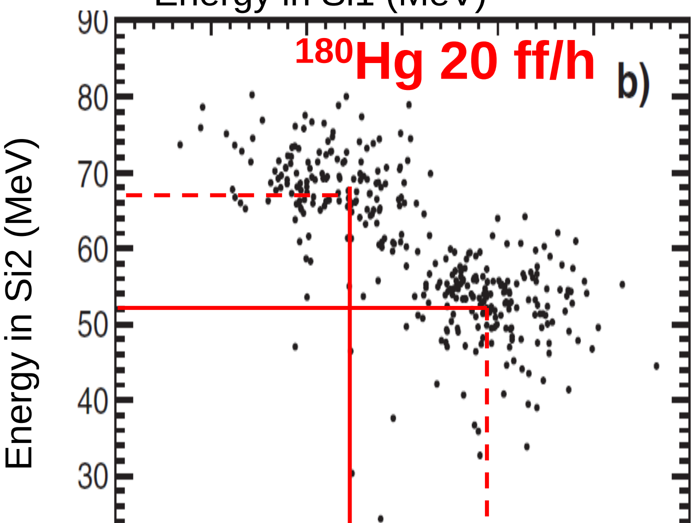
IS534 (ISOLDE) , 9-14 May 2012: Mass Distributions Measurements of ^{194,196}Po via βDF of ^{194,196}At

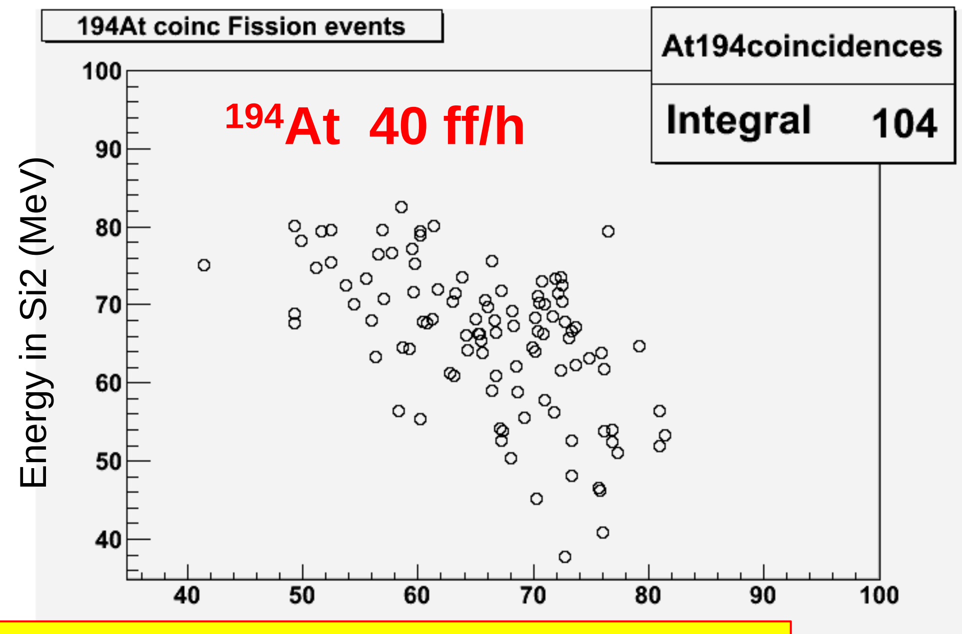


Fission Fragments Energy

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

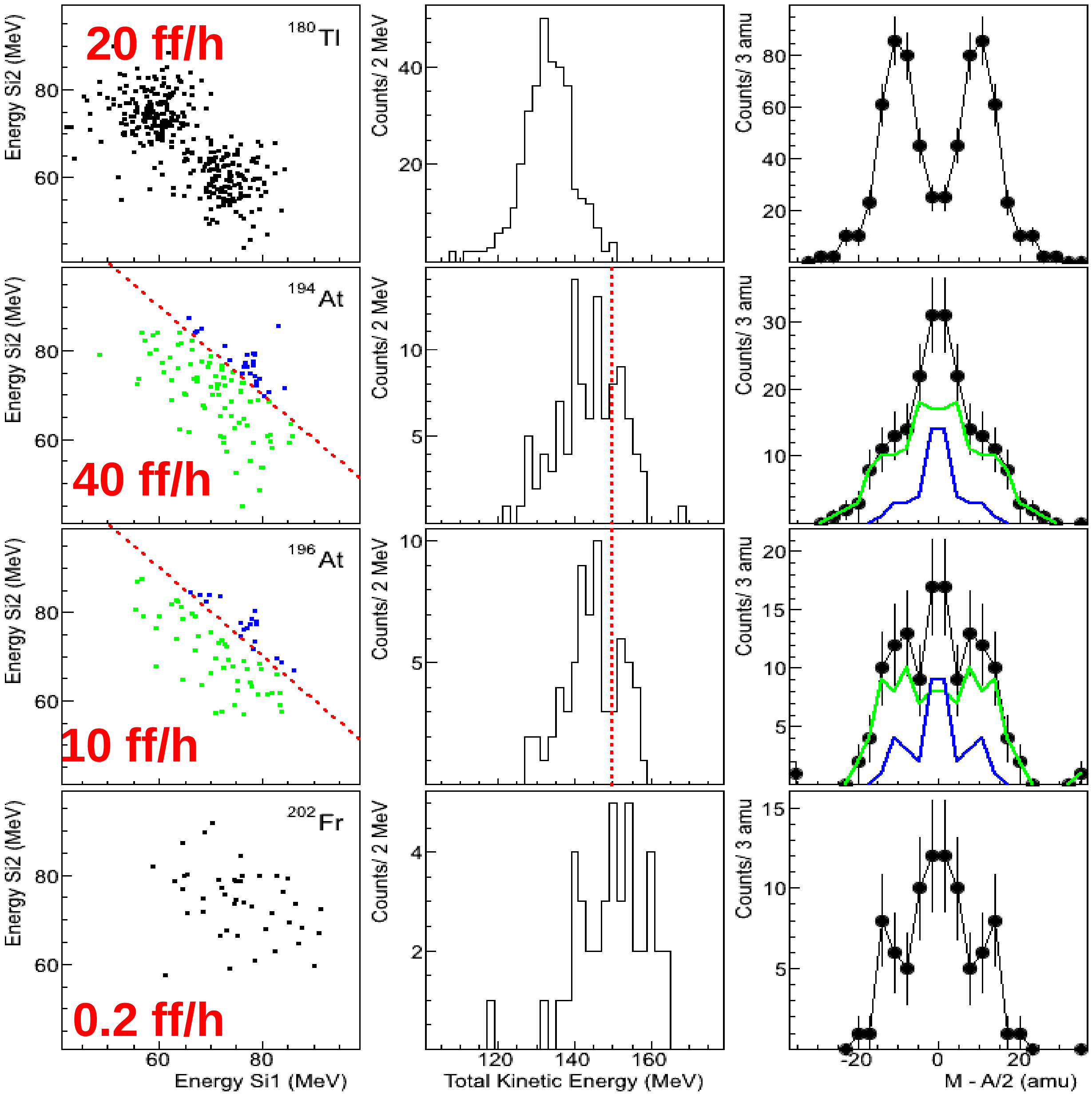






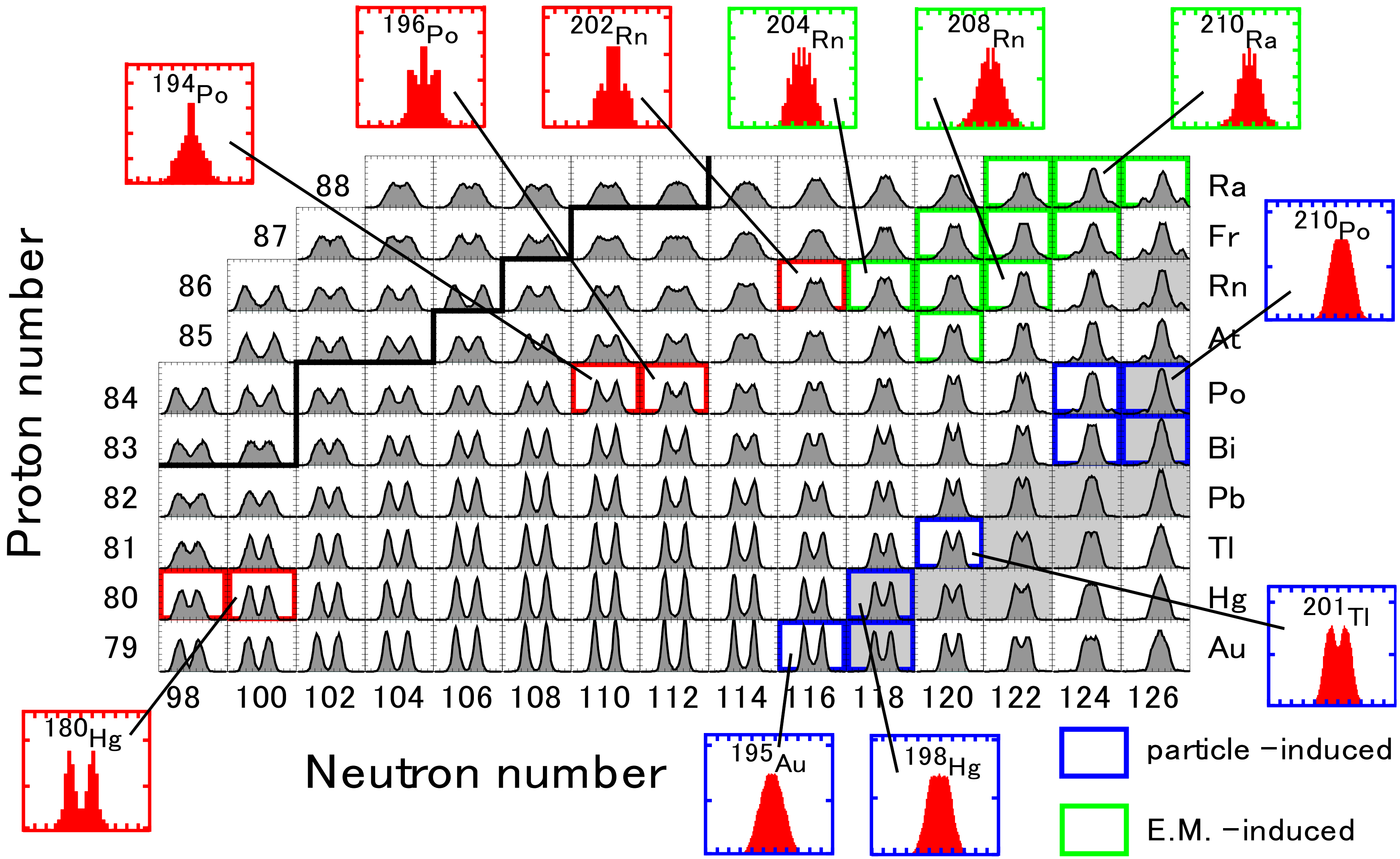
Clear difference in energy (thus, mass) distribution between 2-peaked fission of ^{180}Hg and a broad distribution in ^{194,196}Po

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



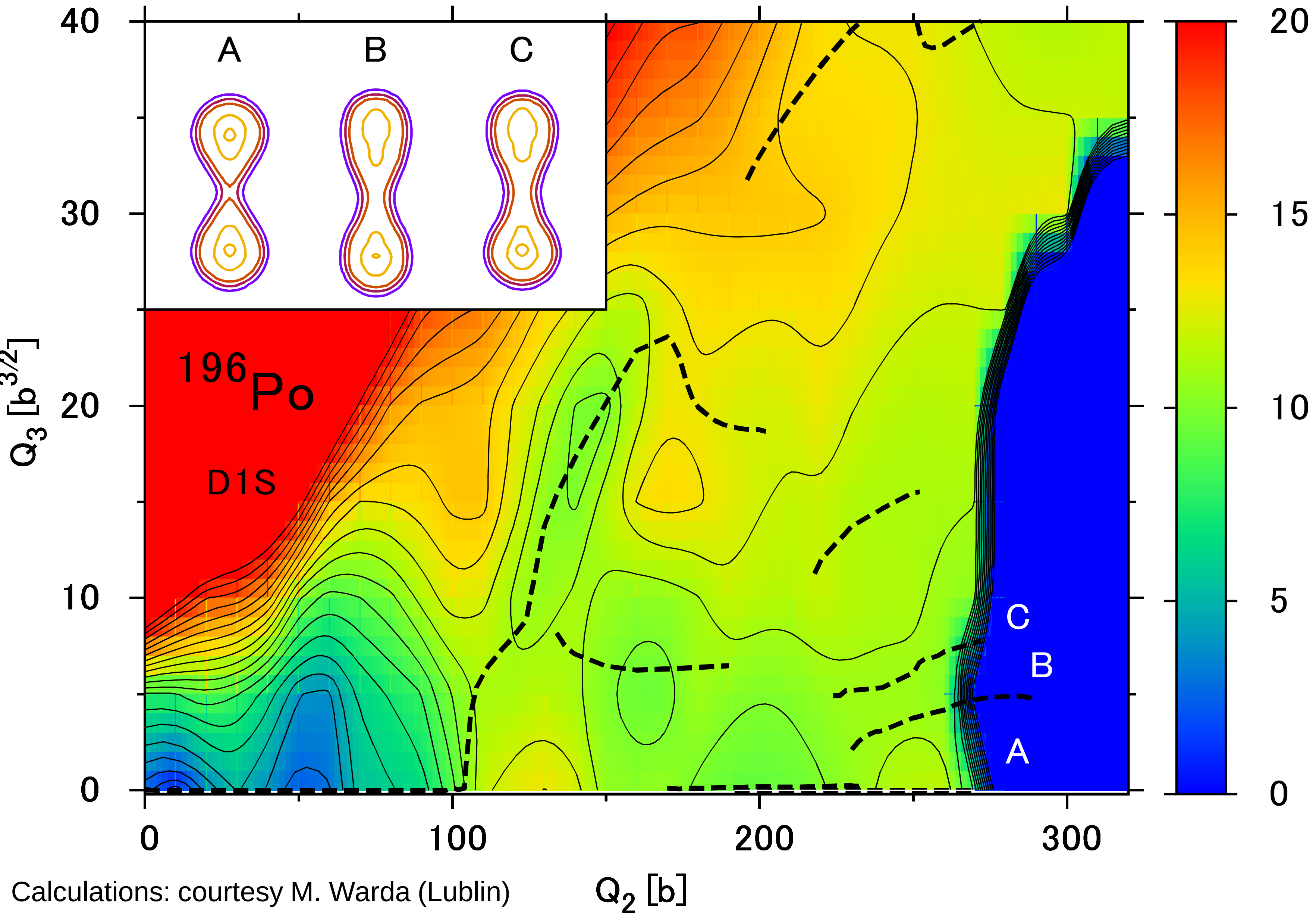
Courtesy L. Ghys (KU Leuven)

Experiment vs Theory



Calculations: courtesy P. Moller (LANL) and J. Randrup (LBNL)

Experiment vs Theory (^{196}At)



Calculations: courtesy M. Warda (Lublin)

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

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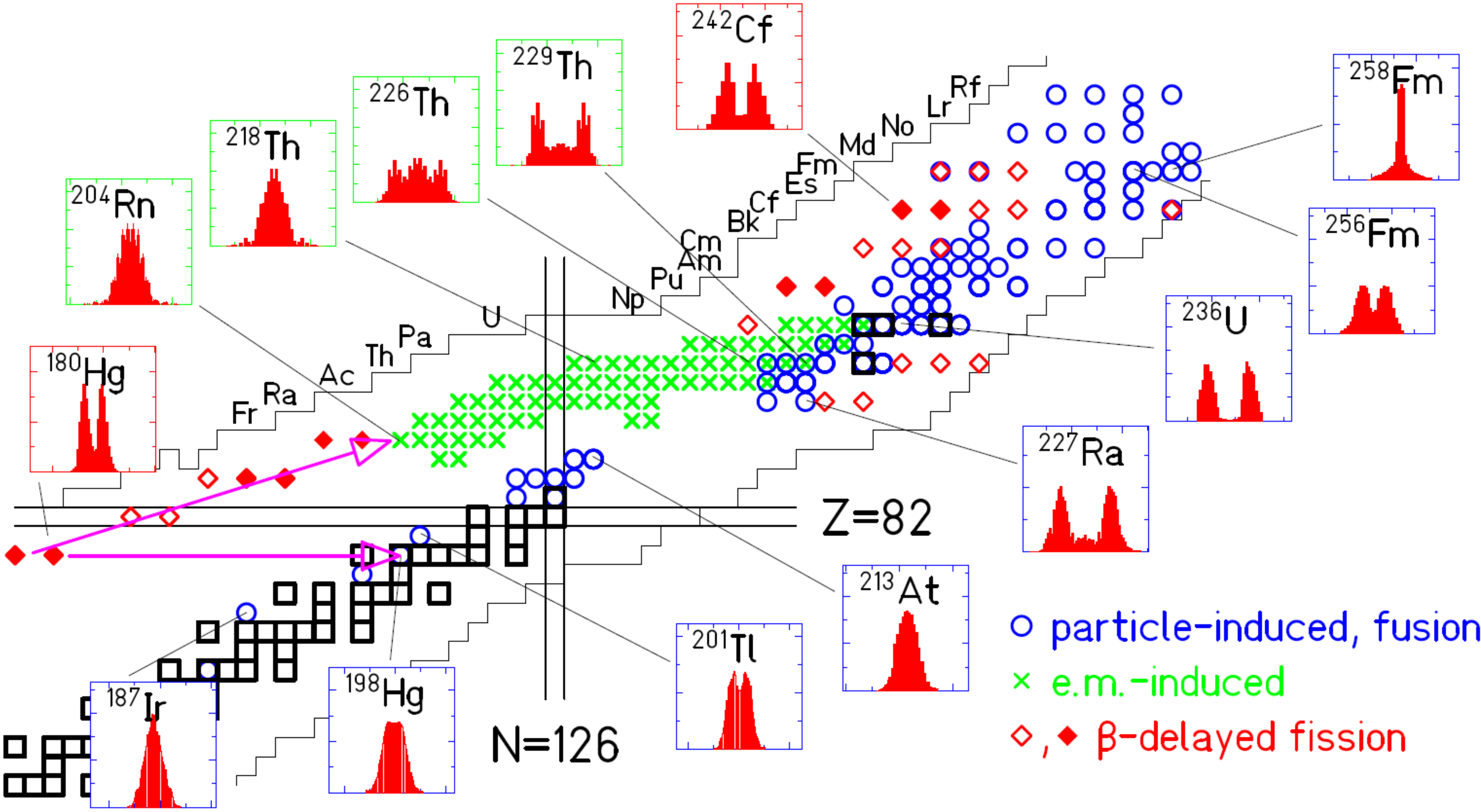
This Colloquium reviews the studies of exotic type of low-energy nuclear fission, the β-delayed fission (βDF). Emphasis is made on the new data from very neutron-deficient nuclei in the lead region, previously scarcely studied as far as fission is concerned. These

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	~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)

2013: ^{230}Am at GARIS(RIKEN)

Mapping 'Terra Incognita' in Low-Energy Fission



A. N. Andreyev, M. Huyse, P. Van Duppen, "Beta-delayed Fission in atomic nuclei", Reviews of Modern Physics, 85, 1541 (2013)

Thank you!

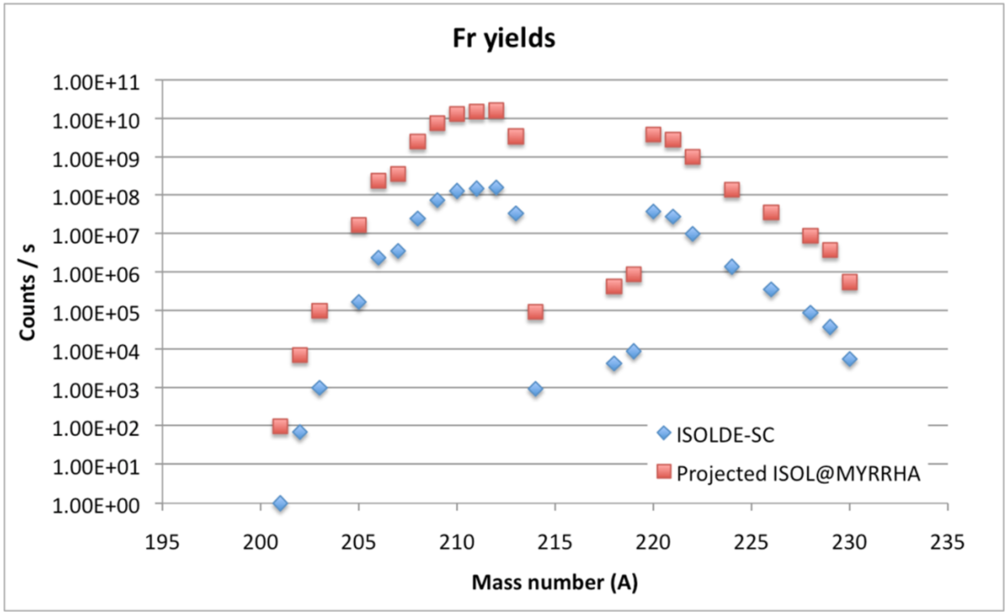
Strong support from Reimei Program of ASRC (JAEA) is very much appreciated

Beta-delayed fission in the neutron-rich Fr nuclei?

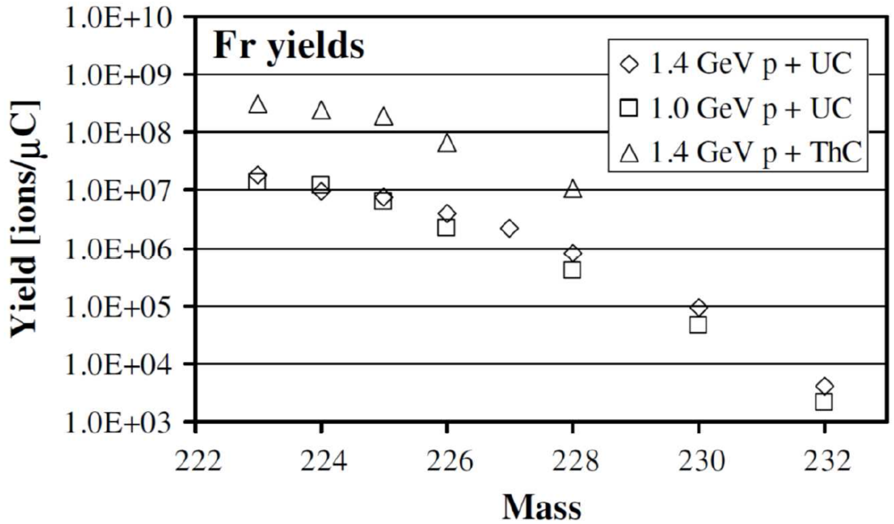
Earlier Gatchina attempts

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.



ISOLDE yields (UC, ThC)

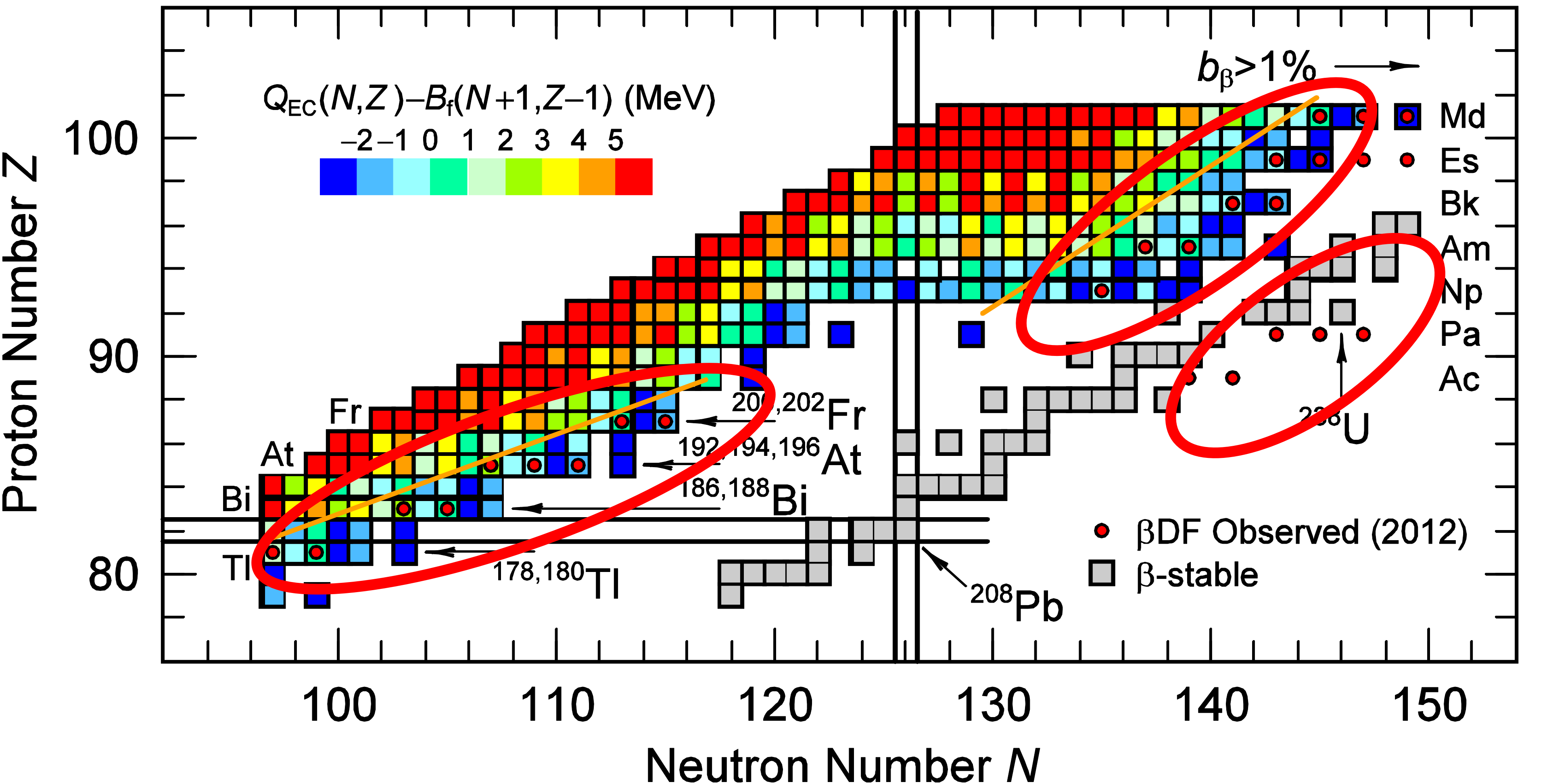


ThC targets?
~10^{-8} branching in 1 day now

Beta-delayed fission studies at recoil separators (e.g. at Lanzhou?)

Why recoil separators to search for βDF?

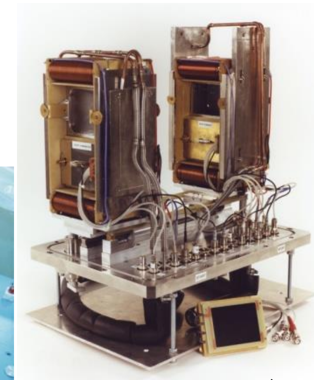
- **Unlike lead region, heavy actinides cannot be accessed by projectile fragmentation (as at ISOLDE)**
- **The only method at present: complete-fusion reactions**



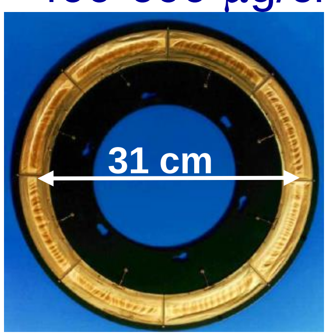
An example: βDF of ^{194}At at SHIP (GSI, Darmstadt)

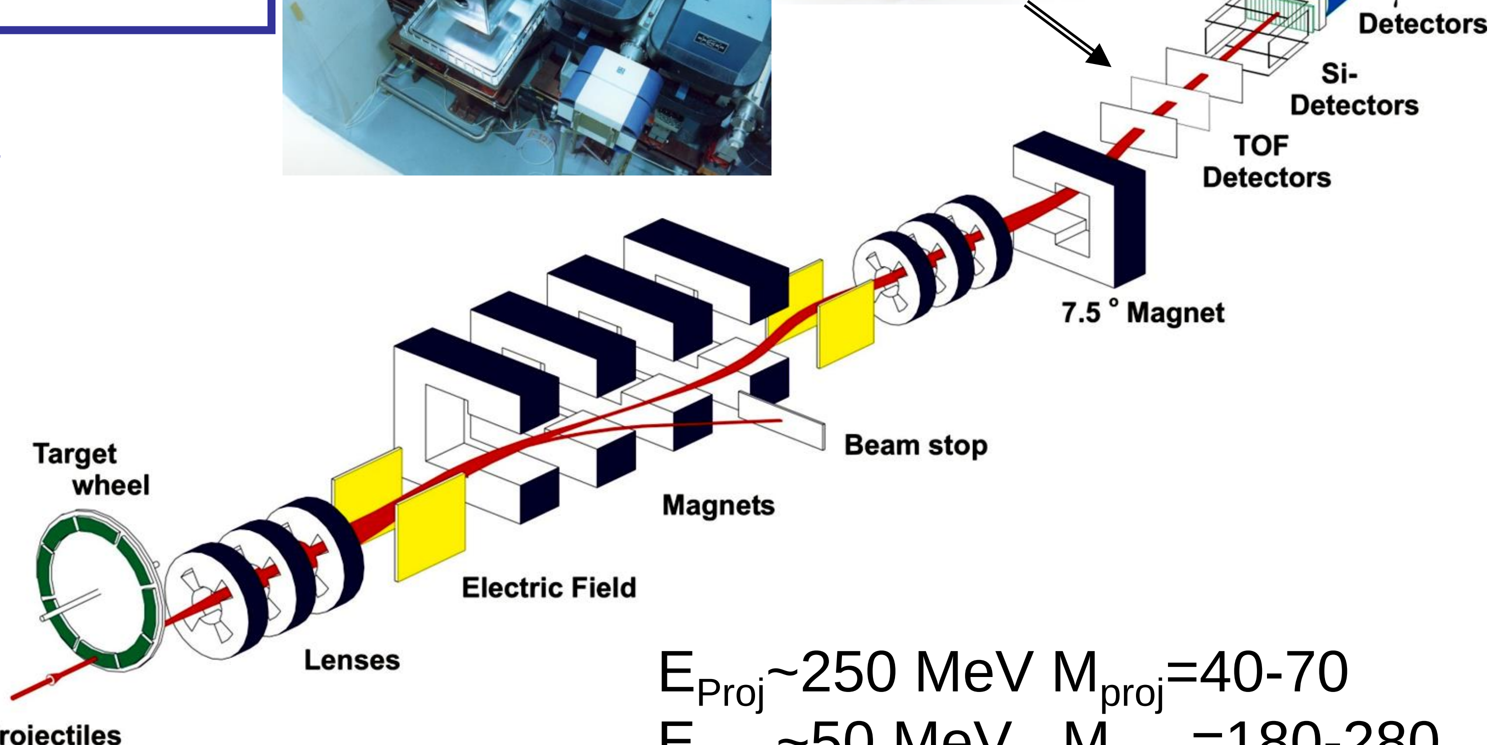
SHIP:

Separation time:	1 – 2 μs
Transmission:	20 – 50 %
Background:	10 – 50 Hz
Det. E. resolution:	18 – 25 keV
Det. Pos. resolution:	150 μm
Dead time:	3 – 25 μs



Rotating targets
~400-600 μg/cm^2

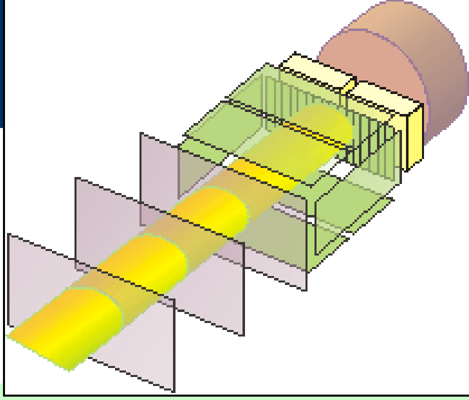




1 pμA of ^{52}Cr,^{58}Ni
~6×10^{12} pps

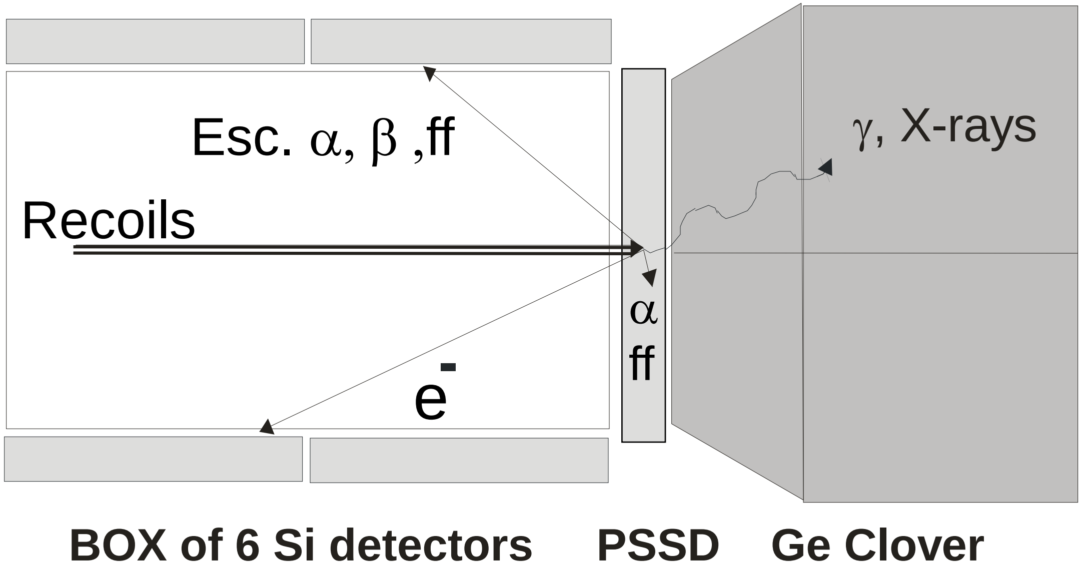
E_{Proj}~250 MeV M_{proj}=40-70
E_{EVR}~50 MeV M_{EVR}=180-280

SHIP Detection System



Measure **efficiently** all possible decays:

- particle decay (α, β, protons, fission) E=0.1-250 MeV
- gamma decay E=10-4000 keV
- internal conversion electrons E=50-500 keV

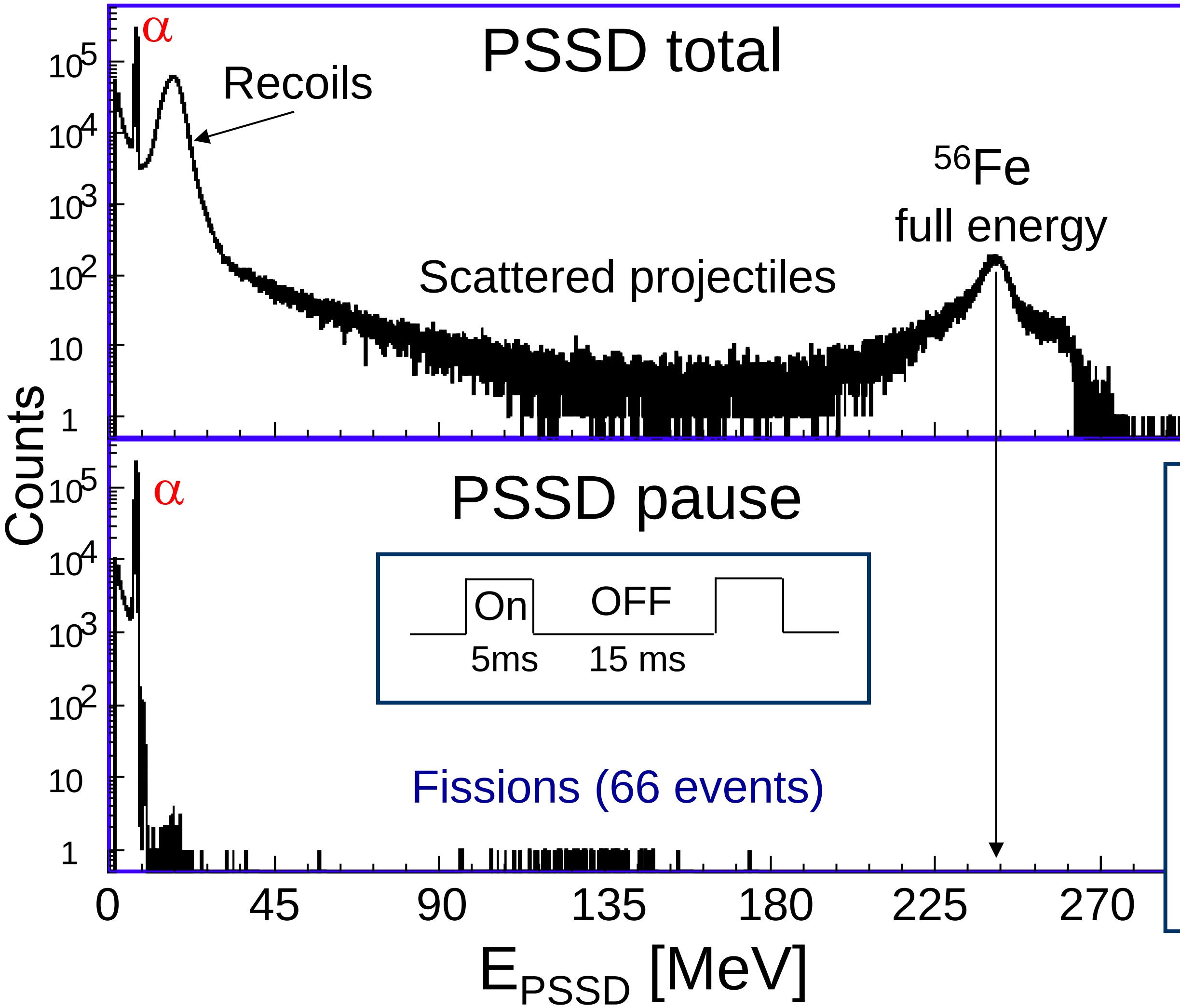


- **3 Time-Of-Flight detectors**
- **STOP detector** – 16 position sensitive Si strips (35×80mm), pos. resolution FWHM=150 μm, energy resolution 14 keV
- **6 BOX Si detectors** – for β and escaping α particles with a solid angle 80% of 2π
- **GAMMA detectors** – large-volume Clover detector for x rays or γ rays in coincidence with α's
- **VETO detector** – reduces background

A.N. Andreyev et al. 'Conversion electron and β decay spectroscopy at SHIP', NIM A533, 416 (2004)

Identification of βDF in ^{194}At, SHIP(GSI)

A. Andreyev et al, PRC, 87, 014317 (2013)



$^{56}Fe + ^{141}Pr \rightarrow ^{194}At + 3n$

I(^{56}Fe)~600 pnA

86×10^3 nuclei

66 fission events (pause)

Identification based on:

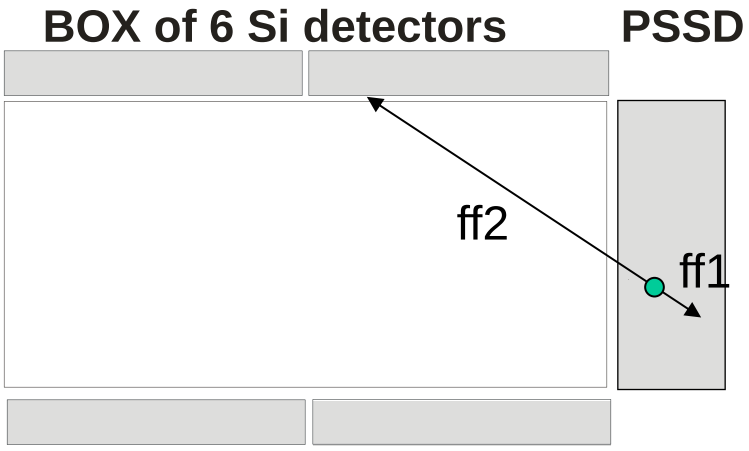
- Half-life
  $T_{1/2,\alpha}(^{194}At)$=280(20) ms
  $T_{1/2,fiss}(^{194}At)$=300(60) ms
- Excitation functions
- Cross-irradiation (^{56}Fe,^{52}Cr)
- Double fold ff events (BOX)
- Coincidences with gammas

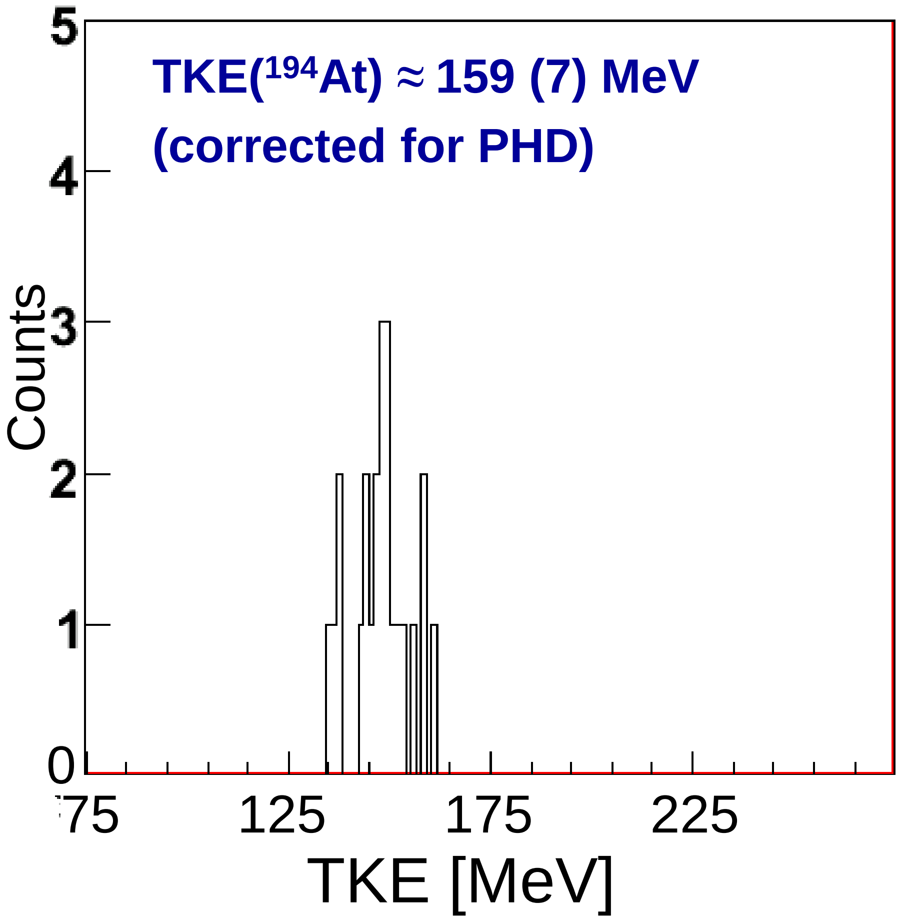
First observed in the $^{52}Cr + ^{144}Sm \rightarrow ^{194}At + pn$ reaction (SHIP,2006)

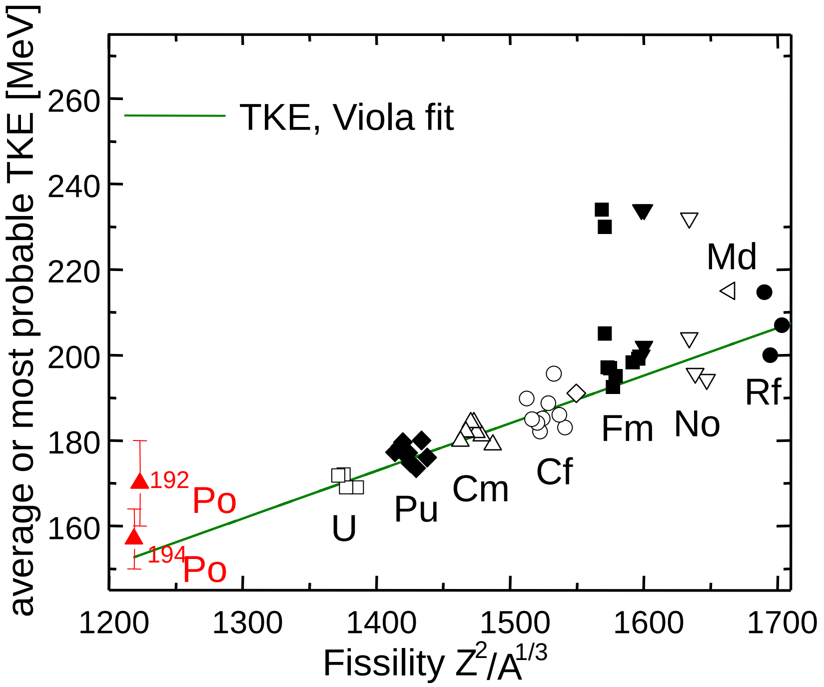
16 fissions in pause

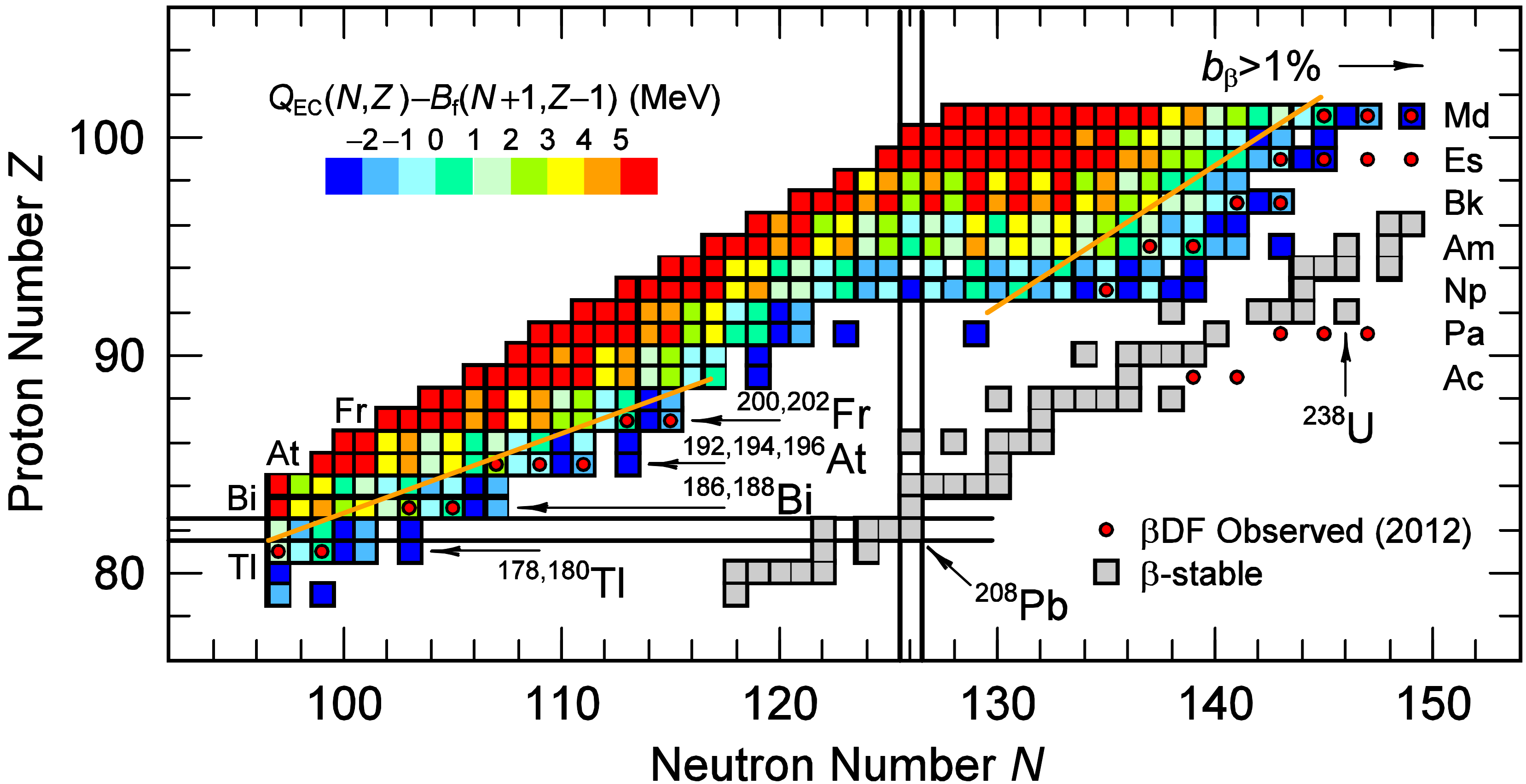
Total Kinetic Energy in βDF of ^{194}At

TKE: Add up the energies of 2ff from the PSSD and BOX detectors









$Q_{EC}(N,Z)-B_f(N+1,Z-1)$ (MeV)
−2 −1 0 1 2 3 4 5
b_β>1%
Md
Es
Bk
Am
Np
Pa
Ac
Fr
At
Bi
Tl
200,202Fr
192,194,196At
186,188Bi
178,180Tl
238U
208Pb
βDF Observed (2012)
β-stable
Proton Number Z
Neutron Number N
80
90
100
110
120
130
140
150

'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

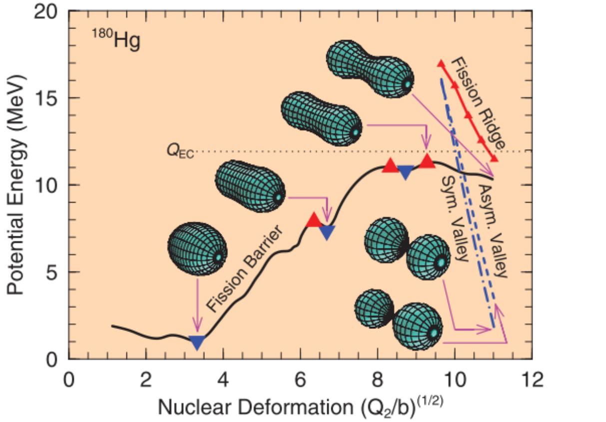
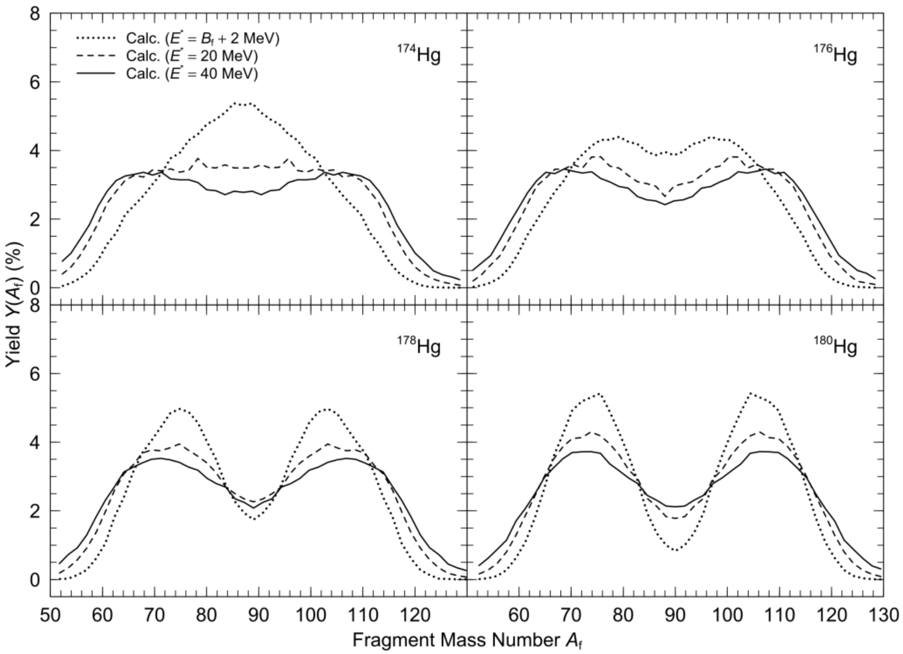
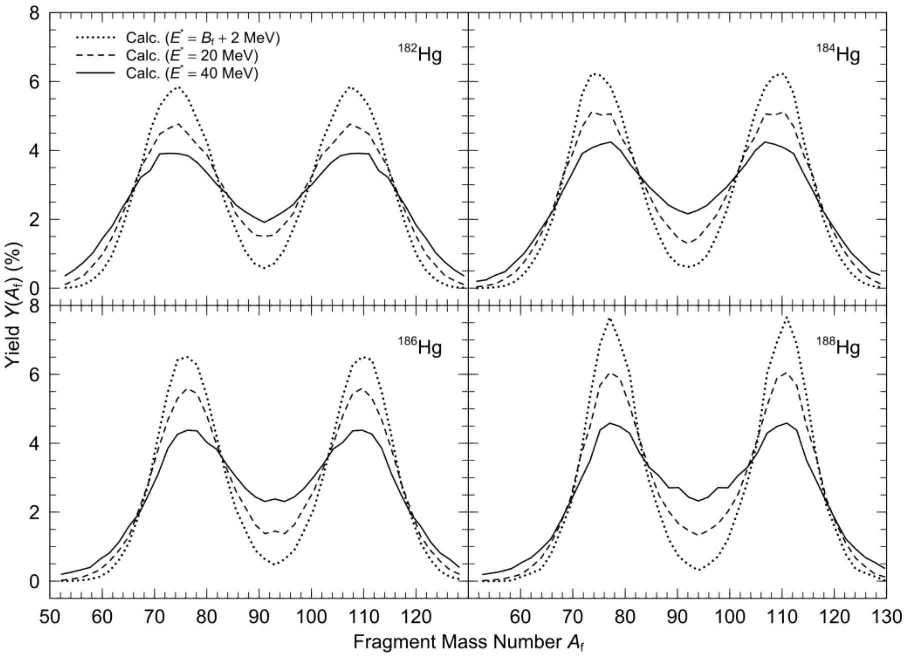


FIG. 4. (Color online) Minima, saddles, major valleys, and ridges in the 5D potential-energy surface of ^{180}Hg (see text). At the last plotted point on the fission barrier, $(Q_2/\mathrm{b})^{(1/2)} \approx 11$, the asymmetry of the shape is $A_\mathrm{H}/A_\mathrm{L} = 108/72$.





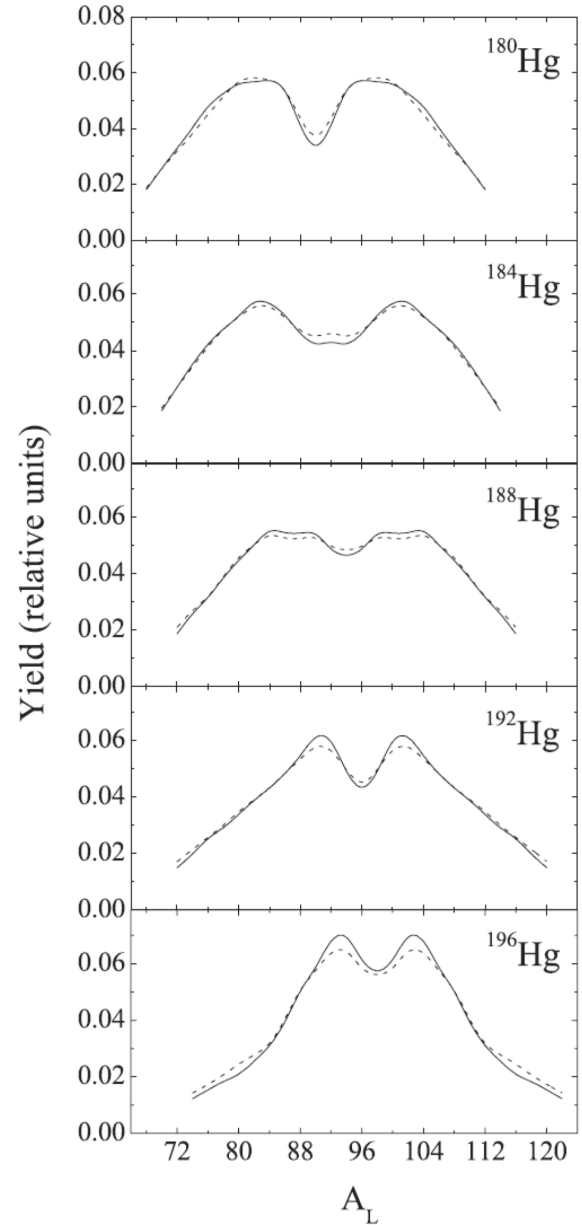
'Improved Scission-Point Model'

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

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

‘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]

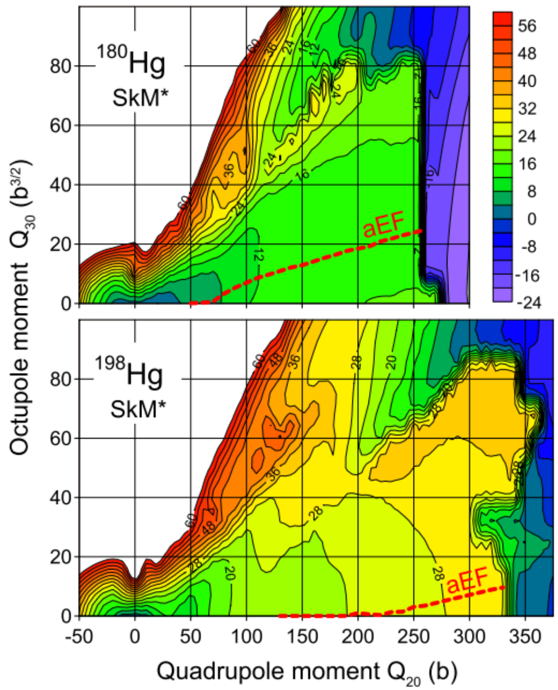


FIG. 2. (Color online) PES for ^{180}Hg (top) and ^{198}Hg (bottom) in the plane of collective coordinates $Q_{20} - Q_{30}$ in HFB-SkM*. The aEF fission pathway corresponding to asymmetric elongated fragments is marked. The difference between contour lines is 4 MeV. The effects due to triaxiality, known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

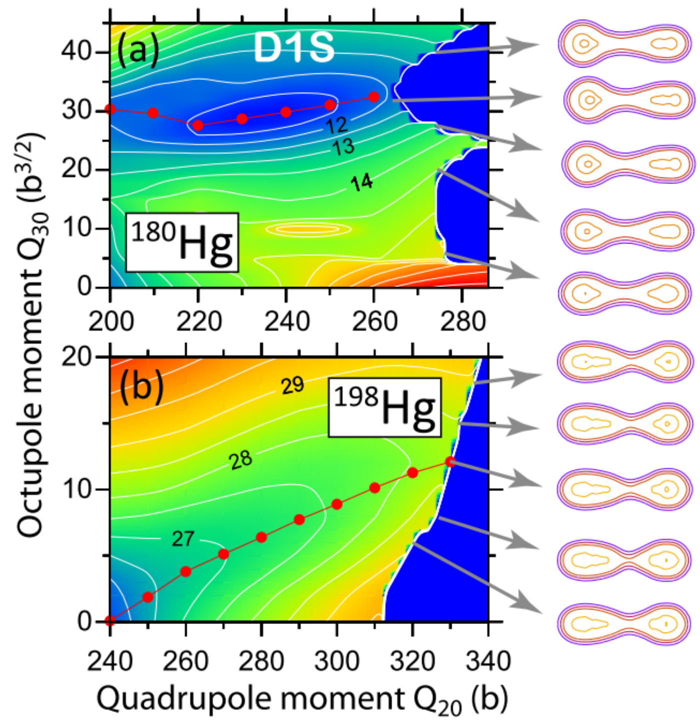
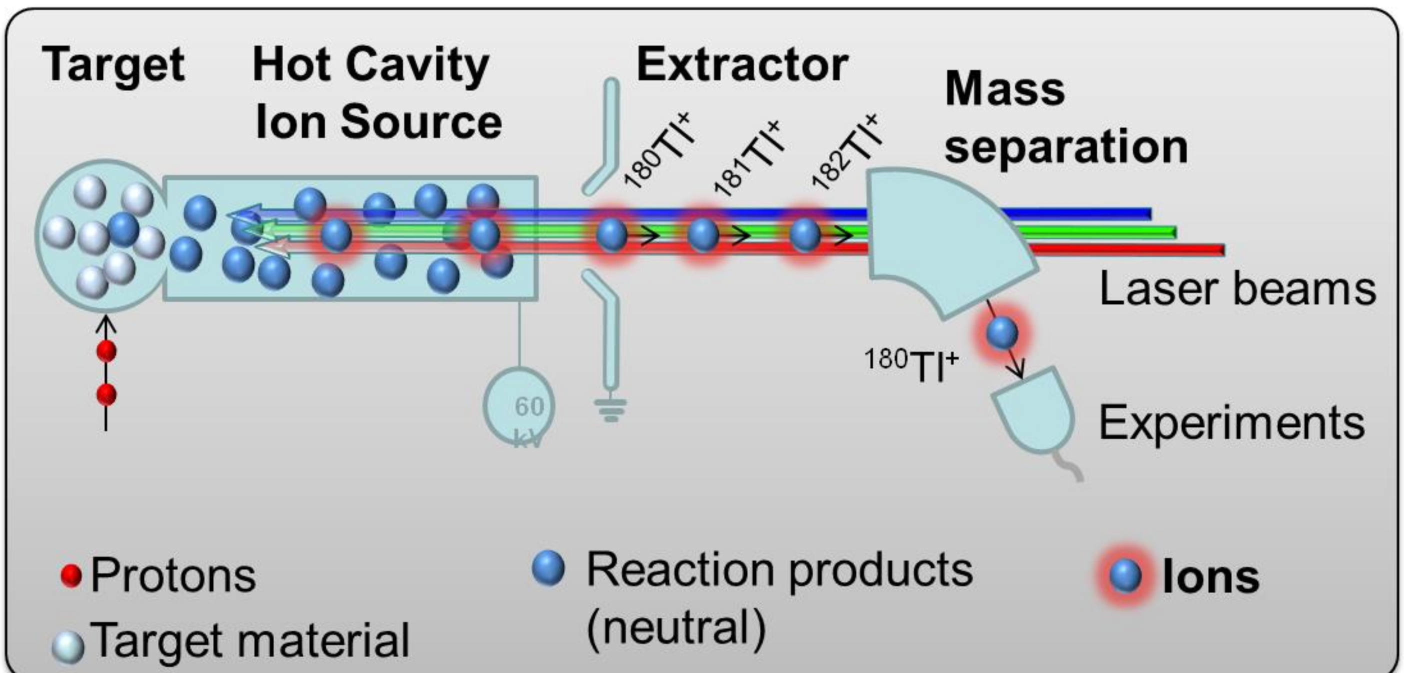


FIG. 3. (Color online) PES in HFB-D1S for ^{180}Hg (top) and ^{198}Hg (bottom) in the (Q_{20}, Q_{30}) plane in the pre-scission region of aEF valley. The symmetric limit corresponds to $Q_{30} = 0$. The aEF valley and density profiles for pre-scission configurations are indicated. The difference between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



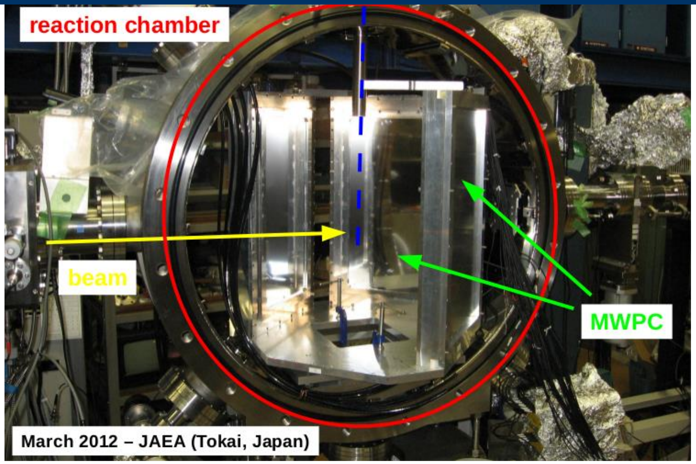
Target
Hot Cavity Ion Source
Extractor
Mass separation
180Tl+
181Tl+
182Tl+
Laser beams
180Tl+
60 kV
Experiments
Protons
Target material
Reaction products (neutral)
Ions

Fusion-Fission Reactions in the Lead Region at JAEA's tandem (K.Nishio et al)

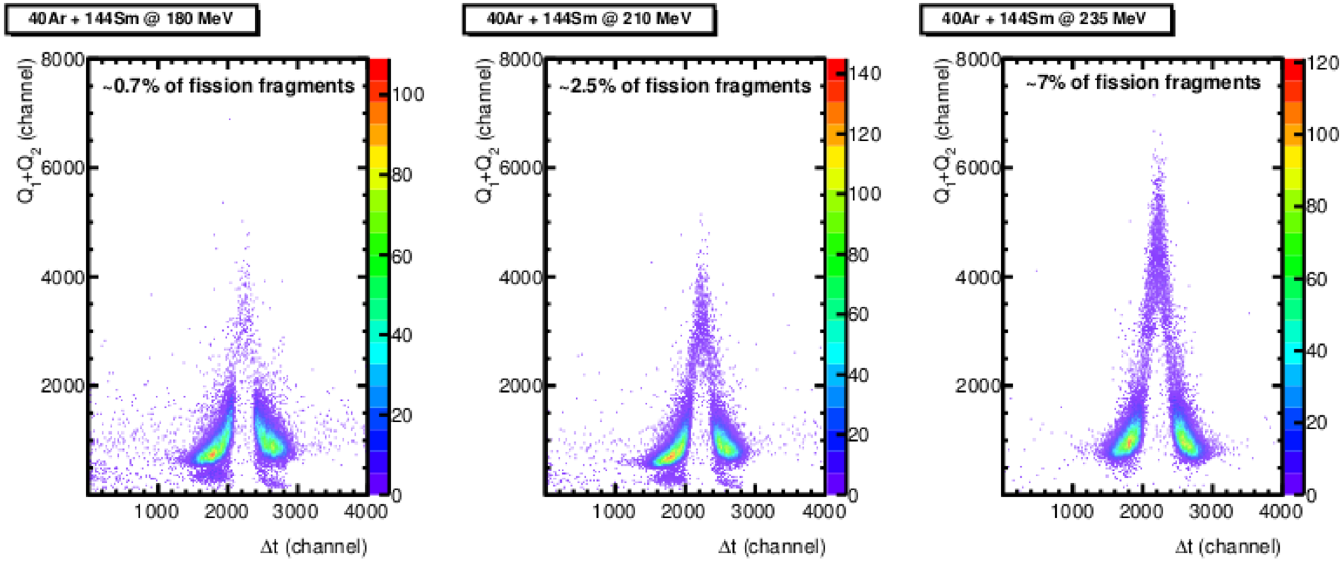
New experiment at JAEA (March-April 2012)

36−40Ar + 144Sm → 180−184Hg
36−40Ar + 154Sm → 190−194Hg
36−40Ar + 142Nd → 178−182Pt
90Zr + 90Zr → 180Hg

Ebeam from 160 to 235 MeV



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



Analysis in progress

How exotic is βDF?

Neutron-deficient side:

Beta-delayed p, d, t, α.. , β2p...emission ~160 cases

M. Borge and B.Blank (2008)

Neutron-rich side:

Beta-delayed neutron emission.. , β2n.. ~217 cases

B. Pfeiffer et al., Prog. Nucl. Ener. 41 (2002) 39

Beta-delayed fission:

neutron-deficient side:

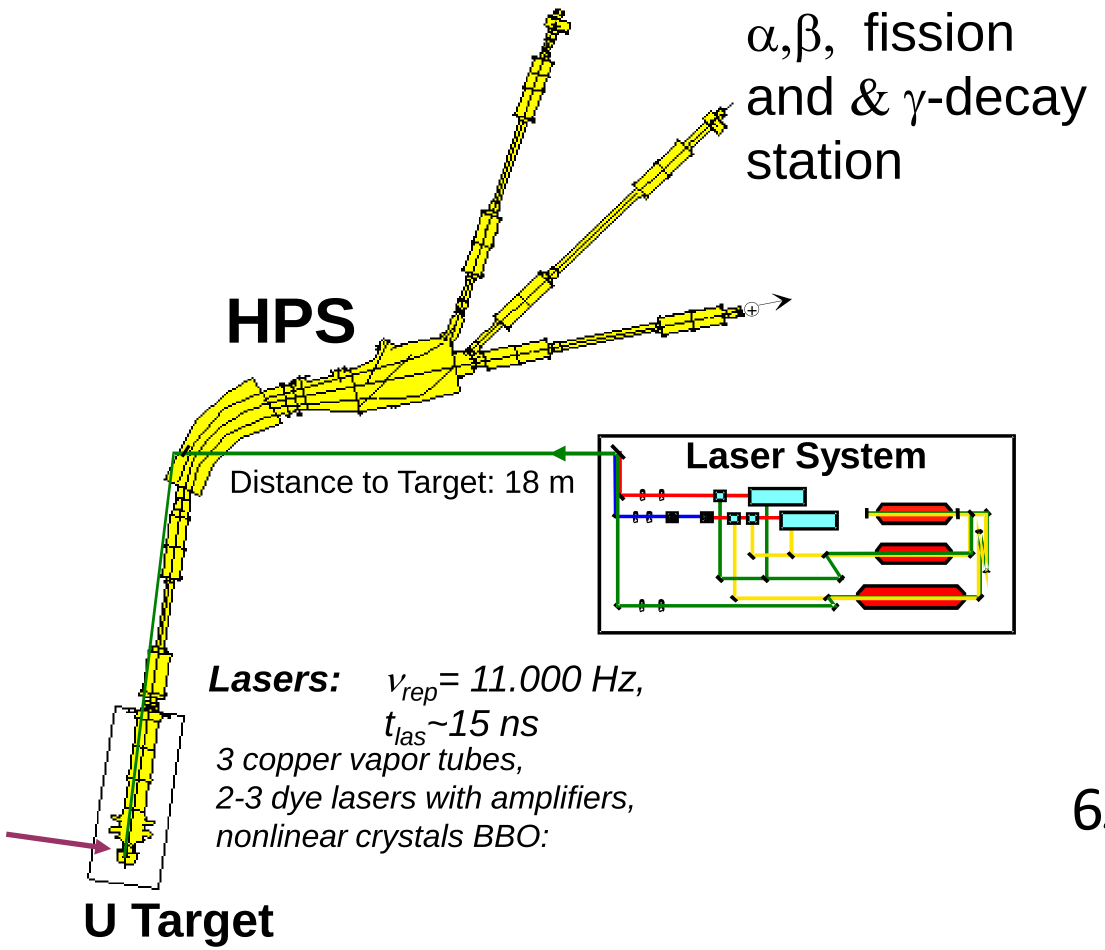
12 cases before our studies, U region (up to ~2008)

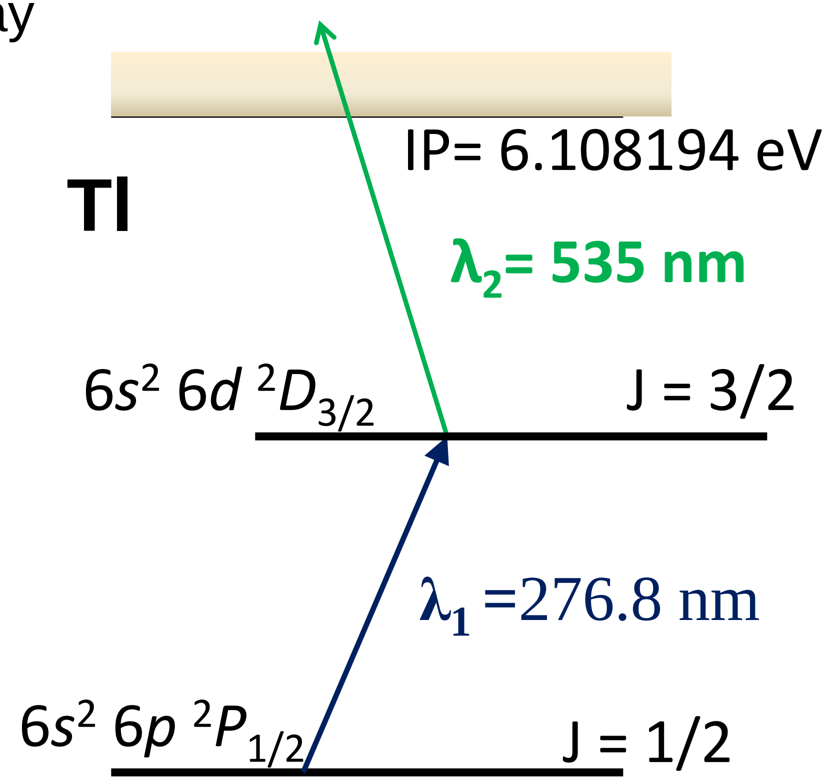
9 new cases in the Pb region (from ~2008 on)

several nuclei on the neutron-rich side (data unclear)

RILIS: Resonance Ionization Laser Ion Source at ISOLDE

Procedure: decay measurements (α, fission, β-γ decays) of Tl ions, resonantly ionized by RILIS and mass-separated by HRS@ISOLDE



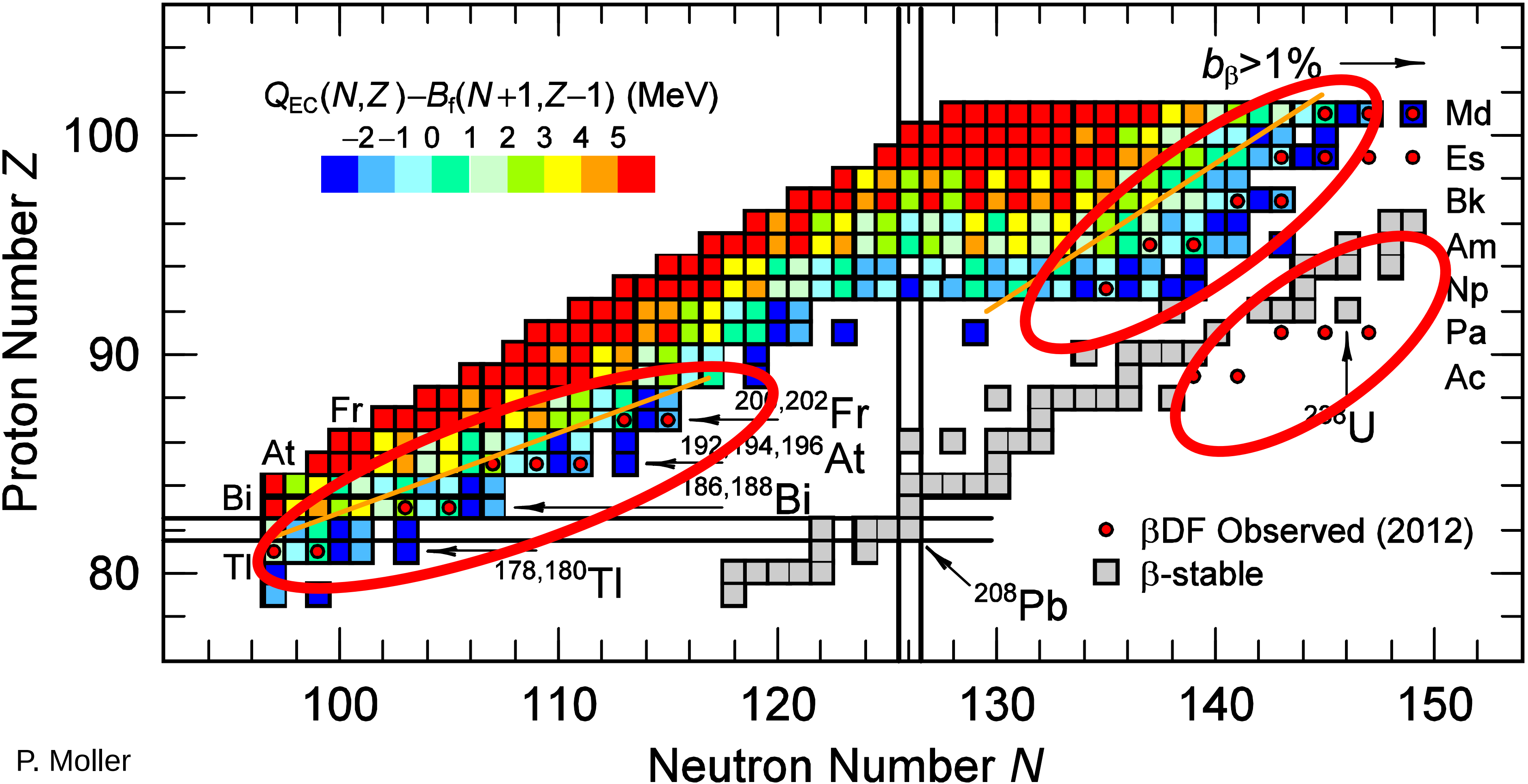


Proton Beam 1.4 GeV, $3\cdot10^{13}$ pps
2.4 μs pulse length, 1.2 s period

Three regions to search for βDF

Necessary conditions for βDF to occur:

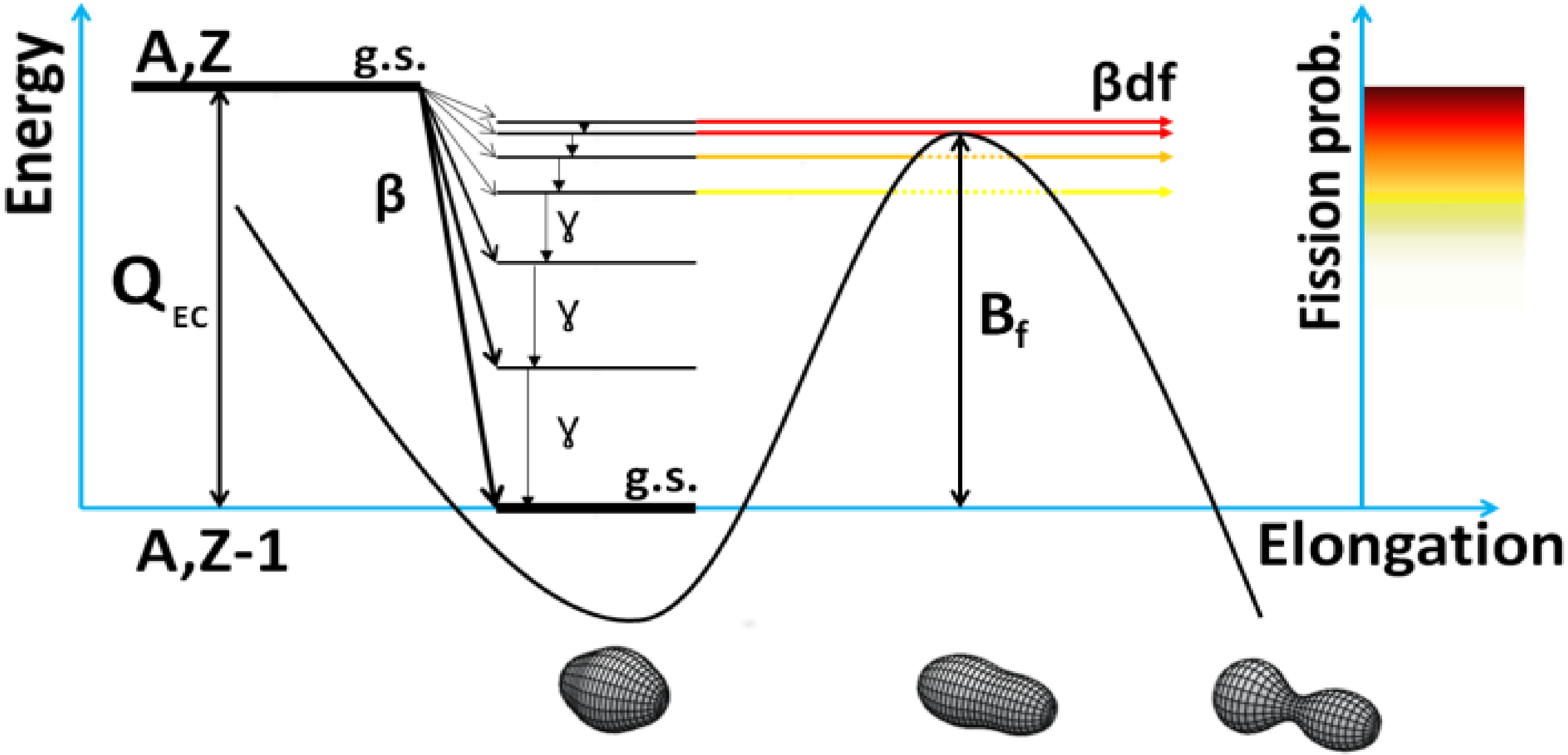
- Q_{EC}(Parent)~B_f(Daughter) [Q_{EC}-B_f > -2 MeV]
- Beta-branching ratio b_β>0



P. Moller

Beta-Delayed Fission

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



βDF branch

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

$P_{\beta DF}$ Probability: Extraction of fission barriers?!

$$P_{\beta df} = \frac{\int_0^{Q_\beta} F(Q_\beta - E) S_\beta(E) \frac{\Gamma_f(E)}{\Gamma_f(E)+\Gamma_\gamma(E)} dE}{\int_0^{Q_\beta} F(Q_\beta - E) S_\beta(E) dE}$$

Need to know S_β!? (next slide)

$$\frac{\Gamma_f}{\Gamma_{tot}} = \frac{\Gamma_f}{\Gamma_f + \Gamma_\gamma}$$ -ratio of the fission and total widths of excited levels in daughter (Γ_n is not important for neutron-deficient nuclei)

$$\Gamma_\gamma = \frac{9.7\times10^{-7} \times T^4 \times \exp(E/T)}{2\pi\rho}$$, ρ – level density, T - temperature

$$\Gamma_f = \frac{1}{2\pi\rho}\left\{1+\exp\left[\frac{2\pi(B_f-E)}{\hbar\omega_f}\right]\right\}^{-1}$$ -inverted parabola approximation

D.L. Hill and J.A.Wheeler

Measurement of $P_{\beta DF}$ allows to deduce Fission Barrier B_f

e.g . H.V. Klapdor et al., Z.Phys.A292, 1979,249; D. Habs et. al. Z.Phys. A285 (1978), 53

$P_{\beta DF}$ Probability: Extraction of fission barriers?!

PHYSICAL REVIEW C **86**, 024308 (2012)

Fission-barrier heights of neutron-deficient mercury nuclei

M. Veselský,[1,*] A. N. Andreyev,[2] S. Antalic,[3] M. Huyse,[4] P. Möller,[5] K. Nishio,[6] A. J. Sierk,[5]
P. Van Duppen,[4] and M. Venhart[1,4]

$$P_{\beta df} = \frac{\int_0^{Q_\beta} F(Q_\beta - E) S_\beta(E) \frac{\Gamma_f(E)}{\Gamma_f(E)+\Gamma_\gamma(E)} dE}{\int_0^{Q_\beta} F(Q_\beta - E) S_\beta(E) dE}$$

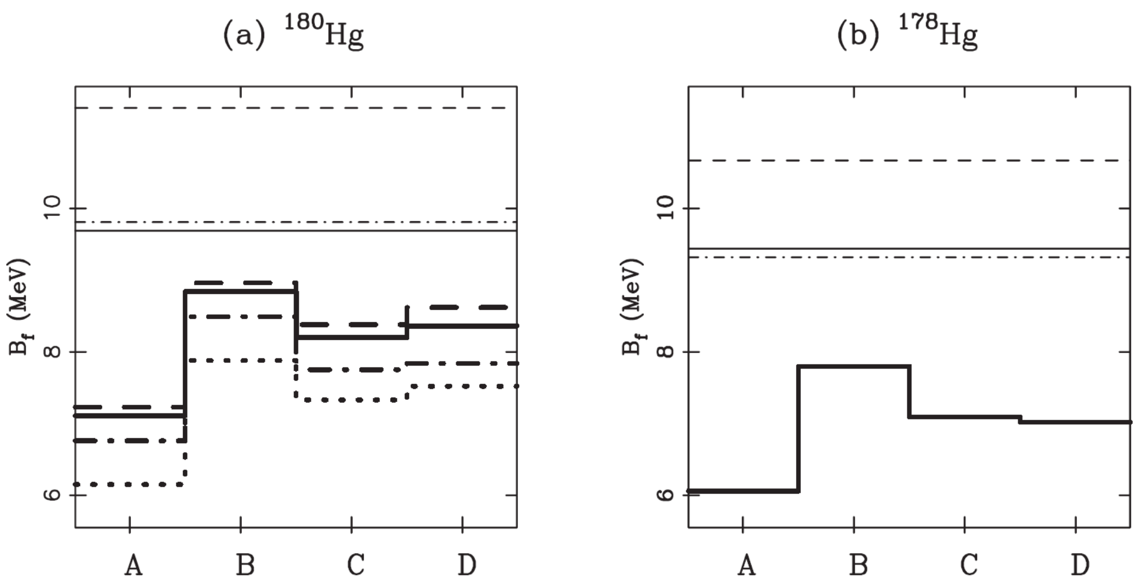
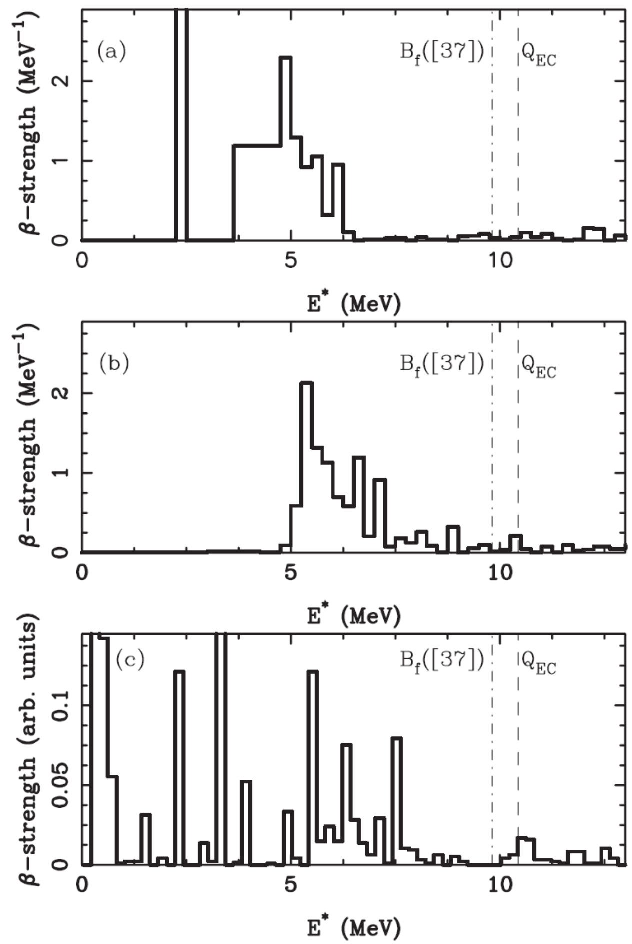


FIG. 3. (Color online) (a) Fission-barrier heights of ^{180}Hg in four variants A–D. Four β-strength functions were used: calculated

Need to know S_β!?



Clearly – model-dependent (but we tried many parametrizations)
Conclusion: "experimental barriers" are always lower than calculated

Development of At beams

The Problem: Element At has no stable isotopes, $T_{1/2}$=8 h (^{210}At)
Only ~70 mg of At present in the 1st mile of Earth' core
Must be produced and studied 'on-line' at an accelerator

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-INTC-2010-010
INTC-I-086

Letter of Intent to the ISOLDE and N-ToF Experiments Committee (INTC)

Development of astatine ion beams with RILIS

A. Andreyev[1], S. Antalic[2], L.-E. Berg[3], T. Cocolios[4], V.N. Fedosseev[5], T. Gottwald[6], M. Huyse[4], Yu. Kudryavtsev[4], U. Köster[7], W. Kurcewicz[8], J. Lassen[9], H. Mach[10], B.A. Marsh[5,11], R. Page[12], D. Pauwels[4], S. Räder, S. Rothe[5,6], A.M. Sjödin[5], T. Stora[5], P. Van Duppen[4], K. Wendt[6]

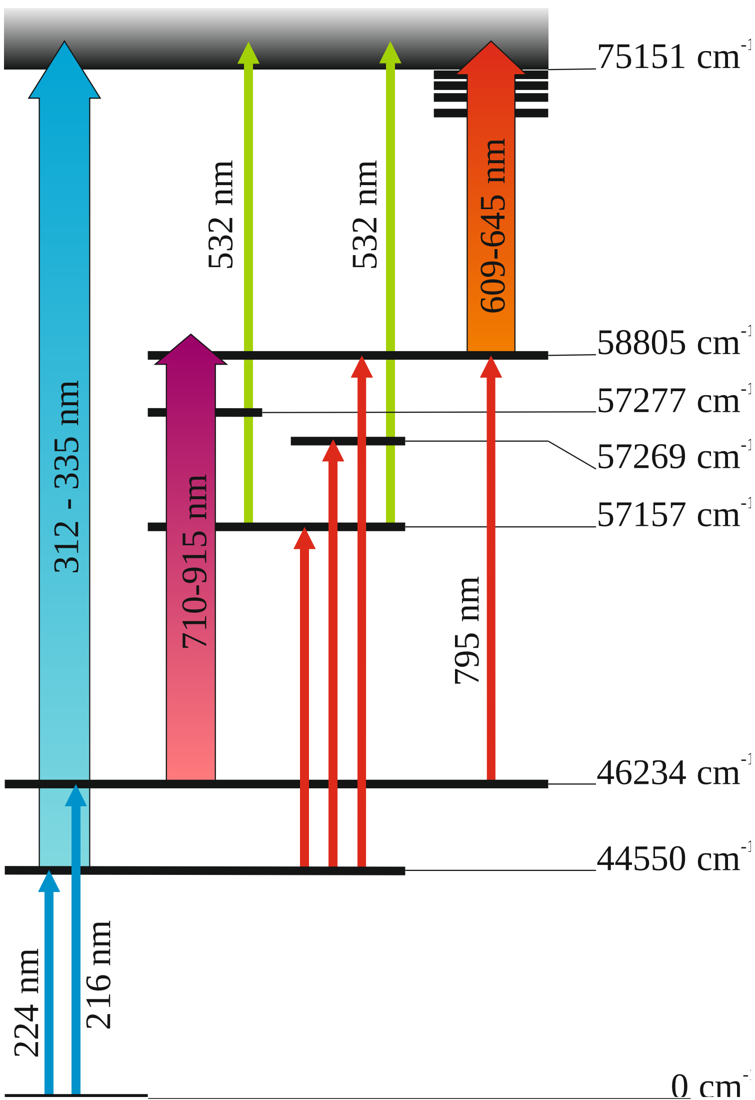
1: University of the West of Scotland, Paisley, UK
2: Comenius University, Bratislava, Slovakia
3: Royal Institute of Technology (KTH), Stockholm, Sweden
4: IKS, KU Leuven, Belgium
5: CERN, Geneva, Switzerland
6: Institut für Physik, Mainz University, Mainz, Germany
7. ILL, Grenoble, France
8. University of Warsaw, Poland
9. TRIUMF, Vancouver, Canada
10. Department of Nuclear and Particle Physics, Uppsala University, Sweden
11: The University of Manchester, Manchester, UK
12: University of Liverpool, UK

Spokespersons: A. Andreyev, V.N. Fedosseev
Contact person: S. Rothe

2010: Letter of Intent (CERN):
"Development of astatine ion beams with Resonance Ionization Laser Ion Source (RILIS)"

Spokespersons:
A. Andreyev and V. Fedosseev

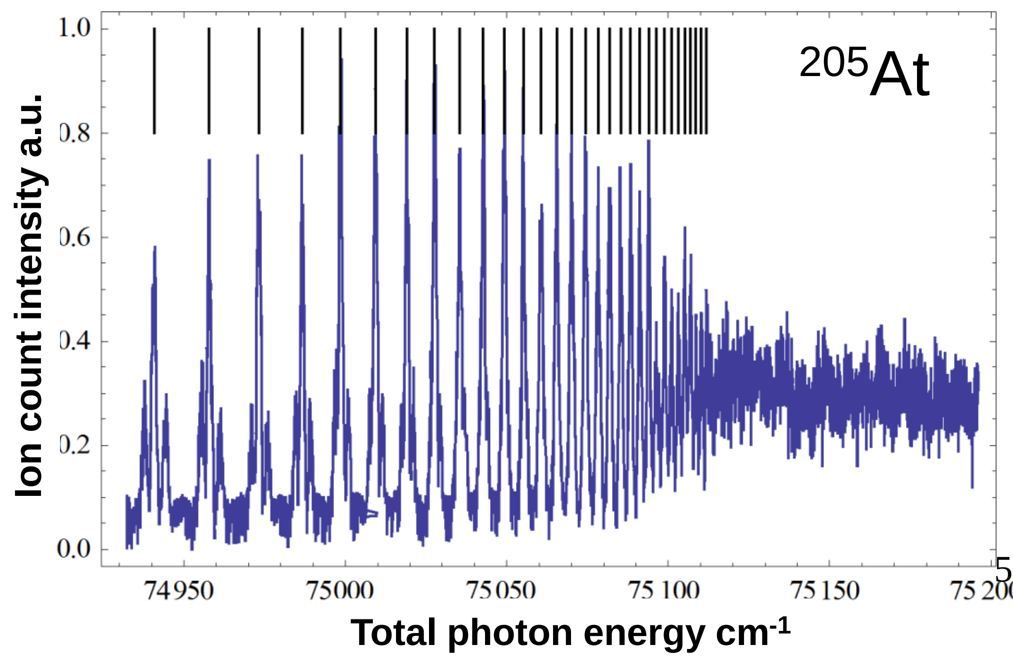
First determination of the Ionization Potential for the radioactive element At



3 successful **on-line** development runs
ISOLDE (Nov. 2010, May 2011)
TRIUMF, Canada (Dec. 2010)

- Many new atomic levels found
- Transition strengths measured

- **Ionization potential measured** (scan of ionizing laser: converging Rydberg levels allow precise determination of the IP)



First determination of the Ionization Potential for the radioactive element At

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Measurement of the first ionization potential of astatine by laser ionization spectroscopy

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