Mapping Low-Energy Fission with RIBs

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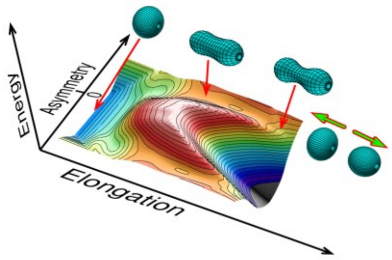
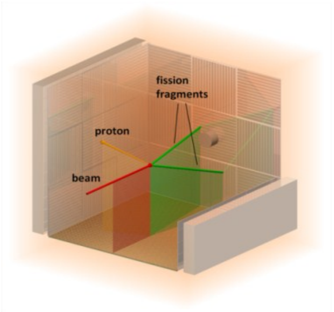
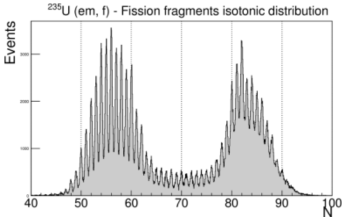
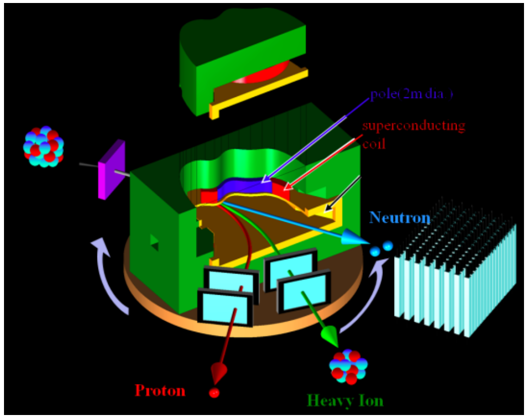
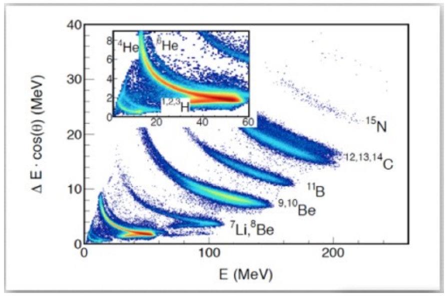










Thanks to:

F. Farget for VAMOS@GANIL
J.-F. Martin and J. Taieb (CEA) for SOFIA@GSI
M. Veselsky (Bratislava) for IS581@ISOLDE
D. Mucher and M. Sako for SAMURAI@RIKEN

Orsay EURISOL TOWN Meeting, 30-31st October 2014

Outlook

- Brief (experimental) review on low-energy fission
- Low-energy fission in “new” regions of the Nuclear Chart
- Beta Delayed Fission (βDF) at ISOLDE at 60 keV
- 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)

Outlook

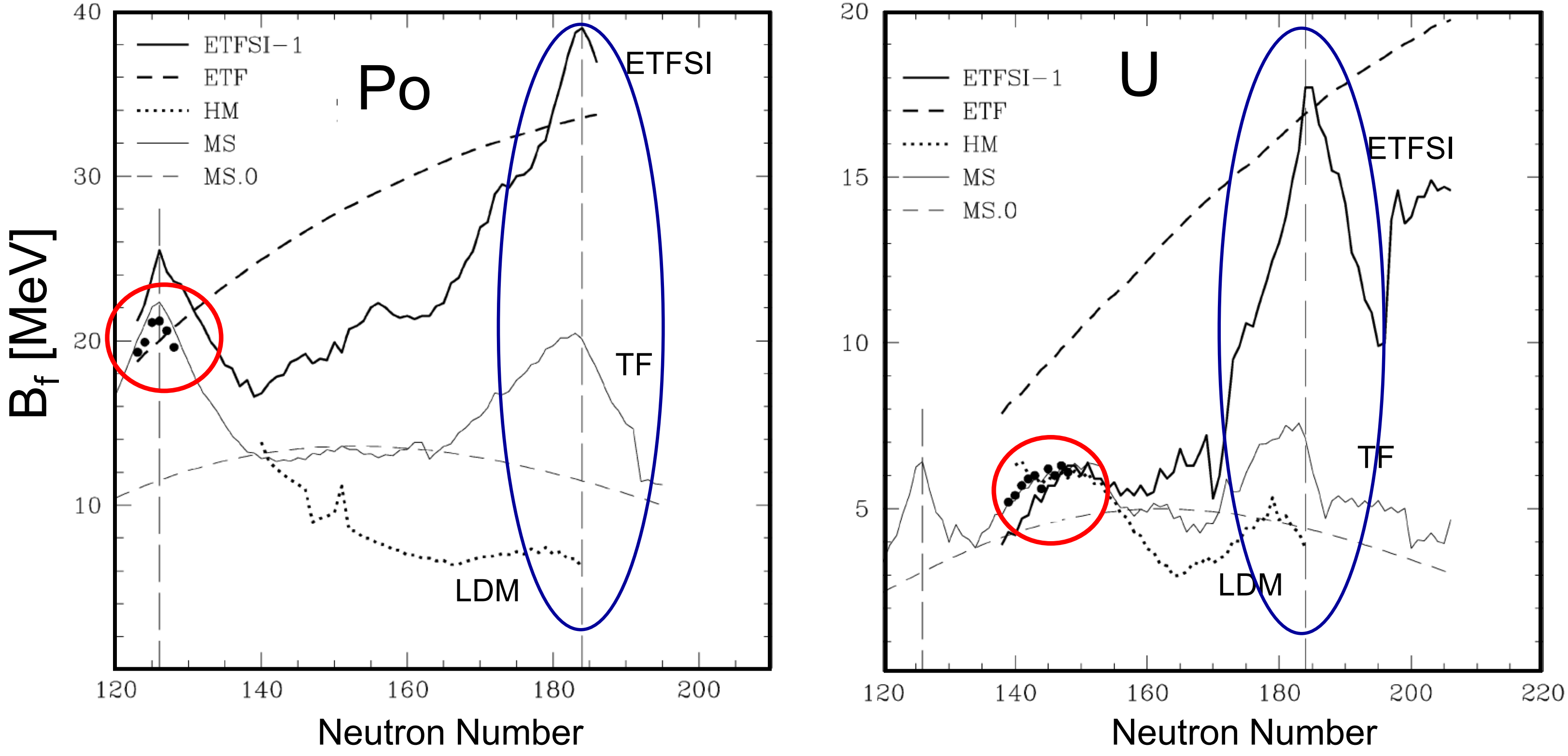
•Many nuclear properties change far from stability line (e.g. disappearance of traditional magic numbers; appearance of new shell gaps; halos, skins…

•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.

Example: Fission Barrier Calculations for r-process nuclei

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

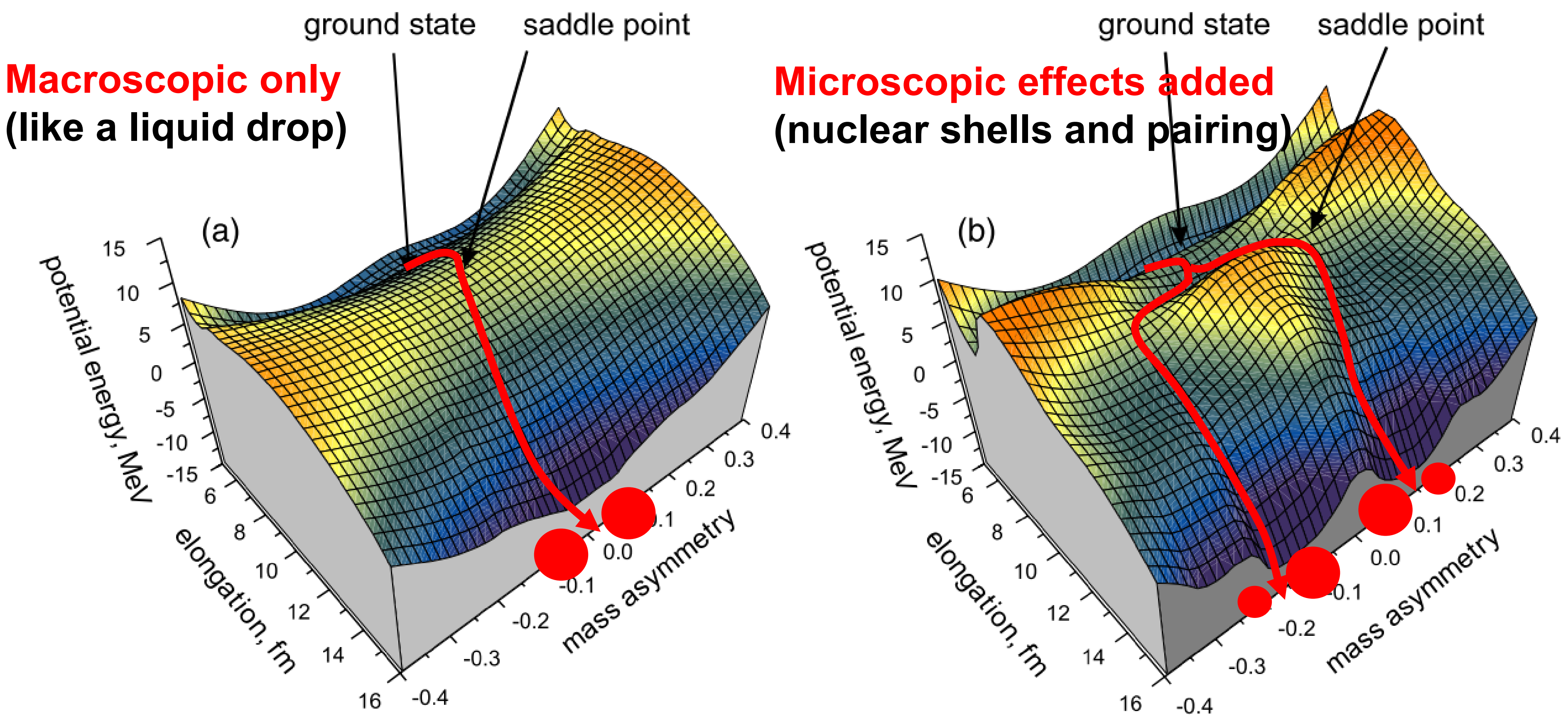


A. Mamdouh et al. NPA679 (2001), 337

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

Symmetric vs Asymmetric Fission

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



Macroscopic only
(like a liquid drop)

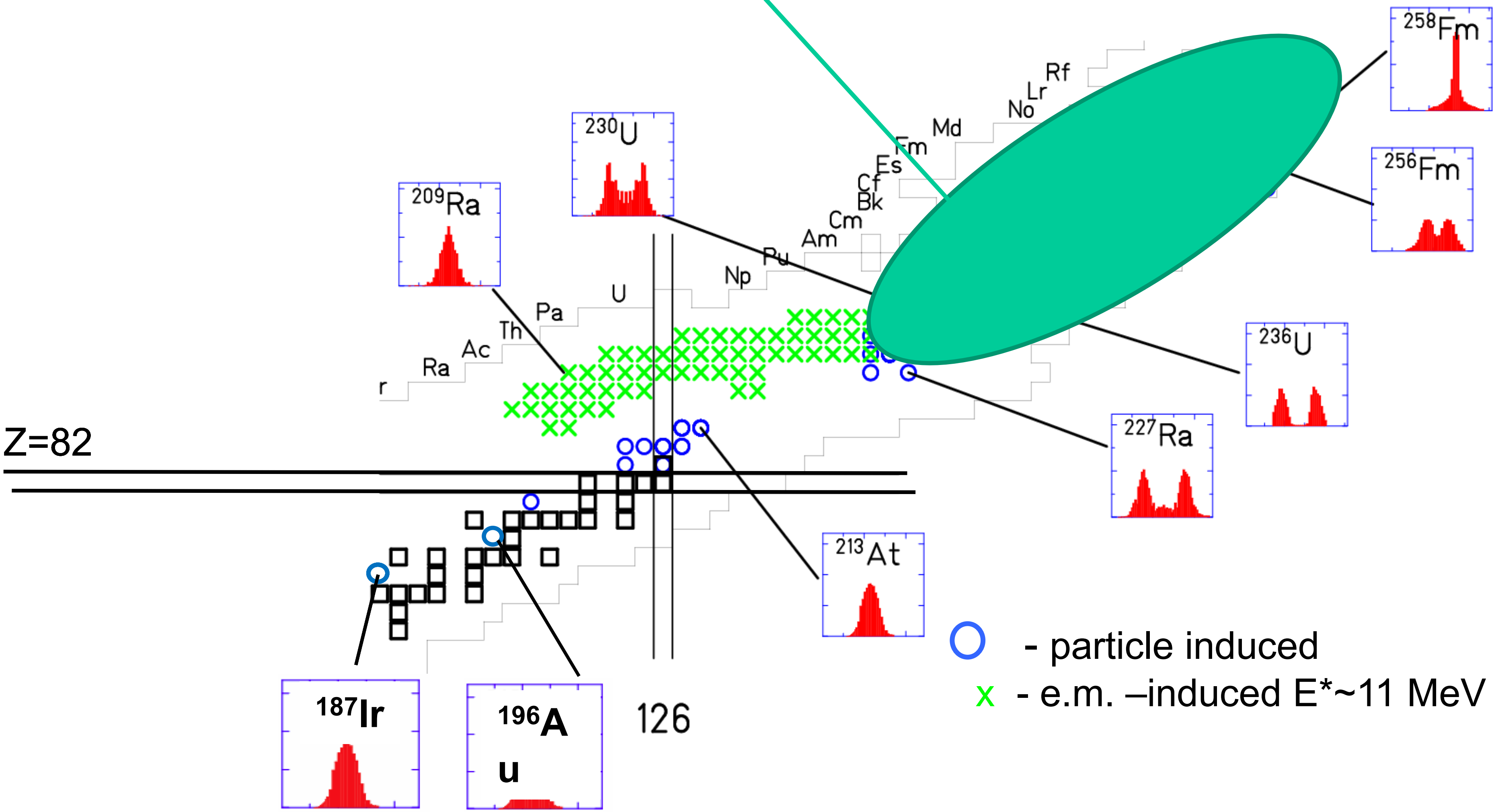
Microscopic effects added
(nuclear shells and pairing)

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.

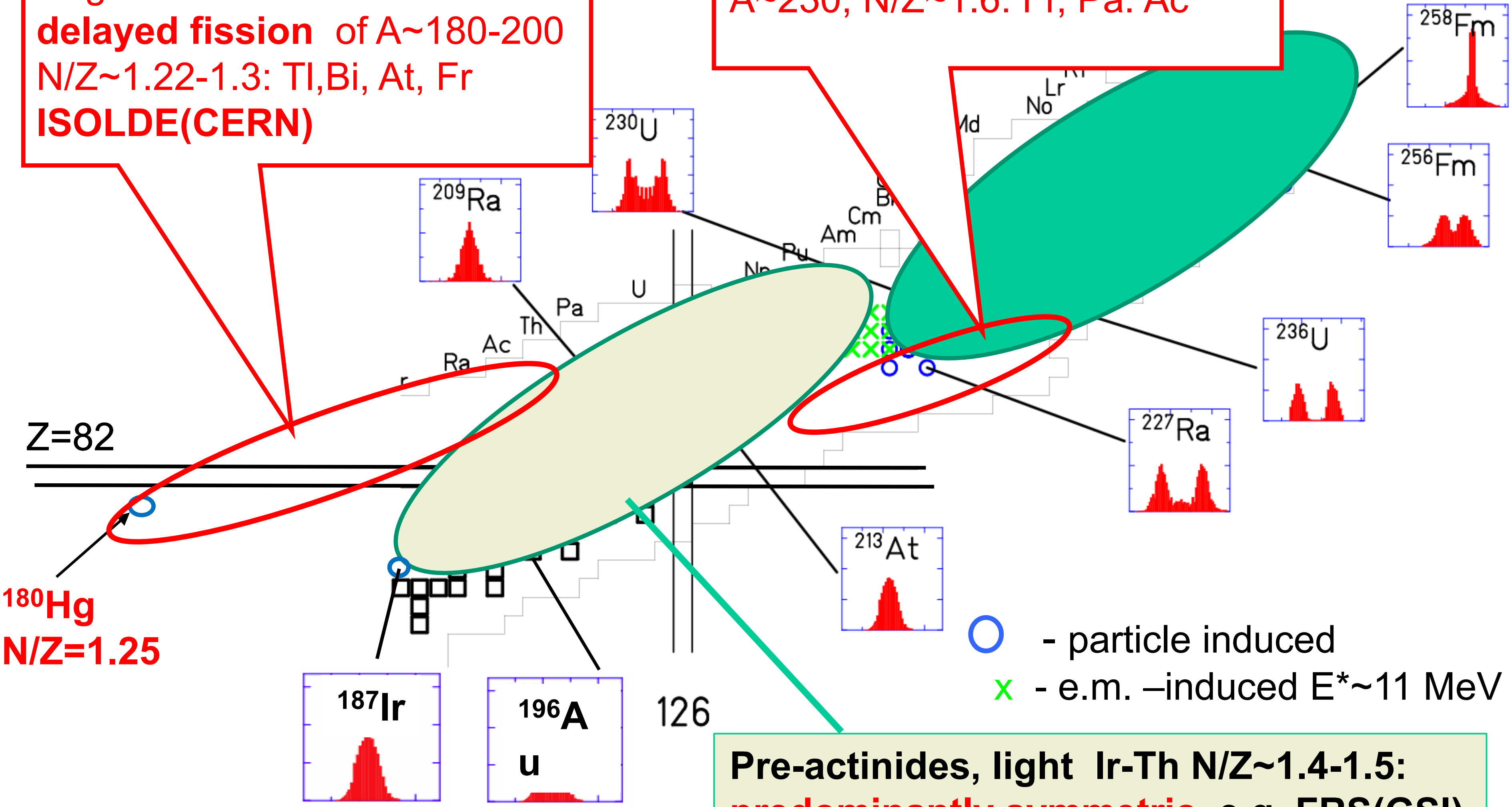
Experimental information on low-energy fission

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

Heavy Actini … **aneous** … **symmetric;**

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

Region of our interest II: **beta-delayed fission** of nuclei with A~230, N/Z~1.6: Fr, Pa. Ac

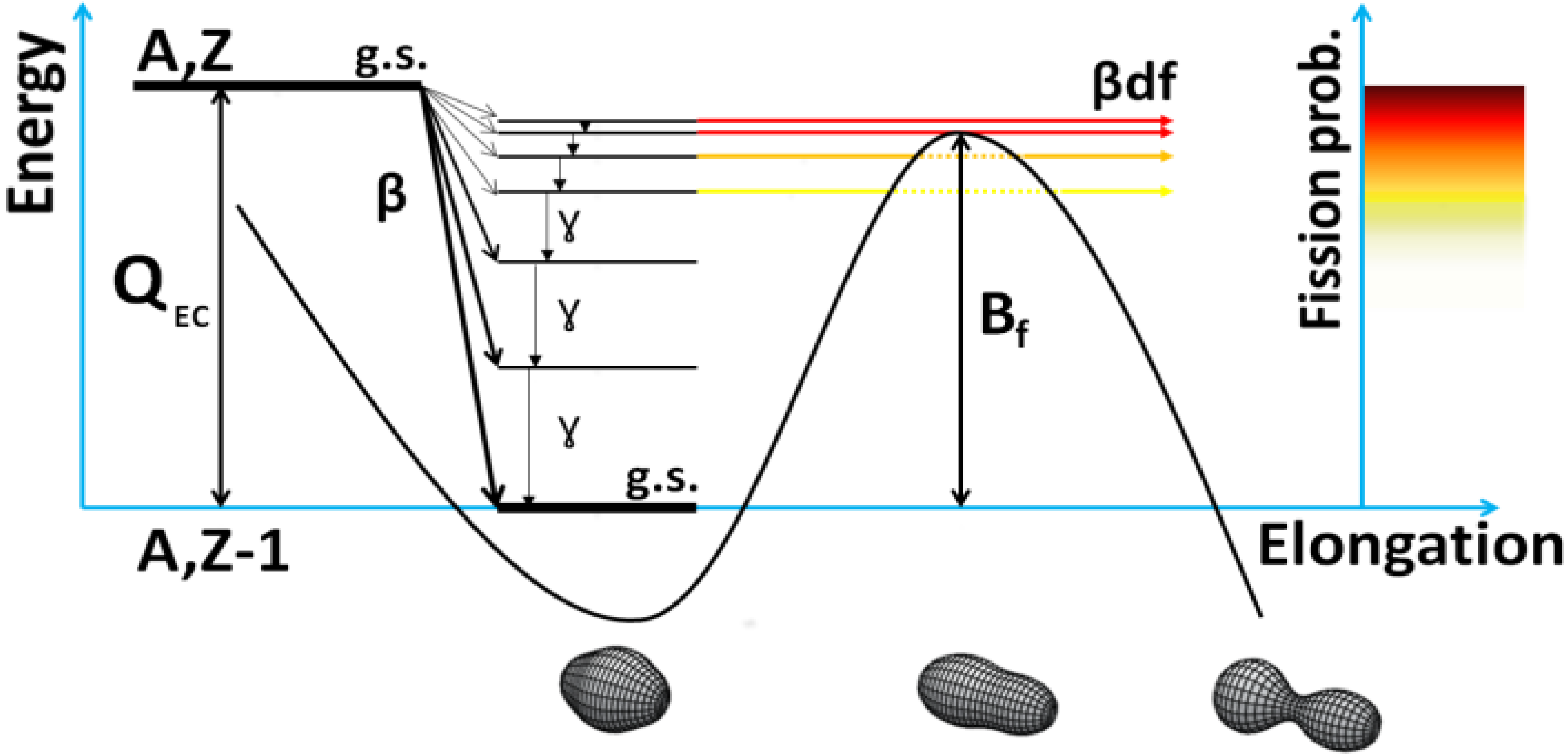


^{180}Hg
N/Z=1.25

○ - 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)**

Beta-Delayed Fission (ISOLDE and SHIP)



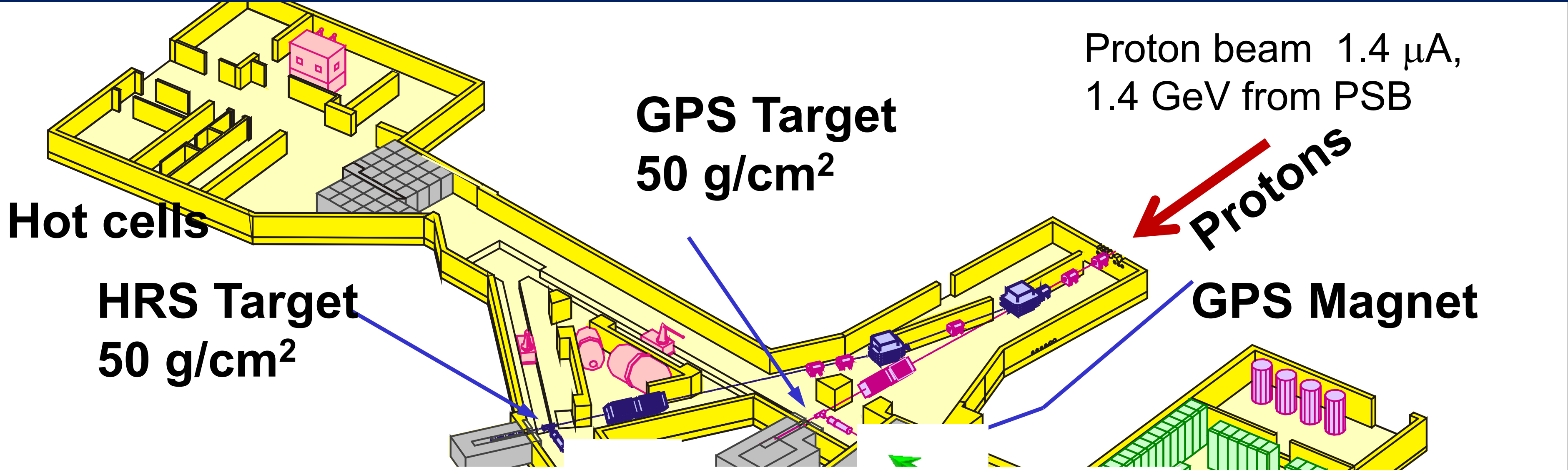
- Two step process: β decay followed by fission
- Low-energy fission (E*~3-12 MeV, limited by Q_{EC})

  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)

Example: βdf of ^{180}Tl at ISOLDE (CERN)



Proton beam 1.4 µA, 1.4 GeV from PSB

GPS Target
50 g/cm^2

Protons

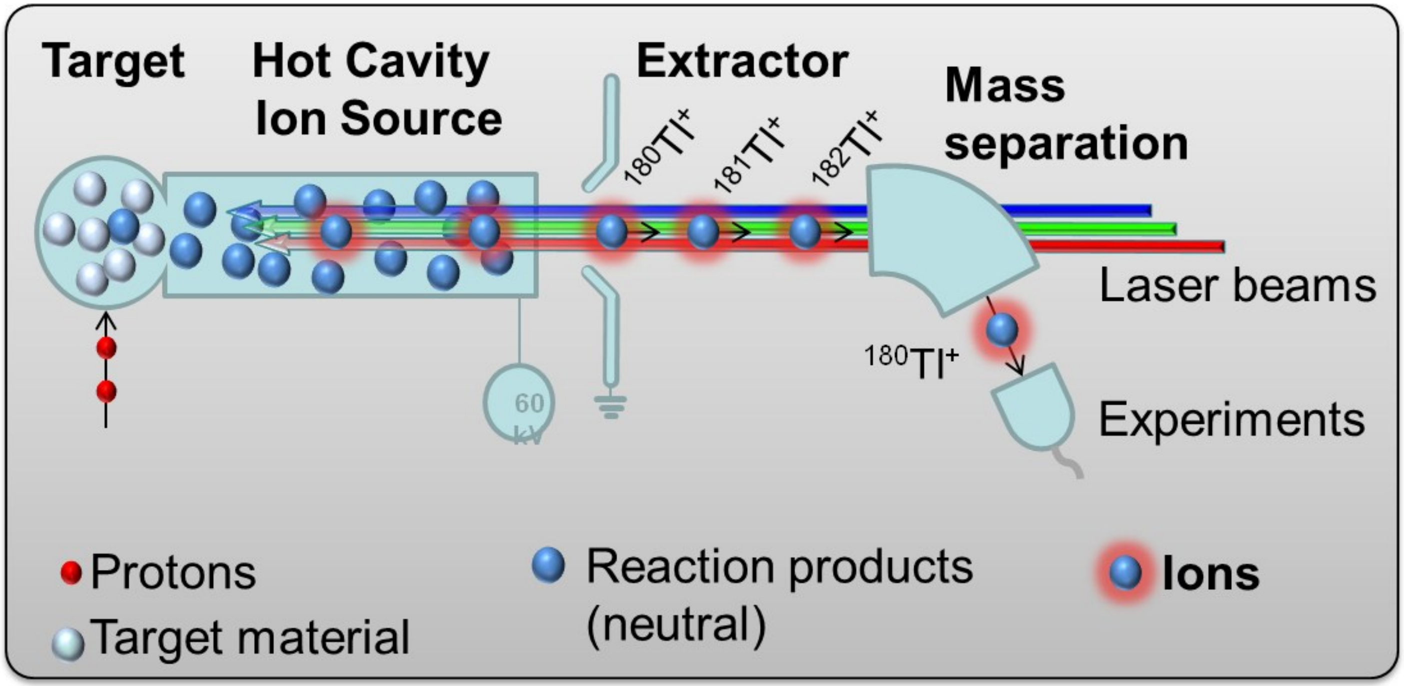
Hot cells

HRS Target
50 g/cm^2

GPS Magnet

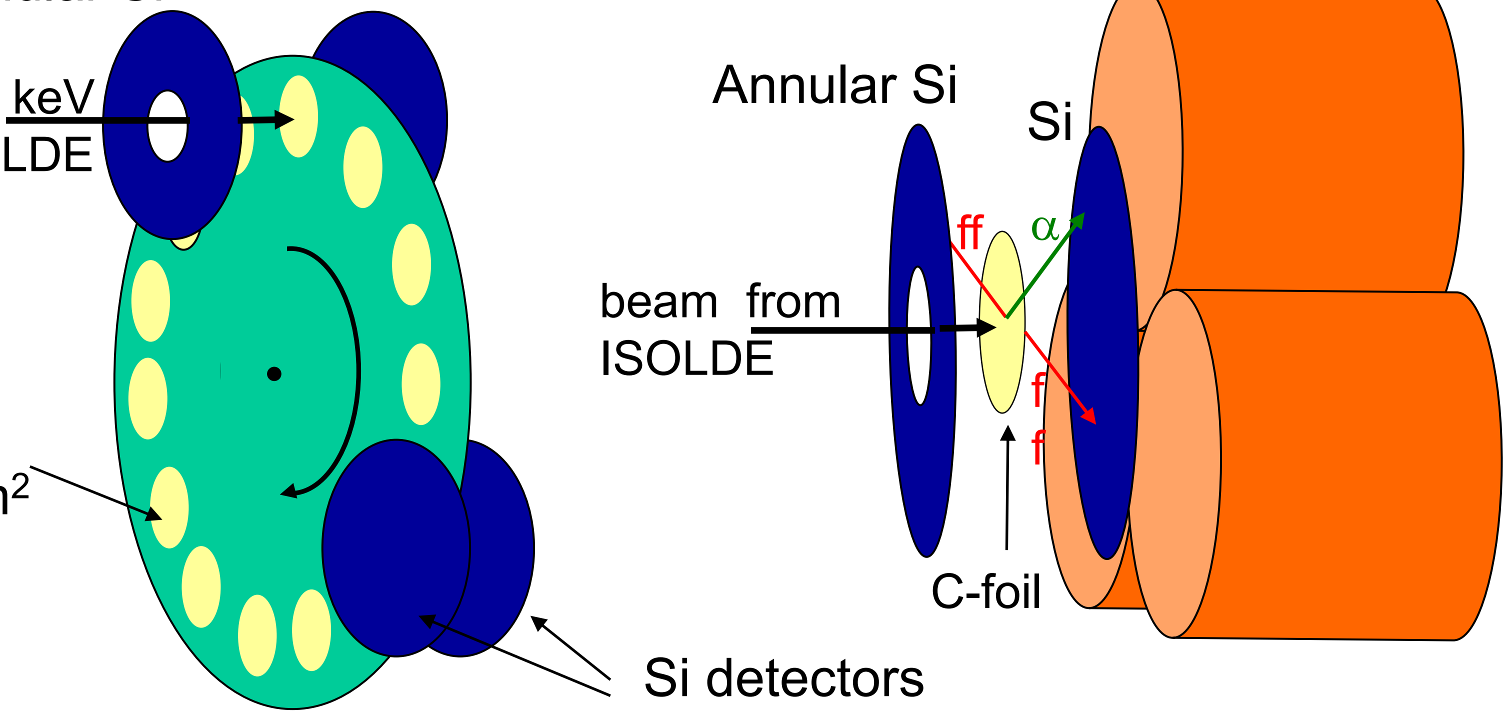
Control Room

xperiments



- ● Protons
- ● Target material
- ● Reaction products (neutral)
- ● **Ions**

Detection system for βDF studies at ISOLDE



Annular Si

Si

pure ^{180}Tl 30-60 keV
from RILIS+ISOLDE

C-foils
20 μg/cm^2

Si detectors

MINIBALL Ge cluster

Annular Si

Si

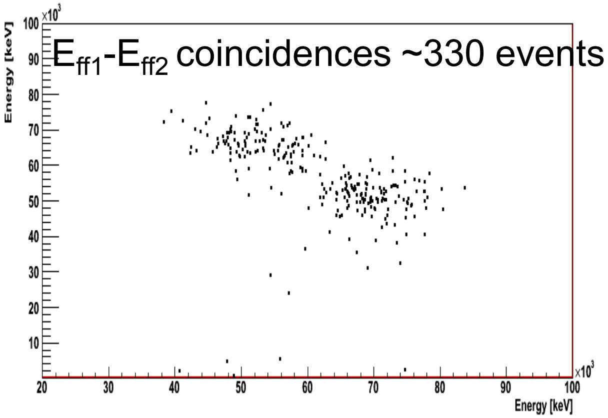
beam from
ISOLDE

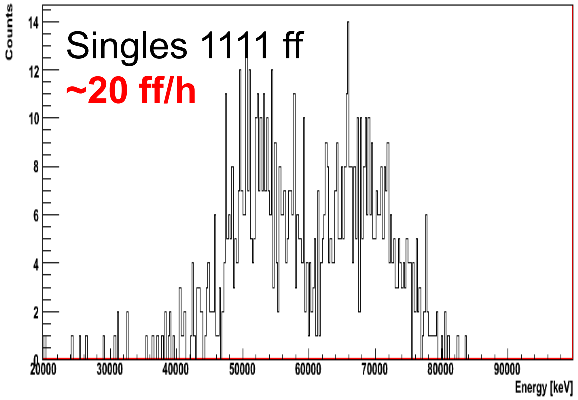
C-foil

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

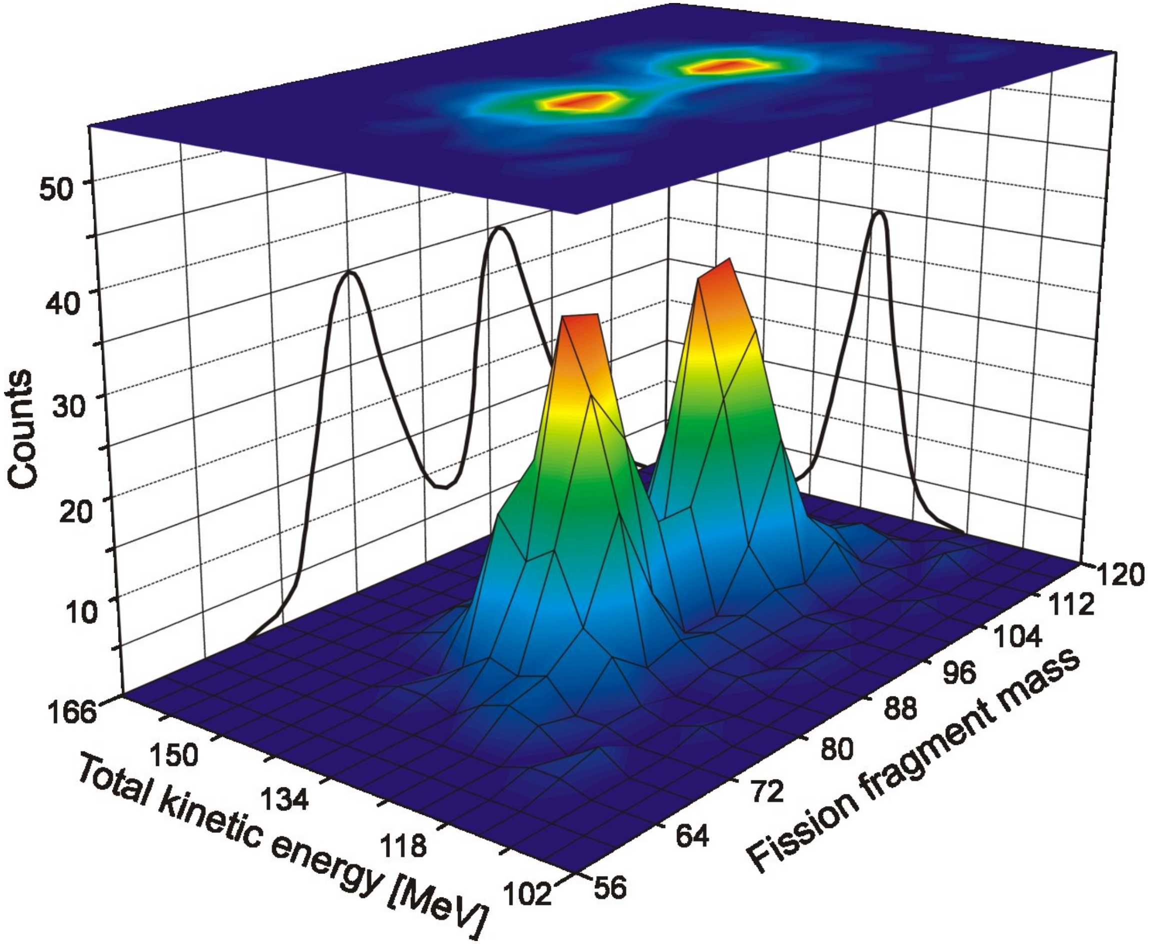
Mass distribution of fission fragments from bDF of ^{180}Tl

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


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


Singles 1111 ff

~20 ff/h



A problem: “low-energy” FF’s - 1 AMeV only, A and 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

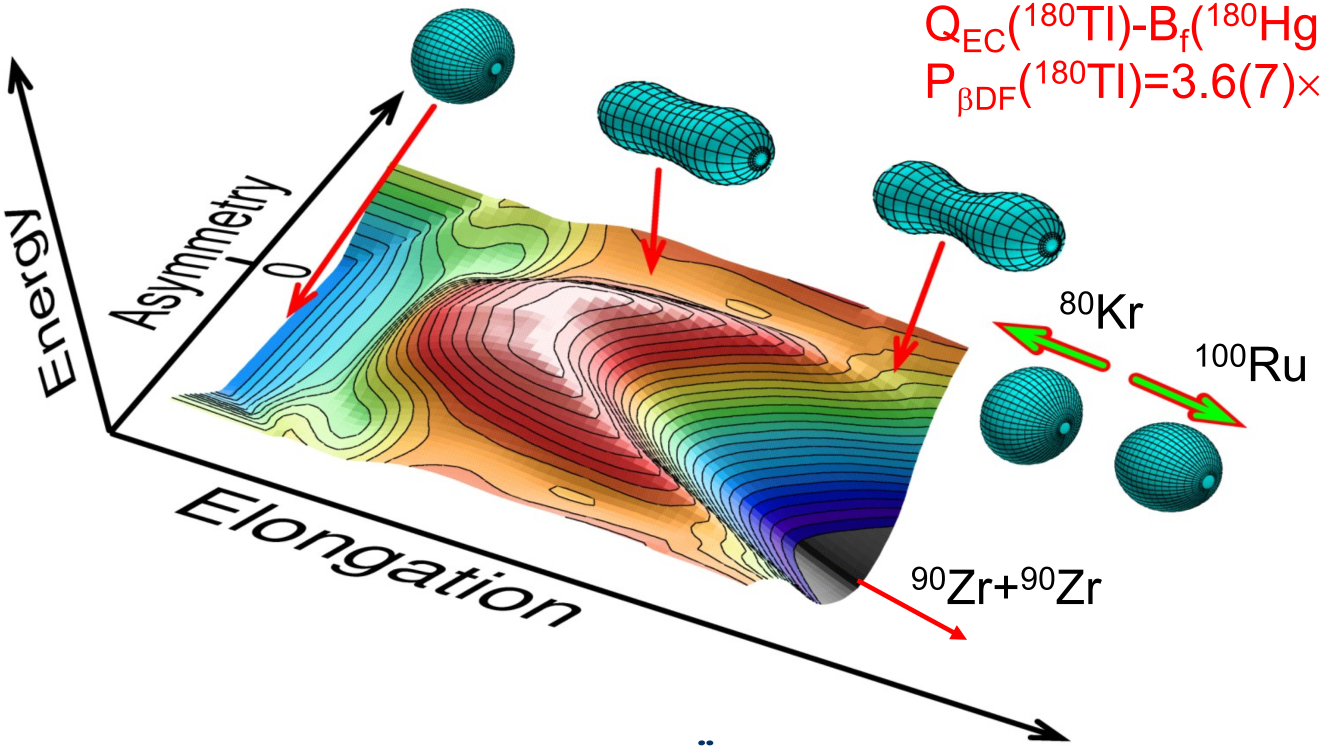
New Type of Asymmetric Fission in Proton-Rich Nuclei

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]

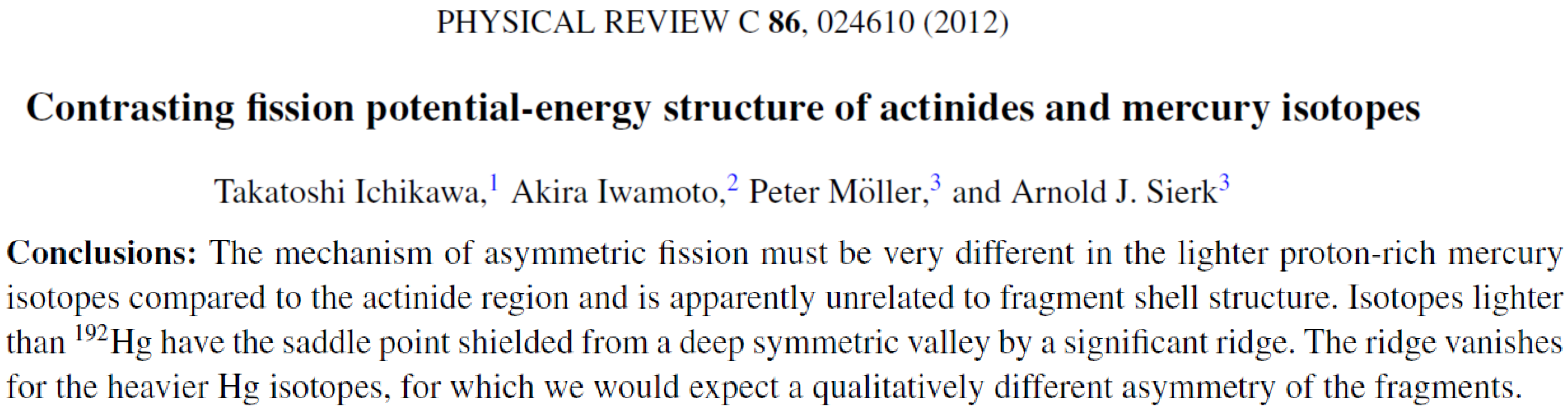
[1]Instituut voor Kern- en Stralingsfysica, K.U. Leuven, University of Leuven, B-3001 Leuven, Belgium
[2]School of Engineering, University of the West of Scotland, Paisley, PA1 2BE, United Kingdom, and the Scottish Universities Physics Alliance (SUPA)

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



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

Two types of asymmetry: what's the difference?

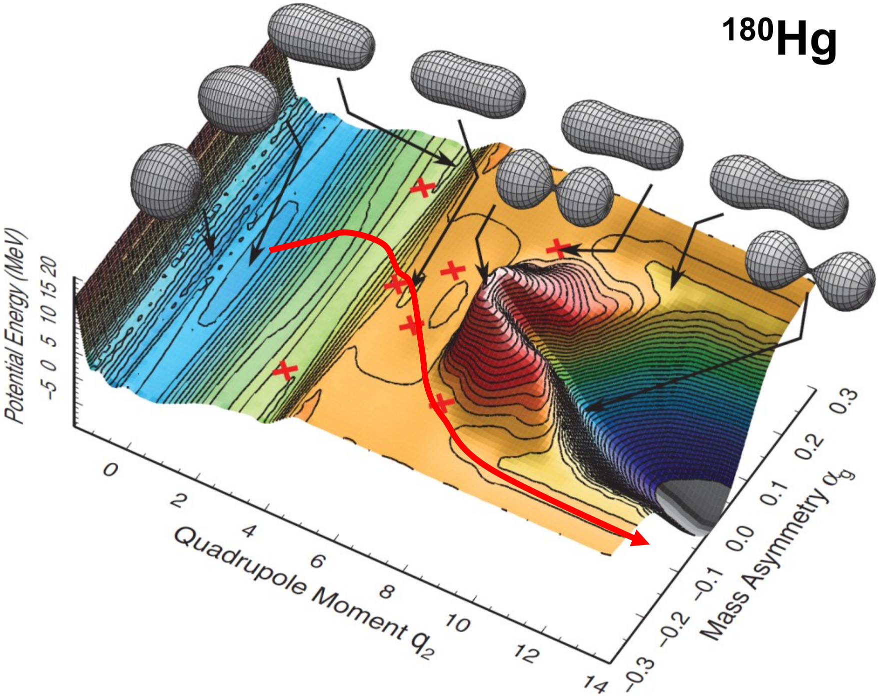


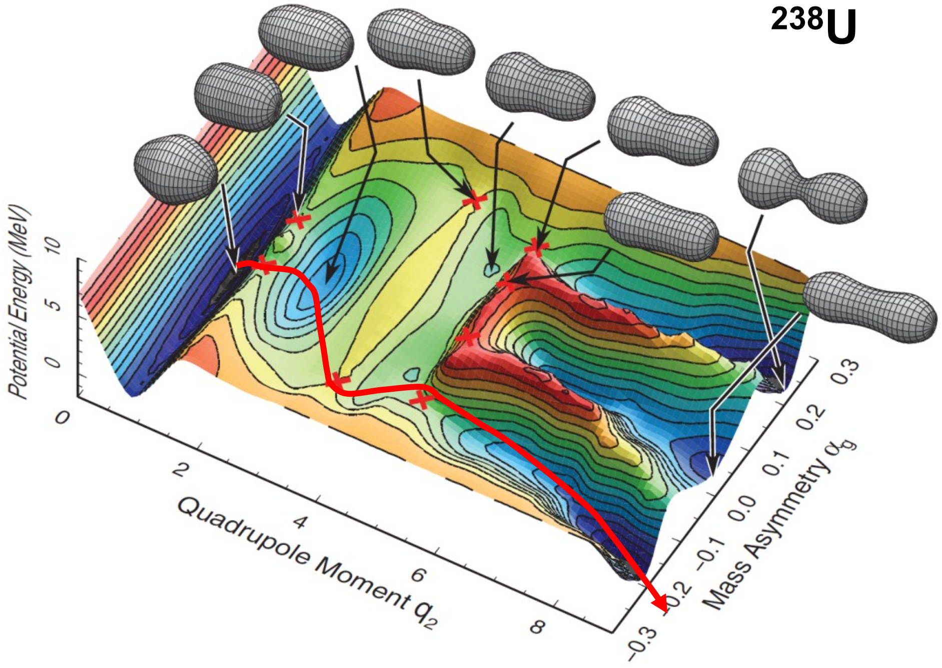
PHYSICAL REVIEW C **86**, 024610 (2012)

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.

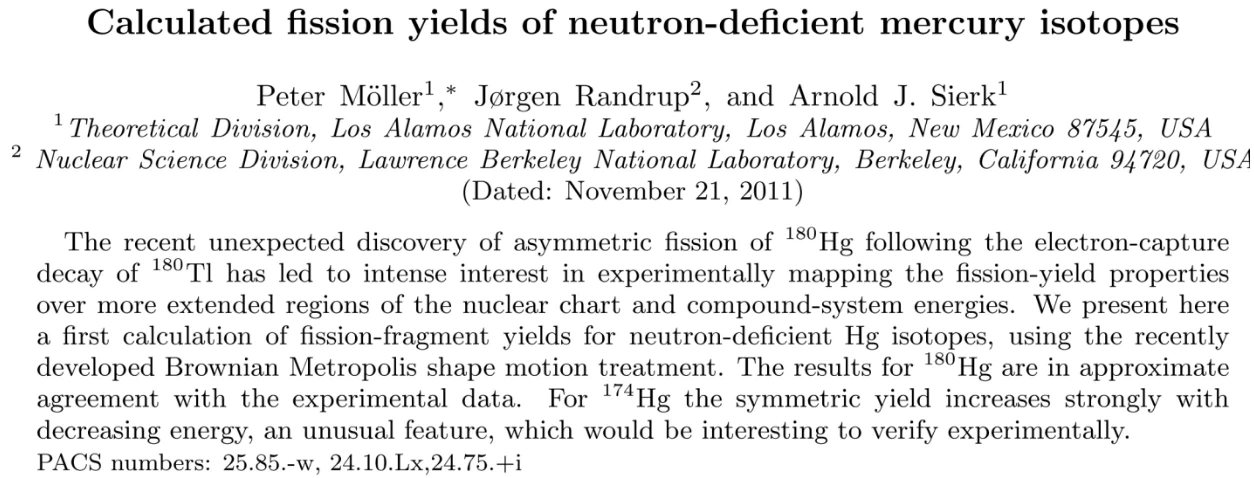




Brownian Metropolis Shape Motion

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

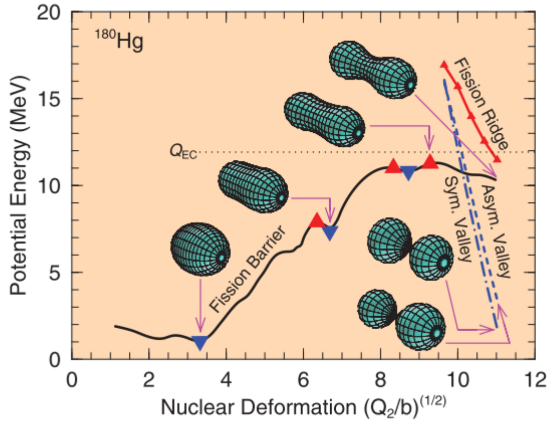
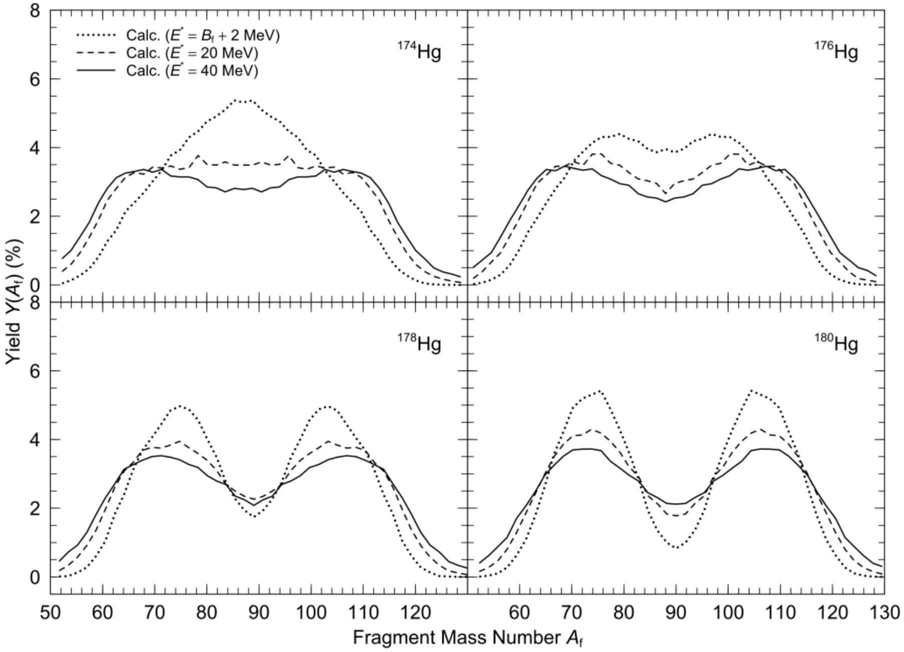
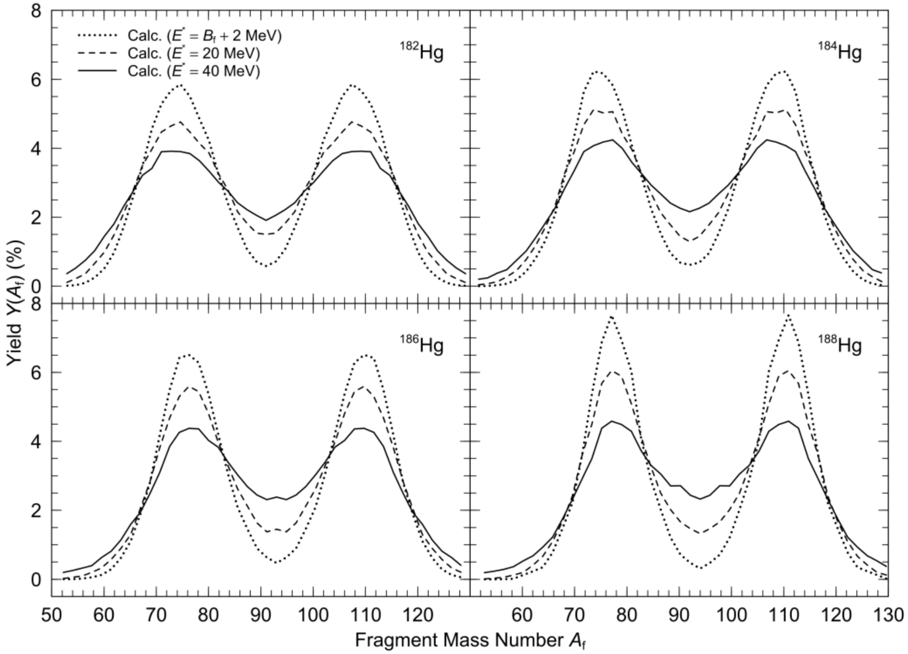
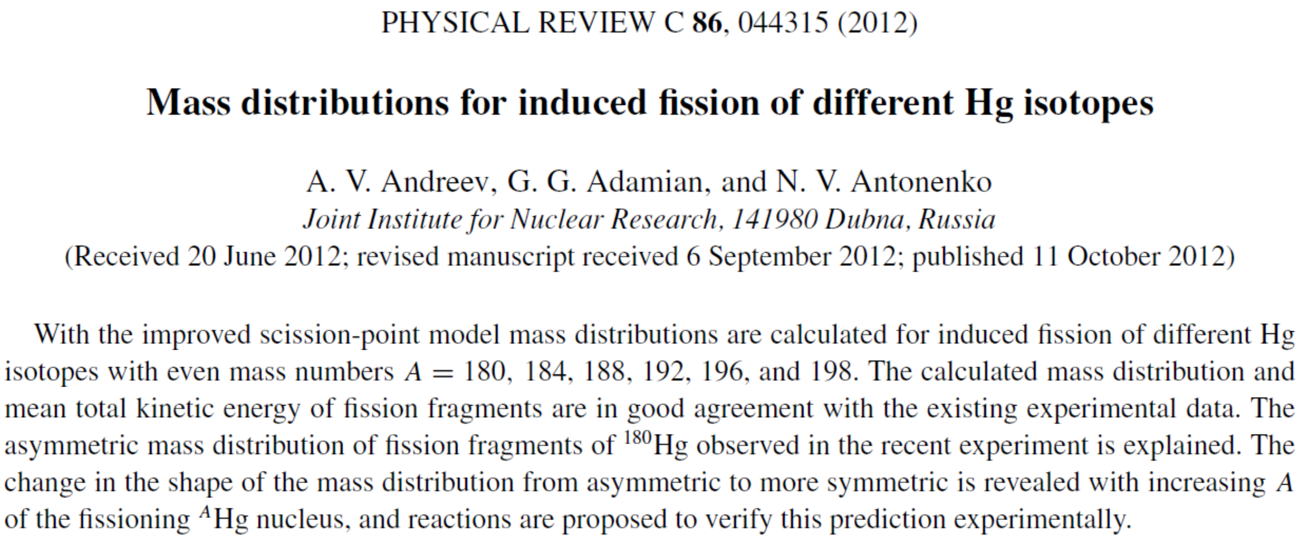


FIG. 4. (Color online) Minima, saddles, major valleys, and ridges in the 5D potential-energy surface of ^{180}Hg (see text). At the last plotted point on the fission barrier, $(Q_2/\mathrm{b})^{(1/2)} \approx 11$, the asymmetry of the shape is $A_\mathrm{H}/A_\mathrm{L} = 108/72$.





‘Improved’ Scission-Point Model



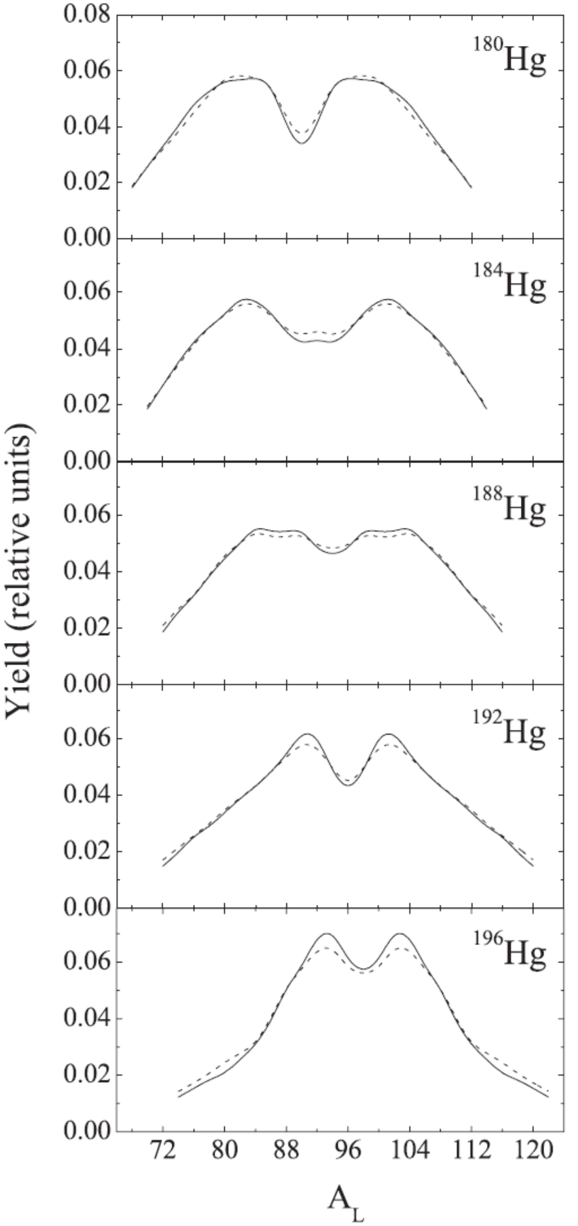
PHYSICAL REVIEW C **86**, 044315 (2012)

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

‘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
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Noël Dubray and Stéphane Hilaire
CEA, DAM, DIF, F-91297, Arpajon, France

(Received 9 October 2012; published 3 December 2012)

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

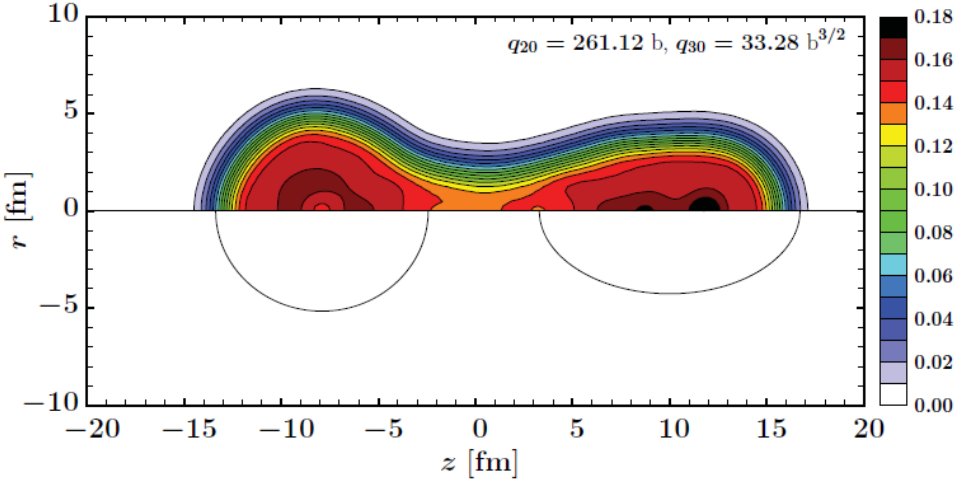


FIG. 4. (Color online) Total nuclear density for the most energetically favorable scission configuration in ^{180}Hg fission, extracted from a self-consistent HFB calculation. In the lower part of the figure, two

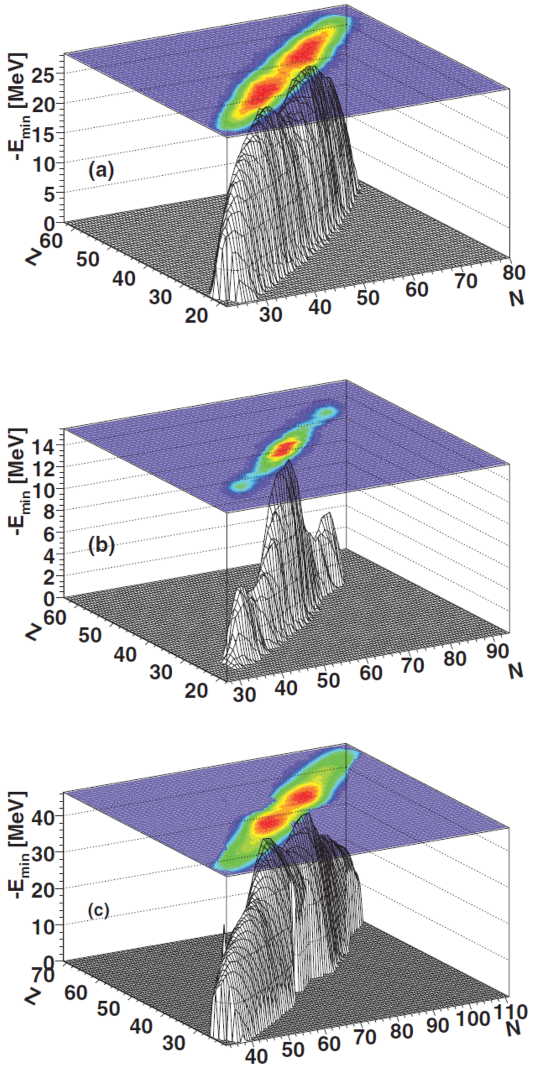


FIG. 2. (Color online) Minimum absolute available energy at scission calculated for all possible fragmentations in (a) ^{180}Hg and (b) ^{198}Hg fission at 10 MeV and in (c) the thermal n-induced fission of ^{235}U.

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]

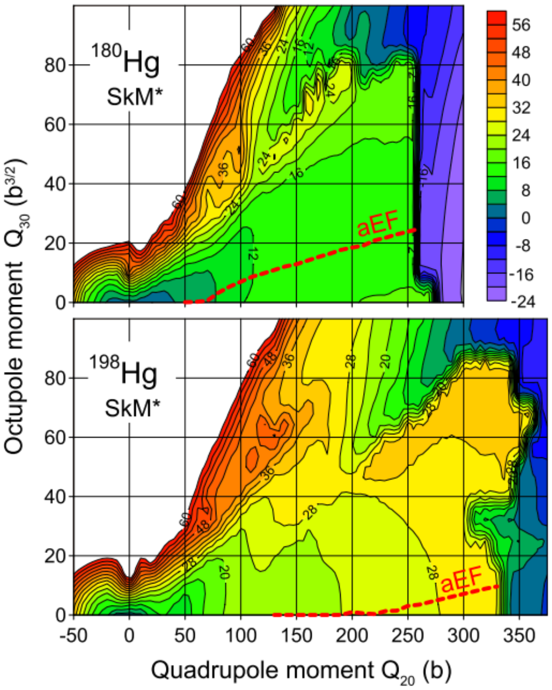


FIG. 2. (Color online) PES for ^{180}Hg (top) and ^{198}Hg (bottom) in the plane of collective coordinates $Q_{20} - Q_{30}$ in HFB-SkM*. The aEF fission pathway corresponding to asymmetric elongated fragments is marked. The difference between contour lines is 4 MeV. The effects due to triaxiality, known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

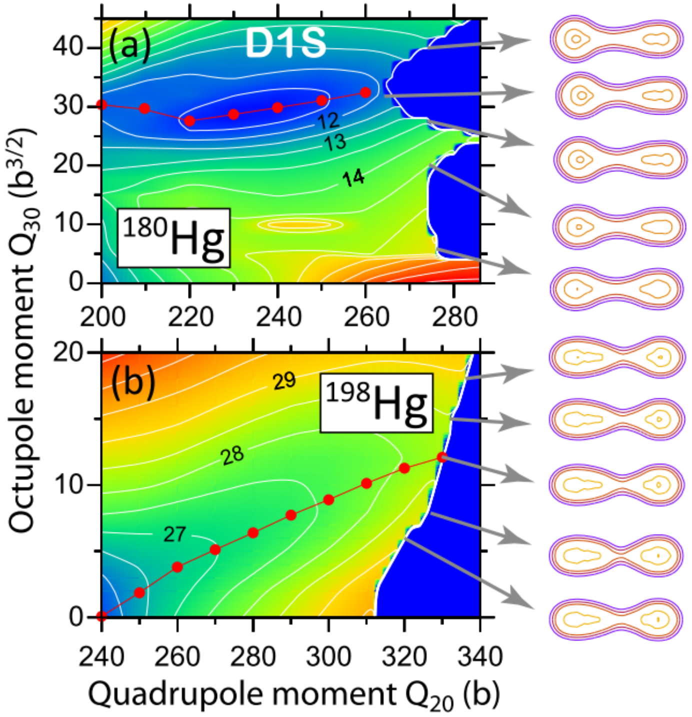
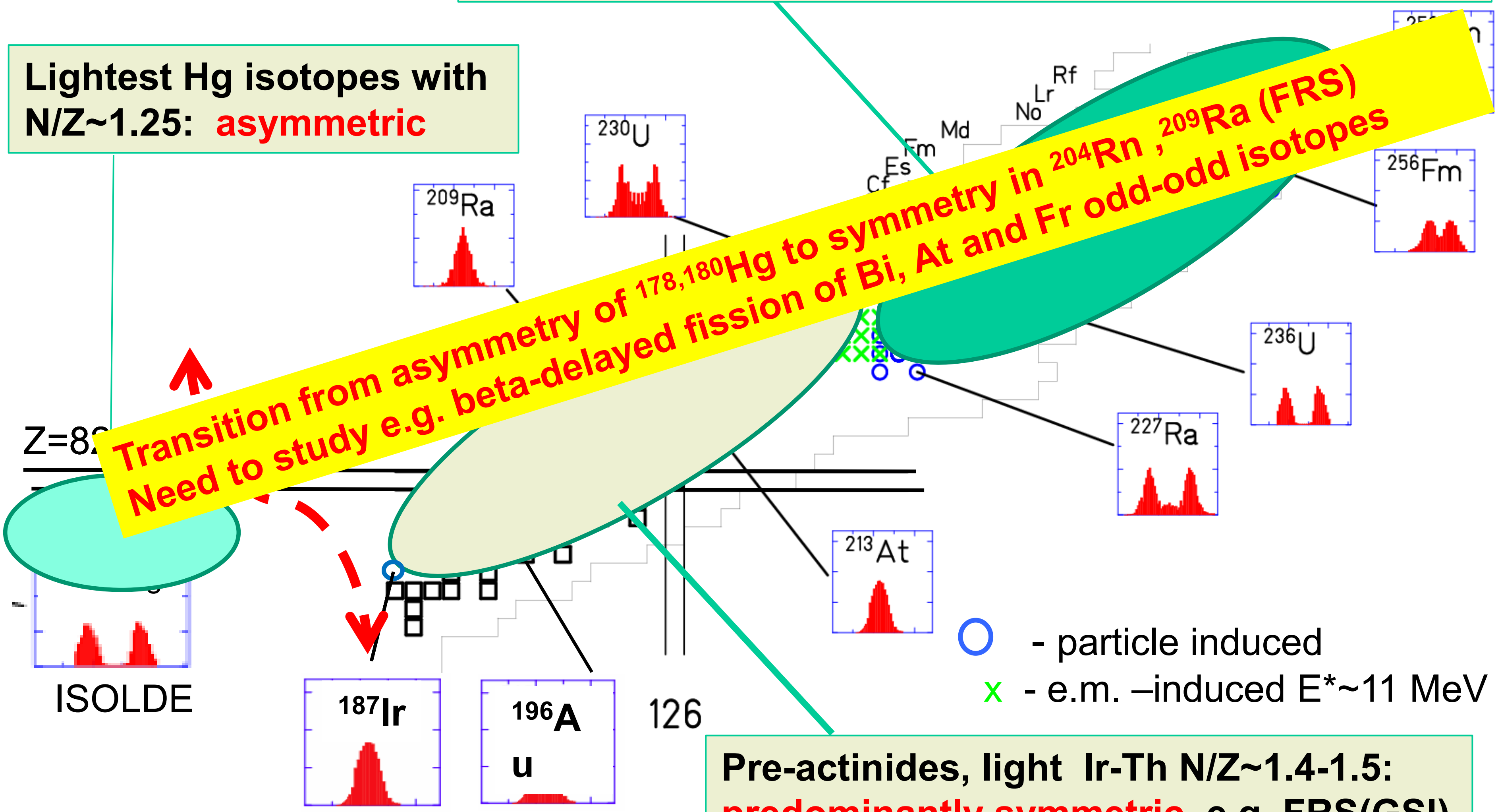


FIG. 3. (Color online) PES in HFB-D1S for ^{180}Hg (top) and ^{198}Hg (bottom) in the (Q_{20}, Q_{30}) plane in the pre-scission region of aEF valley. The symmetric limit corresponds to $Q_{30} = 0$. The aEF valley and density profiles for pre-scission configurations are indicated. The difference between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

From Asymmetry to Symmetry



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

Lightest Hg isotopes with N/Z~1.25: asymmetric

Transition from asymmetry of ^{178,180}Hg to symmetry in ^{204}Rn ,^{209}Ra (FRS)
Need to study e.g. beta-delayed fission of Bi, At and Fr odd-odd isotopes

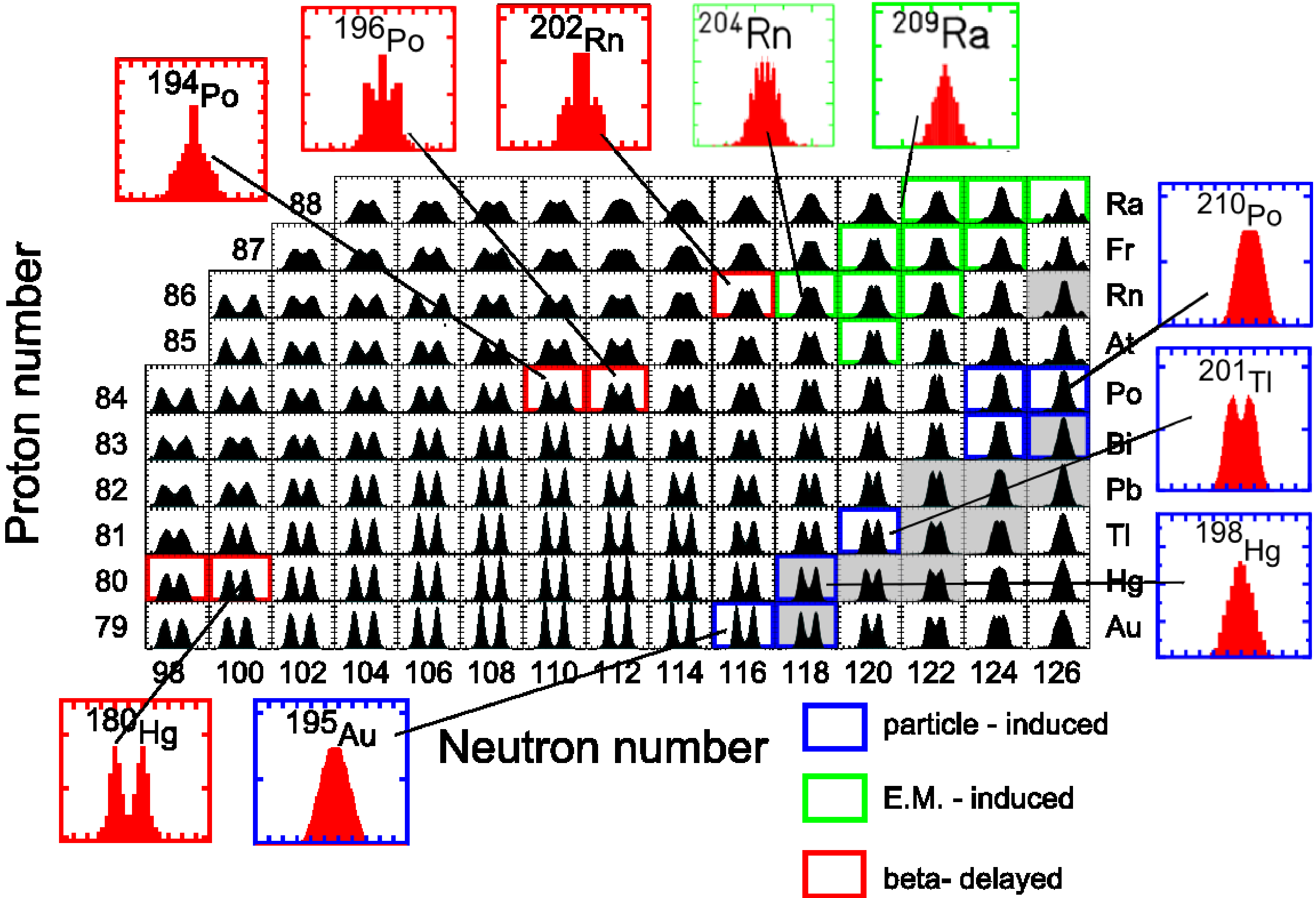
Pre-actinides, light Ir-Th N/Z~1.4-1.5: predominantly symmetric, e.g. FRS(GSI)

○ - particle induced

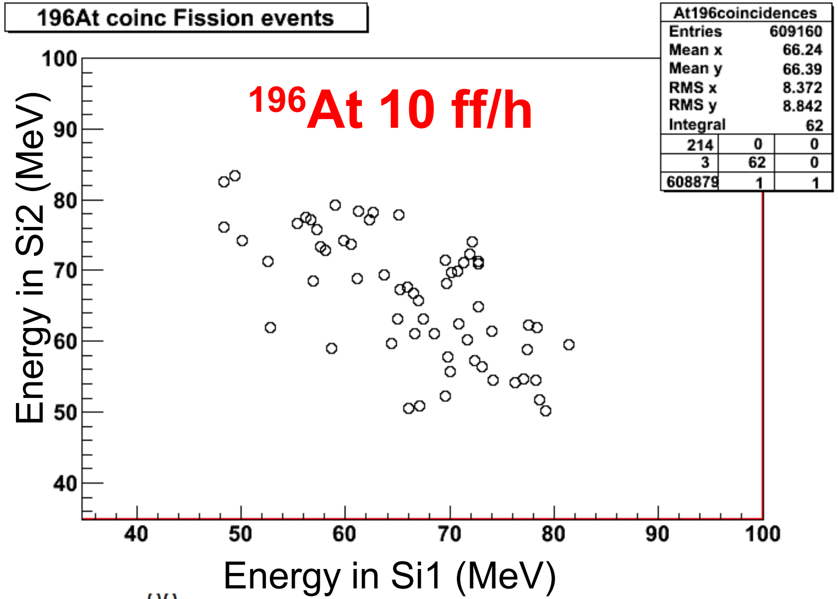
x - e.m. –induced E*~11 MeV

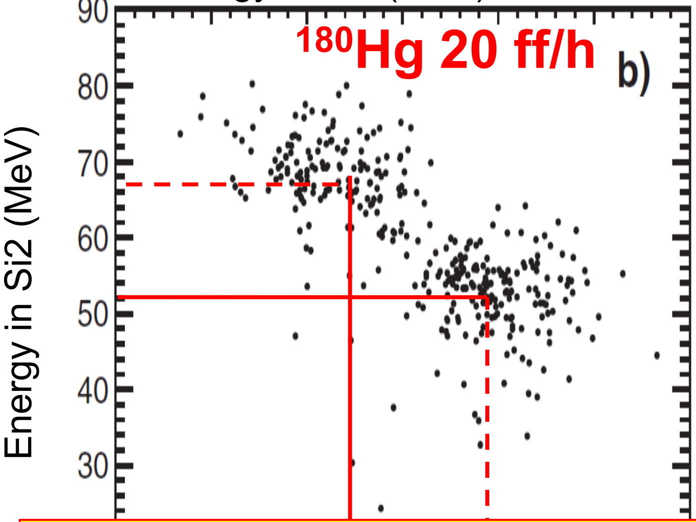
Fission of Proton-rich nuclei with A~180-200

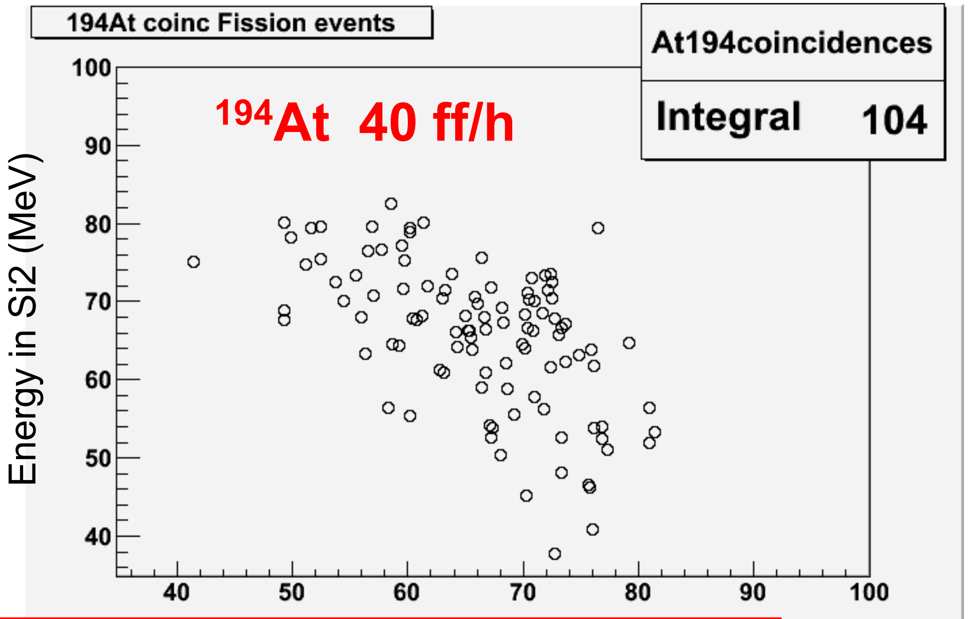
L.Ghys et al., Phys. Rev. C 90, 044305 (2014)



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



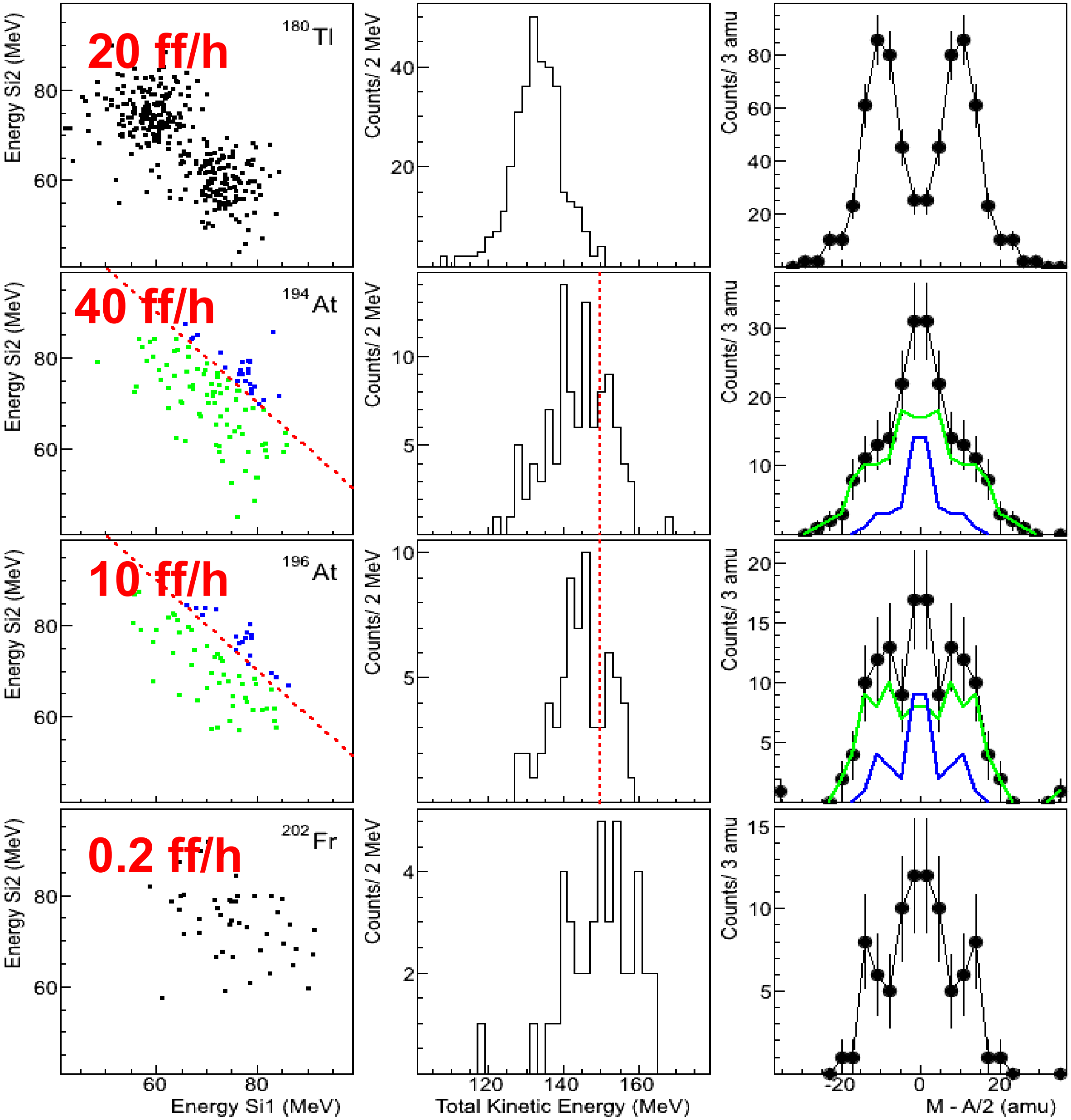




Clear difference in energy (thus, mass) distribution between 2-peaked fission of ^{180}Hg and a broad distribution in ^{194,196}Po

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

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



20 ff/h

40 ff/h

10 ff/h

0.2 ff/h

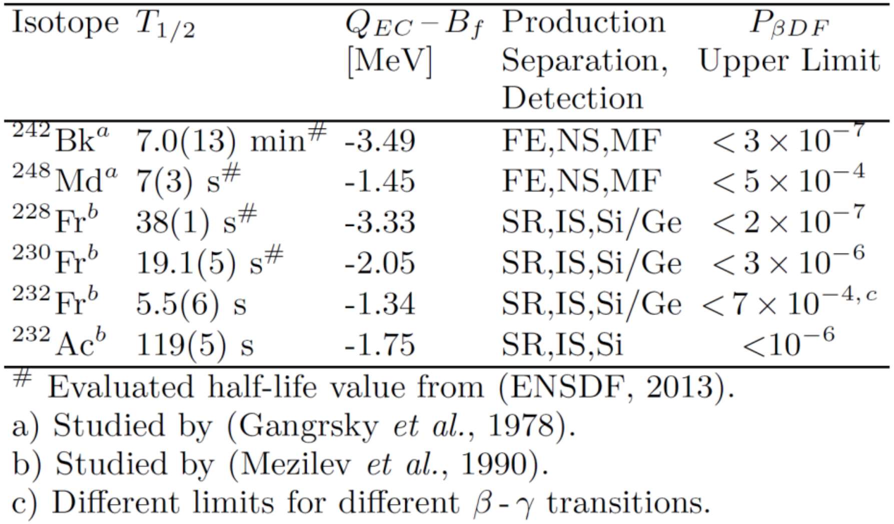
A problem: "low-energy" FF's - 1 AMeV only, A and Z identification difficult

EURISOL:

- x10^3 yield increase(?)
- Detailed studies
- FF's en. distributions
- FF's mass distributions
- TKE(M)
- n,γ –multiplicities

βDF in the neutron-rich Fr nuclei at ISOLDE?

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	$< 3\times10^{-7}$
^{248}Md^a	7(3) s$^\#$	-1.45	FE,NS,MF	$< 5\times10^{-4}$
^{228}Fr^b	38(1) s$^\#$	-3.33	SR,IS,Si/Ge	$< 2\times10^{-7}$
^{230}Fr^b	19.1(5) s$^\#$	-2.05	SR,IS,Si/Ge	$< 3\times10^{-6}$
^{232}Fr^b	5.5(6) s	-1.34	SR,IS,Si/Ge	$< 7\times10^{-4,c}$
^{232}Ac^b	119(5) s	-1.75	SR,IS,Si	$<10^{-6}$

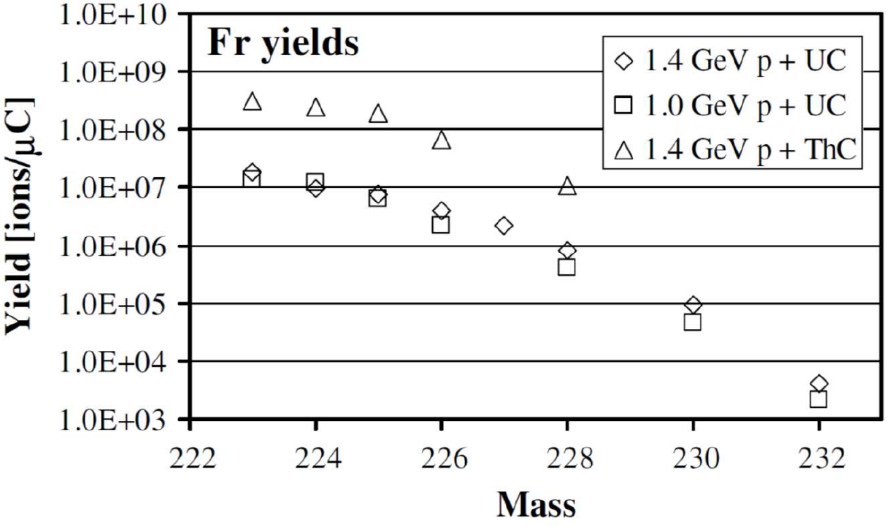
\# Evaluated half-life value from (ENSDF, 2013).

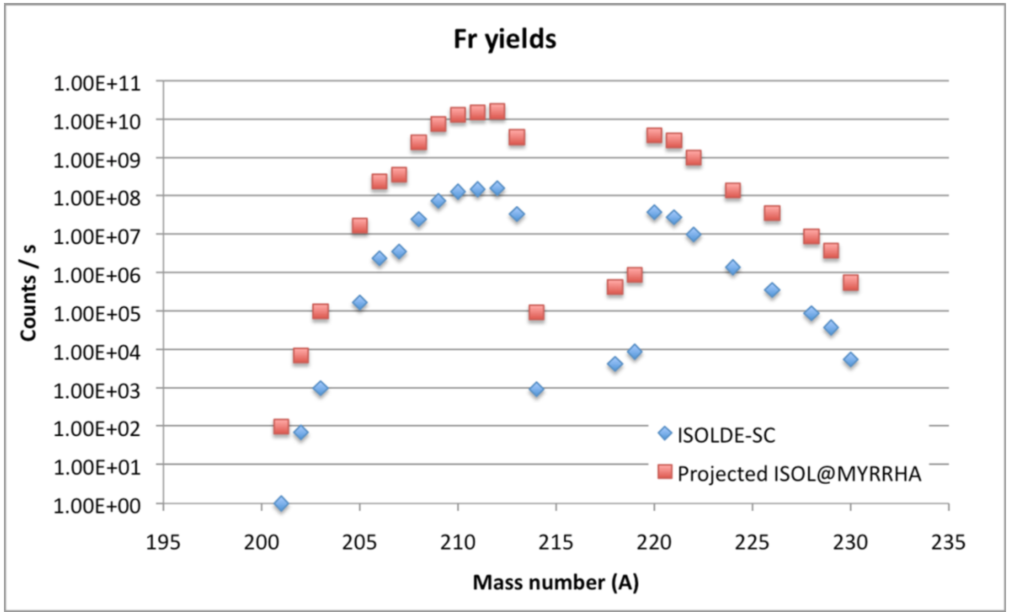
a) Studied by (Gangrsky *et al.*, 1978).

b) Studied by (Mezilev *et al.*, 1990).

c) Different limits for different β-γ transitions.

ISOLDE yields (UC, ThC)



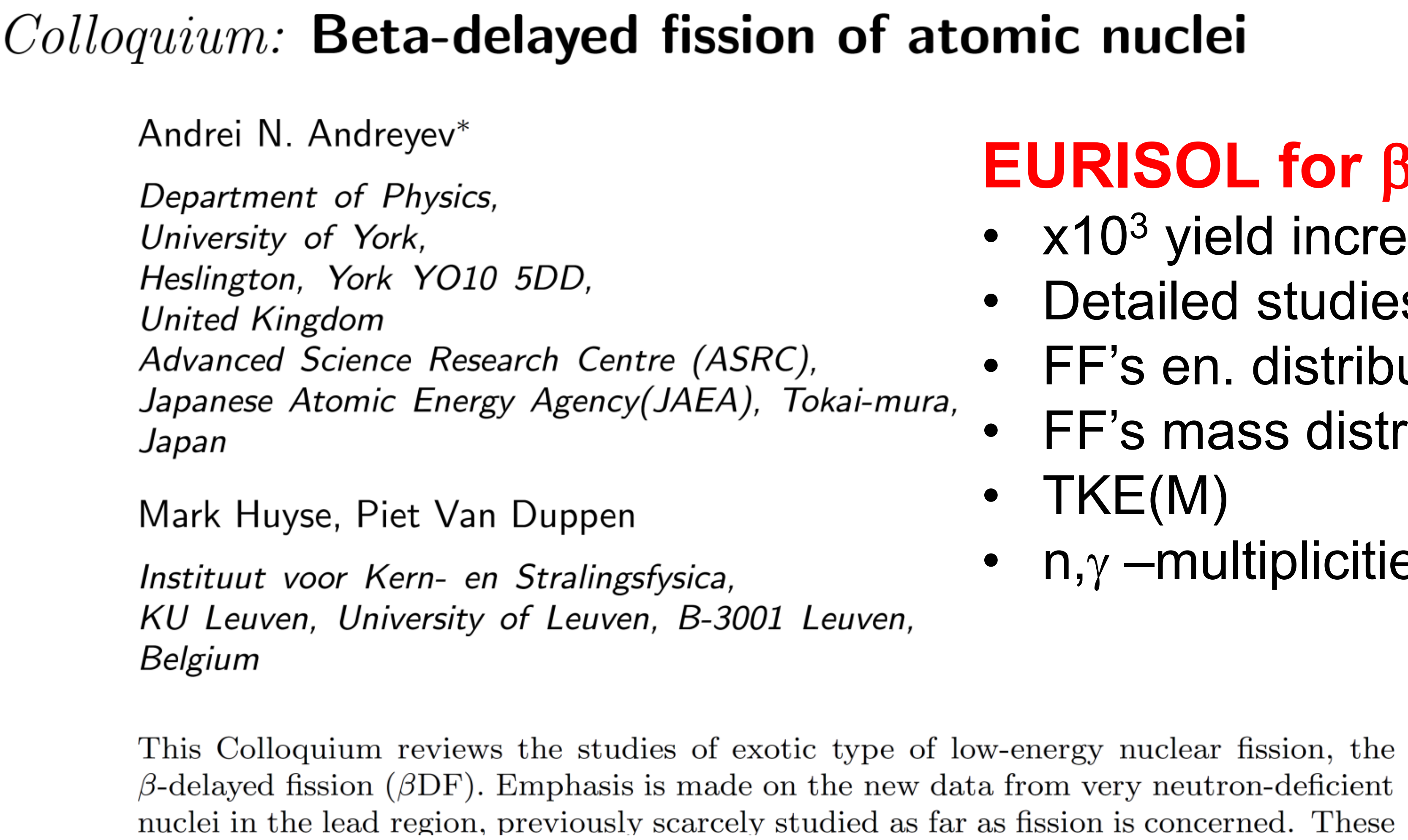


ThC targets?

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

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,
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United Kingdom
Advanced Science Research Centre (ASRC),
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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 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

EURISOL for βDF:

- x10^3 yield increase(?)
- Detailed studies
- FF's en. distributions
- FF's mass distributions
- TKE(M)
- n,γ –multiplicities

Outlook

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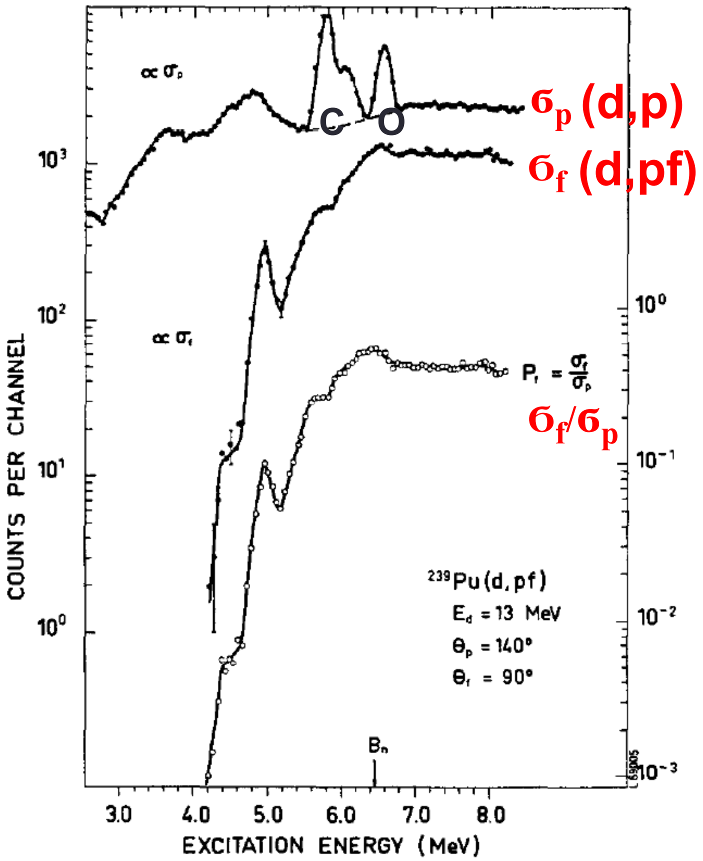
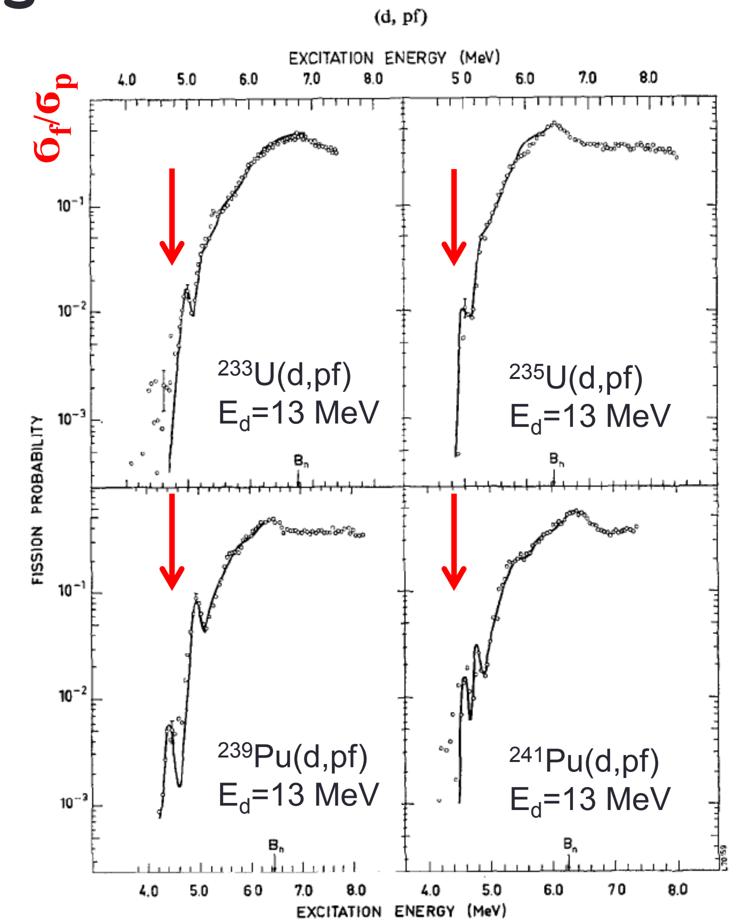
- Transfer-induced fission at VAMOS@GANIL at 6 AMeV
- Further plans (ELISe@FAIR, SCRIT@RIKEN)

http://asrc.jaea.go.jp/soshiki/gr/chiba_gr/workshop3/index3.html

Earlier fission barrier studies: fission probability as a function of E* : **direct nucleon-transfer, e.g. (d,pf)** reactions with **stable or long-lived** targets

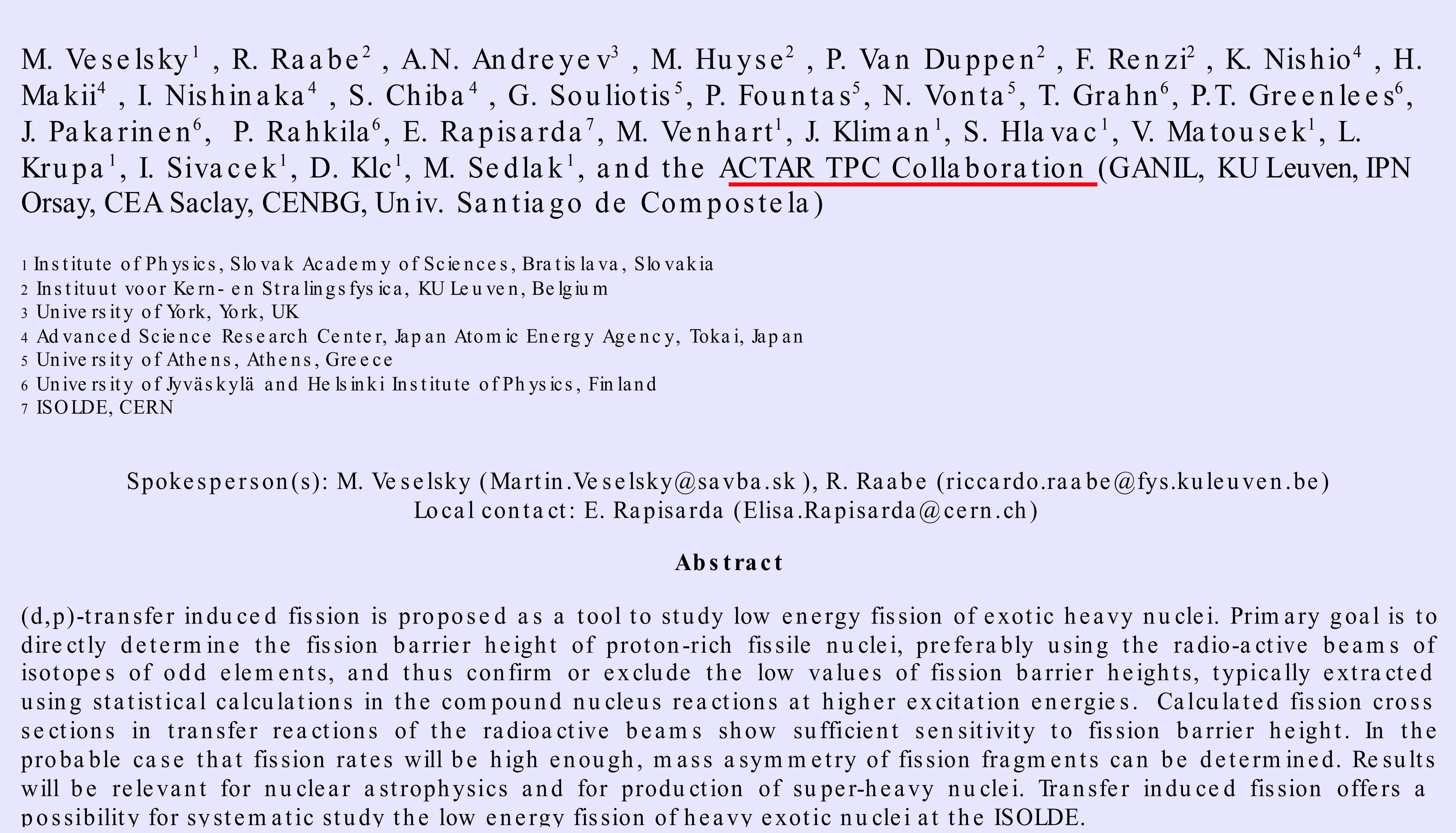




B.B. Back et al.; Nucl. Phys. **A165** (1971) 449

E. Konecny et al.; Phys. Lett. B **45** (1973) 329

IS581: New method: (d,pf)-transfer induced fission of RIBs in inverse kinematics at HIE-ISOLDE



M. Veselsky[1] , R. Raabe[2] , A.N. Andreyev[3] , M. Huyse[2] , P. Van Duppen[2] , F. Renzi[2] , K. Nishio[4] , H. Makii[4] , I. Nishinaka[4] , S. Chiba[4] , G. Souliotis[5], P. Fountas[5], N. Vonta[5], T. Grahn[6], P.T. Greenlees[6], J. Pakarinen[6], P. Rahkila[6], E. Rapisarda[7], M. Venhart[1], J. Kliman[1], S. Hlavac[1], V. Matousek[1], L. Krupa[1], I. Sivacek[1], D. Klc[1], M. Sedlak[1], and the ACTAR TPC Collaboration (GANIL, KU Leuven, IPN Orsay, CEA Saclay, CENBG, Univ. Santiago de Compostela)

1 Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia
2 Instituut voor Kern- en Stralingsfysica, KU Leuven, Belgium
3 University of York, York, UK
4 Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Japan
5 University of Athens, Athens, Greece
6 University of Jyväskylä and Helsinki Institute of Physics, Finland
7 ISOLDE, CERN

Spokesperson(s): M. Veselsky (Martin.Veselsky@savba.sk), R. Raabe (riccardo.raabe@fys.kuleuven.be)
Local contact: E. Rapisarda (Elisa.Rapisarda@cern.ch)

Abstract

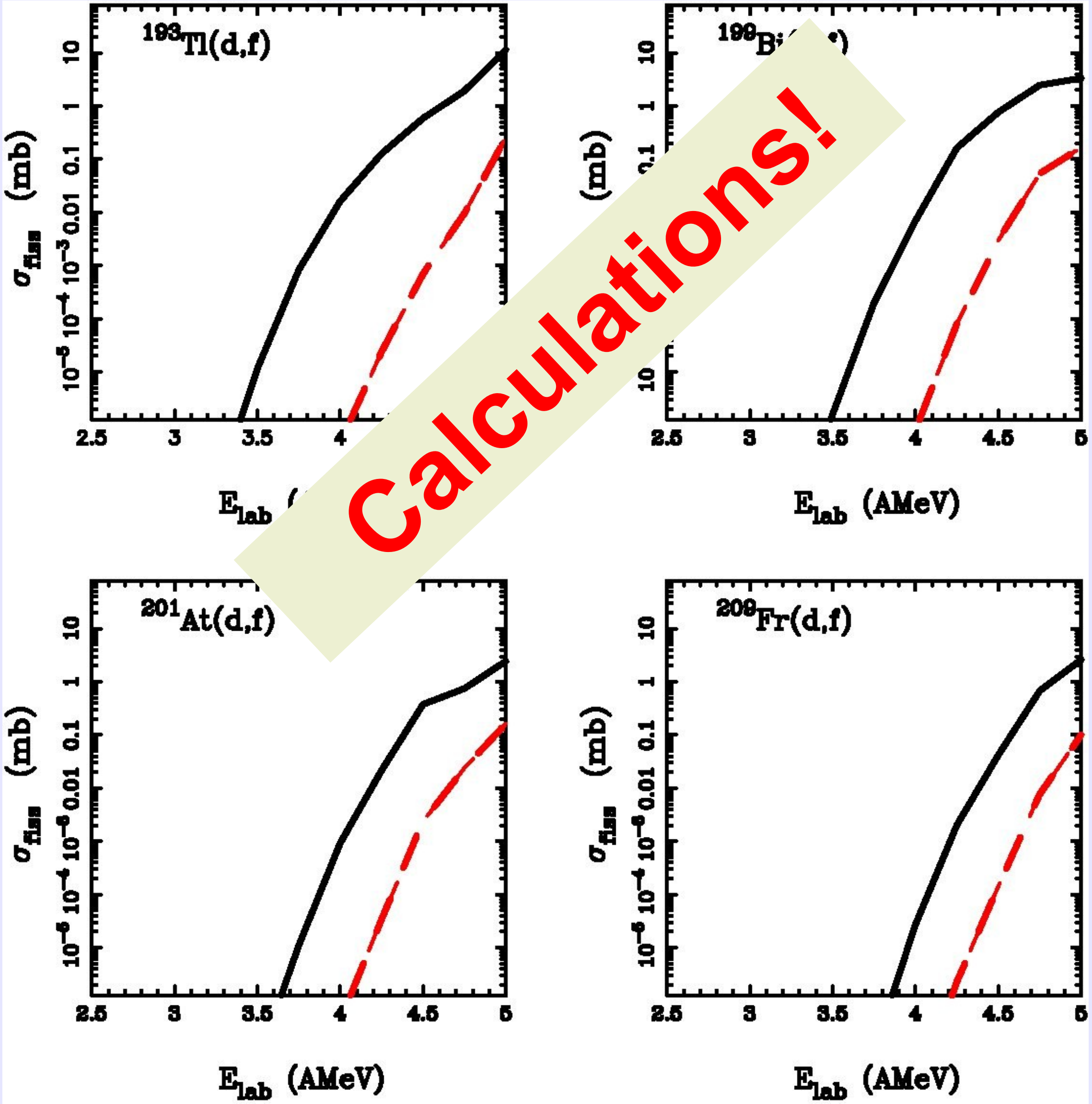
(d,p)-transfer induced fission is proposed as a tool to study low energy fission of exotic heavy nuclei. Primary goal is to directly determine the fission barrier height of proton-rich fissile nuclei, preferably using the radio-active beams of isotopes of odd elements, and thus confirm or exclude the low values of fission barrier heights, typically extracted using statistical calculations in the compound nucleus reactions at higher excitation energies. Calculated fission cross sections in transfer reactions of the radioactive beams show sufficient sensitivity to fission barrier height. In the probable case that fission rates will be high enough, mass asymmetry of fission fragments can be determined. Results will be relevant for nuclear astrophysics and for production of super-heavy nuclei. Transfer induced fission offers a possibility for systematic study the low energy fission of heavy exotic nuclei at the ISOLDE.

Courtesy M. Veselsky (Slovak Academy of Sciences), Approved IS581 ISOLDE proposal

IS581: New method: (d,pf)-transfer induced fission of RIBs in inverse kinematics at HIE-ISOLDE

It is of primary interest to observe **transfer-induced fission of odd elements such as Tl, Bi, At or Fr**, since in this case the estimated fission barriers will not be influenced by uncertainty in estimation of the pairing gap in the saddle configuration.

Observed fission rates of these beams can be used to **directly determine values of the fission barrier heights**.



Calculations!

ACTAR for fission studies at HIE-ISOLDE

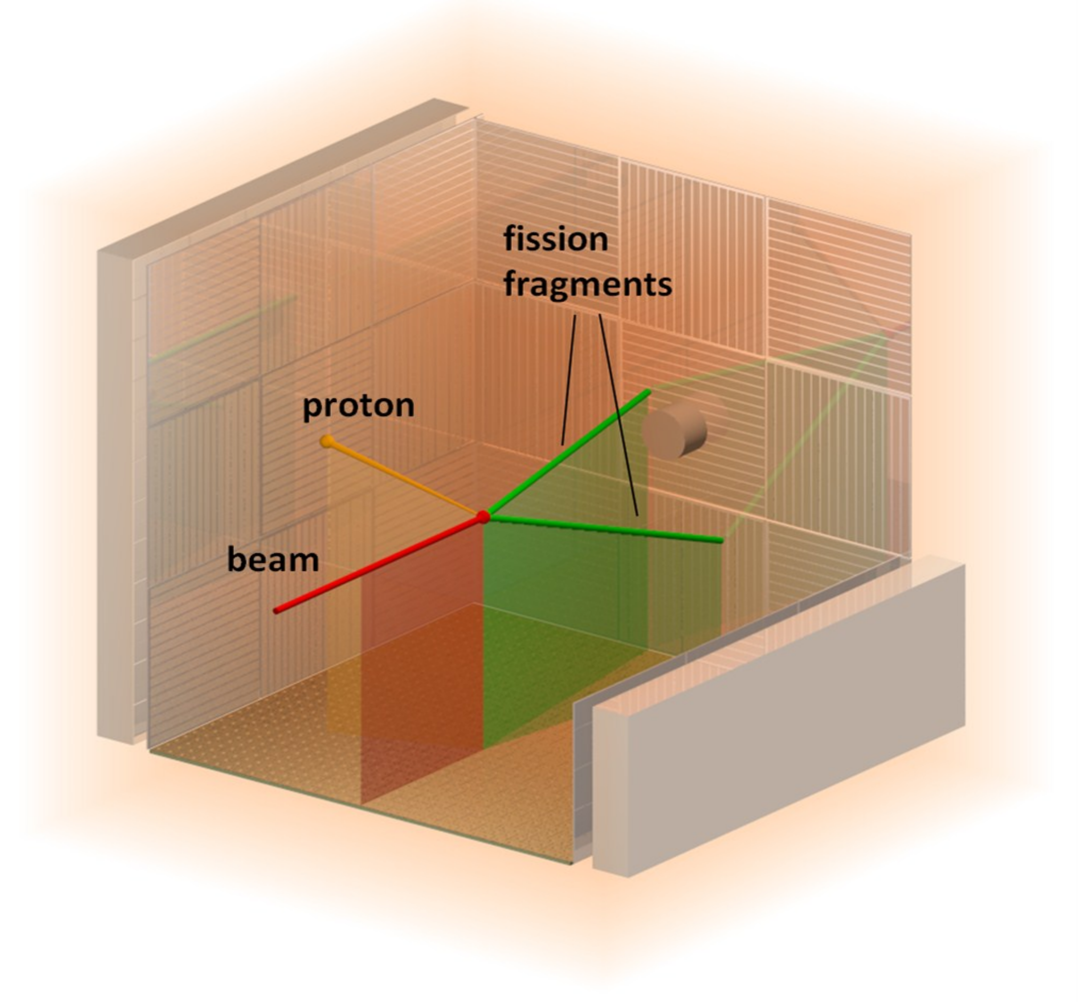
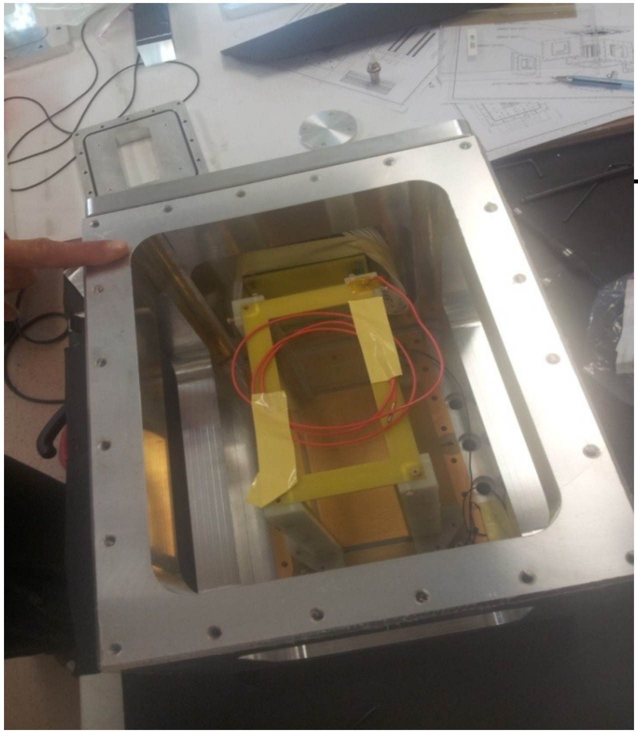
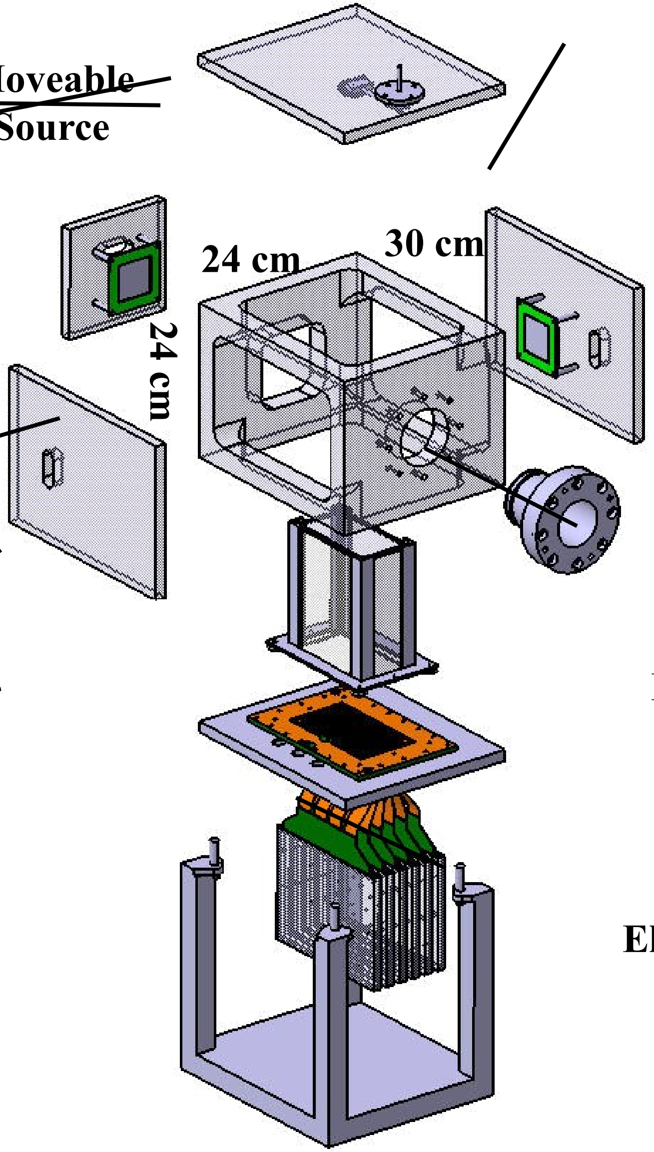


Figure 2: Configuration of ACTAR TPC for the measurement of the transfer-induced fission events. The two fission fragments are detected in the forward-placed silicon array; the proton from the transfer is either stopped in the volume (as shown) or detected in the Si-CsI telescope arrays surrounding the active volume (only partly shown).

ACTAR TPC Demonstrator

- 12 × 6 cm2; 2 × 2 mm2 × 2,048 pads
- Test high-density connection
  - High-density connector (IPNO)
  - Direct insertion to Micromegas
- Test GET electronics





Moveable Source

Si Strip Detector

Enclosure
IPNO

Field Cage
GANIL

Pad Plane 1
IPNO

Pad Plane 2
CENBG

Beam Entrance

Electronics

Outlook

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SOFIA@GSI - Studies Of FIssion with Aladin

Courtesy Julie-Fiona Martin and Julien Taieb (CEA)

SOFIA

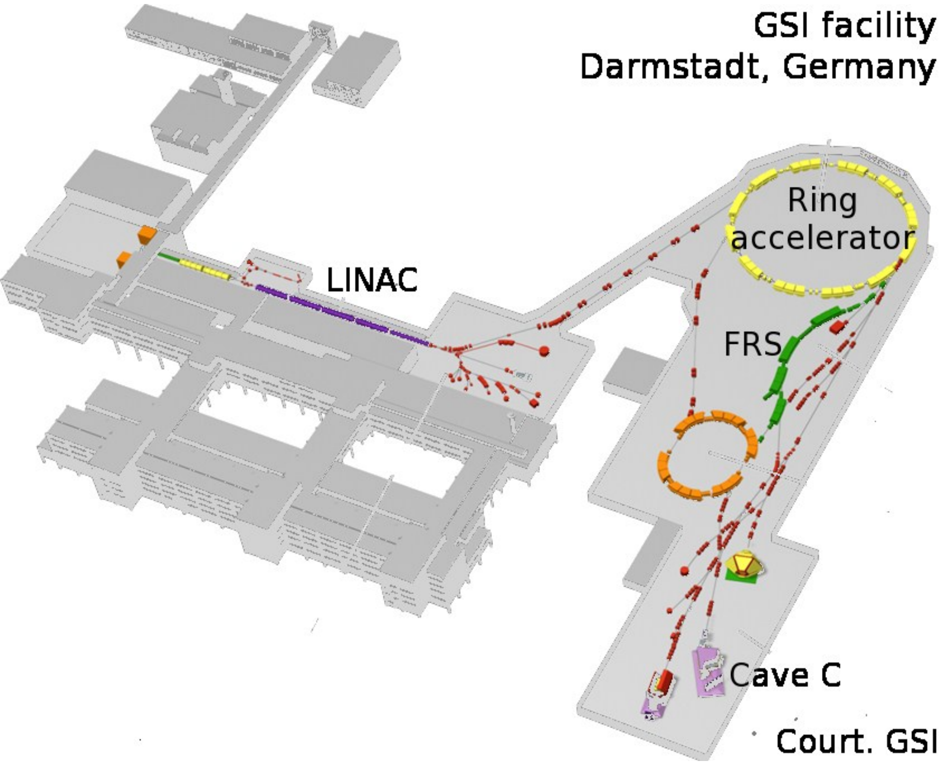
STUDIES ON FISSION WITH ALADIN

DE LA RECHERCHE À L'INDUSTRIE

cea

See also: J-F.Martin, 16th ASRC JAEA Workshop: http://asrc.jaea.go.jp/soshiki/gr/chiba_gr/workshop3/&Martin.pdf

SOFIA – Fission studies at GSI



At GSI in Darmstadt, Germany

- **Primary beam of ^{238}U**, 1 A GeV

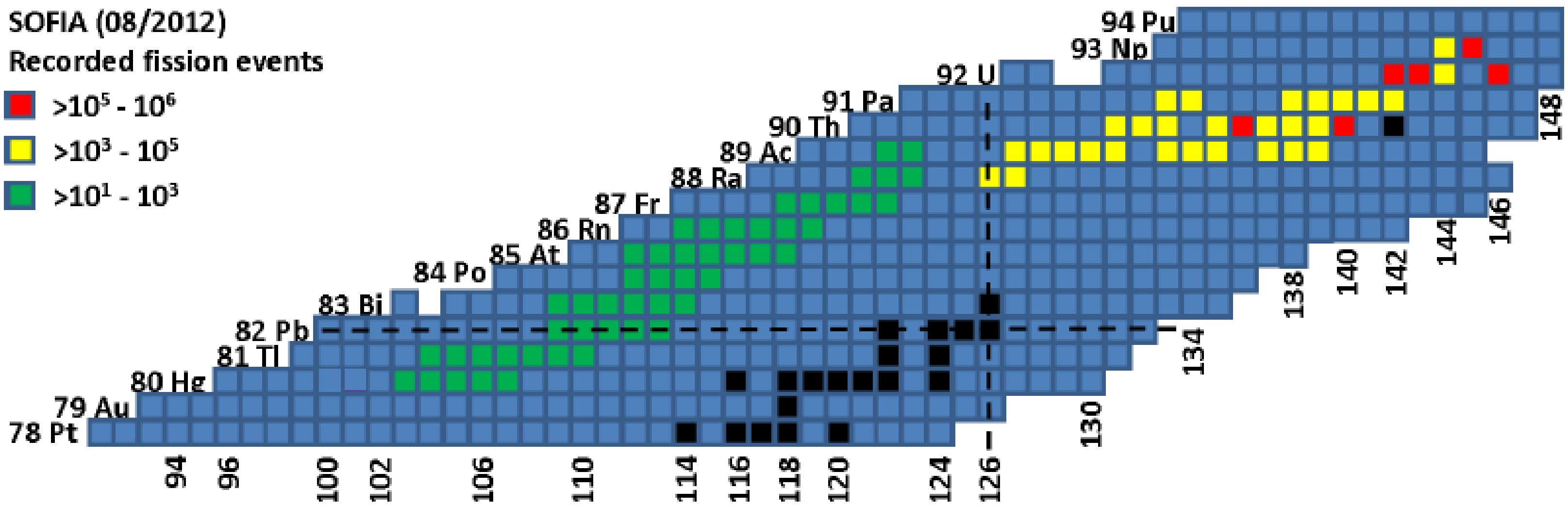
- **Fragmentation reaction** : secondary beam of fissile ions (from Mercury up to Neptunium), sorted through FRS

- **Selected secondary beam** ions sent to Cave C for the fission experiment

- **Fission induced in flight by Coulomb excitation (E*~11-13 MeV)**

- **Both fission fragments identified simultaneously, both in mass and in charge (now FF's are at ~400 AMeV!)**

Studied nuclei



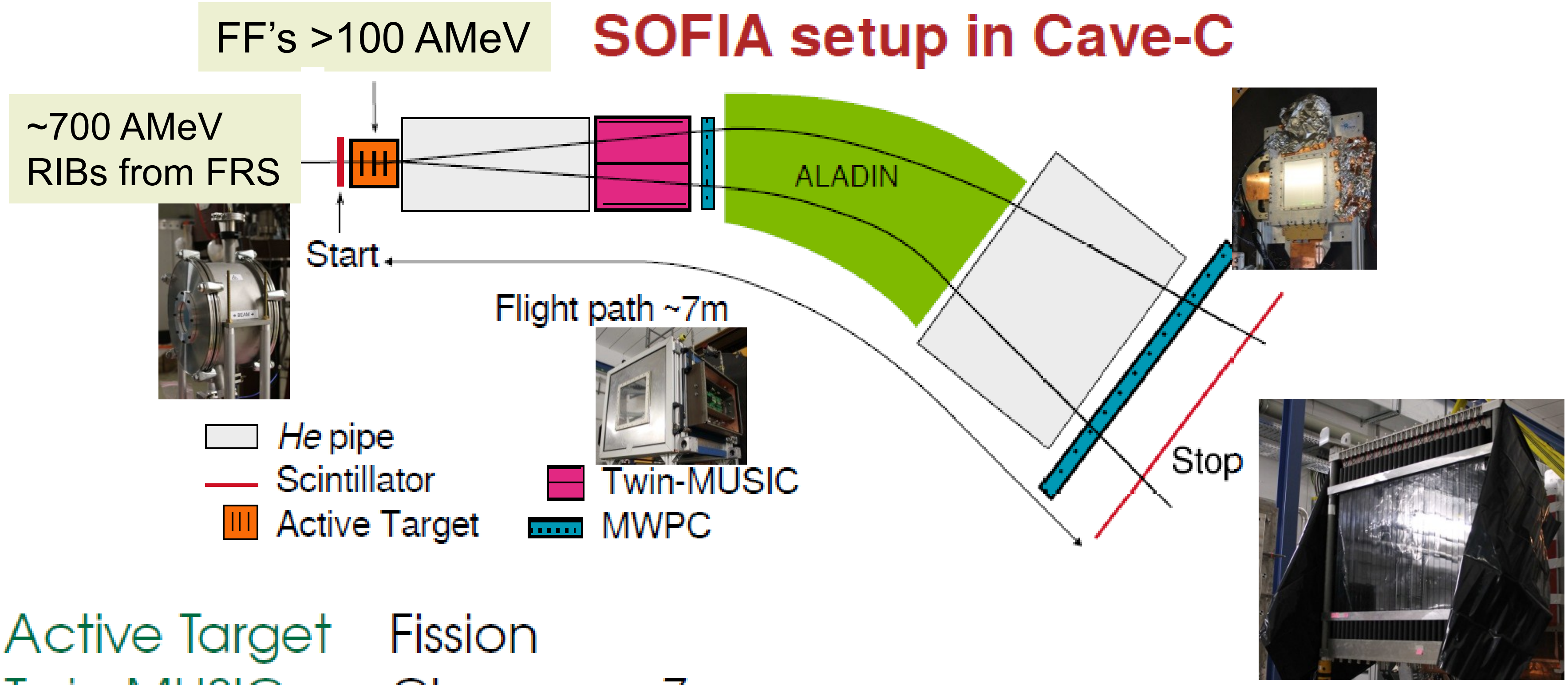
Actinides : High statistics for applications

- *U, Np*
- 1.5 days

Pre-actinides and lighter actinides : browse the nuclide chart

- Lower statistics, a few hours

SOFIA Setup in Cave-C

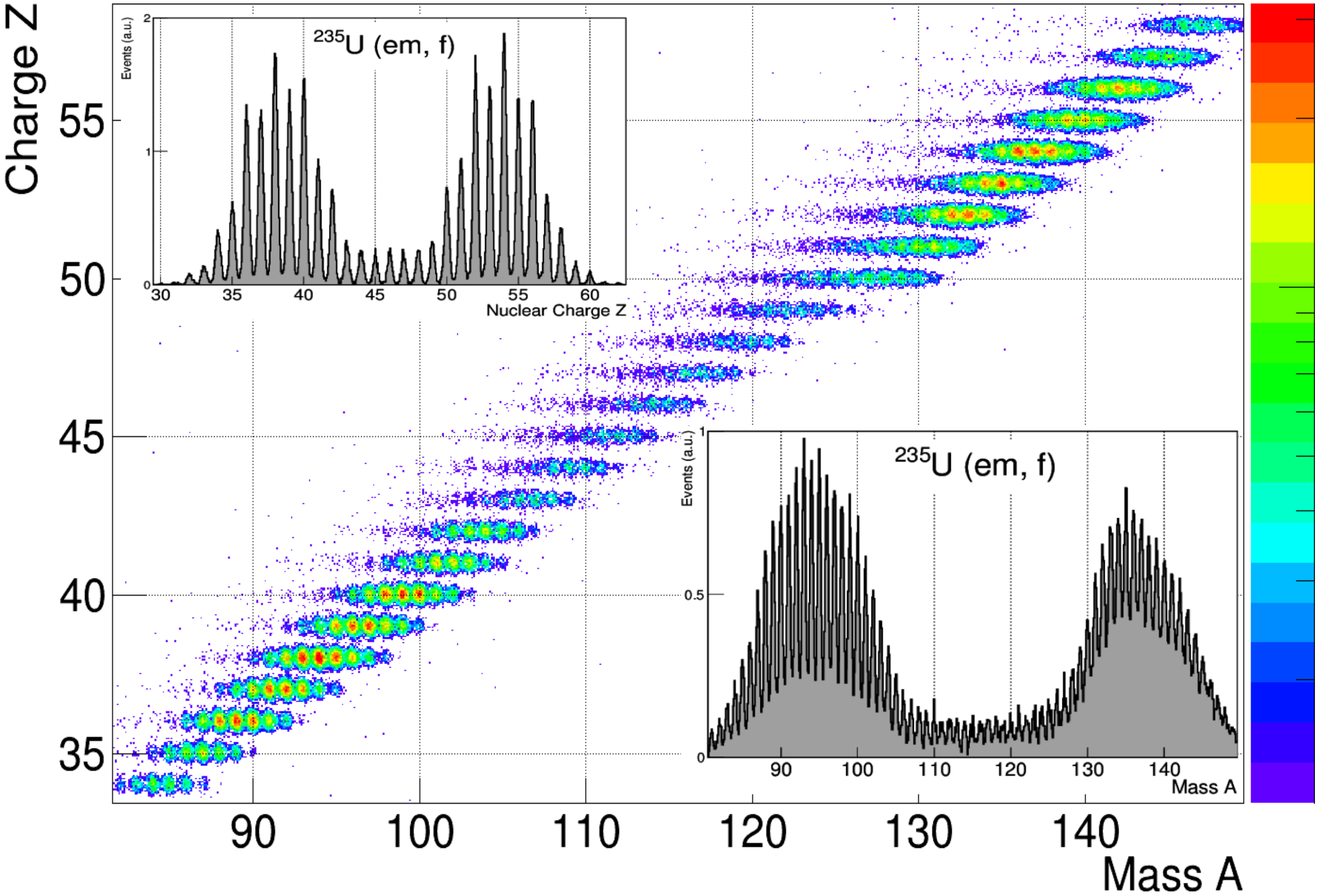


Active Target	Fission	
Twin-MUSIC	Charges	Z
MWPCs	Positions	ρ
ToF	Velocity	$\gamma\ v$
ALADIN	Dipole	B

$$(B\rho, Z, \gamma v) \to A$$

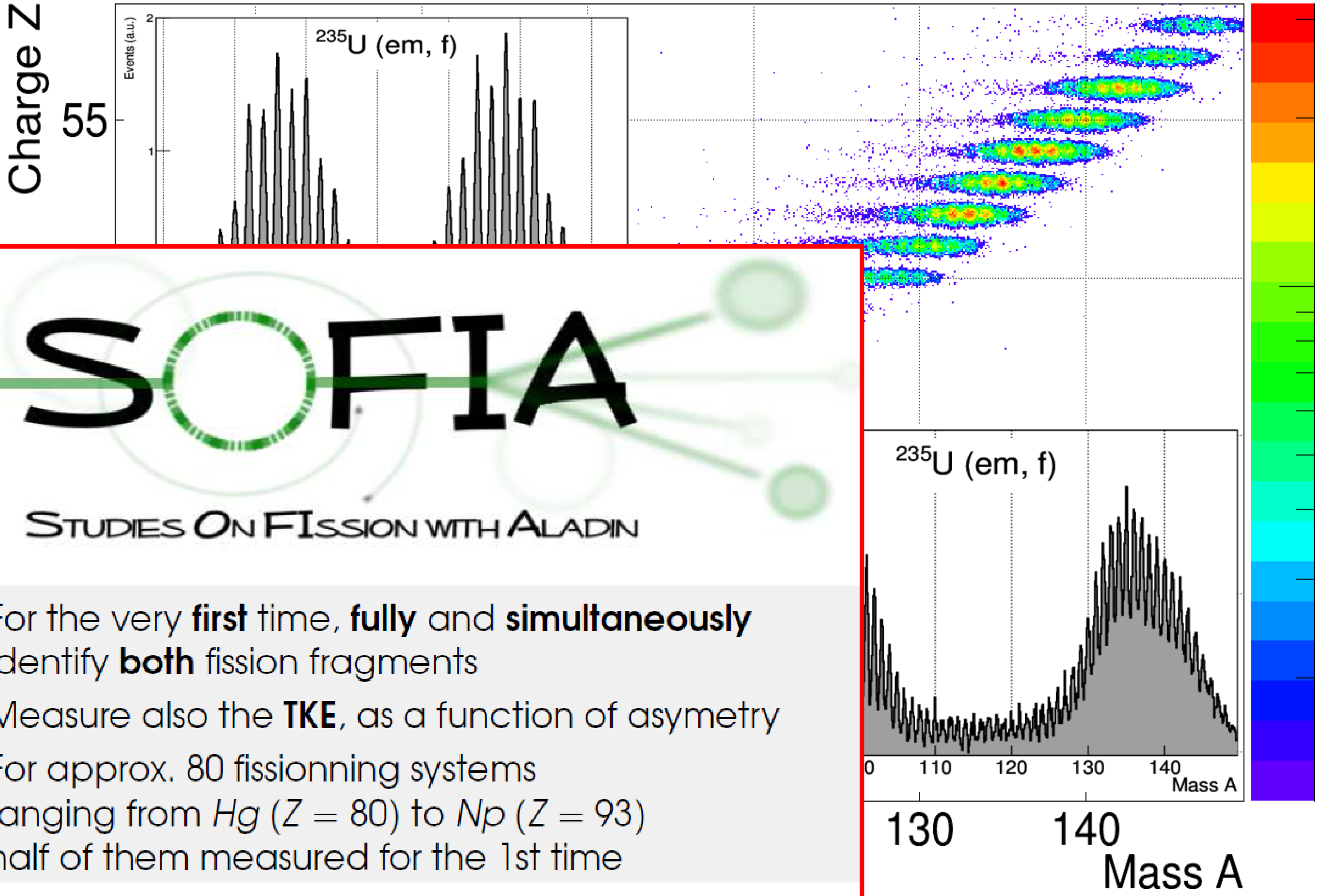
Some examples (courtesy J.F. Martin)

STUDIES ON FISSION WITH ALADIN



Some examples (courtesy J.F. Martin)

SOFIA
STUDIES ON FISSION WITH ALADIN



SOFIA
STUDIES ON FISSION WITH ALADIN

- For the very **first** time, **fully** and **simultaneously** identify **both** fission fragments
- Measure also the **TKE**, as a function of asymetry
- For approx. 80 fissionning systems ranging from *Hg* ($Z = 80$) to *Np* ($Z = 93$) half of them measured for the 1st time

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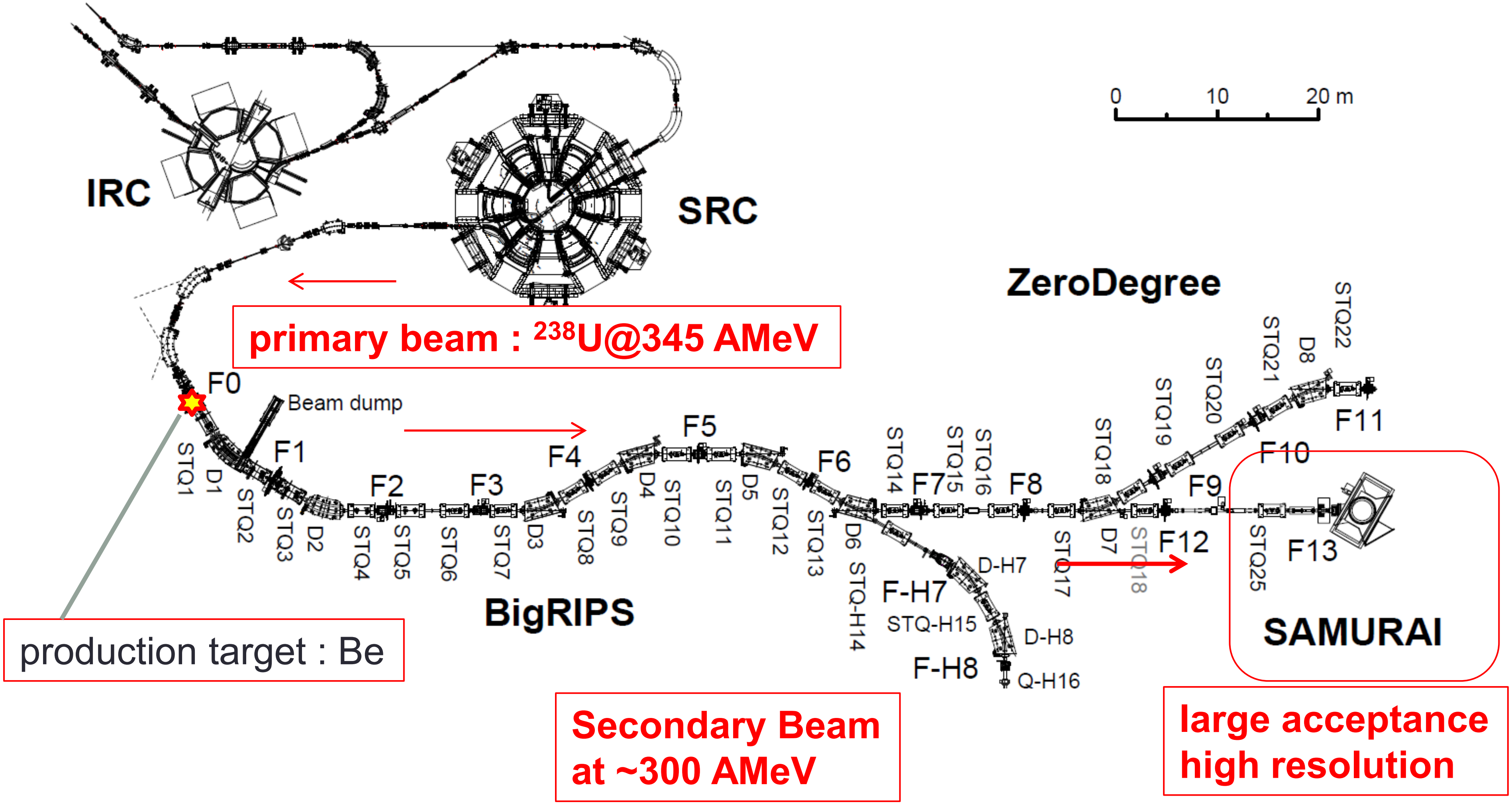
Fission Barrier Studies of **Neutron-Rich Nuclei** via the proton-knockout (p,2p) reactions with ~300 AMeV RIBs with SAMURAI@RIKEN

Courtesy Dennis Mücher and Masami Sako

See also: 16th ASRC JAEA Workshop:
http://asrc.jaea.go.jp/soshiki/gr/chiba_gr/workshop3/Program3.html
http://asrc.jaea.go.jp/soshiki/gr/chiba_gr/workshop3/&Sako.pdf

RIBF and BigRIPS and SAMURAI magnet



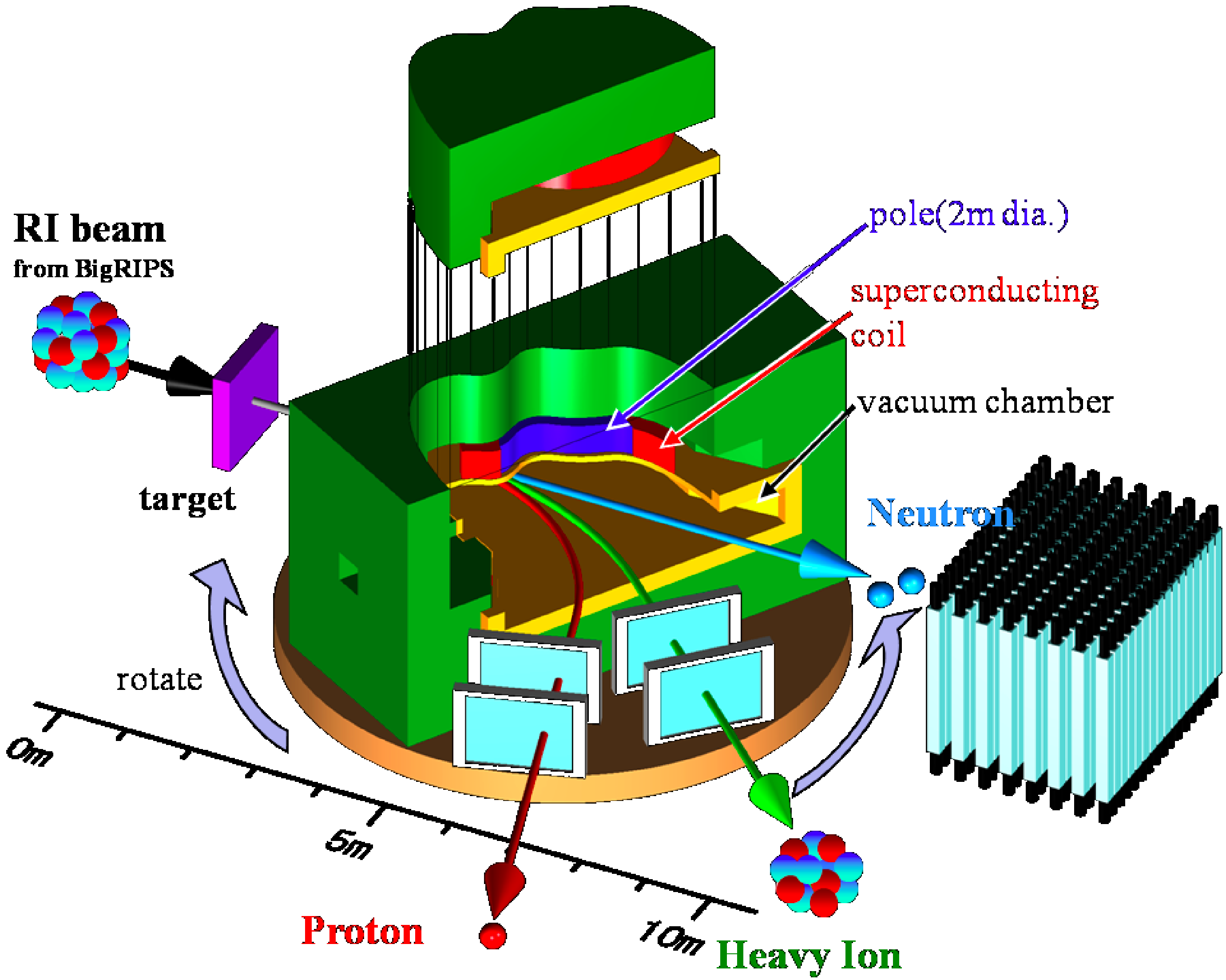
primary beam : ^{238}U@345 AMeV

production target : Be

Secondary Beam
at ~300 AMeV

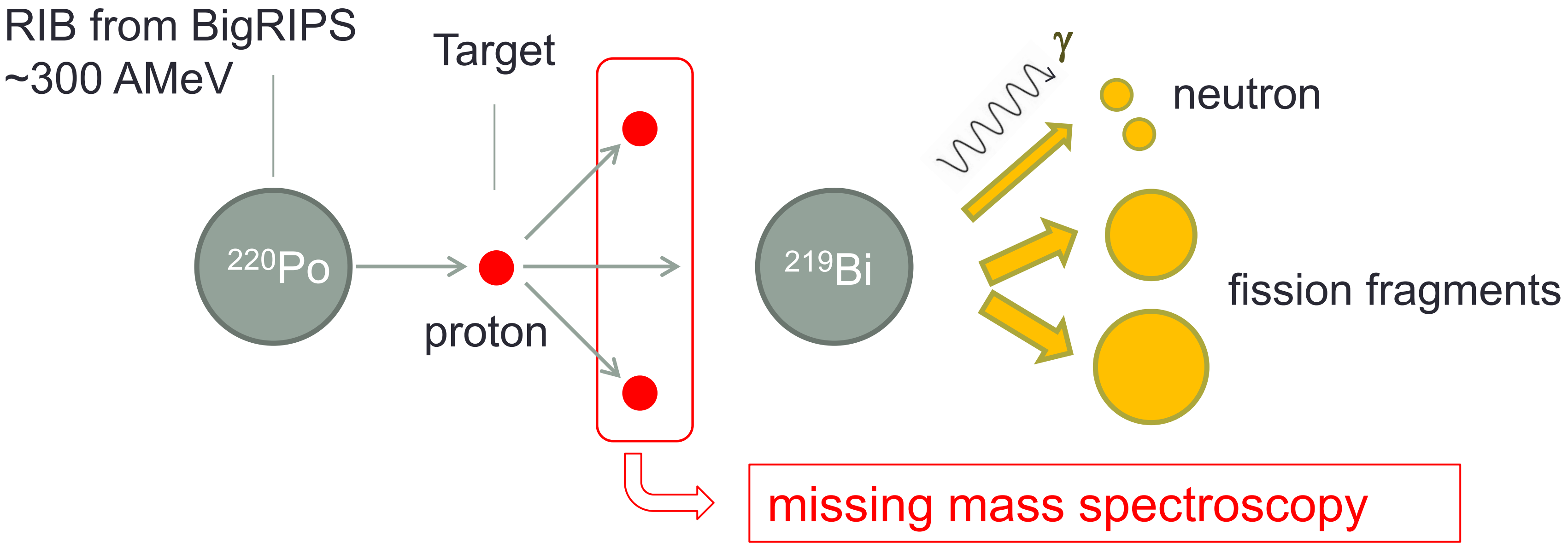
large acceptance
high resolution

SAMURAI（**S**uperconducting **A**nalyser for **MU**lti-particle from **RA**dio **I**sotope beam） magnet



Method: Inverse kinematics with (p,2p-fission) reaction

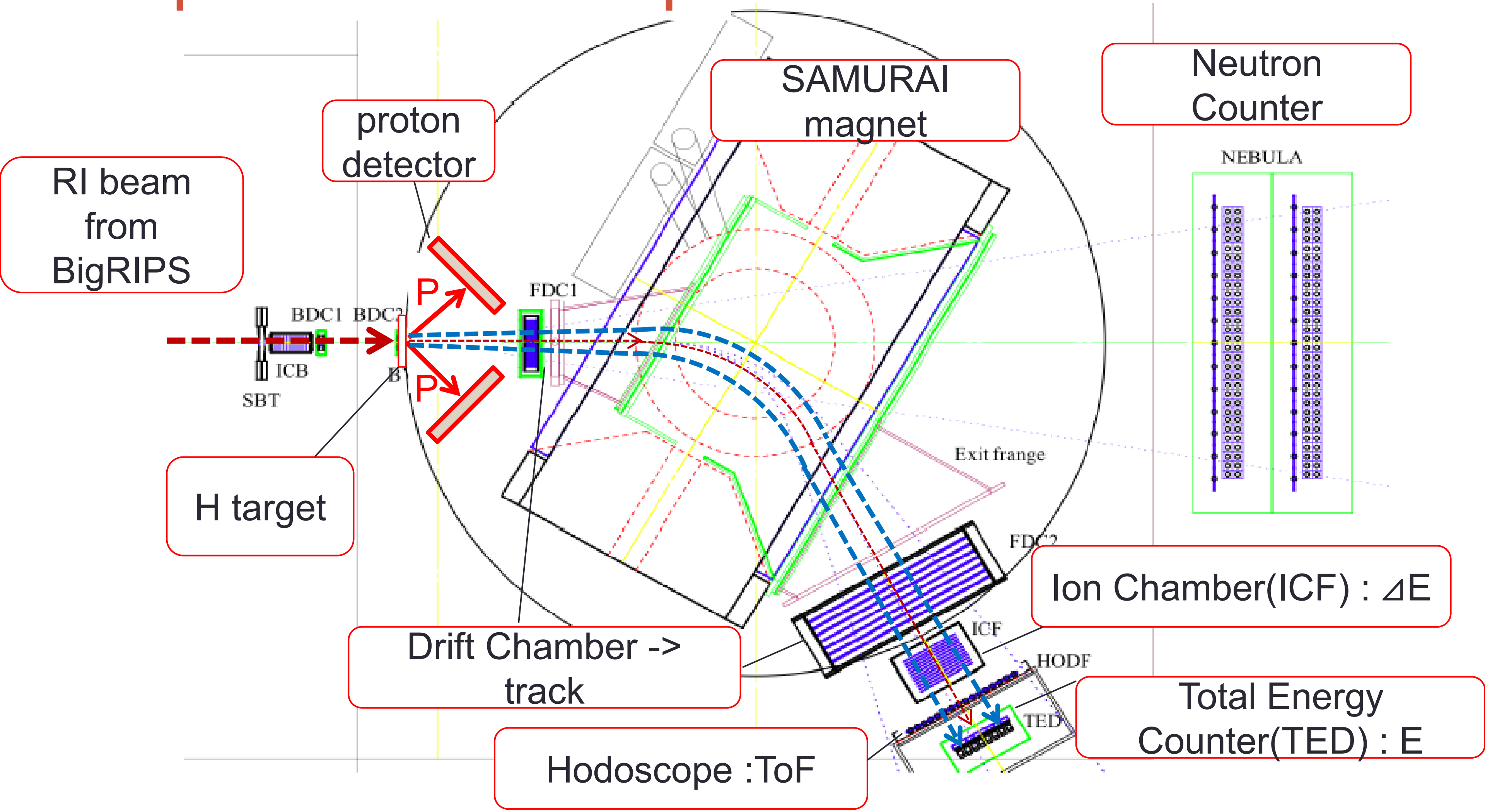
(a similar idea with the p,pn-fission reaction, needs to measure also neutrons!)



missing mass spectroscopy

- proton knockout (p,2p) reaction
  - cross section : large
  - high momentum transfer, large acceptance for forward-focused FF's
  - 2 proton measurement -> **low background**
- Excitation energy is directly deduced by missing mass spectroscopy

Experimental Setup



RI beam from BigRIPS

proton detector

SAMURAI magnet

Neutron Counter

H target

Drift Chamber -> track

Ion Chamber(ICF) : ⊿E

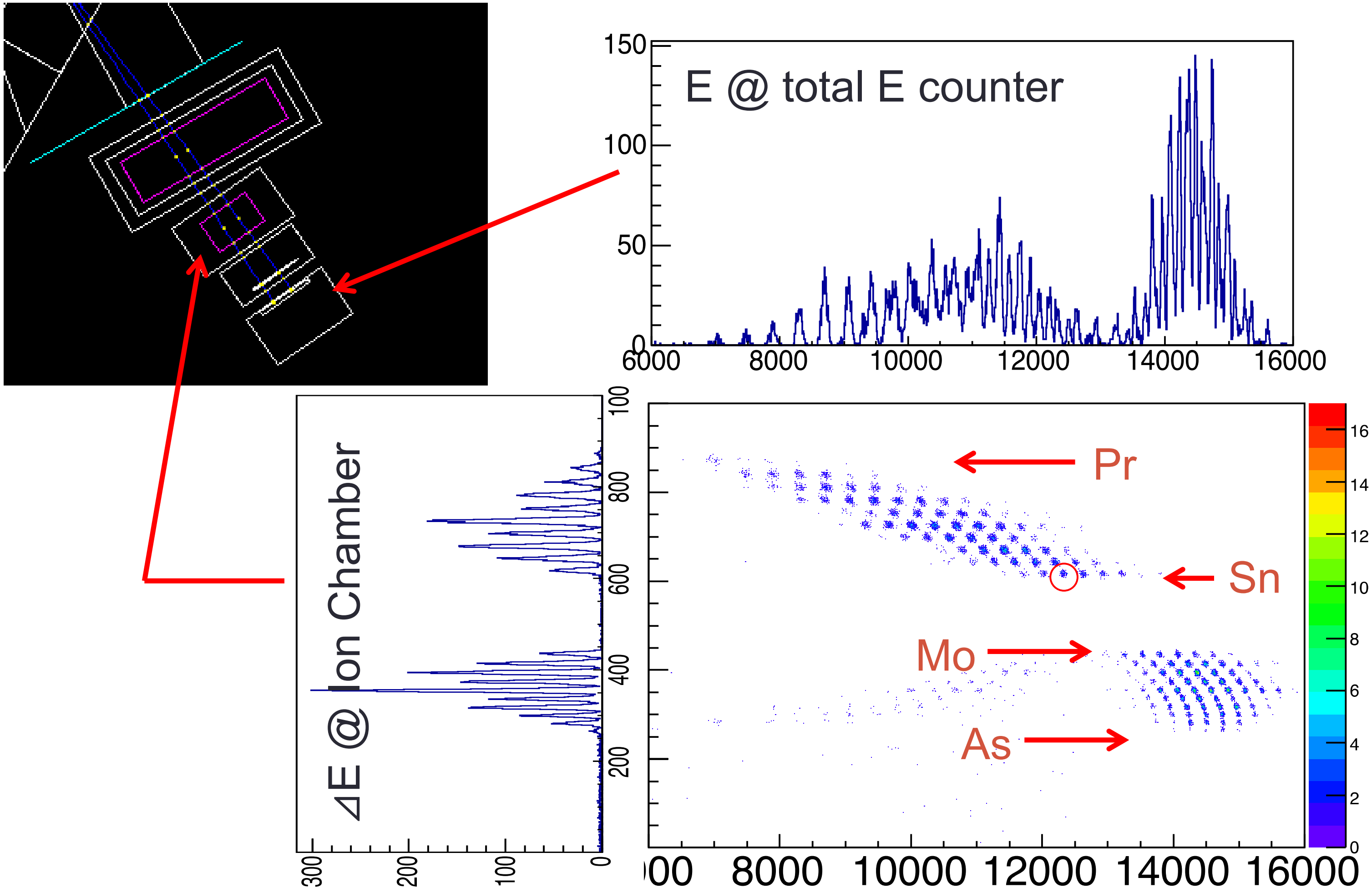
Hodoscope :ToF

Total Energy Counter(TED) : E

Charge(Z) and Mass(A) can be separated by Bρ−⊿E-ToF(E)

SAMURAI and fragment counters

Simulation!


E @ total E counter
150
100
50
0
6000
8000
10000
12000
14000
16000
ΔE @ Ion Chamber
300
200
100
0
100
800
600
400
200
Pr
Sn
Mo
As
16
14
12
10
8
6
4
2
0
00
8000
10000
12000
14000
16000

Next Experiment

- Beam : ^{210}Bi (300 pps)
  ^{213}Po (270 pps)
  ^{219}At (130 pps)
  -> Total Beam rate ~ $4*10^3$ pps by LISE++
- Target : Solid H
- Estimation
  - N=1.1 x 10^7 fragment events per day for ^{218}Po
  - (p,2p) cross section ~ 100 ub/MeV at 1g/cm^2 H_2 target
    ->$5*10^2$ events/day･MeV

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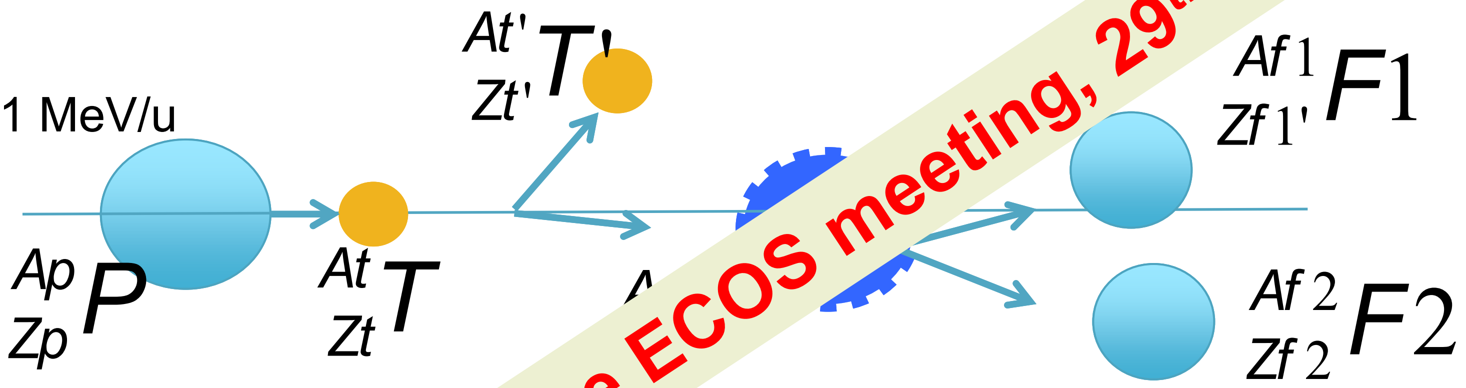
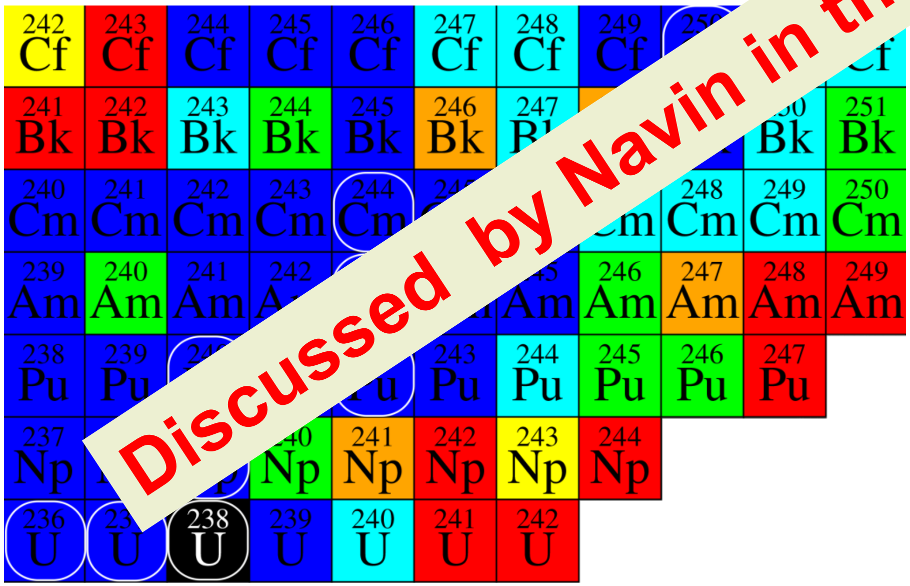
Transfer-induced fission in inverse kinematics @ GANIL

F. Farget et al., GANIL

$^{238}U + ^{12}C$ @ 6.1 MeV/u

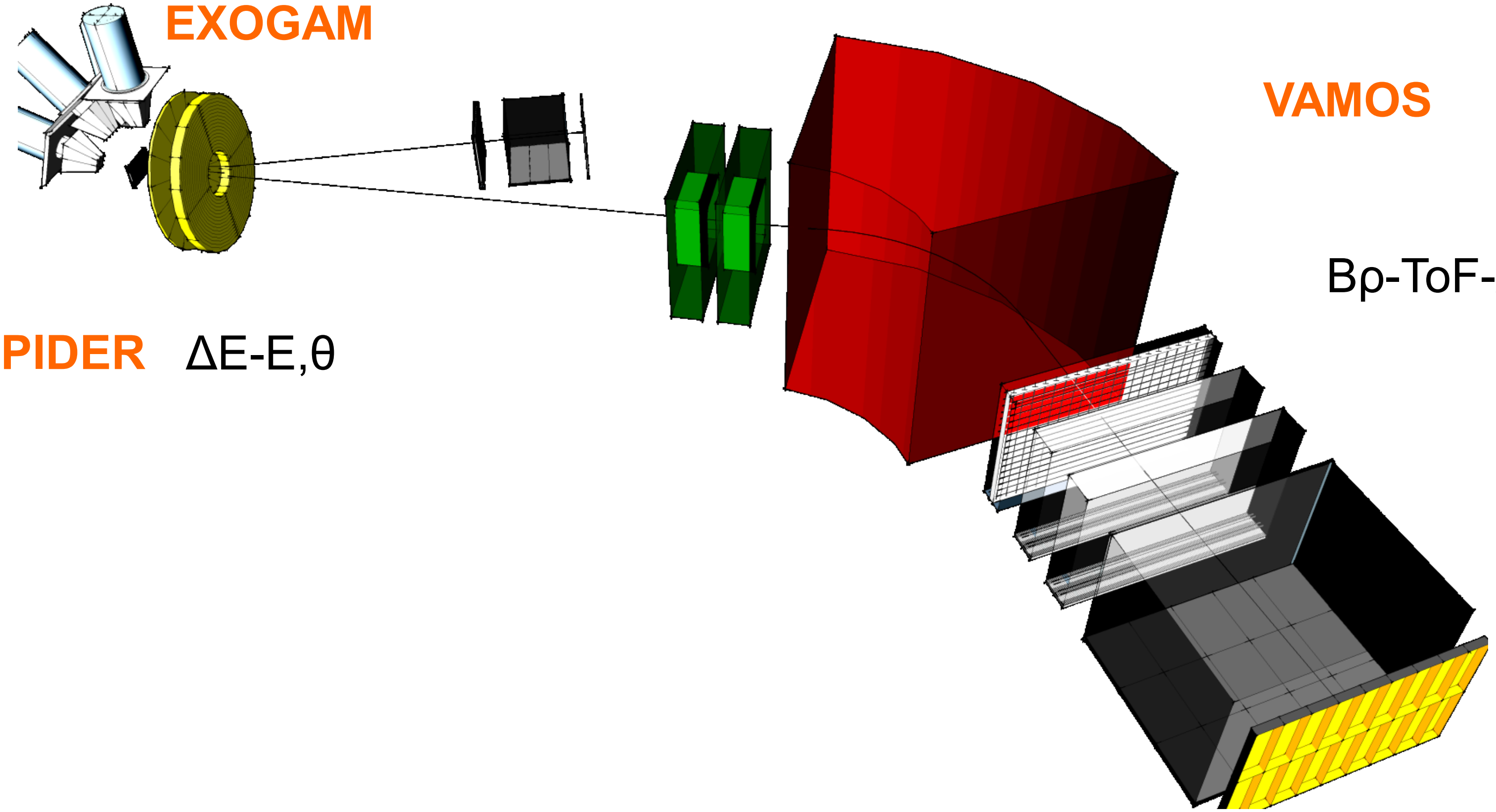


Discussed by Navin in the ECOS meeting, 29th October



- 10 actinides produced
- E* distribution
- Full resolution in (Z,A) of fragments
- TKE

Transfer-induced fission in inverse kinematics



EXOGAM

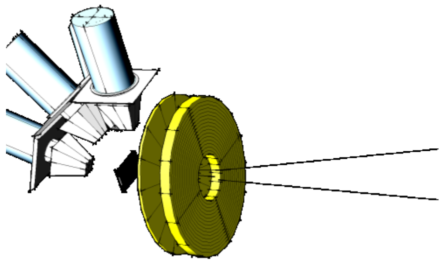
VAMOS

Bρ-ToF-ΔE-E

SPIDER ΔE-E,θ

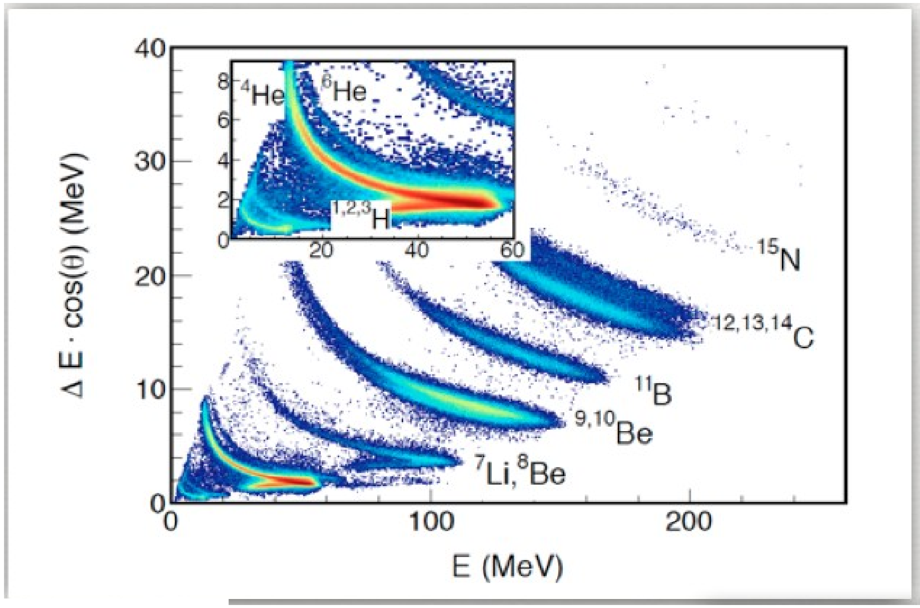
S. Pullanhiotan et al., NIM 593 (2008) 343
M. Rejmund et al., NIMA 646 (2011) 184

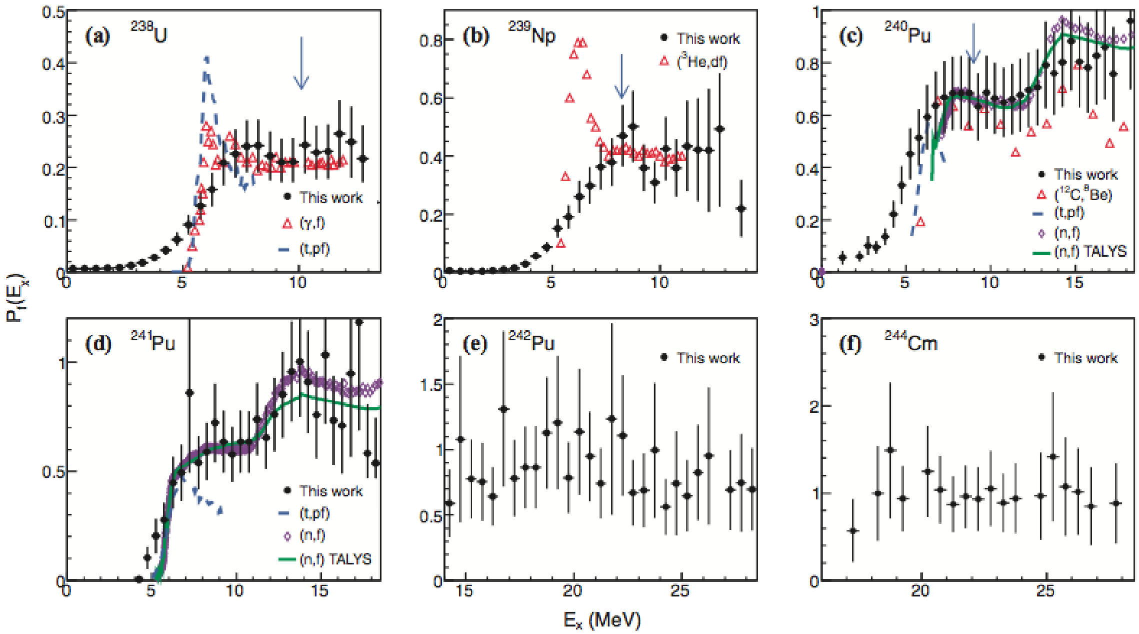
Transfer-induced fission in inverse kinematics

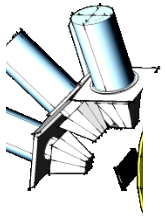


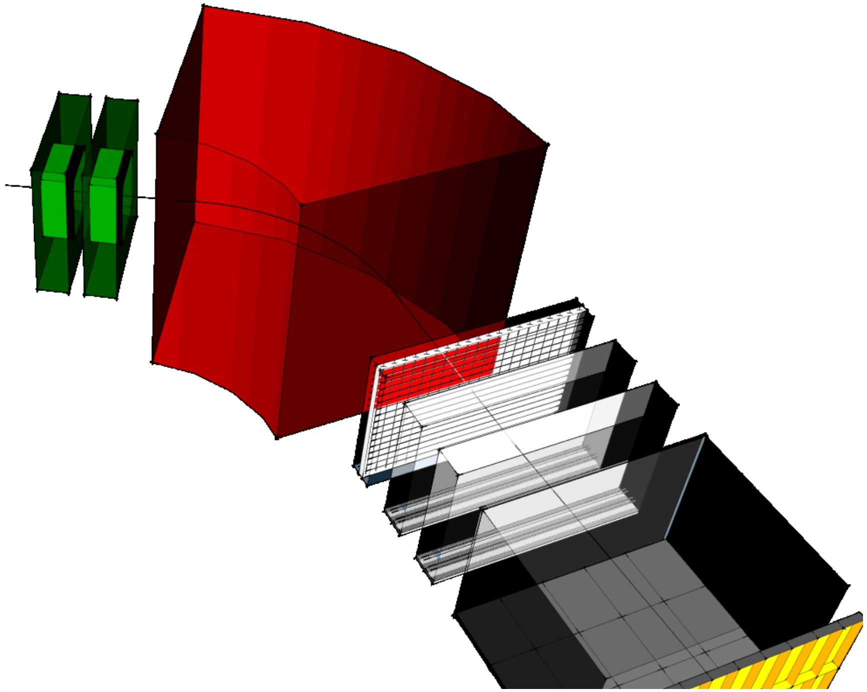
SPIDER ΔE-E,θ

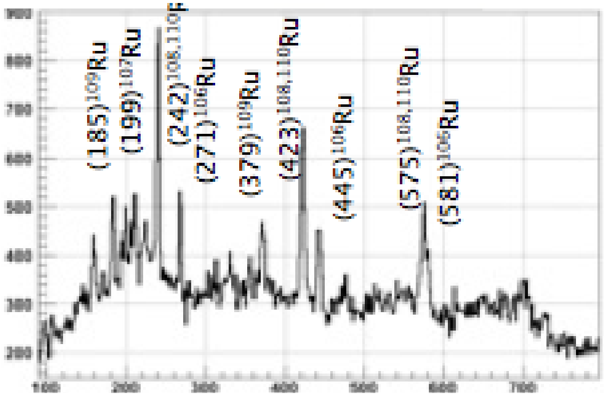
C. Rodriguez-Tajes et al., PRC (2014) 024614

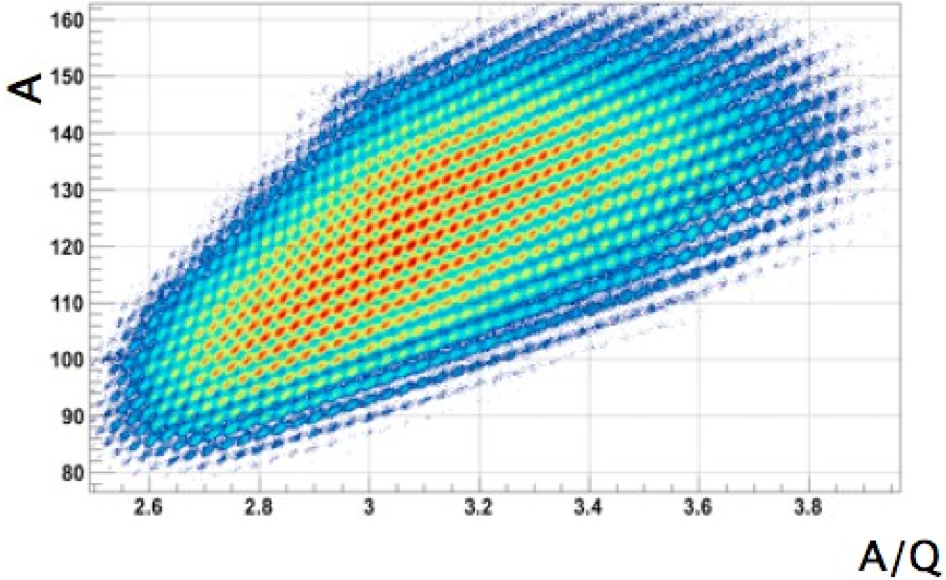


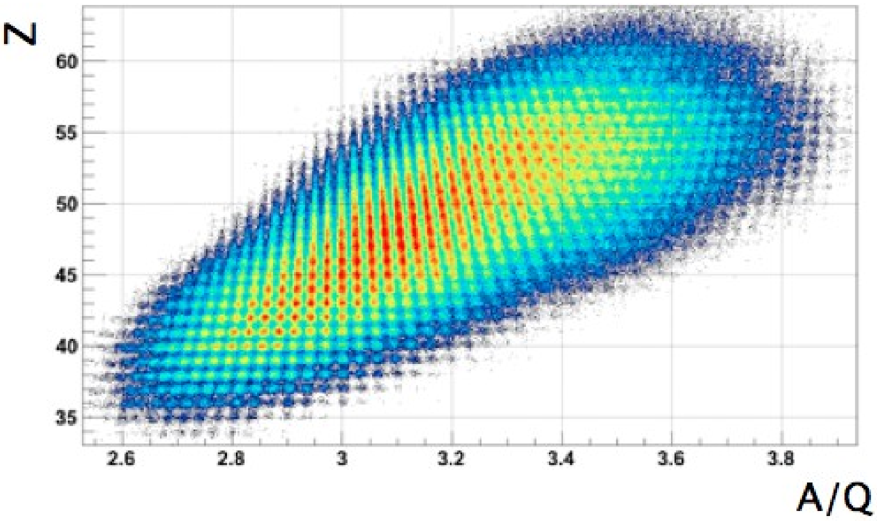




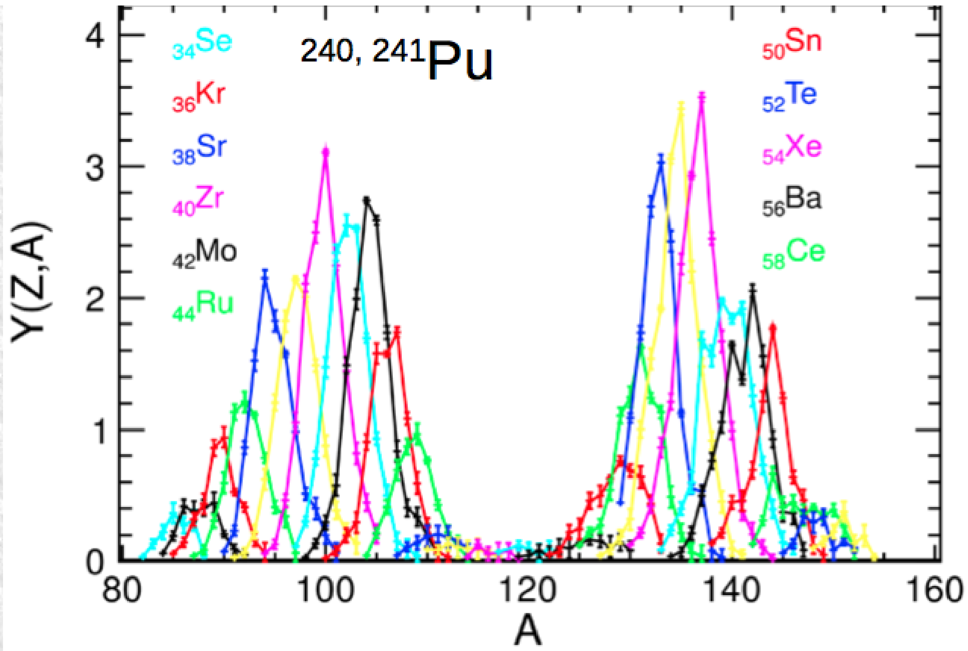



(185) ^{109}Ru
(199) ^{107}Ru
(242) ^{108,110}F
(271) ^{106}Ru
(379) ^{109}Ru
(423) ^{108,110}Ru
(445) ^{106}Ru
(575) ^{108,110}Ru
(581) ^{106}Ru
900
800
700
600
500
400
300
200
1000
2000
3000
4000
5000
6000
7000

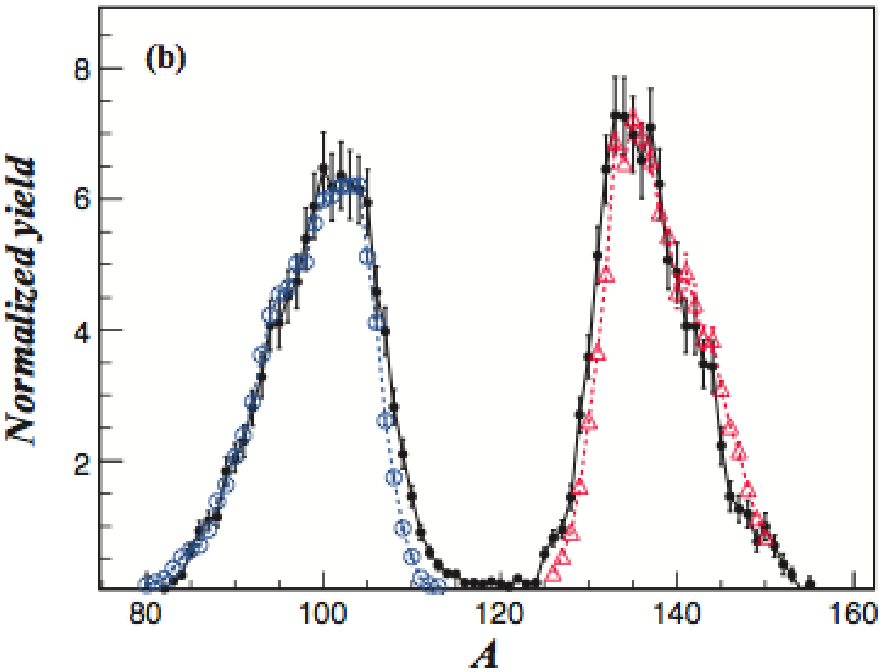

A
160
150
140
130
120
110
100
90
80
2.6
2.8
3
3.2
3.4
3.6
3.8
A/Q


Z
60
55
50
45
40
35
2.6
2.8
3
3.2
3.4
3.6
3.8
A/Q

Isotopic distribution of fission fragments



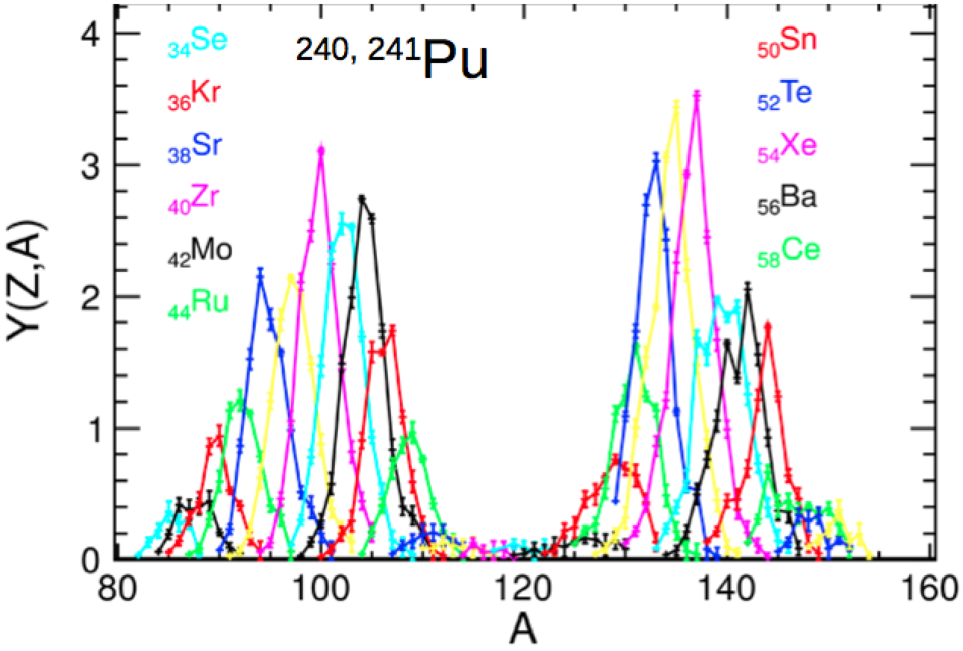
M. Caamaño et al., PRC 88 (2013) 024605



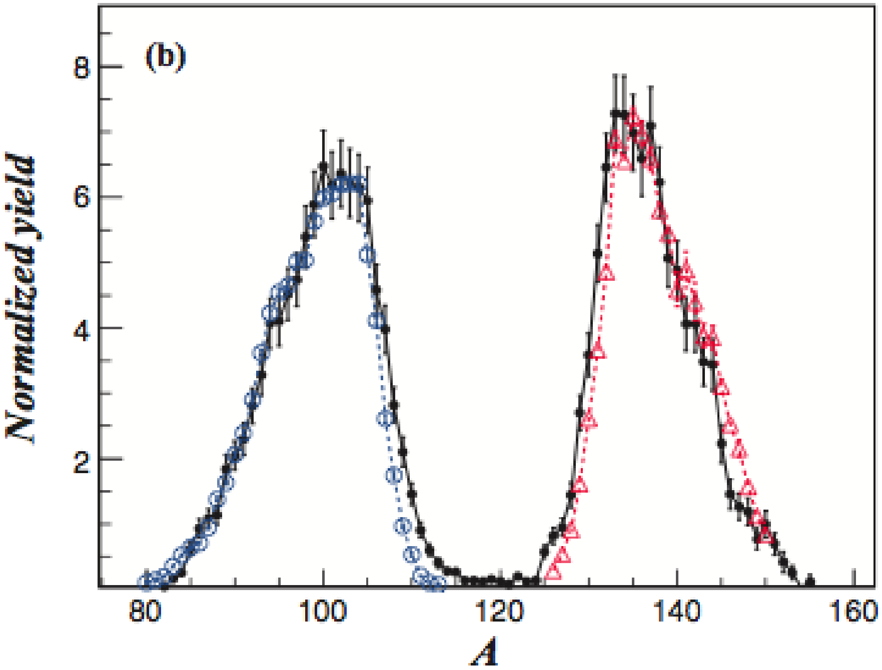
C. Schmitt et al, NPA430 (1984) A. Bail, PRC84 (2011)

Excellent control of the spectrometer transmission

Isotopic distribution of fission fragments



M. Caamaño et al., PRC 88 (2013) 024605



C. Schmitt et al, NPA430 (1984) A. Bail, PRC84 (2011)

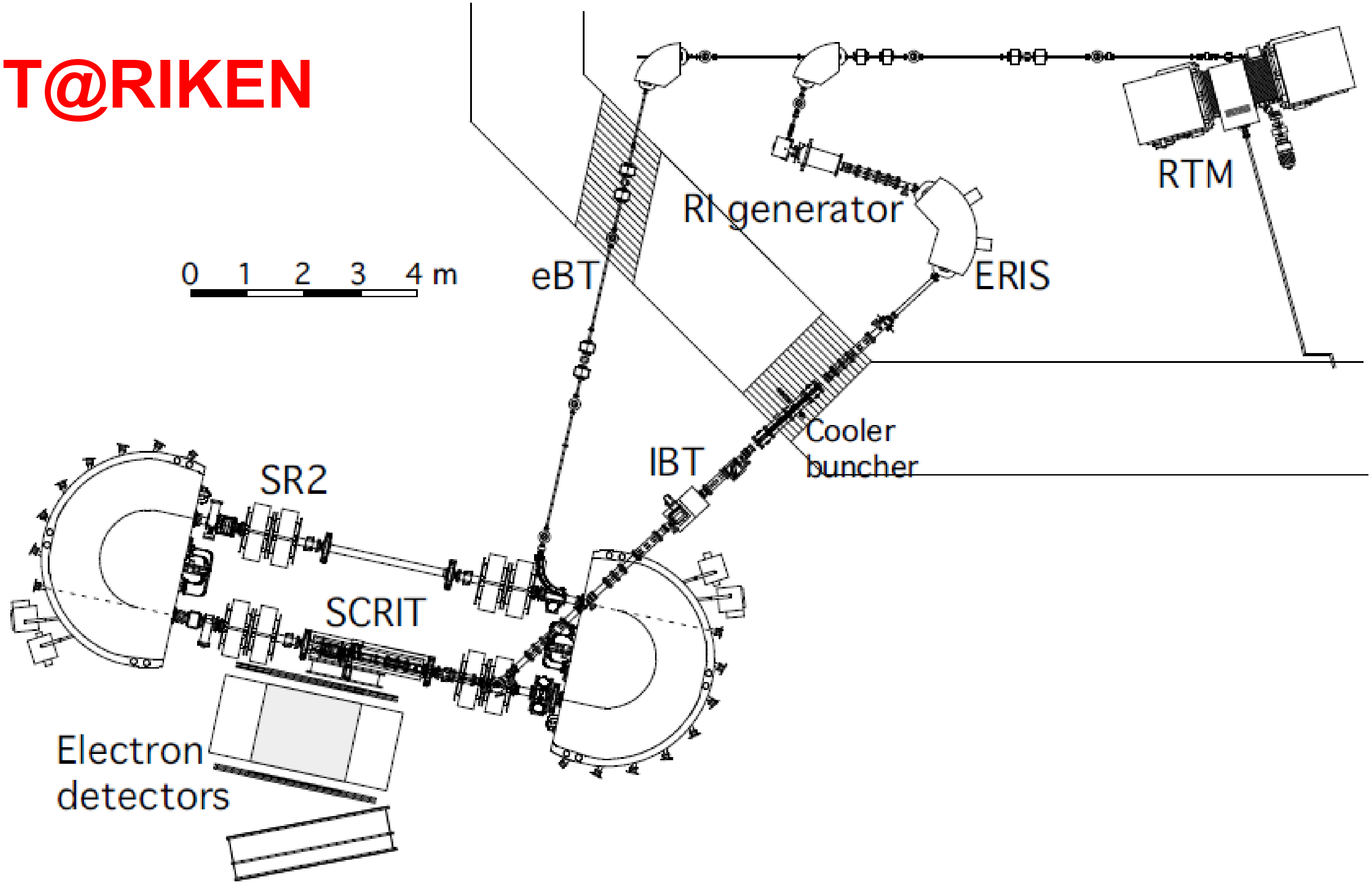
Excellent control of the spectrometer transmission

Future(?): Fission via Electron scattering from unstable nuclei

e.g. electron scattering from unstable nuclei (colliding accelerated electrons and low-energy radioactive ions!)

SCRIT at RIKEN (Japan) and ELISe at GSI (Darmstadt, Germany)

SCRIT@RIKEN



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Conclusions:

Bright future for fission studies with RIBs
Access to both proton- and neutron- rich nuclei
Un-precendented precision in Z,A determination

Thanks to:
Fanny Farget for VAMOS@GANIL
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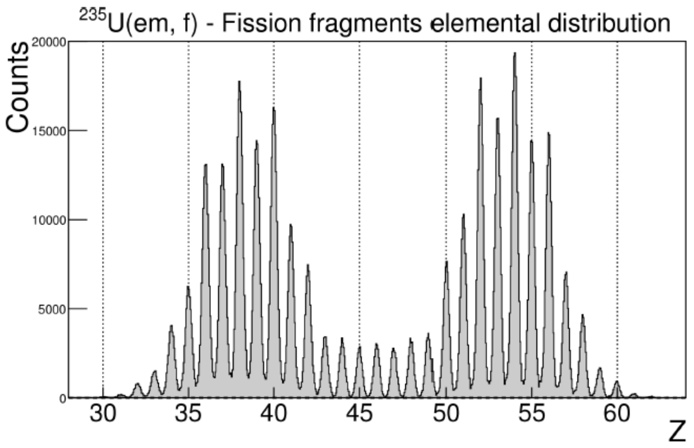
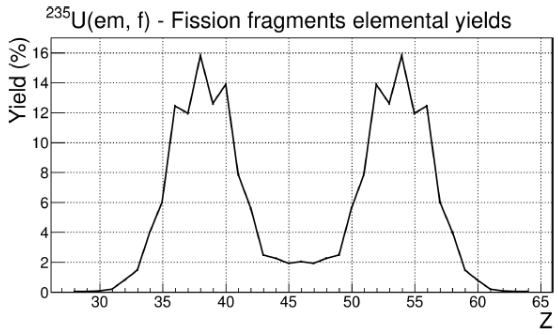
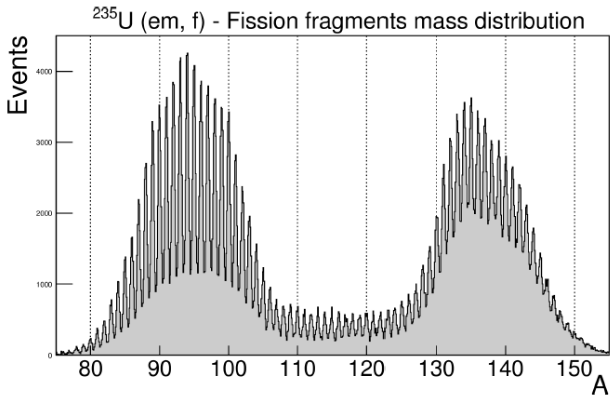
Some Results (courtesy J.-F. Martin)



- Complete disentanglement of charges
- Landmarks : even-odd staggering and $Z = 54$
- Width of gaussians 0.41 *FWHM*

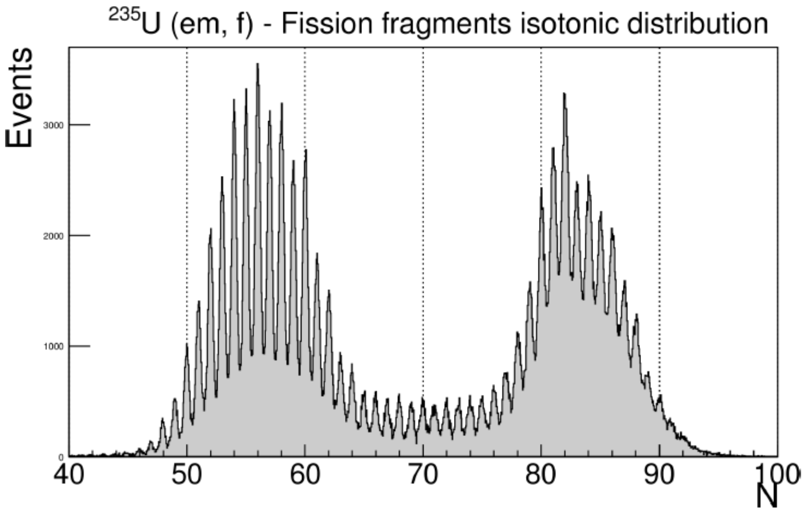


- Statistical uncertainty : ranging from 0.3 % to 1.2%
- Fine even-odd staggering (incl. at symmetry)
- Sharp increase at $Z = 50$
- Strong contribution of $Z = 54$
- Asymmetric/symmetric ratio → $E^* \approx 13 - 14\ MeV$



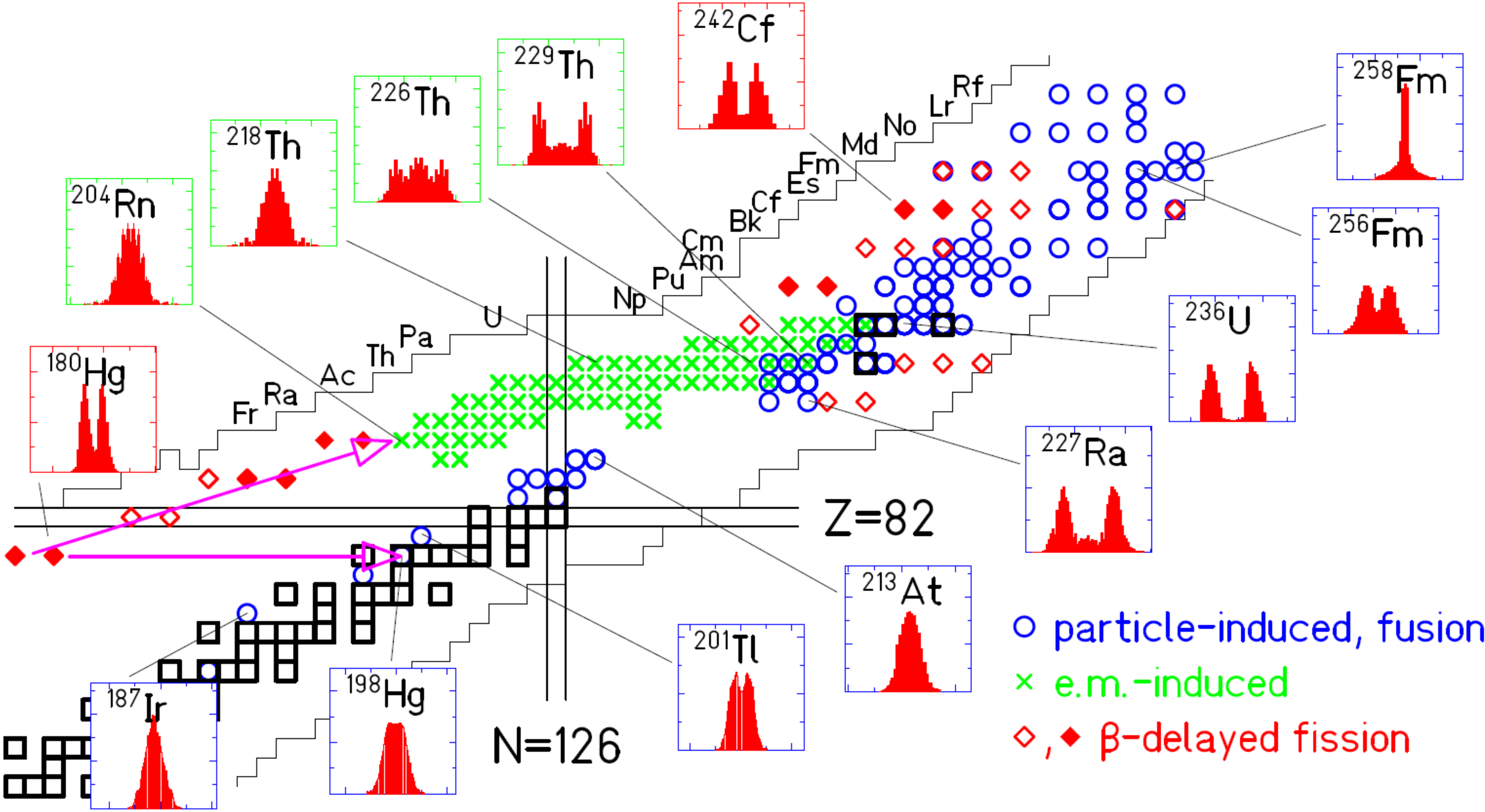
Uncertainties

- Width of gaussians 0.58 – 0.75 *u.m.a. FWHM*
- Statistical uncertainty : 1.6 % to 3%



- $N = A - Z$
- Landmarks : even-odd staggering and $N = 82$

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)

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	**$1.5(6)\times 10^{-3}$**	Z,A,T,KE,TKE,MD,GF	(Liberati *et al.*, 2013)
^{180}Tl	1.09(1) s	0.63	SR,IS,WM	**$3.2(2)\times 10^{-5}$**	Z,A,T,KE,TKE,MD,GF	(Elseviers *et al.*, 2013)
	$0.97^{+0.09}_{-0.08}$ s		FE,NS,MF	$\sim 3\times 10^{-(7\pm1)}$	T,EXF	(Lazarev *et al.*, 1987, 1992)
^{186m1,m2}Bi	9.8(4), 14.8(8) ms$^{\#}$	2.09	FE,RS,Si/Ge	$7.6\times 10^{-2,e}$	T,EXF,KE,GF	(Lane *et al.*, 2013)
^{188m1,m2}Bi	$\sim$0.3 s^{c}	0.51	FE,NS,MF	$3.4\times 10^{-4,\,a,c}$	T,EXF	(Lazarev *et al.*, 1992)
	265(10), 60(3) ms$^{\#}$		FE,RS,Si/Ge	$(0.16-0.48)\times 10^{-2,f}$	T,EXF,KE,GF	(Lane *et al.*, 2013)
^{192m1,m2}At	88(6), 11.5(6) ms$^{\#}$	2.09	FE,RS,Si/Ge	$(7-35)\times 10^{-2}$	T,EXF,KE,GF	(Andreyev *et al.*, 2013)
^{194m1,m2}At	310(8), 253(10) ms$^{\#}$	-0.04	FE,RS,Si/Ge	$\sim(0.8-1.6)\times 10^{-2}$	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	$8.8\times 10^{-4,\,a}$	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	**$2.0(9)\times 10^{-4}$**	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	**$6.9(10)\times 10^{-4}$**	Z,T,KE,TKE,MD,GF	(Hall *et al.*, 1990a)
	55(7) s		FE,NS,Si	$(1.3^{+4}_{-0.8})\times 10^{-2}$	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	**$6.6(18)\times 10^{-5}$**	Z,T,KE,TKE,MD,GF	(Hall *et al.*, 1989a, 1990b)
	2.6(2) min		FE,NS,MF	$\sim 6.95\times 10^{-5}$	T,EXF	(Kuznetsov *et al.*, 1967)
^{238}Bk	144(5) s	-0.15	FE,RC,MG	**$4.8(20)\times 10^{-4}$**	Z,T,KE,TKE,MD,GF	(Kreek *et al.*, 1994b)
^{240}Bk	4.2(8) min	-1.99	FE,NS,MF	**$(1.3^{+1.8}_{-0.7})\times 10^{-5}$**	T	(Galeriu, 1983)
	5(2) min		FE,NS,MF	$1\times 10^{-5,\,b}$	T	(Gangrsky *et al.*, 1980)
^{242}Es	11(3) s	-0.94	FE,RC,MG	**$0.6(2)\times 10^{-2}$**	Z,T,KE,TKE,MD	(Shaughnessy *et al.*, 2000)
	5 – 25 s		FE,RS,Si	$1.4(8)\times 10^{-2}$	T,KE	(Hingmann *et al.*, 1984)
	17.8(16) s		FE,RS,Si	$(1.3^{+1.2}_{-0.7})\times 10^{-2}$	T,KE	(Antalic *et al.*, 2010)
^{244}Es	38(11) s	-2.24	FE,RC,MG	**$1.2(4)\times 10^{-4}$**	Z,T,KE,TKE,MD	(Shaughnessy *et al.*, 2002)
			FE,NS,MF	$1\times 10^{-4,\,b}$	T	(Gangrsky *et al.*, 1980)
^{246}Es	7.7(5) min	-3.47	FE,RC,MG	**$(3.7^{+8.5}_{-3.0})\times 10^{-5}$**	Z,T,KE	(Shaughnessy *et al.*, 2001)
	8 min		FE,NS,MF	$3\times 10^{-5,\,b}$	T	(Gangrsky *et al.*, 1980)
^{248}Es	23(3) min	-4.26	FE,RC,MG	**$3.5(18)\times 10^{-6}$**	Z,T,KE	(Shaughnessy *et al.*, 2001)
			FE,NS,MF	$3\times 10^{-7,\,b}$	T	(Gangrsky *et al.*, 1980)
^{246m1,m2}Md	0.9(2), 4.4(8) s	0.14	FE,RS,Si	$>1\times 10^{-1}$	T,KE	(Antalic *et al.*, 2010)
	1.0(4) s^{c}		FE,RS,Si	$\sim 0.65\times 10^{-1}$	T,KE	(Ninov *et al.*, 1996)
^{250}Md	52(6) s$^{\#}$	-2.64	FE,NS,MF	$2\times 10^{-4,\,b}$	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	$5(2)\times 10^{-12}$		(Yanbing *et al.*, 2006)
^{230}Ac	122(3) s$^{\#}$	-2.73	TR,RC,MF/Ge	$1.19(40)\times 10^{-8}$		(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	$3\times 10^{-12,\,d}$	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	$\sim 10^{-9}$	T	(Batist *et al.*, 1977)
			FE/GI,NS,MF	$10^{-9,\,d}/3\times 10^{-10,\,d}$	T	(Gangrsky *et al.*, 1978)
^{238}Pa	2.3(1) min$^{\#}$	-2.14	NI,NS,MF	6×10^{-7}, $1\times 10^{-8,\,d}$	T	(Gangrsky *et al.*, 1978)
			NI,RC,MF	$<2.6\times 10^{-8}$		(Baas-May *et al.*, 1985)