Low energy fission studies and possibilities at RAON

Focused workshop on rare isotope physics

KIM Yung Hee (IBS CENS)

24/Nov/2022

Overview

1. Introduction
   - Brief history of fission discovery
   - Why study fission after ~80 years of research?
   - Fission process - Effect of nuclear structure in fission
   - Dynamics of energy/angular momentum of fission fragments

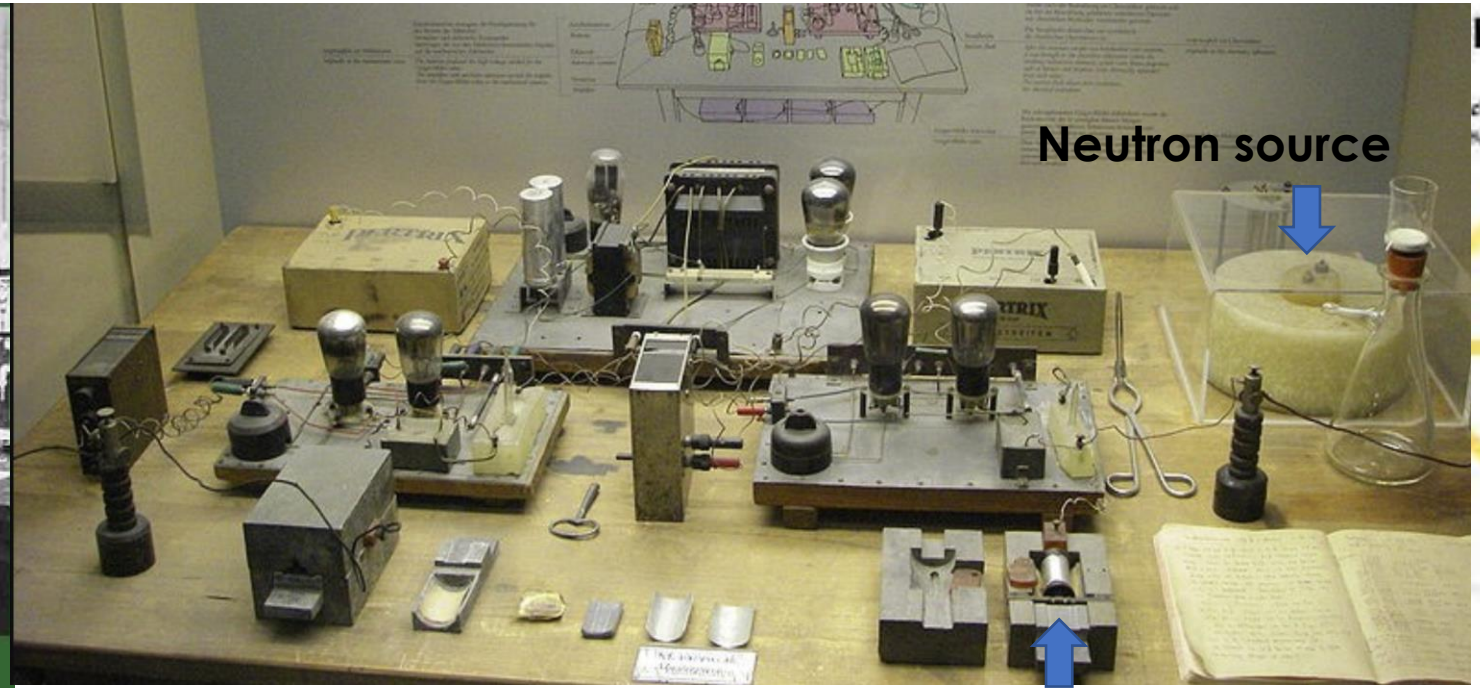
2. Neutron induced fission
   - Thermal n-induced fission (ILL)
   - High energy n induced fission (nTOF-CERN, LANCE-LosAlamos, NFS-GANIL, LICORNE-IJCLab)
3. Charged particle induced fission
   - Fission studies at JAERI, ANU, JINR… using ToF detectors
   - Spectrometers: detailed fission study
     (GANIL/GSI: fission produced at Coulomb barrier/relativistic energy)
4. Possible observables and derived quantities

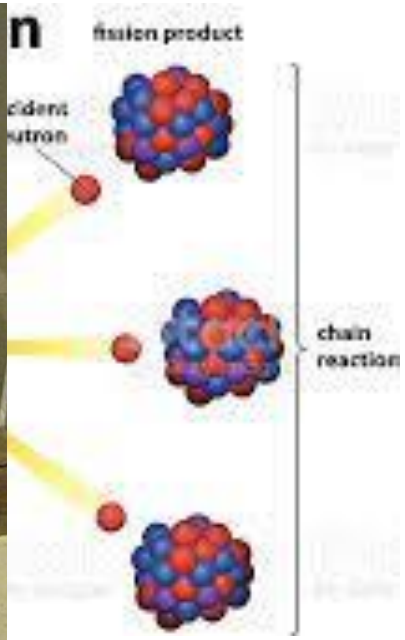
Exp. Techniques & observables

5. What can be done at RAON?
   - Neutron induced fission : fission dynamics (NDPS)
   - Charged particle induced fission : fission barrier (Low energy beamline)
6. Summary

How fission was discovered by Otto Hahn & Lise Meitner (1938)


Lise Meitner and Otto Hahn,
Kaiser-Wilhelm Institute, Berlin





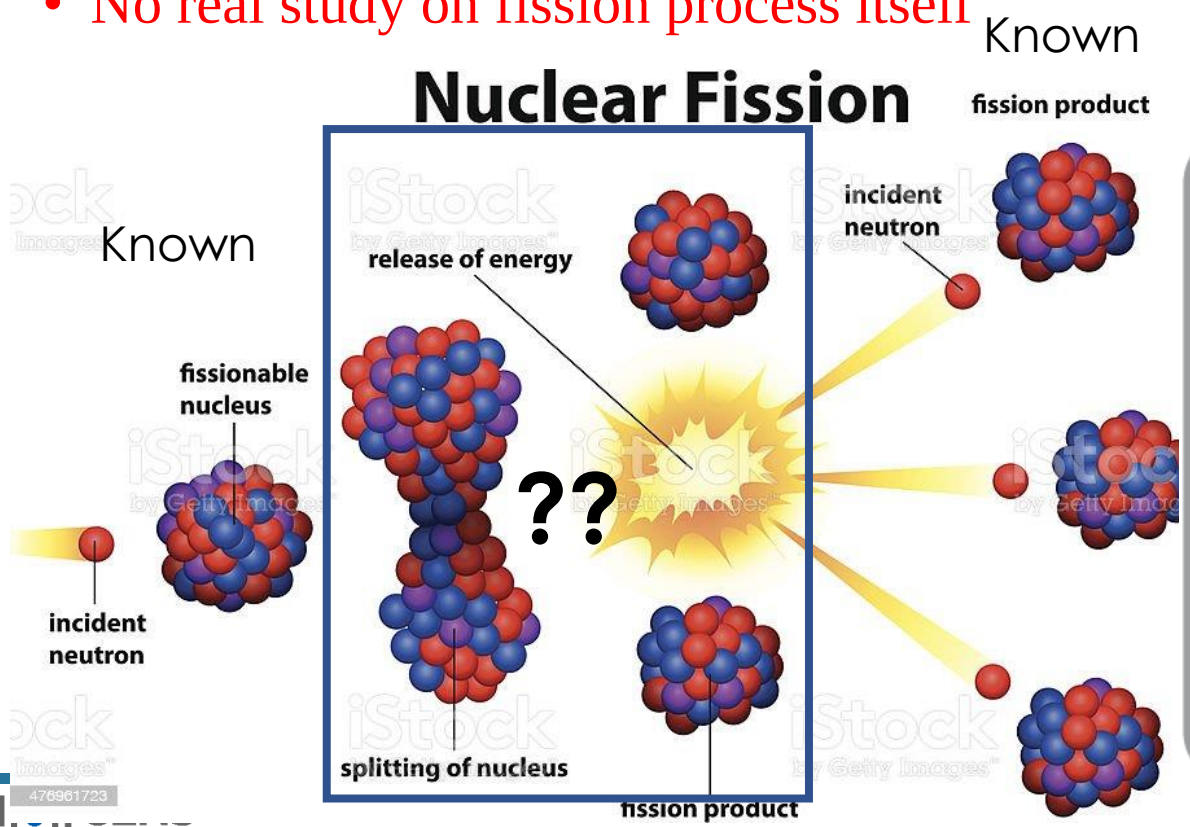
- Radio activity measurement (Geiger counter) + Chemical separation

Neutron source-> Ba was in the decay products

- Why they became first? Strong chemistry background of Otto Hahn+Insight of Lise Meitner
- e.g. Enrico Fermi, Curies knew neutron irradiation on U there was some change in the element. But explained it as Ra using known alpha & beta decay

Application after discovery of fission

- Energy generation: only cross section & #of neutrons/fission is needed.
- Discovery of neutron(1932)->Discovery of fission(1938)
  ->First nuclear reactor(1942)-> first atomic bomb (1945)
- No real study on fission process itself



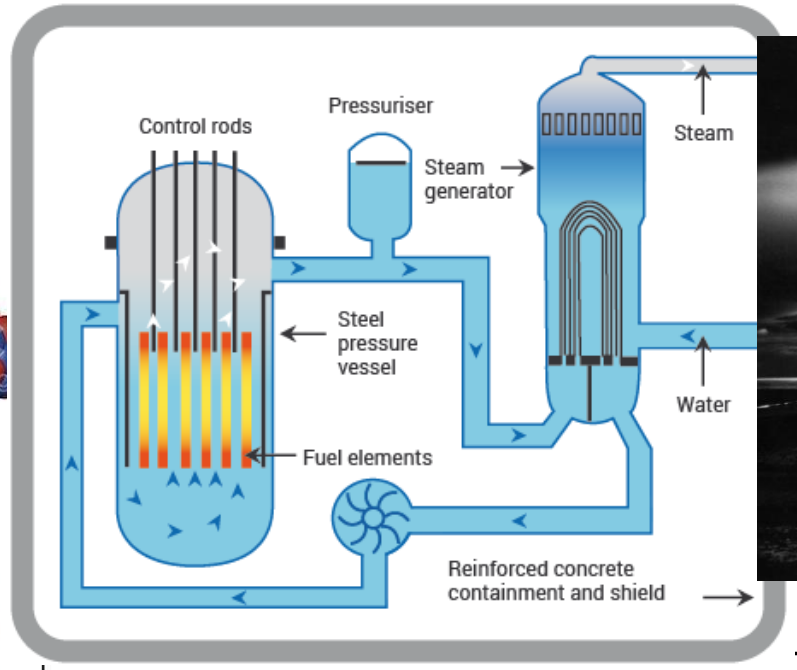
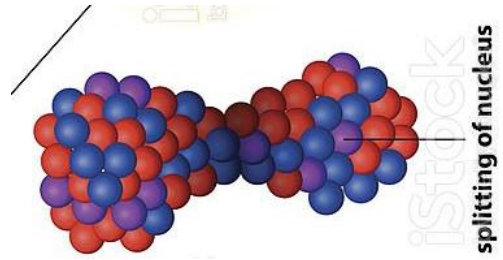
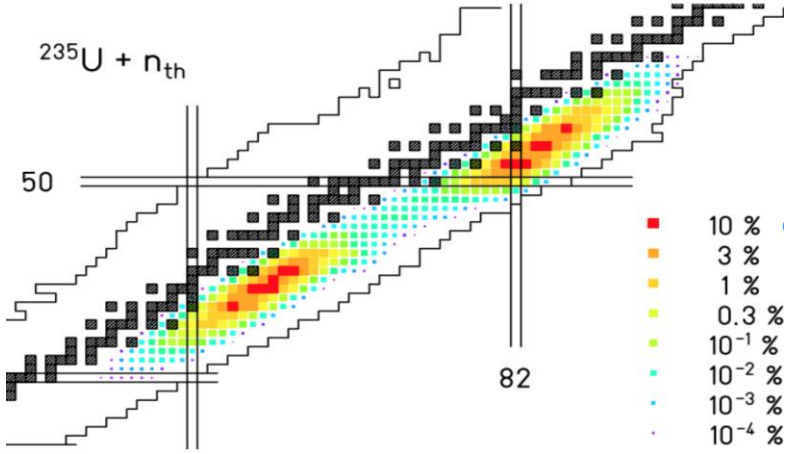


Fig. 1 | Microscopic calculations of asymmetric fission of ^{240}Pu.

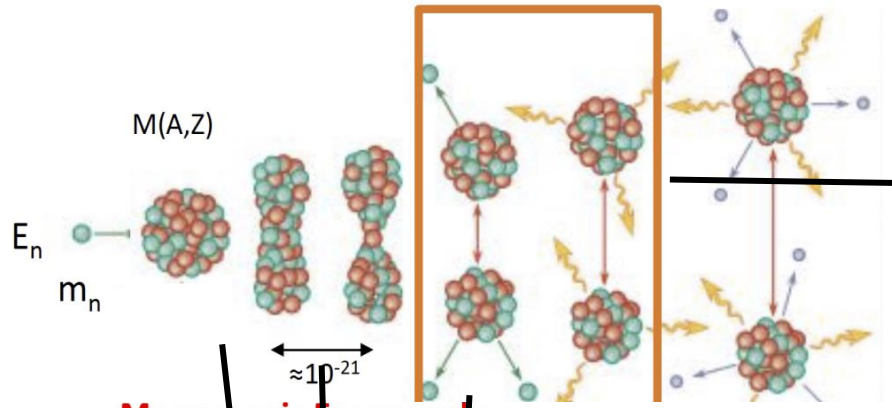
Why study fission after 80+ years?

- Complex multi-nucleon system
- Method for producing n-rich nuclei (FRIB, RIKEN, RAON…)
- Rich application opportunities e.g. Next generation reactors
- Interesting physics still awaits (fission dynamics, nuclear structure, new fissioning systems, relation with r-process etc…)

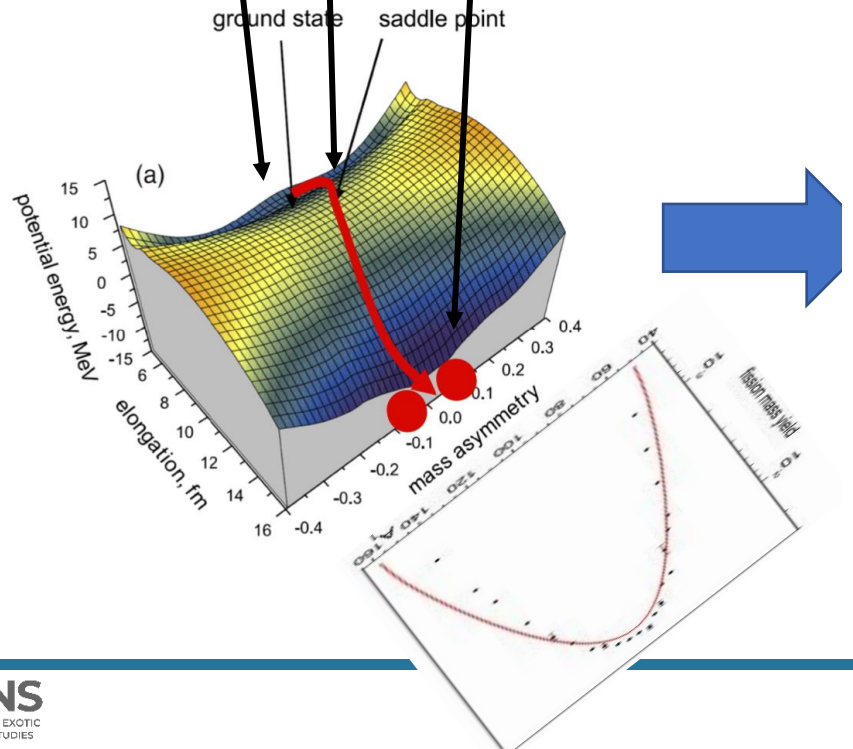


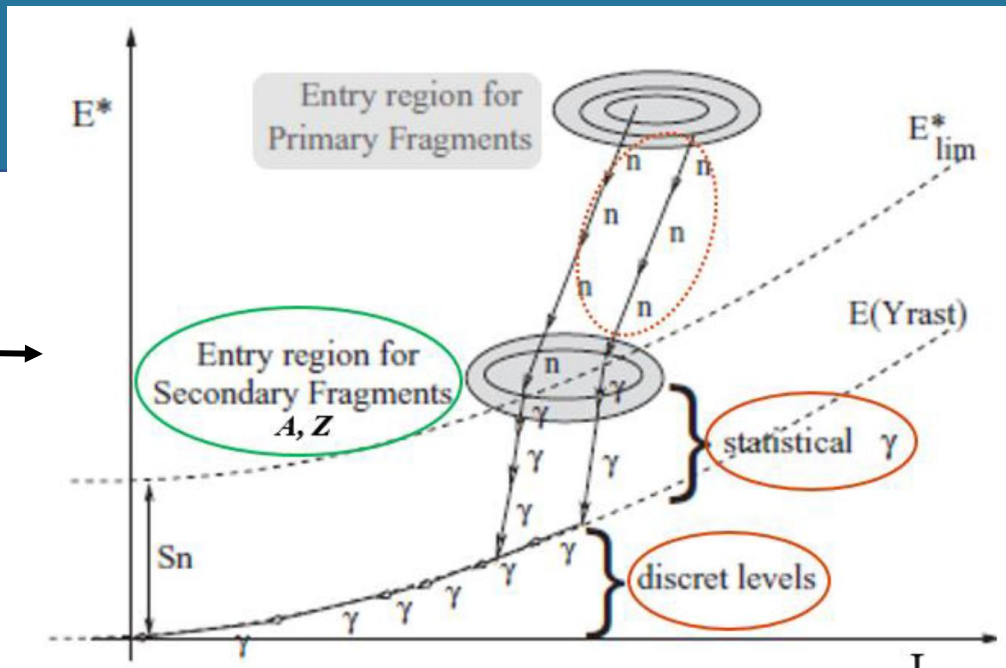


Fission process



Macroscopic Energy only
(like a Liquid Drop)





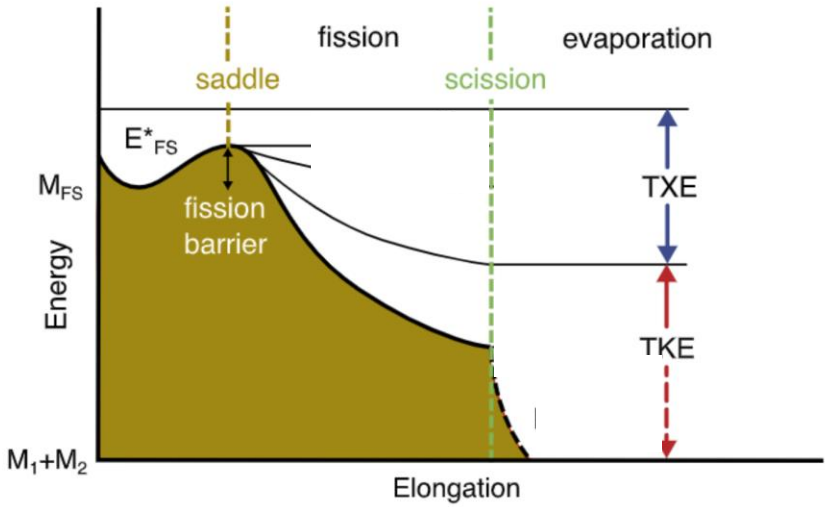
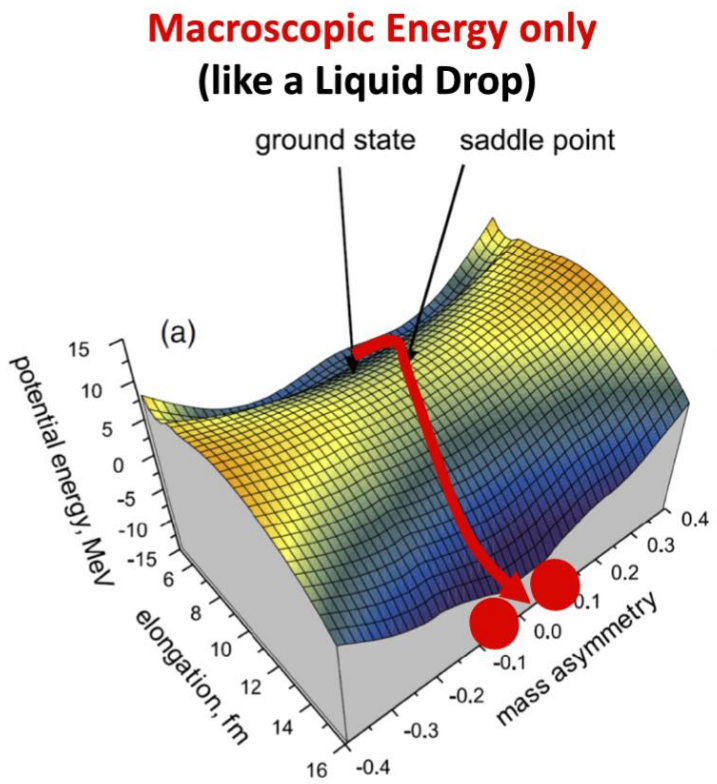
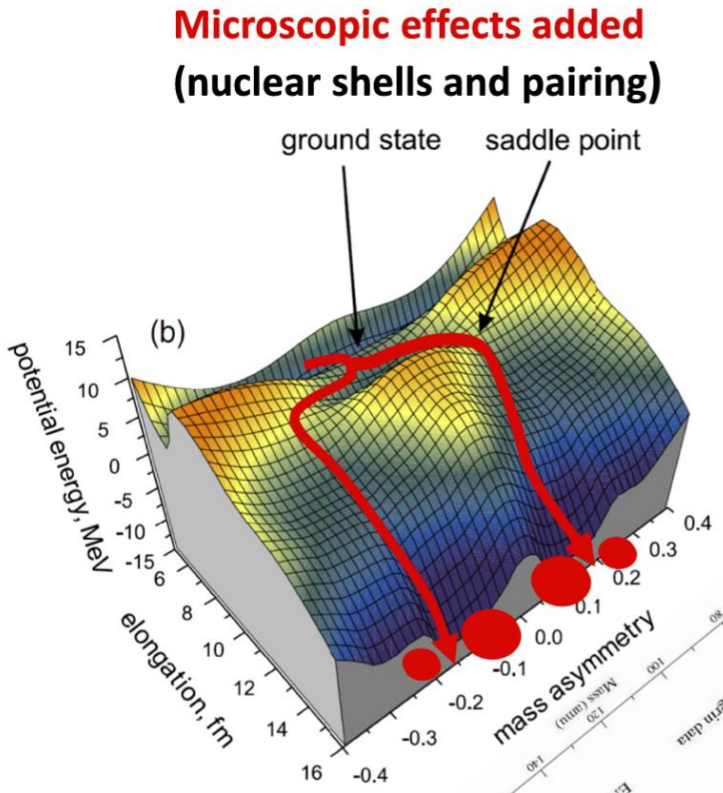
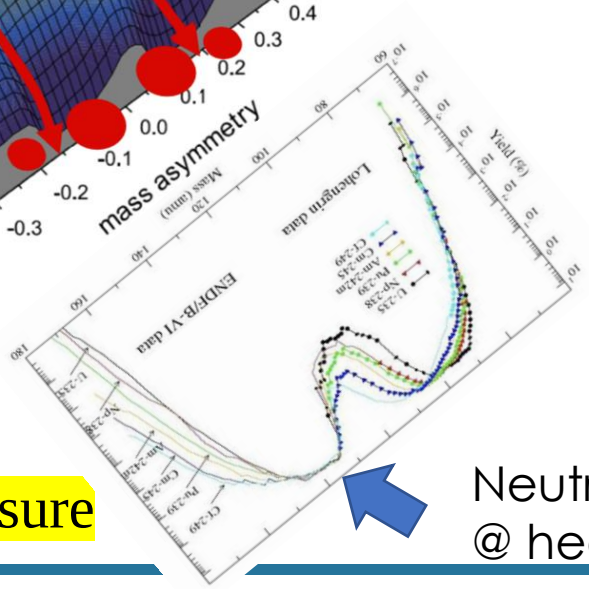


Fig. 1. Graphical explanation of the main components of the energy balance throughout the fission process. See text for details.

Fission complex nuclear manybody system - effect of nuclear shell



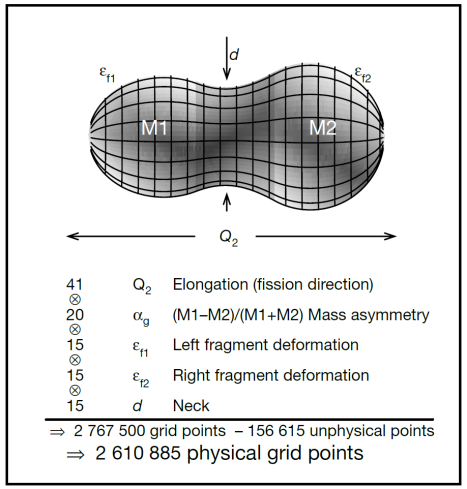


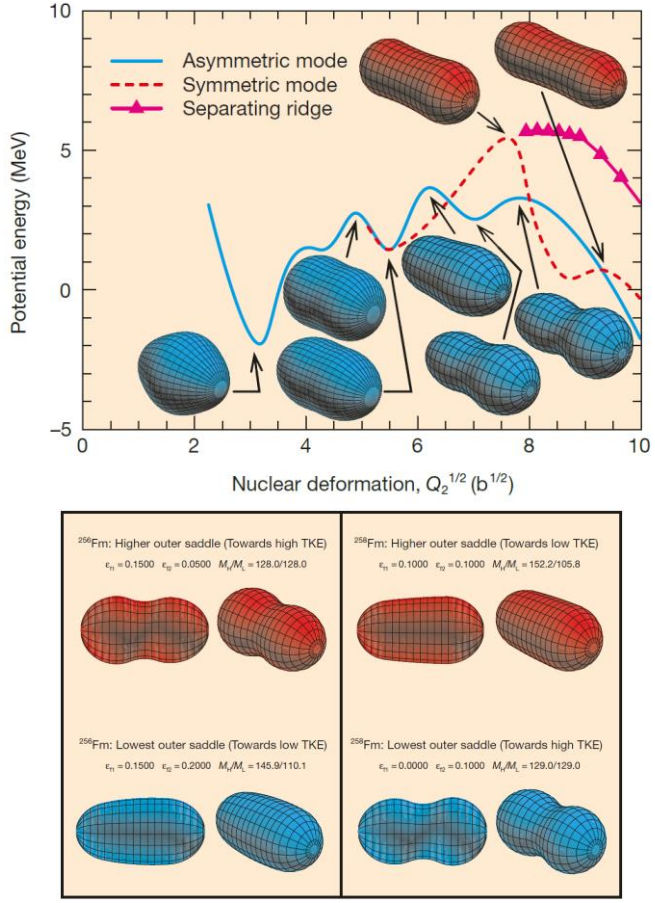


- Nuclear shell structure effect -> Asymmetric fission
- But peak of mass is not at Sn (Z=50) But Z=52-56, A~138
- *Explained by N=82 and deformed N=88 neutron shell closure

Neutron shell closure
@ heavy fission fragment

Fission: complex nuclear many body system - effect of deformation





- Calculation including quadrupole deformation

P. Moller et al., Nature 409, 785 (2001)

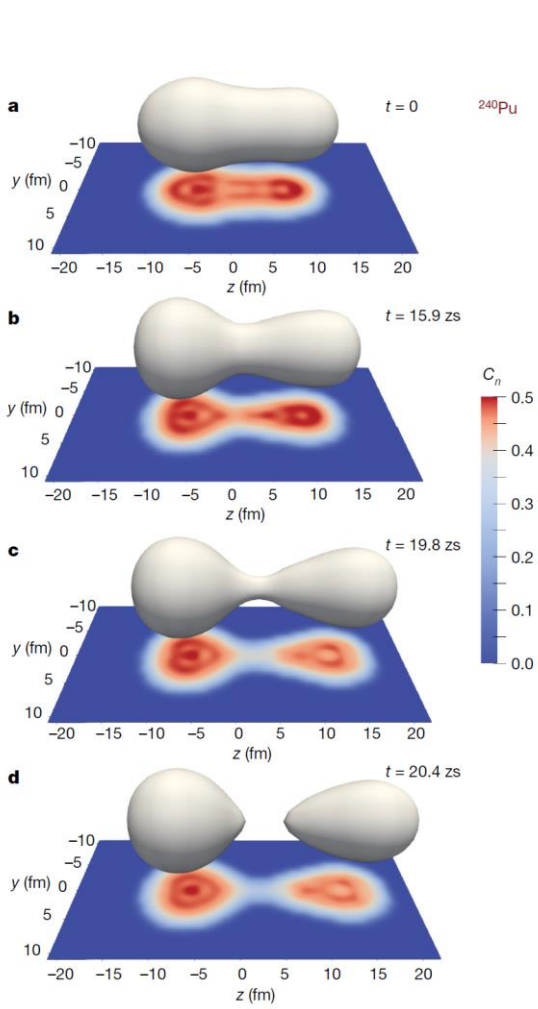


Fig. 1 | Microscopic calculations of asymmetric fission of ^{240}Pu.

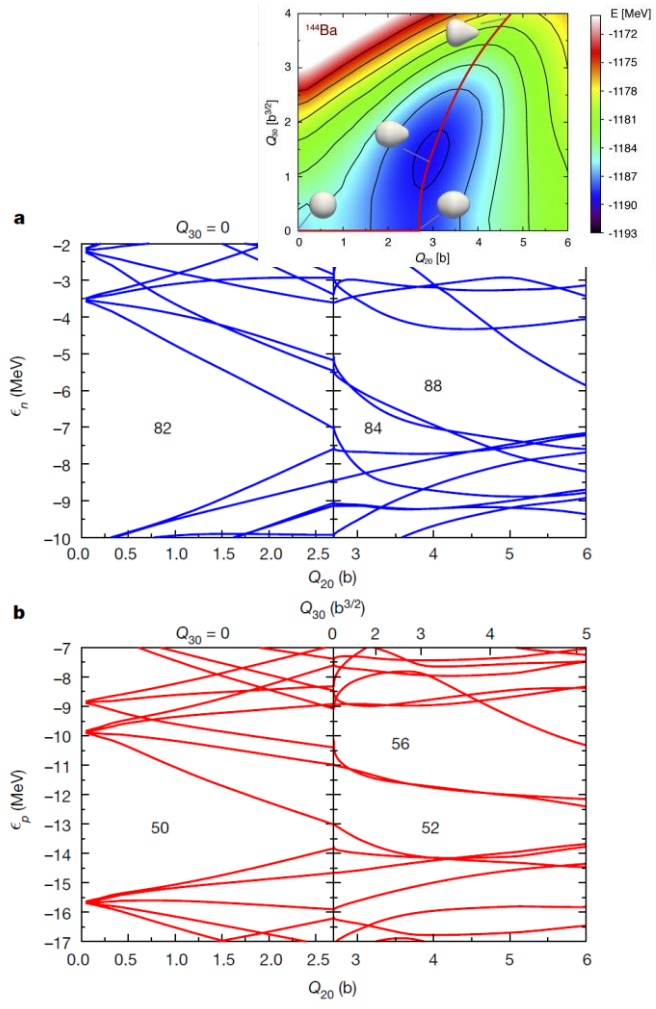
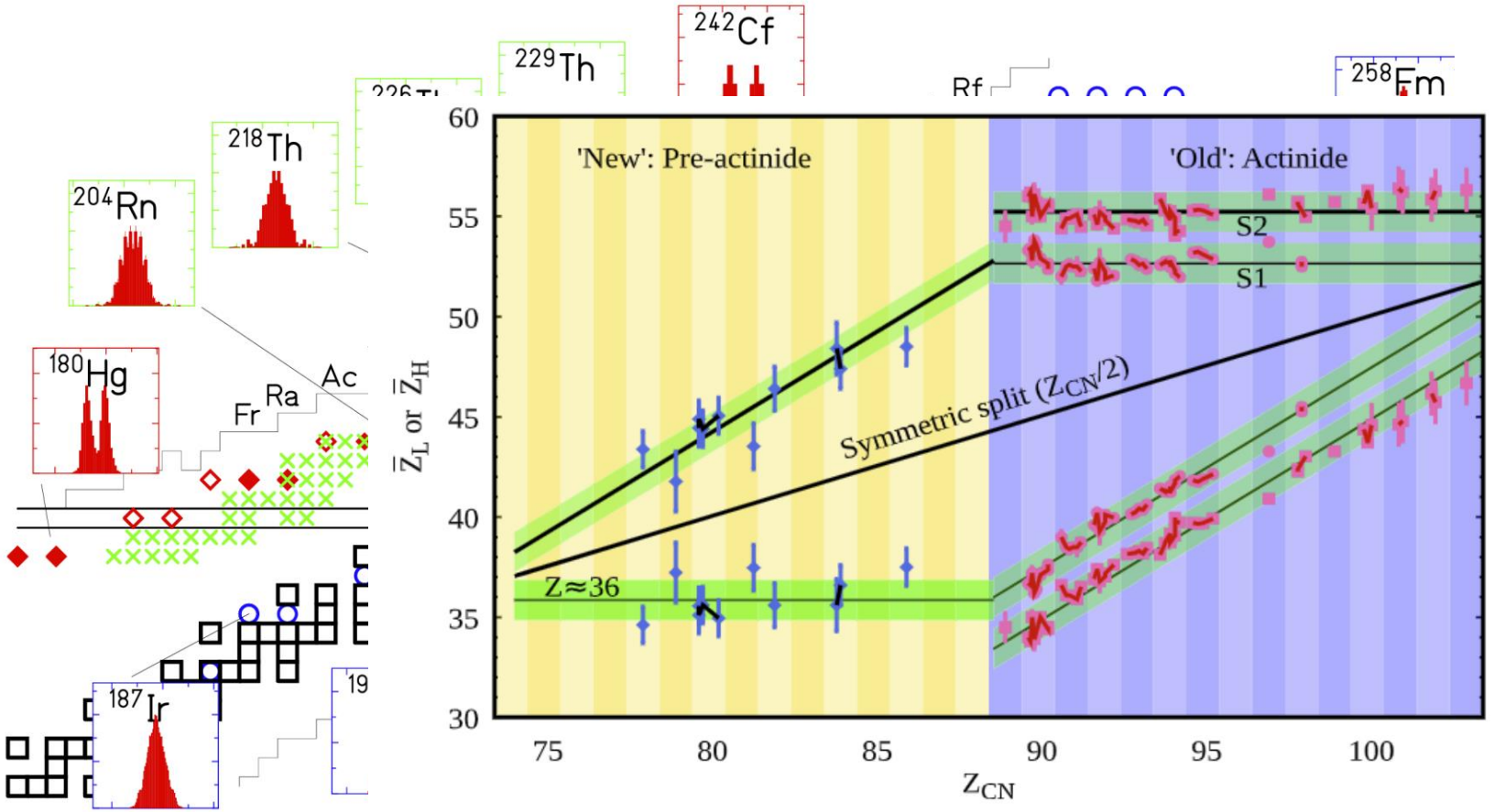


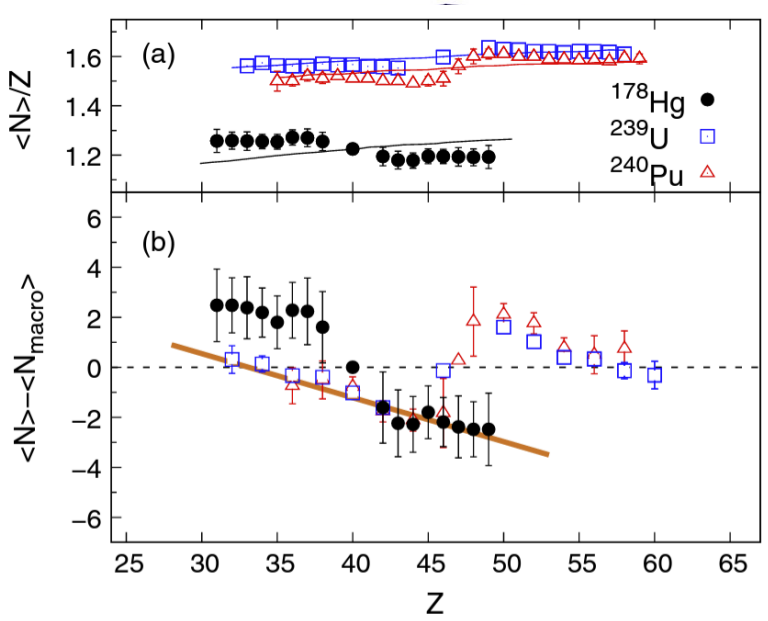
Fig. 4 | Evolution of single-particle energies with deformation.

- HF+BCS calculation including octupole deformation

G. Scamps and C. Simenel, Nature 564, 382 (2018)].

Fission: complex nuclear manybody system -Isospin dependency





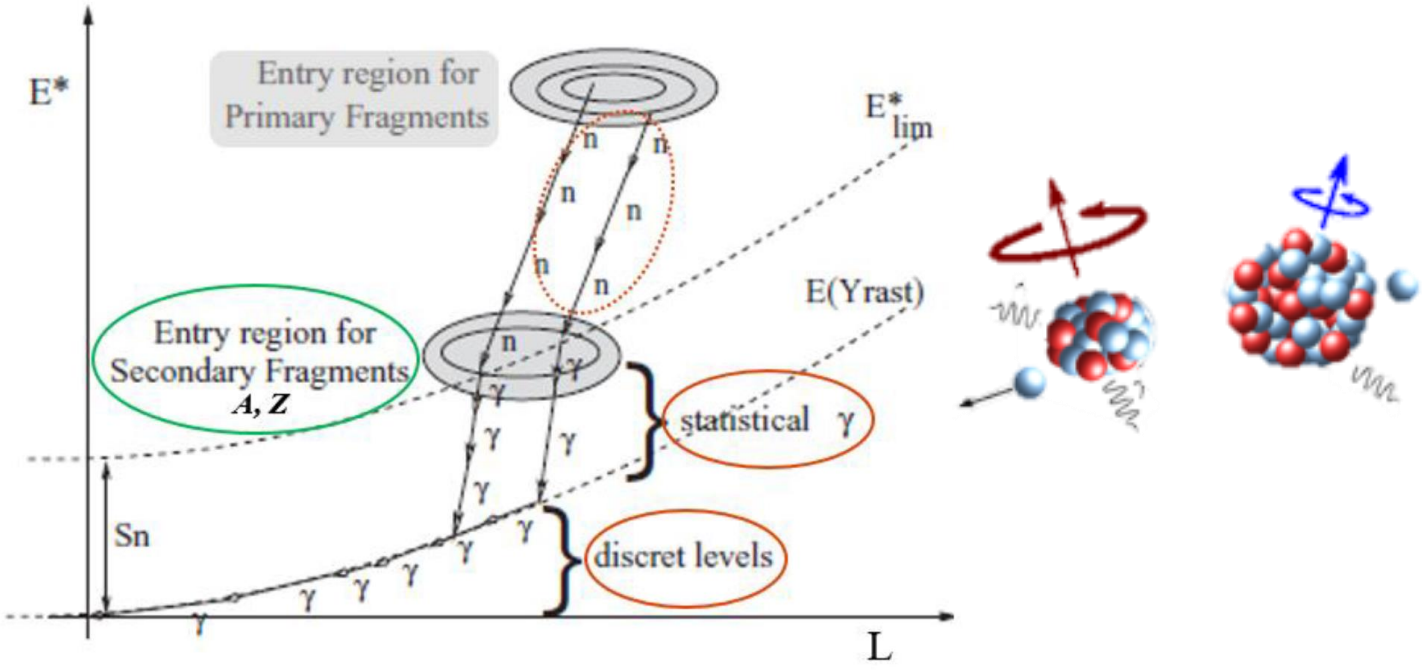
Actinides: Neutron shell closure at heavy fission fragment main source mass asymmetry

Pre-actinides(^{178}Hg) : Proton shell closure at light fission fragment dominates mass asymmetry

- Fission mass distribution shows dramatic change over different systems.
- Difficult to reproduce by theoretical calculations.

A. N. Andreyev, K Nishio and K-H Schmidt Rep. Prog. Phys. 81 (2018) 016301
A. N. Andreyev et al., PRL 105, 252502 (2010)
C. Schmitt..Y. H. Kim… et al., Phys Rev. Lett 126, 132502 (2021)
K. Mahata et al., Phys Lett. B 825 (2022) 136859

Fission: complex nuclear manybody system – Angular momentum generation



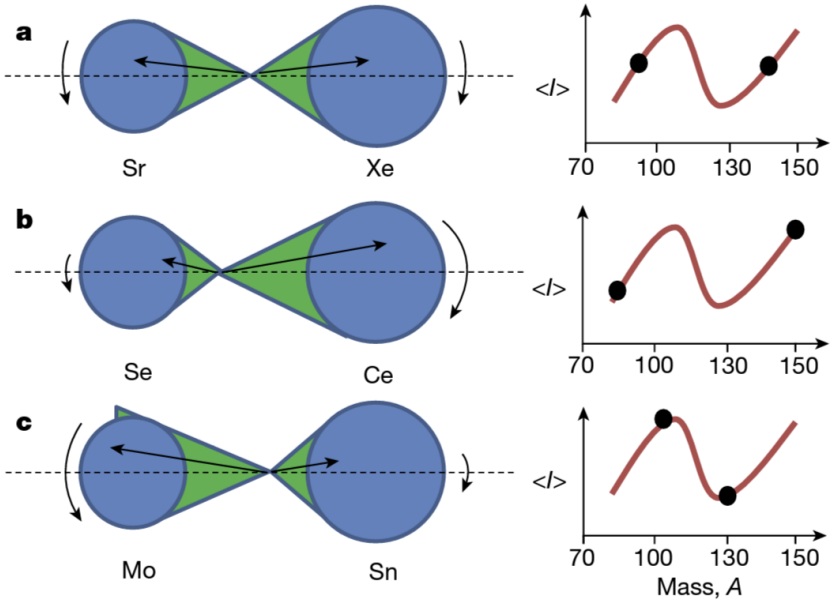
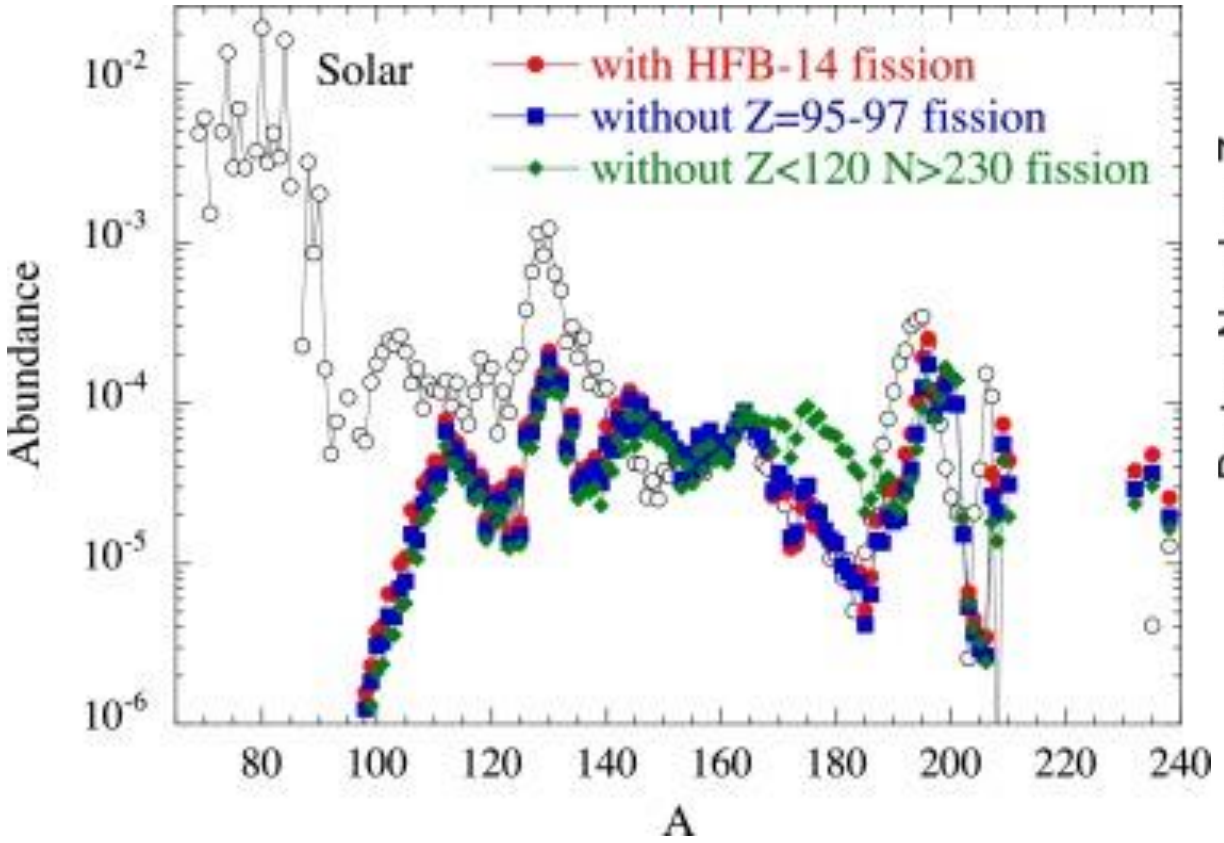


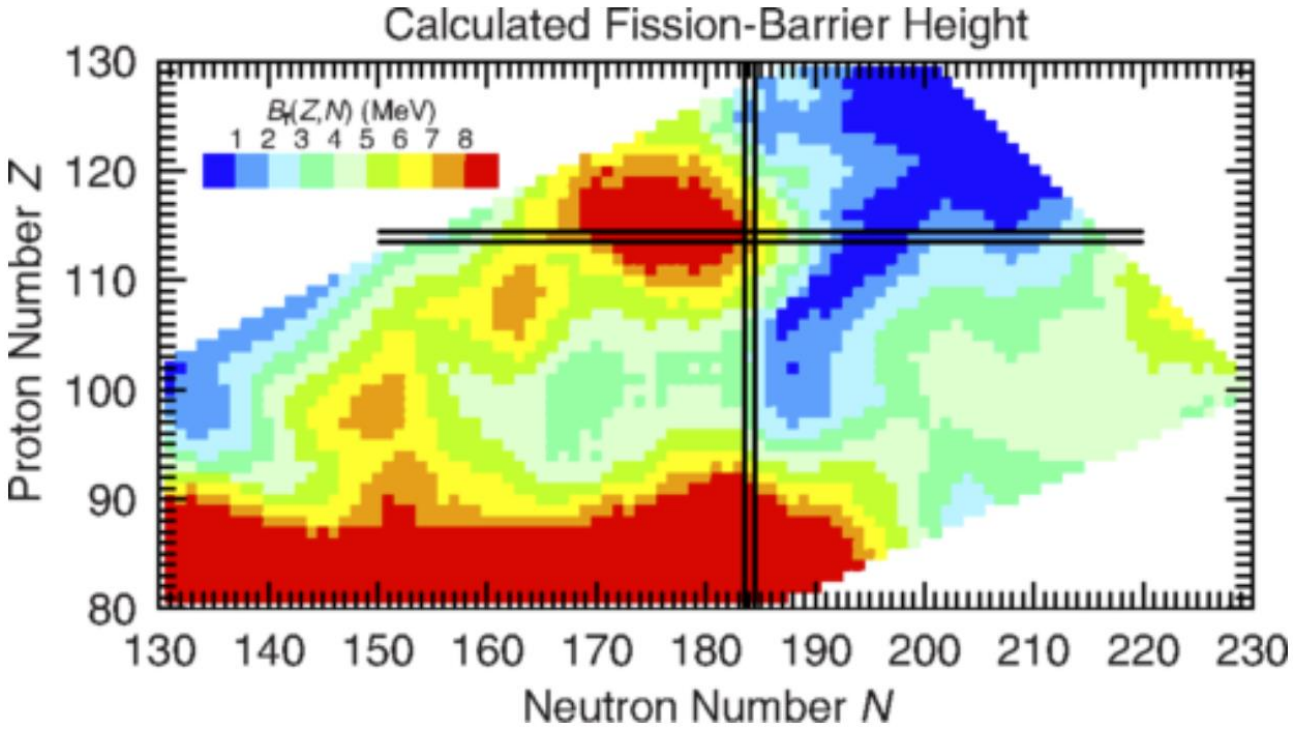
Fig. 3 | Schematic diagram of post-scission angular momentum generation.

- How fission angular momentum is generated? (gamma-ray measurement)
- How fission excitation energy is distributed? (light particle evaporation)
- Simultaneous measurement is not yet made…(attempt with PARIS detector+VAMOS spectrometer)

Fission in the r-process

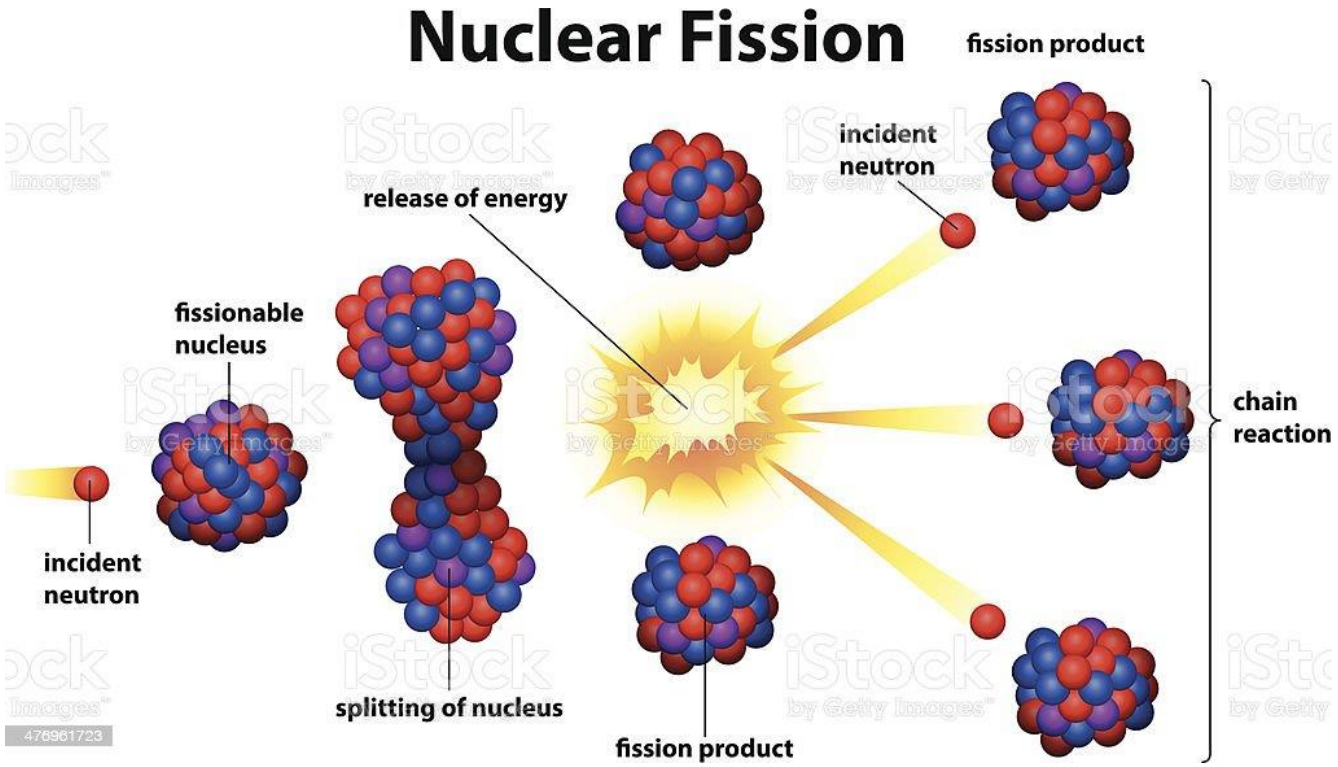
- Last part of r-process actinide fissions & refuel r-process with n-rich nuclei
- Fission barrier (<->fission prob) is one of most important input



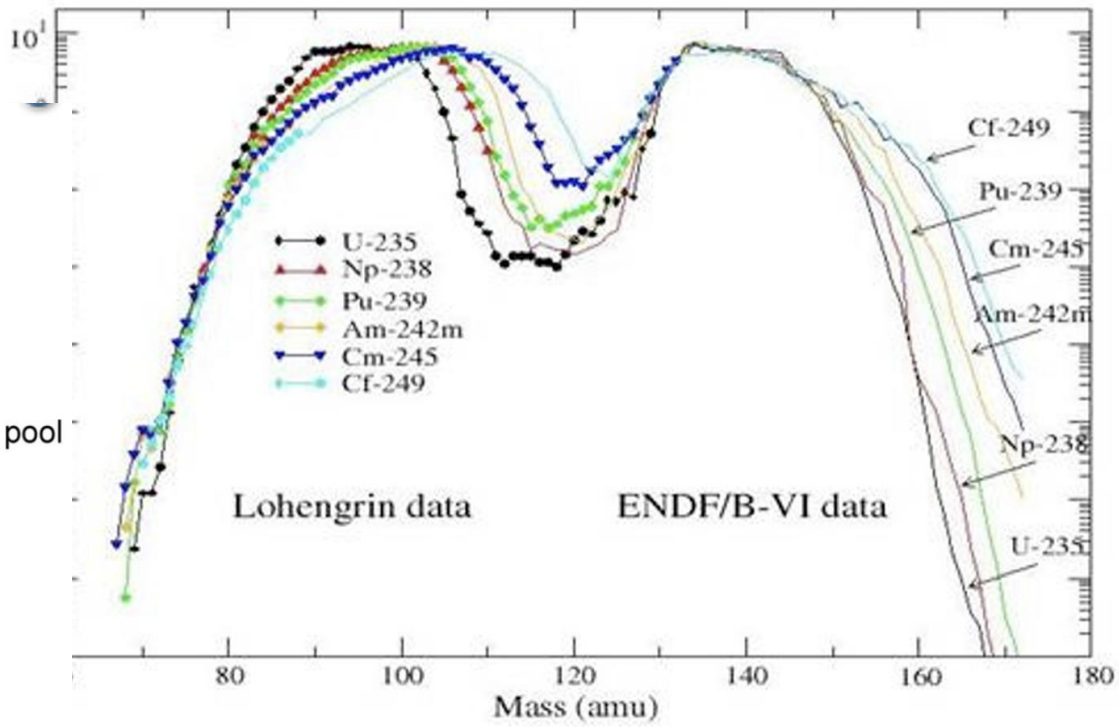


S Goriely and G.Martínez-Pinedo Nucl. Phys. A, 944 (2015)158-176
P. Moller et al., Phys. Rev. C 91,024310 (2015)
G.Martínez-Pinedo et al., Prog. Ptl. Nucl. Phys 59 (2007) 199

Neutron induced fission



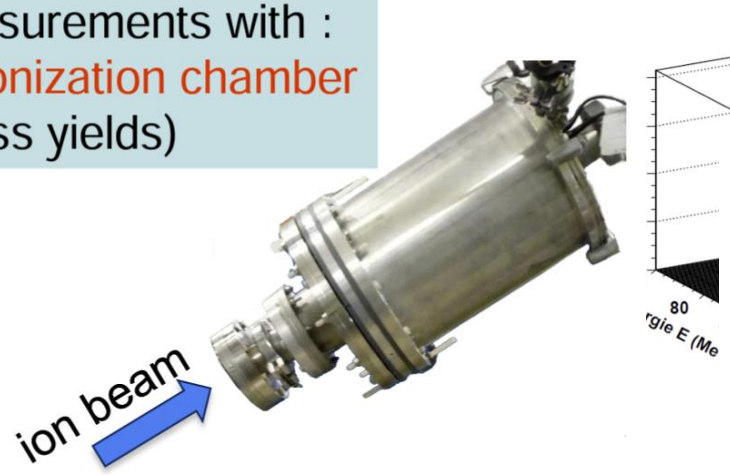
Neutron induced fission -Lohengrin spectrometer



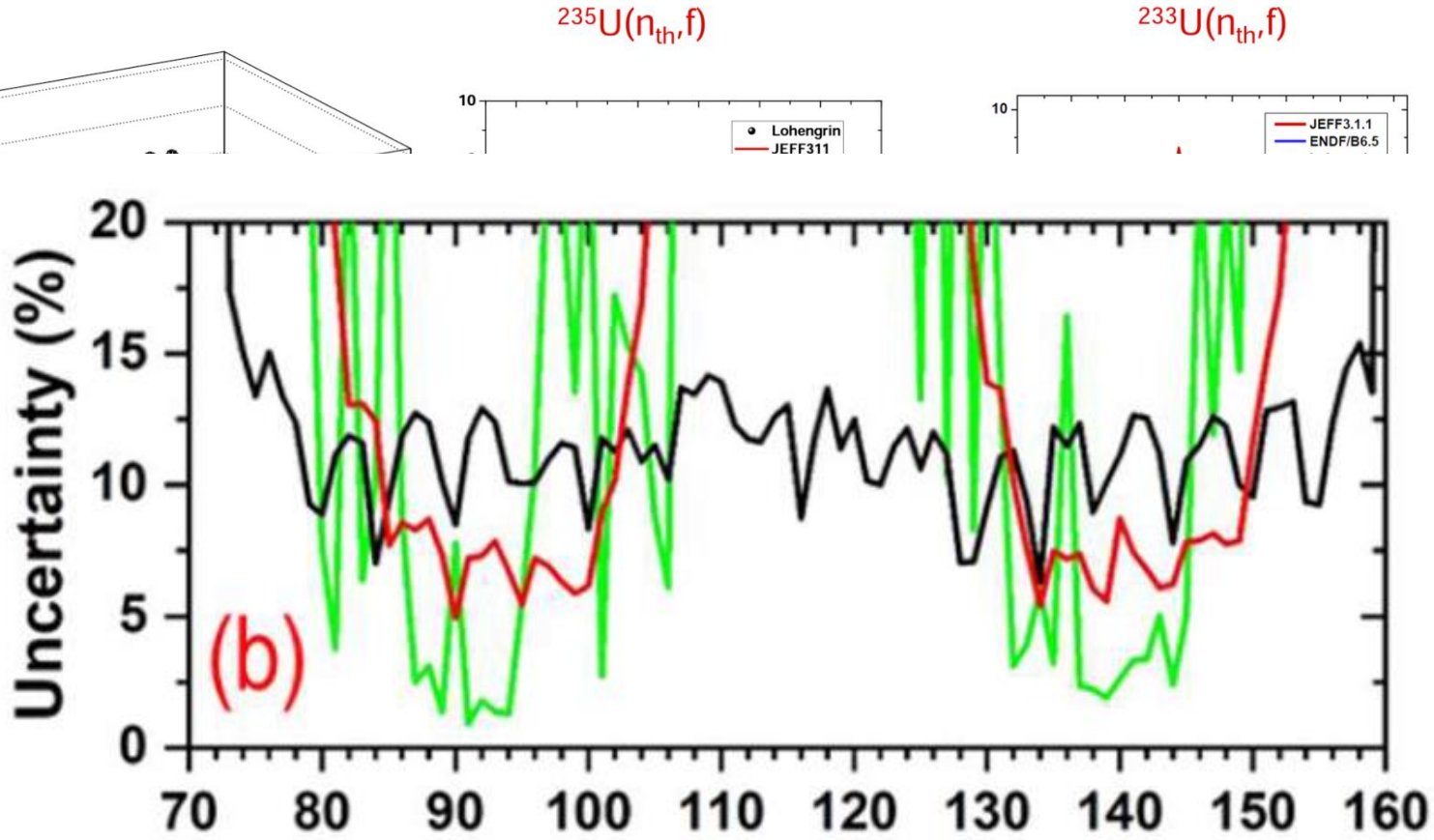
- Very high mass resolution ΔA/A=1500
- The standard instrument for fission mass measurement
- Experiment 1980-90 light fission fragment mass distribution

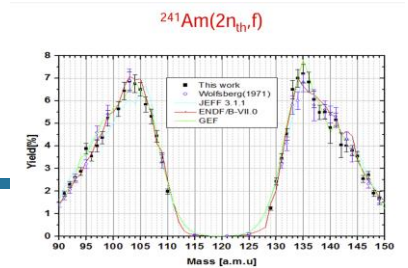
Mass distribution of fission fragments

Measurements with :
an ionization chamber
(mass yields)



- Heavy mass fission fragme
  recently (difficult due to c
- Higher precision mass yie
  measurement on going



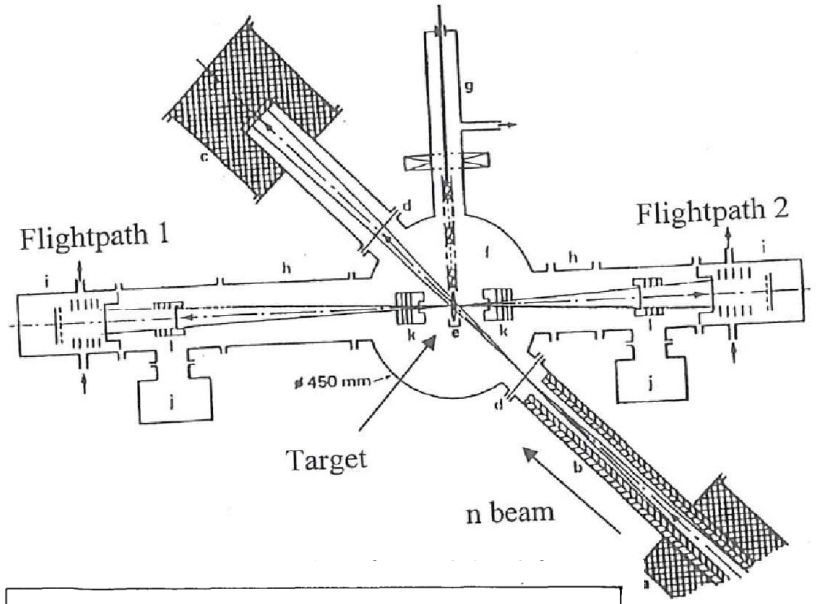


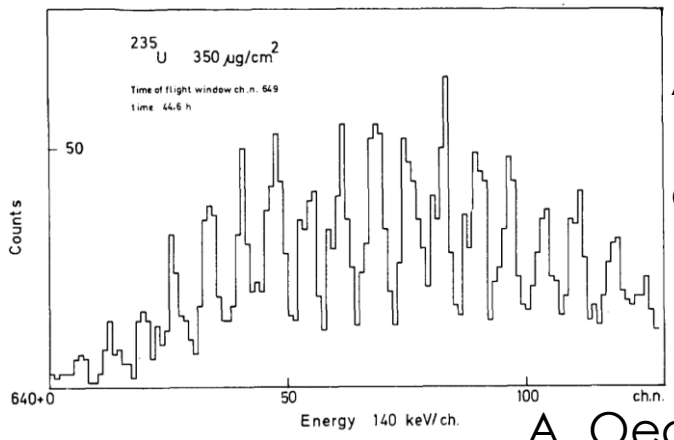
A. Bail, PhD Thesis (2009)

F. Martin, PhD Thesis (2013)
F. Martin et al., IEEE Conf. Proc. Of ANIMMA (2011)

D.A. Brown et al., Nuclear Data Sheets 148, 1-142 (2018)

n-induced fission with v-E spectrometer





ΔA/A=0.6%
But very low acceptance

- Fission fragment v, E measurement

⇒A1=2E1/v1^2, A2=2E2/v2^2

- 2 arm spectrometer A1*, A2*, E* can be measured

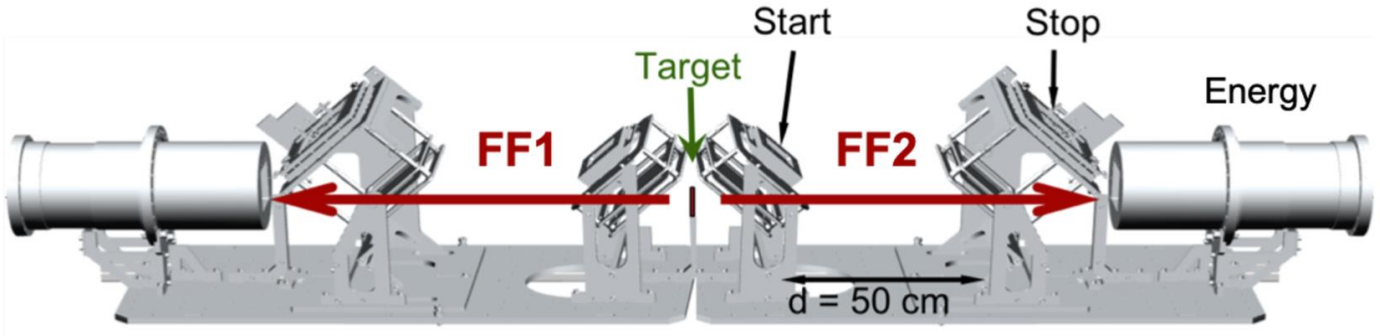
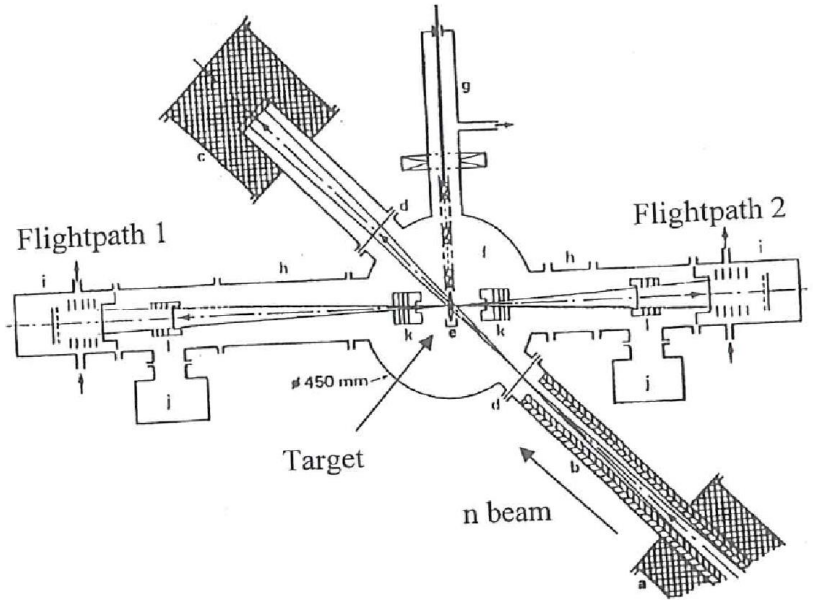
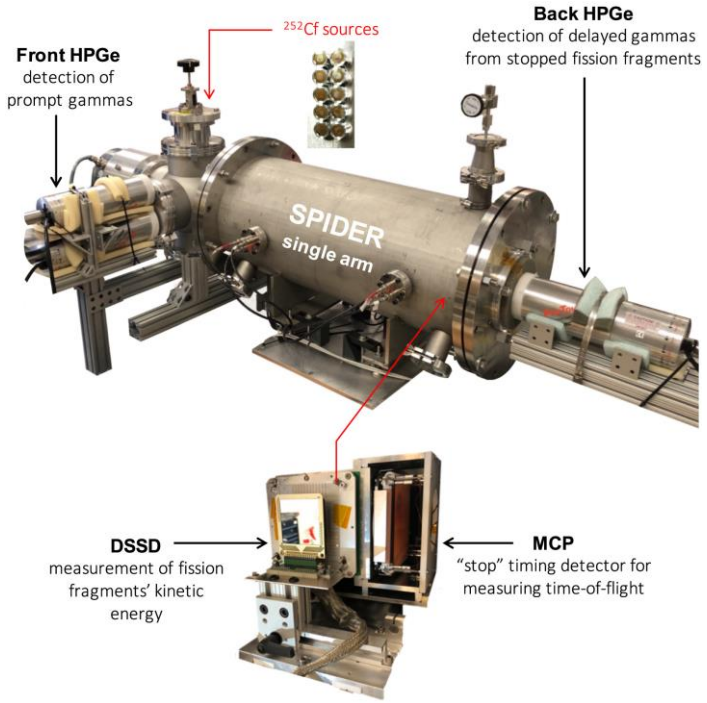


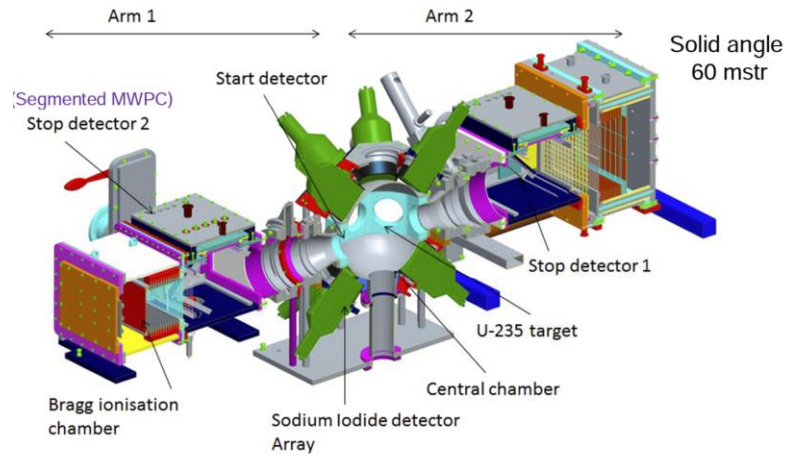
Figure 1. Drawing of the two-arm-FALSTAFF-spectrometer. Each arm is made of two ToF detectors followed by an energy detector to collect the remaining kinetic energy of the fragments. At the moment the first arm has been built.

A. Oed et al., NIM 219 (1984) 569

n-induced fission with v-E spectrometer

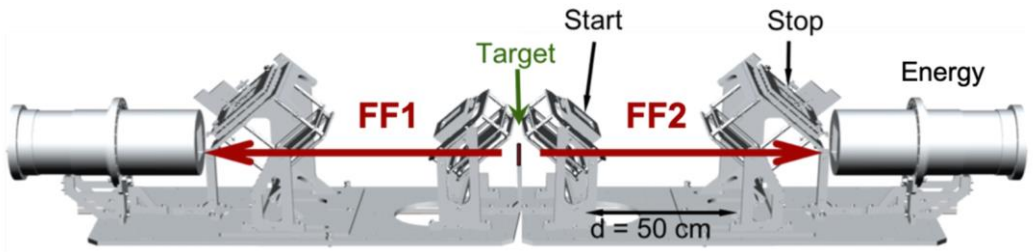






Warren, Stuart PhD Thesis Manchester (2018) UK

- Fission fragment i



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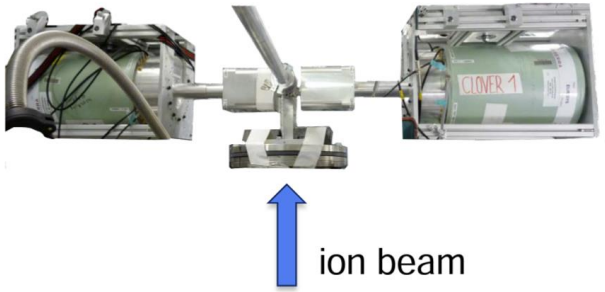
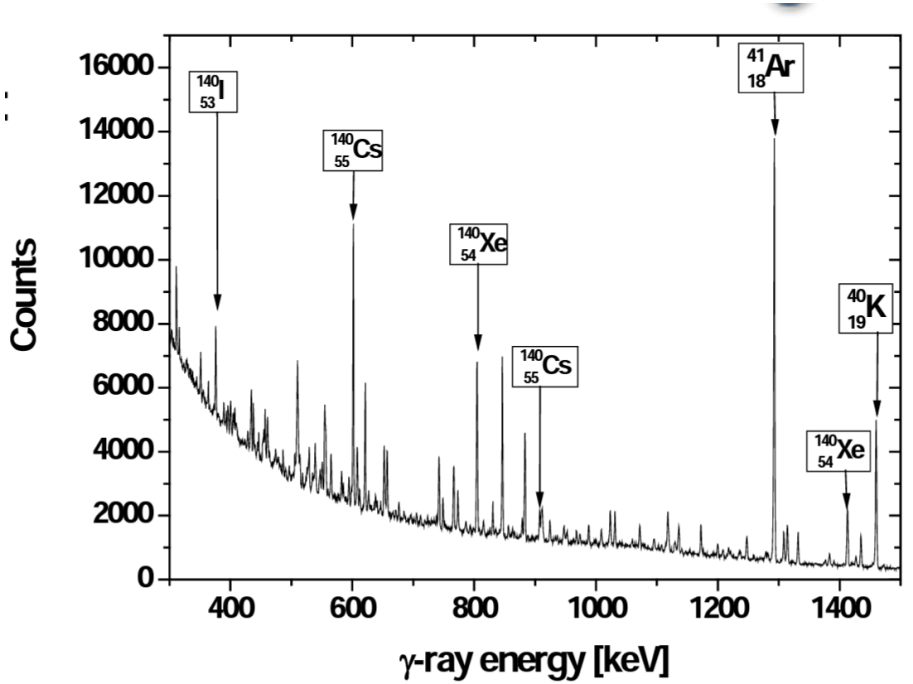
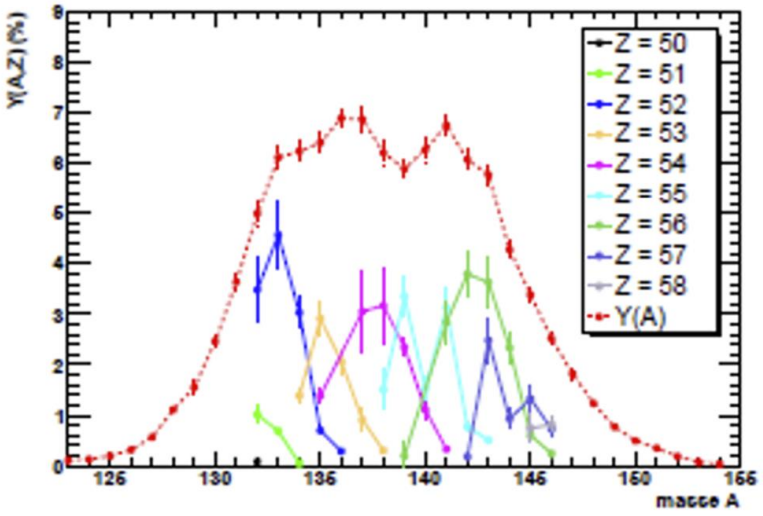
Atomic number distribution

or with : Ge detectors (isotopic yields)





$^{233}U(n_{th},f)$



F. Martin, PhD Thesis (2013)

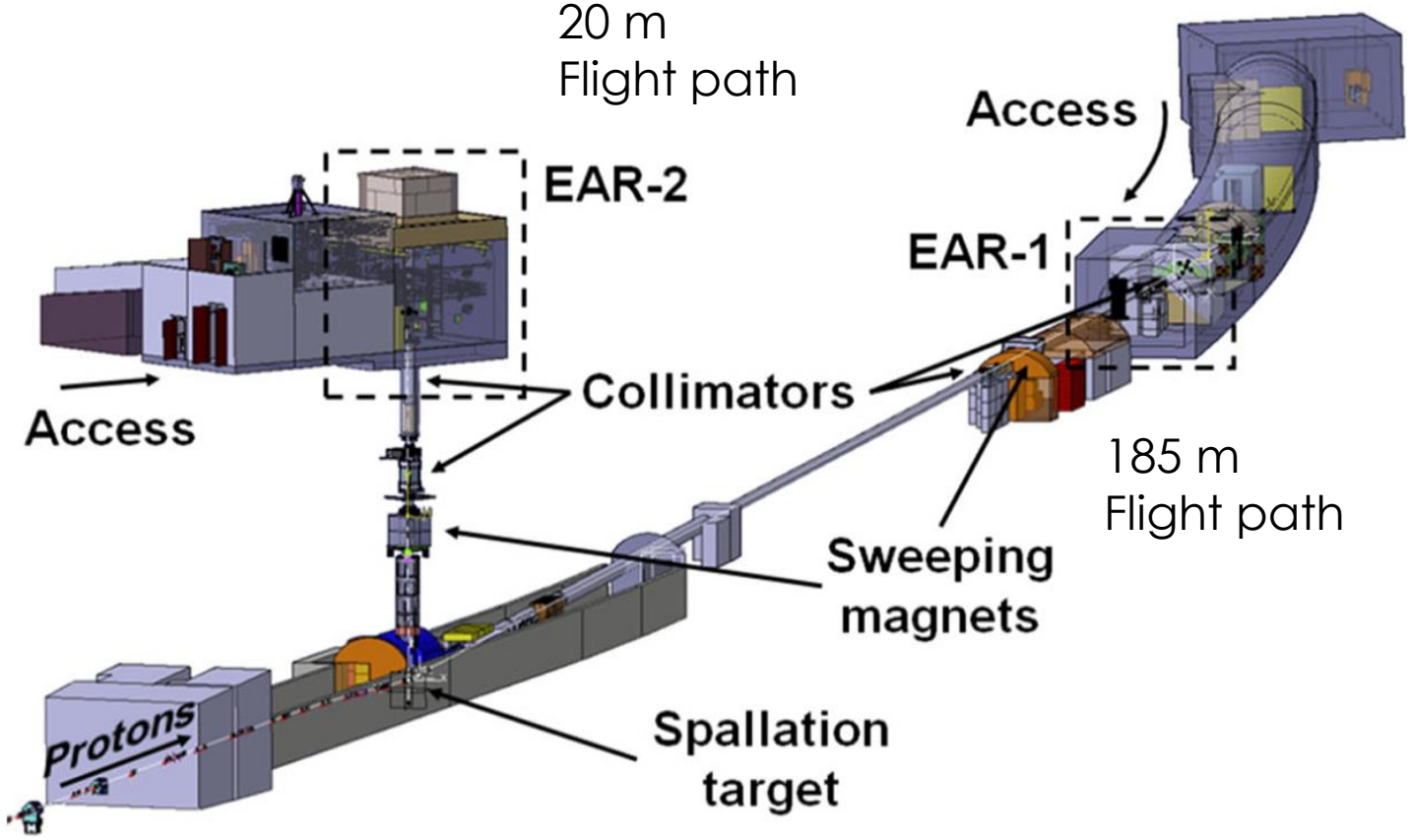
- Atomic number cannot be separated due to low energy (1MeV/u)
- Gamma-ray from Beta-decay used (Ge detector+tape station)

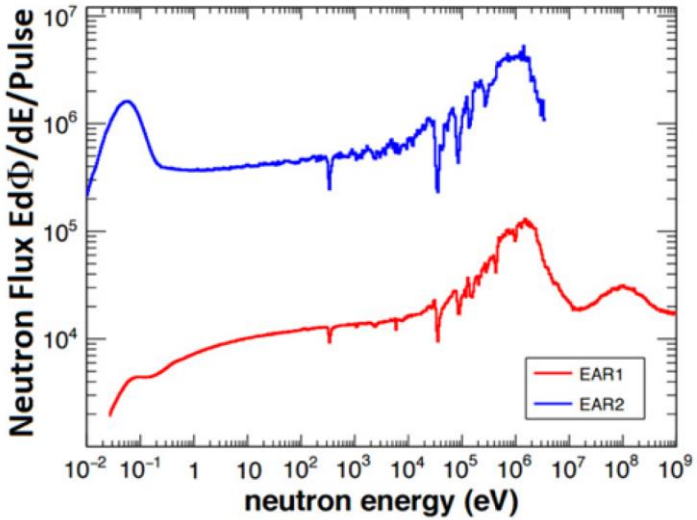
Part2

Fast neutron induced fission

- nToF, LANCE, NFS, GEEL etc…

nToF facility @ CERN





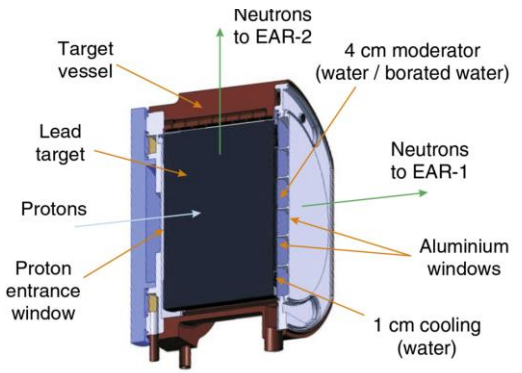


Fig. 5 A cross section of the n_TOF spallation target-moderator assembly

M. Barbagallo et al., Eur. Phys. J. A **49**, 156 (2013)
N. Colonna et al., Eur. Phys. J. A (2020) 56 :48

Standard experimental setup @ nToF

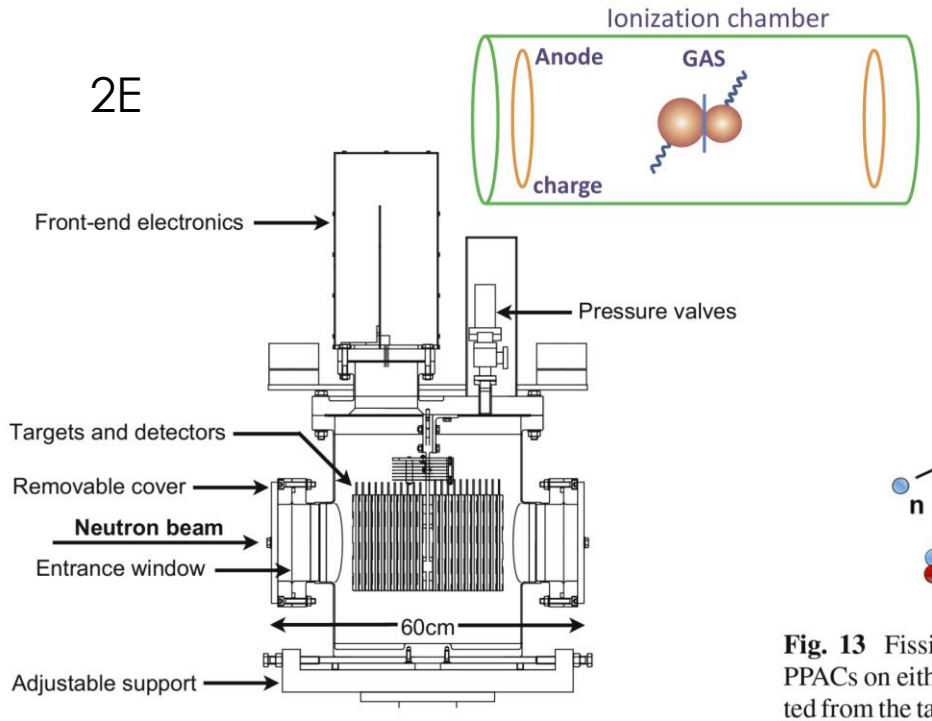


Fig. 12 Schematic view of the FIC detector used for fission cross section measurements

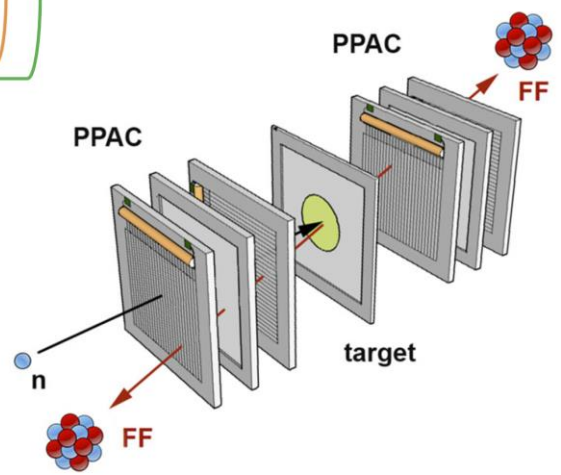
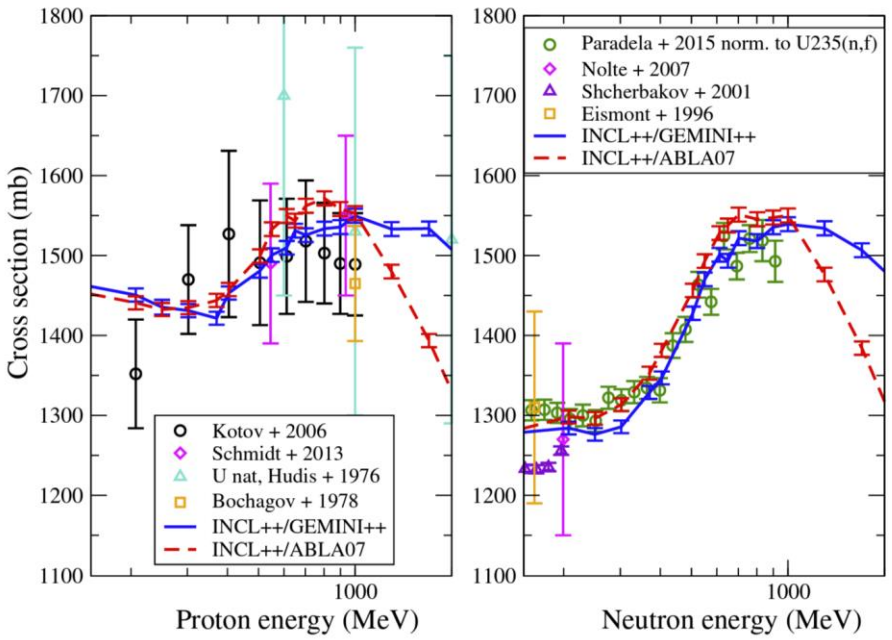


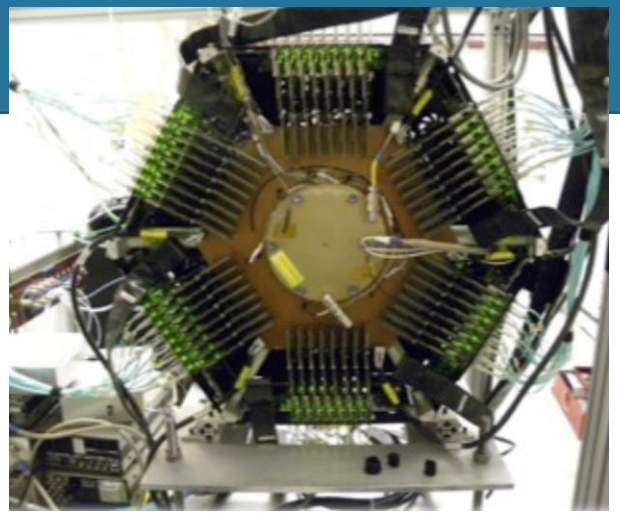
Fig. 13 Fission detection with the coincidence method, using two PPACs on either side of an actinide sample. The fission fragments emitted from the target cross the detectors and the coordinates of the crossing points are obtained from the localisation delivered by the two delay lines in each detector

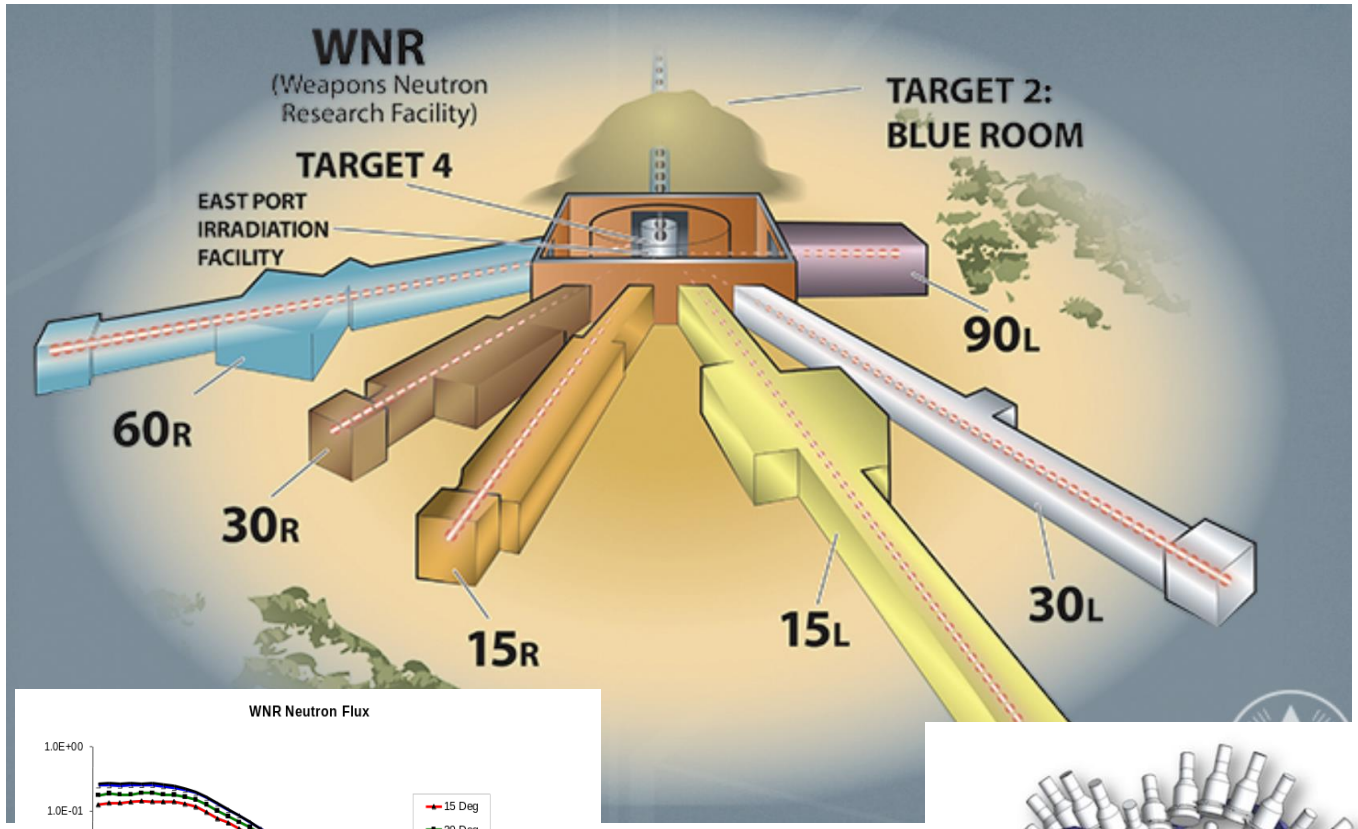


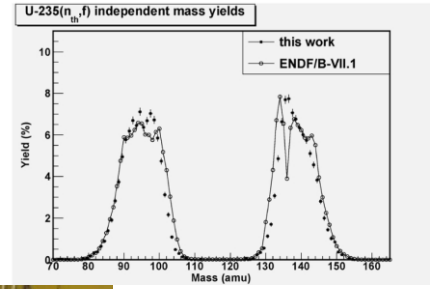
- Total Fission cross section @ very broad energy range at once
- No mass or atomic number identification. (project exists e.g. STEFF)
- Large prompt flash gamma-ray, charged particle makes difficult to analyze.

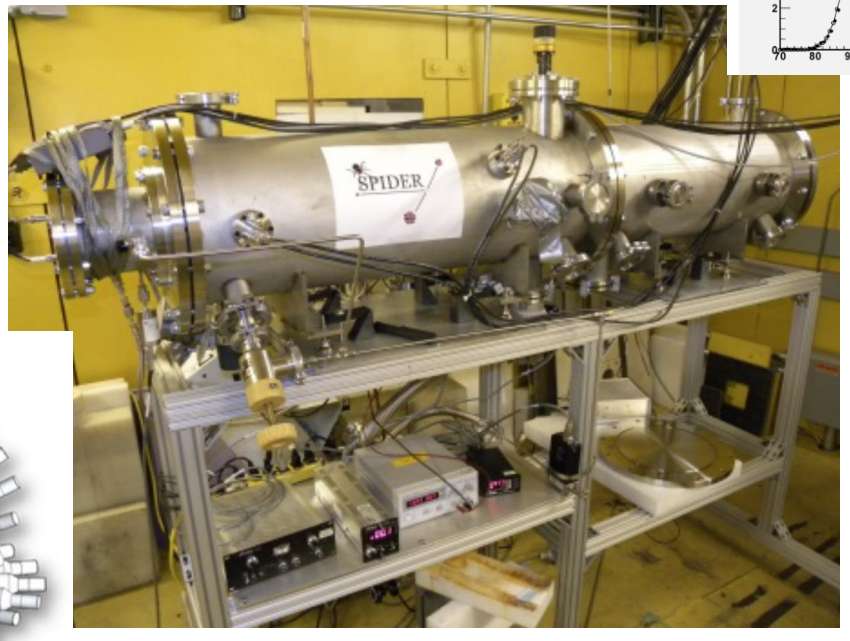
LANCE WNR

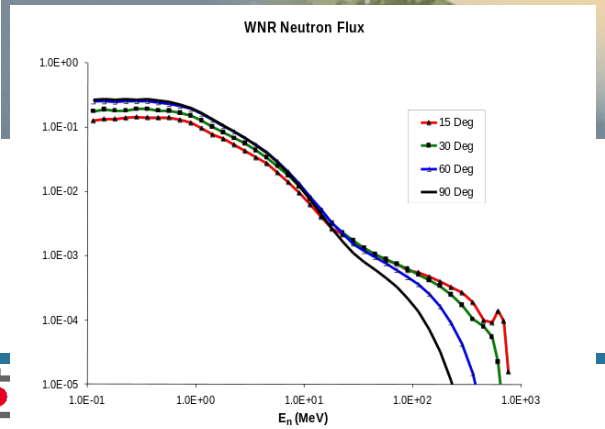
NIFFTE Time Projection Chamber

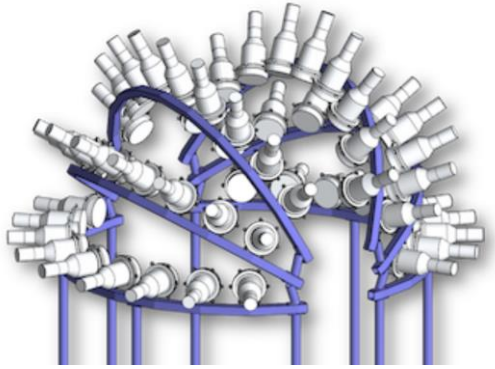






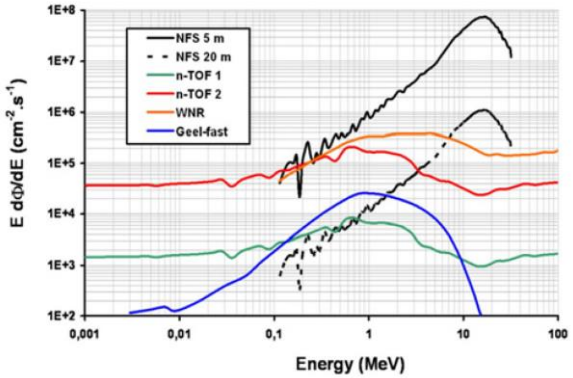


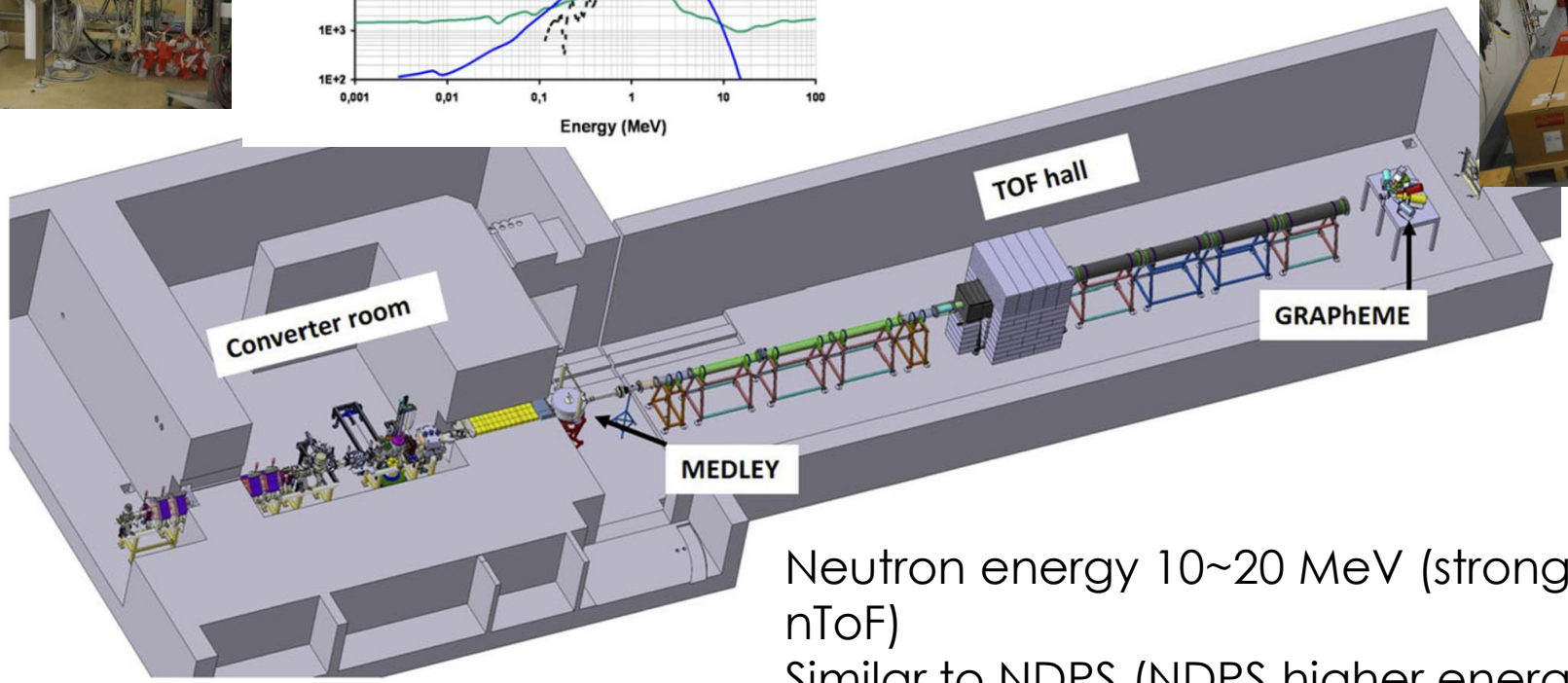




Chi-Nu

(Rel.) New facilities-NFS GANIL





Neutron energy 10~20 MeV (stronger neutron flux than nToF)
Similar to NDPS (NDPS higher energy)
Currently under study

X. Ledoux et al., EPJ Web of Conferences **146**, 03003 (2017)
X. Ledoux et al., Eur. Phys. J. A (2021) 57:257

(Rel.) New facilities-NFS GANIL

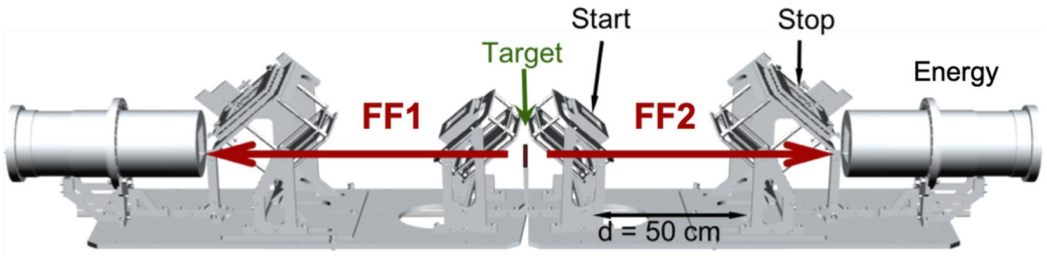
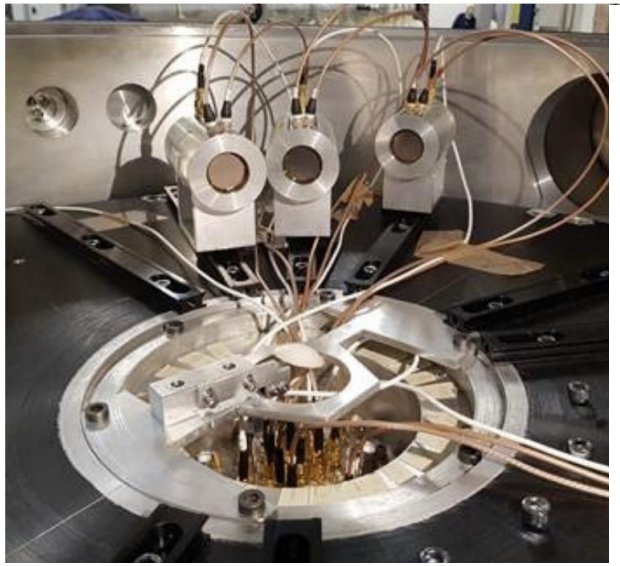
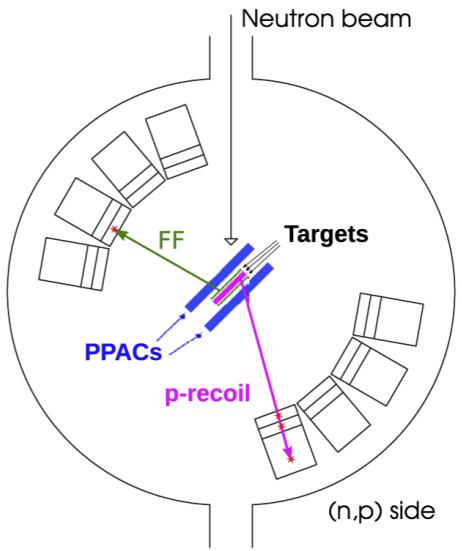
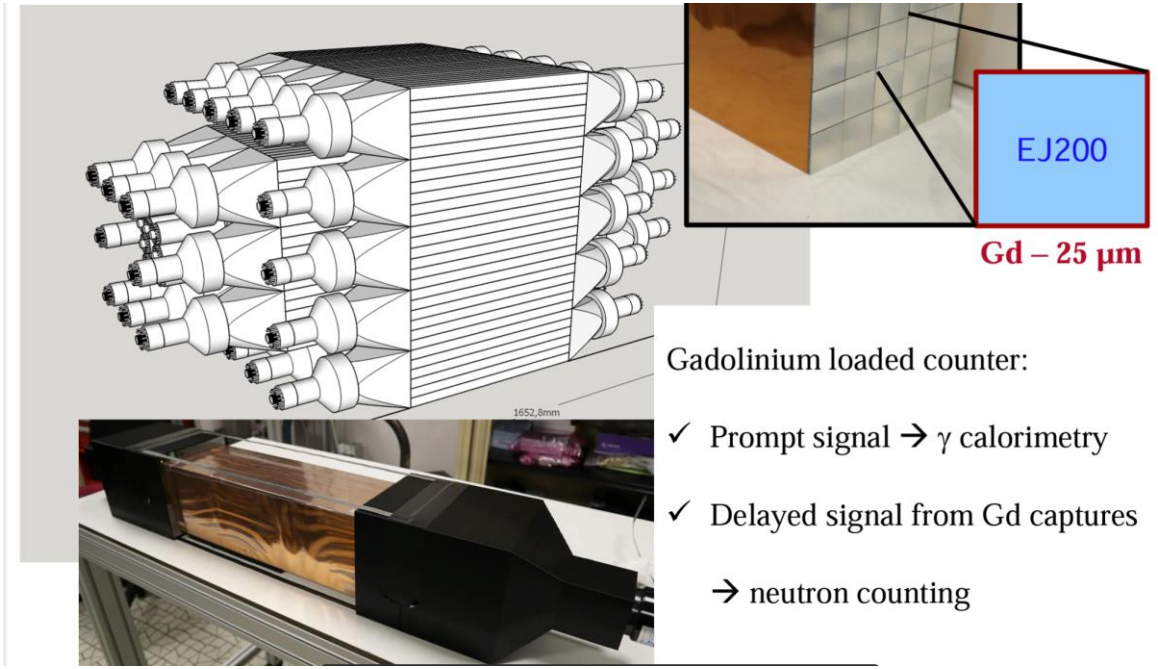


Figure 1. Drawing of the two-arm-FALSTAFF-spectrometer. Each arm is made of two ToF detectors followed by an energy detector

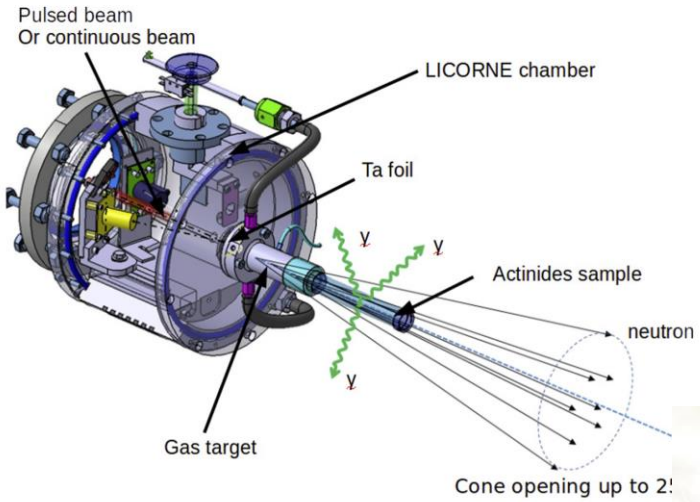


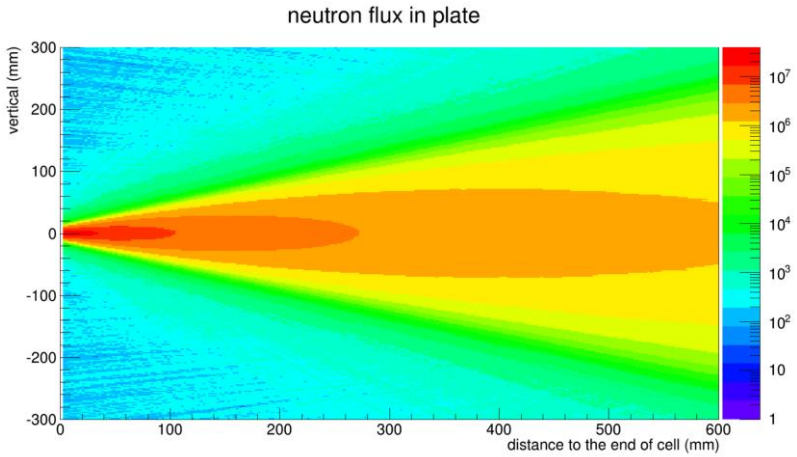


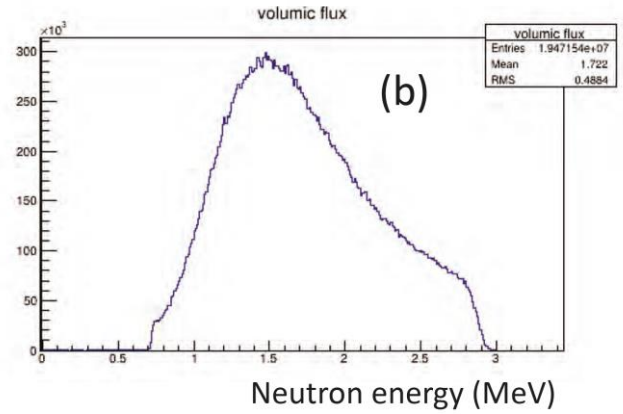


- Fission mass spectroscopy
- Absolute fission cross section angular correlation
- Fission cross section 238U(n,FFxn), dynamics gamma, neutron

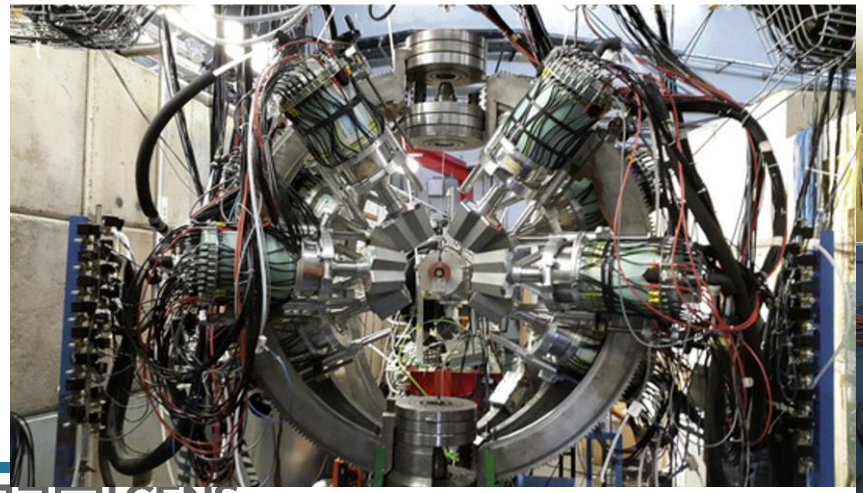
(Rel.) New facilities-LICORNE

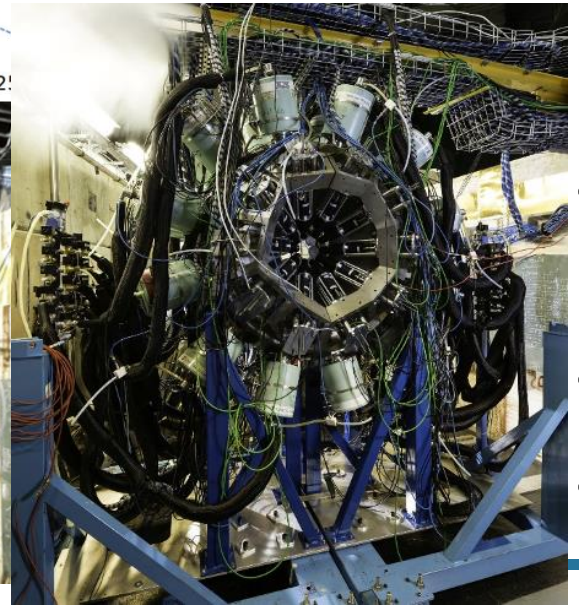






"White" source: highest fluxes 10^8 n/str/s (long gas cells, high pressures)





- 7Li beam induced neutron source (1~2 MeV neutron)
- Coupled to Ge-detector array
- Fission study 238U, 232Th etc…

(Rel.) New facilities-LICORNE

Article

Angular momentum generation in nuclear fission

https://doi.org/10.1038/s41586-021-03304-w
Received: 18 June 2020
Accepted: 9 December 2020
Check for updates

J. N. Wilson[1✉], D. Thisse[1], M. Lebois[1], N. Jovančević[1], D. Gjestvang[2], R. Canavan[3,4], M. Rudigier[3,5], D. Étasse[6], R-B. Gerst[7], L. Gaudefroy[8], E. Adamska[9], P. Adsley[1], A. Algora[10,11], M. Babo[1], K. Belvedere[3], J. Benito[12], G. Benzoni[13], A. Blazhev[7], A. Boso[4], S. Bottoni[13,14], M. Bunce[4], R. Chakma[1], N. Cieplicka-Oryńczak[15], S. Courtin[16], M. L. Cortés[17], P. Davies[18], C. Delafosse[1], M. Fallot[19], B. Fornal[15], L. Fraile[12], A. Gottardo[20], V. Guadilla[19], G. Häfner[1,7], K. Hauschild[1], M. Heine[16], C. Henrich[5], I. Homm[5], F. Ibrahim[1], Ł. W. Iskra[13,15], P. Ivanov[4], S. Jazrawi[3,4], A. Korgul[9], P. Koseoglou[5,21], T. Kröll[5], T. Kurtukian-Nieto[22], L. Le Meur[19], S. Leoni[13,14], J. Ljungvall[1], A. Lopez-Martens[1], R. Lozeva[1], I. Matea[1], K. Miernik[9], J. Nemer[1], S. Oberstedt[23], W. Paulsen[2], M. Piersa[9], Y. Popovitch[1], C. Porzio[13,14,24], L. Qi[1], D. Ralet[25], P. H. Regan[3,4], K. Rezynkina[26], V. Sánchez-Tembleque[12], S. Siem[2], C. Schmitt[16], P.-A. Söderström[6,27], C. Sürder[5], G. Tocabens[1], V. Vedia[12], D. Verney[1], N. Warr[7], B. Wasilewska[15], J. Wiederhold[5], M. Yavahchova[28], F. Zeiser[2] & S. Ziliani[13,14]

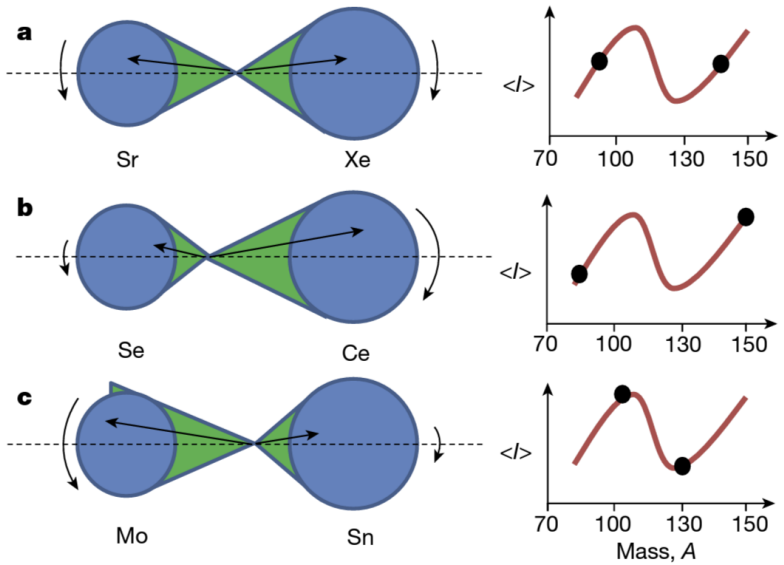
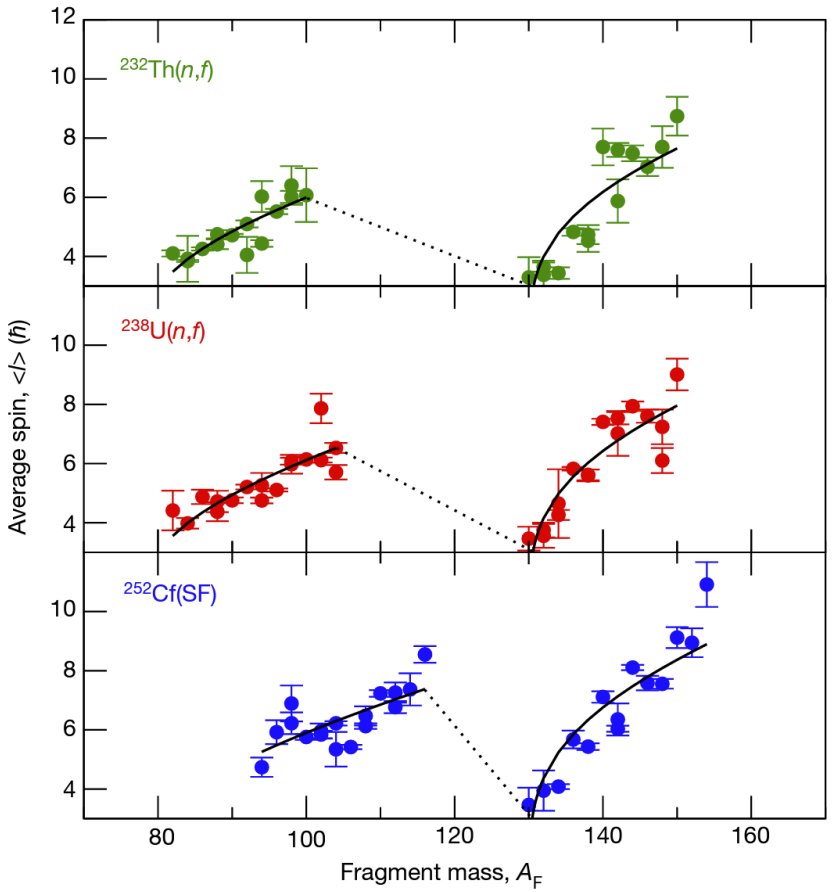
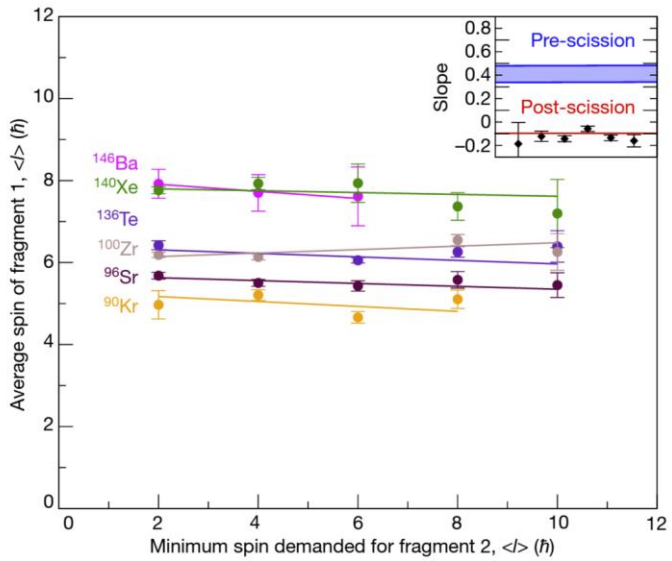


Fig. 3 | Schematic diagram of post-scission angular momentum generation.

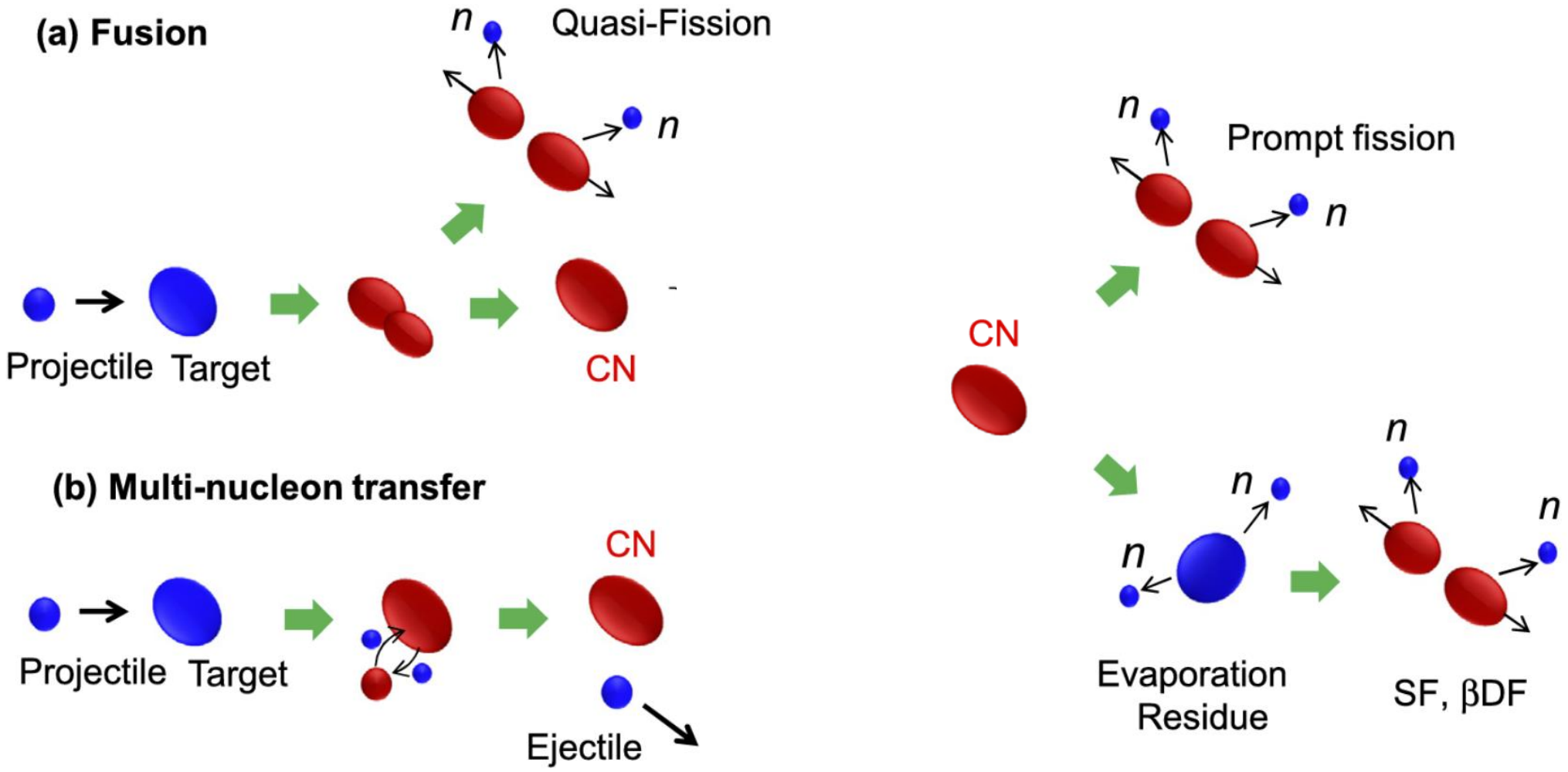




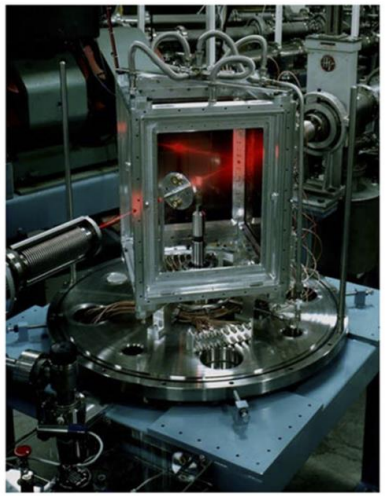
- Fission angular momentum generation <J>=0-> <J>~6
- Fission angular momentum between fission partners are independent to each other

J. N. Wilson et al., Nature **volume 590**, pages566–570 (2021)

Part2
Charged particle induced fission

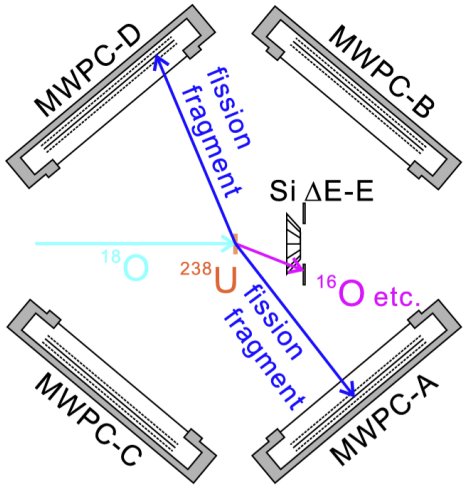


Simplest setup

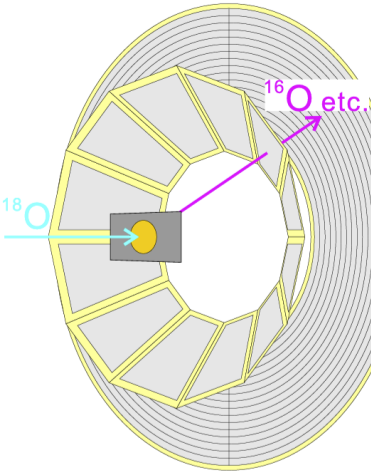


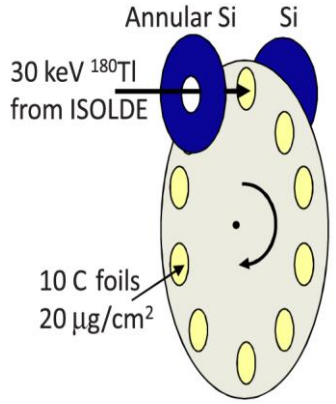
CUBE@ANL

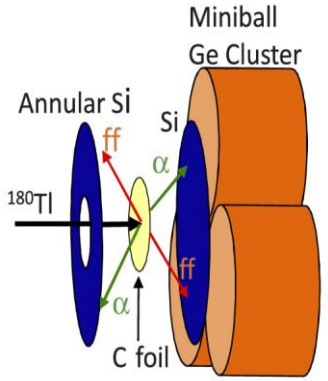
CORSET @JINR



MWPC setup @JAERI



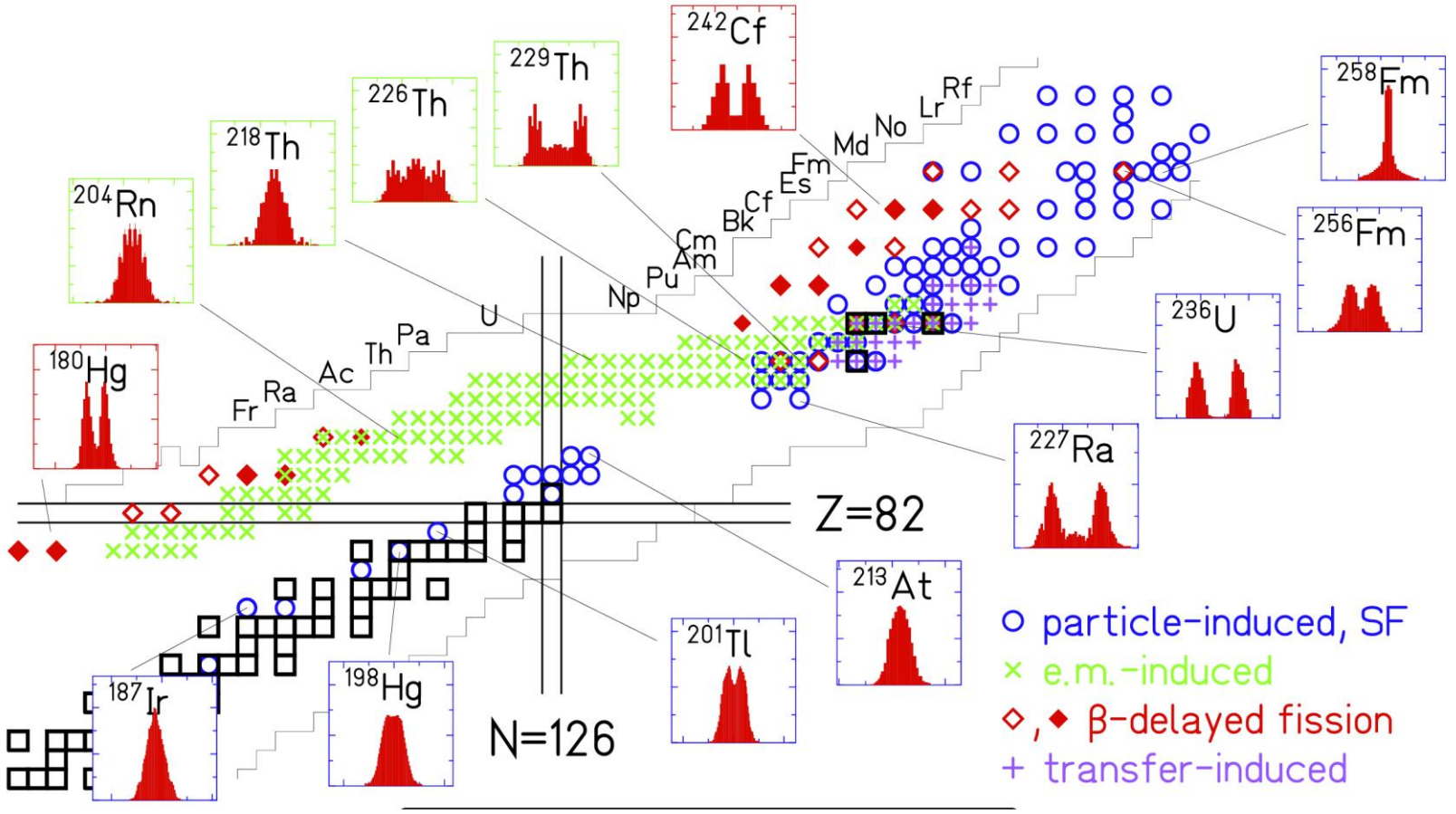


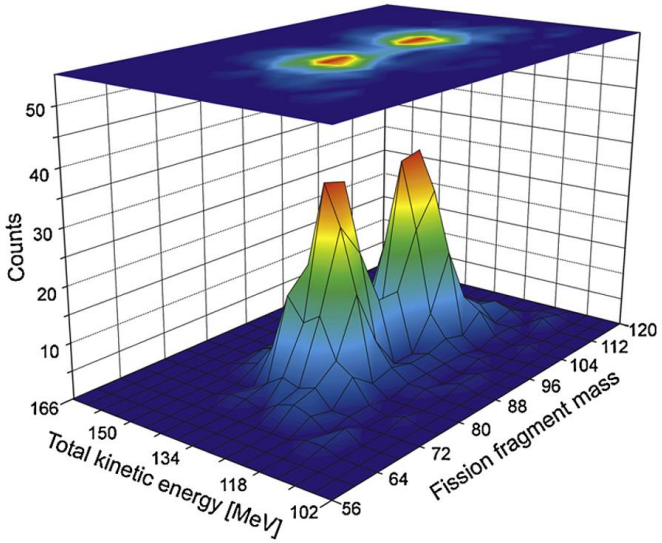


- Transfer particle and only velocity of fission fragment is measured
- Simple but powerful to measure fission in different systems from transfer/fusion-fission.
- Observables: velocity=> AFF*,AFF*, E*

K. Nishio et al., Phys. Proc. 64 (2015)140–144
A. N. Andreyev, K Nishio and K-H Schmidt Rep. Prog. Phys. 81 (2018) 016301
A. N. Andreyev et al., PRL 105, 252502 (2010)

Rich features across the nuclear chart





- Fission mass distribution shows dramatic change over different systems.
- Difficult to reproduce by theoretical calculations.

A. N. Andreyev, K Nishio and K-H Schmidt Rep. Prog. Phys. 81 (2018) 016301
A. N. Andreyev et al., PRL 105, 252502 (2010)

VAMOS transfer induced fission(2011~)

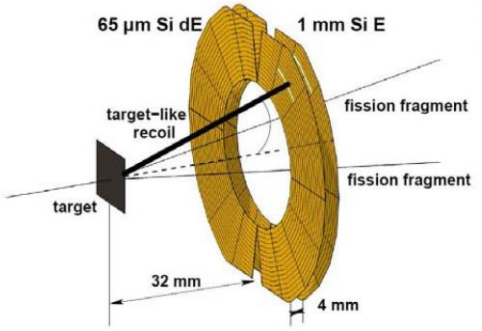
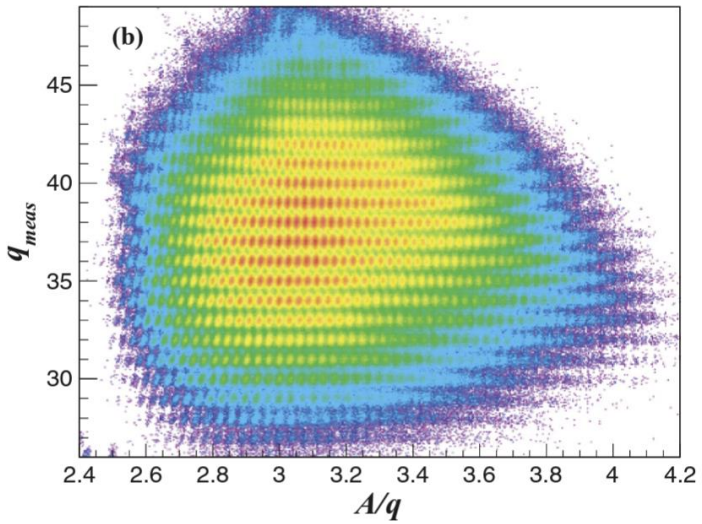
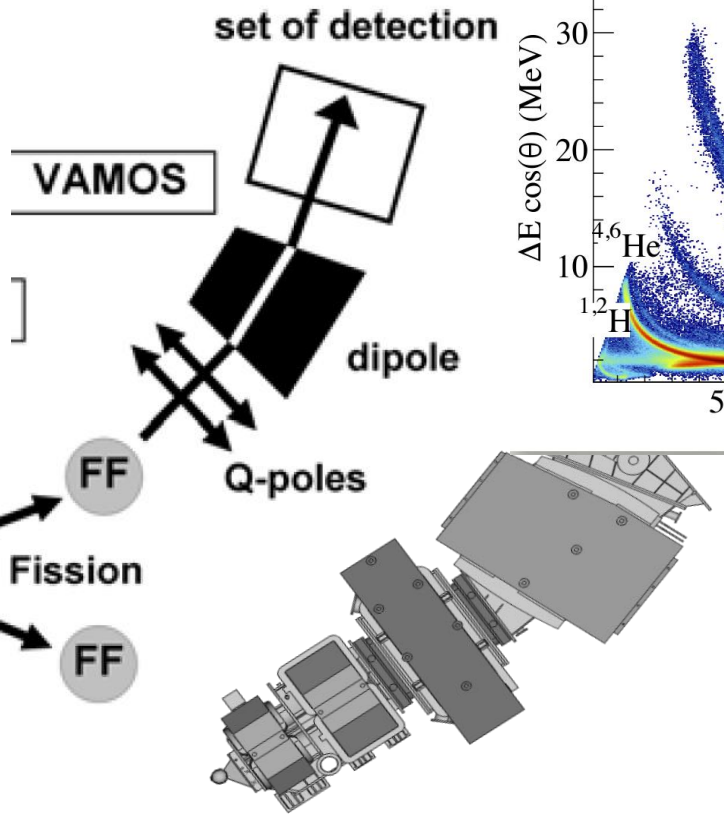


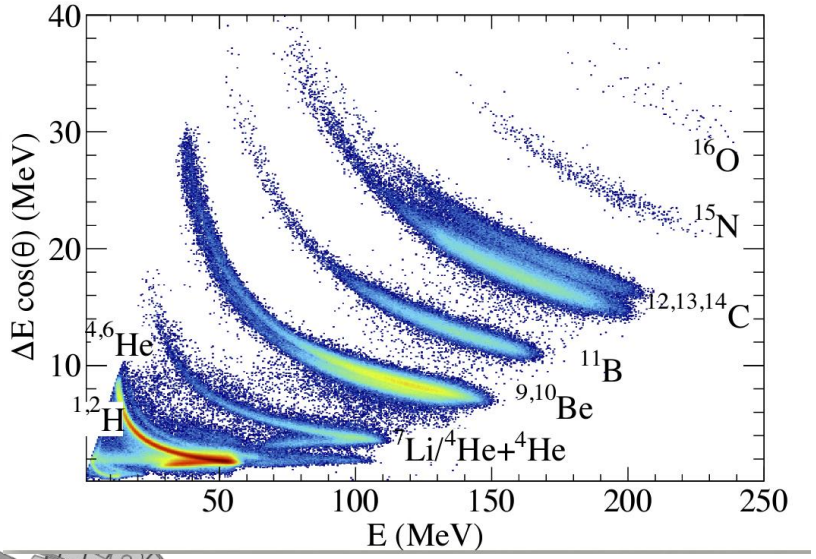
Fig. 1. Scheme of the annular telescope SPIDER

- Light particle transfer induced fission-> access 238U~Cm
- Light transfer particle, one fission fragment is fully analyzed

VAMOS transfer induced fission(2011~)





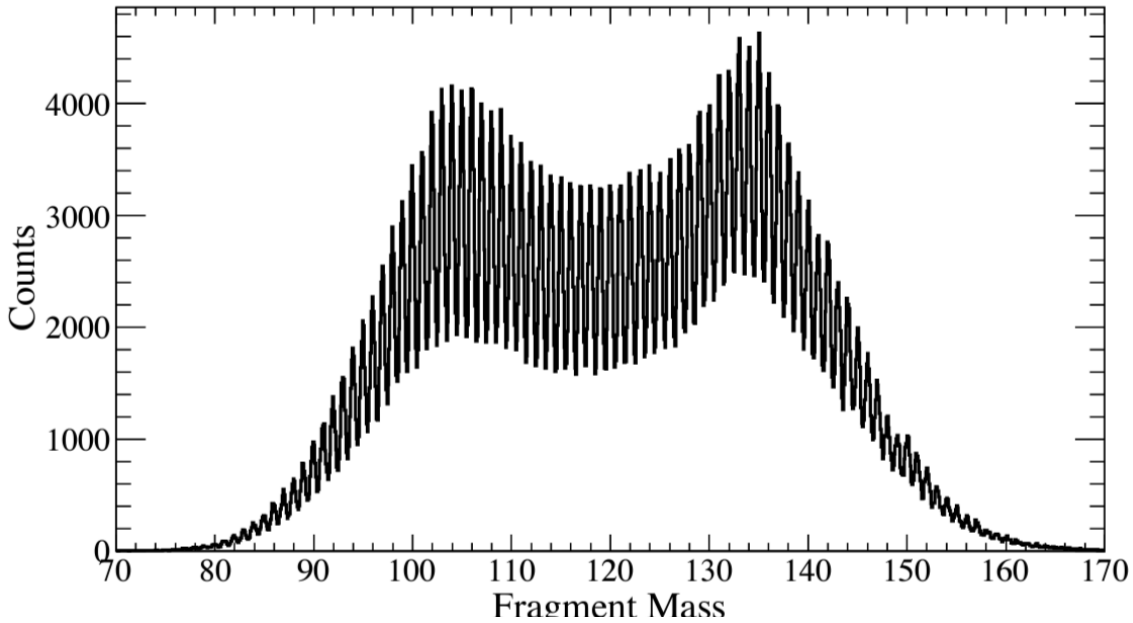


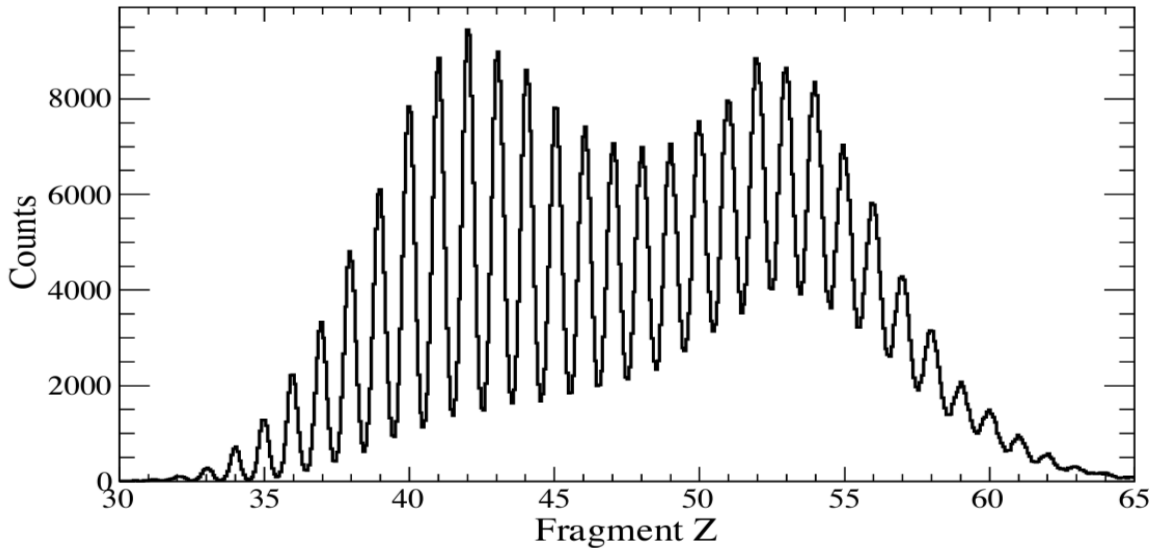
- I nduced fission
- One particle is fully analyzed

M. Caamaño et al., Phys. Rev. C **88** (2013) 024605
Manuel Caamaño and Fanny Farget Phys. Lett. B, 770 (2017) 72
D. Ramos ...Y. H. Kim... et al., Phys. Rev. Lett. 123, 092503 (2019)

Advantage of spectrometer

- Fully identified fission fragments (A,Z,kE) and light ions (E*)
- Many fissioning systems at the same time through transfer

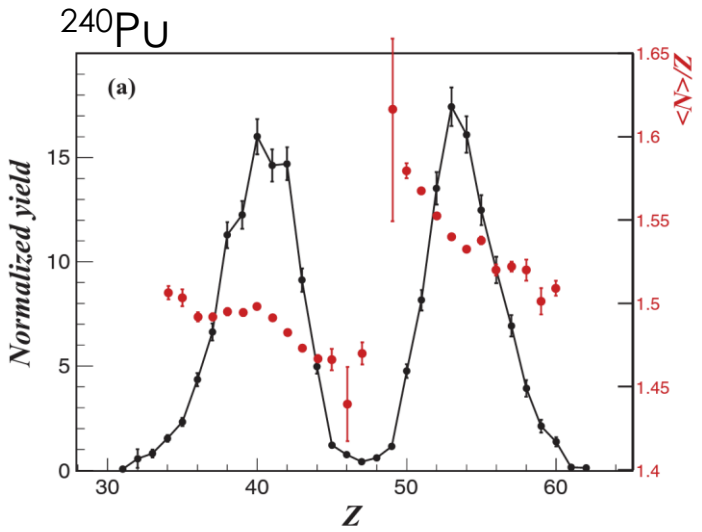


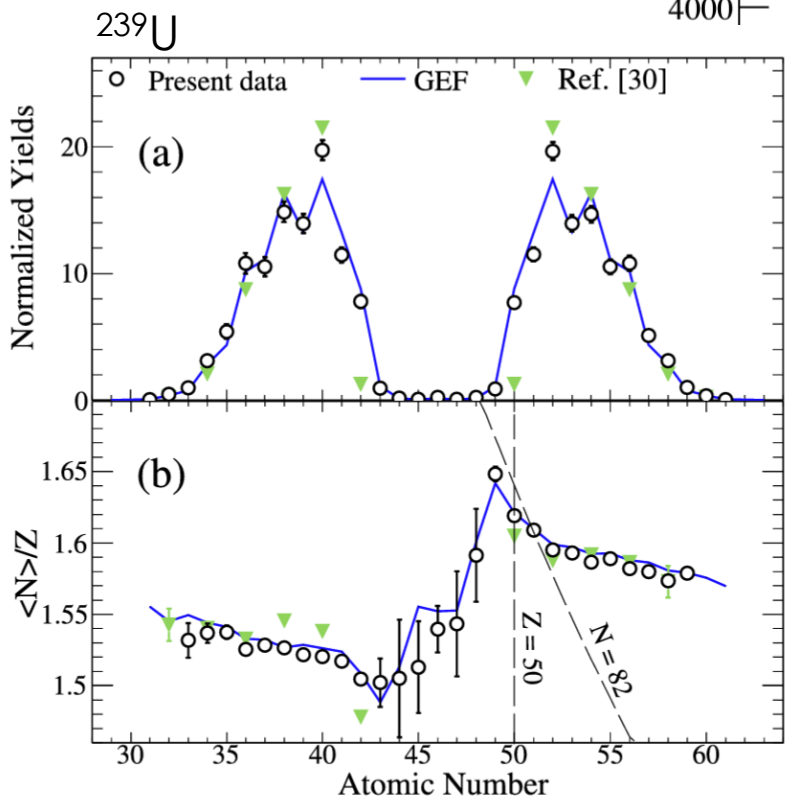


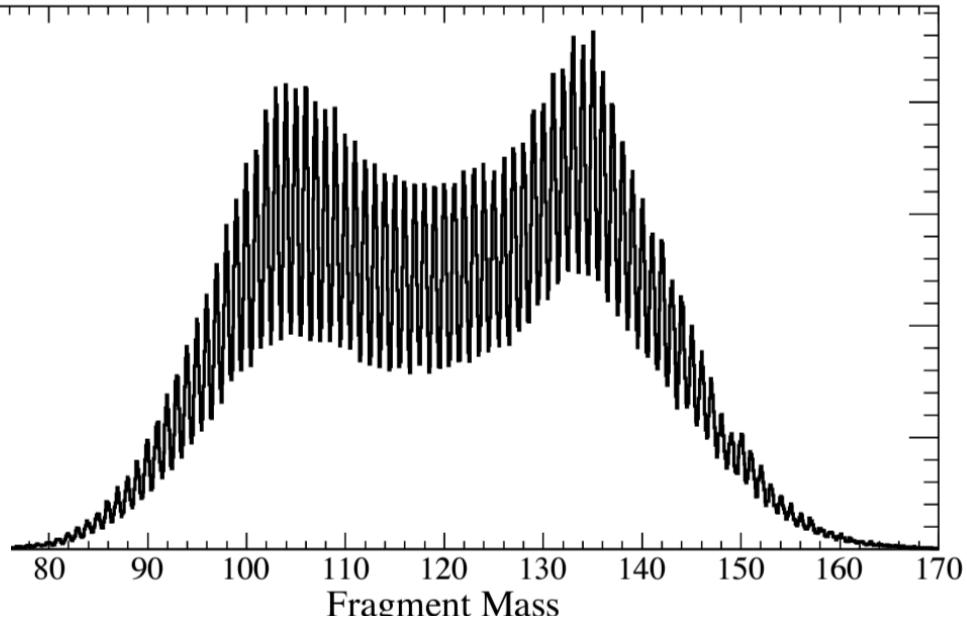
M. Caamaño et al., Phys. Rev. C **88** (2013) 024605
Manuel Caamaño and Fanny Farget Phys. Lett. B, 770 (2017) 72
D. Ramos … H. Kim… et al., Phys. Rev. Lett. 123, 092503 (2019)

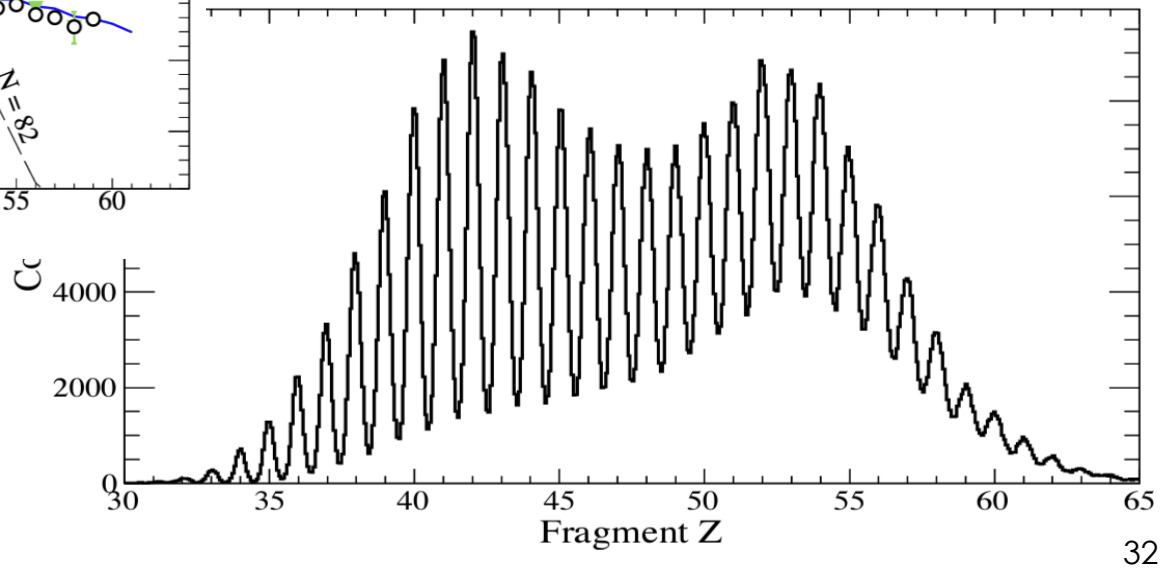
CENS CENTER FOR EXOTIC NUCLEAR STUDIES

New features in fission



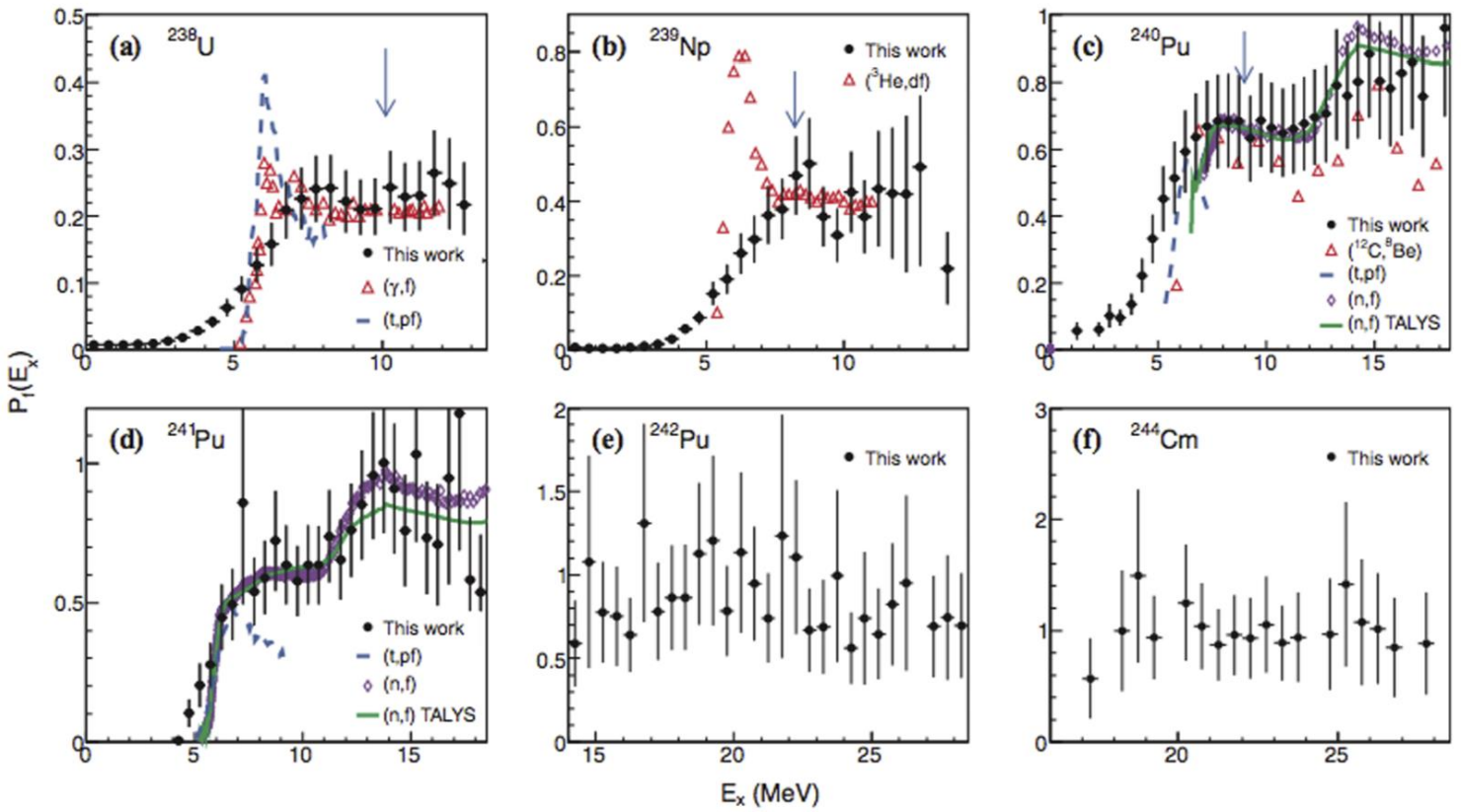


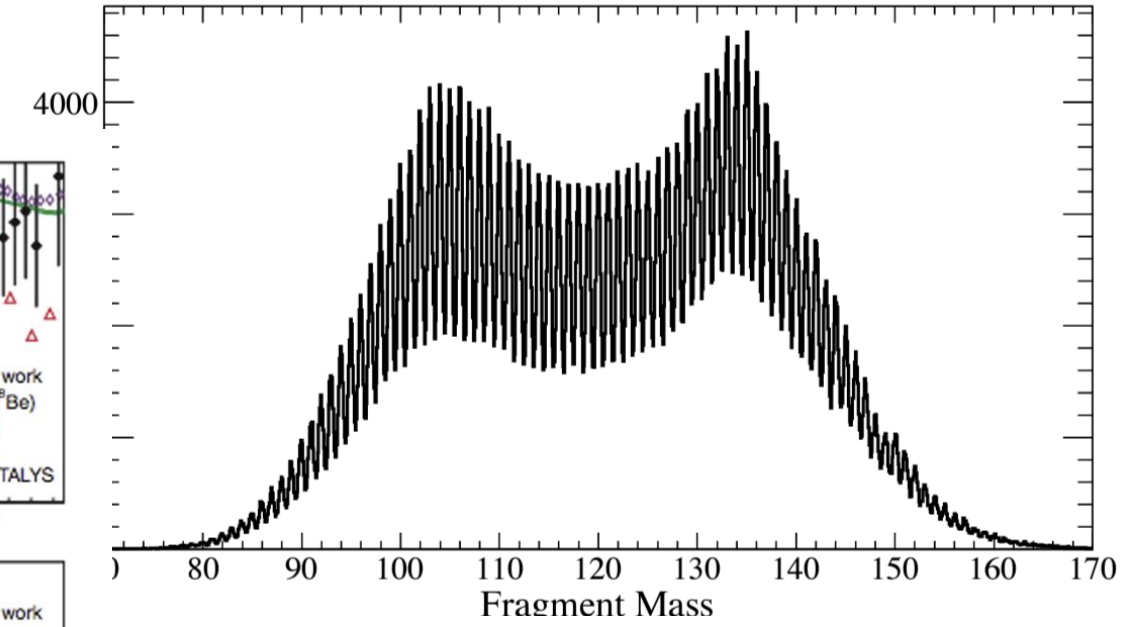


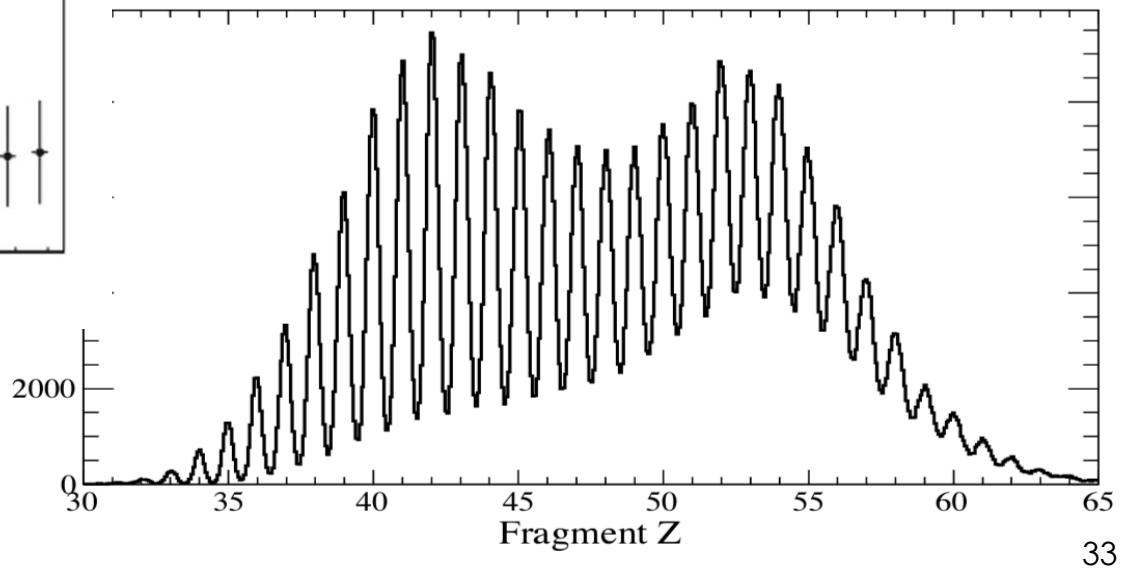


M. Caamaño et al., Phys. Rev. C **88** (2013) 024605
Manuel Caamaño and Fanny Farget Phys. Lett. B, 770 (2017) 72
D.Ramos ,Y. Kim… et al., Phys. Rev. Lett. 123, 092503 (2019)

Fission barrier measurements



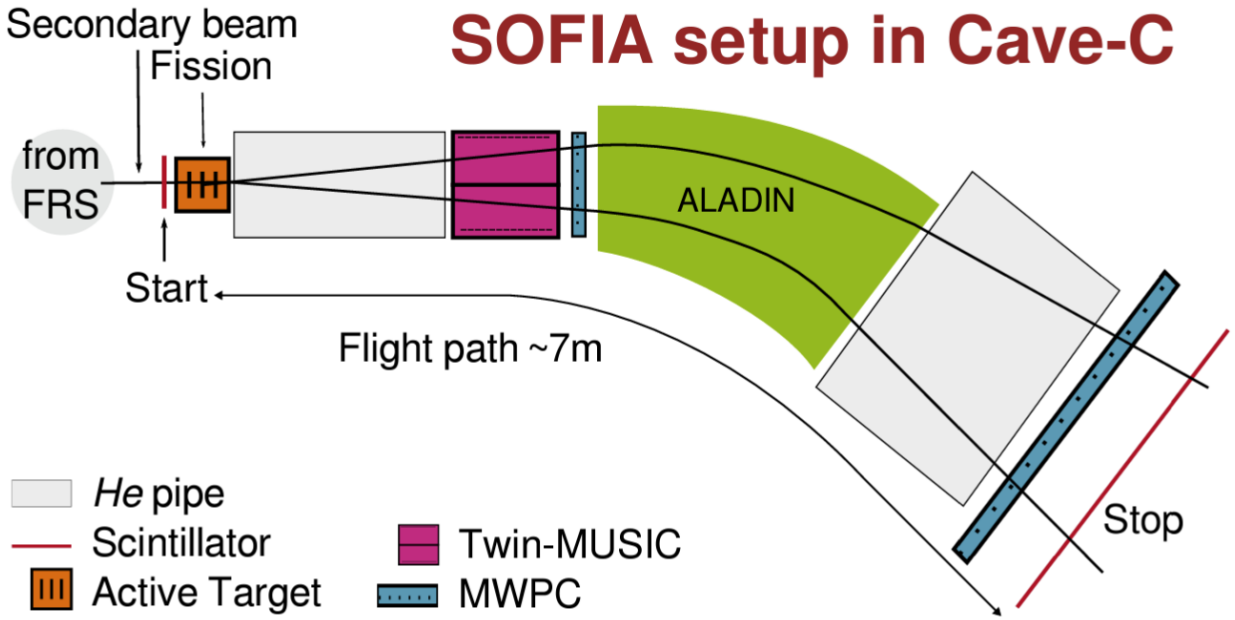


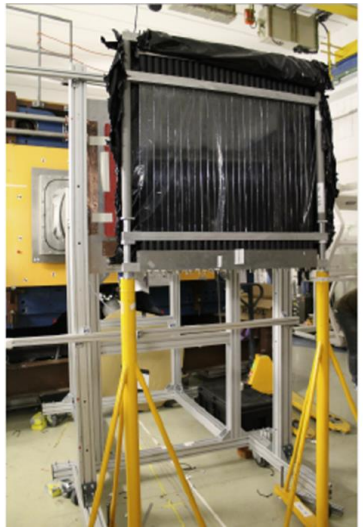


Fission excitation function near actinides.

C. Rodríguez-Tajes et al., Phys. Rev. C 89, 024614 (2014)

SOFIA GSI-



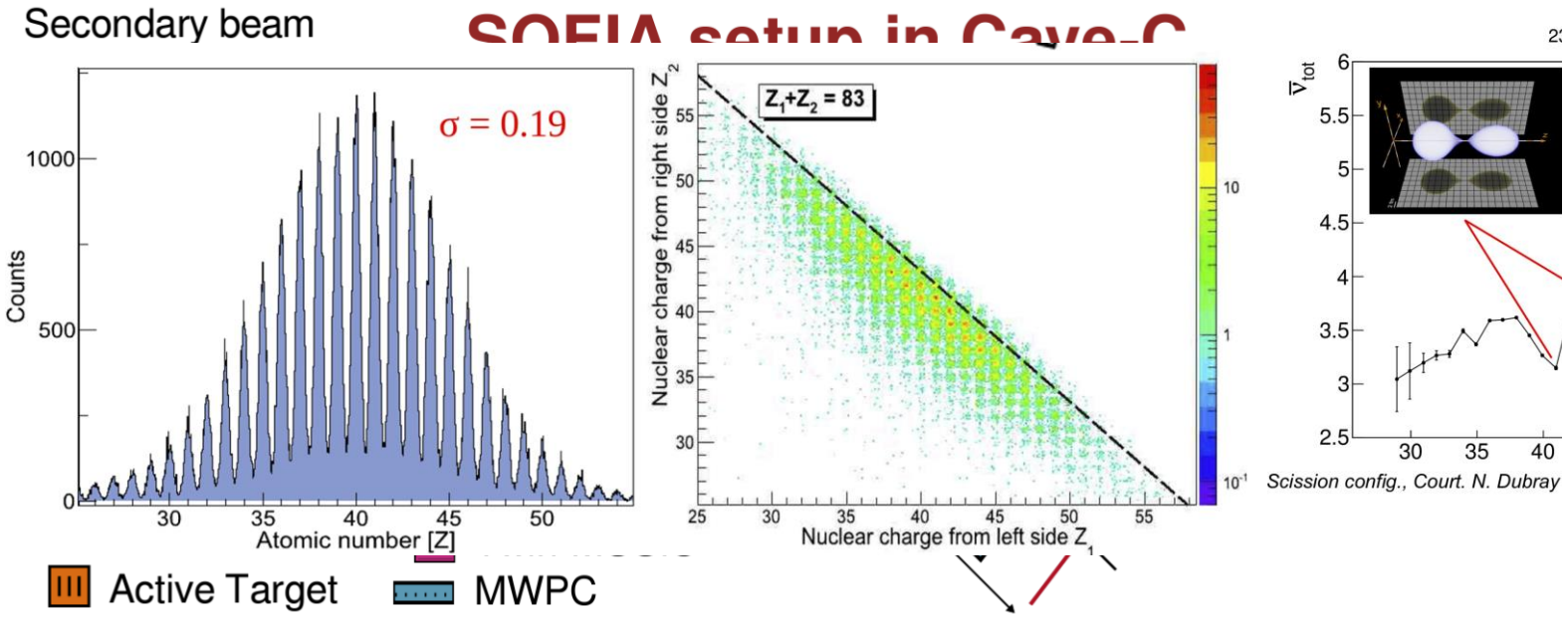


- 238U 1GeV/u -> FRS -> exotic beam 236U
- Fission by Coulomb excitation
- High energy-event-by-event full PID on both fragments
- Determination of fission kinematics

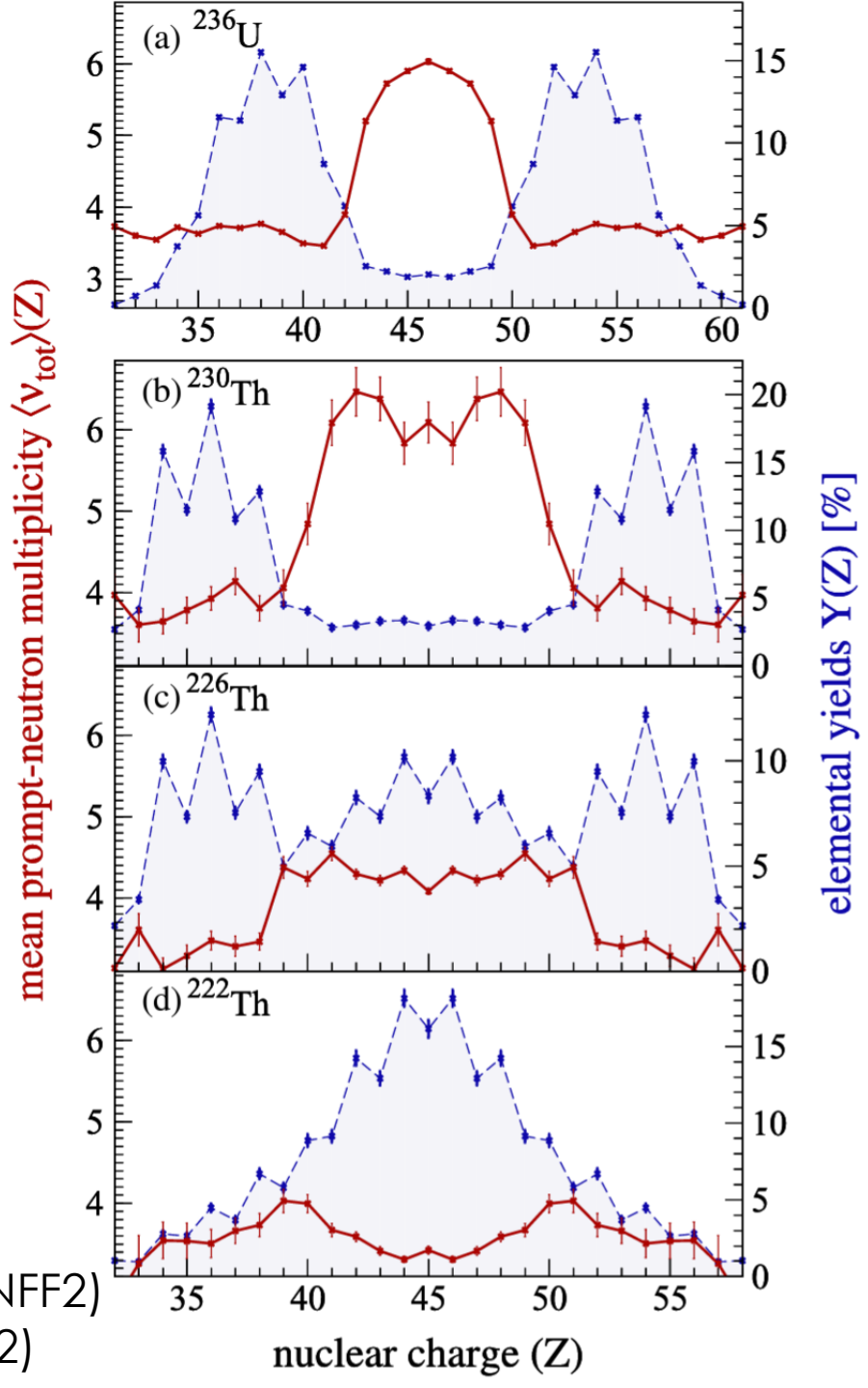
Neutron multiplicity νn = A−(AL+AH)

J.L. Rodriguez-Sanchez et al., Phys. Rev. C 91, 064616 (2015)
E. Pellereau et al., Phys. Rev. C 95, 054603 (2017)
A. Chatillon et al., Phys. Rev. Lett. **124**, 202502 (2020)

High energy fission-SOFIA GSI



- 238U 1GeV/u -> FRS -> exotic beam 238U
- Fission by Coulomb excitation
- High energy-event-by-event full PID on both fragments
- Determination of fission kinematics



J.L. Rodriguez-Sanchez et al., Phys. Rev. C 91, 064616 (2015)
E. Pellereau et al., Phys. Rev. C 95, 054603 (2017)
A. Chatillon et al., Phys. Rev. Lett. **124**, 202502 (2020)

Neutron multiplicity νn = Nb−(NFF1+NFF2)
Proton multiplicity νp = Zb−(ZFF1+ZFF2)

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Observables in fission

Observables	Derived Quantities
(total) Cross section	Nuclear Data, fission probability
Excitation function	fission barrier
Angular distribution (of FF)	fission dynamics, fission modes
Multiplicities neutron, charged particle (Mp), gamma (Mγ)	fission time scale/dynamics
PAST one observable at a time	
NOW multiple observable as function of	
Mass (A), Atomic# (Z) kin. energy (TkE)	Detailed fission dynamics & structure

Summary in fission detection techniques

Method	Advantage	Disadvantage	Observables
Chemical separation etc…	High accuracy	Only long lived nuclei, challenging	σ, A, Z
ToF measurement	Simple	Low resolution, limited observables	σ, θ, Apre,TKE
Gamma-ray spectroscopy	Full PID (cumulative)	High uncertainty from gamma-ray emission probability	σ, A, Z, TKE, Mγ
2v-E	Simple, large acceptance, many observables	Low resolution,	σ, θ, Apre, A, TKE
EM Spectrometer	Very high resolution	Highly complex	σ, θ, A, Z, TKE

- Towards more sophisticated setup with higher resolution…

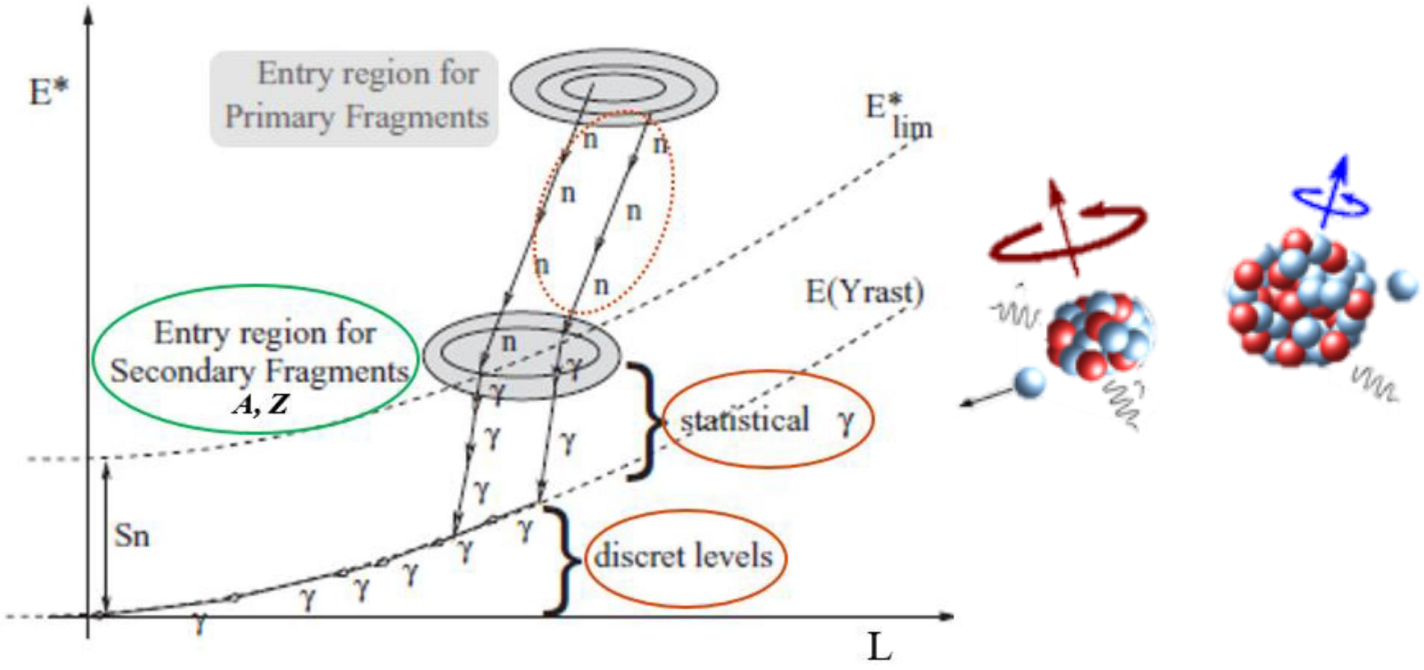
Part3:
Possible fission experiment & Setups at RAON?

- 1. Neutron induced fission (NDPS)
  - a. Fission dynamics study & fission mass distribution
  - c. Exotic fission channels.

- 2. Charged particle induced fission (Low energy beam line)
  - heavy ion transfer induced fission & fission survival probability study at actinide region

NDPS: High energy neutron induced fission

Fission dynamics study



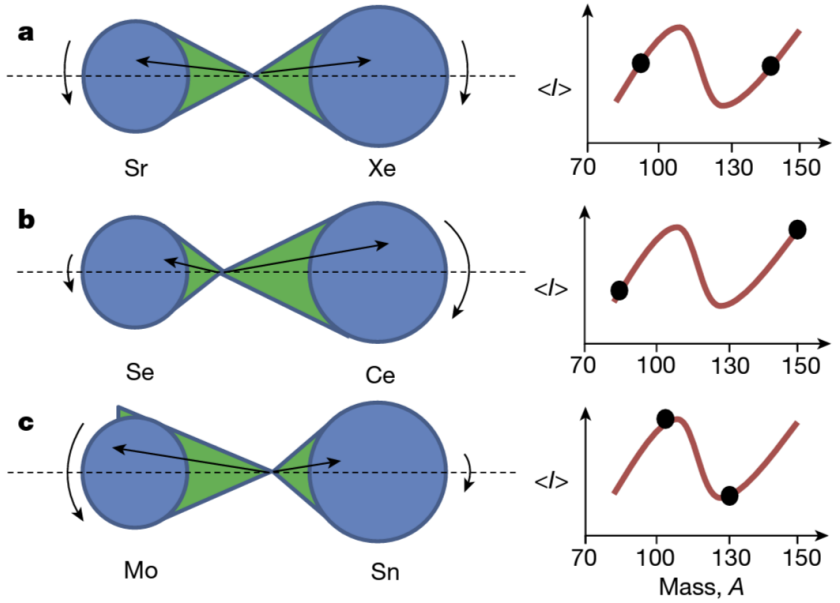
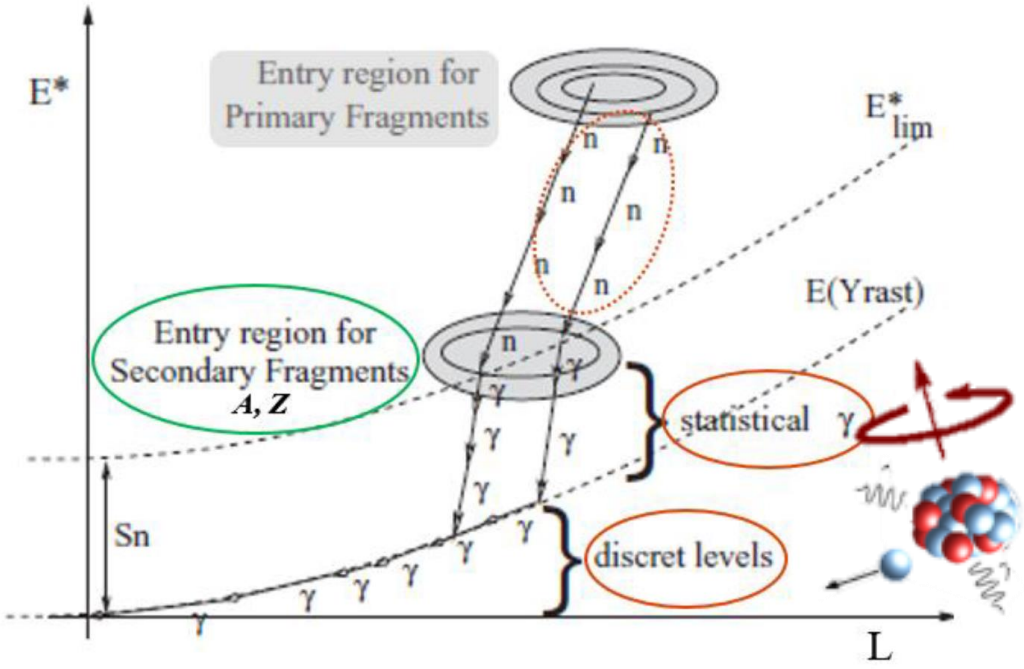


Fig. 3 | Schematic diagram of post-scission angular momentum generation.

- How fission angular momentum is generated? (gamma-ray measurement)
- How fission excitation energy is distributed? (light particle evaporation)
- Spontaneous measurement is not yet made…(attempt with PARIS detector+VAMOS spectrometer)

Fission dynamics study-energy sharing -angular momentum



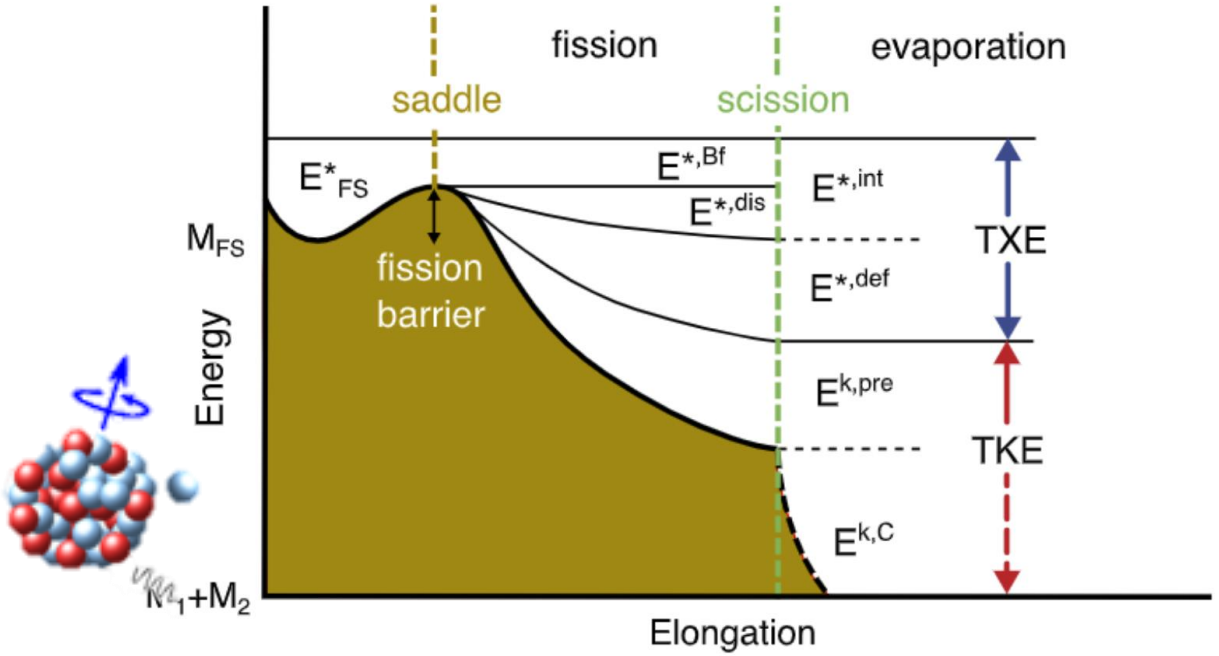
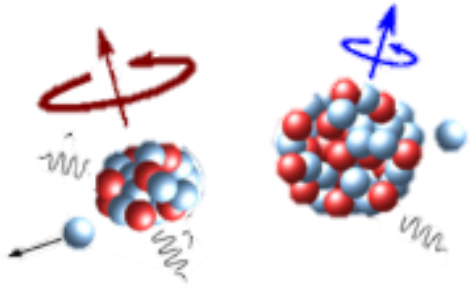


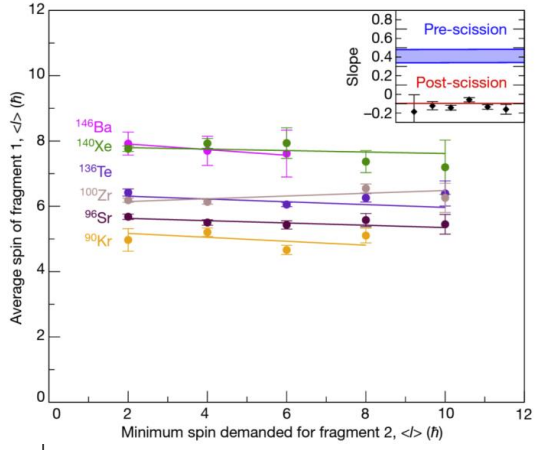
Fig. 1. Graphical explanation of the main components of the energy balance throughout the fission process. See text for details.

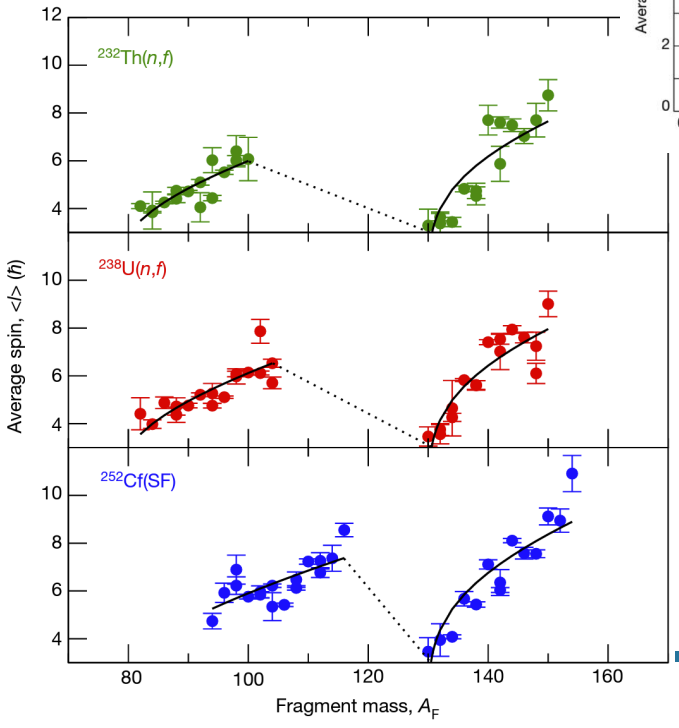
- How fission angular momentum is generated? (gamma-ray measurement)
- How fission excitation energy is distributed? (light particle evaporation)
- Spontaneous measurement is not yet made…(attempt with PARIS detector+VAMOS spectrometer)

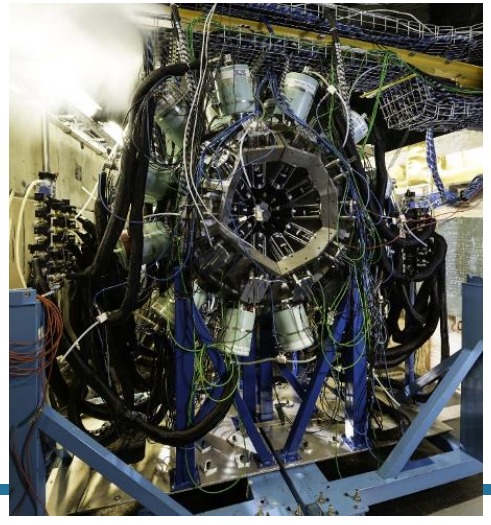
Fission dynamics study
angular momentum generation



How angular momentum is correlated?



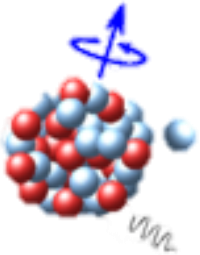




or with : Ge detectors (isotopic yields)

ion beam

132Sn



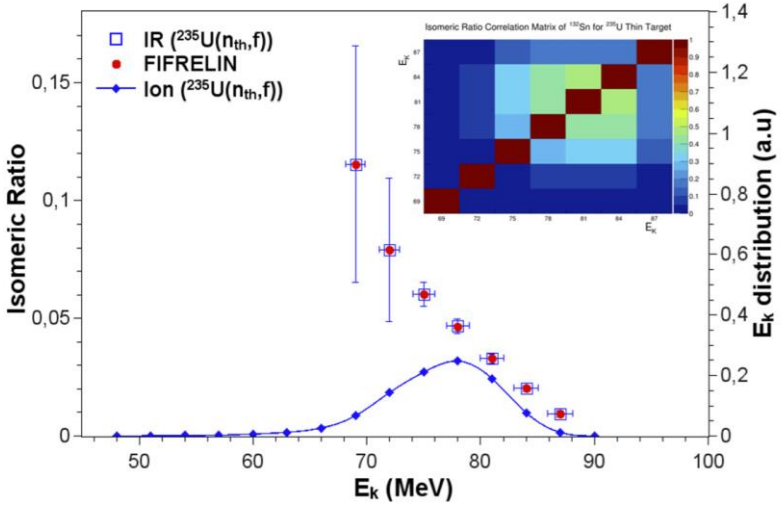
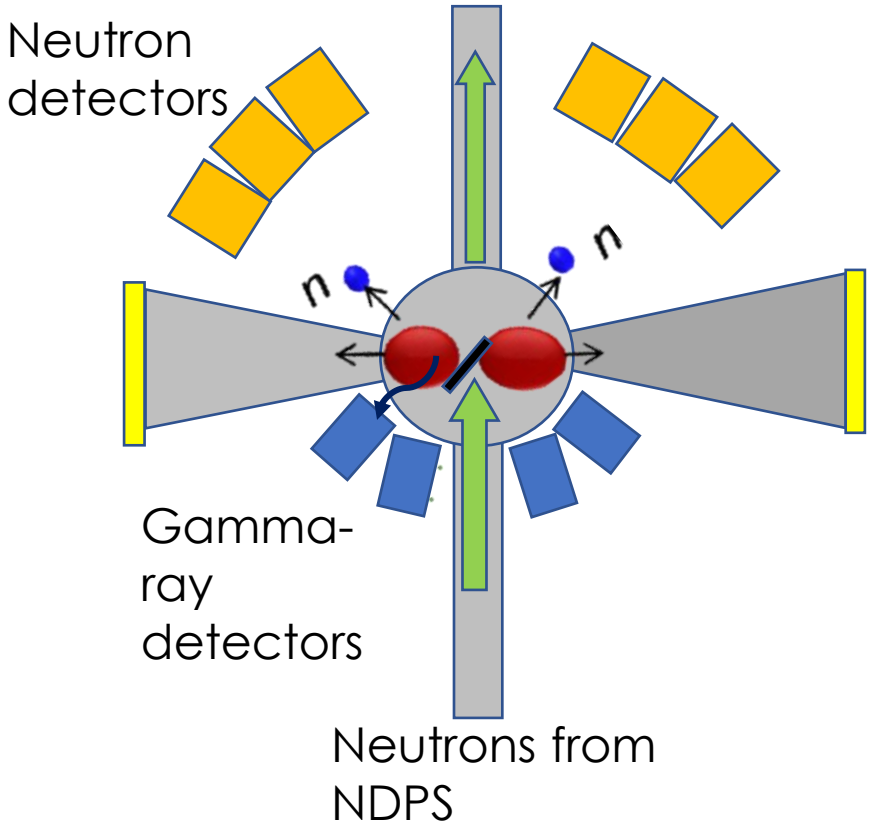


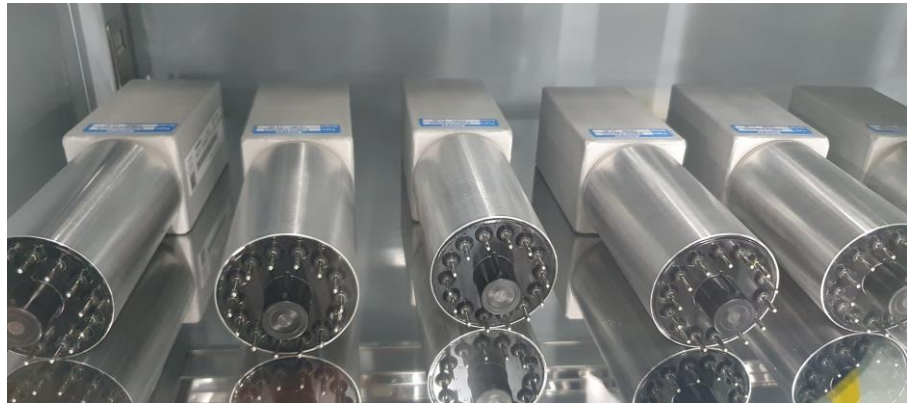
Fig. 2. (Color online.) Dependence of ^{132}Sn IR on the kinetic energy selected by the

doubly magic 132Sn a dependence of IRs and Jrms as a function of kinetic energy

A. Chebboubi et al., Phys. Lett. B 775 (2017) 190–195

Possible setup for fission dynamics @ NDPS?

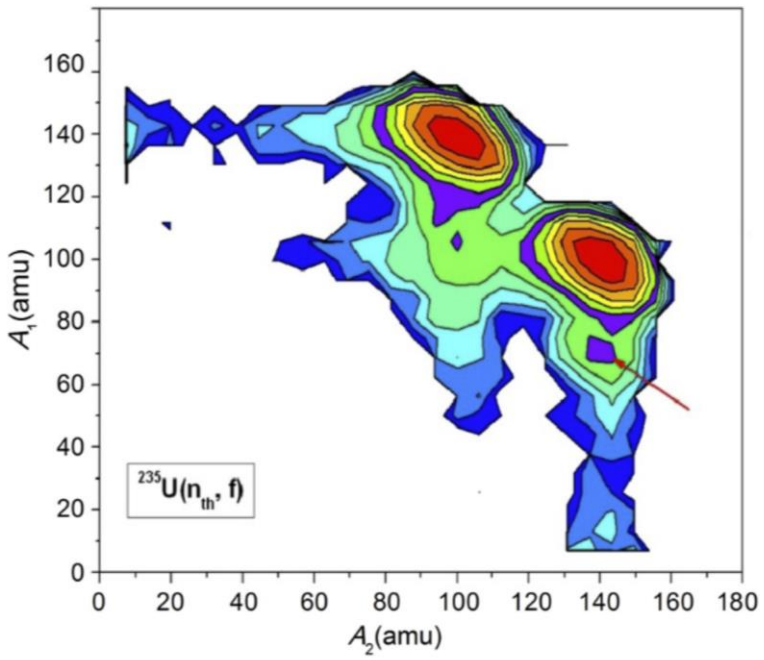


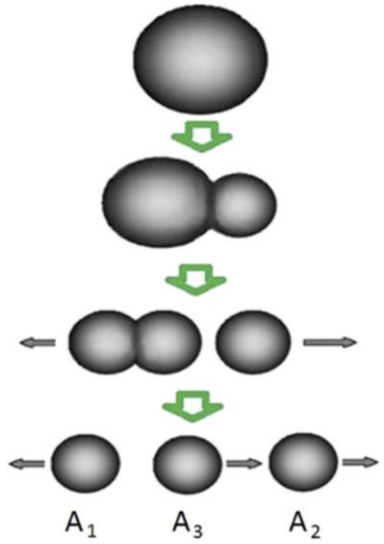


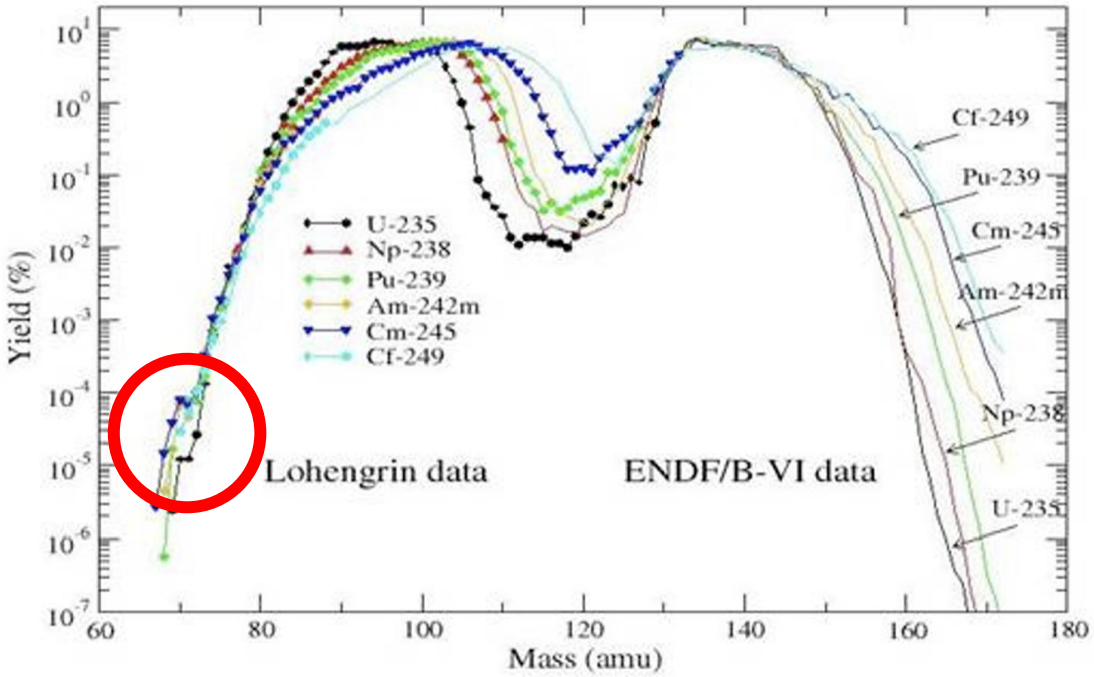
Observable	Possible Detectors
Fission fragment	Large area PPAC
neutron	Plastic scintillator array
Gamma-ray	CsI crystal

- Reaction chamber neutron, gamma-ray measurement
- Full particle measurement+ neutron beam energy (entrance*)
- Total excitation energy can be measured

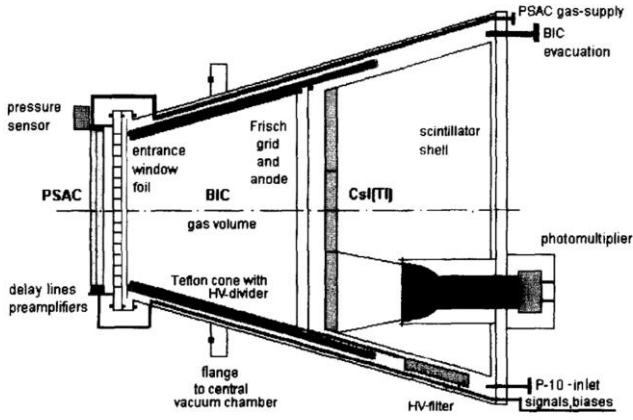
Another possibility?
Exotic fission mode study







- "Controversial" true ternary fission
- FOBOS setup @ JINR russia



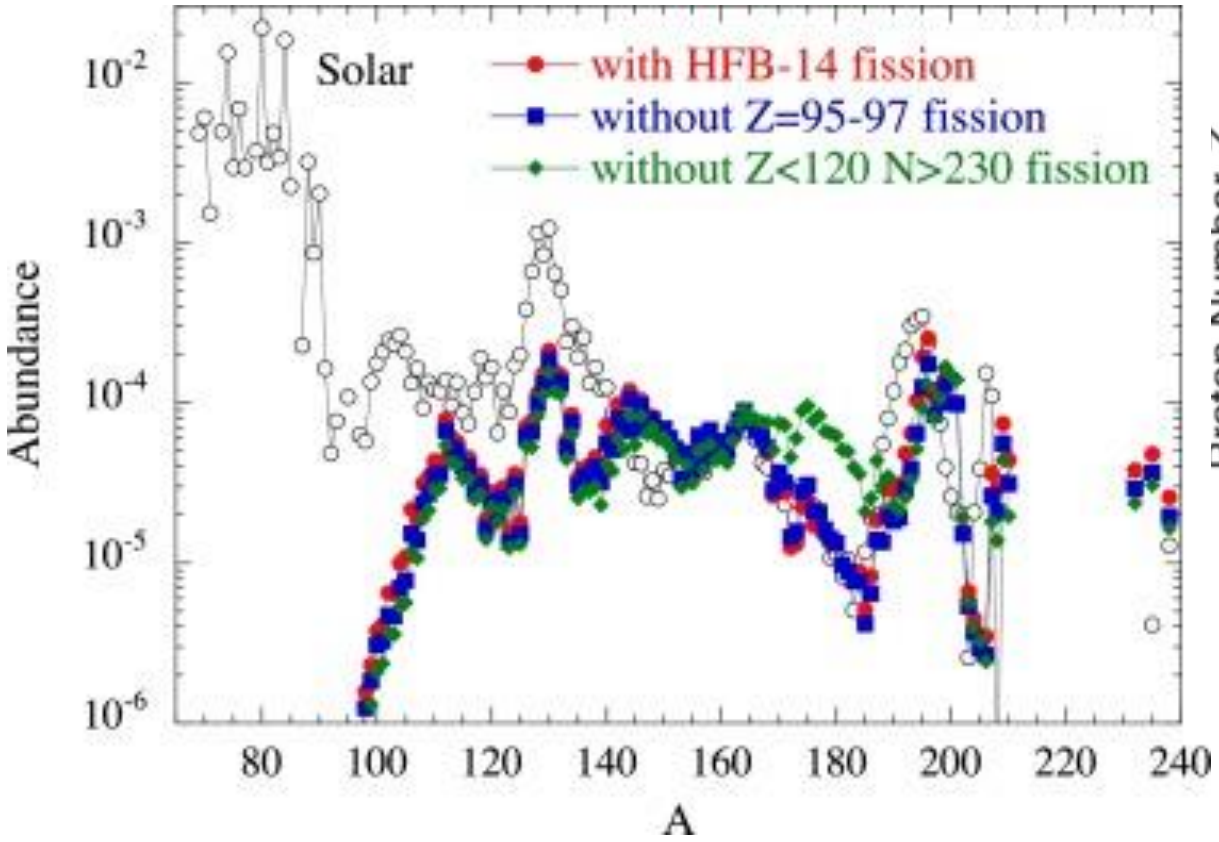
W. von Oertzen, A.K. Nasirov / Physics Letters B 734 (2014) 234–238
Yu.V. Pyatkov et al., Eur. Phys. J. A 45, 29–37 (2010)

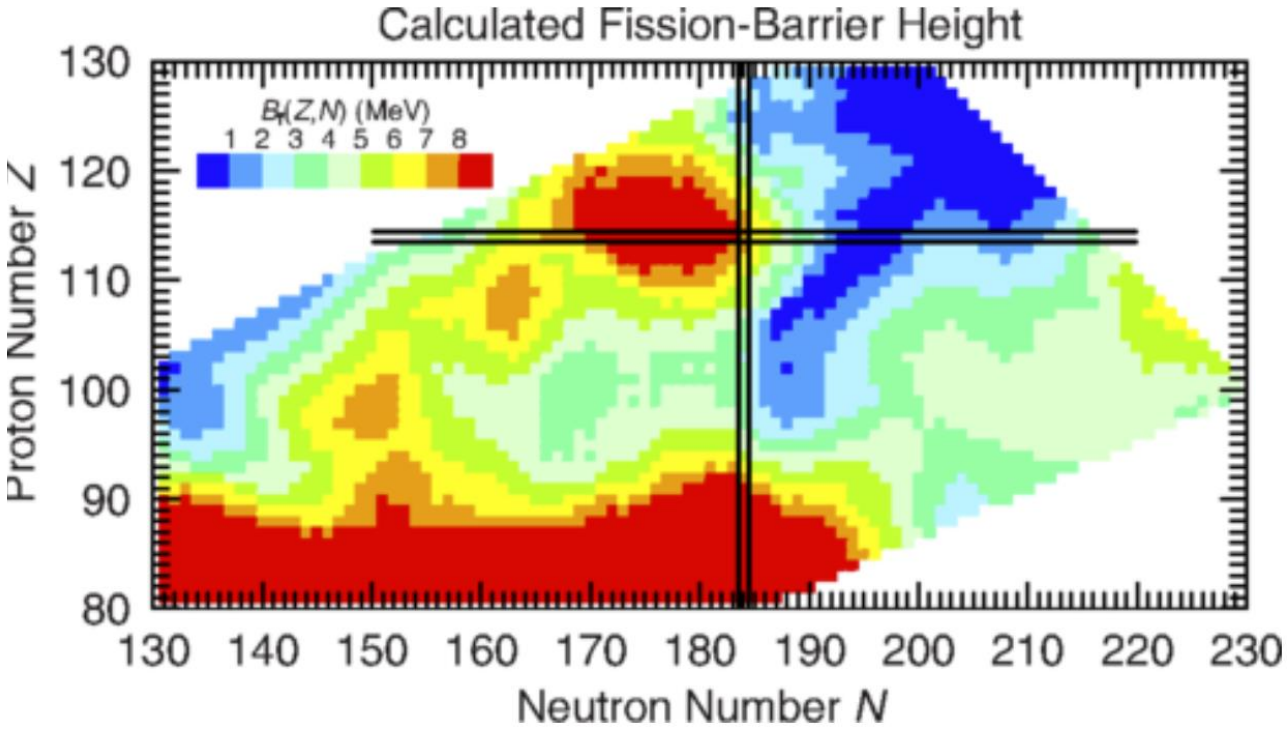
Charged particle induced fission

Multi-nucleon transfer in actinide regions for fission barrier study

Fission in the r-process

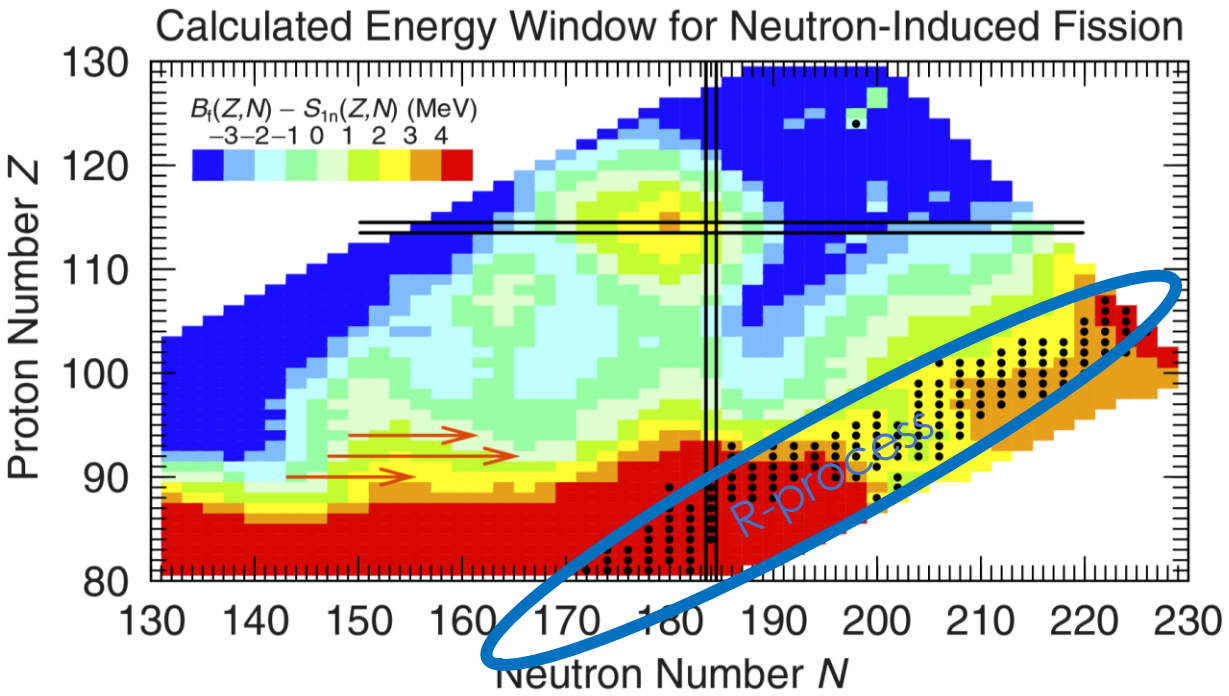
- Last part of r-process actinide fissions & refuel r-process with n-rich nuclei
- Fission barrier is most important input

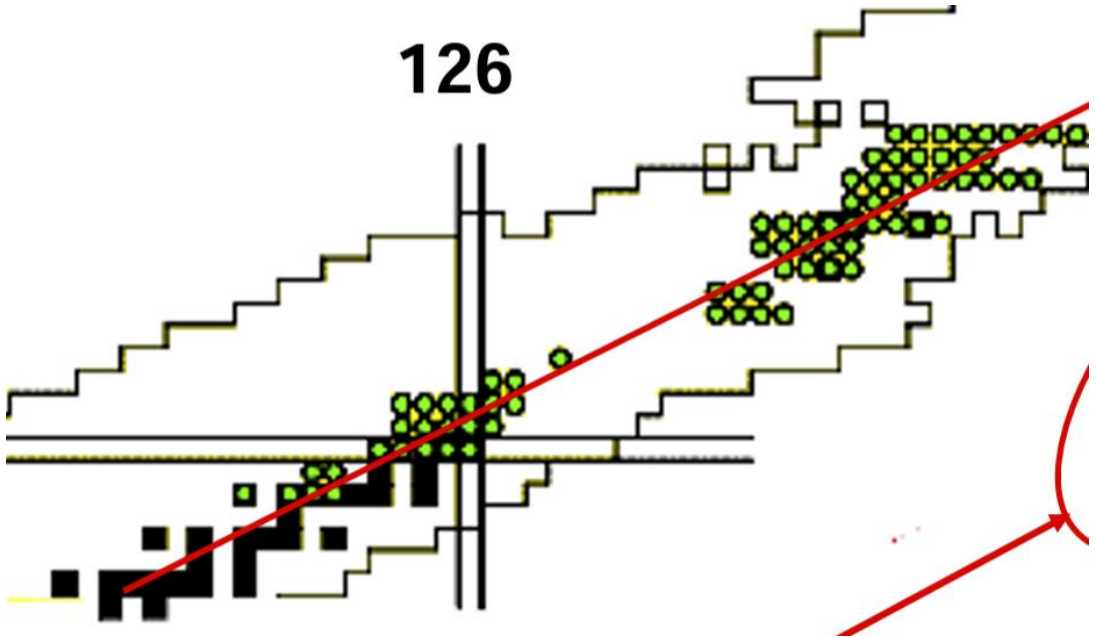




S Goriely and G.Martínez-Pinedo Nucl. Phys. A, 944 (2015)158-176
P. Moller et al., Phys. Rev. C 91,024310 (2015)
G.Martínez-Pinedo et al., Prog. Ptl. Nucl. Phys 59 (2007) 199

Objective: systematic measurement of fission barrier around actinide regions



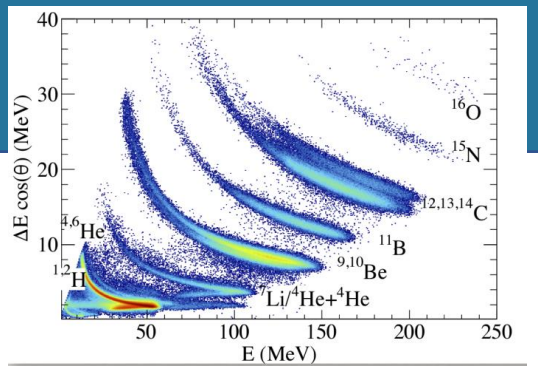


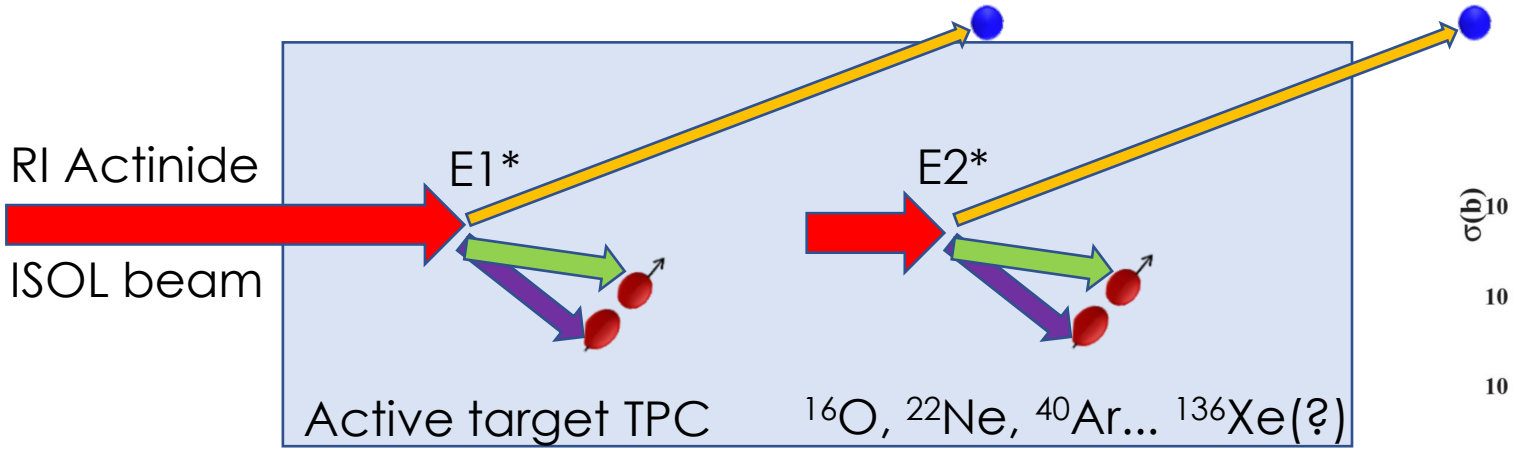
www.nds.iaea.org/ripl-3

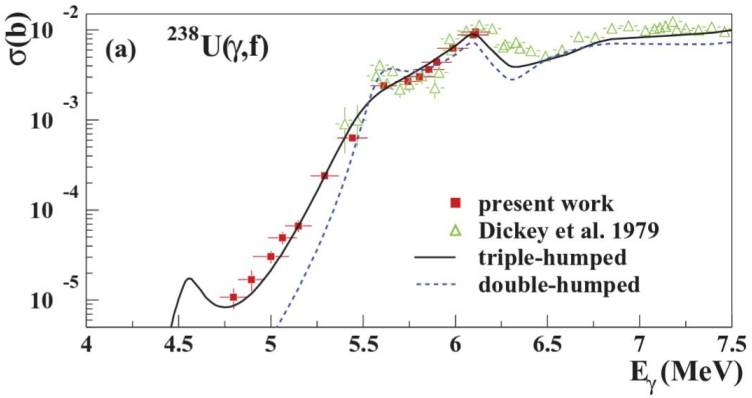
- Fission probability (cross section) as a function of E*=> full particle measurement required
- Important for reaction mechanism r-process modeling
- “Measurement of fission barriers and fission rates in induced fission is demanded” (NuPECC Long Range Plan 2017)

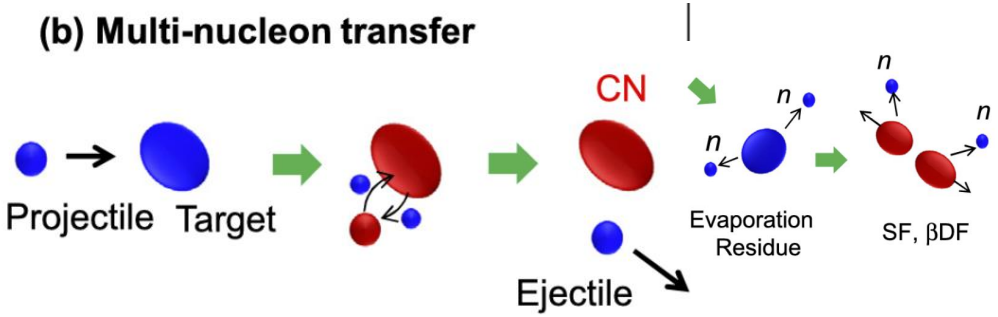
P. Moller et al., Phys. Rev. C 91,024310 (2015)

Possible experiment: Fission barrier near actinides



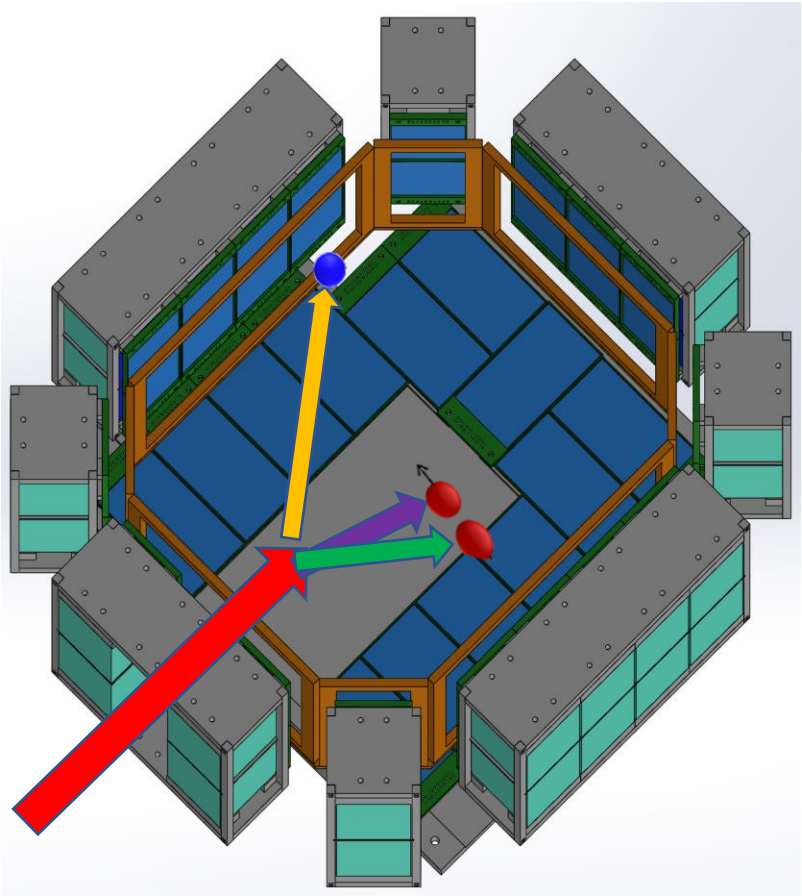


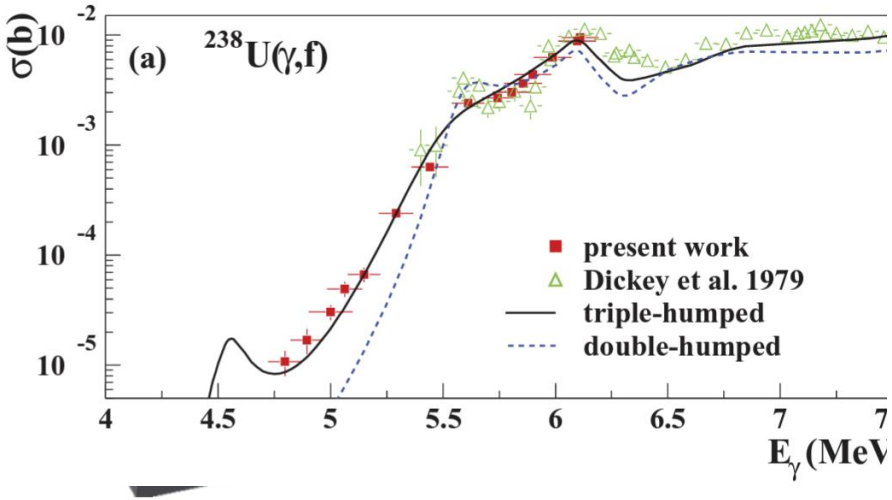


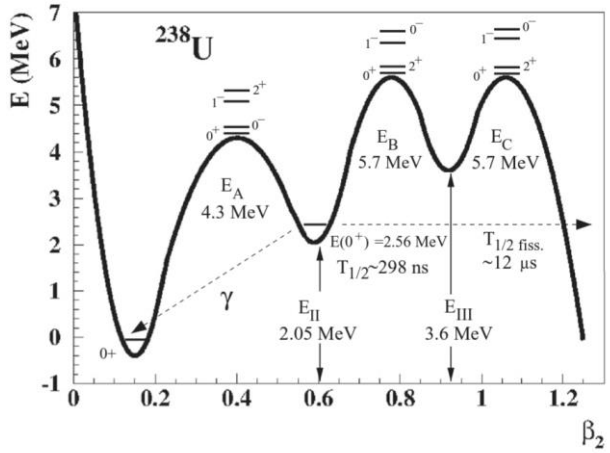


- Full charged particle reconstruction!
- Fission cross section (or survival probability of multi-nucleon transfer reaction)
- Fission barrier measurement for exotic fission systems in actinides

Possible setup:
Fission barrier study







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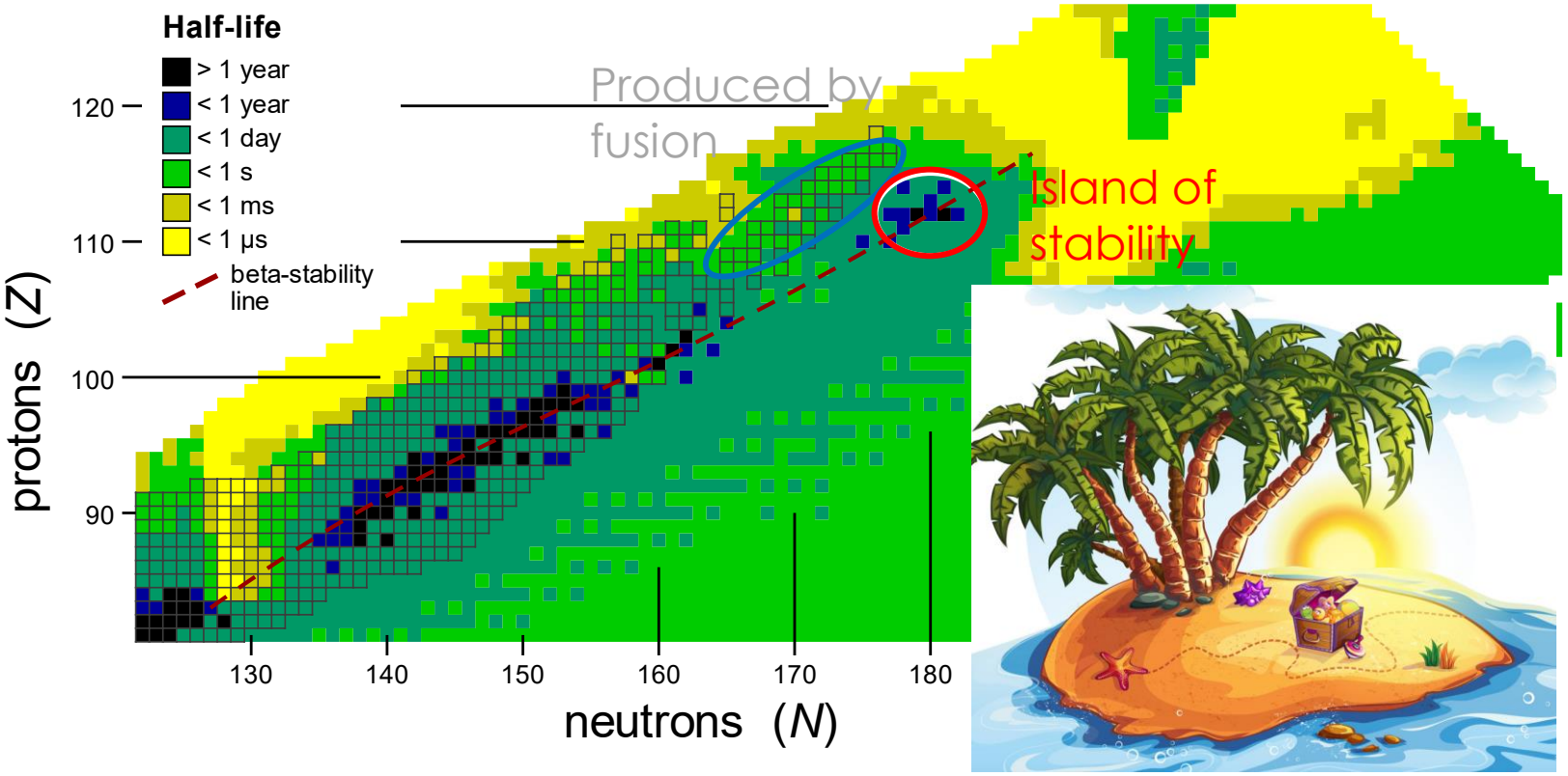
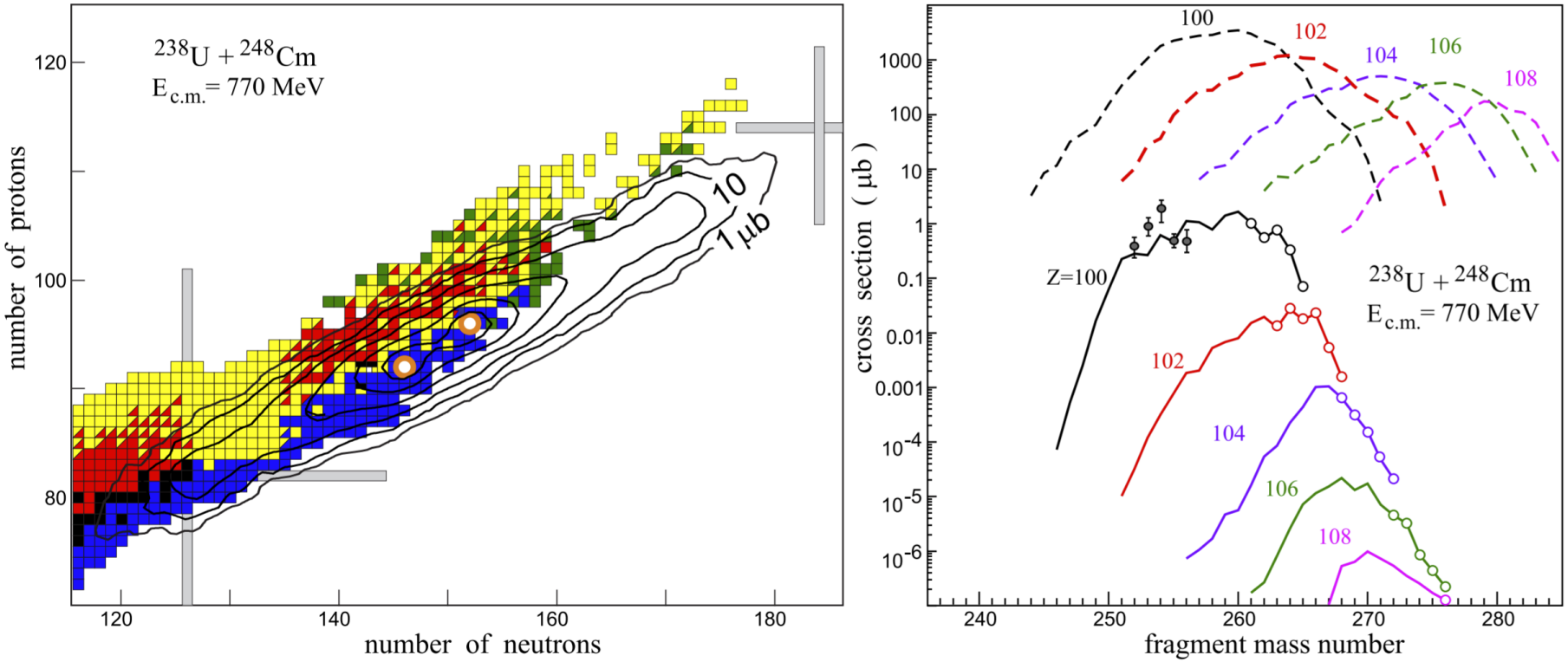
Neutron-rich super heavy isotope



- Fusion: Super-heavy with n-deficint (short T1/2), low cross section (~pb,fb)
- Difficult to reach predicted Island of stability….

V. Zagrebaev, A. Kapov and W. Greiner
J. Phys: Conference Series 420 (2013) 012001

Possibility to use MNT for production of super heavy nuclei



V. Zagrebaev, A. Kapov and W. Greiner
EPJ: Web of conferences 86 00066 (2015)

- Orders of magnitude larger cross section is expected
- N-rich can be expected.

Summary

- Fission process is still exciting field of study even after 80 years of discovery

- New features of fission are observed due to
  - Exclusive and sophisticated measurements
  - More exotic fission systems

  Providing deeper understanding of fission phenomena across the nuclear chart

- Competitive fission experiments at RAON are possible in the future
  - NDPS: fission dynamics study
  - KoBRA/low energy beamline: fission barrier study with active target TPC