Fission isomer studies with the FRS

- Introduction
- Experiment
- Preliminary results
- Summary

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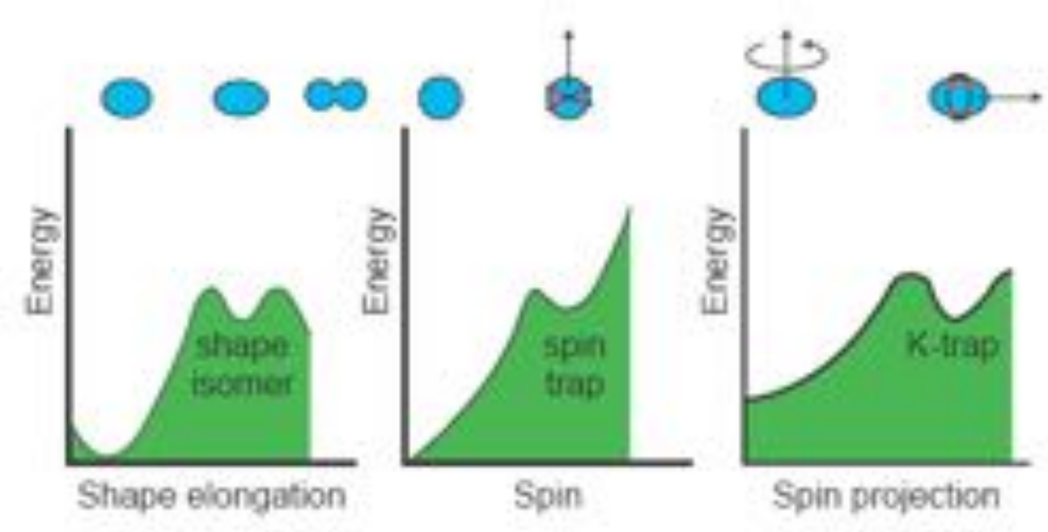
Nuclear isomers: excited, metastable states of atomic nuclei.
decay by emission of α , β , γ, p, fission, cluster.

- **1917**: (different in stability and mode of breaking up) predicted by Soddy.
- **1921**: Hahn found the first isomeric state (UX_2) ^{234m}Pa.
- **1934:** the name "isomeric" first referred by Gamow.
- **1936**: explained by von Weizsäcker in terms of spin (i.e. angular momentum).

F. Soddy, Nature **99** (1917) 433.
O. Hahn, Chem. Ber. **54** (1921) 1131.
G. Gamow, Phys. Rev. **45** (1934) 728.
von Weizsäcker, Naturewiss. **24** (1936) 813.



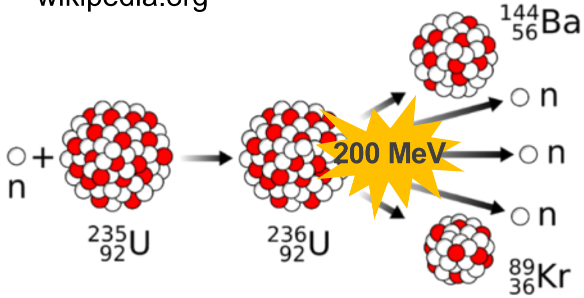
Three types of isomers

P. Walker and G. Dracoulis, Nature **399** (1999) 35.
P. Walker and Z. Podolyák, Phys. Scr. **95** (2020) 044004.

Introduction: nuclear fission

Fission: the nucleus of an atom splits into two or more smaller, lighter nuclei.

wikipedia.org



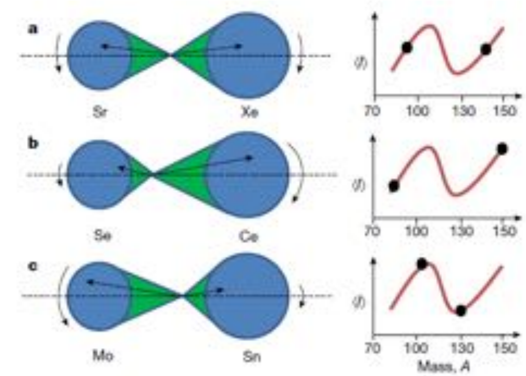


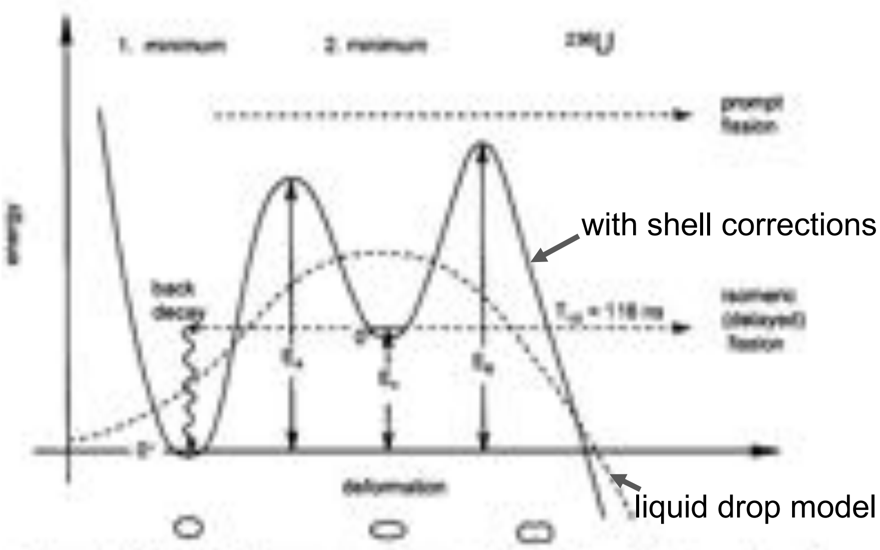
Fig. 3 | Schematic diagram of post-scission angular momentum generation.

J. N. Wilson, et al., Nature **590** (2021) 566.

- **1934**: Fermi and his colleagues irradiated uranium with neutrons
  → new elements with 93 and 94 protons?
- **1939**: Hahn and Strassmann confirmed Ba produced from uranium fission.
- **1939:** Meitner and Frisch explained this “fission” with the liquid drop splitting, predicted the 200MeV energy releasing.
- **1962:** Polikanov et al. found isomeric fission from ^{242m2}Am.
- **2021**: fission fragments angular momentum generation, fission dynamics?

E. Fermi, et al., Proc. Roy. Soc., A, **146** (1934) 483.
O. Hahn and F. Strassmann, Naturwiss, **26** (1938) 756.
O. Hahn and F. Strassmann, Naturwiss. **27** (1939) 89.
L. Meitner and O. R. Frisch, Nature **143** (1939) 239.
G.N. Flerov and S. M. Polikanov C. R. Cong. Int. Phys. Nucl. 1 (1964) 407.
G. Herrmann, Nucl. Phys. A **502** (1989) 141.

Fission isomers: excited nuclear states decay by spontaneous fission.



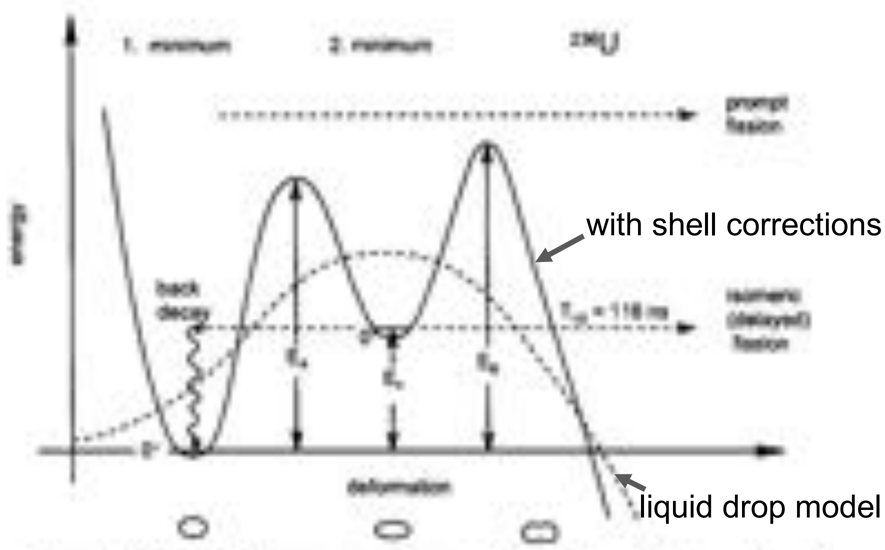
P. Thirolf, D. Habs, *Prog. Part. Nucl. Phys.* **49**, 325–402 (2002).
H. J. Specht, et al. , *Phys. Lett. B*. **41**, 43–46 (1972).

(Superdeformed) second minimum in potential energy surface appears in actinides → fission isomers

Ideal testing ground for strongly deformed low-spin nuclei and shell corrections in very heavy systems

Introduction: fission isomers

Fission isomers: excited nuclear states decay by spontaneous fission.



P. Thirolf, D. Habs, *Prog. Part. Nucl. Phys.* **49**, 325–402 (2002).

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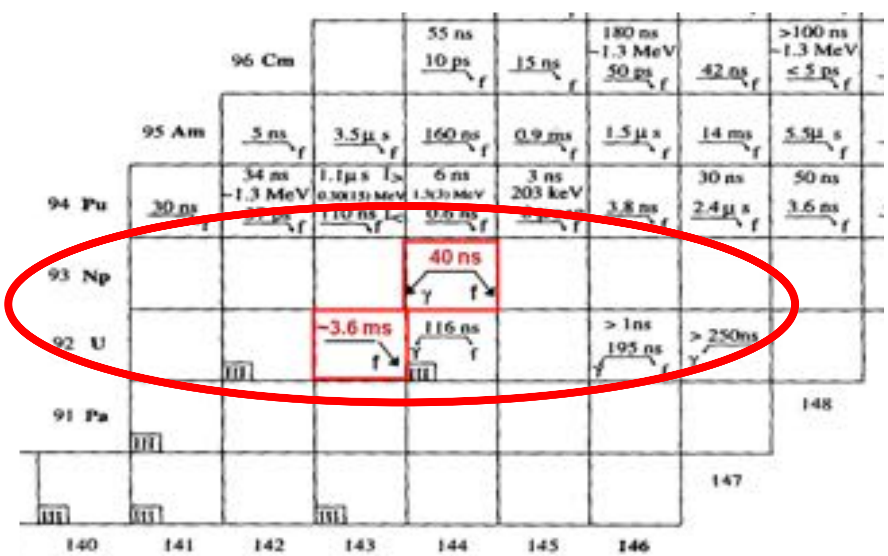
(Superdeformed) second minimum in potential energy surface appears in actinides → fission isomers

Ideal testing ground for strongly deformed low-spin nuclei and shell corrections in very heavy systems

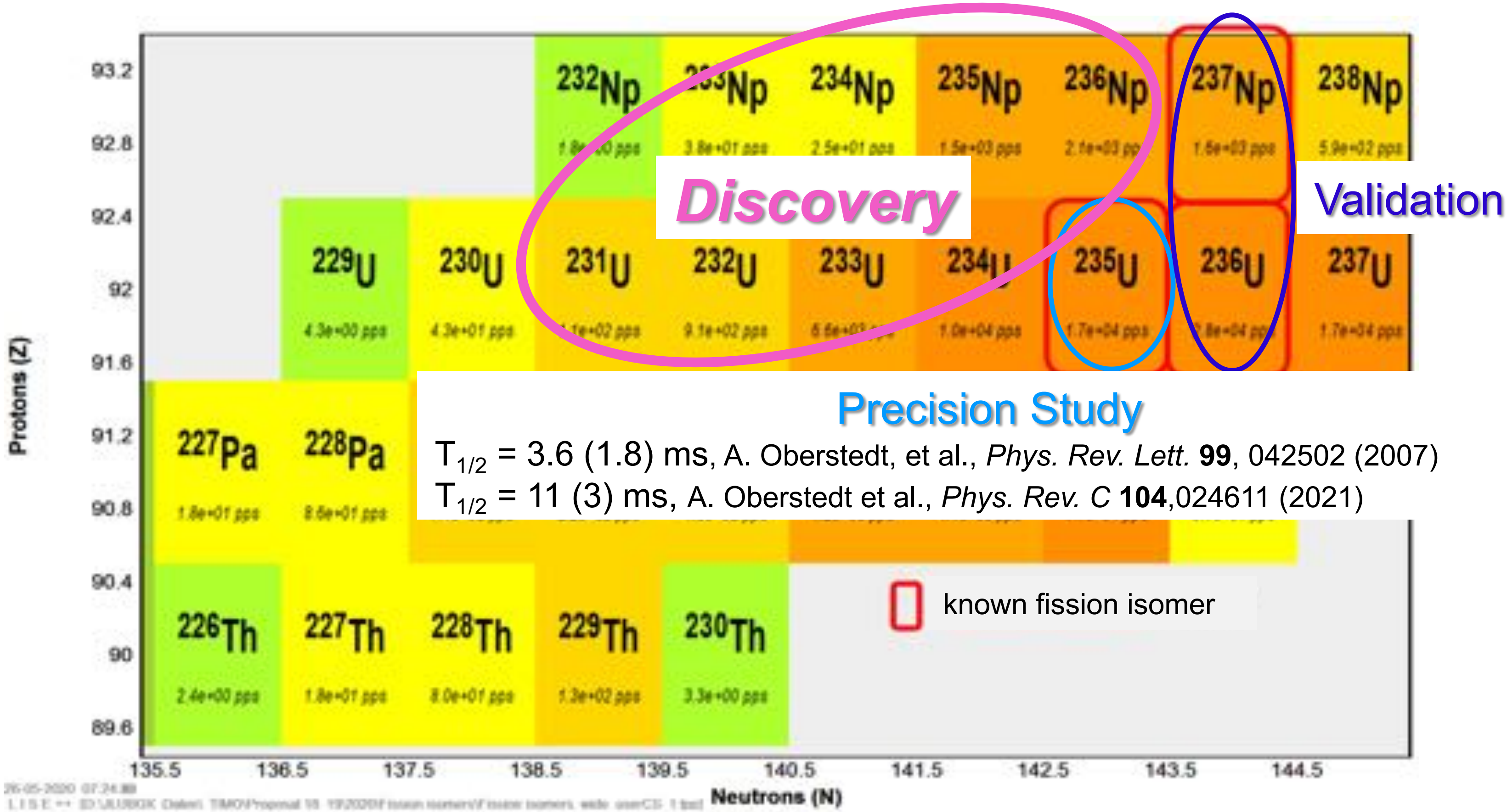


Studies in the past by n, p, d, α-induced reactions;

Disadvantages:

- Huge prompt fission background
- Low excitation energy and population probability (~ μbarn)
- Challenging to get targets to study U and Np

Fission isomer studies with the FRS

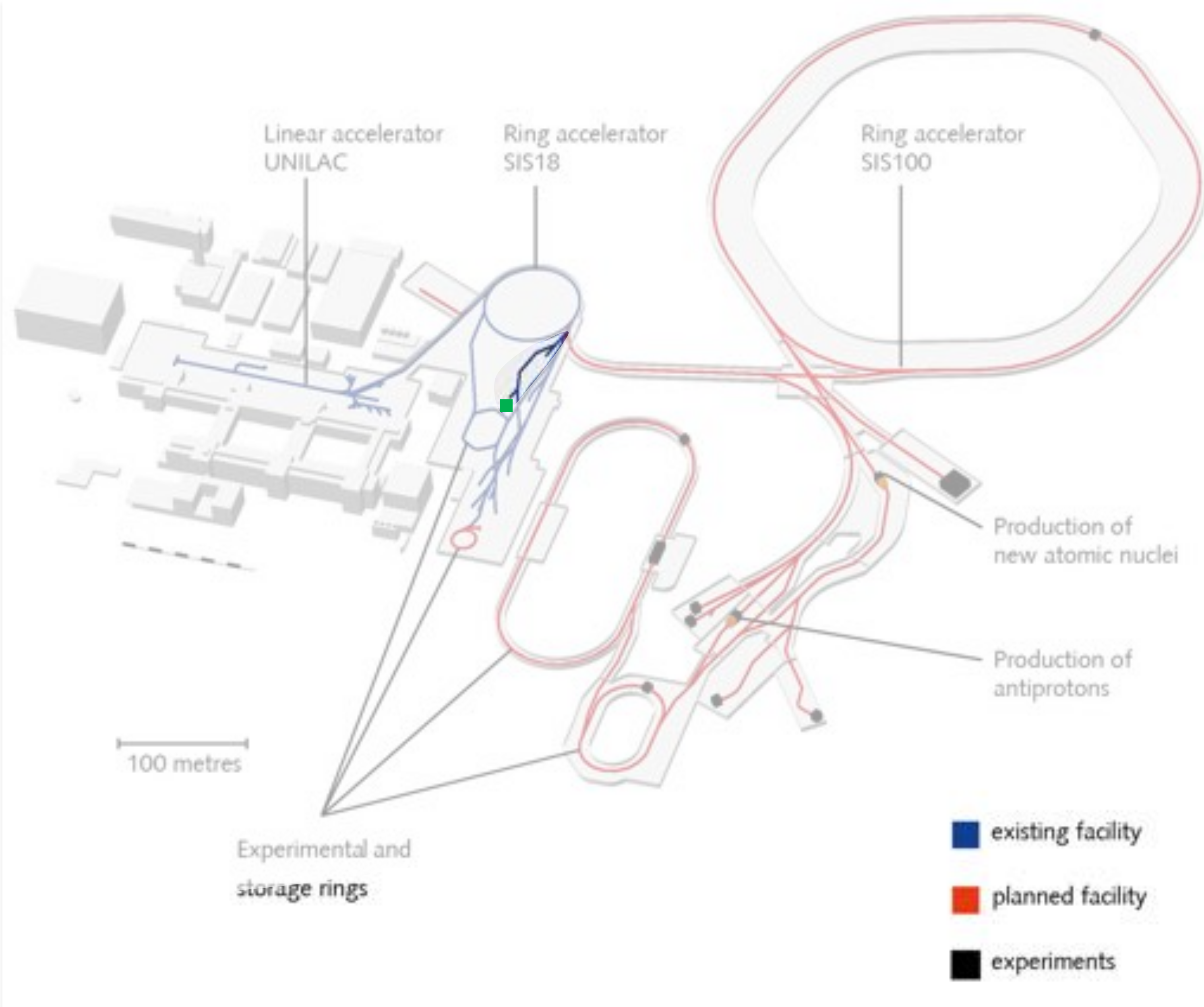


$T_{1/2}$ = 3.6 (1.8) ms, A. Oberstedt, et al., *Phys. Rev. Lett.* **99**, 042502 (2007)

$T_{1/2}$ = 11 (3) ms, A. Oberstedt et al., *Phys. Rev. C* **104**,024611 (2021)

- Isomers population via ^{238}U fragmentation→ high population probability?
- Fast production and separation (~280ns) → isomers with ns half-lives
- Event-by-event identification → background suppression
- ^{235f}U, U and Np isotopes that are so far not well studied

FRS at GSI

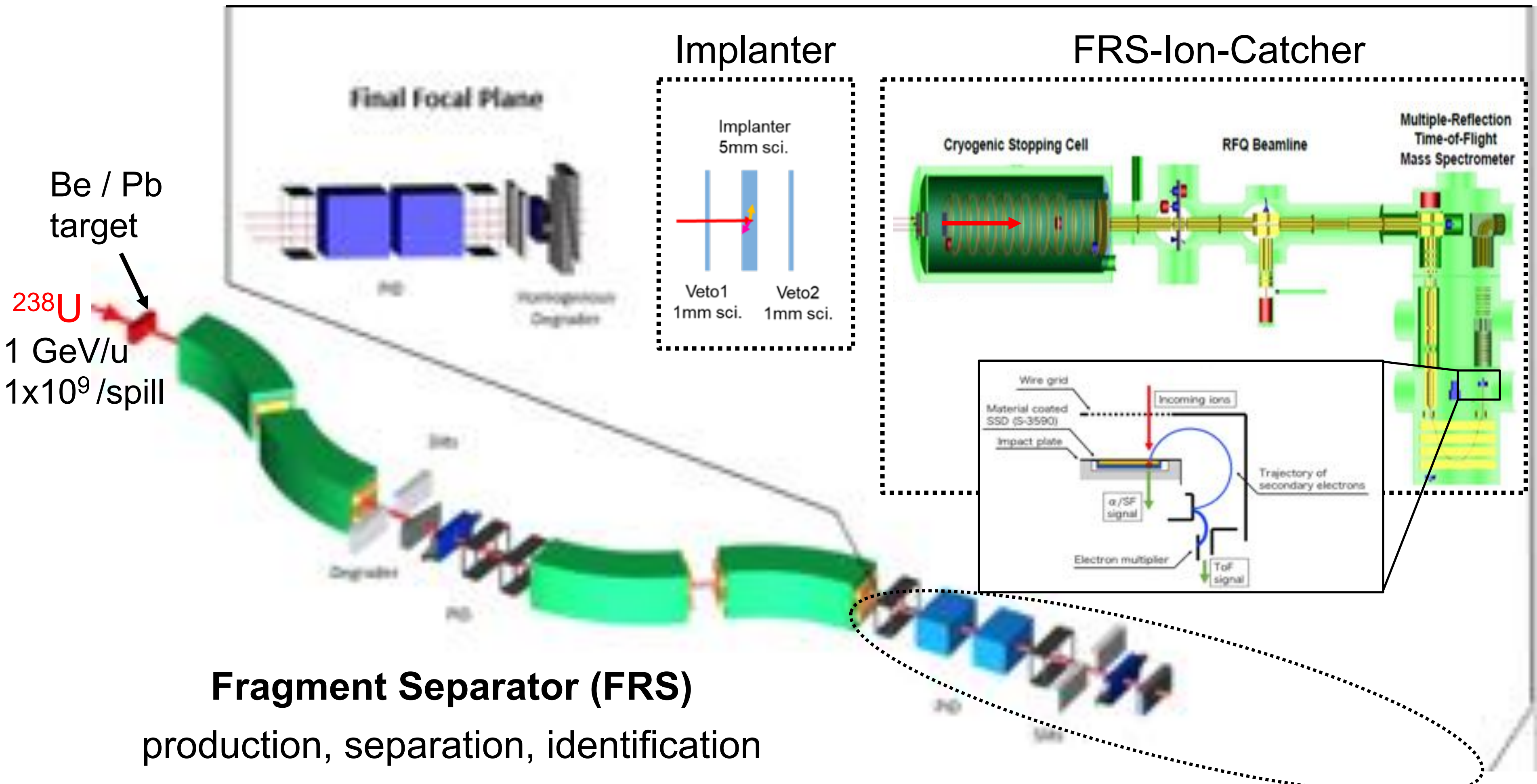


Linear accelerator
UNILAC
Ring accelerator
SIS18
Ring accelerator
SIS100
Production of
new atomic nuclei
Production of
antiprotons
100 metres
Experimental and
storage rings
existing facility
planned facility
experiments

Experiment: FRS at GSI

Ions of interest (e.g., $^{235,\,235f}U$)

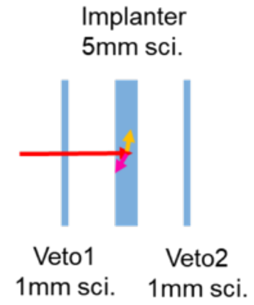
- Produced via ^{238}U fragmentation
- Stopped in the detectors (in the Implanter or FRS-Ion-Catcher)



Detector system

Fast SCI

- ns to μs half-lives (e.g., ^{236f}U)
- Background suppression
  → by event-by-event particle identification
  → by position correlation
- Rate capability: MHz



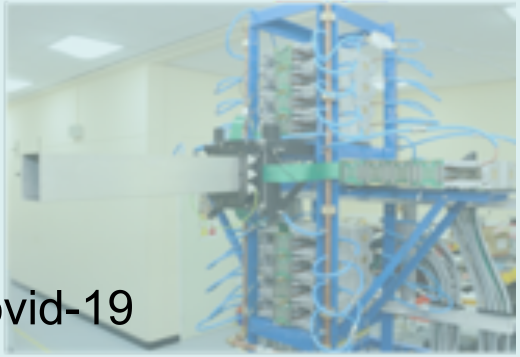
Implanter:
70x70x5 mm^3
plastic scintillator

AIDA

- Implantation correlated (in-time and spatially) to the FRS-PID
- background-free, because the fission order of mag. higher signals
- rate capability: kHz
- μs to ms half-lives

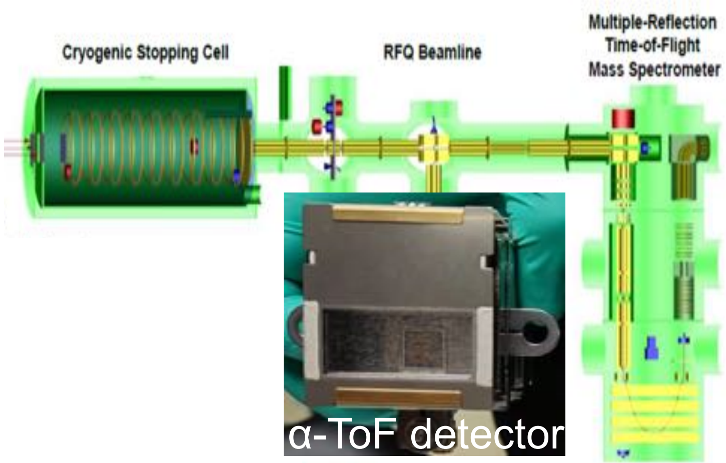
X

due to the Covid-19



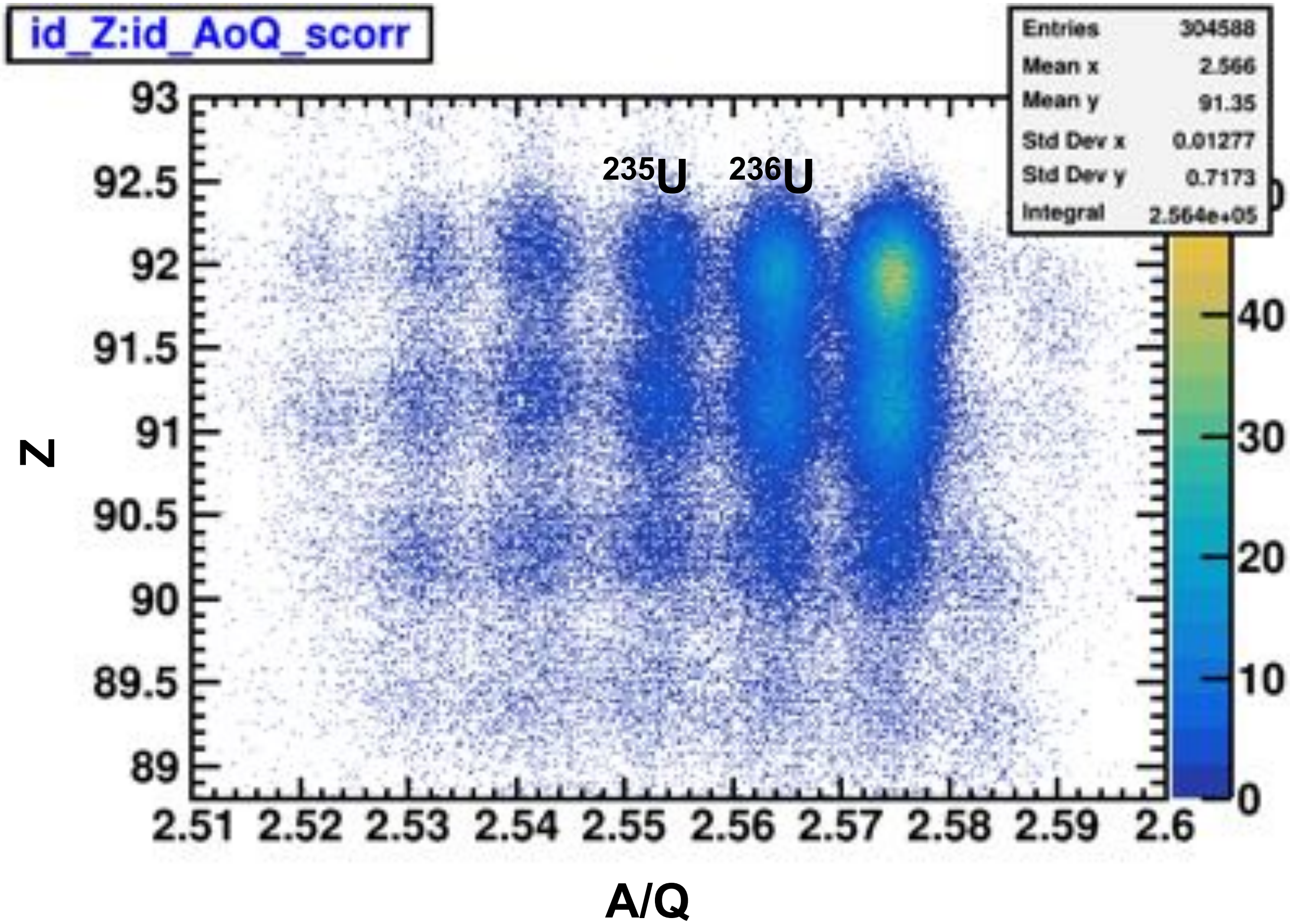
Ion Catcher

- ms and longer half-lives (e.g., ^{235f}U)
- Measurement time ~10 ms
  → shorter DC-cage for faster extraction
  → MR-TOF-MS running with 200Hz
- Background suppression
  → α-ToF detector (mass & decay)
- Rate capability: 0.1 MHz



T. Niwase et al., NIM. A 953, 163198 (2020)

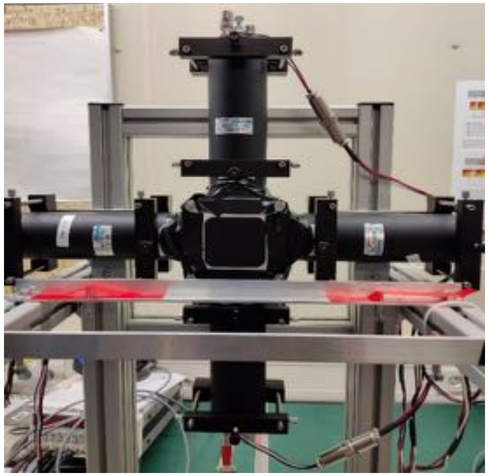
Data analysis: particle identification



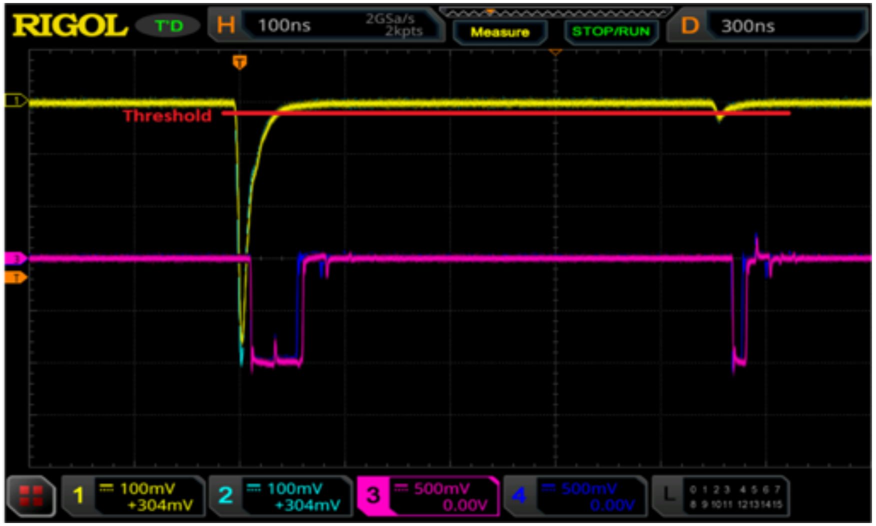
- Ions of interested can be clearly identified

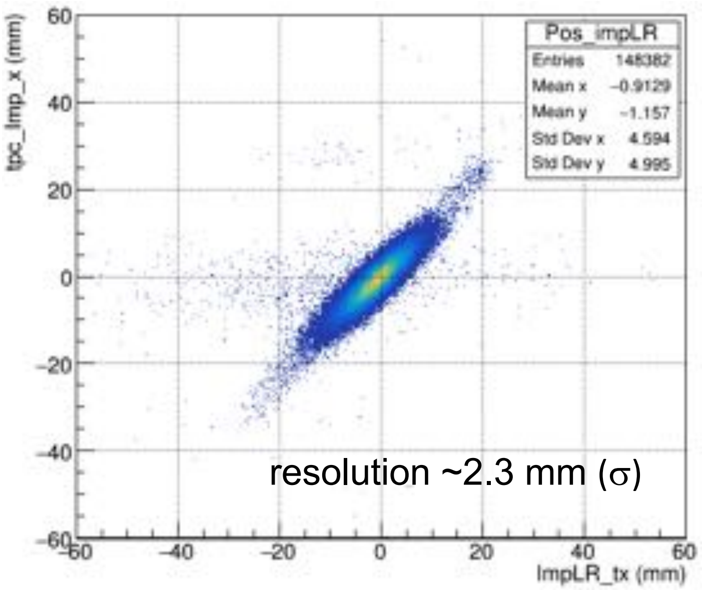
Implanter

5mm^t plastic sci. readout by 4 PMTs



Time-over-threshold, pulser signals!



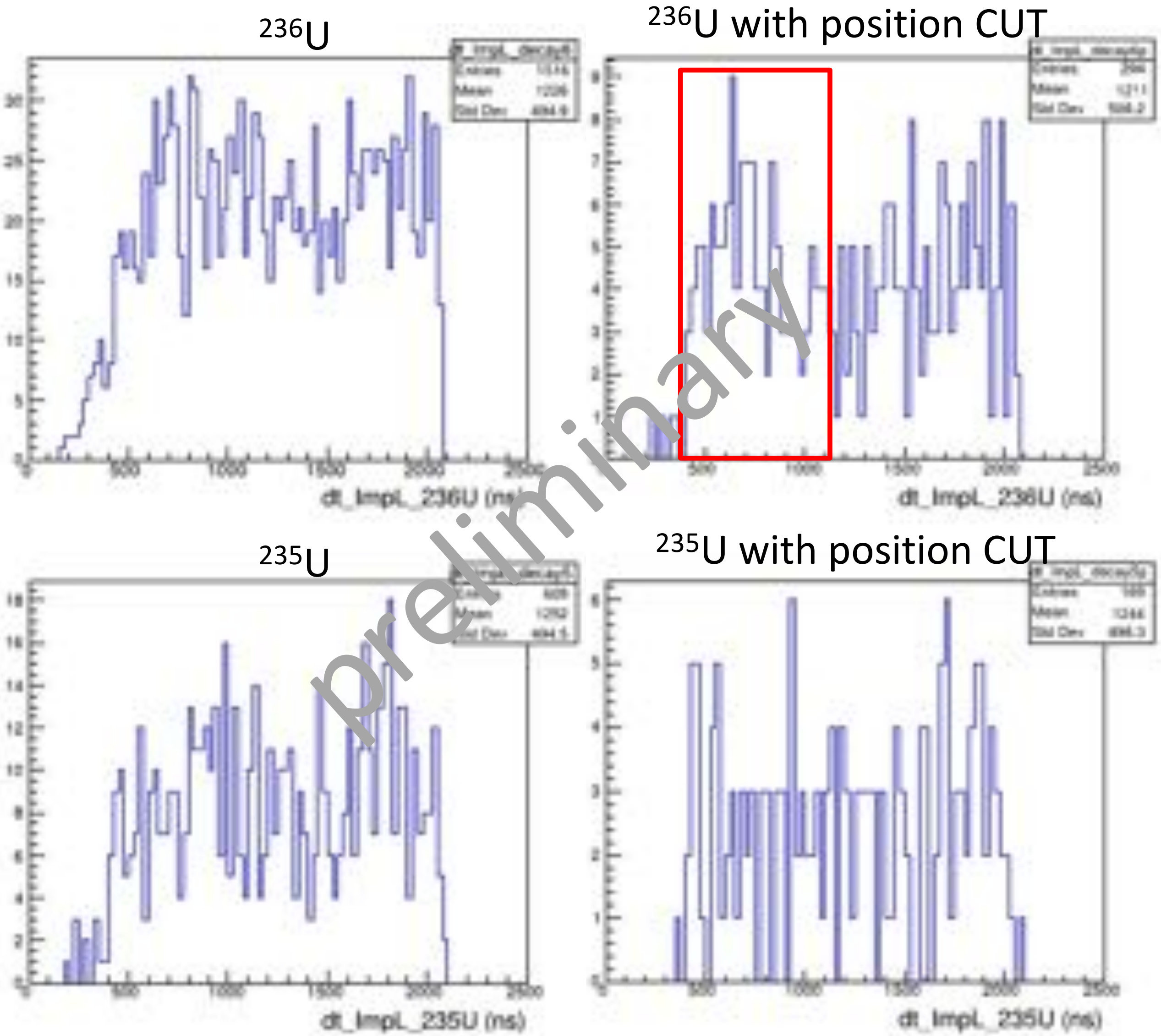


- Detect implantation and fission decay with time-over-threshold: ΔE -> ΔT .
- Background suppression by the position (e.g., t_L - t_R) correlation

Implanter: first glance of dt

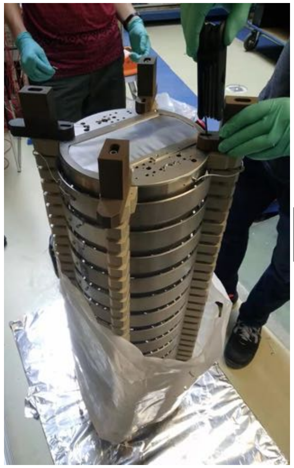
- ^{236}U $T_{1/2}$ ~ 100 ns
- ^{235}U $T_{1/2}$ ~ 10 ms

  background like



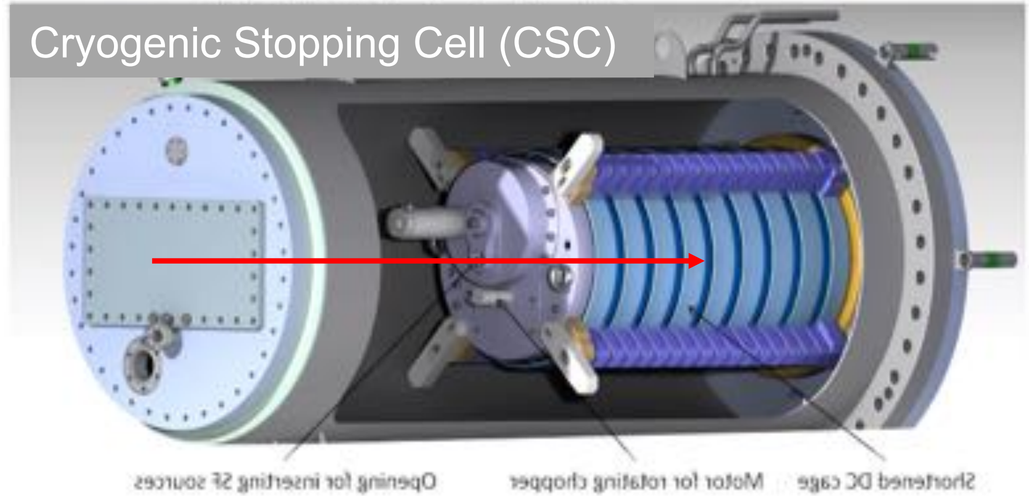
- Time difference (dt) between fission decay and Implantation.

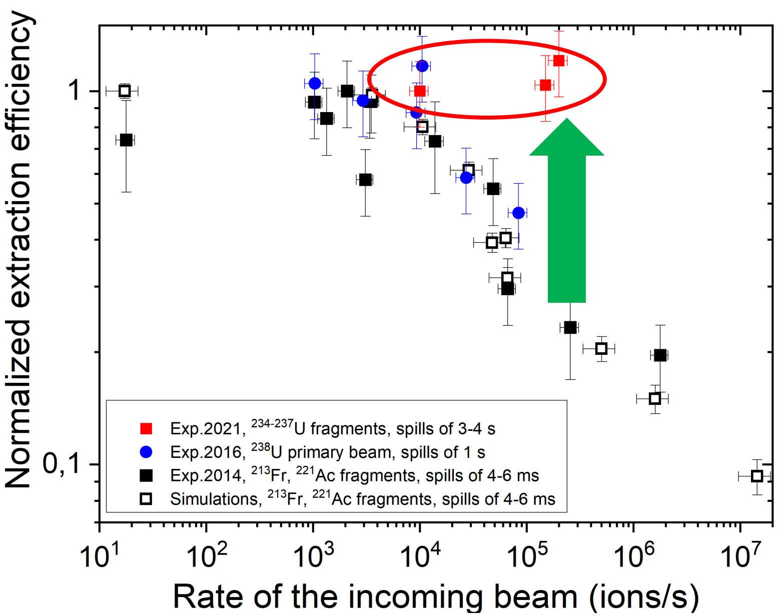
FRS-Ion-Catcher



Long cage ~100cm

Short cage~50cm





High rate record for efficient data taking:

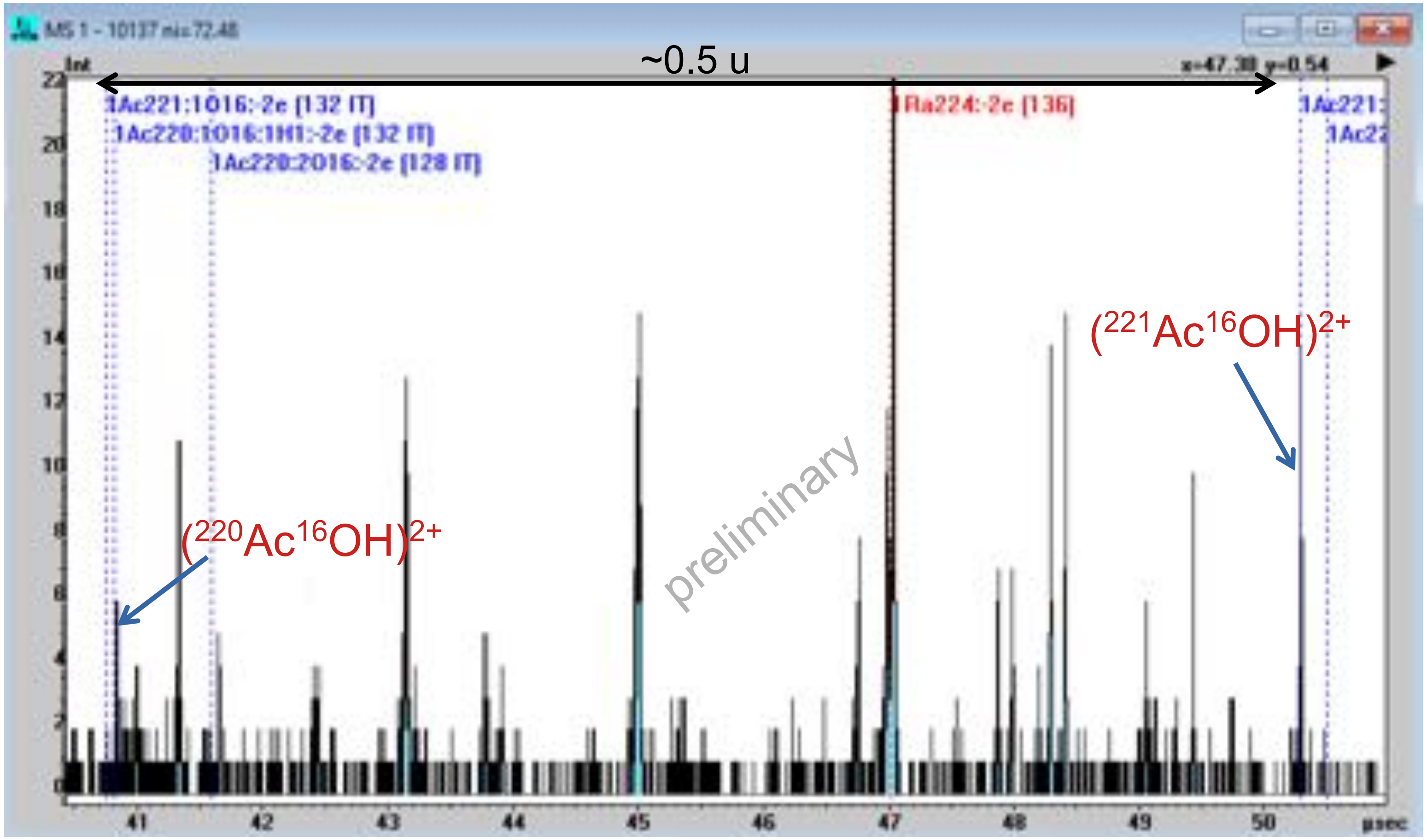
- Shorter DC-cage (100 cm -> 50 cm), less loss due to space charge.
- High extraction efficiency with $2x10^5$ ion/s with spill length of 3-4 s.

- Short extraction time ~10ms, access short lived isomers
- MR-TOF-MS ran with 200Hz to deal with short half-lives and high rate

M.P. Reiter et al. NIM B 376 (2016) 240, I. Miskun, PhD thesis, JLU Giessen (2019)

FRS-Ion-Catcher: mass (ToF) spectrum

With $^{220,221}Ac$ stopped in the CSC:

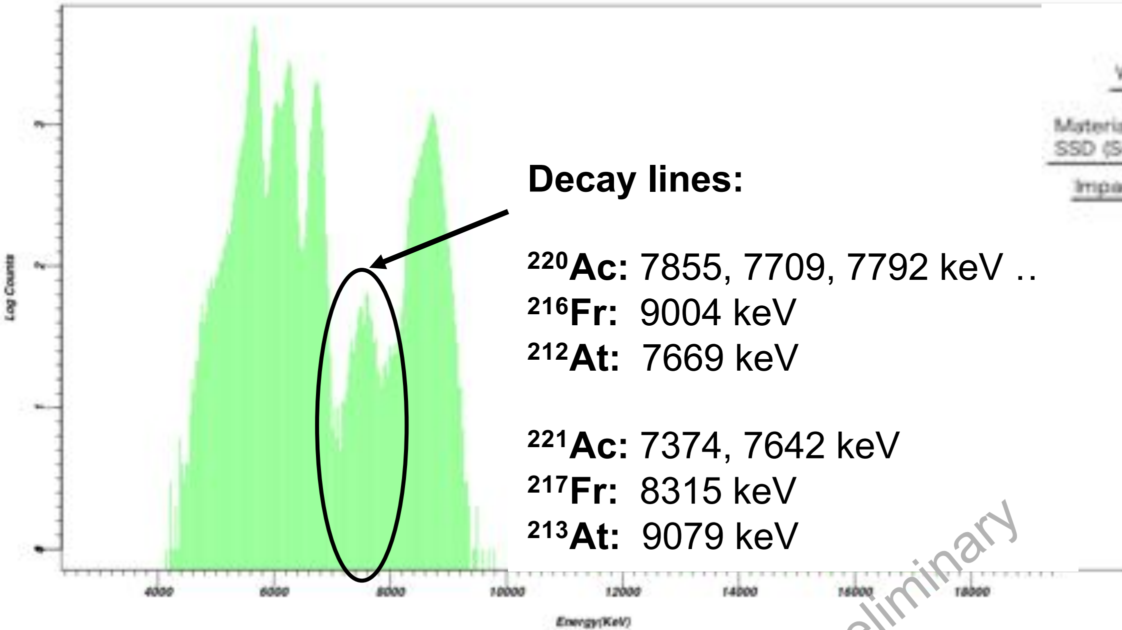


Time of Flight

- Resolving power of >100k with the measurement time ~5 ms
- Direct mass measurement of short-lived fission isomers (e.g., ^{235f}U, Ex ~2.4 MeV)

FRS-Ion-Catcher: energy spectrum

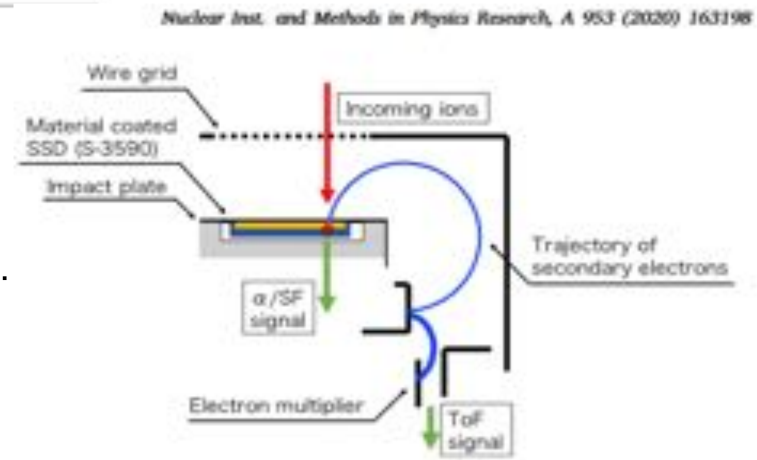
With ^{220,221}Ac stopped in the CSC:



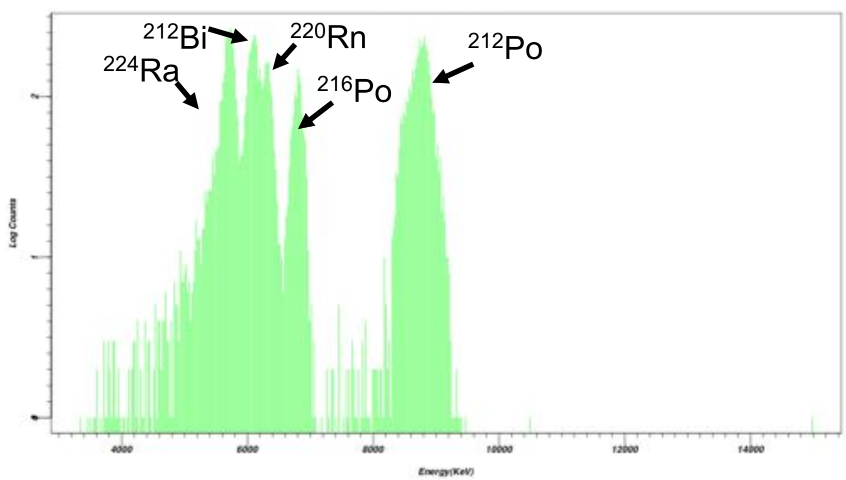
Decay lines:

^{220}**Ac:** 7855, 7709, 7792 keV ..
^{216}**Fr:** 9004 keV
^{212}**At:** 7669 keV

^{221}**Ac:** 7374, 7642 keV
^{217}**Fr:** 8315 keV
^{213}**At:** 9079 keV

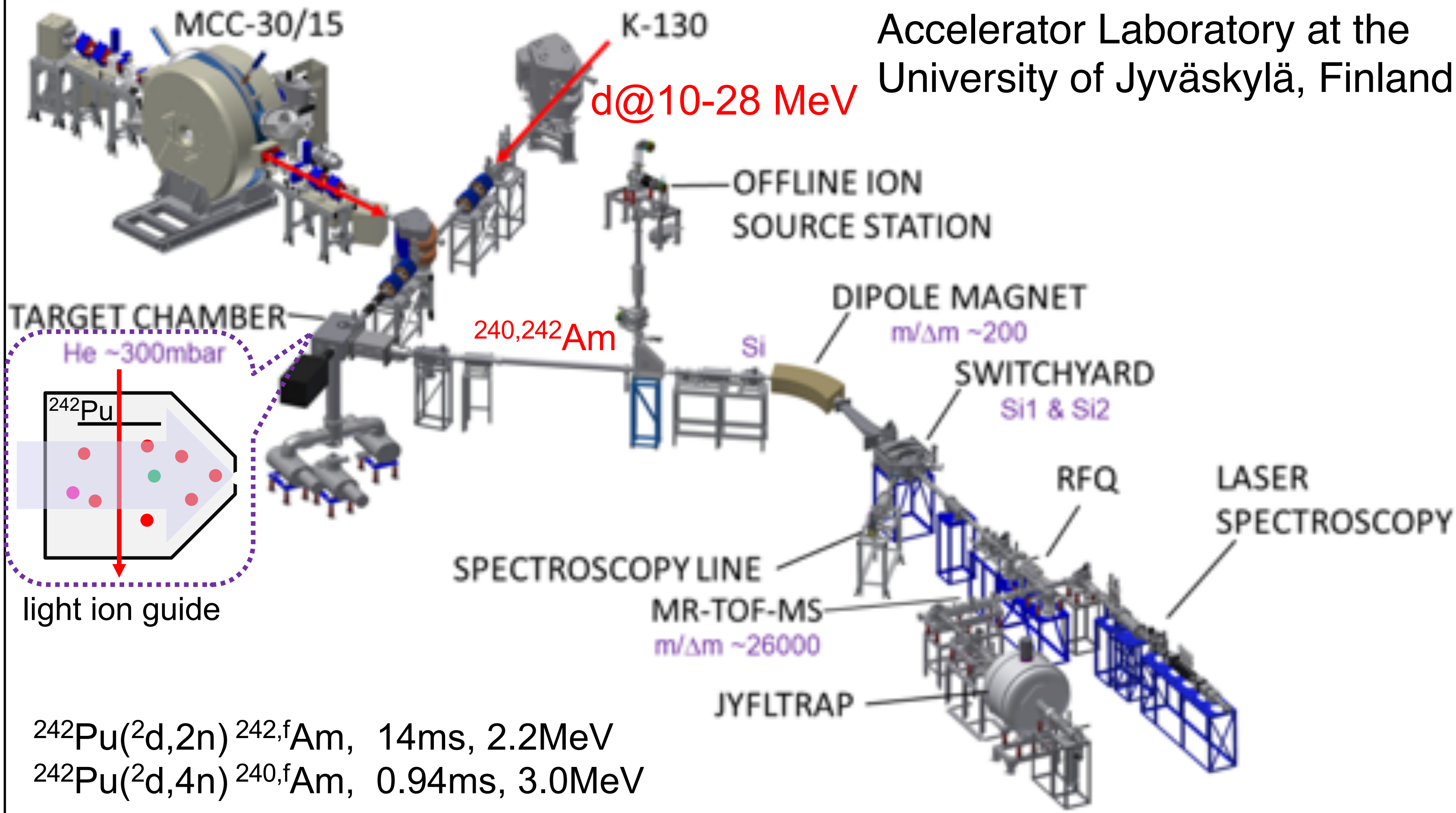


Background



- Decay measurement works well
- Next is to correlate the mass and decay measurements
- Analyze the ^{235}U data

Fission isomers ^{240f,242f}Am study at JYFL



Accelerator Laboratory at the University of Jyväskylä, Finland

^{242}Pu(^{2}d,2n) ^{242,f}Am, 14ms, 2.2MeV
^{242}Pu(^{2}d,4n) ^{240,f}Am, 0.94ms, 3.0MeV

Obtain fission barrier properties from:

- Yield vs. Energy
- Excitation energy of the fission isomer states
- Isomer-to-ground state ratio

Summary

- Populating U and Np fission isomers via ^{238}U fragmentation
- Search for fission isomers with ns – ms half-lives
- Fast plastic scintillator based implantation detector
- FRS-Ion-Catcher with new developments

  CSC with shorter DC-cage allows fast extraction, high rate

  MR-TOF-MS running with 200Hz handles high rate

  α-ToF allows correlated mass and decay measurements
- Data analysis is on going
- $^{240,242}Am$ fission isomers studies at JYFL are planned

Acknowledgements

Spokesperson: T. Dickel[1,2] , Co-Spokespersons: M. P. Reiter[3], P. G. Thirolf[4], M. Wada[5]

A. Al-Adili[6], D. Amanbayev[2], S. Ayet[1], S. Bagchi[1], D. Balabanski[7], S. Beck[2], T. Cap[8], P. Constantin[7], L. Csige[9], D. Curien[10], O. Charviakova[8], T. Davinson[3], I. Dedes[11], F. Didierjean[10], G. Duchene[10], J. Dudek[10], H. Geissel[1,2], J. Gerl[1], T. Grahn[12,13], M. Gorska[1], M. Gupta[14], E. Haettner[1], O. Hall[3], M. Harakeh[15], C. Hornung[2], J.-P. Hucka[16], P. Jachimowicz[17], A. Kankainen[12], N. Kalantar-Nayestanaki[15], M. Kowal[8], A. Krasznahorkay[9], G. Kripko-Koncz[2], N. Kuzminzuk[1], M. Lantz[6], S. Lalkovski[18], I. Mardor[19,20], V. Metag[2], N. Minkov[21], I. Miskun[2], I. Moore[12,13], G. Münzenberg[1], A. Oberstedt[7], S. Oberstedt[22], Z. Patyk[8], S. Pietri[1], I. Pohjalainen[12], S. Pomp[6], W. R. Plaß[1,2], S. Purushothaman[1], C. Scheidenberger[1,2], P. Schury[5], J. Skalski[8], A. Solders[6], Y. Tanaka[1,23], M. Vencelj[24], H. Weick[2], P. Woods[3], J. Zhao[1,25] and the Super-FRS Experiment Collaboration

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Thanks for your attention!