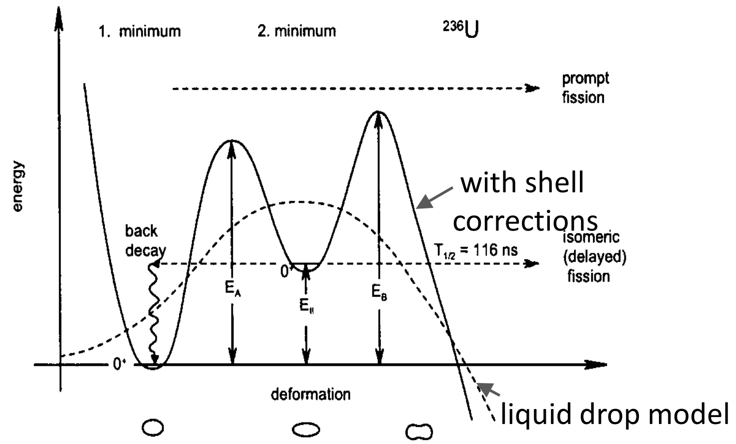
FAIR — Facility for Antiproton and Ion Research in Europe

Fission isomer studies at FRS/GSI and IGISOL/JYFL-ACCLAB

Timo Dickel, Jianwei Zhao

Amorim, B., Bagchi, S., Charviakova, V., Kar, D., Narang, M., Oberstedt, A., Oberstedt, S., Patyk, Z., Tortorelli, N., Thirolf, P.

Fission isomers: excited metastable nuclear states decay by spontaneous fission.



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

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

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

Difficulties:

- Huge prompt background
- Low population probability (~ µbarn)
- Challenging to get targets to study U and Np
- Direct excitation energy measurement needs gamma back decay

Solutions that we explore

→ Spatially separating productions and detection

→ Exploring new production methods

→ Measuring excitation energy directly by mass spectrometry

Fission Isomer at FRS / in-flight separator

- Population by three new production schemes: fragmentation, electromagnetic dissociation, charge-exchange reactions
  → high production cross-section ?
- Fast production and separation (~300ns → 150 ns due Lorentz factor)
  → access to isomers with ns half-lives
- High beam purity and event-by-event identification
- No direct prompt fission background, due to spatial separation of production and detection
- Production of U and Np isotopes that are so far not well studied

background-free precision studies of previously known cases

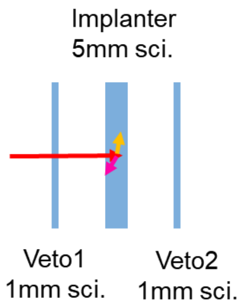
&

Discovery of new fission isomers

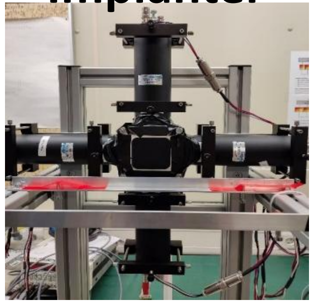
Detector system for first proposal

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



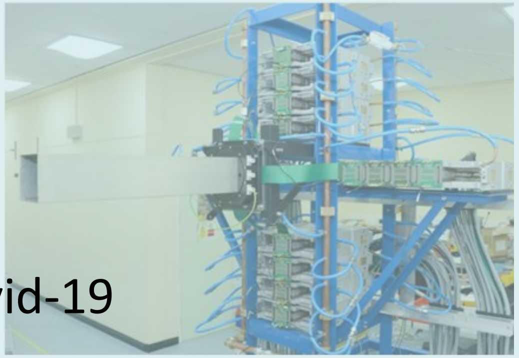
Implanter



AIDA

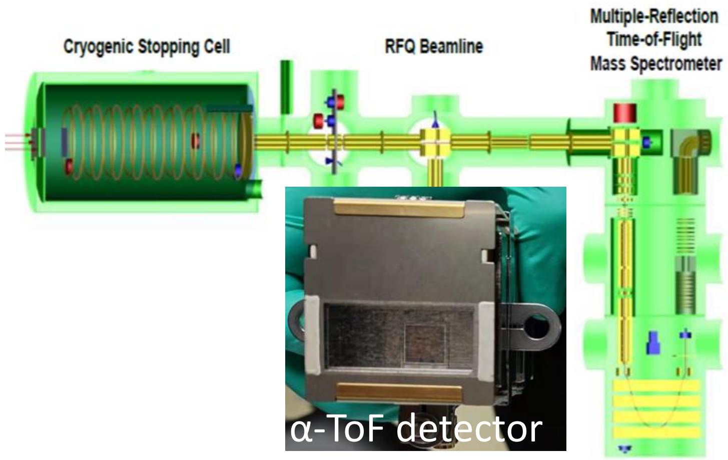
- Implantation correlated (in-time and spatially) to the FRS-PID
- background-free, because the fission order of mag. higher signals
- rate capability: kHz
- µs to ms half-lives

X due to the Covid-19



FRS Ion Catcher

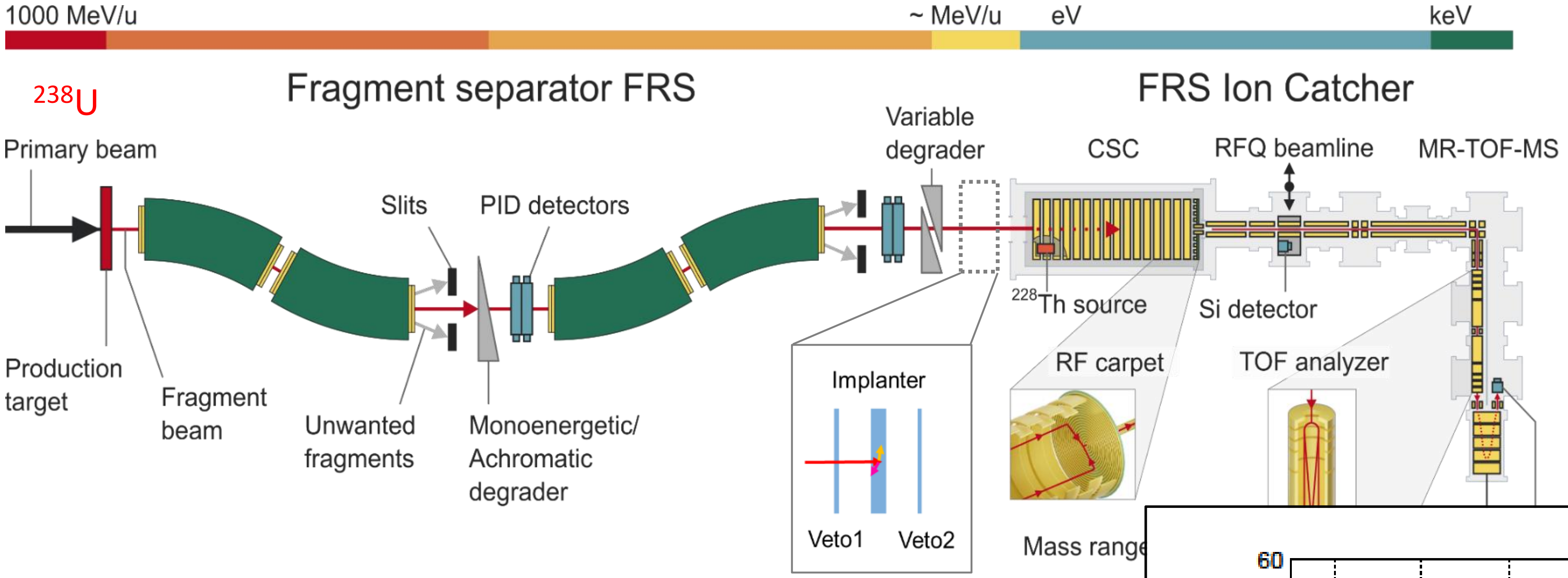
- ms and longer half-lives (e.g., ^{235f}U)
- Measurement time ~10 ms
  → shorter DC-cage for faster extraction
  → MR-TOF-MS running with 200Hz
- Background suppression
  → α-ToF detector (mass & decay)
- Rate capability: 0.1 MHz



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

Fission isomer studies at FRS, GSI

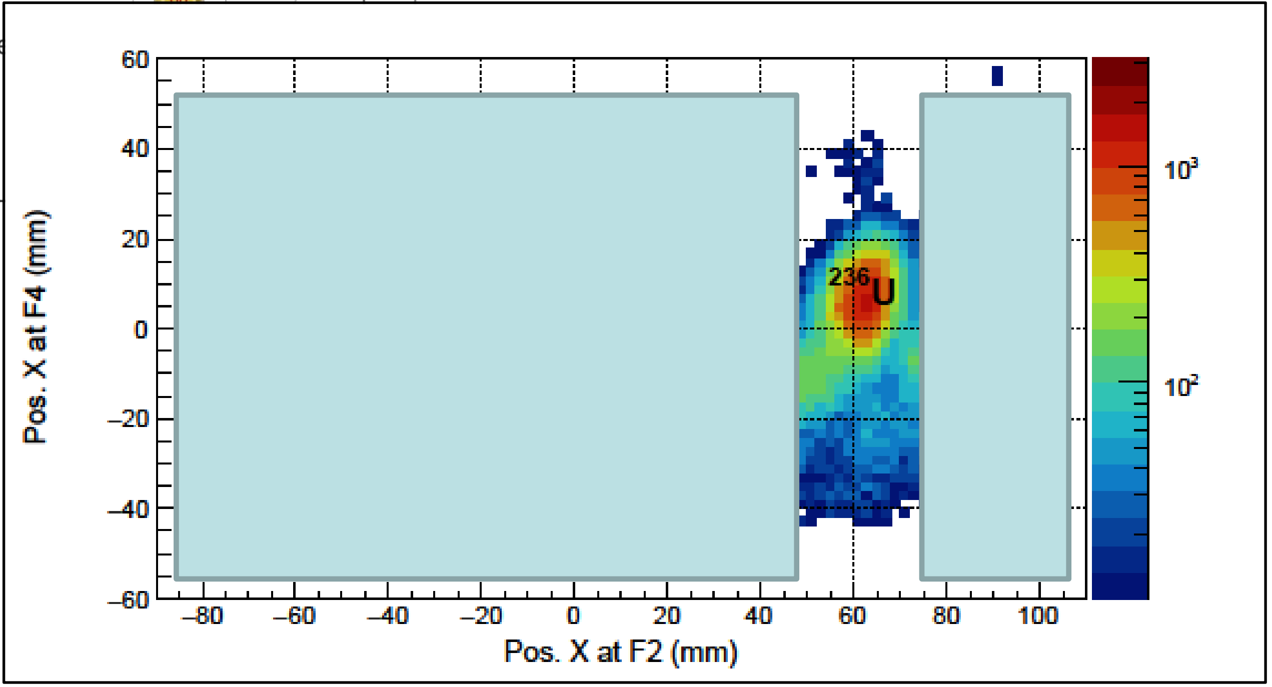
Nazarena Tortorelli, PhD thesis, LMU
J. Zhao et al. PoS 419 (FAIRness2022) 063



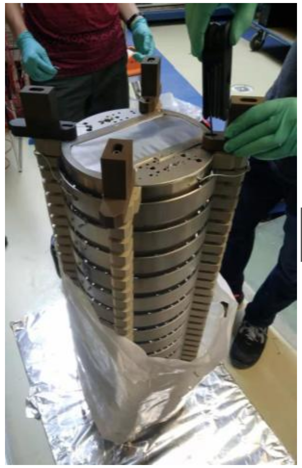
production, separation, identification

Lessons learned:

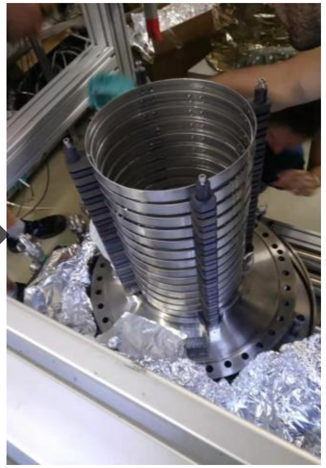
- High intensity (10^5 ^{236}U per sec) can be produced and separated for both production methods
- Half of the FRS is sufficient for this
  → Future experiments at the mid focal plane, with shorter TOF and higher rate



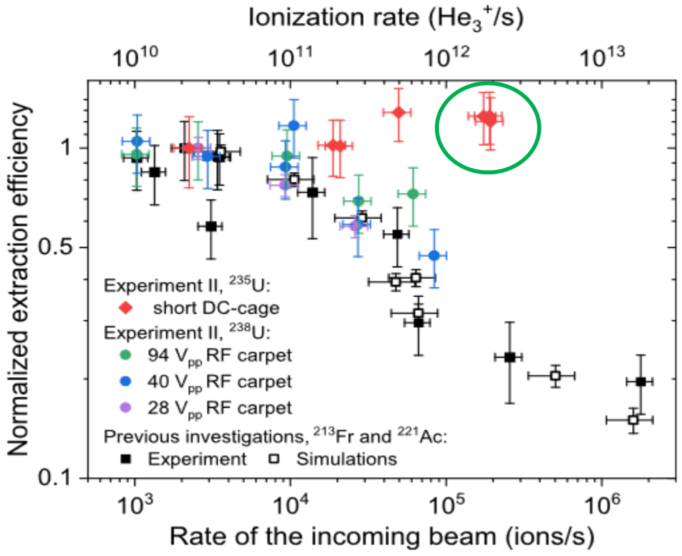
FRS Ion Catcher (^{235}U)



Long cage ~100 cm



Short cage ~50 cm



J. Zhao et al. NIM B 574 (2014) 165175.
N. Tortorelli, PhD thesis, LMU, 2024.

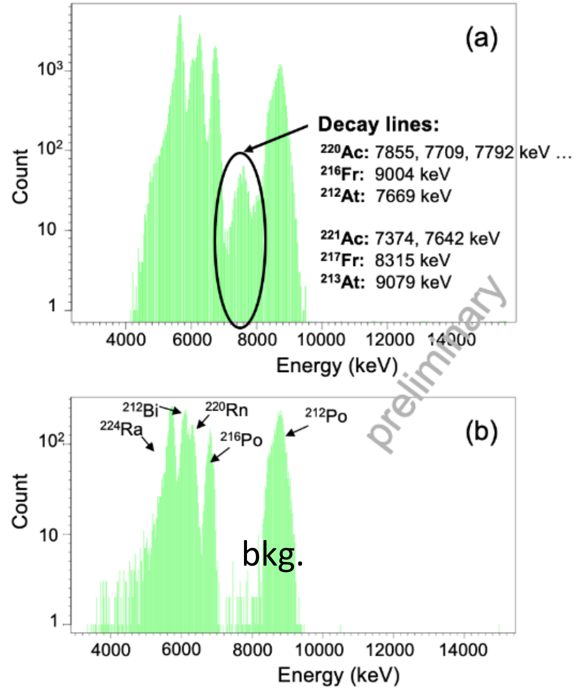
Technical achievement: CSC rate capability

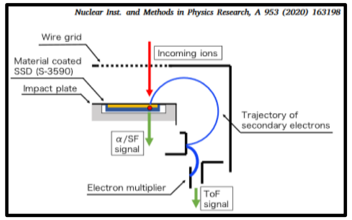
- Shorter DC-cage (100 cm → 50 cm), less loss due to space charge.
- High extraction efficiency with 2×10^5 ion/s with spill length of 3-4 s.

Result analysis: from α-TOF detector

- Feasible: ^{219}Ra ($t_{1/2}$~10ms) decay lines are seen
- 2 x 10^5 ^{235}U detected
- Further analysis is challenging.

COVID → expert from Japan could not travel

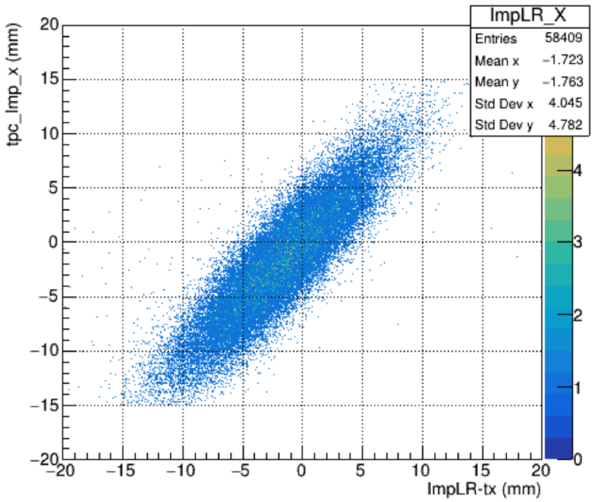




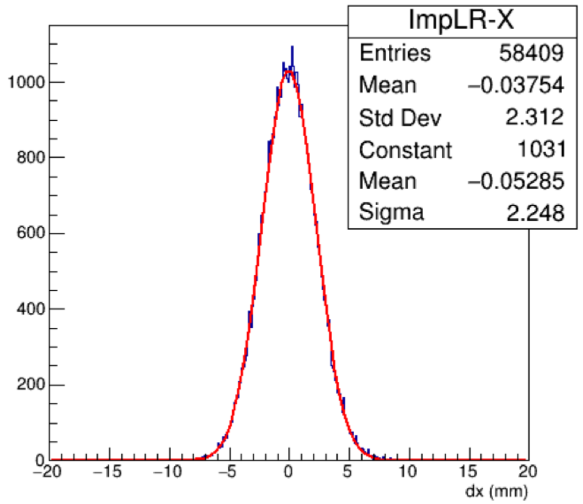
T. Niwase et al., NIM. A 953, 163198 (2020)

Fast Scintilating Implater performance

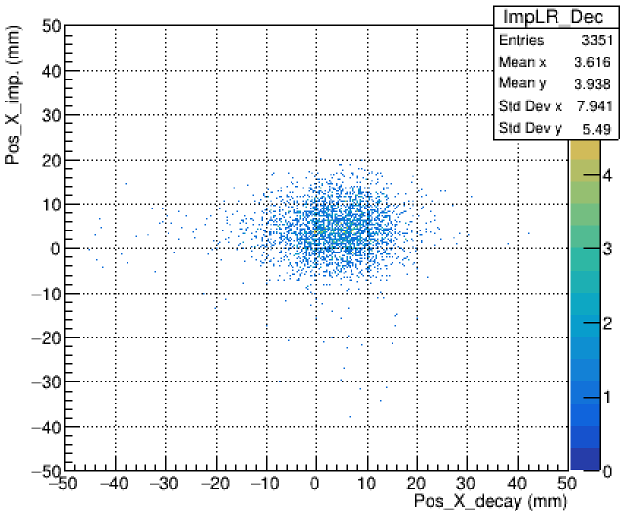
Position SCI vs TPC

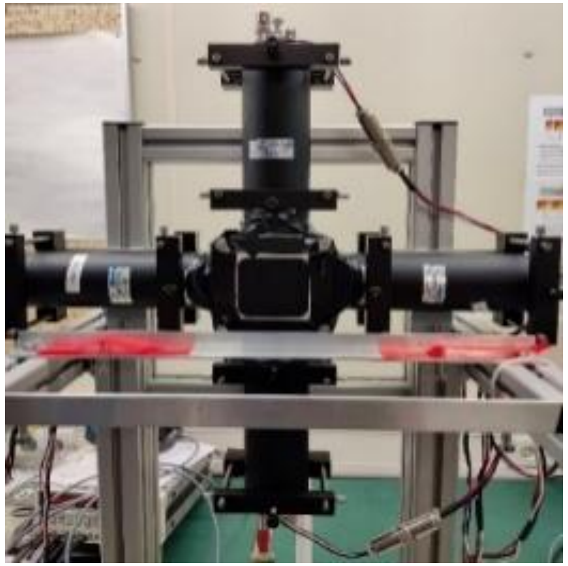


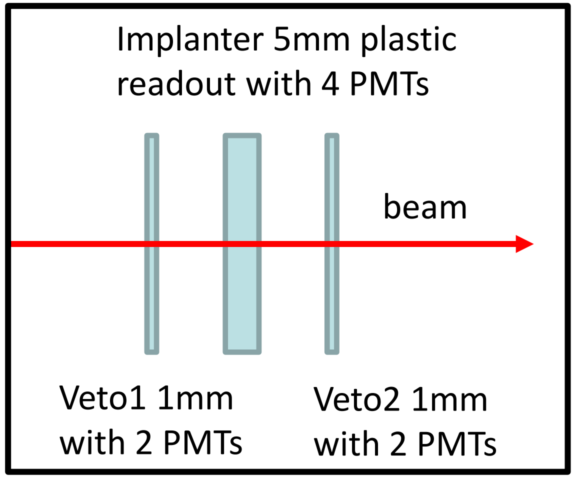
Position resolution



Pos. Imp. Vs Decay





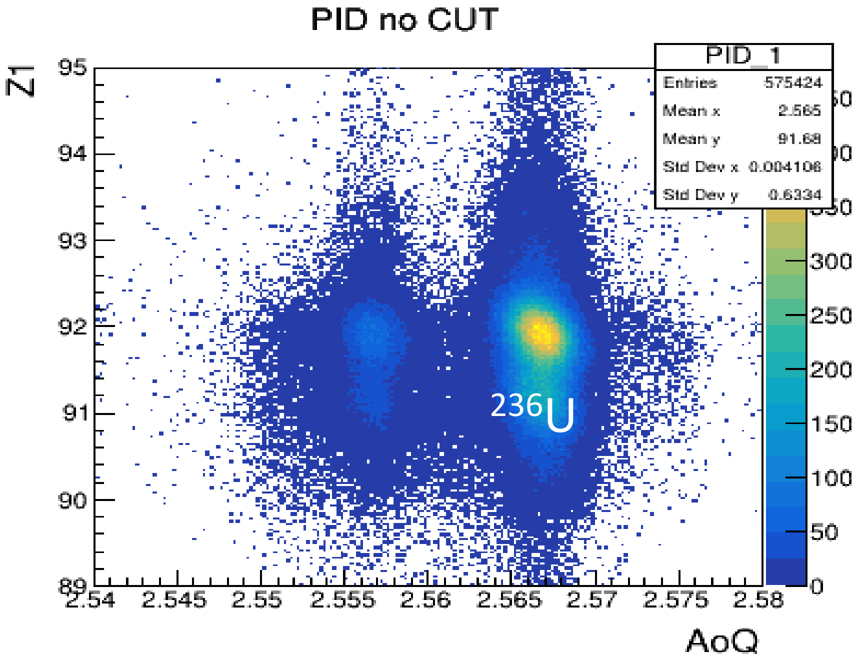


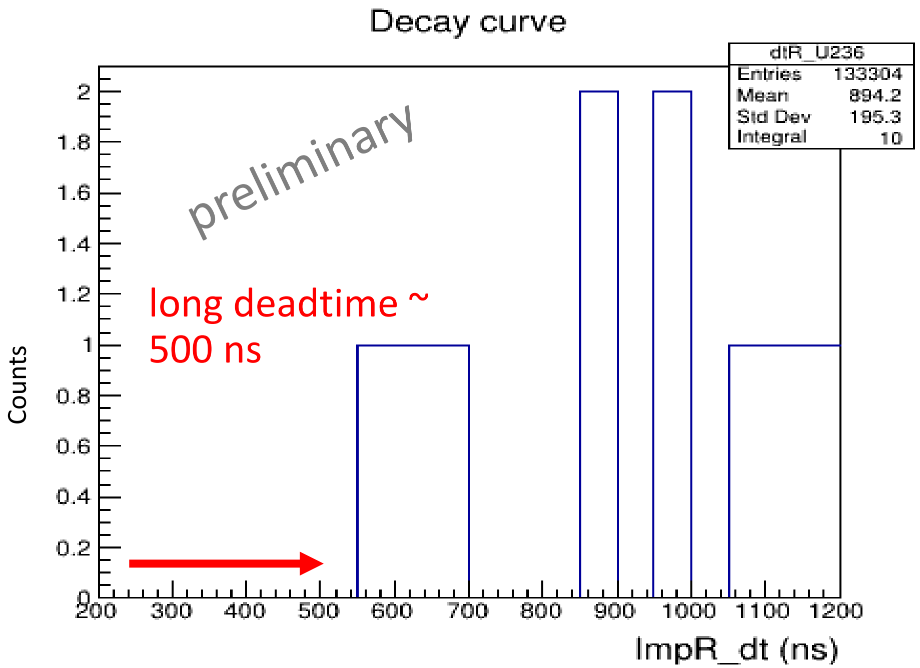
- Implantation and Decay defined by veto detectors
- dif in x for implantation and decay is less than 4.6 mm (2 sigma of the resolution)
- Lesson learned:
  1. y-position not needed
  2. Defocus beam to handle higher rate

Fast SCI: with FRS DAQ

5mm thick plastic scintillator, read out by 4 PMTs

- time-over-threshold: dE → width
- data recorded with: multi-hit TDC in FRS-DAQ (allows PID) rate limit (~kHz)



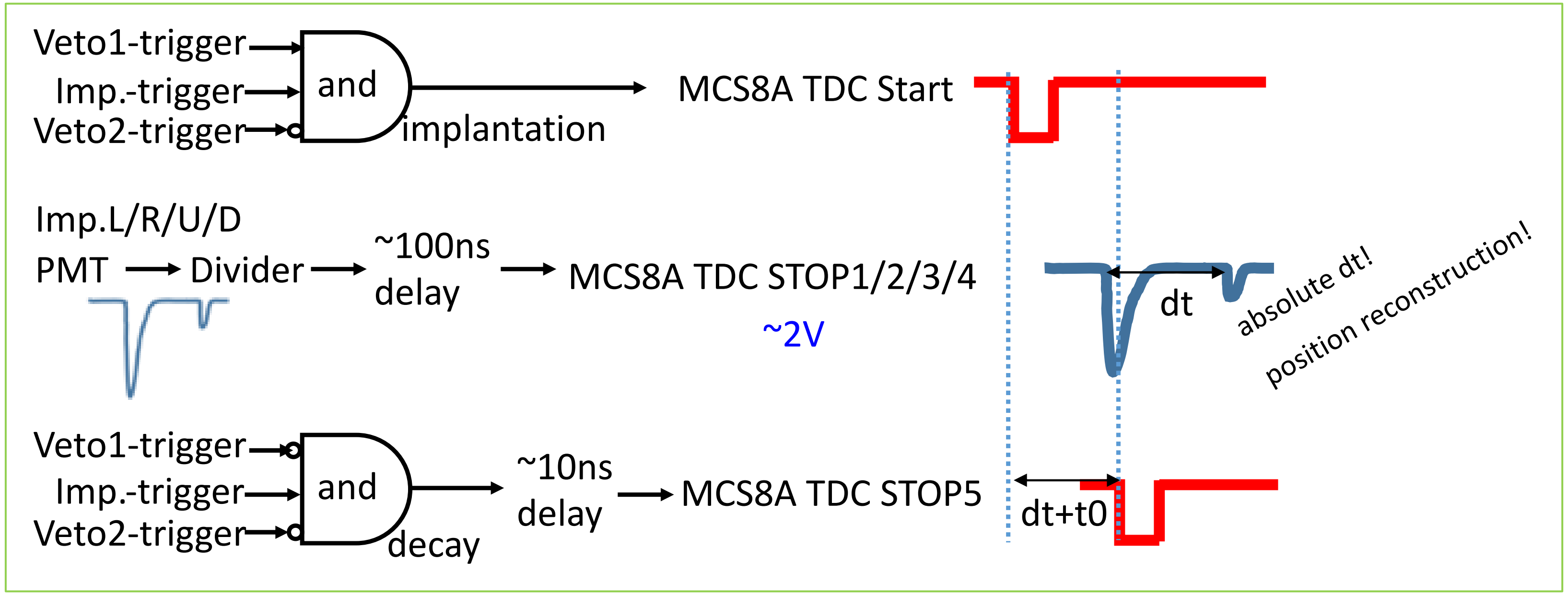


- 1×10^7 ^{236}U (produced by a Be target) implanted
- only 10 events survived → Estimate of upper limit of population ratio (controversial $T_{1/2}$ in literature: 120 ns or 68 ns)
- Lesson learned:
  1. Reduce deadtime
  2. Increase rate capability

Fast SCI: Standalone TDC

5mm thick plastic scintillator, read out by 4 PMTs

- time-over-threshold: dE → width
- data recorded with: standalone TDC (high rate ~500kHz), rate limited by detector to ~20kHz



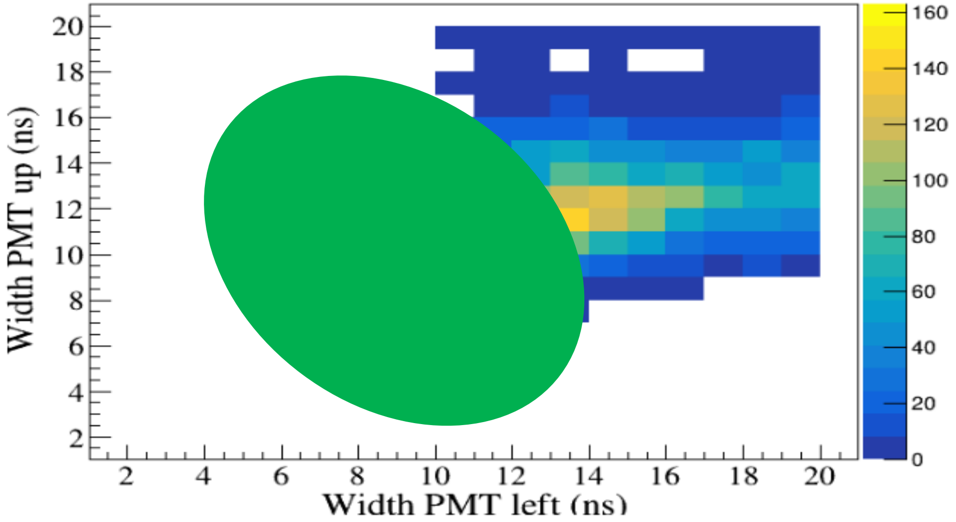
Standalone TDC:

- no PID, but with more statistics
- bkg. suppression with decay trigger
- width information for further bkg. suppression

Fast SCI: Standalone TDC

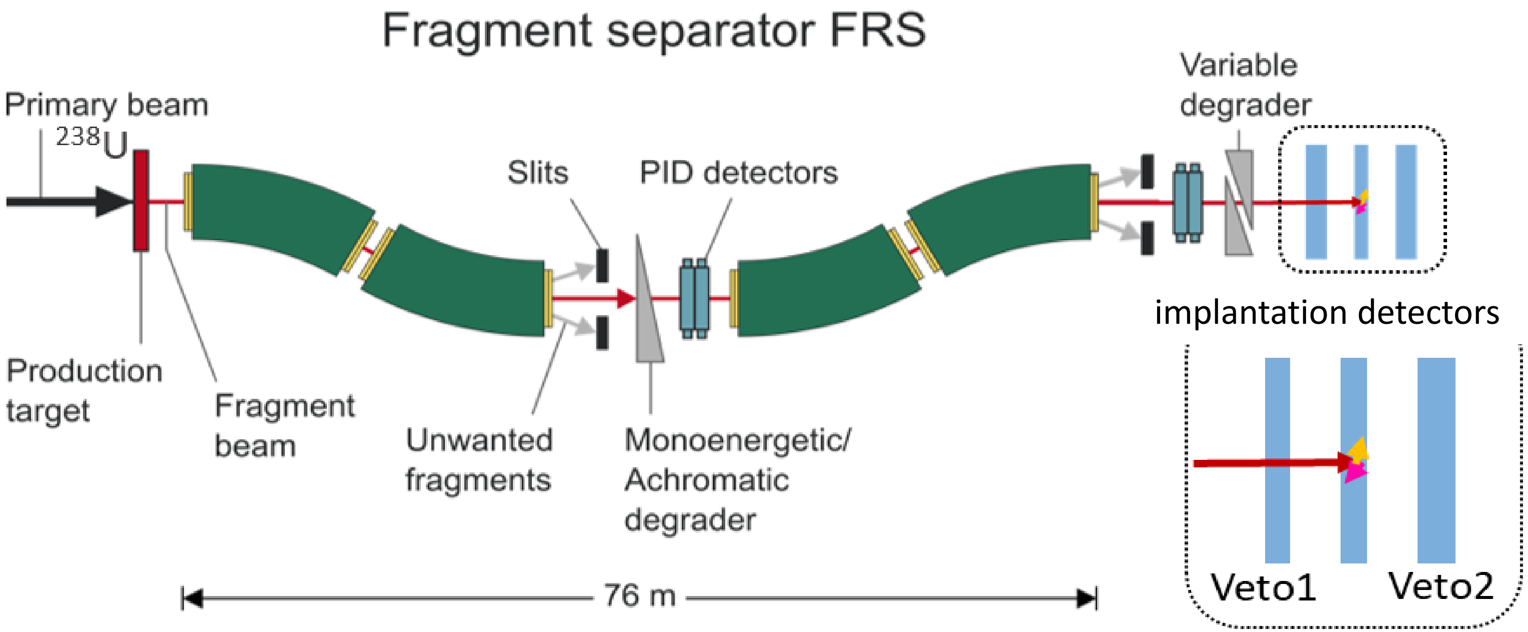
5mm thick plastic scintillator, read out by 4 PMTs

- time-over-threshold: dE → width
- data recorded with: standalone TDC (high rate ~500kHz), rate limited by detector to ~20kHz

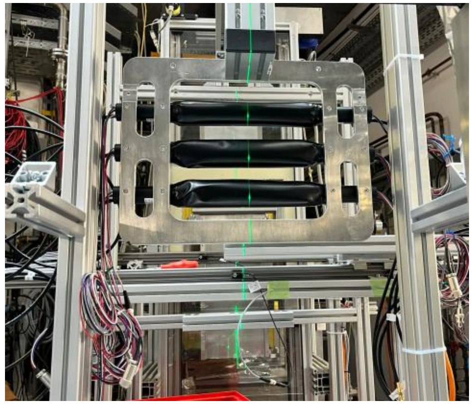


3 x 10^7 implantations measured

Experiment with improved detector, optics and DAQ



Beatriz Amorim
York, UK; Lisboa, Portugal; GSI



Implanter
installed on a drive

- Special optics: Selection before the last dipole and then defocused beam on the detector

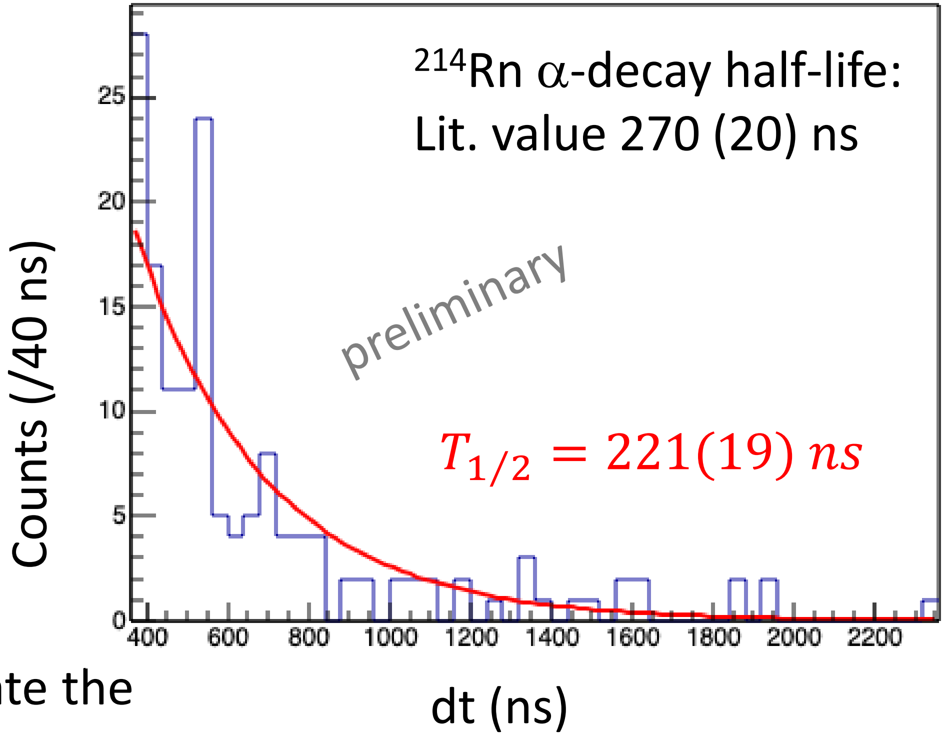
→ More then an order of mag. higher rate capability

- Faster FRS-DAQ
- Selective decay trigger

New implantation detectors

- thin (1 mm plastic sci.) implanter: narrow band, selective and lower implantation signal
- thick (5 mm plastic sci.) Veto2 detector: better suppression of light particle background
- Waveform digitizer

Measurement program and preliminary results



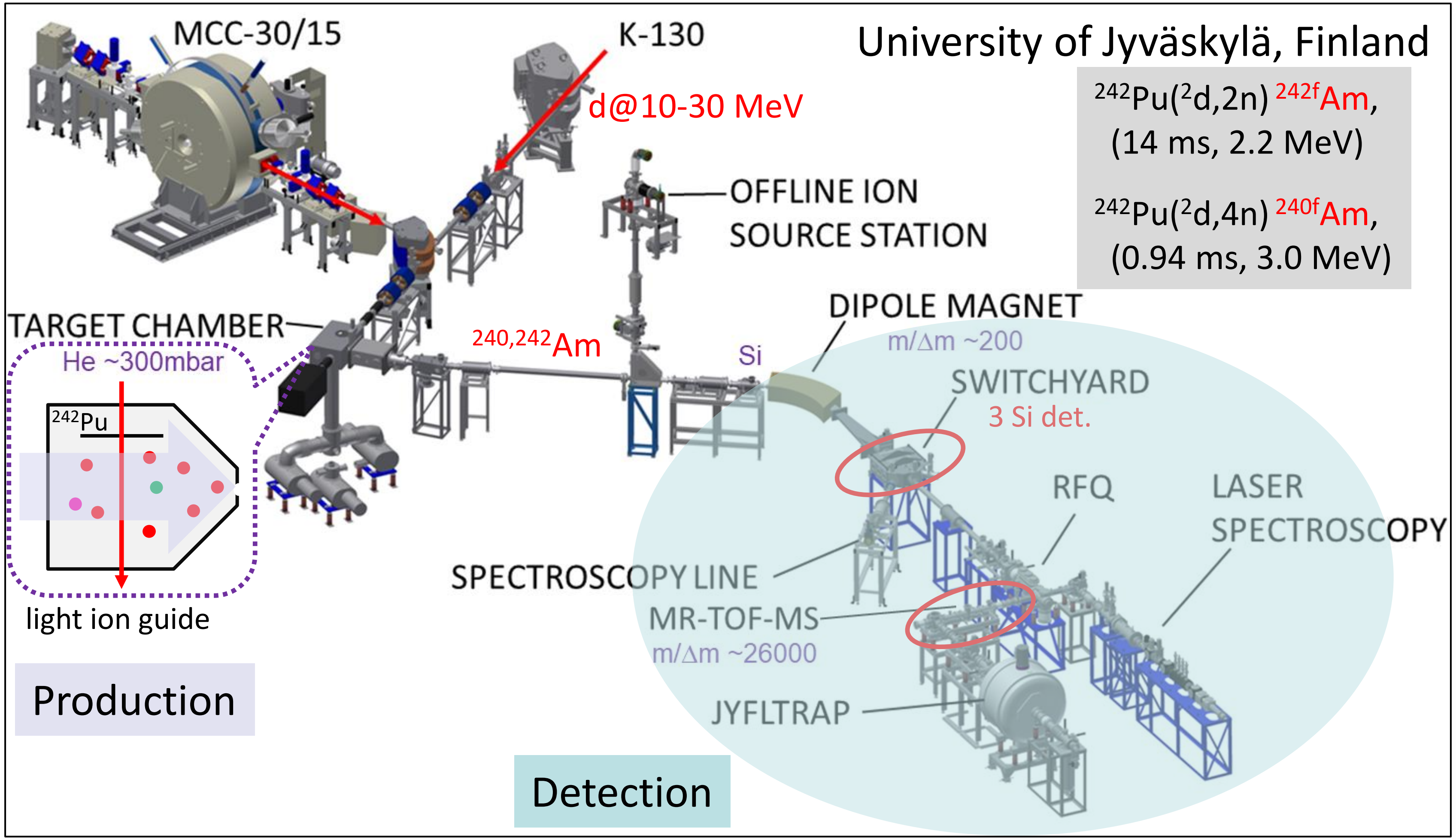
Data taken for:

- Alpha emitter (^{214}Rn) test to show the method works.
- Production of the isomer ^{237m}Np (945 keV, 710 ns) to investigate the isomer production by charge-exchange reaction (LaBr$_3$ det.s).
- Production (Be and Pb targets) and half-life measurement of the fission isomer ^{236f}U. Be: ~5*10^8 ^{236}U implanted, Pb: ~1*10^8 ^{236}U implanted.
  - **50 times more implantations than previous experiment**
    - **deadtime reduced from 500 to ~ 200ns**

Data analysis ongoing

→ **More than 300 times improvement in sensitivity**

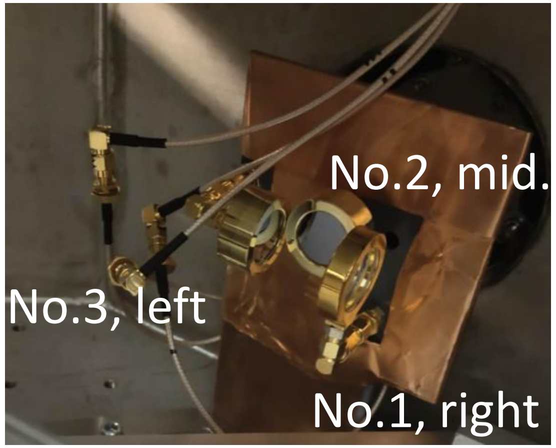
Fission isomers ^{240f,242f}Am studies at IGISOL



Proof-of-principle investigation:

- Isomer yields vs. beam energy (10,14, 20, 25, 30 MeV)
- Excitation energy of the fission isomer state in ^{242}Am

3 Si det. and beam pulsing

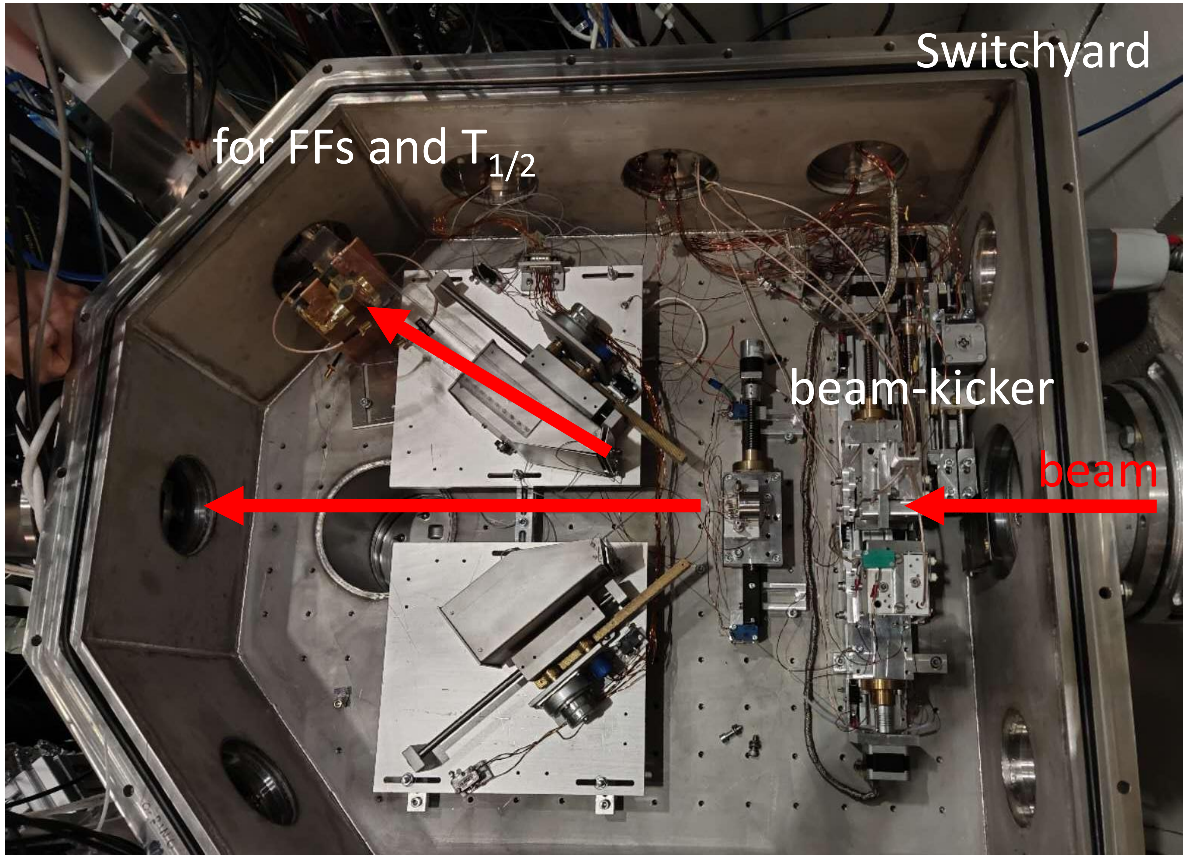


Si det.	Active area (mm^2)
No.1	200
No.2	300
No.3	100

Switchyard

- Pulsed beam with beam-kicker
- Si detectors for FFs measurement
  - 100% detection efficiency for each fission event
  - ~ 8% for coincidences of both fission fragments

to MR-TOF-MS



Excitation functions and other results

TALYS calculations by Nataliia Dzysiuk

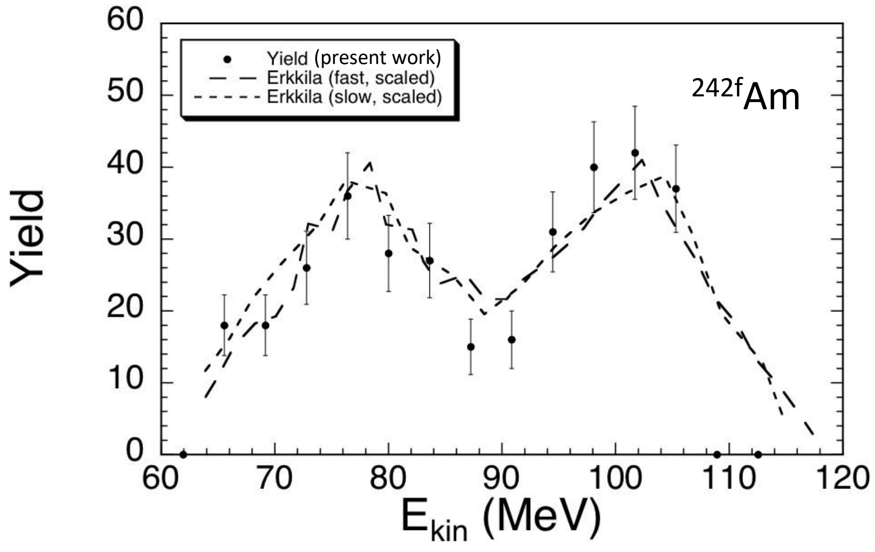
- ^{242f}Am was successfully produced at IGISOL
- ^{242}Am was extracted as singly charged ions
- Two types of ^{242}Pu targets were tested

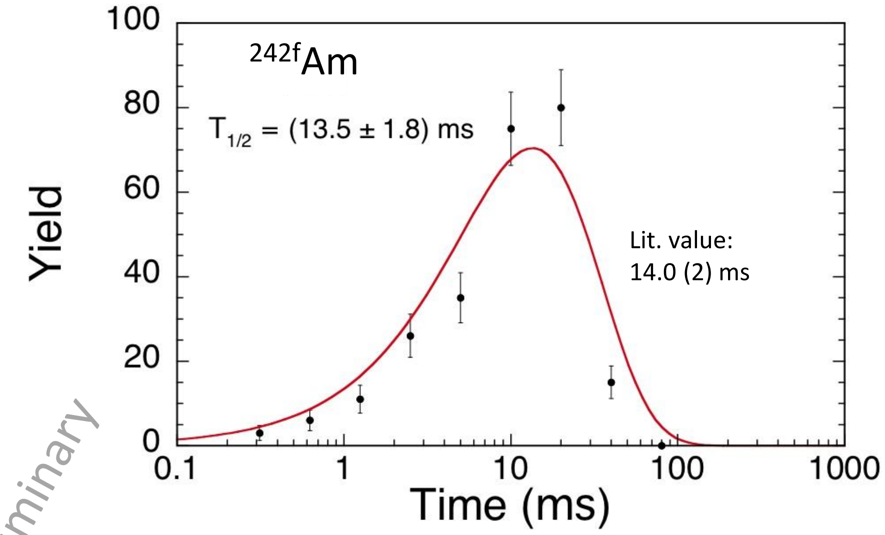
  (Mainz, Dennis Renisch, Christoph E. Düllmann)
  - drop-on-demand inkjet printing target → higher yield
  - molecular plating ^{242}Pu target → lower yield

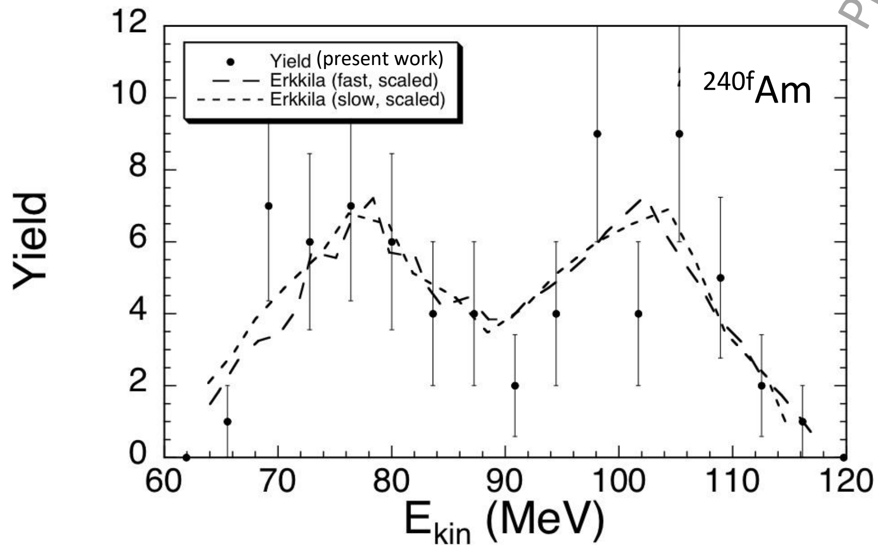
- Peak production energies are higher than TALYS prediction
- Production yields of ^{240f}Am and ^{242f}Am appear to be the same at 30MeV

  (further investigation ongoing)

Important proof: FFs yields and half-lives of $^{240f,242f}Am$







Preliminary

- Half-lives of ^{240f}Am and ^{242f}Am
- $\mathbf{E_{kin}}$ of two FFs and single FF
- Method (separation of the production and detection) works

Summary

- Background free experiments on fission isomers have been performed
- Exploration of the new production method with ^{238}U fragmentation at FRS, GSI
  - Upper limit for population of ^{236f}U
  - Follow-up experiment on ^{236f}U, ^{237f}Np with 300 fold improved sensitivity in 2025
- Production of fission isomers in $^{240,242}Am$ at IGISOL, Finland
  - Measurement of half-lives and TKE of $^{240f,242f}Am$
  - Measurement of excitation energy of ^{242f}Am with MR-TOF-MS

Super-FRS EC

Super-FRS Experiment Collaboration

I290@IGISOL