Super-FRS EC

Identification of MNT reaction products from slowed down beams

Super-FRS EC

- program for production and study of heavy (A=160-260) n-rich isotopes
- generate RIBs inside the (HADO-)CSC ion catcher via MNT reactions
- staged approach:
  - proof-of-principle with stable slowed-down ^{238}U beam at FRS-Ion Catcher
  - measurement of new n-rich actinides with the same configuration
  - exotic n-rich isotopes with radioactive slowed-down beams at Super-FRS-Ion Catcher

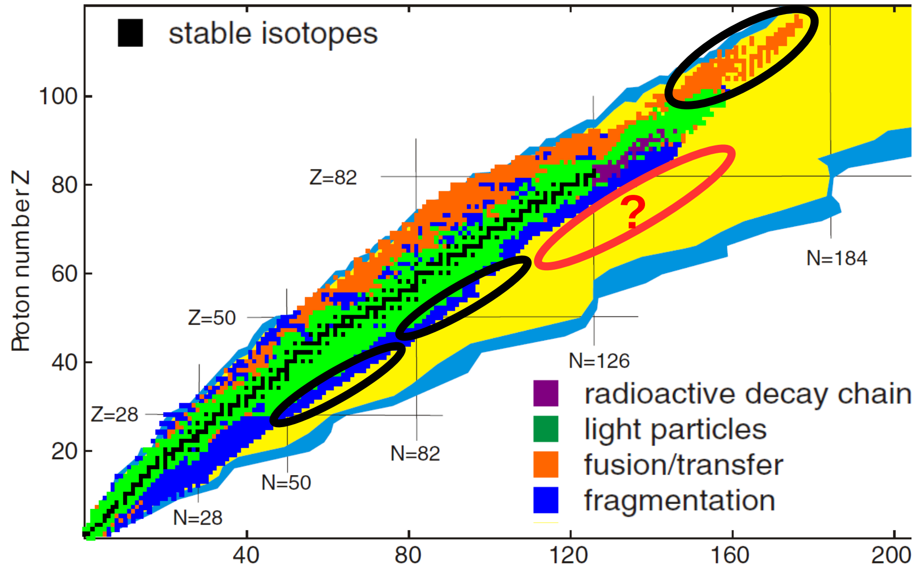
Identification of MNT reaction products from slowed down beams

Heavy n-rich isotopes via MNT

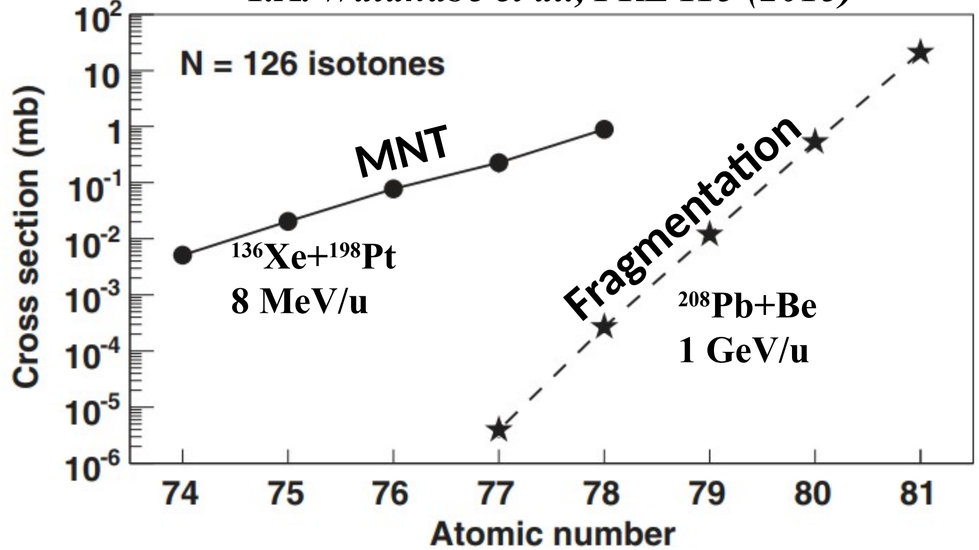
Heavy (A=160-260) n-rich region:

– MNT has much larger cross section than fragmentation

Large yields: high performance ion catcher
– high acceptance → in-cell target
– high efficiency → ion transport by electric fields
– high separation, broadband → MR-TOF-MS



Y.X. Watanabe et al., PRL 115 (2015)

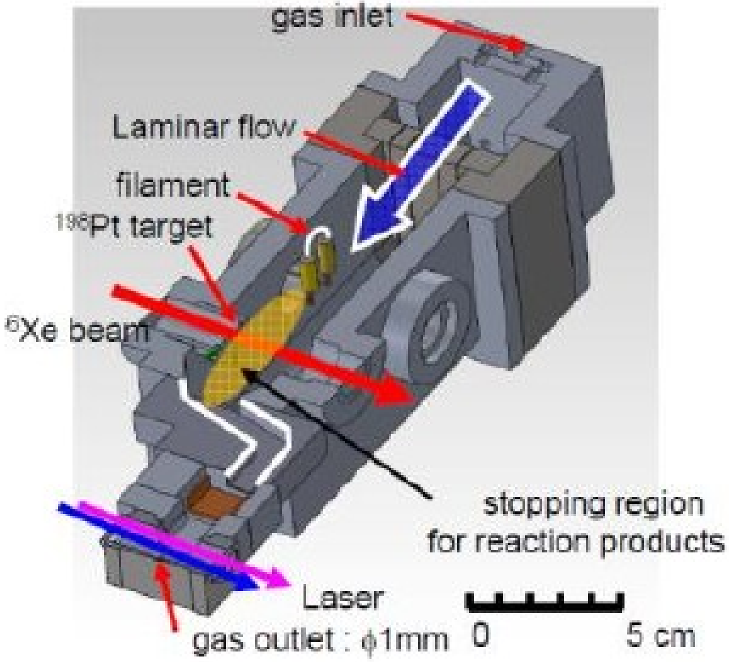


Identification of MNT reaction products from slowed down beams

KISS @ RIKEN

Worldwide leading MNT RIB facility

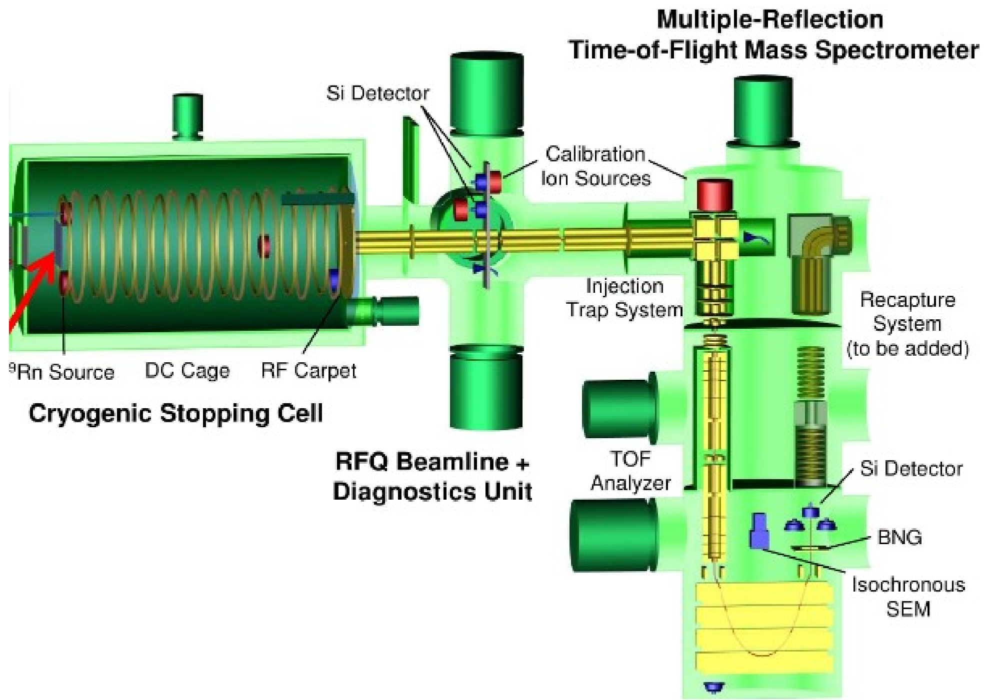
Y. Hirayama et al., NIMB 317 (2013)



– high beam intensities
– room temp → laser ionization → **very selective**
– extraction with Ar gas flow:
  τ~300ms, ε~0.1%
– mass separation with magnet → **m/Δm~10^3**

Upgrade program at RIKEN: KISS 2 ~2027
– (almost) same technologies as currently at FRS-IC: target in cell; He gas; ion transport by electric fields; MR-TOF-MS

FRS-Ion Catcher @ GSI



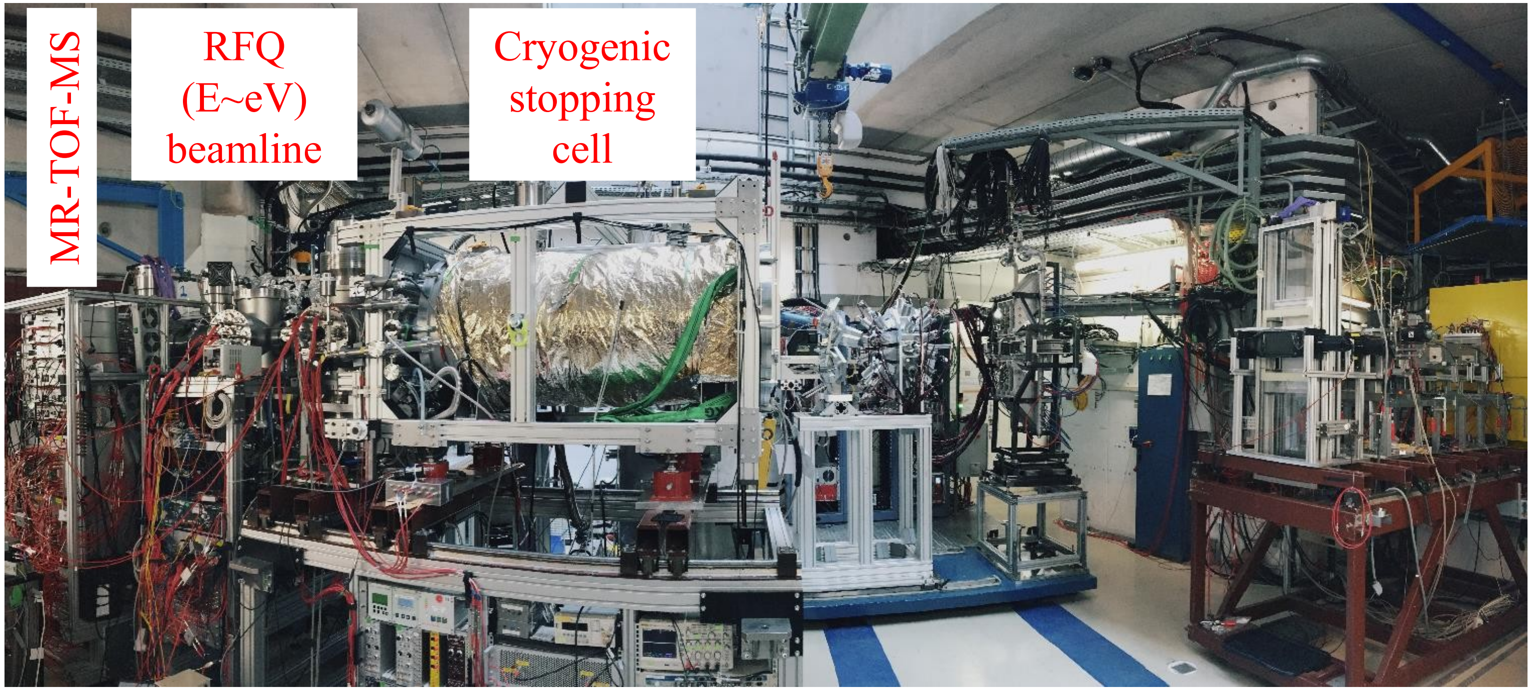
– high beam intensities
– cryogenic He operation → **broad isotope production**
– extraction with DC&RF fields:
  τ~7ms, ε>60%
– mass separation with MR-TOF-MS → **m/Δm~10^6, tof~10ms**

Other developments:
IGISOL @ JYFL, N=126 factory @ ANL

MNT program at FRS-IC

Exploratory program: in-cell MNT reactions with slowed-down ^{238}U beam on targets inside CSC
1) proof-of-principle measurements: ^{209}Bi target, performed in May 2024
2) new n-rich actinide isotopes: ^{238}U target, scheduled in December 2027 → rescheduled?

Expected challenges:
– slow-down of relativistic beam to Coulomb barrier + fine focusing
– space charge effects in the gas cell
– high-density, high-purity gas cell



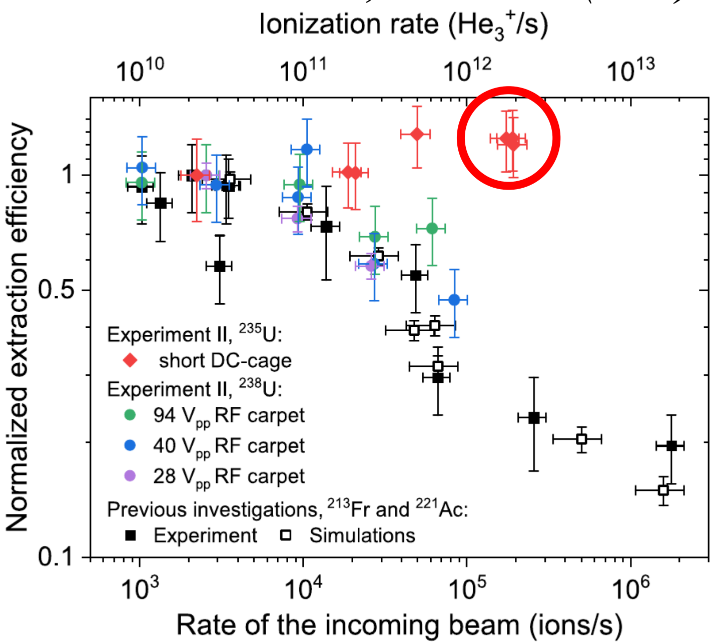
Identification of MNT reaction products from slowed down beams

Space charge effects

Ion transport with electric fields: ε>60%, τ~7ms, broadband
$E_{induced} \approx E_{applied}$: ion loss by neutralization
...drop in extraction efficiency of stopped fragments!

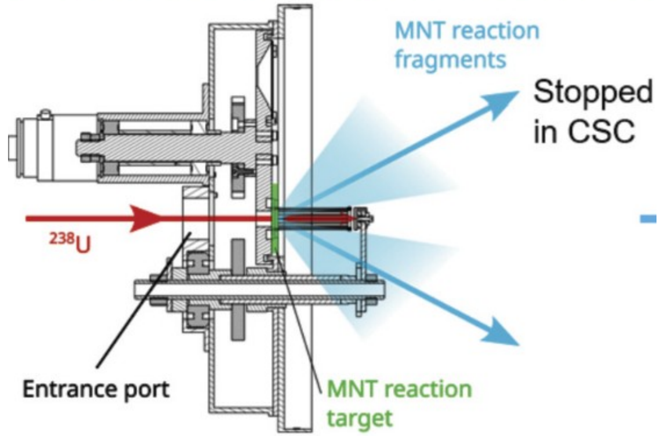
MNT in INCREASE has two sources:
1) primary space charge
– by penetrating U beam: between target and beam dump
2) secondary space charge
– by MNT products: whole volume

J.W. Zhao et al., NIM B 547 (2024)

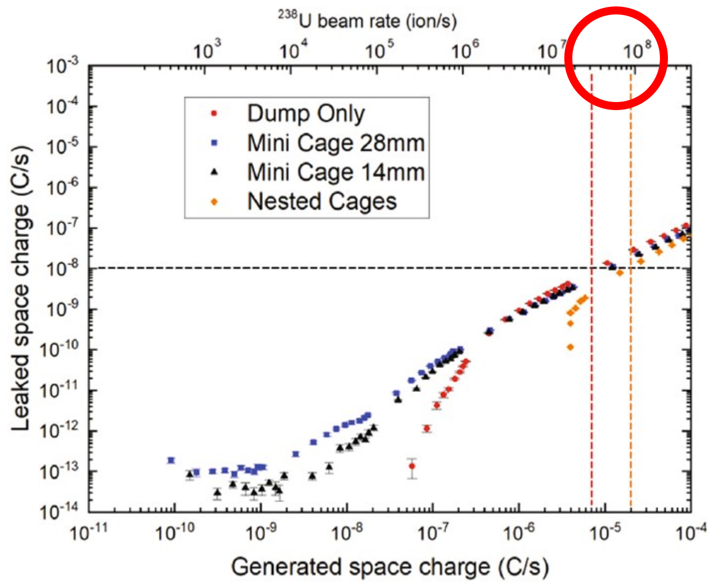


No impact in INCREASE *at least* up to **$2 \cdot 10^5$ ions/s**

INCREASE: remote controlled target wheel (6); space charge containment; shorter DC cage (faster extraction)



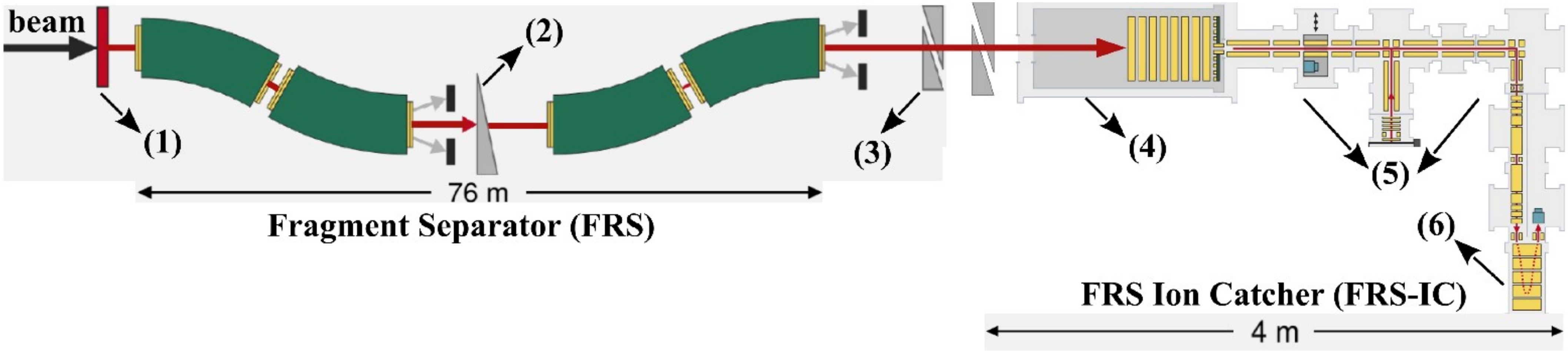
A. Rotaru et al., NIM B 512, 83 (2022)



Simulations: no impact in INCREASE up to **~10^8 ions/s**

Identification of MNT reaction products from slowed down beams

G-22-00117 experiment (May 2024)



500MeV/u ^{238}U slowed down by variable degrader at S4 to ~12MeV/u on ^{209}Bi target inside INCREASE

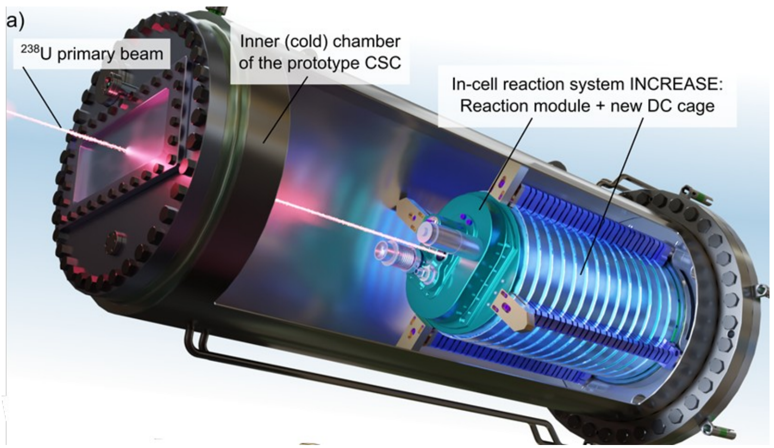
– MNT TLFs identified by the MR-TOF-MS:
→ **proof-of-principle MNT reactions with slowed-down beam**

– intensity on target 10^5–$3\cdot10^6$ U/s without FRS-IC efficiency decrease:
→ **rate capability realized**

– S4 degrader thickness scan: energy scan for MNT reactions

– primary beam of 0.2pA on target is sufficient to generate and identify secondary RIBs

– **G-22-00179 (A. Mollaebrahimi et al.)**: ^{236}U at FRS TA on ^{209}Bi target **successful MNT with secondary beam**



Identification of MNT reaction products from slowed down beams

G-22-00117 experiment (May 2024)

Upgrades:

1. Degrader optimization:
   vacuum at S2, thinner S4 degrader
   decrease beam energy: 500MeV/u→200MeV/u
   → both beam energy spread and spot on target decrease by ~50%; less radiation at CSC (~1/3)
2. HRU (Helium Recovery Unit) operational:
   → increased gas purity and density
3. CSC shielding: high radiation levels in S4
   → avoid electronics failure and radiation alarms

Higher MNT rates:

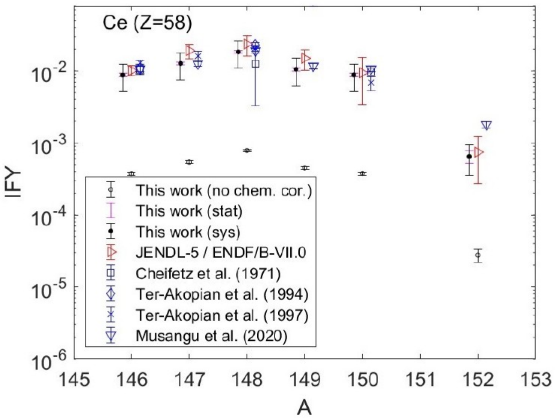
– smaller σ_E, $\sigma_{X/Y}$
– less FRS matter: higher beam transmission, less radiation
– larger target and beam dump
– **up to ~x100**

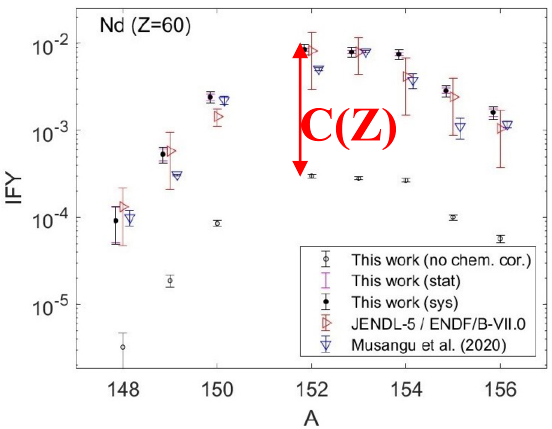
Identification of MNT reaction products from slowed down beams

High-purity He gas

– method developed for 252Cf:
  independent fission fragment yields IFY(N,Z)
– for an experiment at non-optimal gas purity,
  the extracted the chemical efficiency C<10%

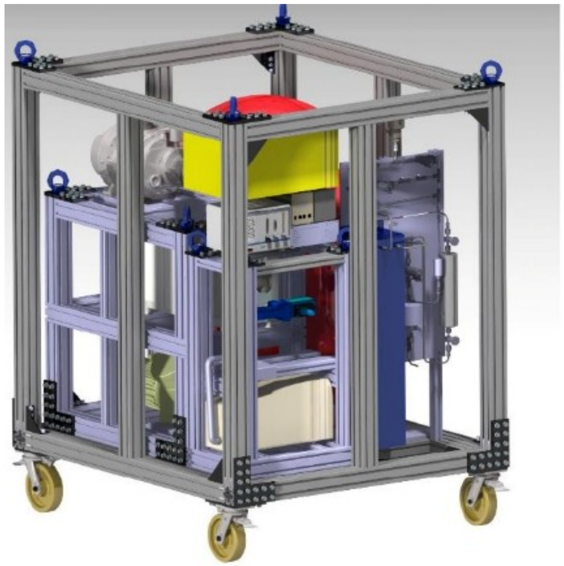
I. Mardor et al., EPJ Web of Conferences 239 (2020)
Y. Waschitz et al., EPJ Web of Conferences 284 (2023)





$$\sum_Z IFY(N,Z)_{exp}^{N+Z=A} \cdot C(Z) = frac(FY_{lit}(A)) \cdot FY_{lit}(A)$$

HRU (Helium Recovery Unit)
– gas recirculation and purification
– maintain and control a high gas density and purity over extended running periods



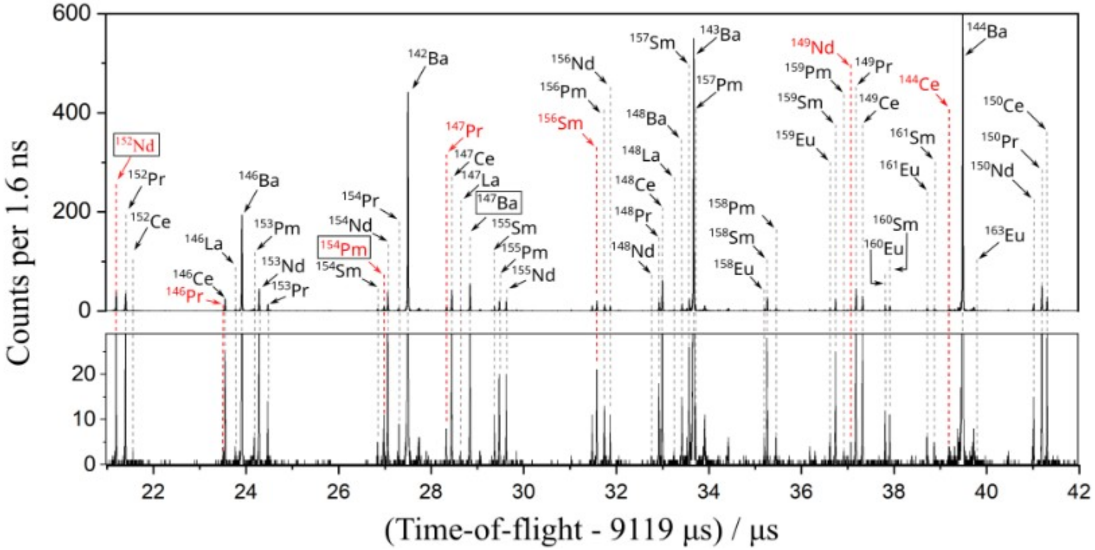
Identification of MNT reaction products from slowed down beams

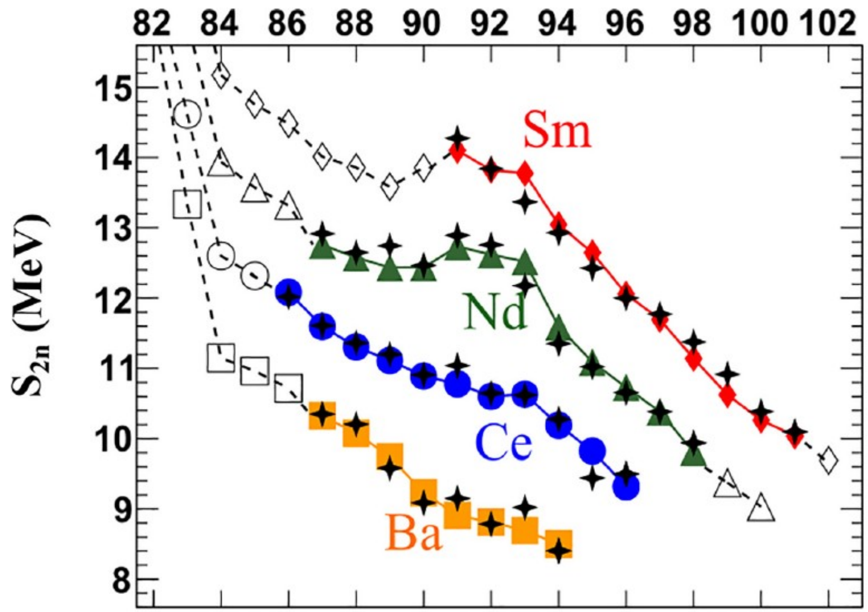
^{252}Cf s.f. mass measurements

Several offline runs with ^{252}Cf (20kBq):
– broad-range simultaneous direct measurement of 64 masses:
  51 in a single setting, 13 first direct, 4 improved accuracy
– studies of the N = 90 shape phase transition via S_{2n} systematic measurements

Extensive offline experimental program (10MBq)

A. Spătaru et al , Phys. Scr. 99 (2024)
A. Spătaru et al., Phys. Rev. C 111 (2025)





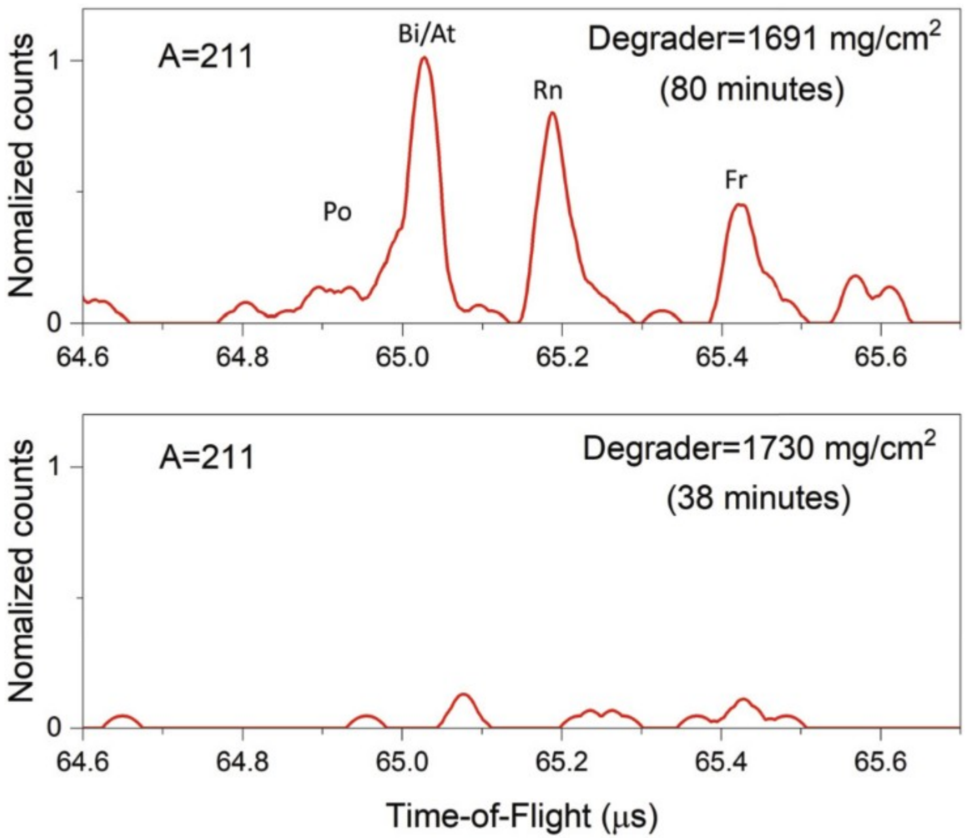
Identification of MNT reaction products from slowed down beams

Super-FRS EC

MNT data analysis

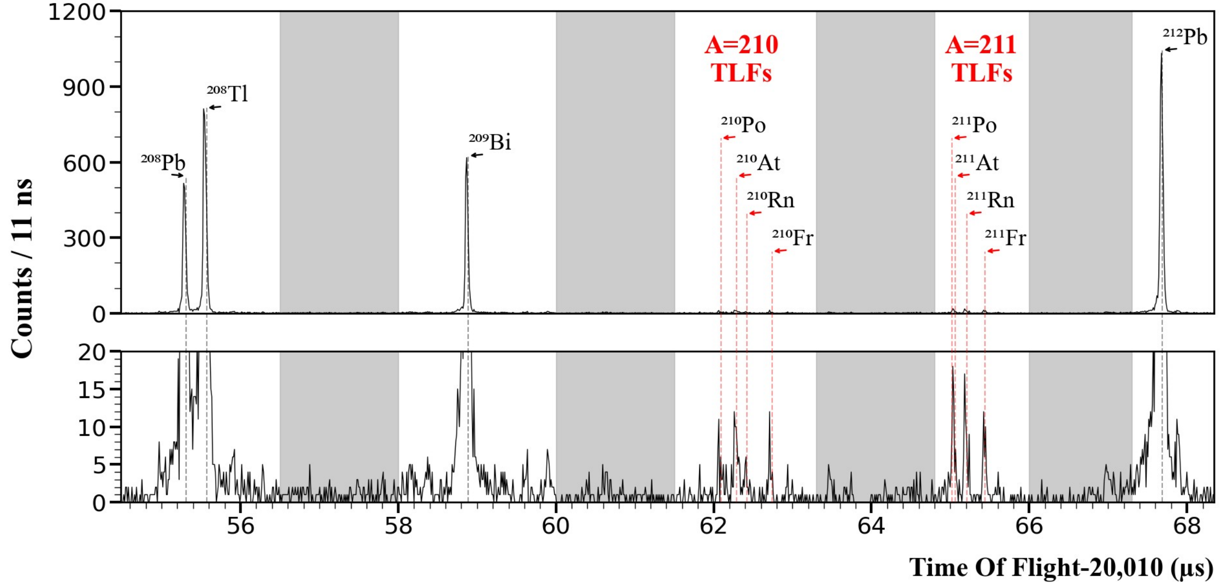
Min&max degrader thickness: T=1691&1730mg/cm^2
MR-TOF-MS spectra of identified TLFs in ^{238}U+^{209}Bi with A=211: sudden rate drop

A. Mollaebrahimi et al., Nucl. Phys. A 123041 (2025)



Large degrader scan data set:
1) ^{238}U beam stopping: 7 S4 degrader settings
2) MNT stopping: 7 S4 degrader settings
3) ^{228}Th source: ^{208}Pb, ^{208}Tl, ^{212}Pb

A. Shraier et al., to be submitted to Eur. Phys. J. A

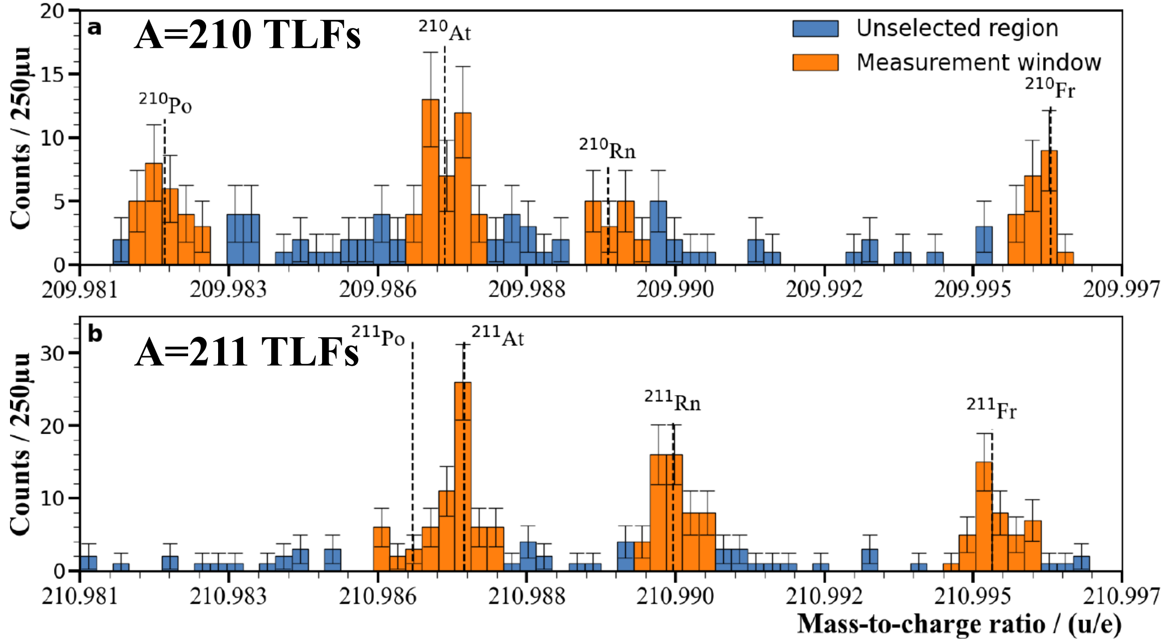


After standard calibrations (TRC)
– FWHM≈30ns from elastic ^{209}Bi channel
  → peak integration ±30ns around mass
– $m/\Delta m \approx t/(2\Delta t)$=20010μs/(2·30ns)=333,500
  consistent with N_t=449
– background from peak-free areas (grey)

Identification of MNT reaction products from slowed down beams

Super-FRS EC

MNT data analysis



Degrader scan results:

– several identified TLFs in A=210 and A=211 spectra

– expected rate dependence on degrader thickness

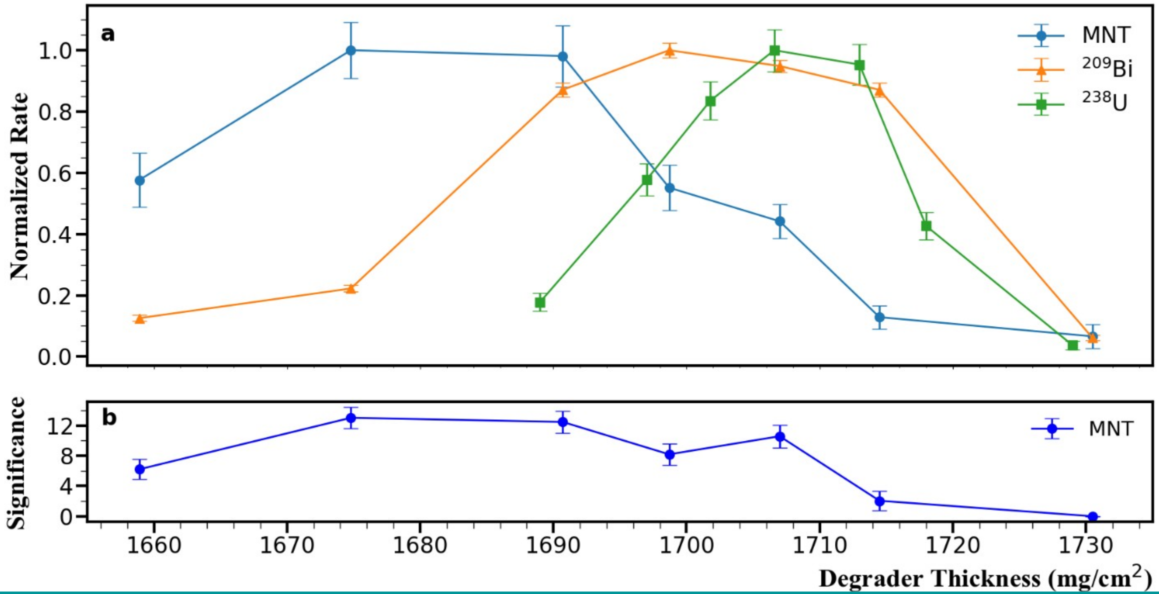
– signal significance S=√L reaches12
(L=Poisson log-likelihood ratio)

A. Shraier et al., to be submitted to EPJA

beam ^{238}U

elastic ^{209}Bi

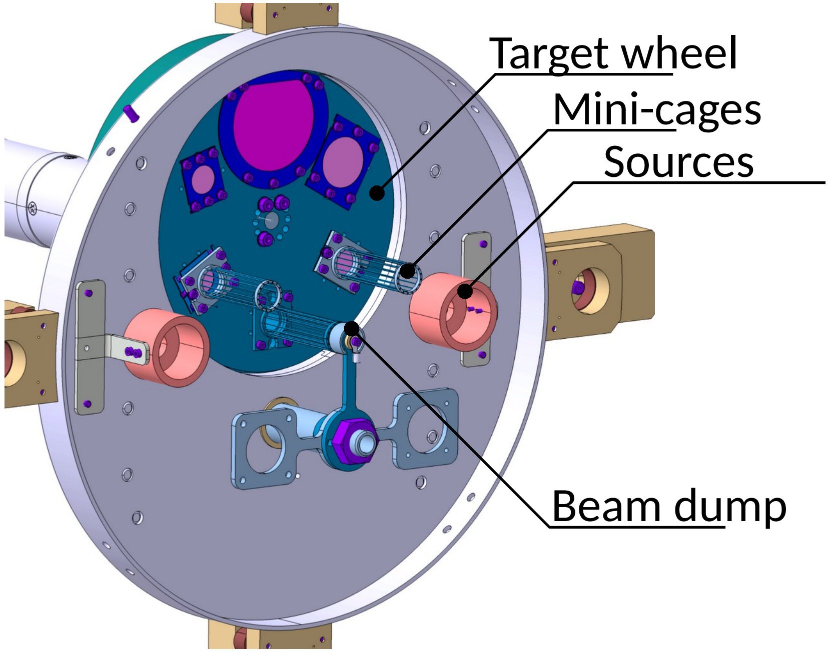
MNT A=210+211



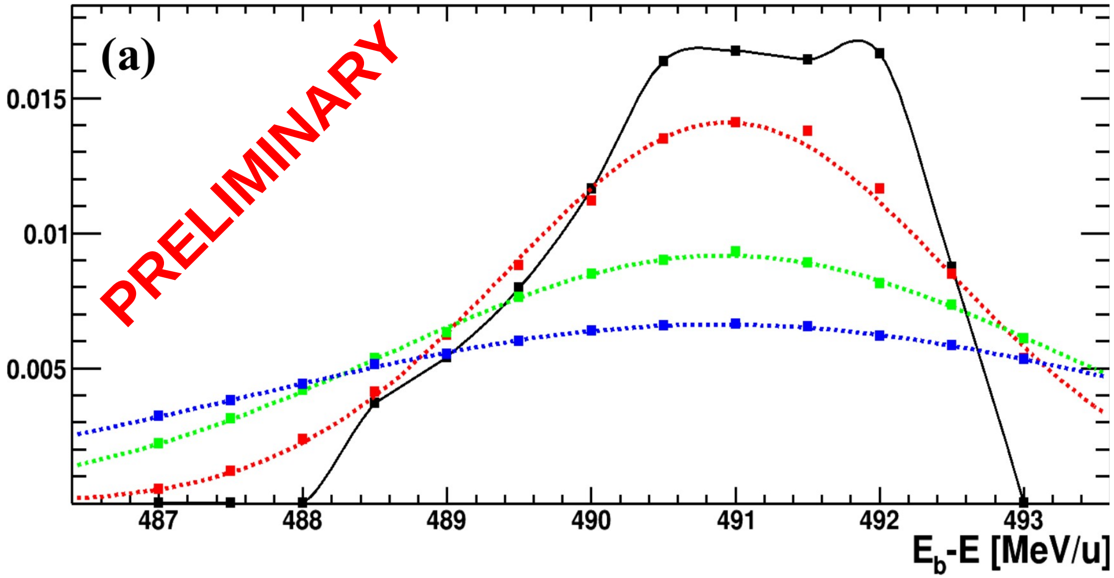
Identification of MNT reaction products from slowed down beams

Ongoing data analysis

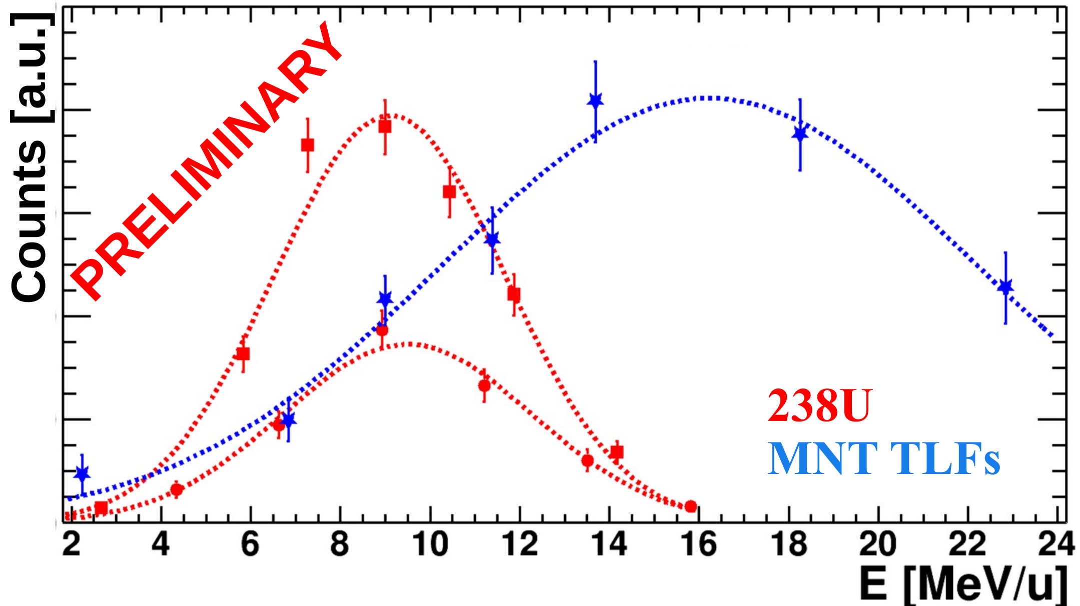
Beam energy dependence:
– convert degrader thickness into beam energy on target
– systematics: small Bi target (d=1cm) + large Bi target (d=2.5cm)
– Geant4: full CAD upload
– fraction of ^{238}U beam stopped in CSC vs. mean E and RMS σ_E
– ^{238}U generated at entrance in target; use E_b-E~T (E_b=500MeV/u)



σ_E=0MeV/u **σ_E=1MeV/u** **σ_E=2MeV/u** **σ_E=3MeV/u**

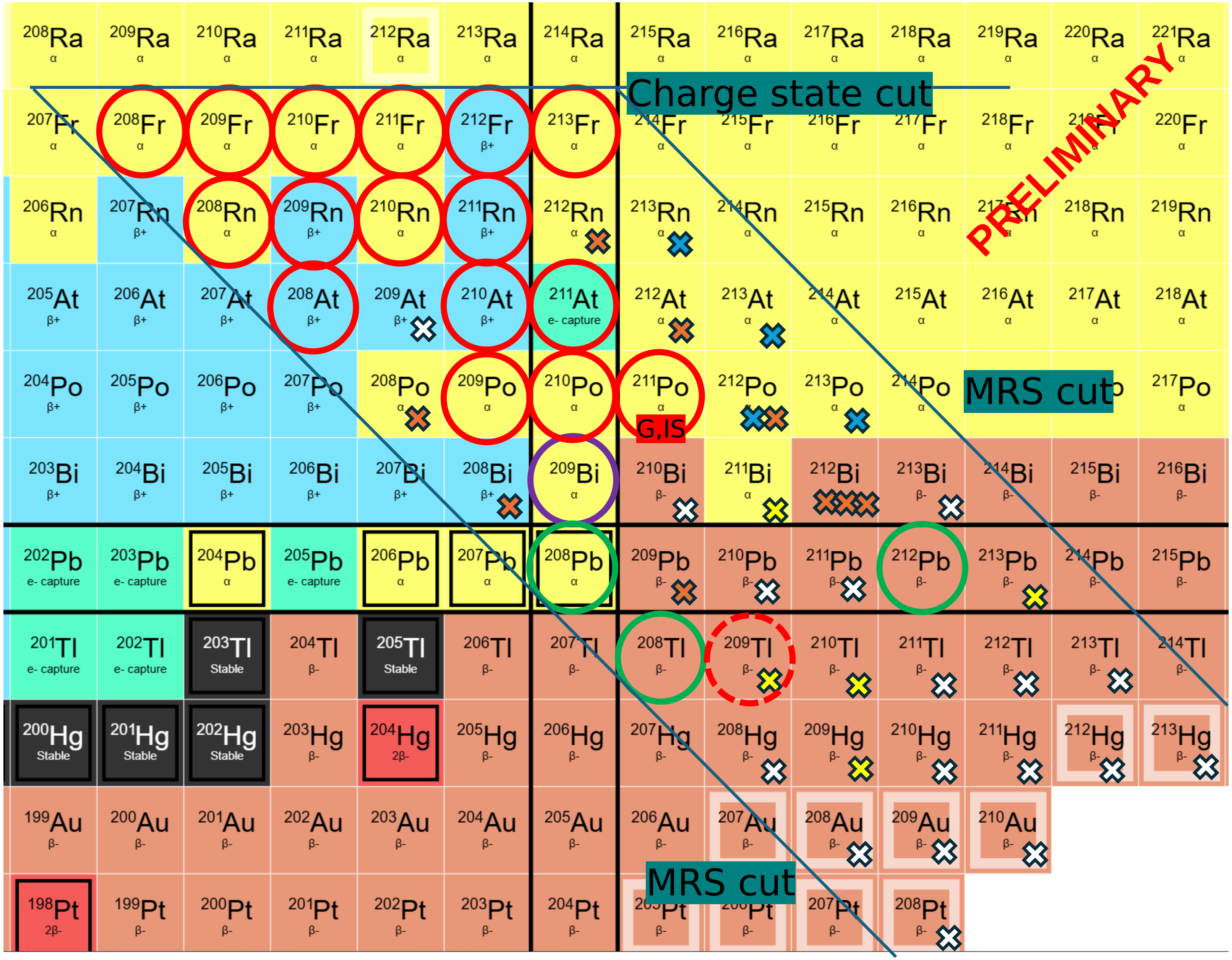


MNT TLFs (A=210&A=211) scaled to ^{238}U with small ^{209}Bi target

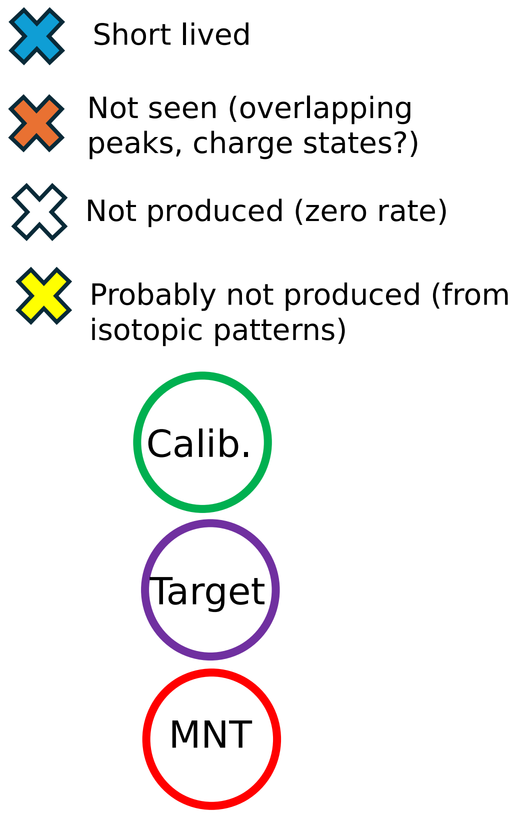


Identification of MNT reaction products from slowed down beams

Ongoing data analysis



Large statistics run at optimal degrader thickness
T = 1707 mg/cm^2
~ 16 isotopes identified
→ MNT production rates vs. A and Z
Analysis by **A. Mollaebrahimi**



Identification of MNT reaction products from slowed down beams

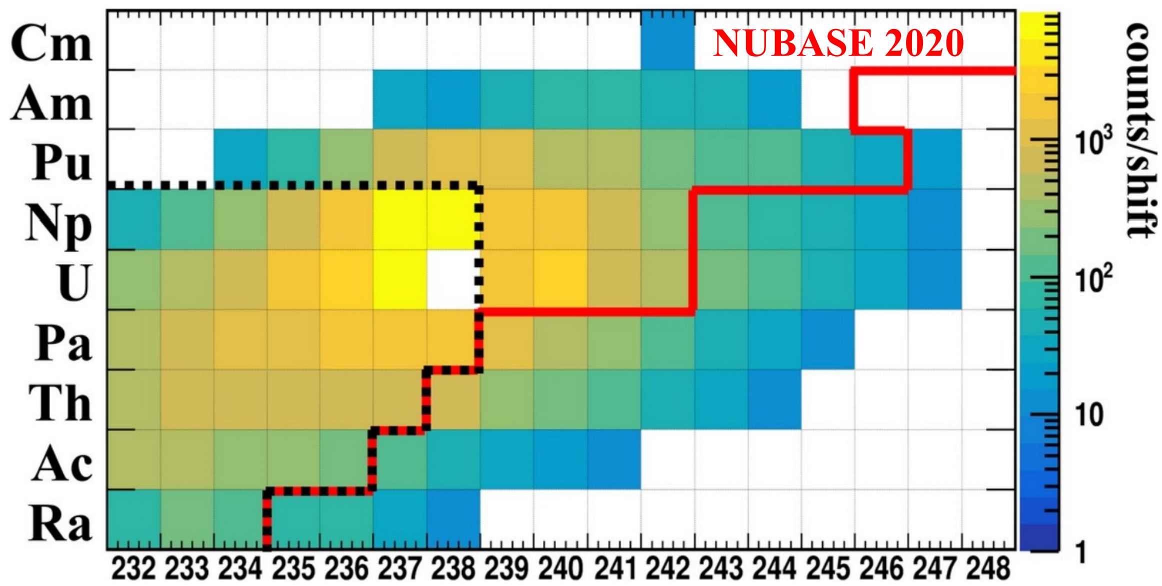
Super-FRS EC

New MNT proposal at FRS Ion Catcher

G-24-00274 P. Constantin, S. Bagchi, T. Dickel, et al.
Measurement of ~20 new n-rich actinides
Ranked A by G-PAC: December 2027, to be rescheduled?

200MeV/u ^{238}U and 10^9 ions/s at FRS TA, ~12 MeV/u and 10^7 ions/s on ^{238}U target → same as FAIR/LEB
– technical run: 3 shifts
– physics run: 15 shifts

Technical run to evaluate upgrades:
1) **beam slow-down and focusing**: new degrader system
2) **gas purity**: HRU deployment
3) **radiation level**: CSC shielding



Identification of MNT reaction products from slowed down beams

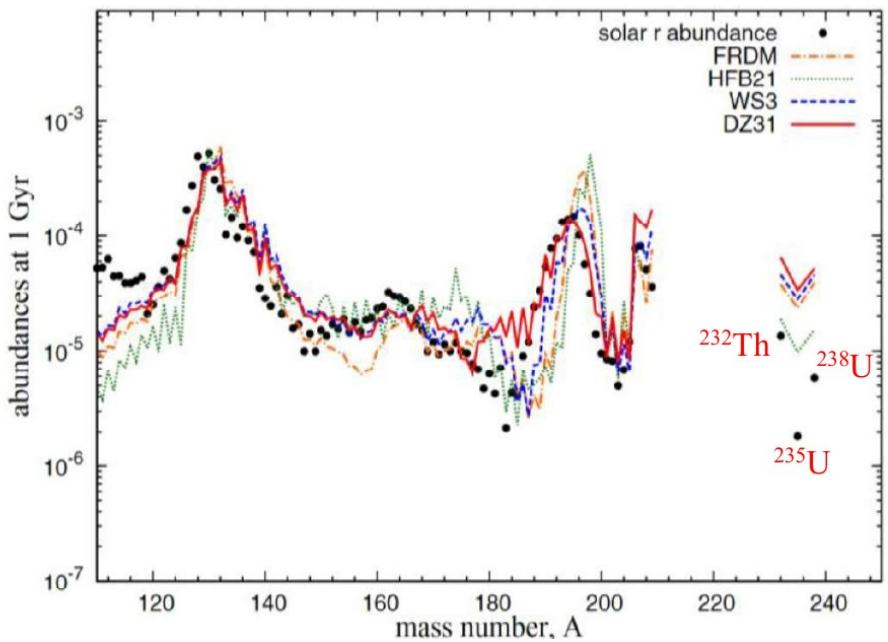
Super-FRS EC

New MNT proposal at FRS Ion Catcher

Physics run: ~20 new n-rich actinide masses and cross sections

1) **Nucleo-synthesis of actinides**:
   data (masses, half-lives, etc.) on n-rich actinide isotopes needed for r-process calculations
2) **Shell structure evolution**:
   masses of n-rich actinide isotopes needed to benchmark nuclear structure towards the limits of stability

J.J. Mendoza-Temis et al., PRC 92 (2015)



Window of opportunity:

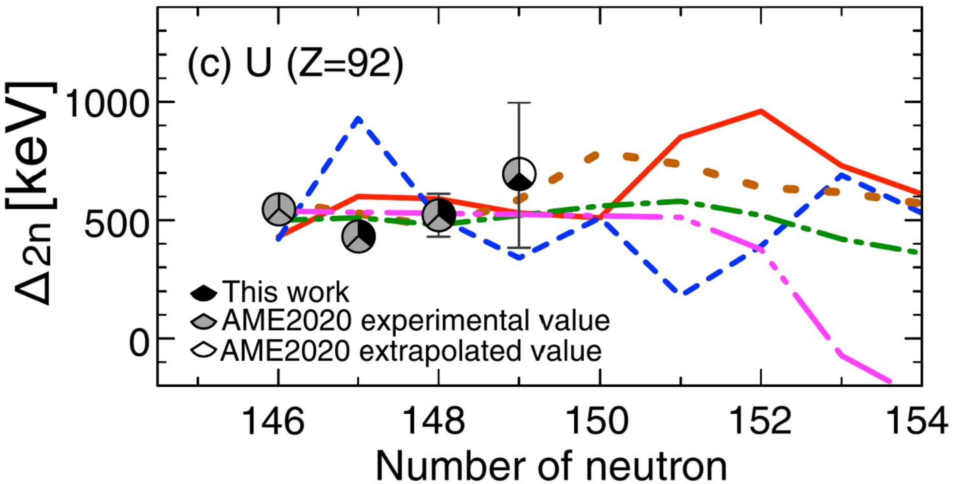
– upgraded KISS@RIKEN by end of 2027; actinide program soon after

– MNT needs special HADO-CSC configuration:
  cannot be moved to FAIR early science

→ ^{238}U beam at low energy and intensity OR
  lighter n-rich beam (^{136}Xe/^{209}Bi)

This does not refer to the wider MNT program at Super-FRS

T. Niwase et al., PRL 130 (2023)



SUMMARY

✔ Proof-of-principle for MNT driven by slowed-down primary beam at FRS-IC

? Looking for solution to run n-rich actinide experiment at FRS-IC

✭ Building the case for MNT driven by radioactive isotope beams at Super-FRS-IC

Acknowledgements

Super-FRS Experiment Collaboration

FRS Ion Catcher

D. Amanbayev, O. Aviv, S. Ayet San Andrés, J. Äystö, S. Bagchi, D.L. Balabanski, S. Beck, O. Beliuskina, J. Bergmann, A. Blazhev, K. Botsiou, Z. Brencic, S. Cannarozzo, V. Charviakova, P. Constantin, D. Curien, I. Dedes, T. Dickel, F. Didierjean, G. Duchene, J. Dudek, T. Eronen, T. Fowler-Davis, M. Friedman, Z. Ge, H. Geissel, S. Glöckner, M. Górska, T. Grahn, F. Greiner, L. Gröf, M. Gupta, E. Haettner, M. Harakeh, J. Harkin, C. Hornung, W. Huang, Y. Ito, A. Jaries, A. Jokinen, N. Kalantar-Nayestanaki, A. Kankainen, D. Kar, A. Karpov, N. Keeppalli, Y. Kehat, K. Khokhar, D. Kostyleva, G. Kripkó-Koncz, D. Kumar, B. Lehnert, K. Mahajan, I. Mardor, A.A. Mehmandoost-Khajeh-Dad, N. Minkov, A. Mollaebrahimi, D. Morrissey, I. Mukha, M. Narang, Z. Patyk, H. Penttilä, A. Perry, S. Pietri, A. Pikhtelev, W.R. Plaß, I. Pohjalainen, S. Pomp, R.K.Prajapat, S. Purushothaman, M.P. Reiter, M. Reponen, H. Rösch, A. Rotaru, J. Ruotsalainen, C. Scheidenberger, P. Schury, A. Shrayer, M. Simonov, S.K. Singh, A. Solders, A. Spataru, A. State, N. Steinbrenner, Y. Tanaka, P. Thirolf, Y. Tian, N. Tortorelli, F. Uhlemann, L. Varga, M. Vencelj, V. Virtanen, M. Wada, H. Weick, L. Welde, M. Will, H. Wilsenach, M.I. Yavor, J. Yu, A. Zadvornaya, J. Zhao, K. Zuber

FAIR Phase 0 Research Program

FRS

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