令和7年度第1回宇宙史研究センター(TCHoU)構成員会議・成果報告&交流会
2025年7月8日
筑波大学自然系学系B棟114 + オンラインZoomのハイブリッド

July 8, 2025

KISS-1.5計画　重元素の起源解明を目指して

KISS-1.5 Project – Towards elucidating the origin of heavy elements

WNSC, IPNS, KEK
Yutaka Watanabe

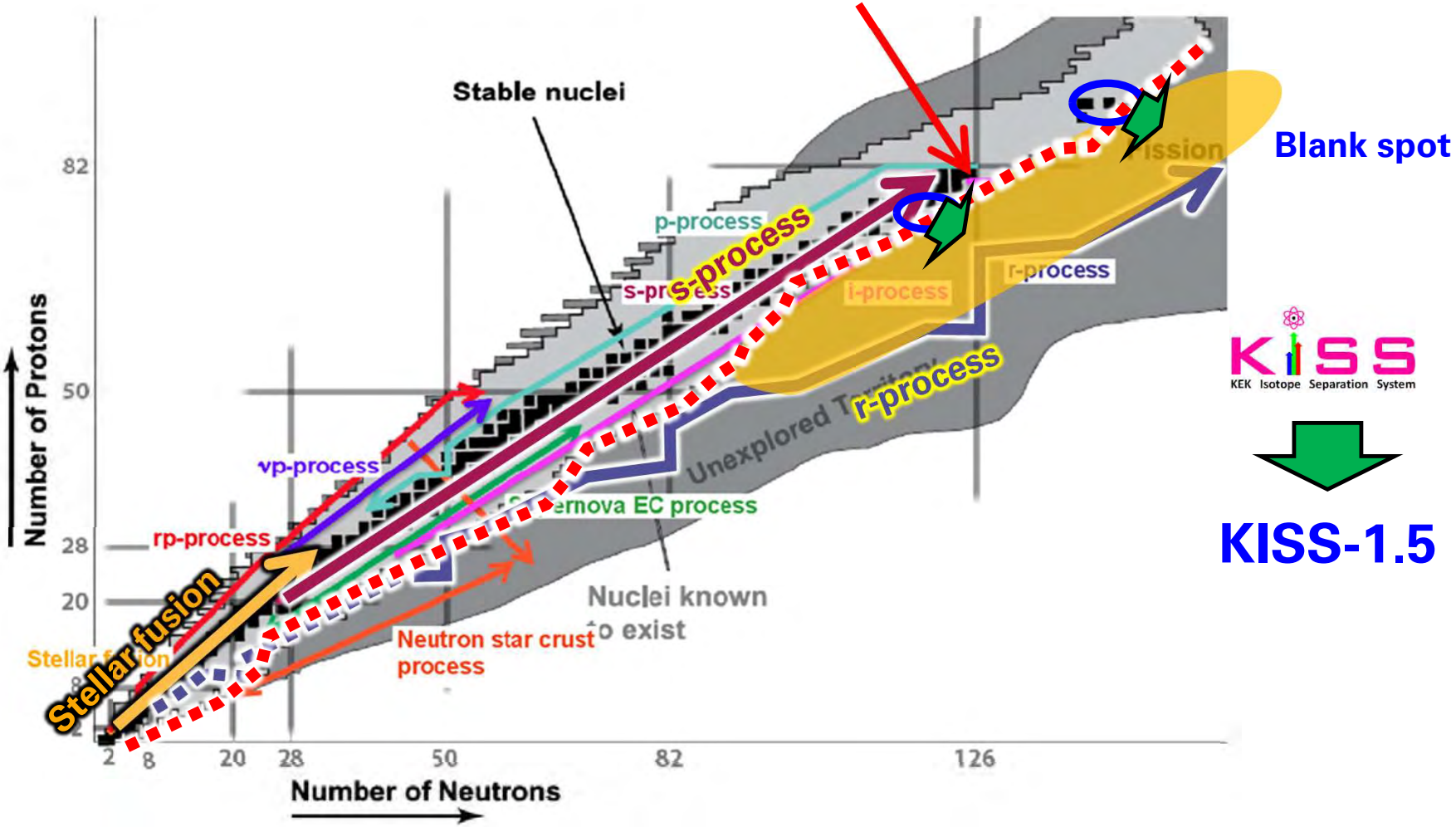
Contents

1. Physics motivation
2. Nuclear production by MNT reactions
3. KISS facility
4. Experimental results around N = 126 and actinides
5. Beyond KISS: KISS-1.5 project
6. Summary

WNSC
KEK Wako Nuclear Science Center

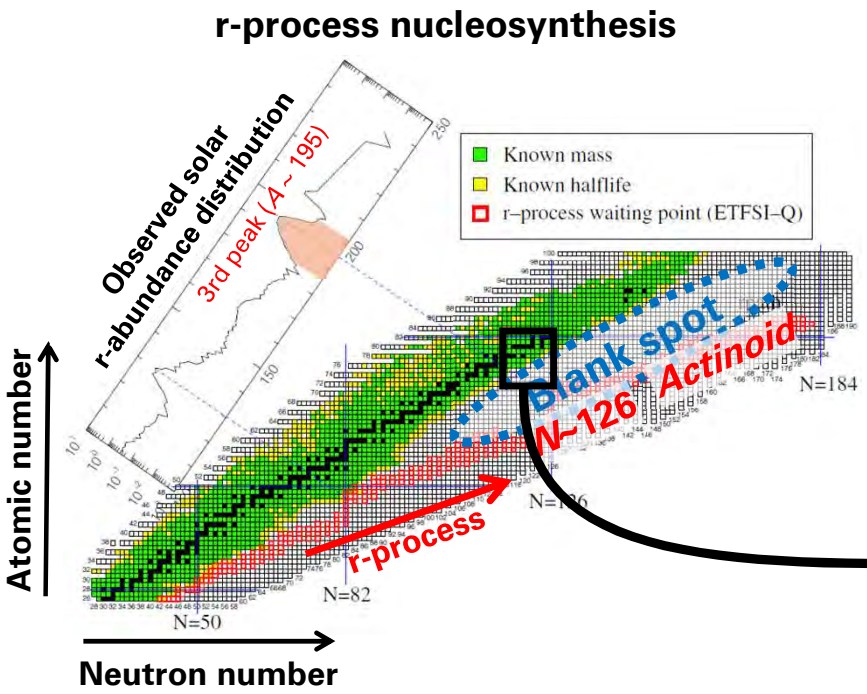
Nucleosynthesis in the universe

Most neutron-rich isotope of each element, synthesized in laboratories

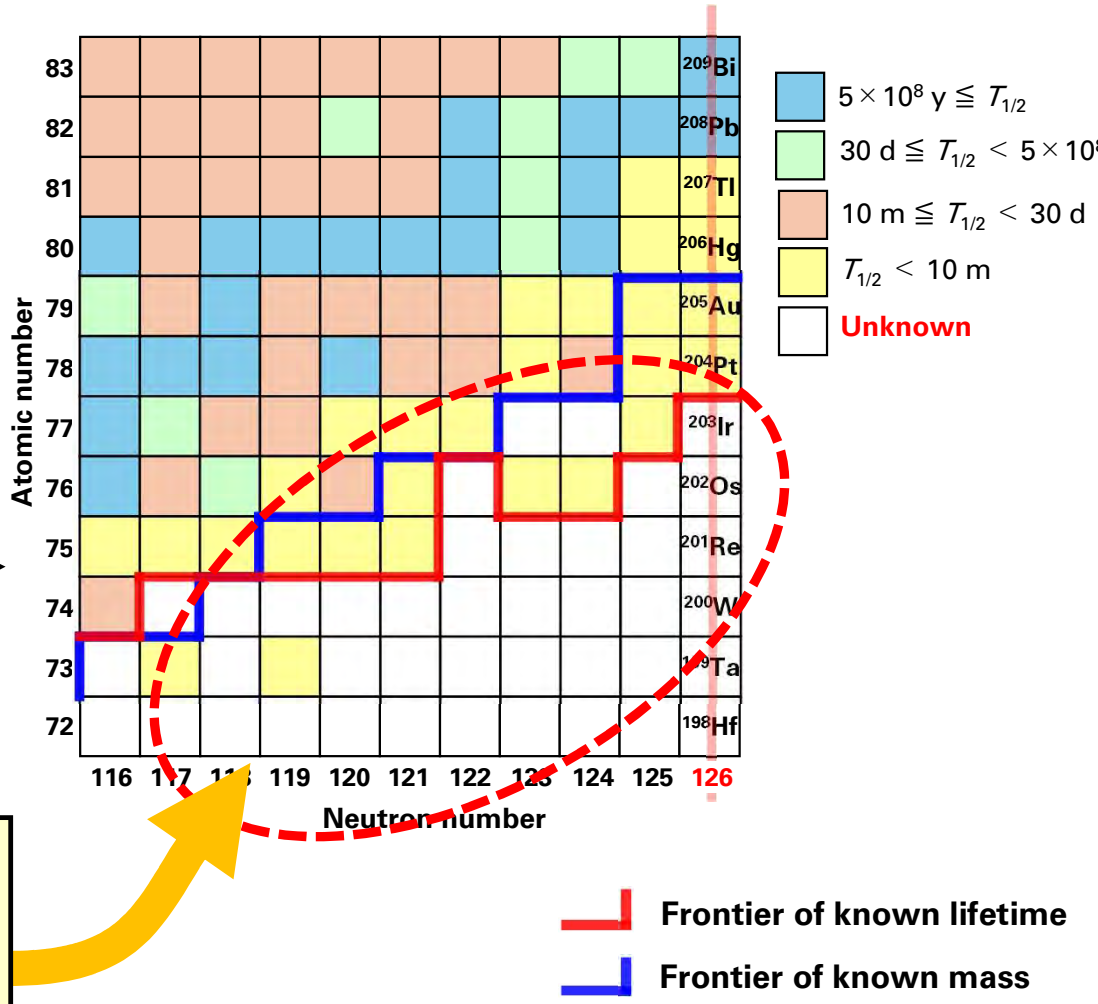


H. Schatz, J. Phys. G: Nucl. Part. Phys. 43, 064001 (2016).

Spectroscopy of neutron-rich nuclei around N=126



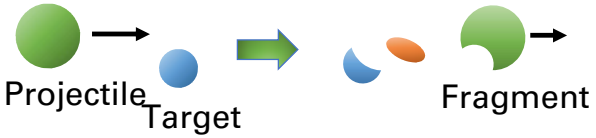
H. Grawe et al., Rept. Prog. Phys. 70, 1525 – 1582 (2007).



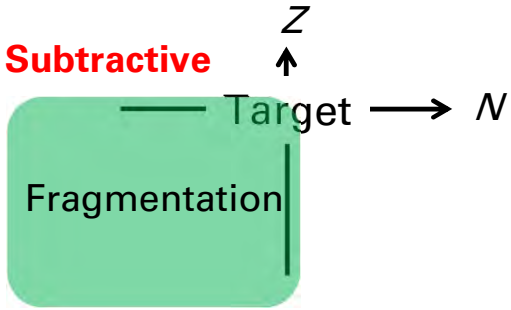
- ◆ Decay spectroscopy
  - ➢ Half life
  - ➢ Decay scheme
- ◆ Laser spectroscopy
  - ➢ Charge radius
  - ➢ Magnetic dipole moment
  - ➢ Electric quadrupole moment
- ◆ Mass spectrometry

How to produce neutron-rich nuclei

Fragmentation (~100 MeV/*A*)



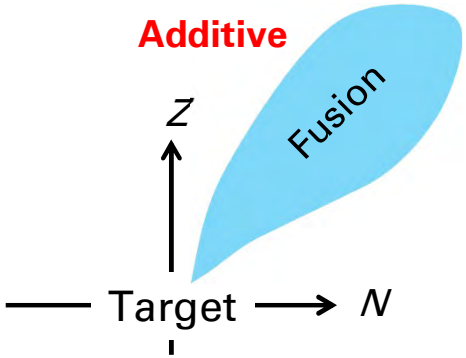
RIBF, FRIB, FAIR, …



Access to the lower left direction.

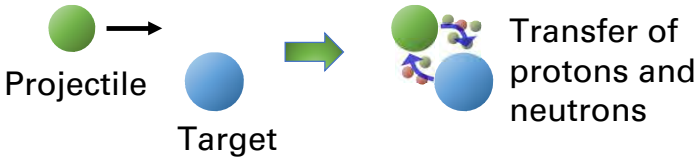
Fusion (~5 MeV/*A*)

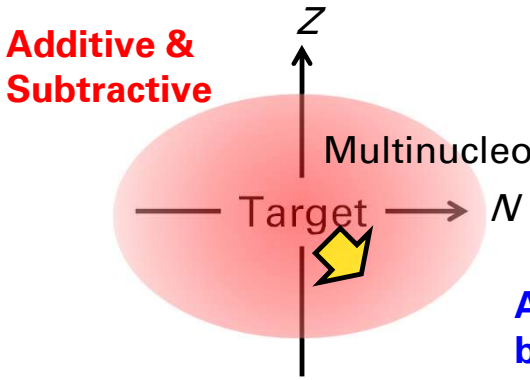
GARIS, SPIRAL2 S³, …



Access to the upper right direction.

Multinucleon transfer (5 – 10 MeV/*A*)

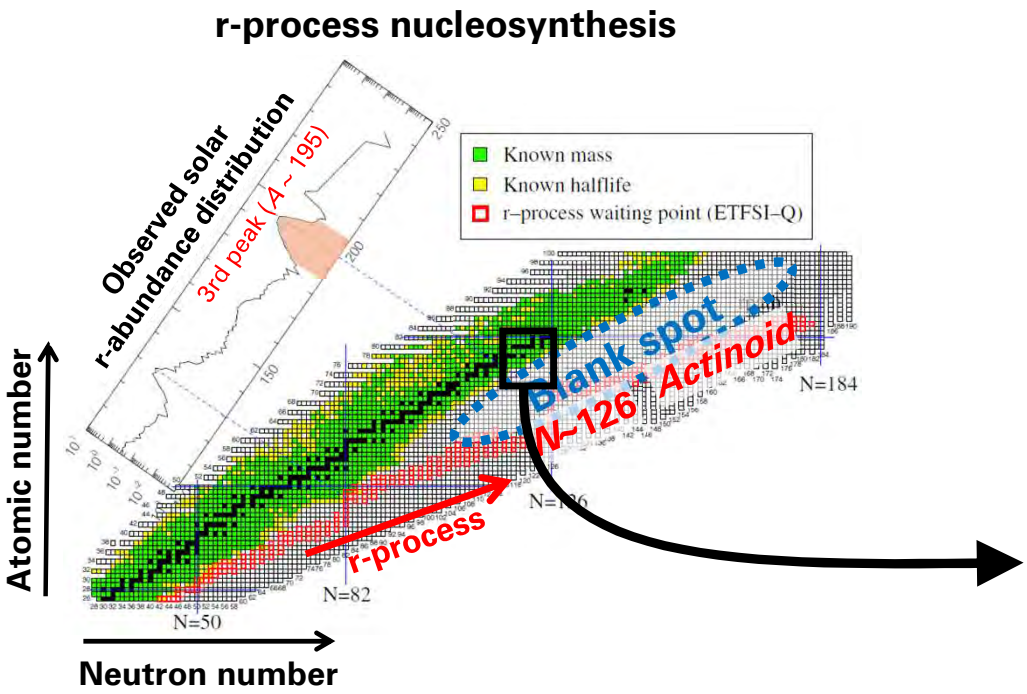




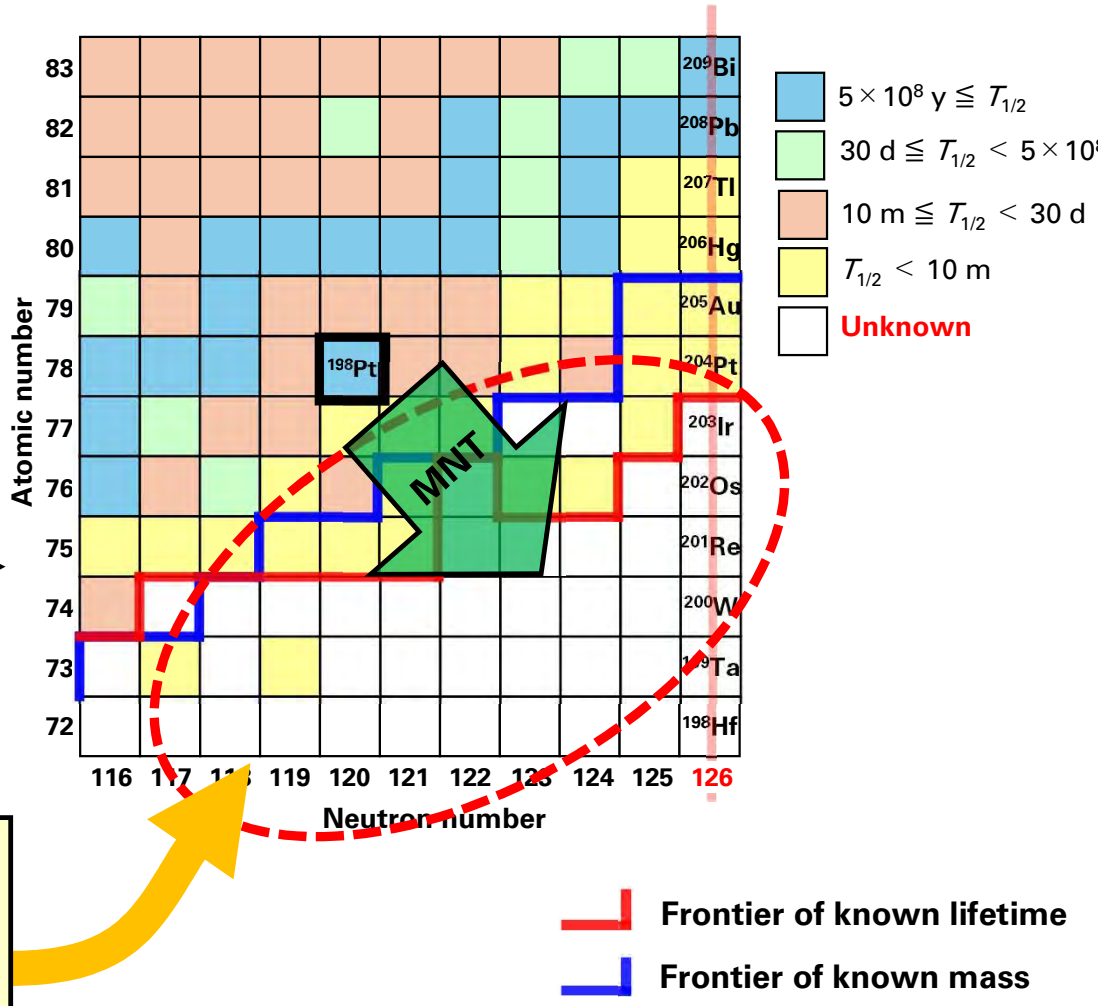
Access to all direction.

Access to the lower right direction
by adding neutrons and subtracting protons.

Spectroscopy of neutron-rich nuclei around N=126 and beyond

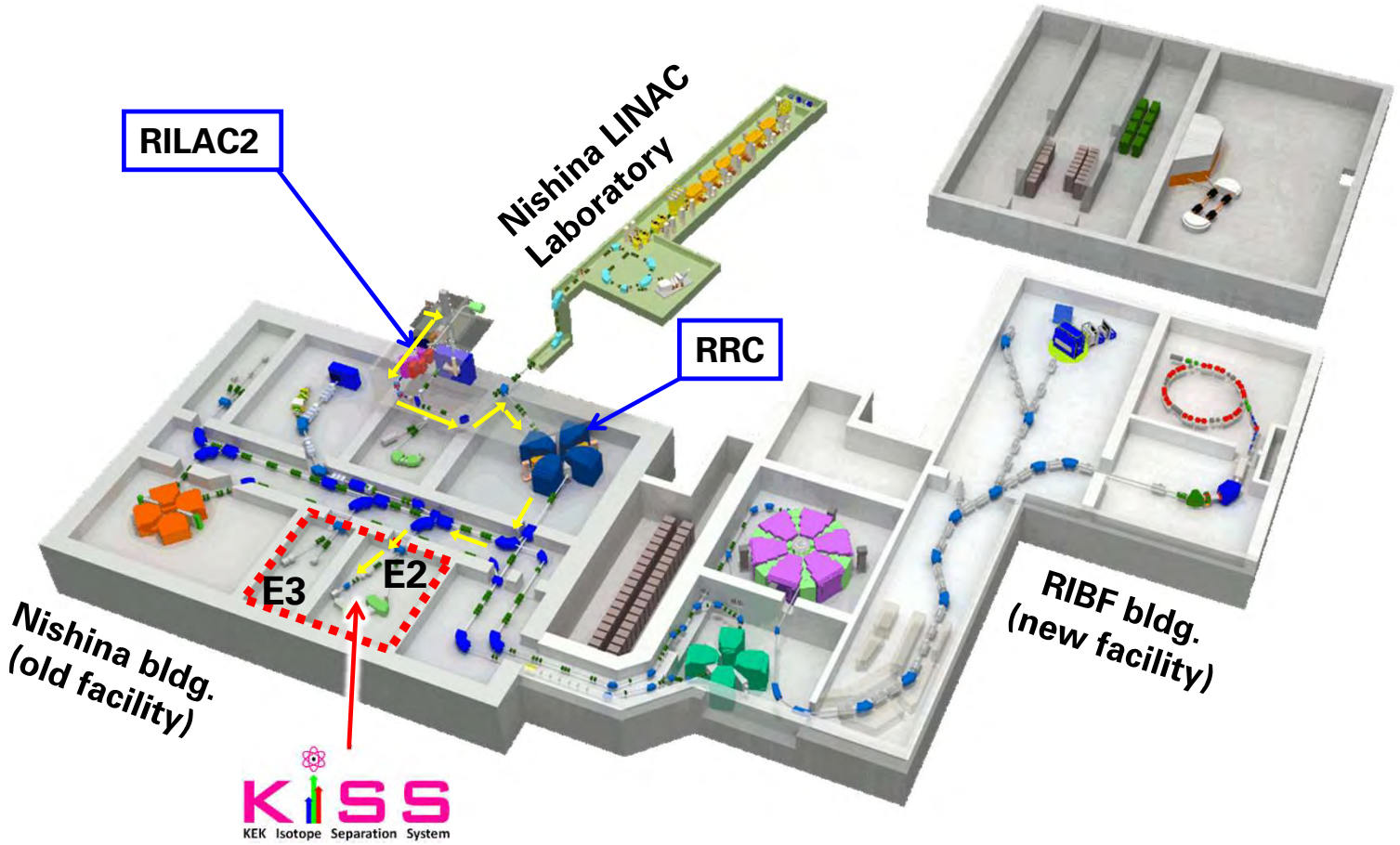


H. Grawe et al., Rept. Prog. Phys. 70, 1525 – 1582 (2007).



- **Decay spectroscopy**
  - Half life
  - Decay scheme
- **Laser spectroscopy**
  - Charge radius
  - Magnetic dipole moment
  - Electric quadrupole moment
- **Mass spectroscopy**

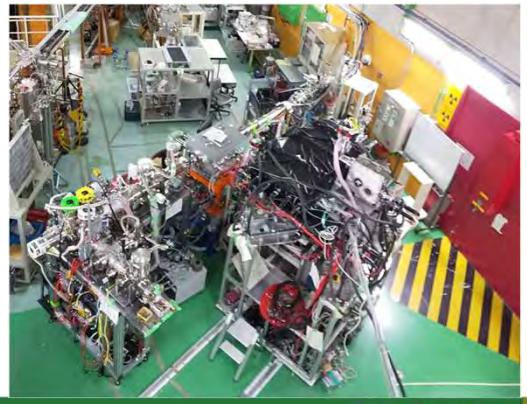
RIKEN RIBF (RI Beam Factory)



KEK Isotope Separation System

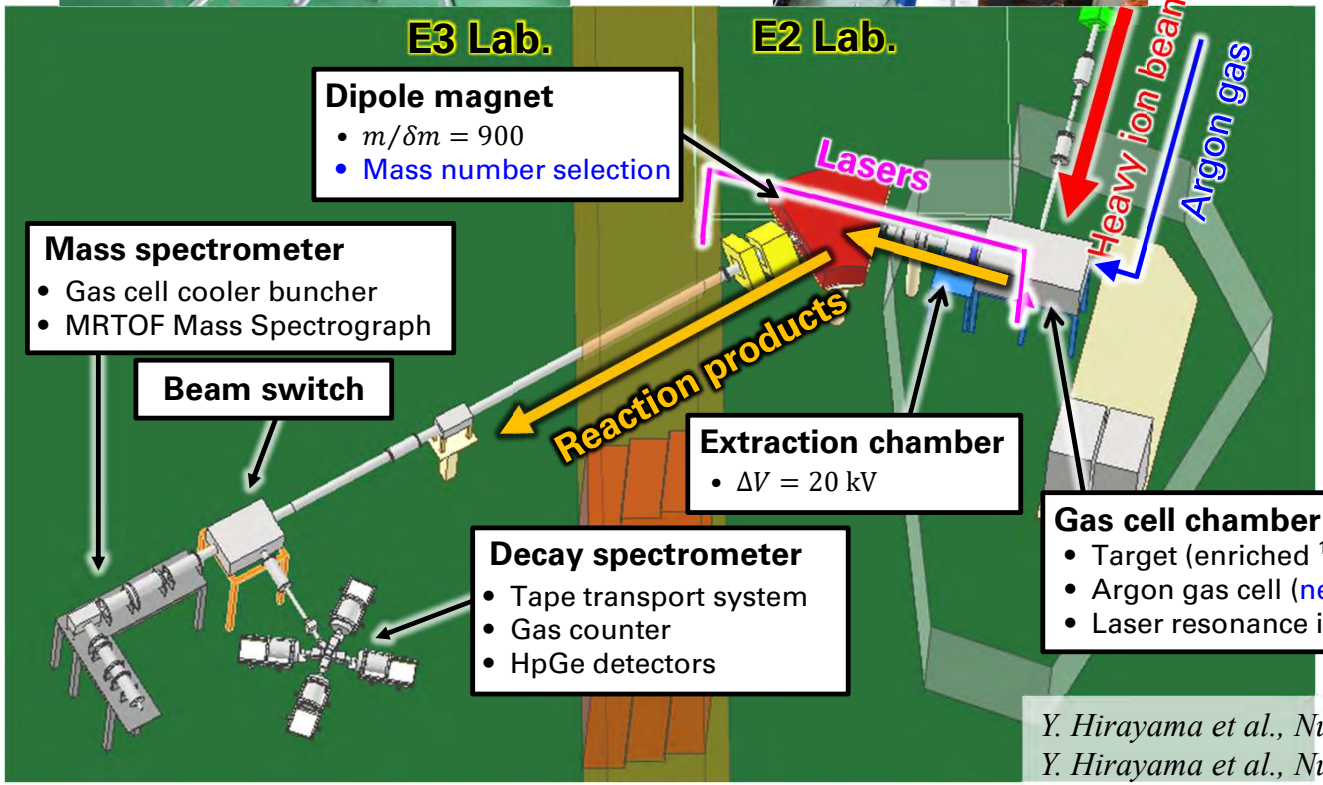
Heavy ion beams (^{136}Xe, ^{238}U, …),* 10.75 MeV/*nucleon,* ≲ *100 pnA

KEK Isotope Separation System (KISS)



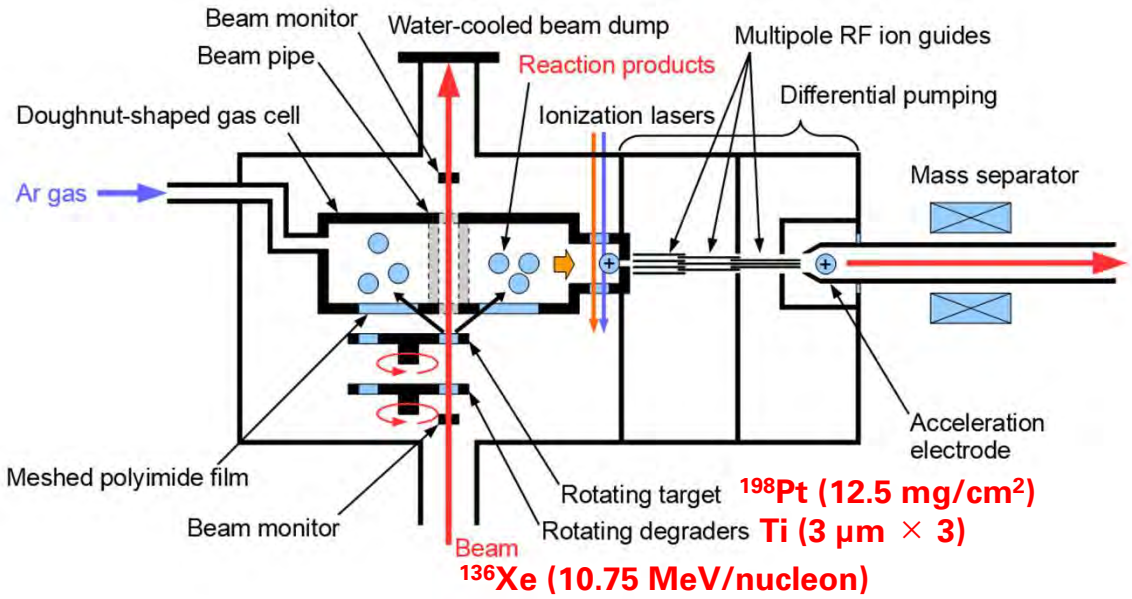
KISS
KEK Isotope Separation System

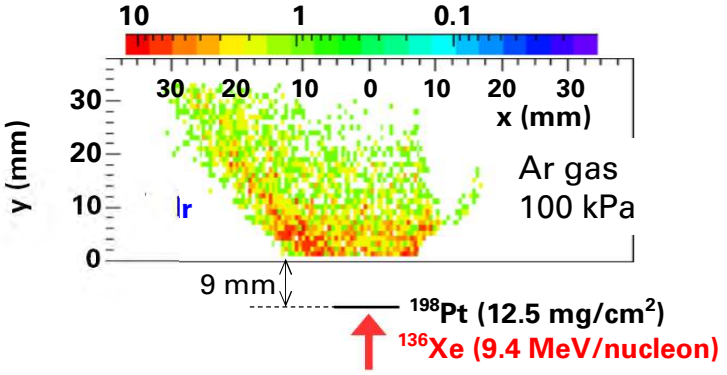
2009: KISS project started
2011: KISS installed
2013: Online testing started
2015: WNSC established
2016: KISS has been open for users



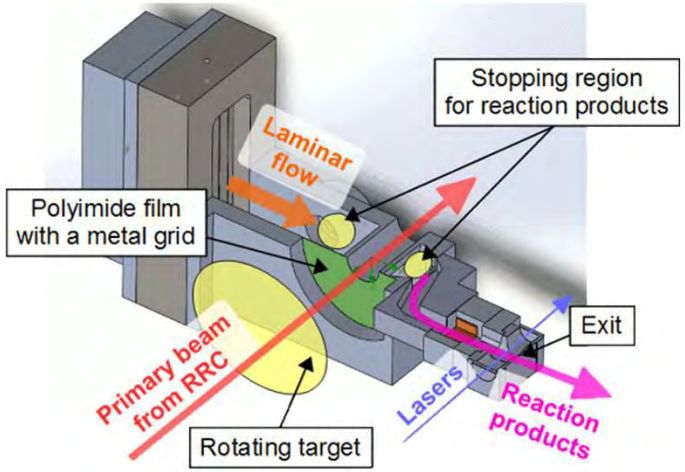
Y. Hirayama et al., Nucl. Instrum. and Meth. B 353, 4 – 15 (2015),
Y. Hirayama et al., Nucl. Instrum. and Meth. B 412, 11 – 18 (2017).

Production, collection, and separation





Doughnut-shaped argon gas cell

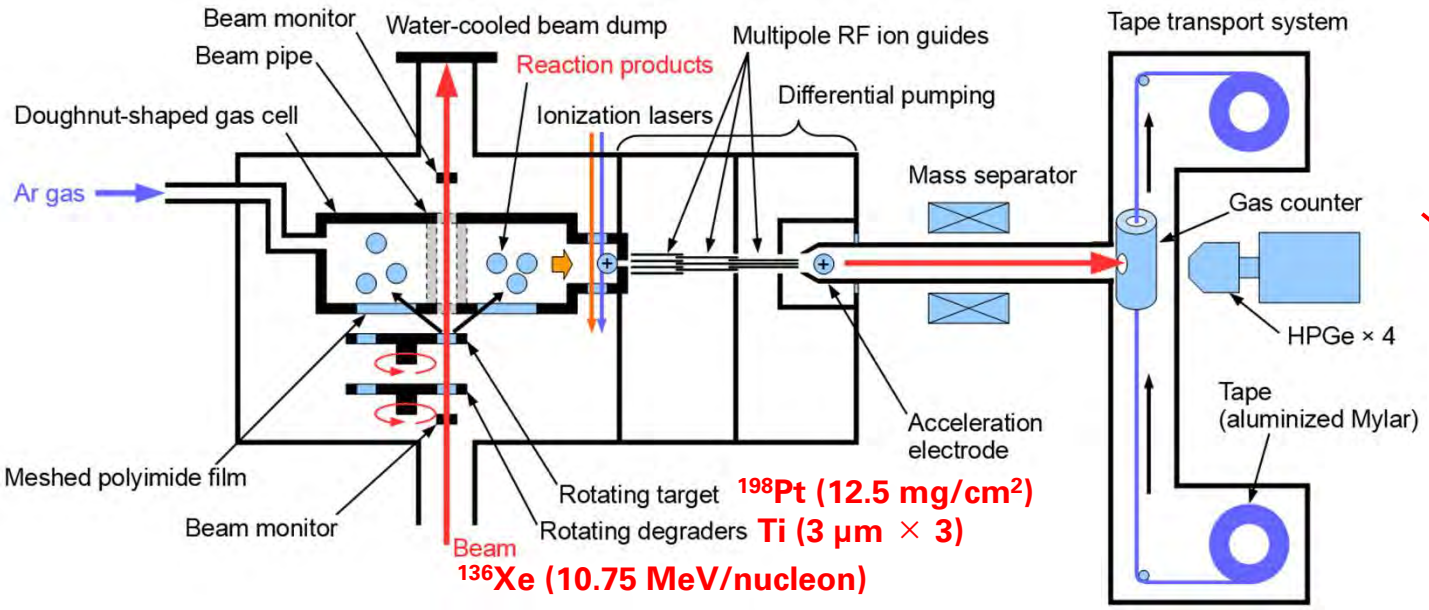


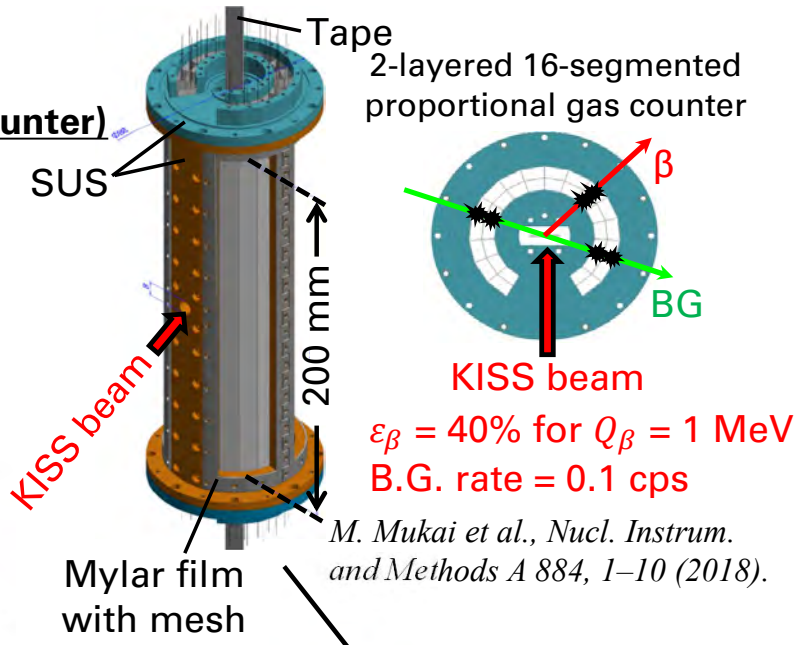
- Nuclear production by multinucleon transfer (MNT) reactions
- Efficient collection of reaction products by gas cell
- Neutralization in argon gas
- Element selection by laser resonance ionization
- Mass selection by dipole magnet

Y. Hirayama et al., Nucl. Instrum. and Meth. B 412, 11 – 18 (2017).

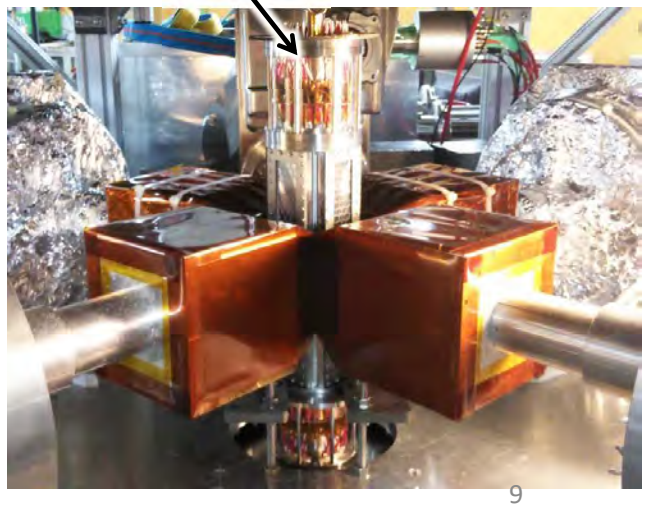
Decay spectroscopy

MSPGC
(Multi-Segmented Proportional Gas Counter)





M. Mukai et al., Nucl. Instrum. and Methods A 884, 1–10 (2018).



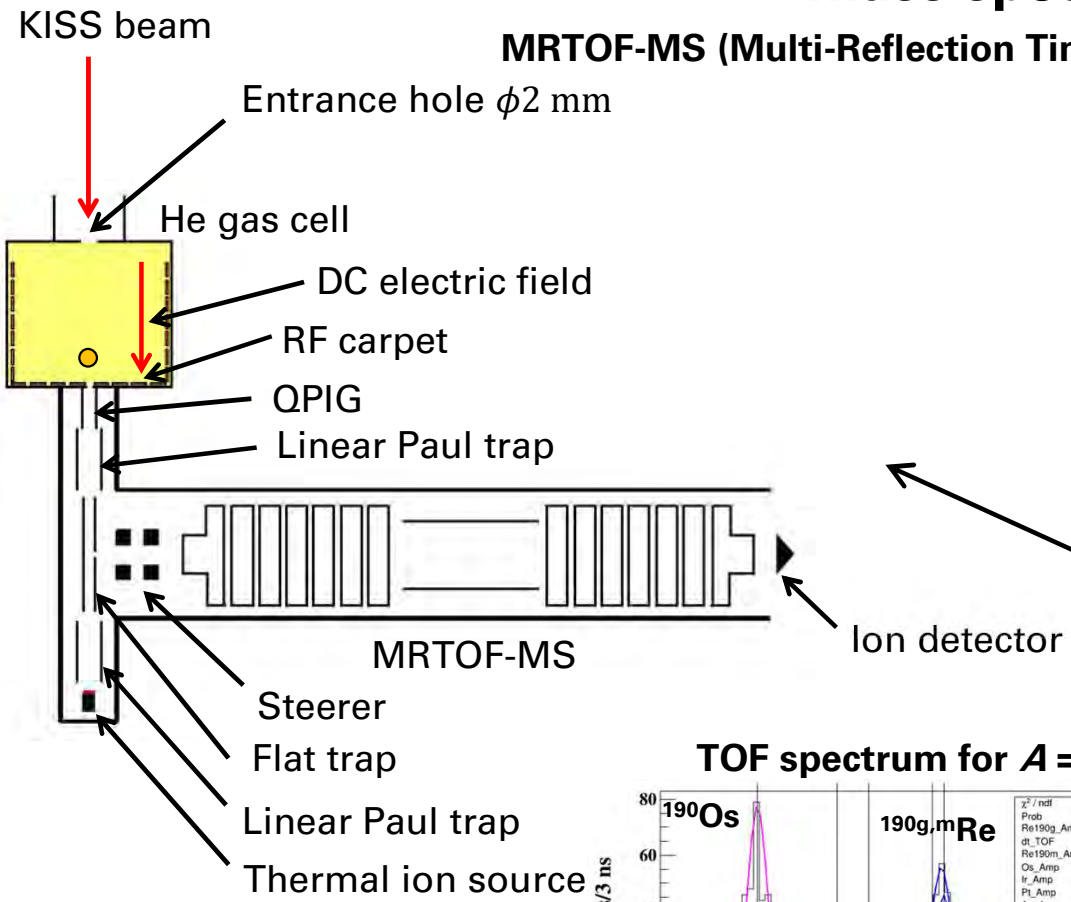
Four HPGe (High-Purity Germanium) clover detectors

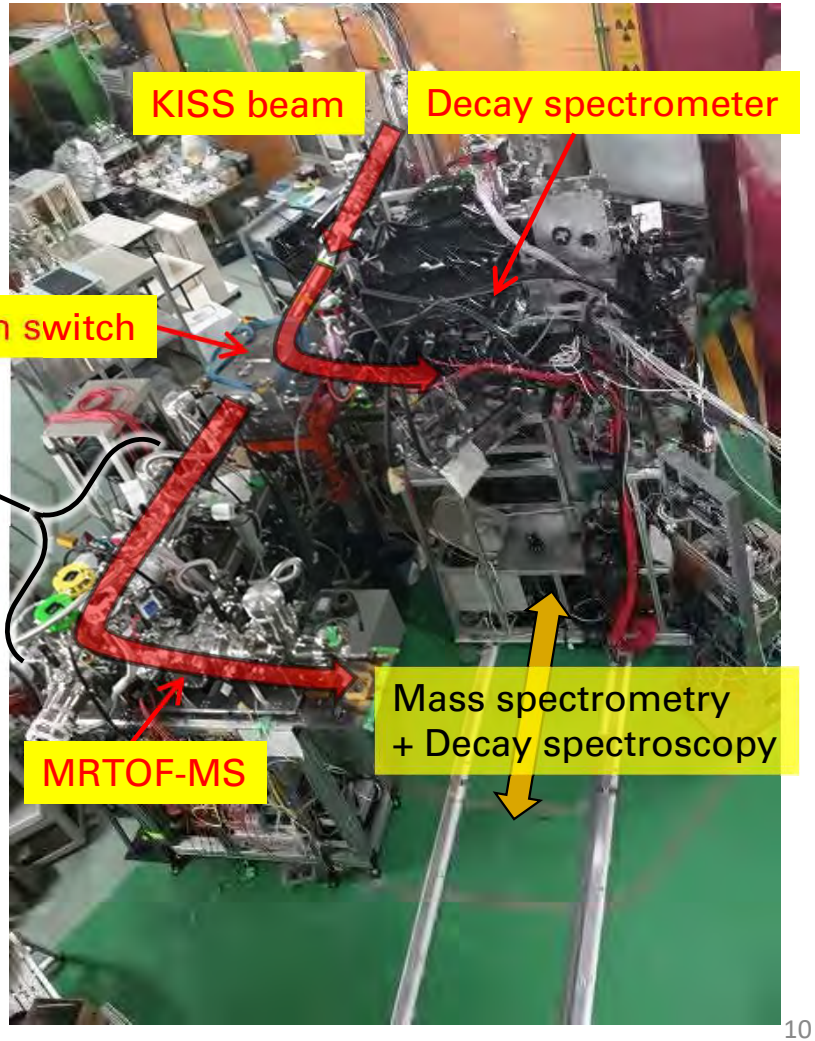
ε_γ = 10% for E_γ = 1 MeV

Collaboration with IBS (Korea), IMP (China)

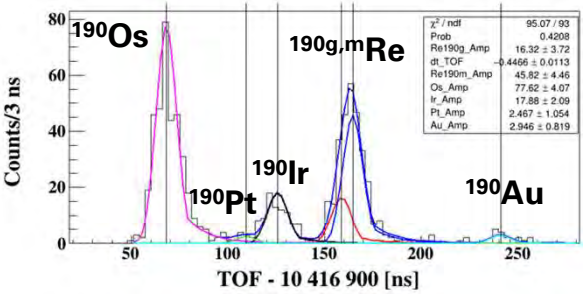
Mass spectrometry

MRTOF-MS (Multi-Reflection Time-Of-Flight Mass Spectrograph)



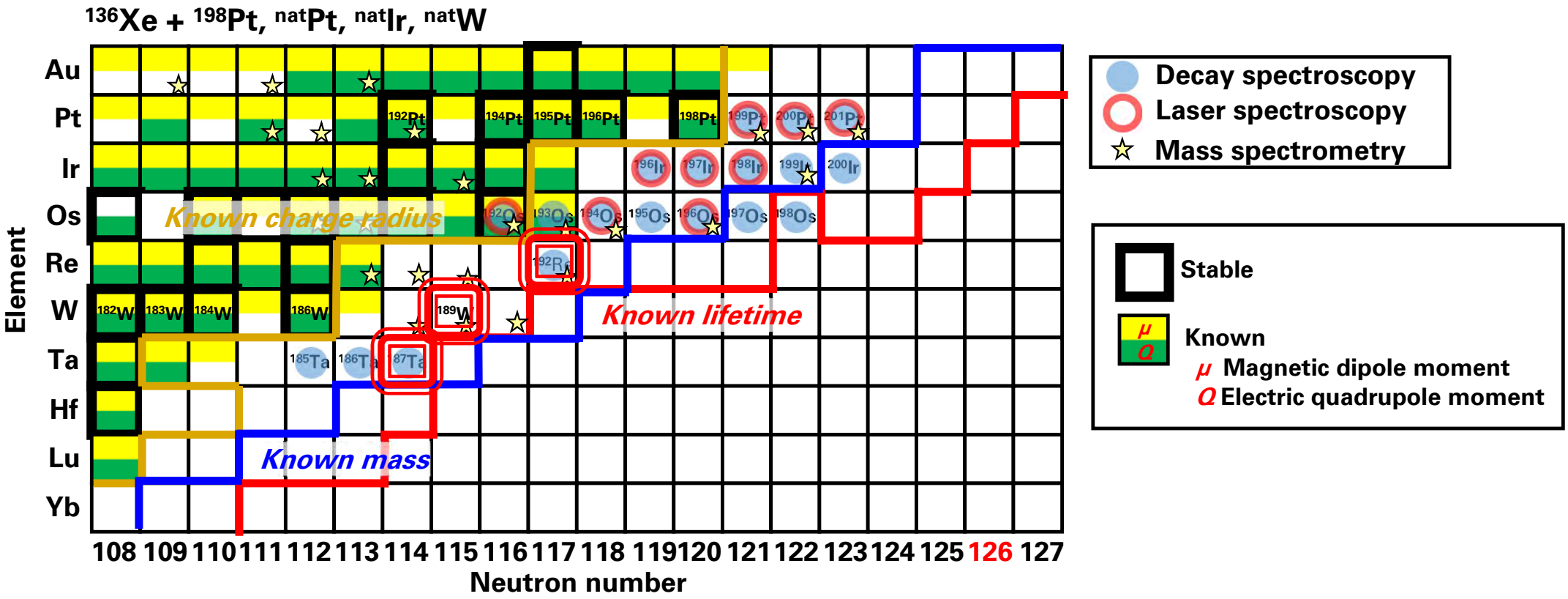


TOF spectrum for $A = 190$



Measurement time: a few 10 ms
Mass resolving power: > 400 000
Efficiency: ~3%

Experimental results ($N \sim 126$)



Decay spectroscopy / Laser spectroscopy / Mass spectrometry

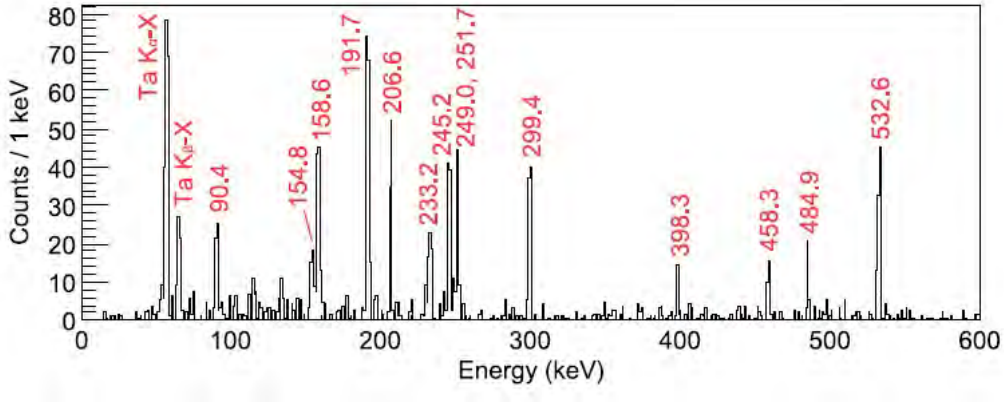
^{189}W, ^{192}Re : *M. Mukai et al., Phys. Rev. C 111, 014322 (2025).*
^{187m2}Ta : *J.L. Chen et al., Phys. Rev. C 111, 014304 (2025).*
$^{200\text{-}201}$Pt: *Y. Hirayama et al., Phys. Rev. C 106, 034326 (2022).*
^{187g}Ta: *M. Mukai et al., Phys. Rev. C 105, 034331 (2022).*
^{186m}Ta: *Y.X. Watanabe et al., Phys. Rev. C 104, 024330 (2021).*
^{195g}Os: *M. Ahmed et al., Phys. Rev. C 103, 054312 (2021).*

^{195m}Os: *Y.X. Watanabe et al., Phys. Rev C 101, 041305(R) (2020), 103, 019902(E) (2021).*
^{192g}Re: *H. Watanabe et al., Phys. Lett. B 814, 136088 (2021).*
^{187m}Ta: *P. Walker et al., Phys. Rev. Lett. 125, 192505 (2020).*
$^{196-198}$Ir: *M. Mukai et al., Phys. Rev. C 102, 054307 (2020).*
^{194,196}Os: *H. Choi et al., Phys. Rev. C 102, 034309 (2020).*
^{197,198}Os: *Y. Hirayama et al., Phys. Rev. C 98, 014321 (2018), 069902(E) (2022).*
^{199g,m}Pt: *Y. Hirayama et al., Phys. Rev. C 96, 014307 (2017).*

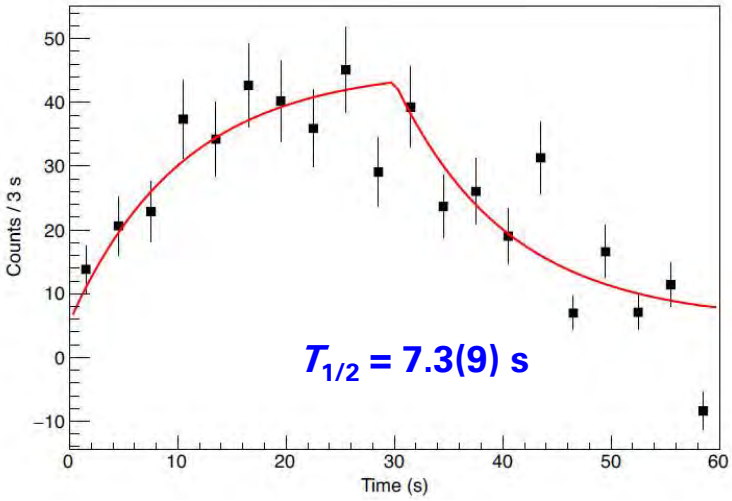
γ-ray spectroscopy of ^{187m1}Ta

^{136}Xe beam + ^{nat}W target

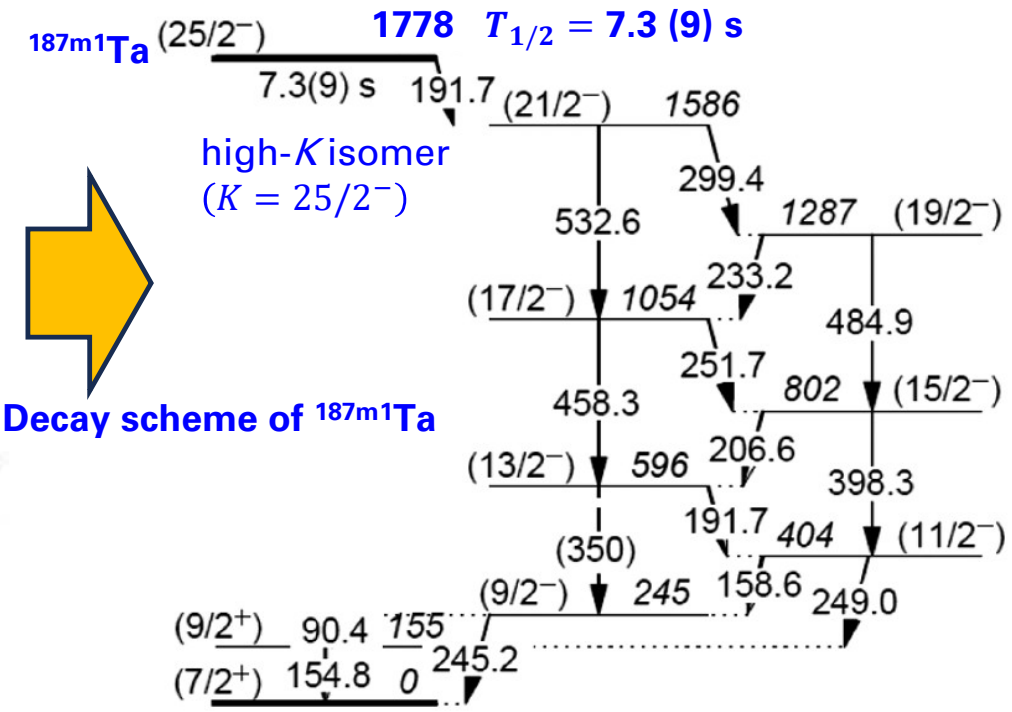
Sum of γ-γ coincidence energy spectra



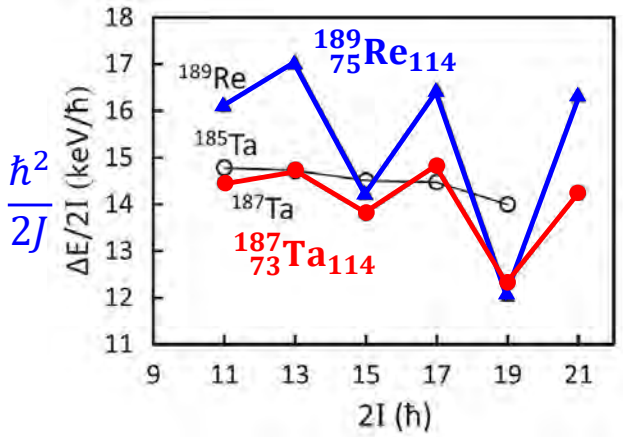
Summed time spectrum of 10 different γ–ray transitions



P.M. Walker et al., Phys. Rev. Lett. 125, 192505 (2020).



Decay scheme of ^{187m1}Ta



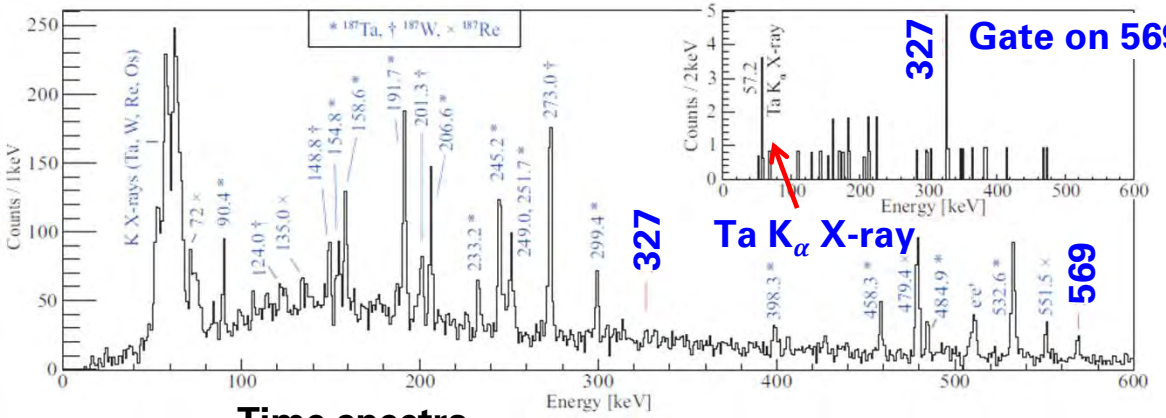
Moment of inertia in $9/2^-$ band

"As Z decreases, the β_2 deformation increases and triaxiality plays a reduced role."

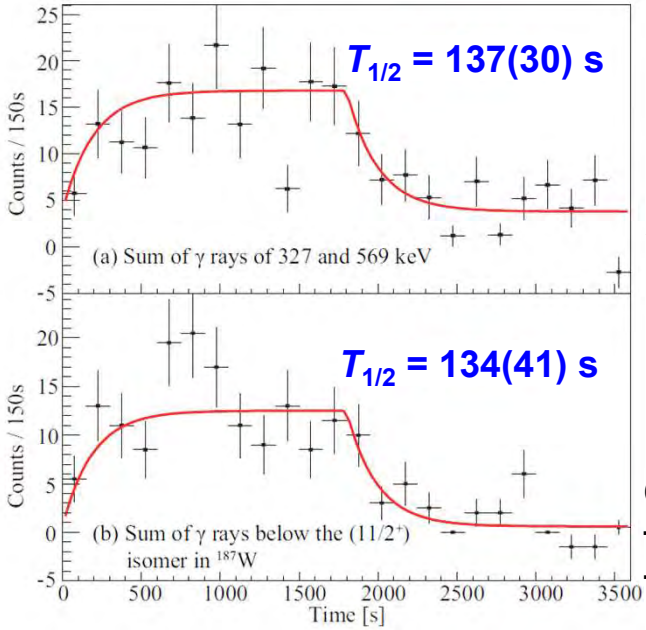
e-γ nuclear spectroscopy of ^{187}Ta

^{136}Xe beam + ^{nat}W target

γ-ray energy spectrum in coincidence with MSPGC (*M* = 1)



Time spectra

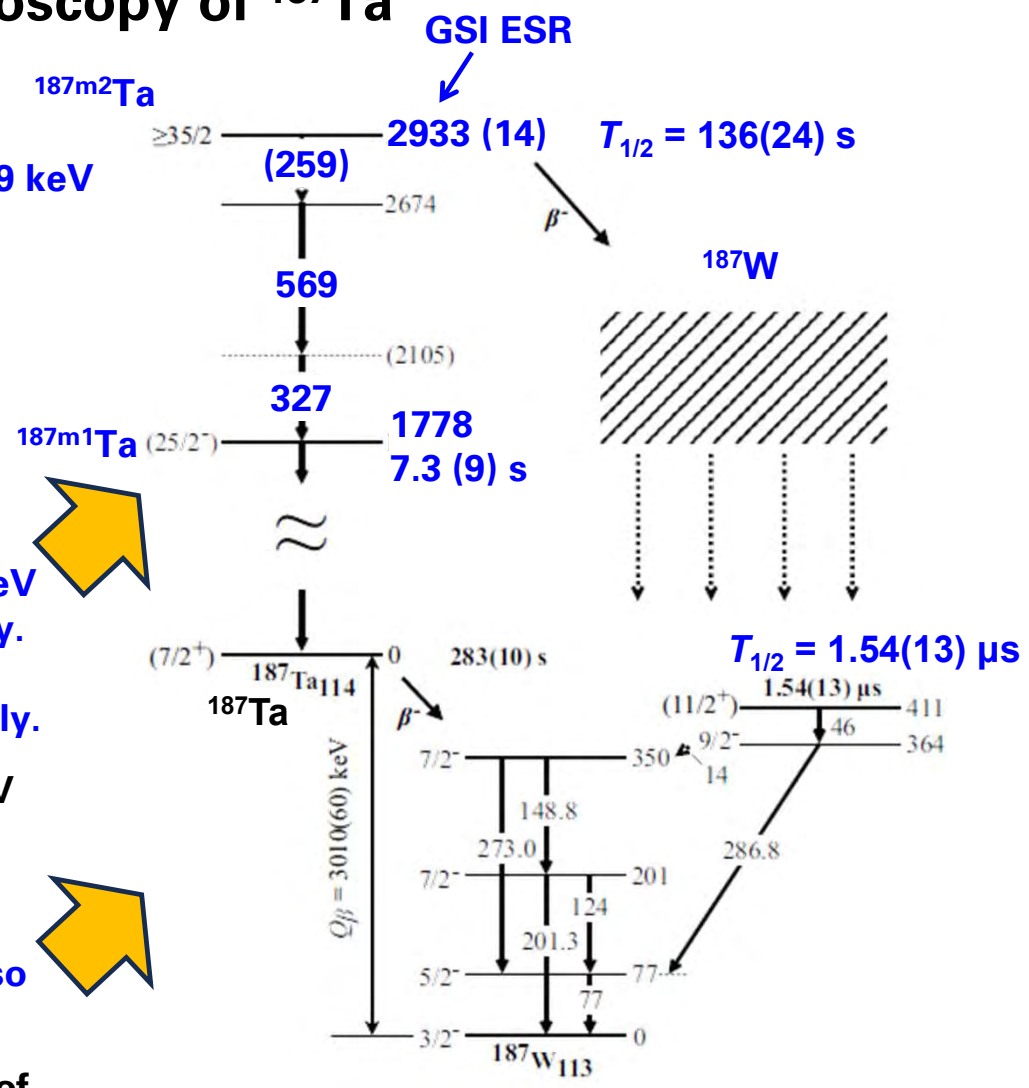


***γ*-rays of 327 keV and 569 keV are observed simultaneously. Ta characteristic X-rays are also observed simultaneously.**

Gate on 327-keV and 569-keV γ-rays

***β* decay branching was also observed.**

Gate on γ-rays downstream of the 11/2⁺ state of ^{187}W with e-γ time window of 0.2 – 0.8 μs.

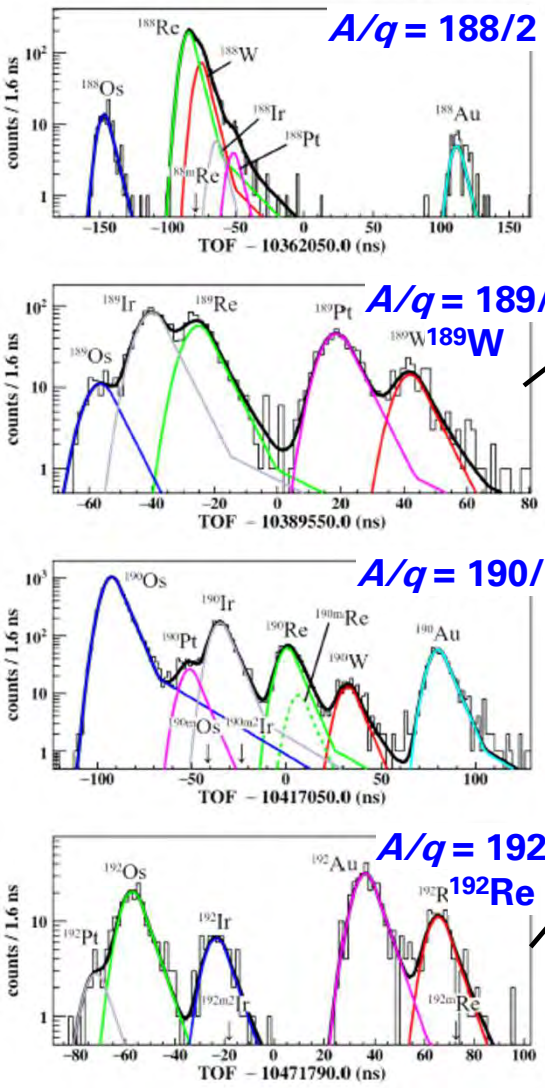


J.L. Chen et al., Phys. Rev. C 111, 014304 (2025).

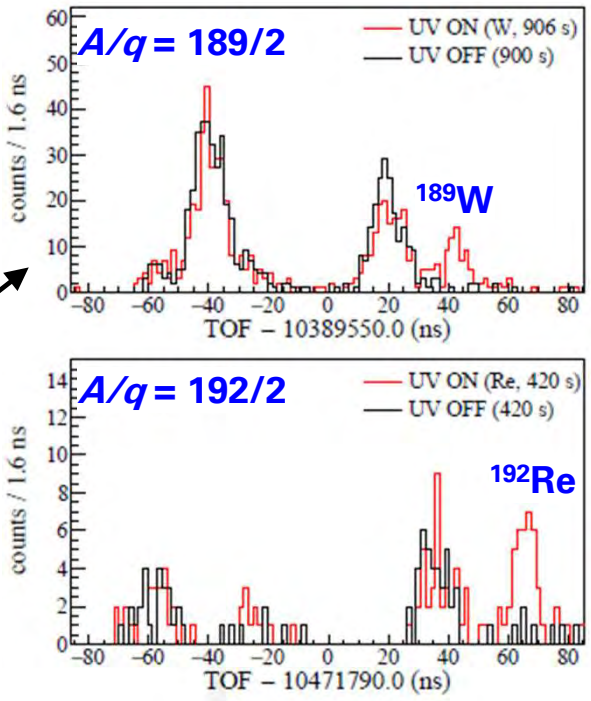
Mass spectrometry of ^{189}W, ^{192}Re

^{136}Xe beam + ^{nat}Ir target

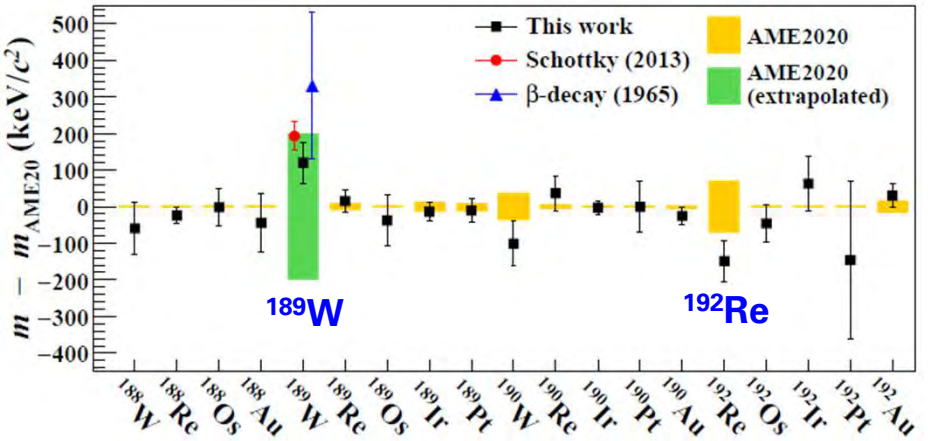
MRTOF time spectra



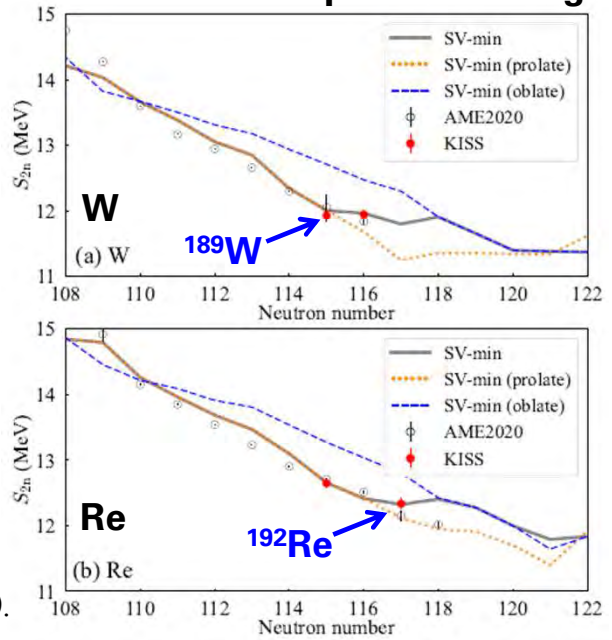
Laser resonance ionization



Atomic mass deviation from AME2020



Two-neutron separation energies

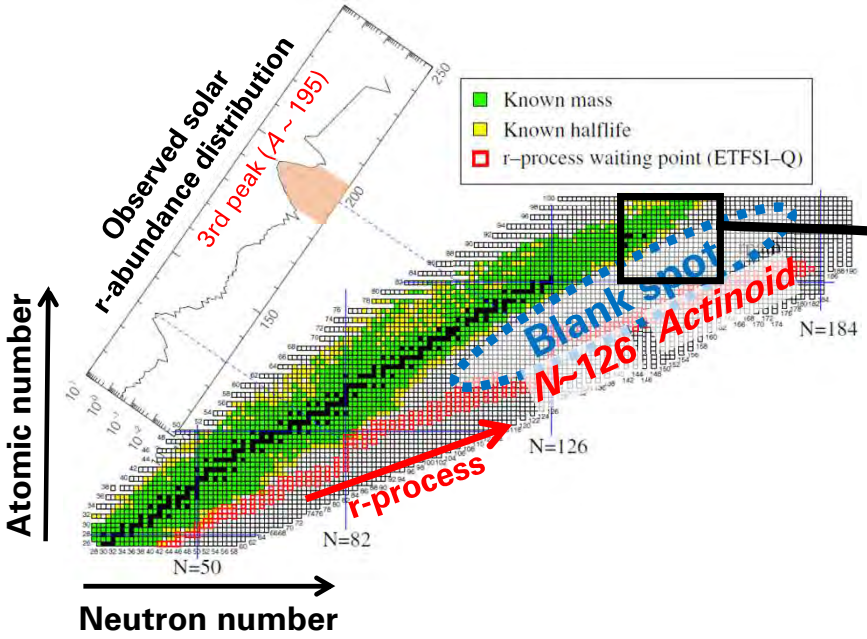


Shape transition from prolate to oblate

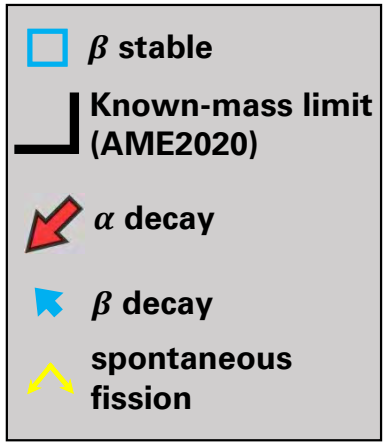
M. Mukai et al., Phys. Rev. C 111, 014322 (2025).

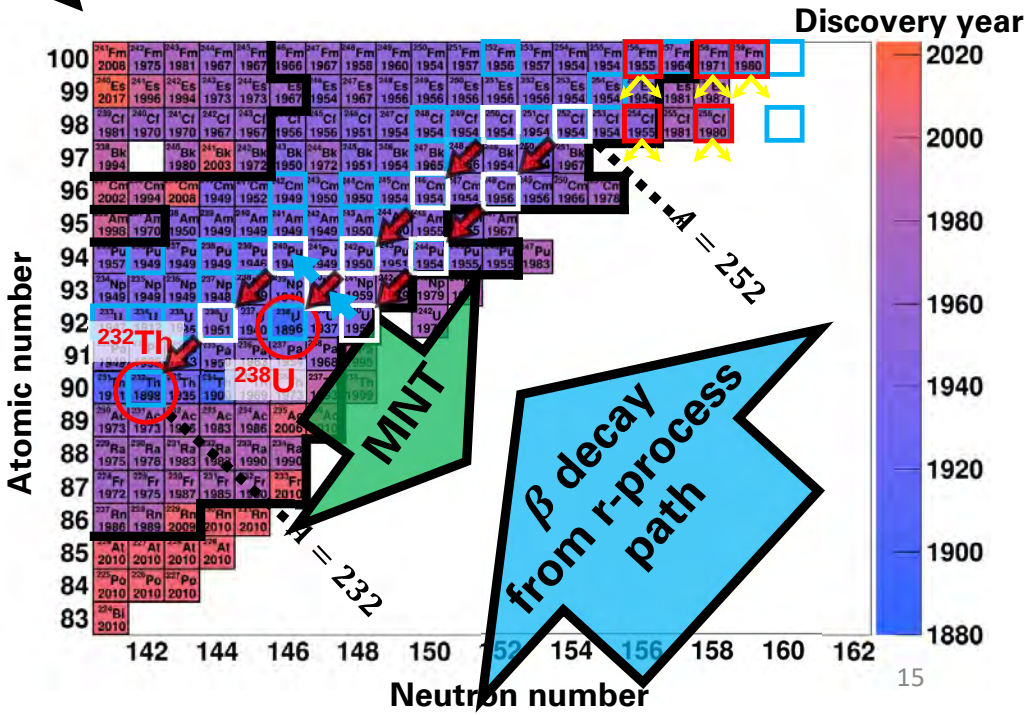
Spectroscopy of neutron-rich actinide nuclei

r-process nucleosynthesis



H. Grawe et al., Rept. Prog. Phys. 70, 1525 – 1582 (2007).

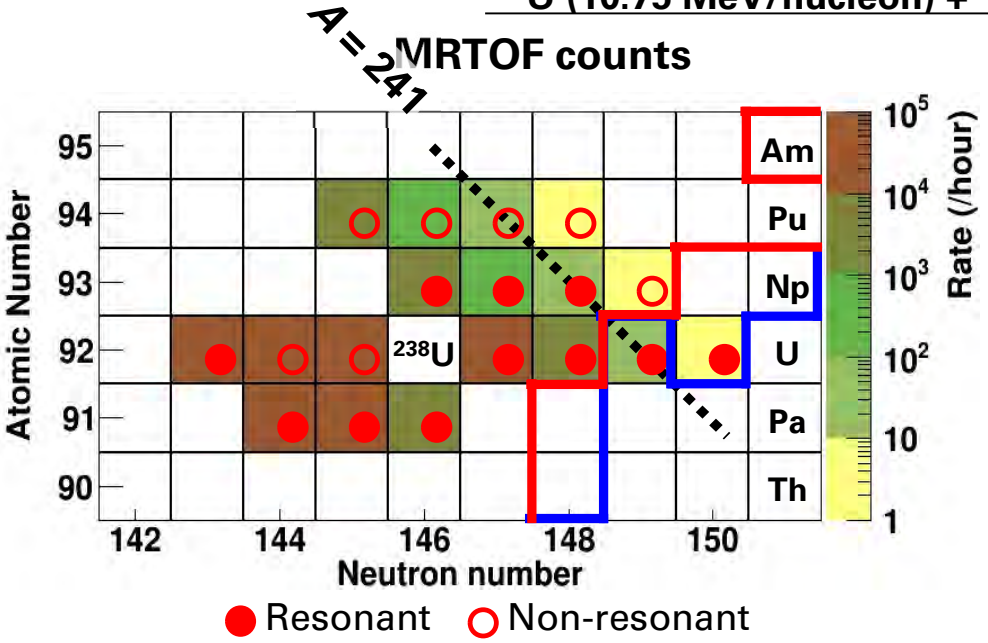




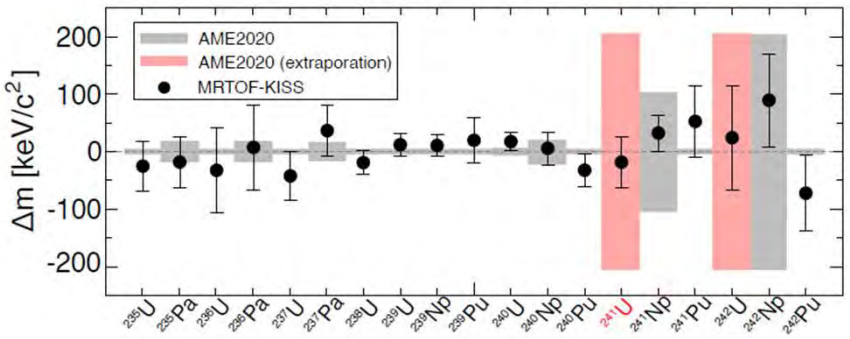
- **Decay spectroscopy**
  - Half life
  - Decay scheme
- **Laser spectroscopy**
  - Charge radius
  - Magnetic dipole moment
  - Electric quadrupole moment
- **Mass spectroscopy**

Mass spectroscopy of neutron-rich actinoids

^{238}U (10.75 MeV/nucleon) + ^{198}Pt (12.5 mg/cm^2)



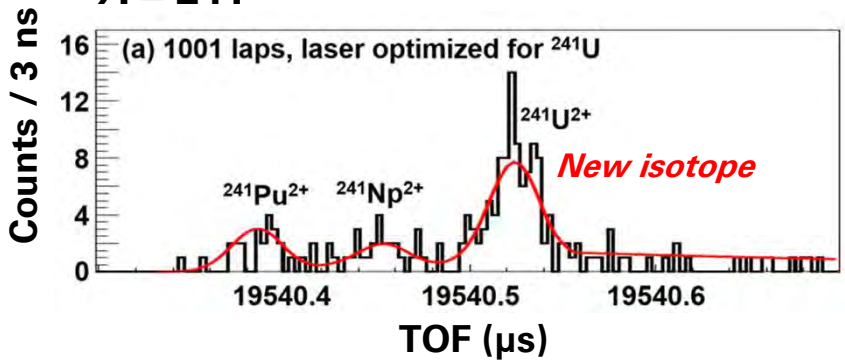
Mass difference from AME2020

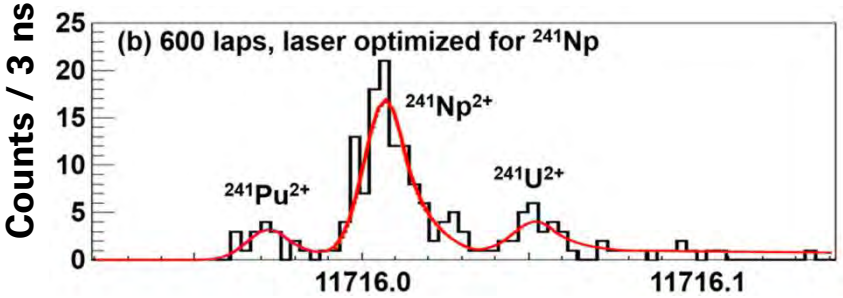


T. Niwase et al., Phys. Rev. Lett. 130, 132502 (2023).

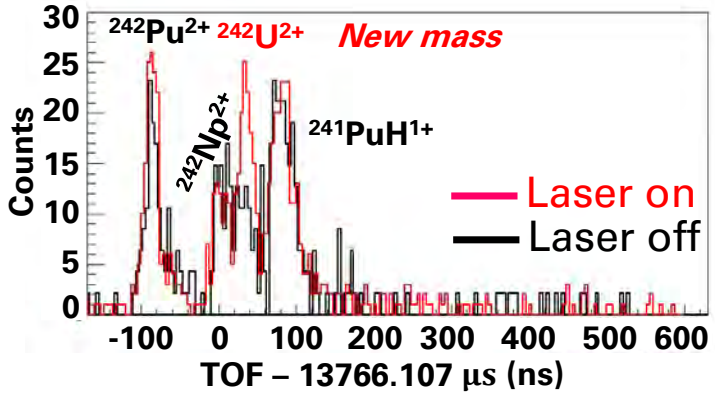
TOF spectrum of MRTOF-MS

A = 241



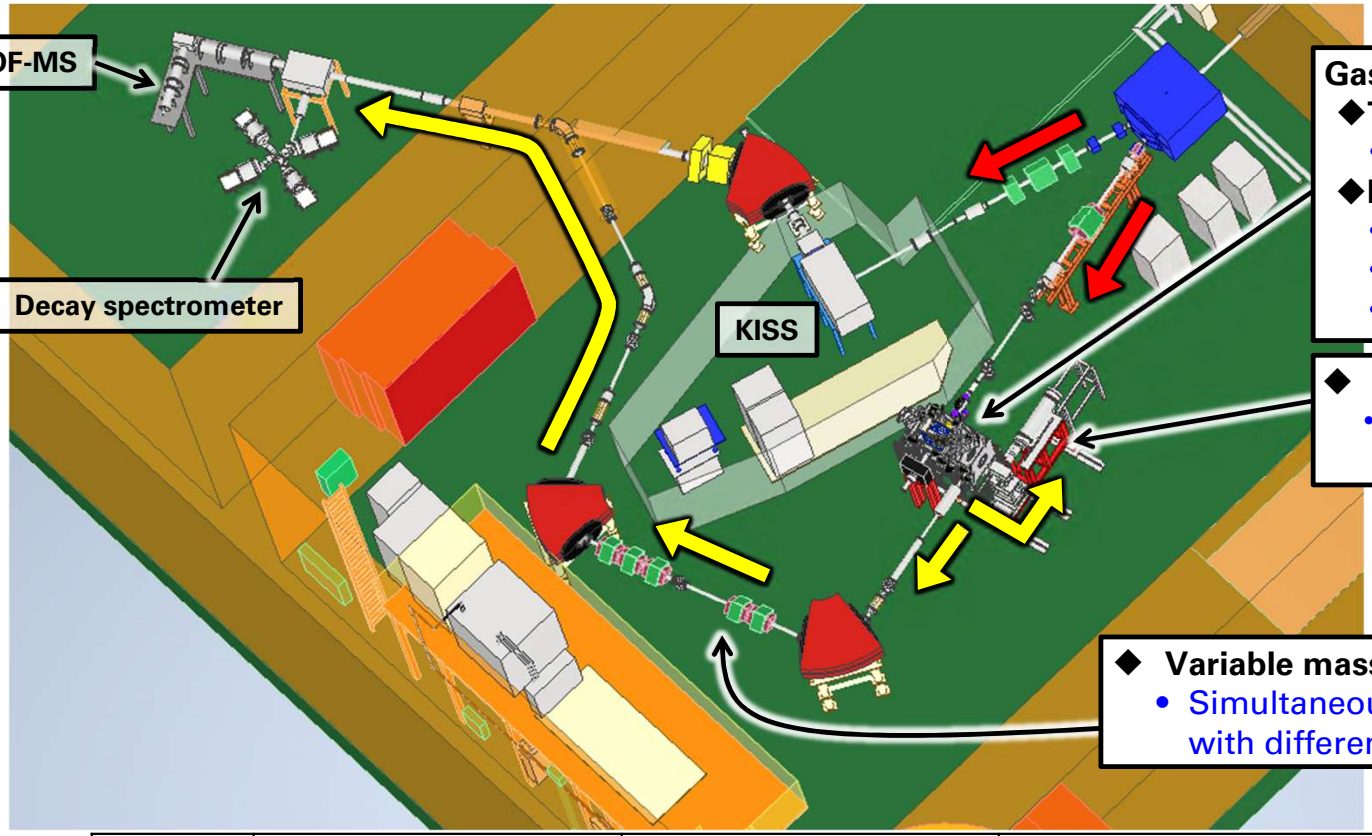


A = 242



Beyond KISS: KISS-1.5

"Don't separate, but measure multiple species at once"



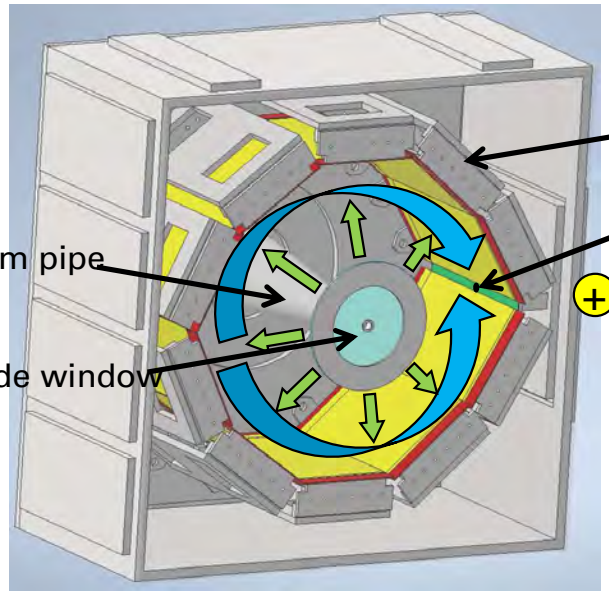
Gas cell chamber
- ◆**Target system**
  - Large rotating ^{nat}U target
- ◆**RF helium gas cell**
  - High beam intensity
  - Collection of reaction products as ions
  - Fast extraction

◆ **MRTOF-MS**
- Direct mass measurements of extracted ions

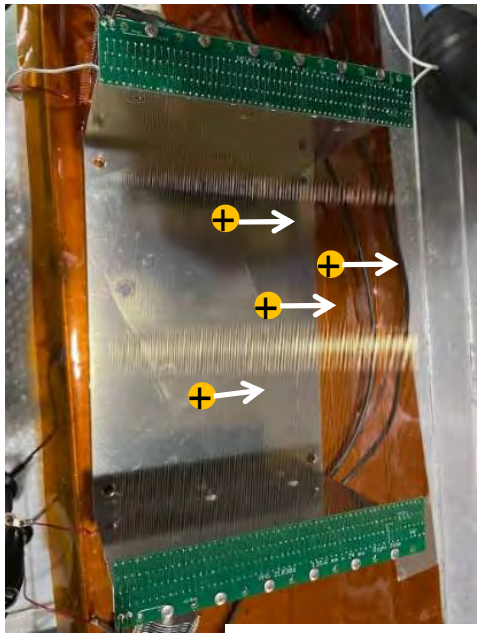
◆ **Variable mass-range separator**
- Simultaneous transport of ions with different mass numbers

	Primary beam	Total efficiency	Simultaneous measured nuclides	Efficacy
KISS	~ 10 pnA	<0.1%	1	1
KISS-1.5	100 pnA	>1%	> 10	100 ~ 1000
	◆ Target system ◆ RF helium gas cell	◆ RF helium gas cell	◆ RF helium gas cell ◆ MRTOF-MS ◆ Variable mass-range separator	

Doughnut-shaped RF helium gas cell

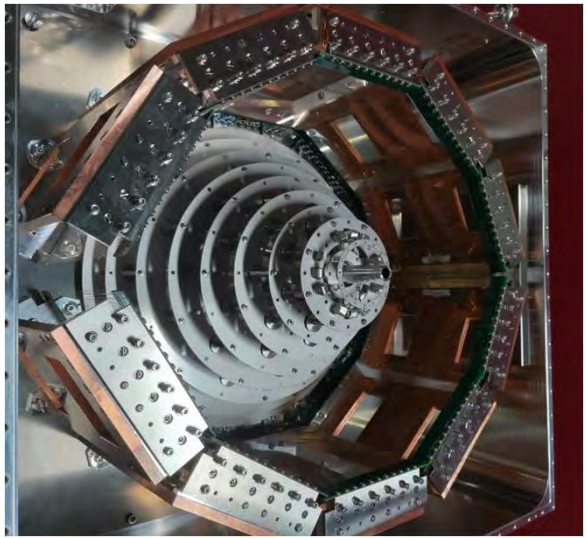


RFWC (RF Wire Carpet)



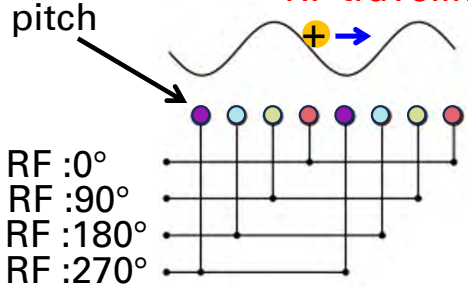
Ion transport by static electric field

Ion transport by RFWC



224 BeCu wires
ϕ100 mm , 0.6 mm pitch

RF traveling wave (RFTW)

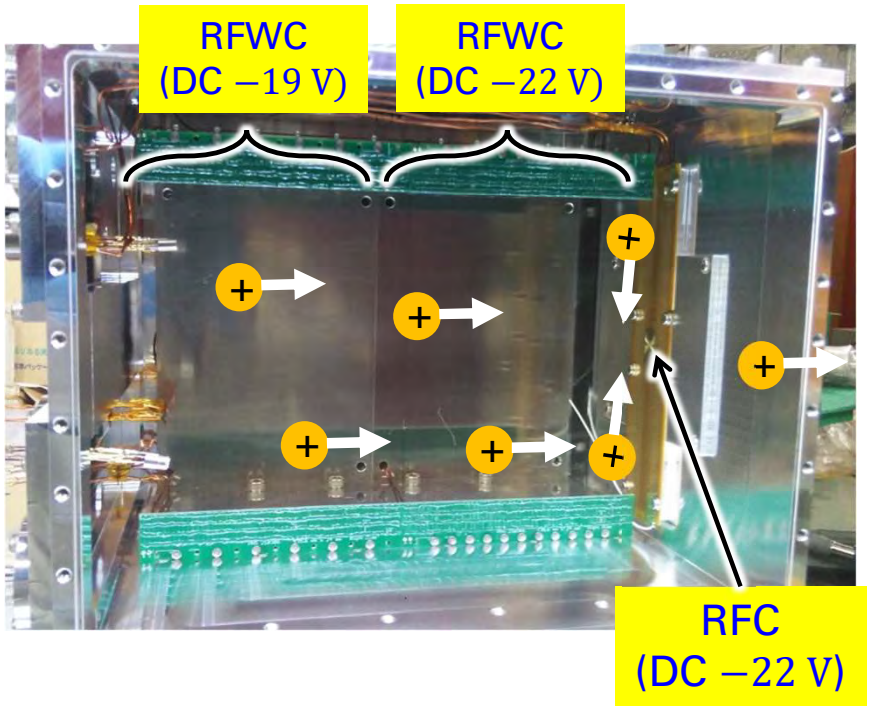


Developed by NSCL : $\varepsilon = 10\%$

K.R. Lund et al., Nucl. Instrum. and Methods B 463, 378.(2020).

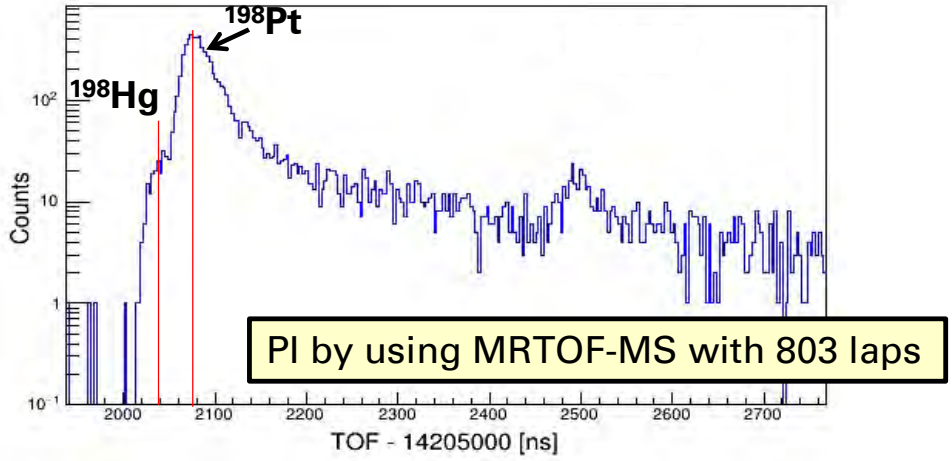
R&D of RF wire carpets

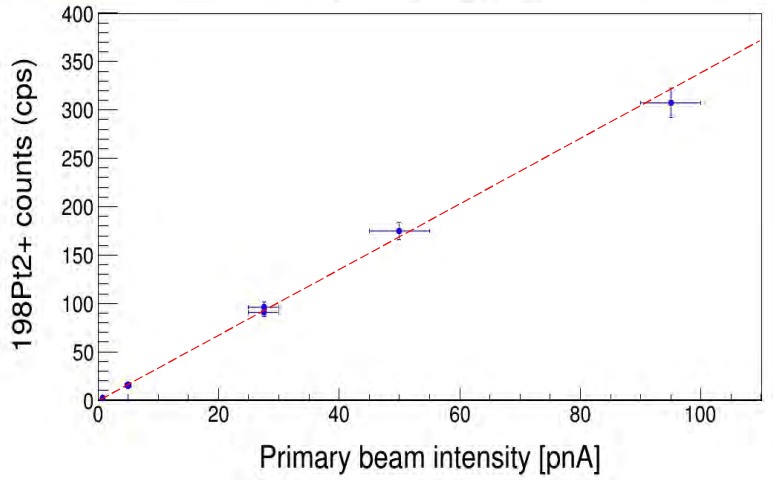
Prototype RF helium gas cell



Y. Hirayama et al., Nucl. Instrument. and Methods A 1058, 168838 (2024).

$^{136}Xe + {}^{198}Pt$

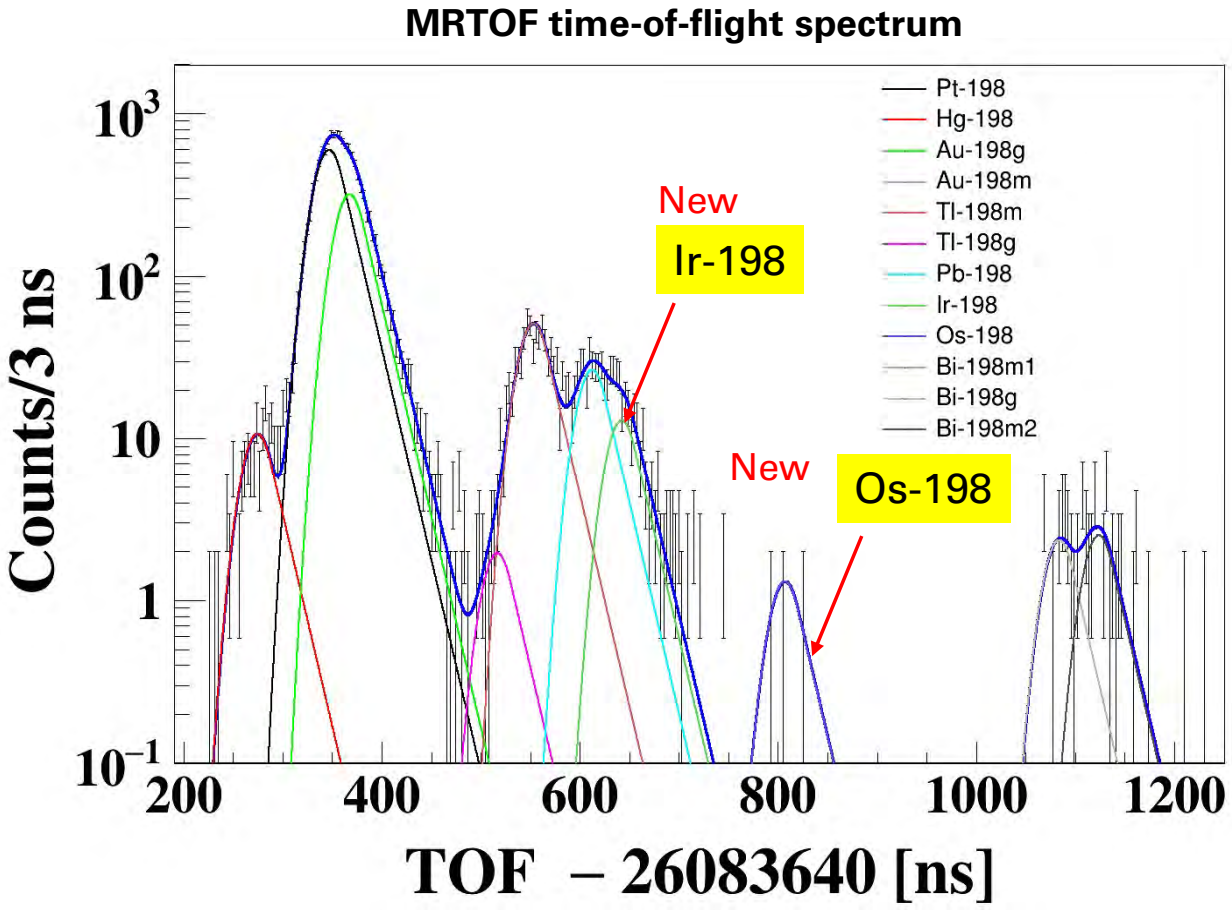


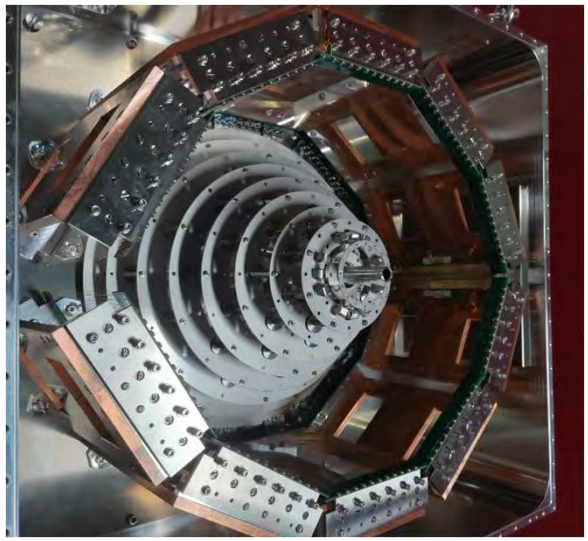


- Beam intensity linearity of the extracted ion counts: up to 100 pnA
  2 times higher than the argon gas cell
- Extraction efficiency: 1%
  10 times higher than the argon gas cell

Online testing of doughnut-shaped RF helium gas cell

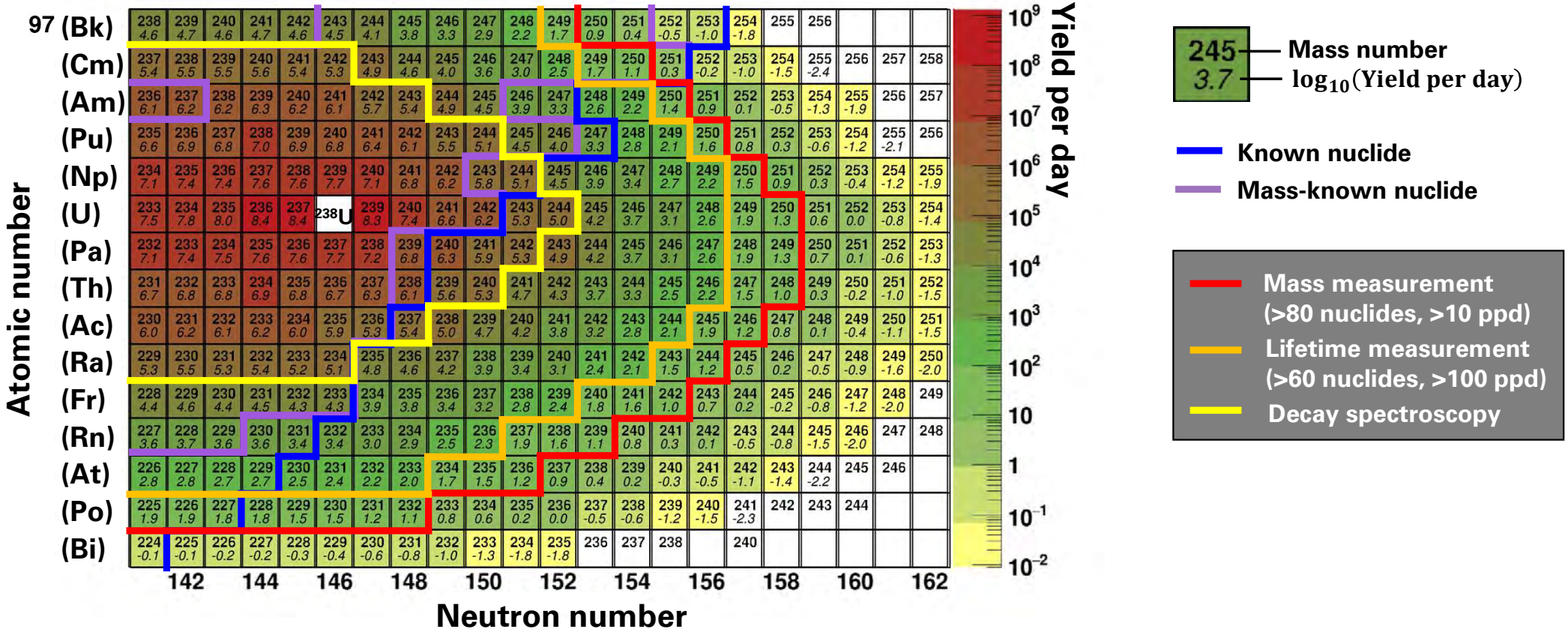
^{136}Xe beam + ^{198}Pt target





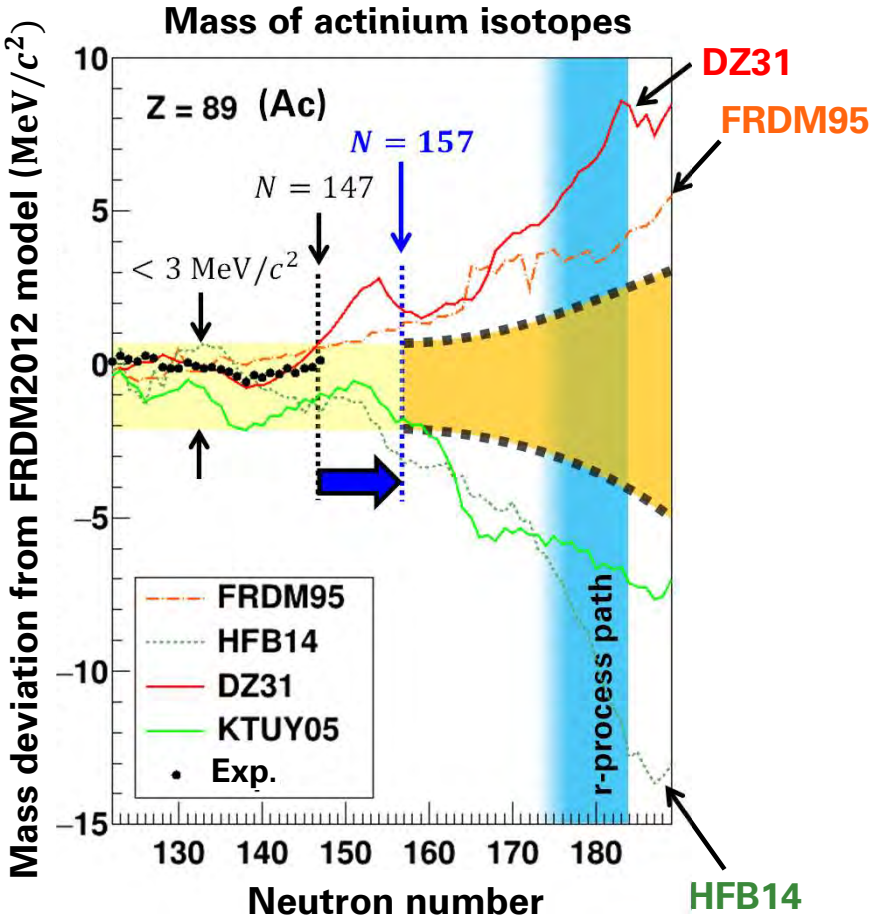
Expected yields at KISS-1.5

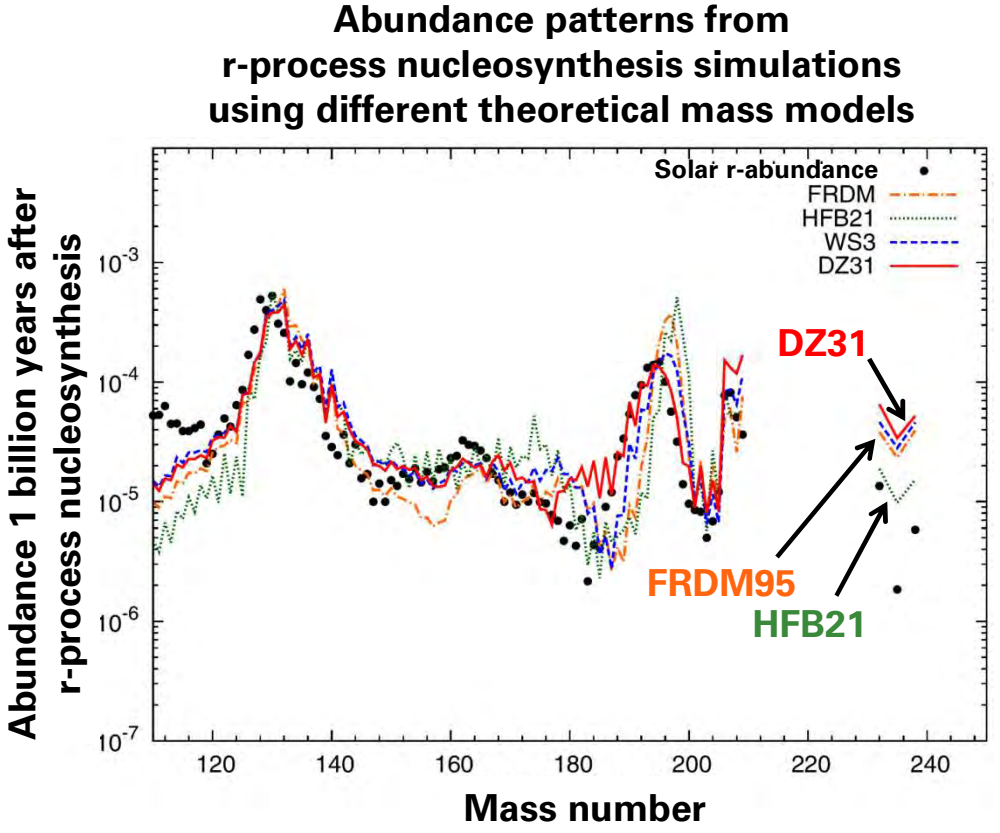
^{238}U (9.4 MeV/nucleon, 100 pnA) + ^{nat}U (13 mg/cm^2)



Fission probability of 90% was assumed.
Extraction efficiency of 1% was assumed.

Mass of actinoids and r-process nucleosynthesis





J.J. Mendoza-Temis et al., Phys. Rev. C 92, 055805 (2015).

Obtaining nuclear spectroscopic data for a wide range of neutron-rich actinoid nuclei reduces theoretical uncertainties in evaluating symmetry energies and understanding nuclear structure, allowing for the improvement of more reliable nuclear models.

Comprehensive understanding of r-process nucleosynthesis

- Synthesis process of uranium and thorium
- Fission cycling
- Abundance pattern
- Light curve of kilonova (Spontaneous fission of ^{254}Cf)

Summary

Spectroscopy of nuclei around $N = 126$ and neutron-rich actinides from astrophysical interest.

- **KISS**
  - Nuclear production by MNT reactions
  - Collection by argon gas cell
  - Element selection by laser resonance ionization
  - Mass selection by ISOL

- **Equipments**
  - MSPGC + HPGe detectors: Lifetime measurement, β-γ spectroscopy
  - Excitation laser: Laser spectroscopy
  - MRTOF-MS: Mass spectrometry

- **Beyond KISS: KISS-1.5**
  - Large rotating uranium target
  - RF helium gas cell
  - Variable Mass-Range Separator
  - 100 ~ 1000 times higher efficacy than KISS
  - More than 80 new isotopes with their precise mass measurements