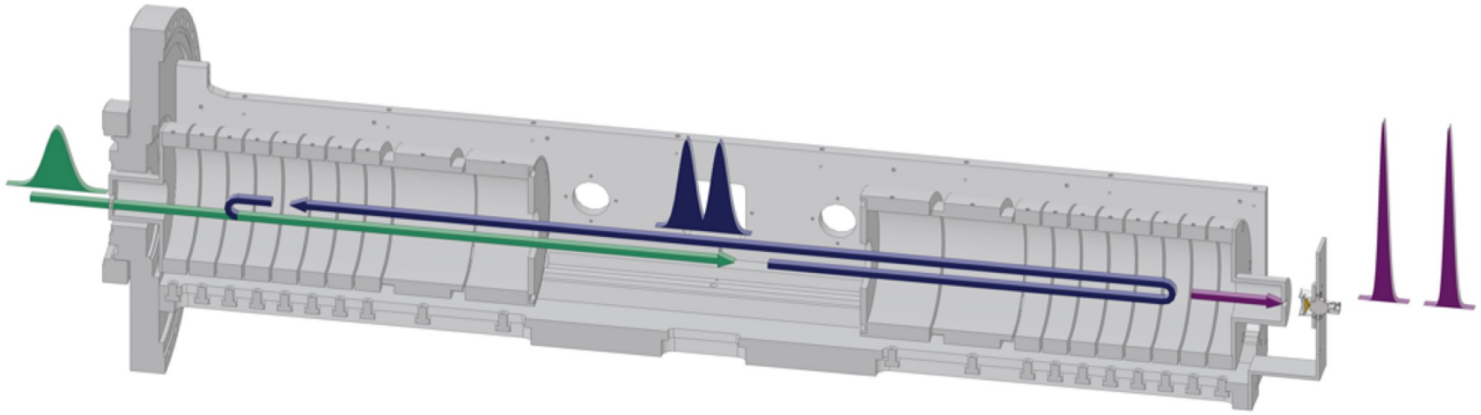
High-precision direct mass measurement of trans-uranium isotopes using the MRTOF systems at RIKEN/KEK

Toshitaka NIWASE

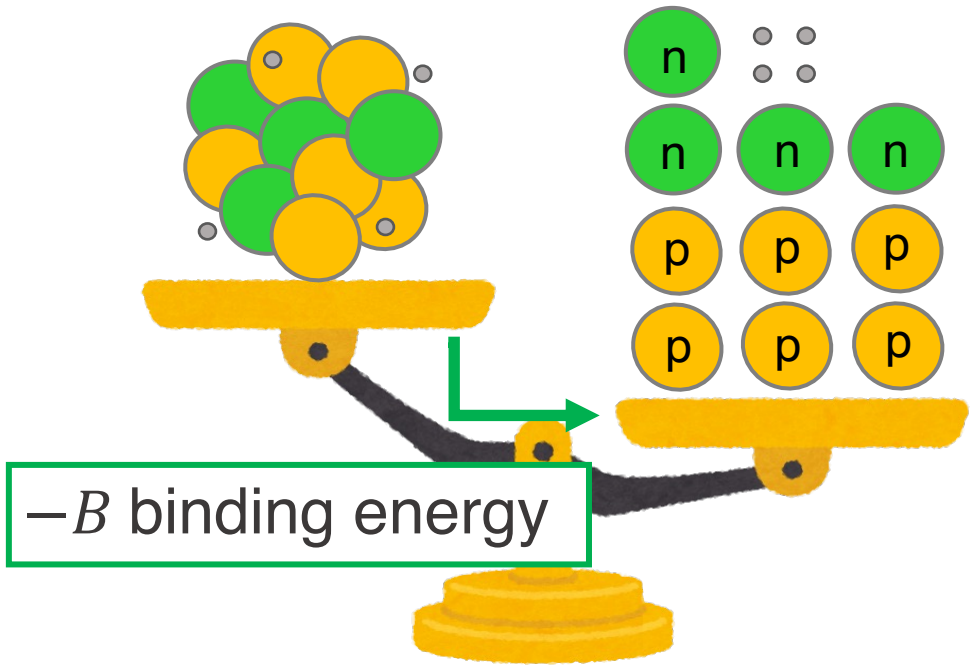
Kyushu University, Assistant Professor



KYUSHU UNIVERSITY RCSHE Research Center for SuperHeavy Elements

九州大学 KYUSHU UNIVERSITY

Nuclear mass



$$Mc^2(Z,N) = \left(Zm_p + Nm_n\right)c^2 - B + Zm_e$$

$E=mc^2$

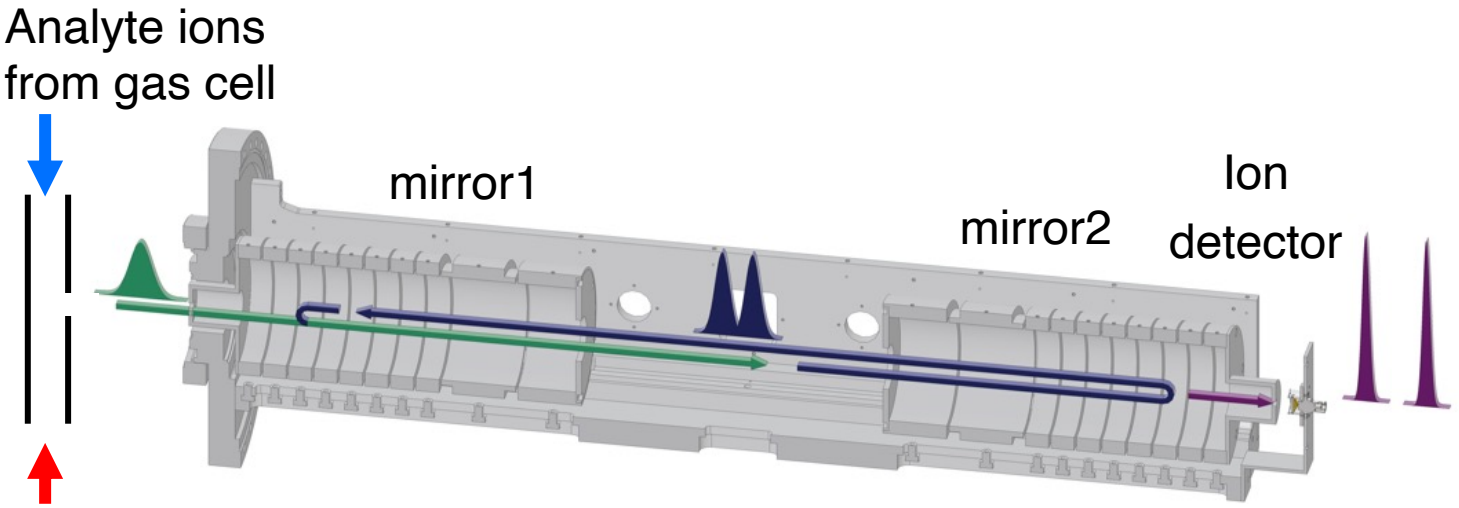
most fundamental quantity of the nuclide

Physics application	Required δm/m
General physics & chemistry Identification of molecules	$\leq 10^{-5}$
Nuclear structure and Astrophysics Separation of isobars	$\leq 10^{-6}$
Isomer studies and Astrophysics Separation of isomers	$\leq 10^{-7}$
Weak interaction studies CVC hypothesis, CKM	$\leq 10^{-8}$
Metrology - fundamental constants	$\leq 10^{-9}$
CPT tests	$\leq 10^{-10}$
QED in highly-charged ions Separation of atomic states	$\leq 10^{-11}$

Chemistry, Atomic physics, Astrophysics
Nuclear physics, Particle physics, etc…

MRTOF

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



P. Schury, *et al.* NIM B376, 425(2016)

$$m = \frac{q}{q_{\mathrm{ref}}}\rho^2 m_{\mathrm{ref}} = \frac{q}{q_{\mathrm{ref}}}\left(\frac{t - t_0}{t_{\mathrm{ref}} - t_0}\right)^2 m_{\mathrm{ref}},$$

Determine the mass from the TOF ratio
between the **analyte ion** and **reference ion**.

Device principle

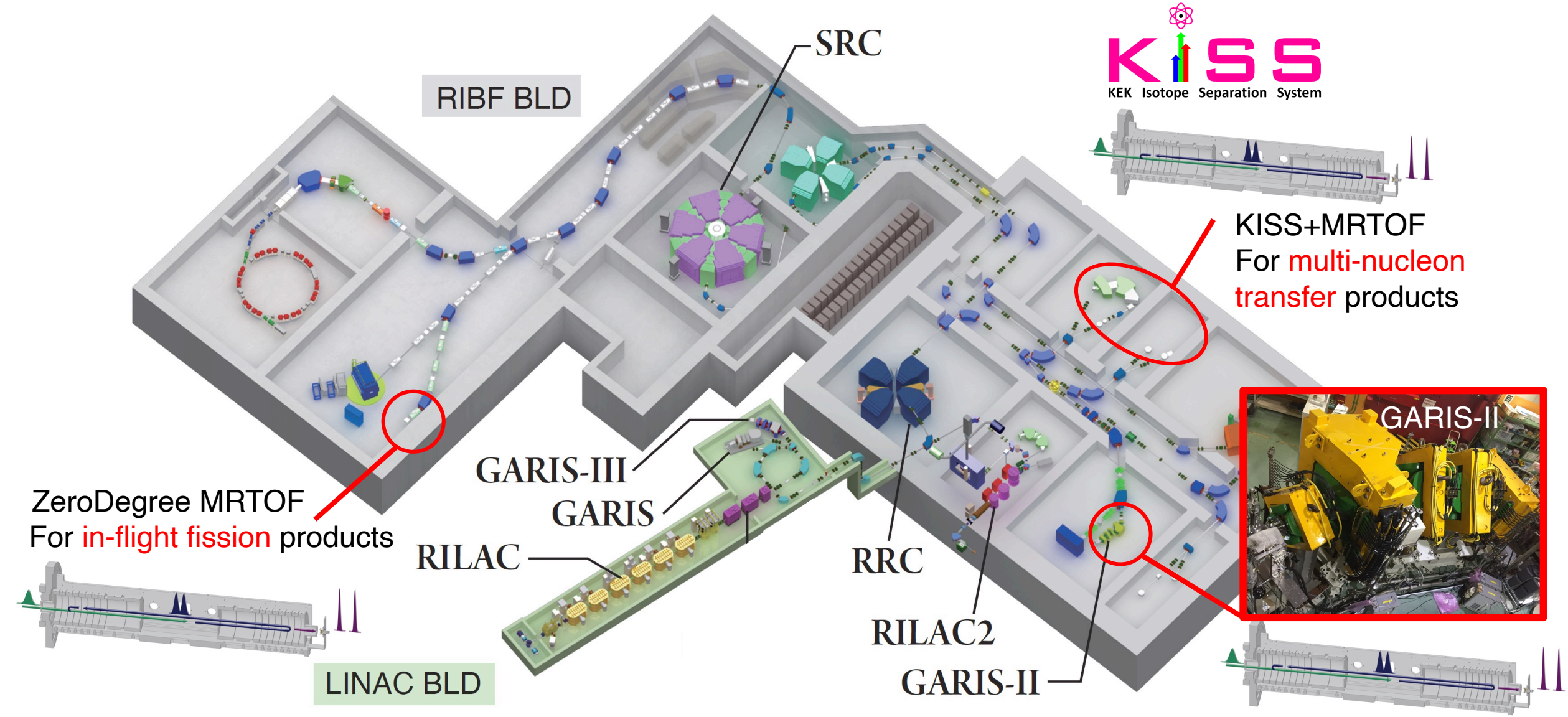
Injected ion into twin ion mirror

Multiple-turn inside of the MRTOF

Open exit, measure total TOF

$T_{1/2}$> ~10ms, Rm ~ 800,000.

MRTOF device in RIKEN

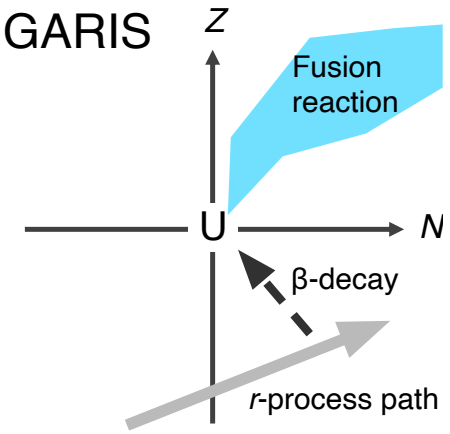


We have operated 3 MRTOF systems

How to produce the unstable nuclides

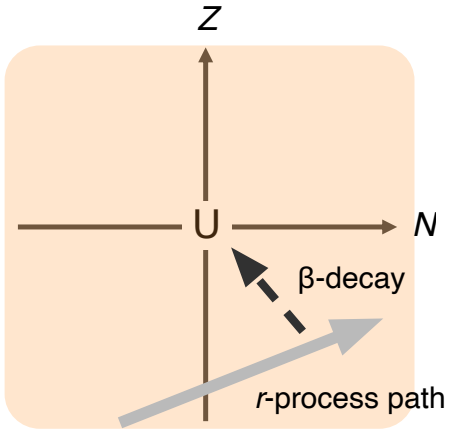
Fusion (~ 5 MeV / nucleon)

GARIS



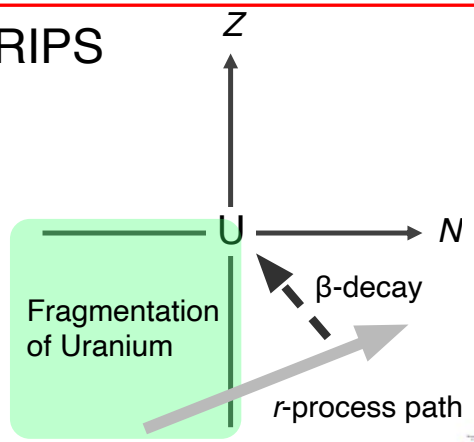
KISS

Multi-nucleon transfer (~10 MeV/ nucleon)



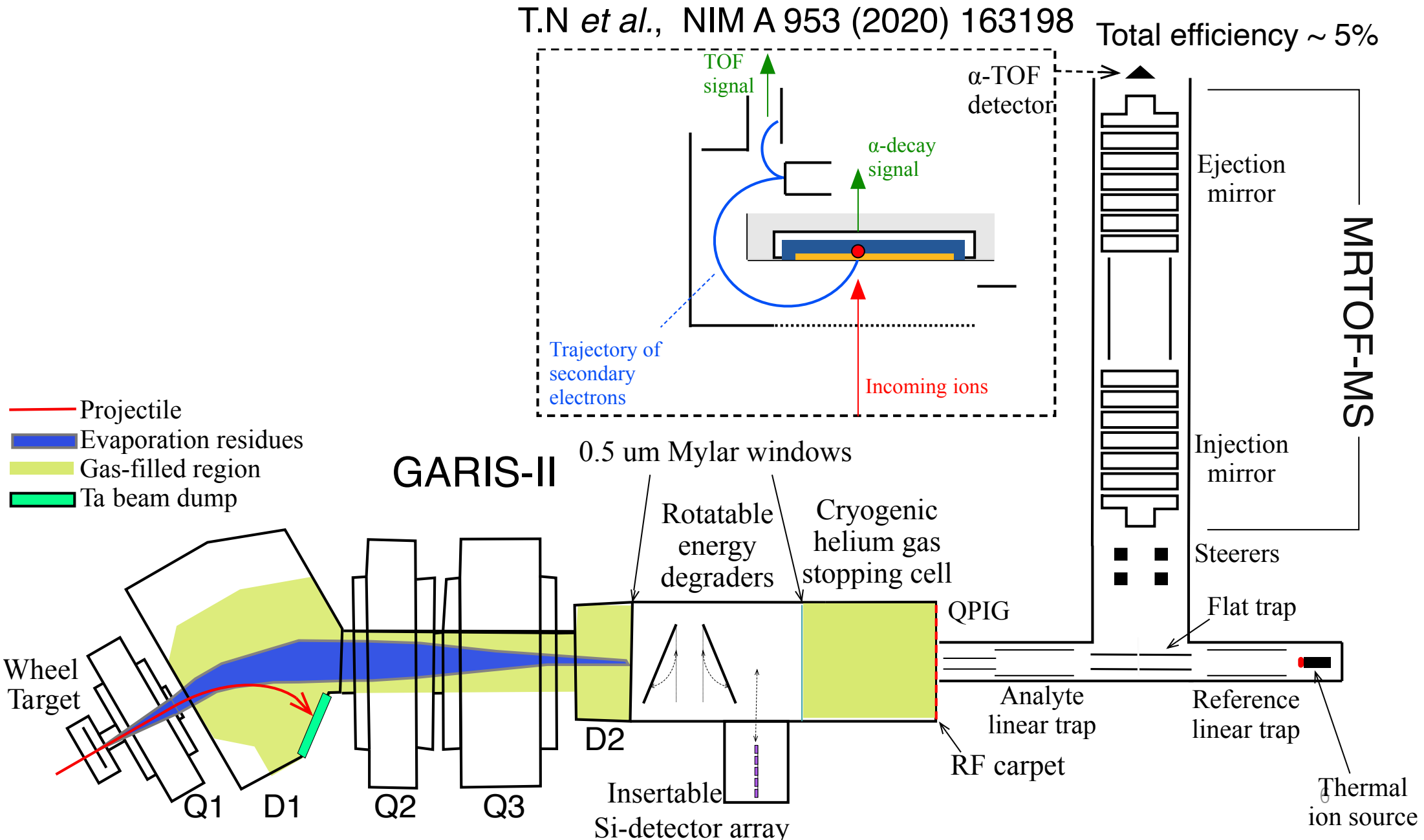
Fragmentation/Spallation (~ 100 MeV / nucleon)

BigRIPS



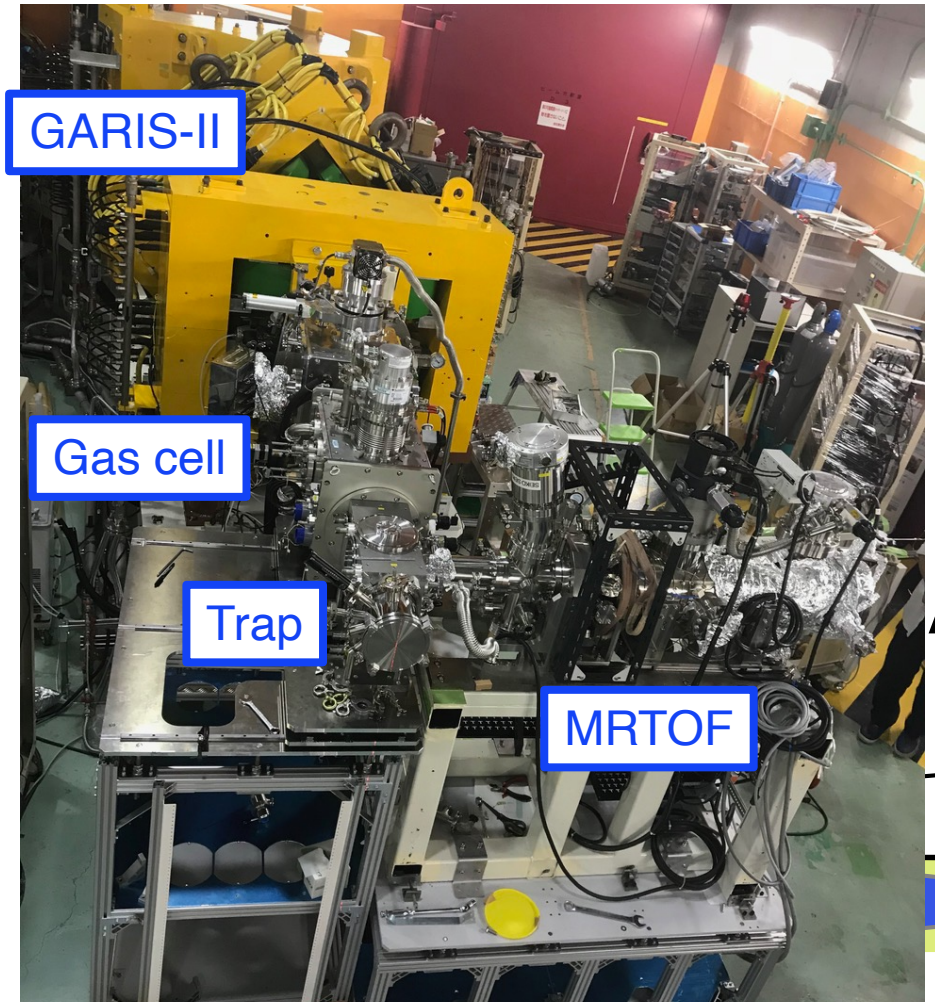
Fusion and multi-nucleon transfer reactions to produce superheavy and actinide nuclide and measure masses

SHE-Mass facility

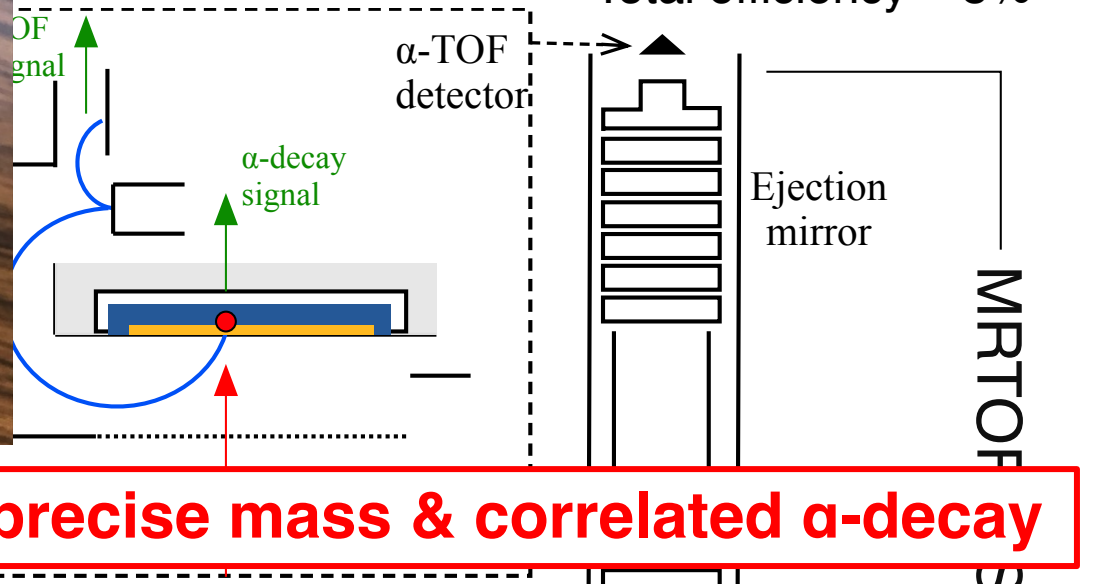


SHE-Mass facility

SHE-Mass facility



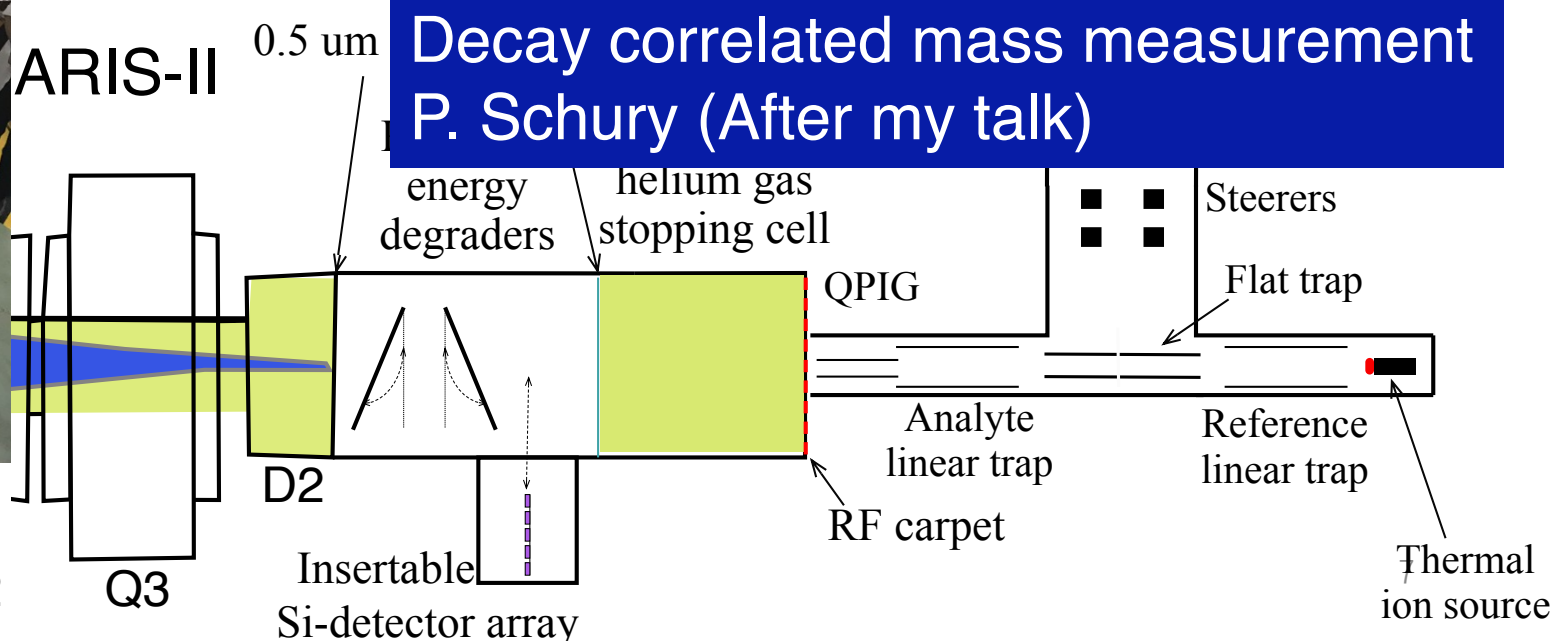
α-TOF T.N *et al.*, NIM A 953 (2020) 163198



Total efficiency ~ 5%

Measure the precise mass & correlated α-decay

Decay correlated mass measurement
P. Schury (After my talk)



SHE-Mass facility

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

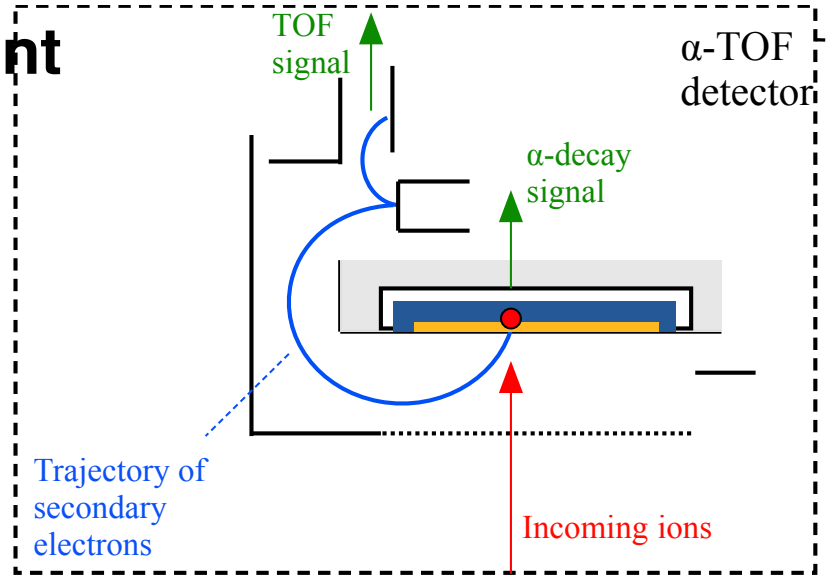
Total efficiency ~ 5%

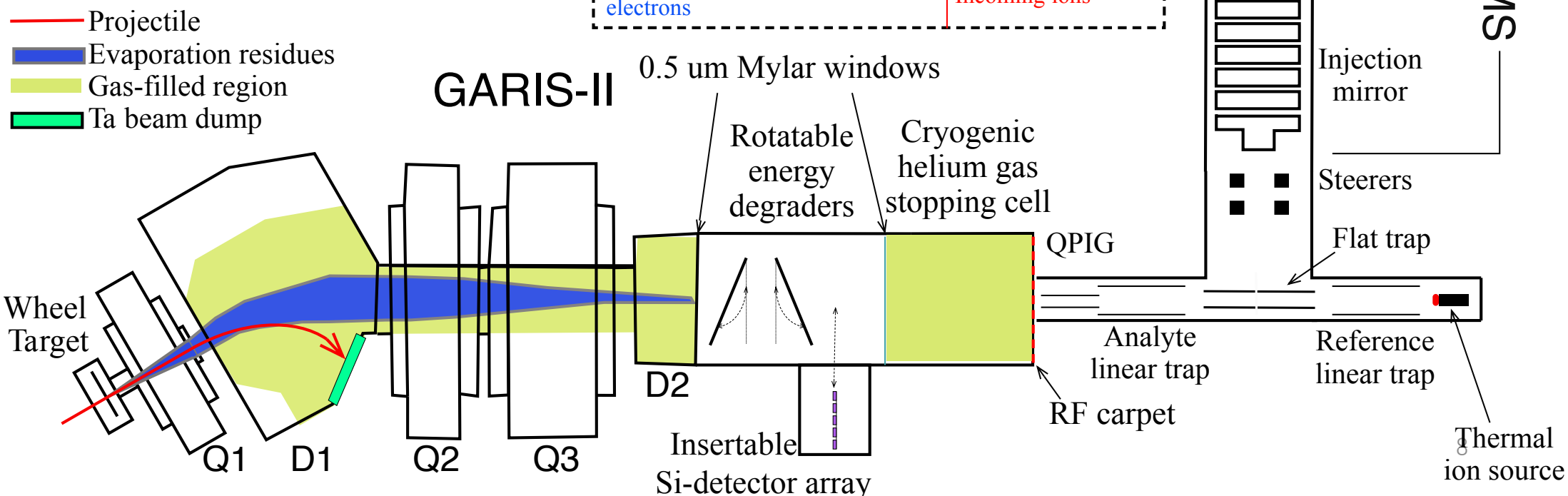
Campaign of SHE mass measurement

First measurement@2020/1

Second measurement @2021/9

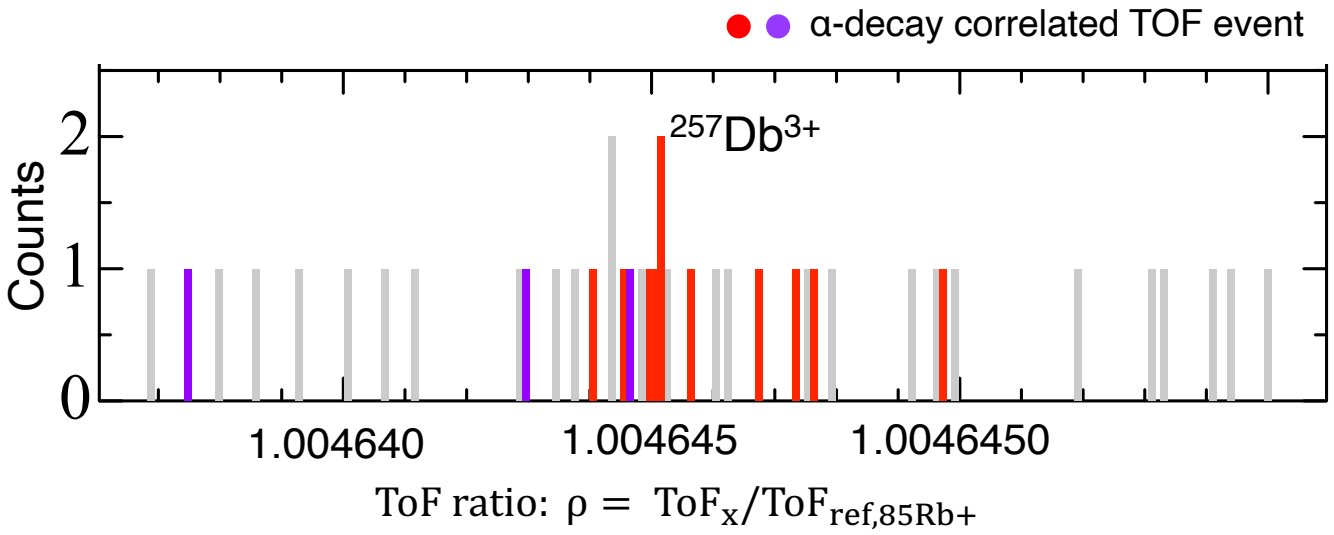
$^{208}Pb(^{51}V,xn)^{257,258}Db$





First result of SHE-mass

A total of 14 TOF-decay correlated event were observed in the vicinity of $^{257}Db^{3+}$ in 4.5 days measurement.

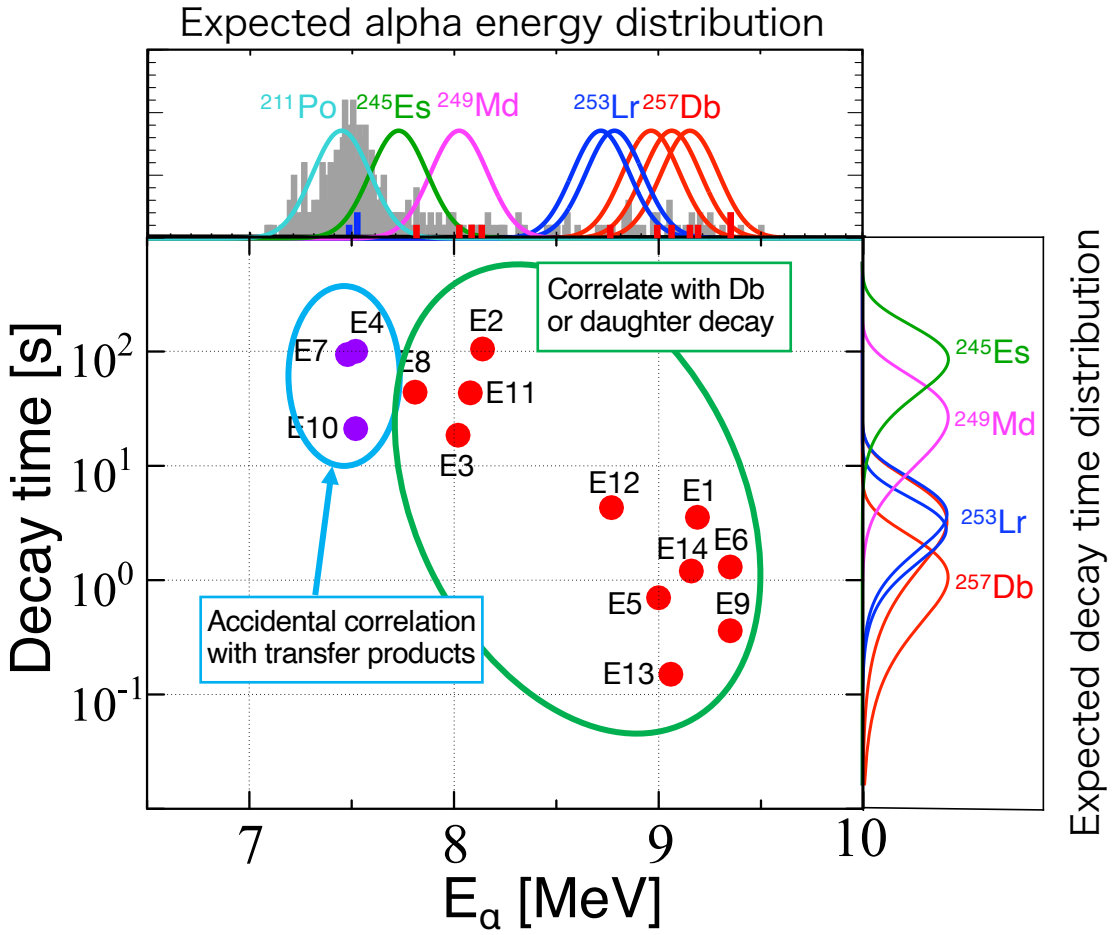


The event rate is 2 events per day; however, we can discriminate from background events using α-TOF.

From the 11 TOF events correlated with α decay

direct determination of the mass of ^{257}Db

$R_m \sim 300{,}000$



$\delta m/m = 9.7\times10^{-7}$

m(^{257}Db)=257.10742(25) u

$ME_{exp,\ direct}$ = 100 063 (231) keV

$ME_{exp,\ indirect}$ = 100 234 (224) keV

First direct mass determination of SHE

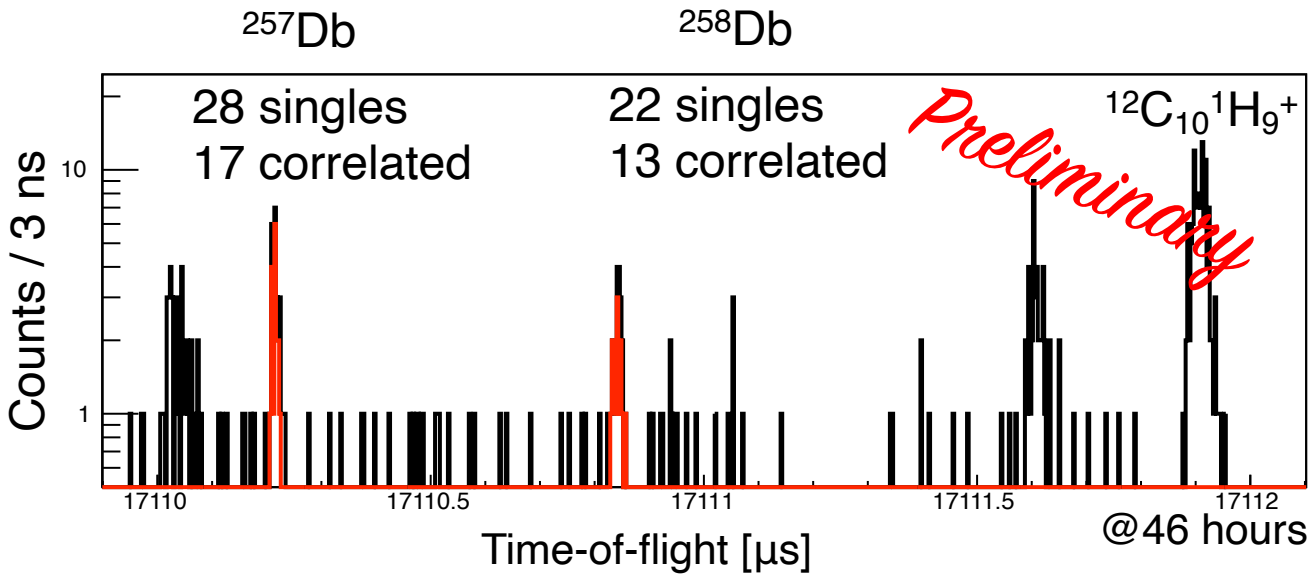
T. Niwase, Ph.D thesis

P. Schury, T. Niwase *et al.*, PRC, 104 (2021) L021304.

T. Niwase *et al.*, J. Nucl. Radiochem. Sci., 23 (2023) 1.

Second result of SHE-mass

2021/09: ^{257,258}Db were measured

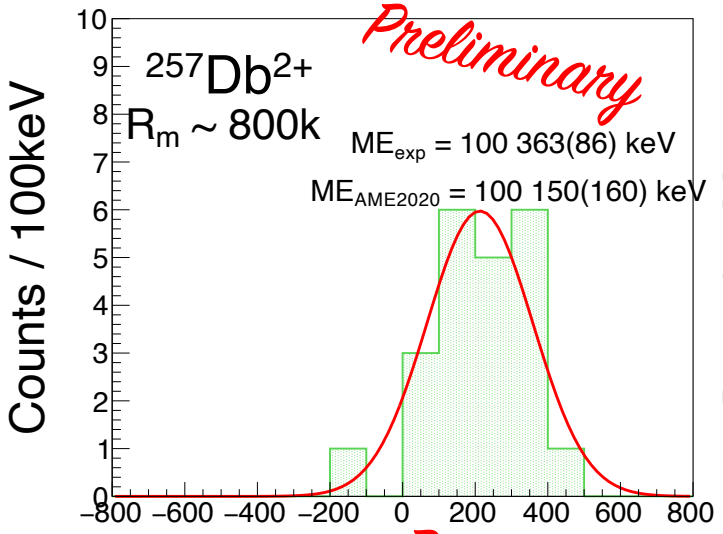


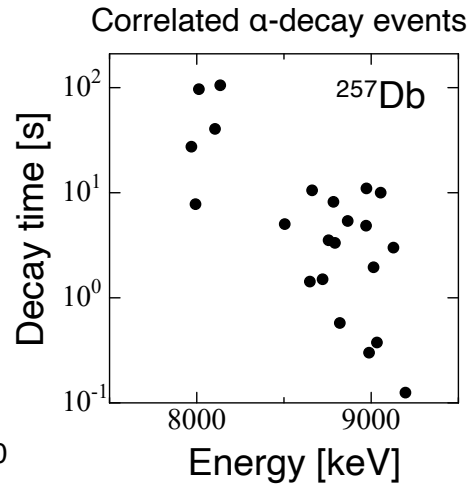
- Beam irradiated with 2 puA

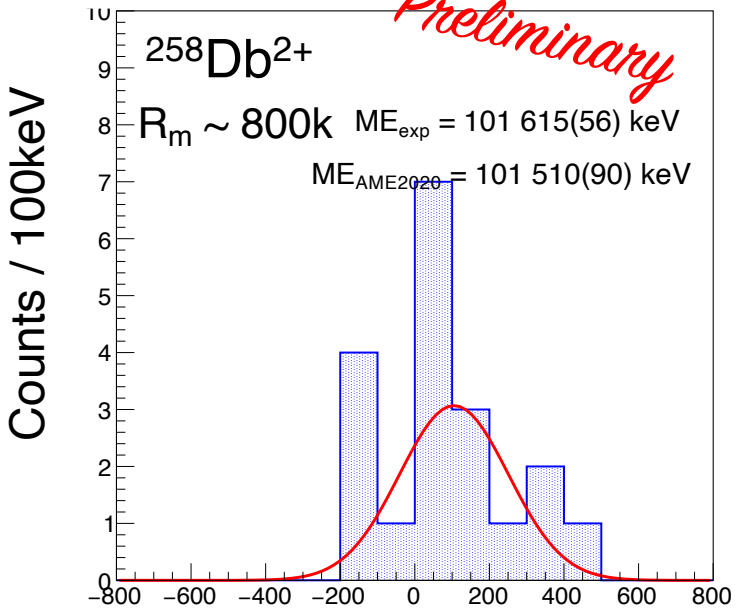
  2 events / day -> **2events / 4 hours**

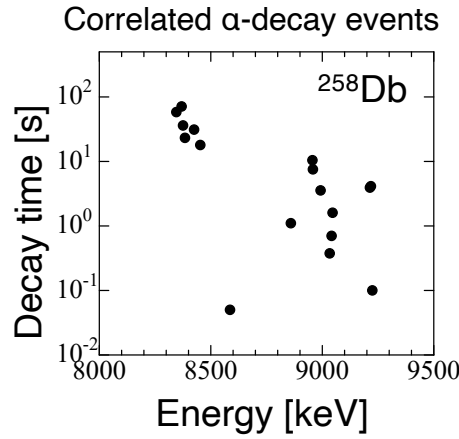
- R_m: 300,000 -> **800,000**

Direct determined the mass of ^{258}Db
Improve the mass of ^{257}Db



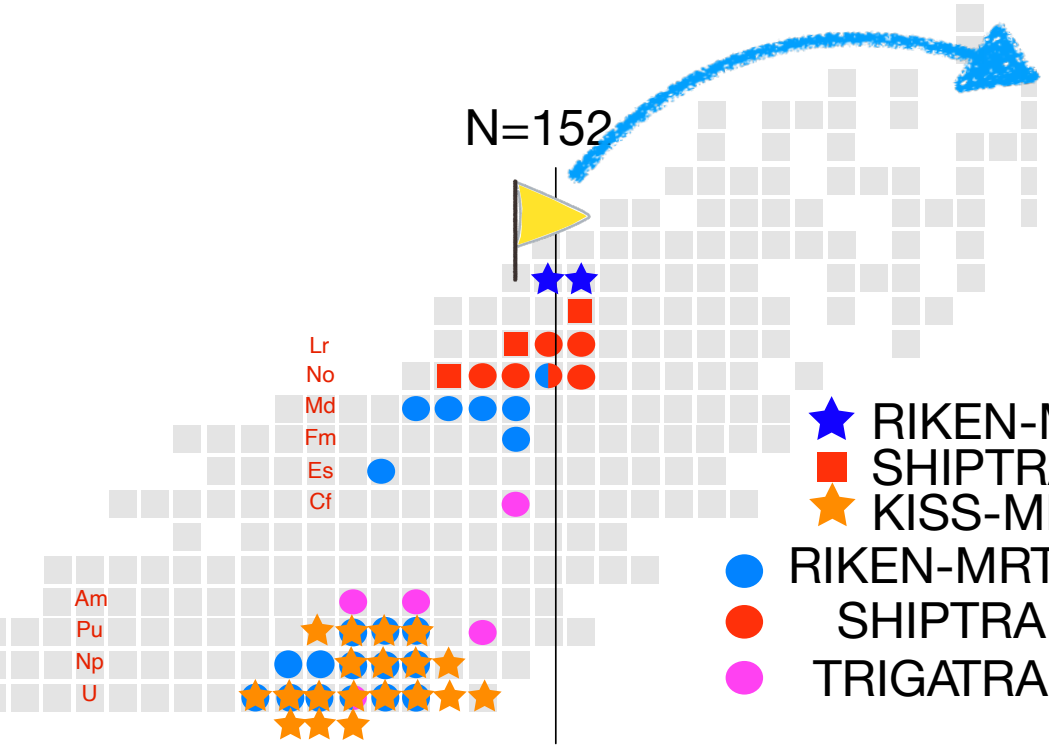




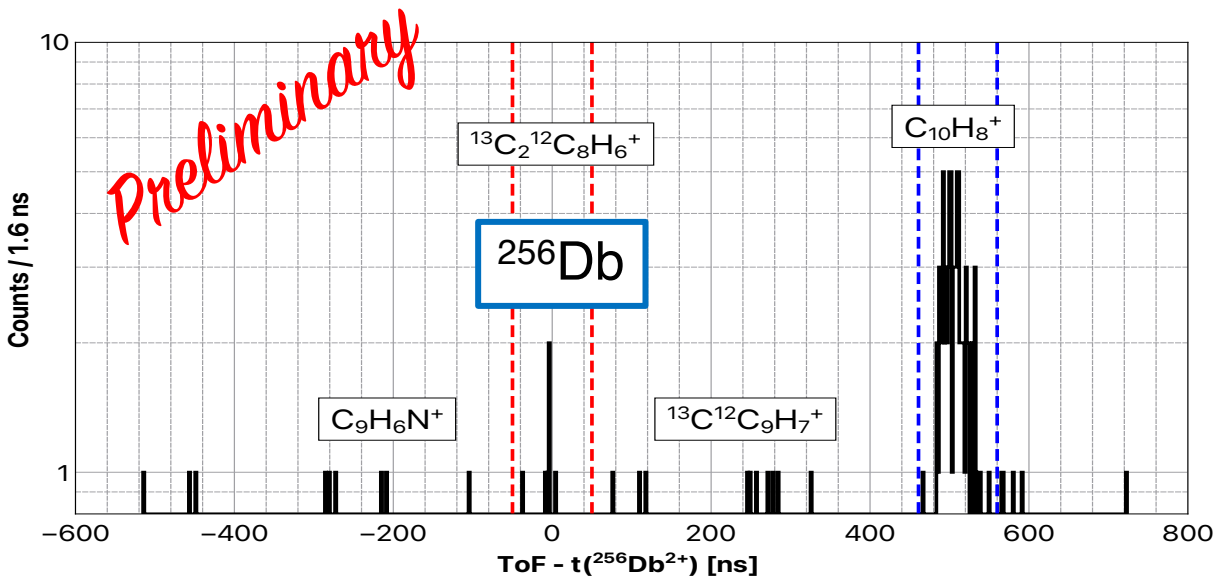


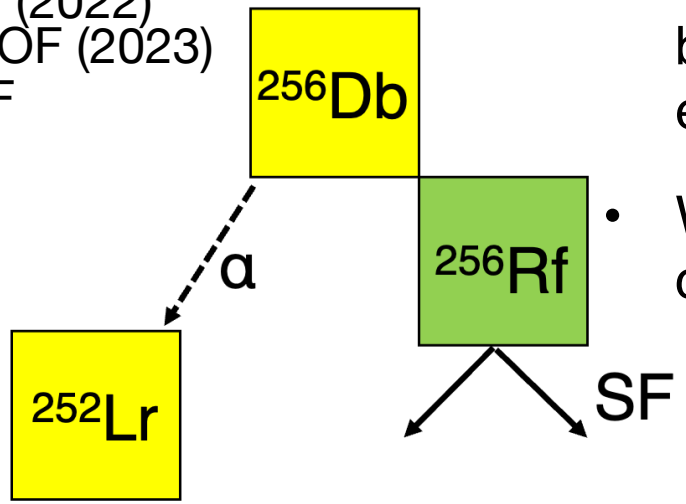
Also correlated with SF events

^{256}Db

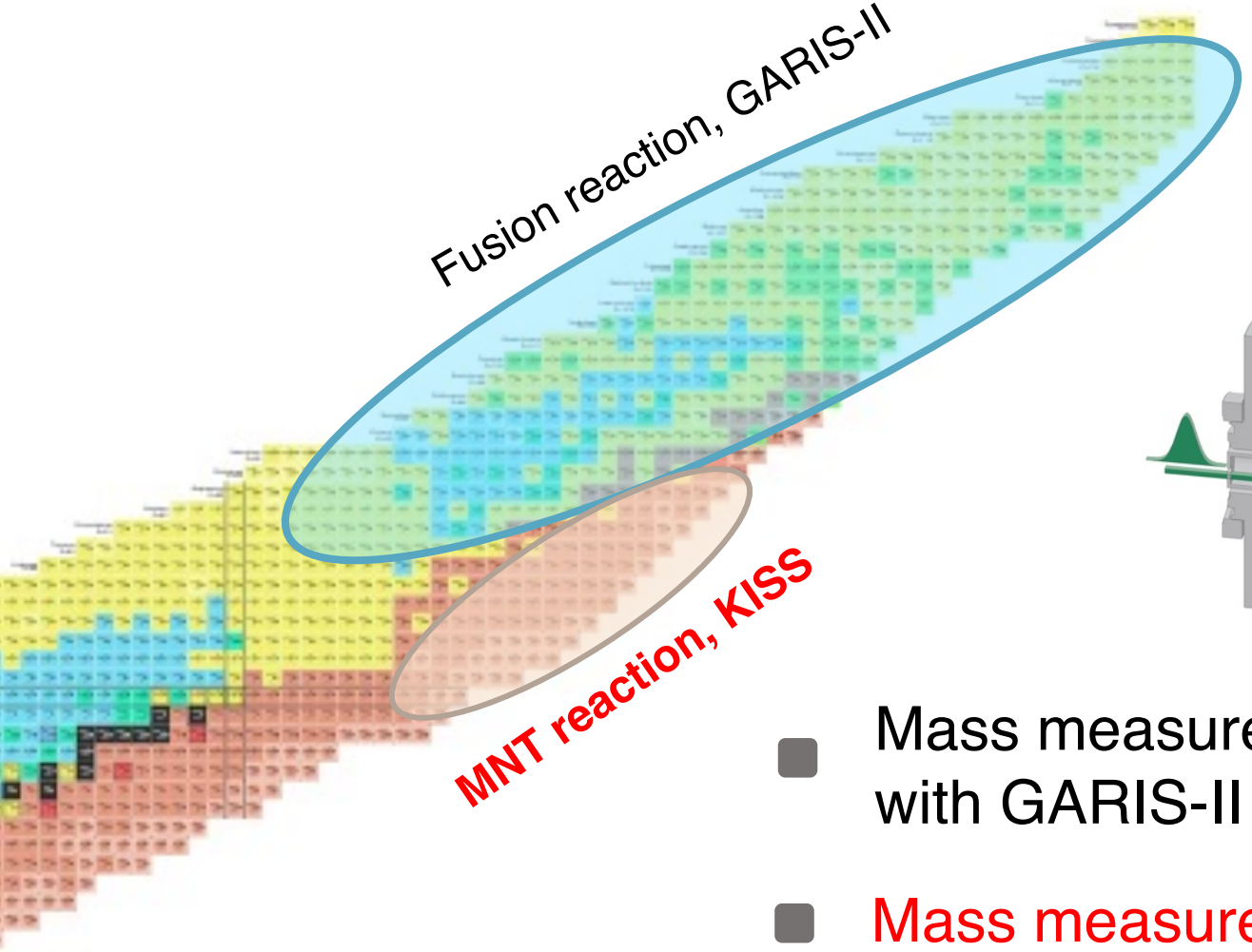


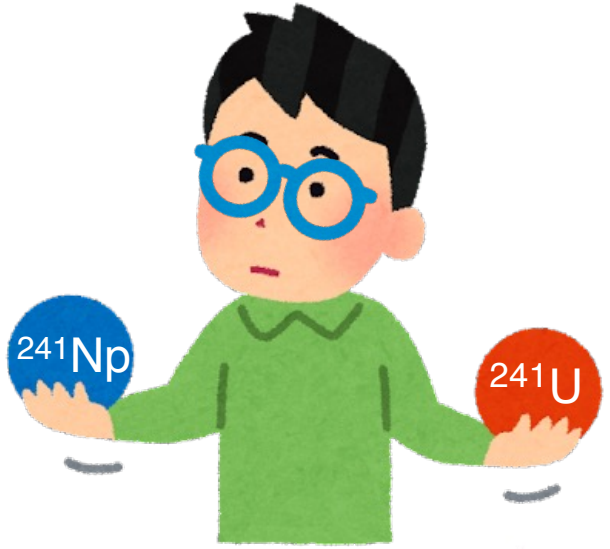
RIKEN-MRTOF (2021)
SHIPTRAP (2022)
KISS-MRTOF (2023)
RIKEN-MRTOF
SHIPTRAP
TRIGATRAP





- We observed the sigh of ^{256}Db, but only correlation with two SF events
- We didn't see the clear correlation with α-decay



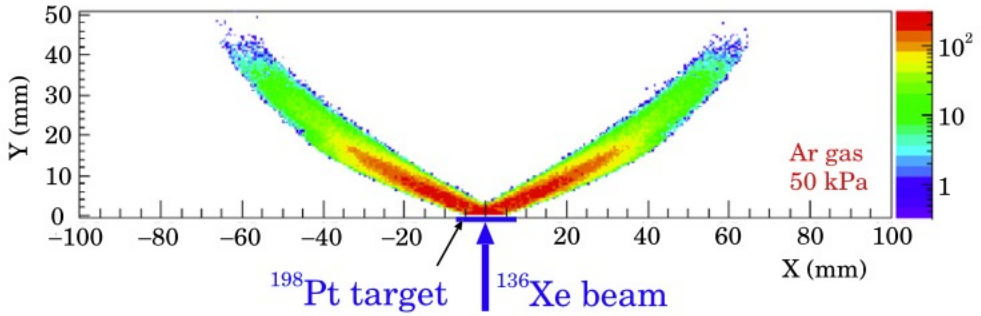


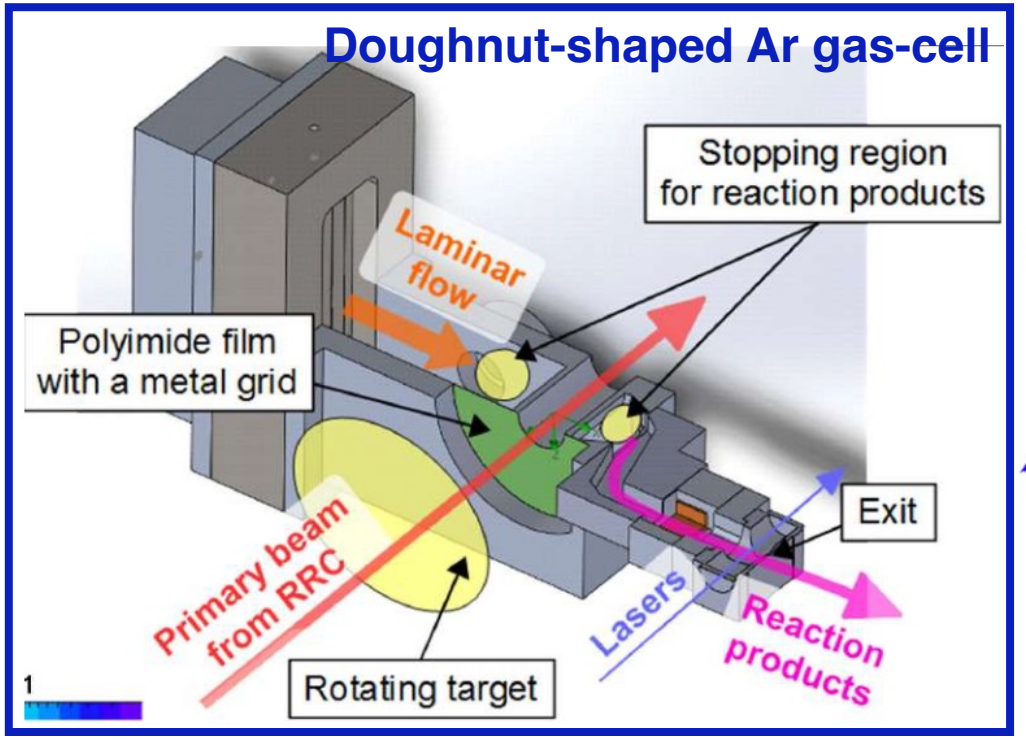
- Mass measurement of superheavy nuclide with GARIS-II MRTOF
- Mass measurement of actinide nuclide with KISS-MRTOF

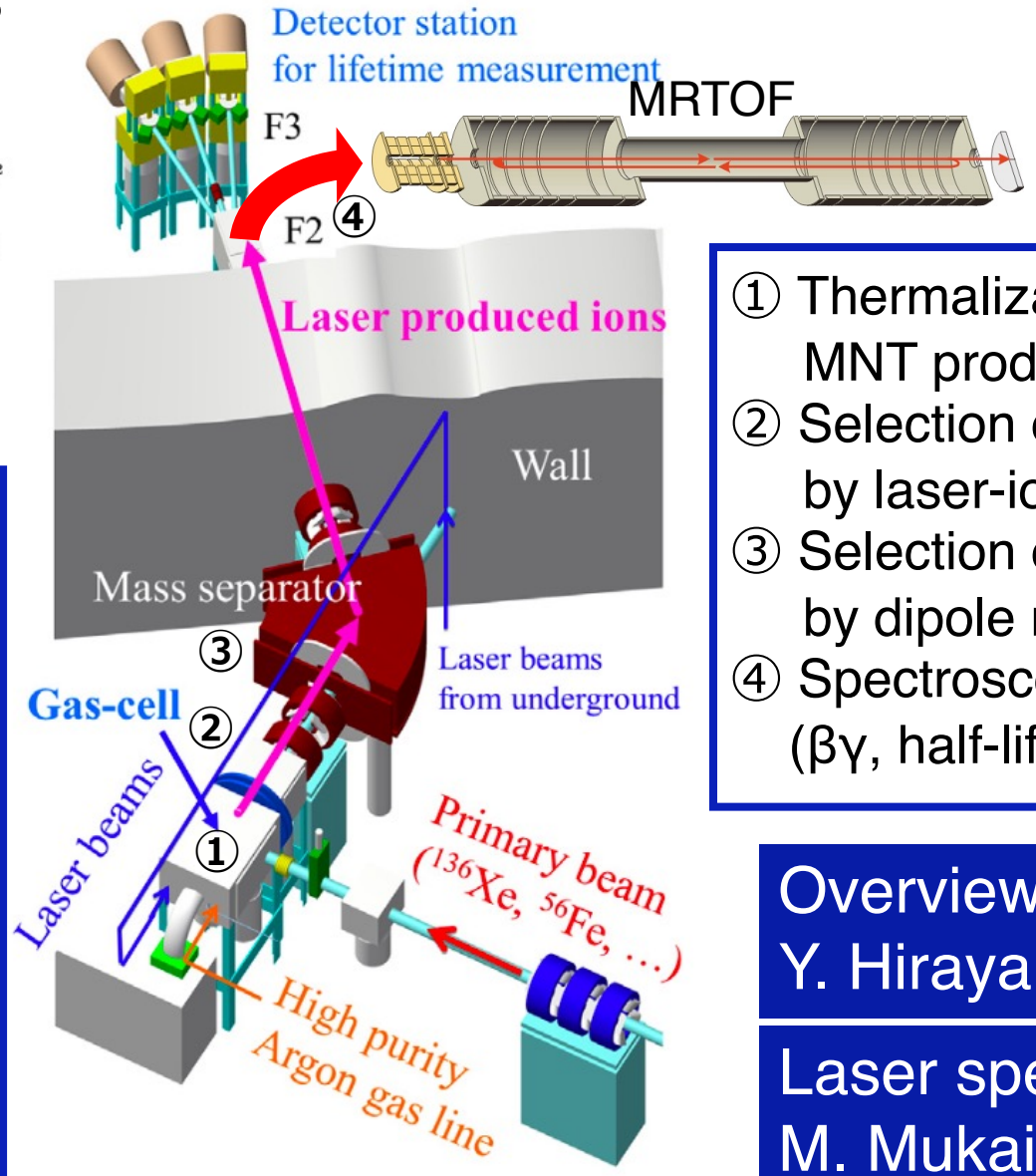
KEK Isotope Separation System, KISS

KEK Isotope Separation System, KISS

Operating in RIBF facility







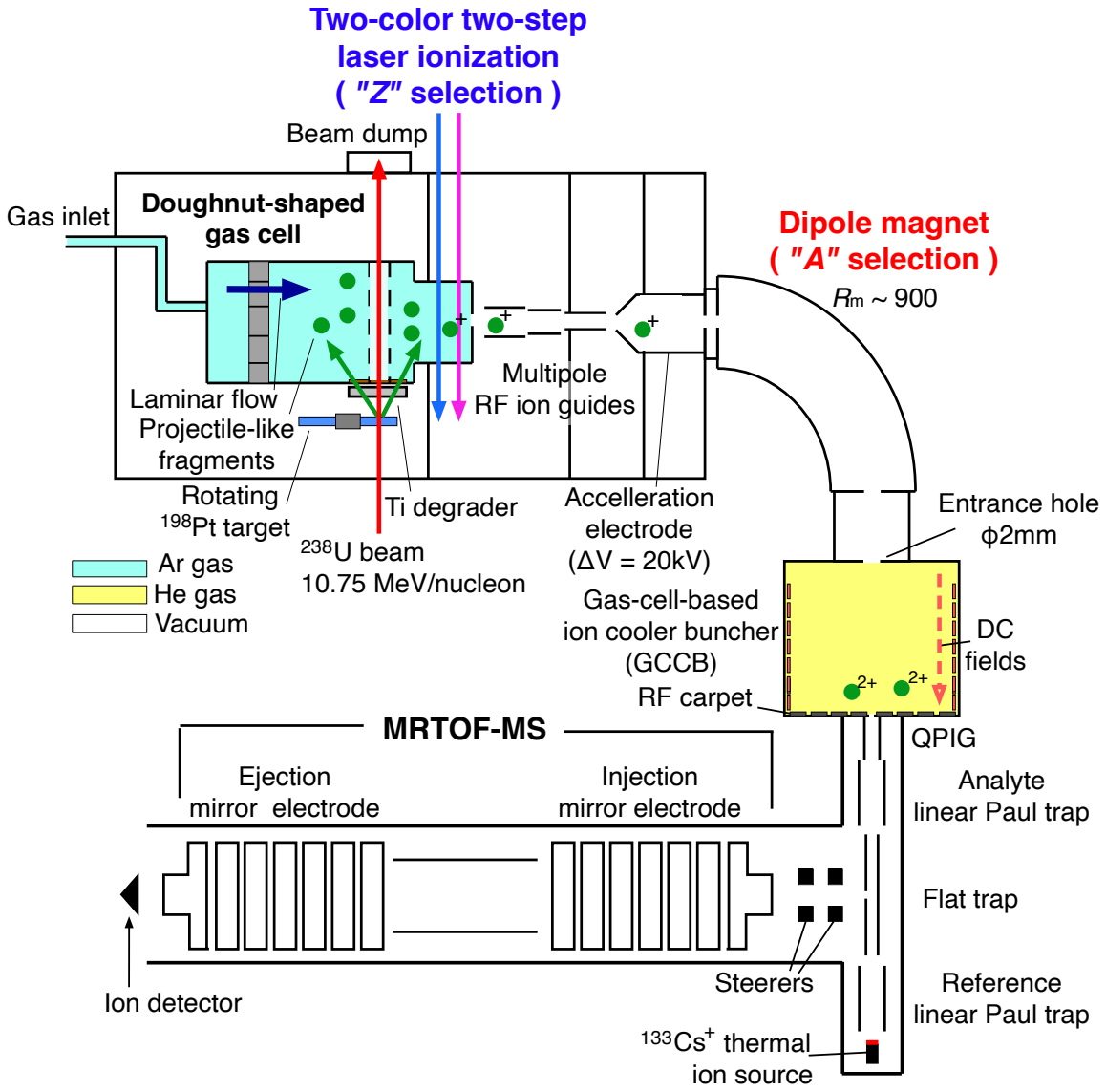
① Thermalization of MNT products in Ar gas
② Selection of **atomic number** by laser-ionization technique
③ Selection of **mass number** by dipole magnet
④ Spectroscopy with pure-beam (βγ, half-life, mass)

Overview/Future plan:
Y. Hirayama, May 27

Laser spectroscopy:
M. Mukai, May 30

First experiment for the actinide nuclides

Schematic view of KISS-MRTOF

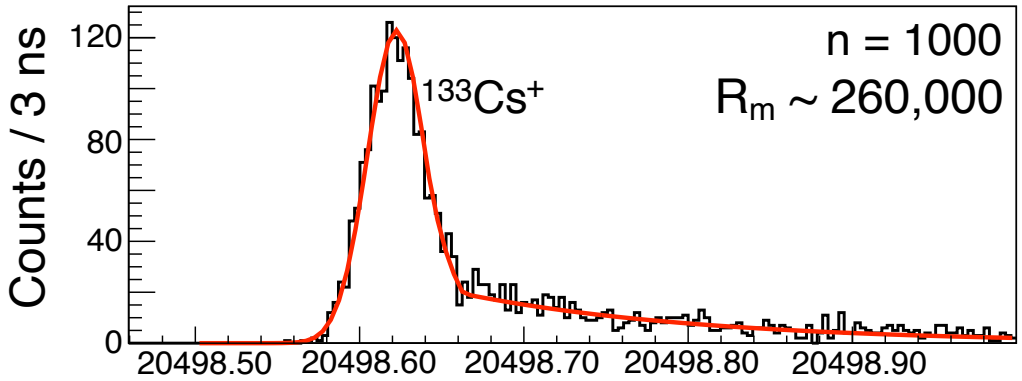


Beam : ^{238}U 10.75 MeV/nucleon ~30pnA

Target : ^{198}Pt target (enriched to 91.63%)

- Select **Z** and **A** of the nuclides using **Laser ionization** and **Dipole magnet**
- Mass measurement by MRTOF-MS

TOF spectrum of reference ^{133}Cs$^+$ ion



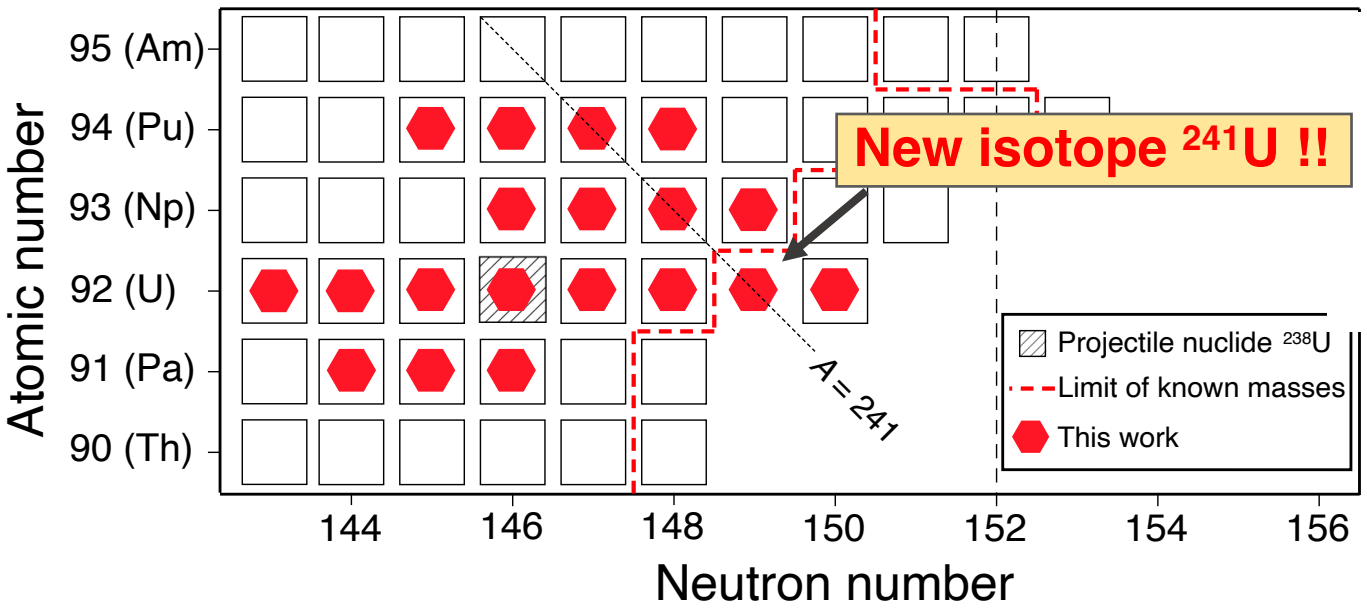
Fitting function:

$$f(t) = \begin{cases} Ae^{-(t-t_m)^2/2\sigma^2} & (t \le t_1), \\ Ae^{-\frac{1}{\tau_1}(t-t_1)-\frac{1}{2}} & (t_1 < t < t_2), \\ Ae^{-\frac{1}{\tau_2}(t-t_2)-\frac{1}{2}-\frac{t_c}{\tau_1}} & (t \ge t_2), \end{cases}$$

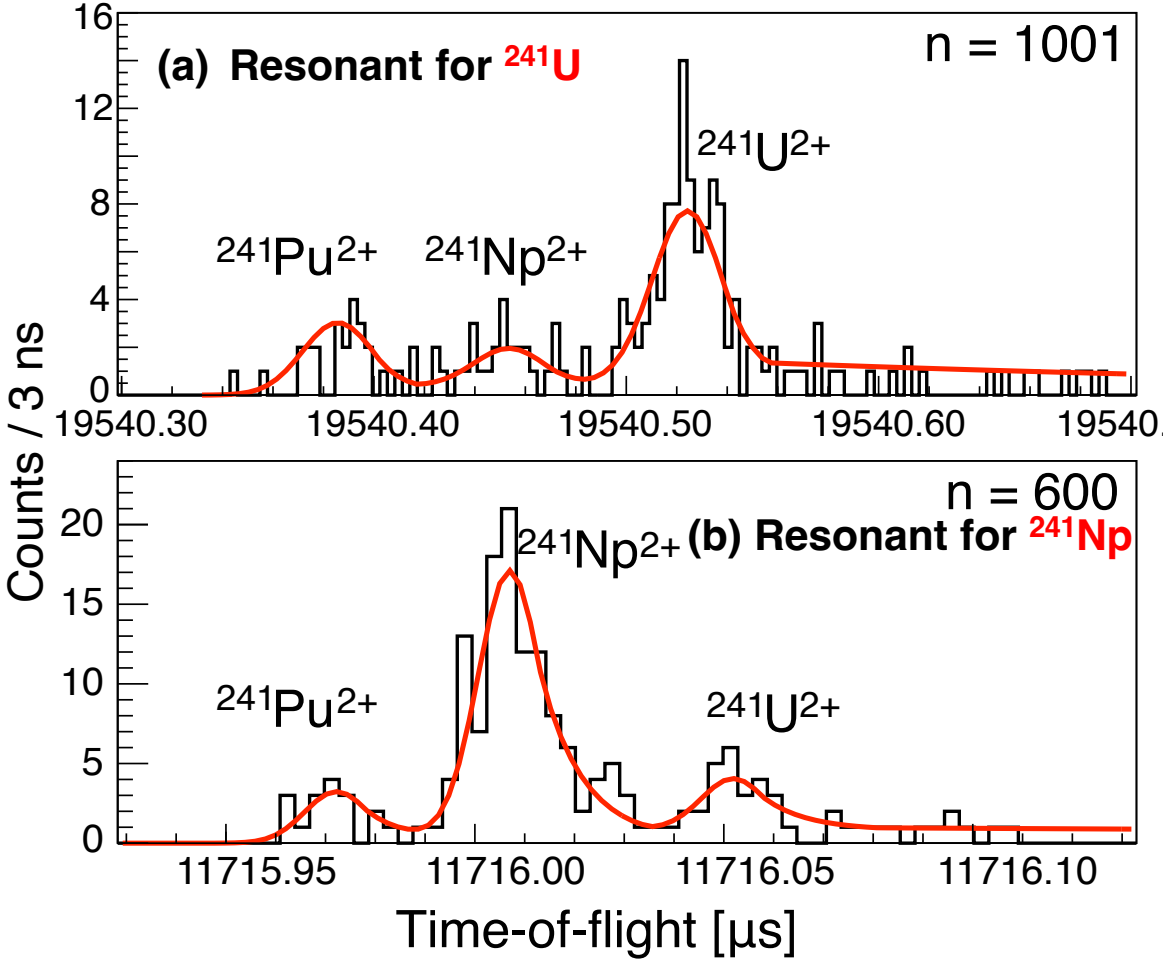
Result of mass measurement

Totally 19 nuclides were measured

$^{235\text{-}242}$U, $^{235\text{-}237}$Pa, $^{239\text{-}242}$Pu, $^{239\text{-}242}$Np



TOF spectrum of A = 241 species



Clearly identified as new isotope ^{241}U

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

Summary

- Comprehensive direct mass measurement of nuclide by MRTOF.

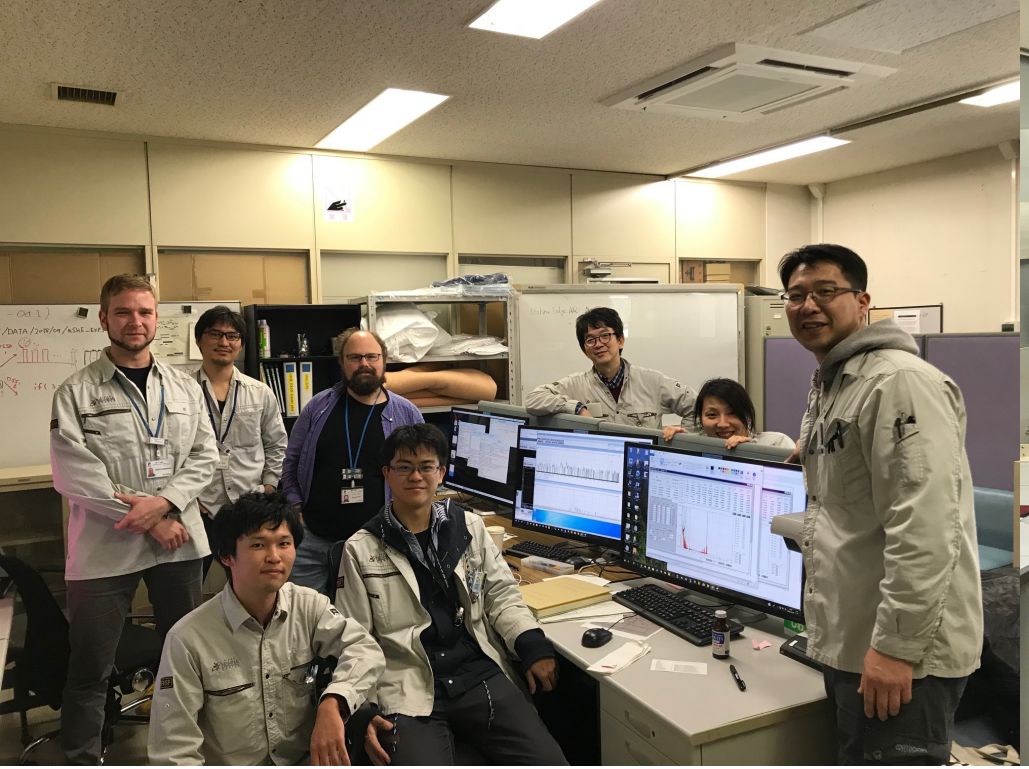
  We have operated 3 MRTOF-MSs in RIBF facility

- **Superheavy nuclides** produced by **Fusion reaction**

  We have measured mass of **^{257,258}Db (and ^{256}Db) in GARIS-II+MRTOF** setup
  +α-TOF detector

- **Trans-uranium nuclides** produced by **multi-nucleon transfer reaction**

  We have measured the mass of 19 nuclides including the **new isotope ^{241}U**
  by **KISS-MRTOF** setup



RIKKYO UNIVERSITY · MDCCCLXXIV

KEK Wako Nuclear Science Center

RIKEN

JAEA

ibs 기초과학연구원 Institute for Basic Science

NM STATE

KURNS

KISS

KEK Isotope Separation System

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