Precision Mass Measurements of Superheavy Nuclei with MRTOF and its application at JAEA

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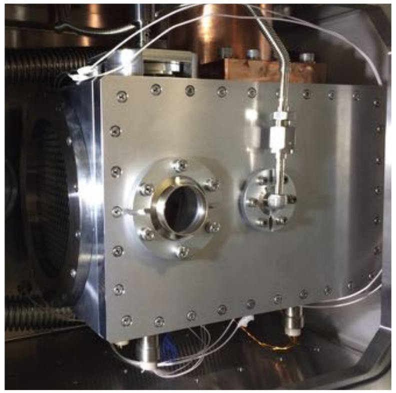
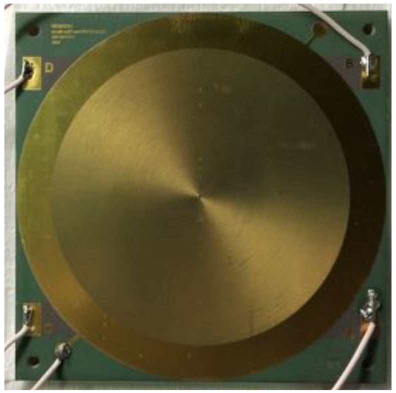
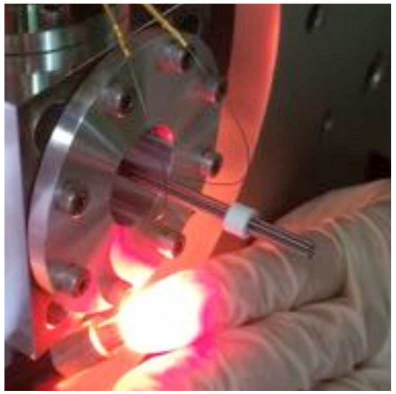


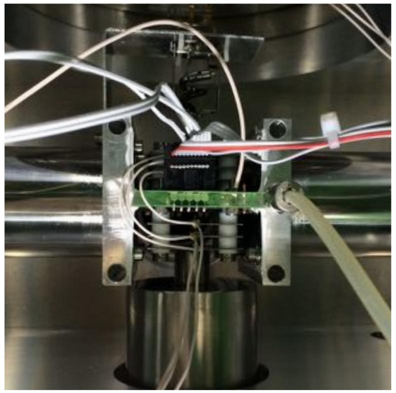
Cryo. Gas Catcher



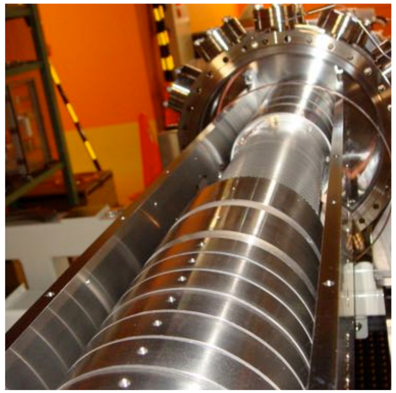
RF Carpet



SPIG

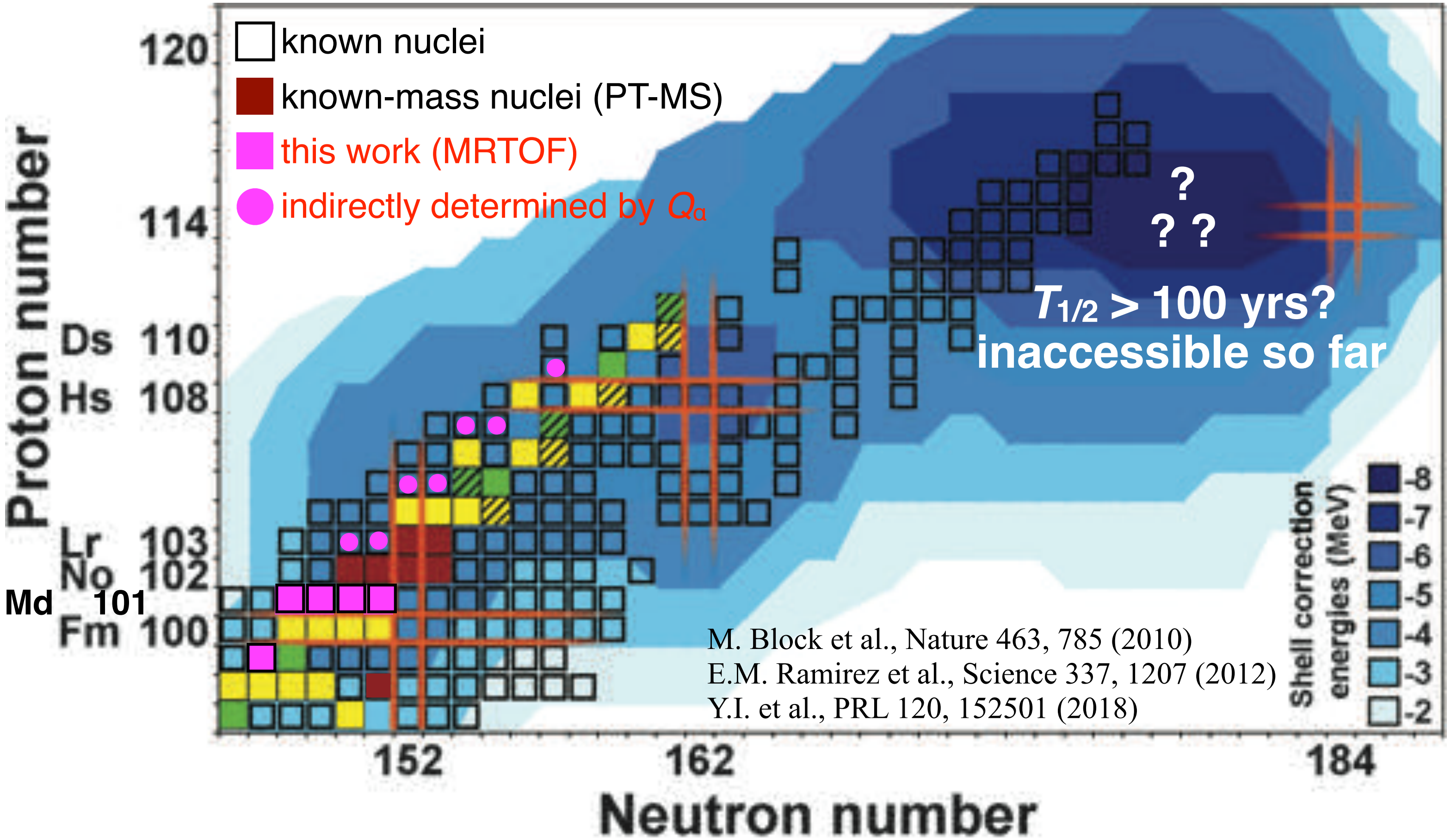


Flat Trap



MRTOF

Shell Effect and Island of Stability in SHE



G.T. Seaborg,
Annu. Rev. Nucl. Sci. 18 (1968) 53

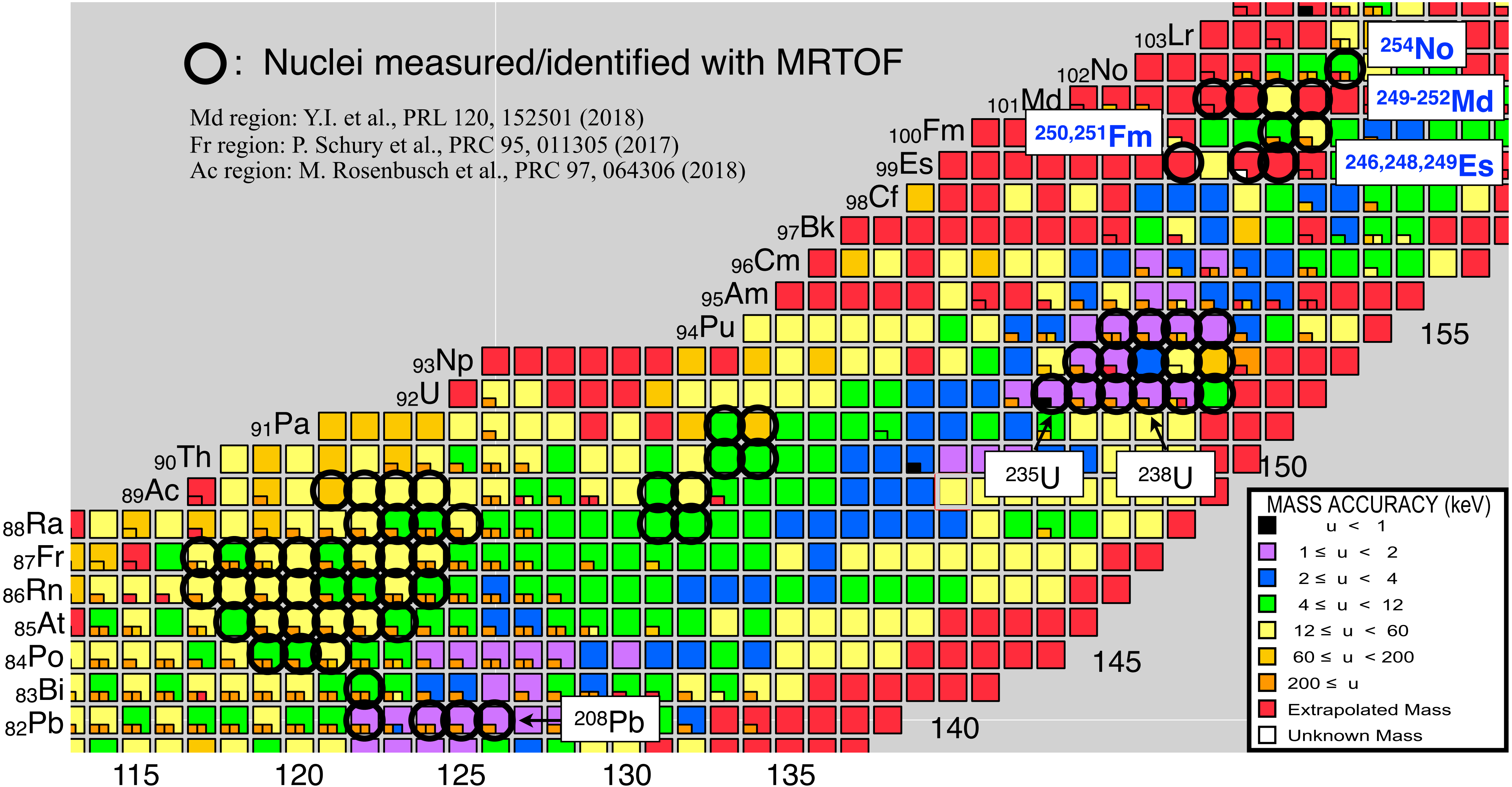
- General questions
  - really exist?
  - where and how stable?
  - how to synthesize?
  - how to identify?
- To answer
  - understand nuclear structure of SHE
  - inspect and establish reliable mass models
  - new identification technique

via high-precision mass spectroscopy with an MRTOF

Nuclei Measured/Identified with MRTOF @RIKEN

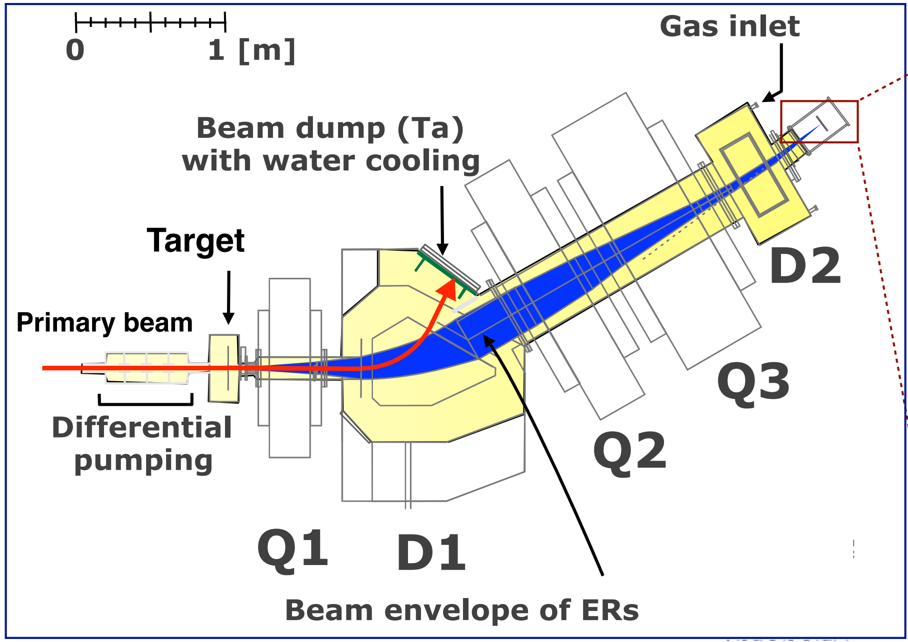
- fusion-evaporation and in-gas-cell decay products (^{48}Ca + ^{208}Pb/^{nat}Tl/^{169}Tm/^{165}Ho, ^{18}O/^{19}F + ^{232}Th/^{nat}U): 55 nuclides
- multi-nucleon transfer products and target recoils (^{18}O/^{19}F + ^{208}Pb/^{232}Th/^{nat}U/): 16 nuclides
- masses of >30 nuclides were directly measured for the first time
- all nuclei observed were mostly q = 2+ at cryogenic condition: cleanness in GC and IP2(X) < IP1(He)

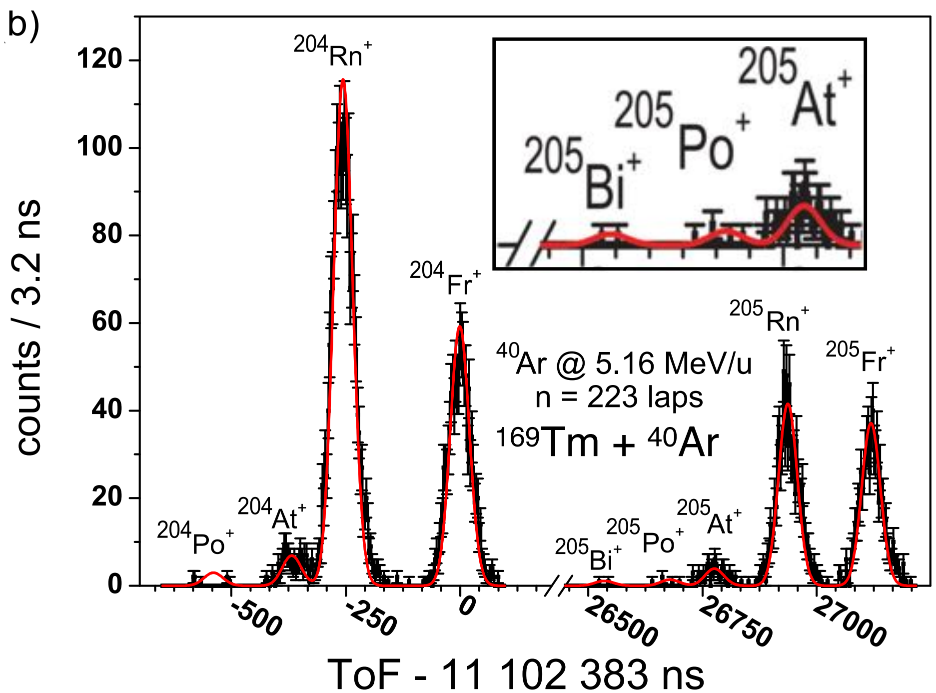
P. Schury et al., NIMB 407, 160 (2017)



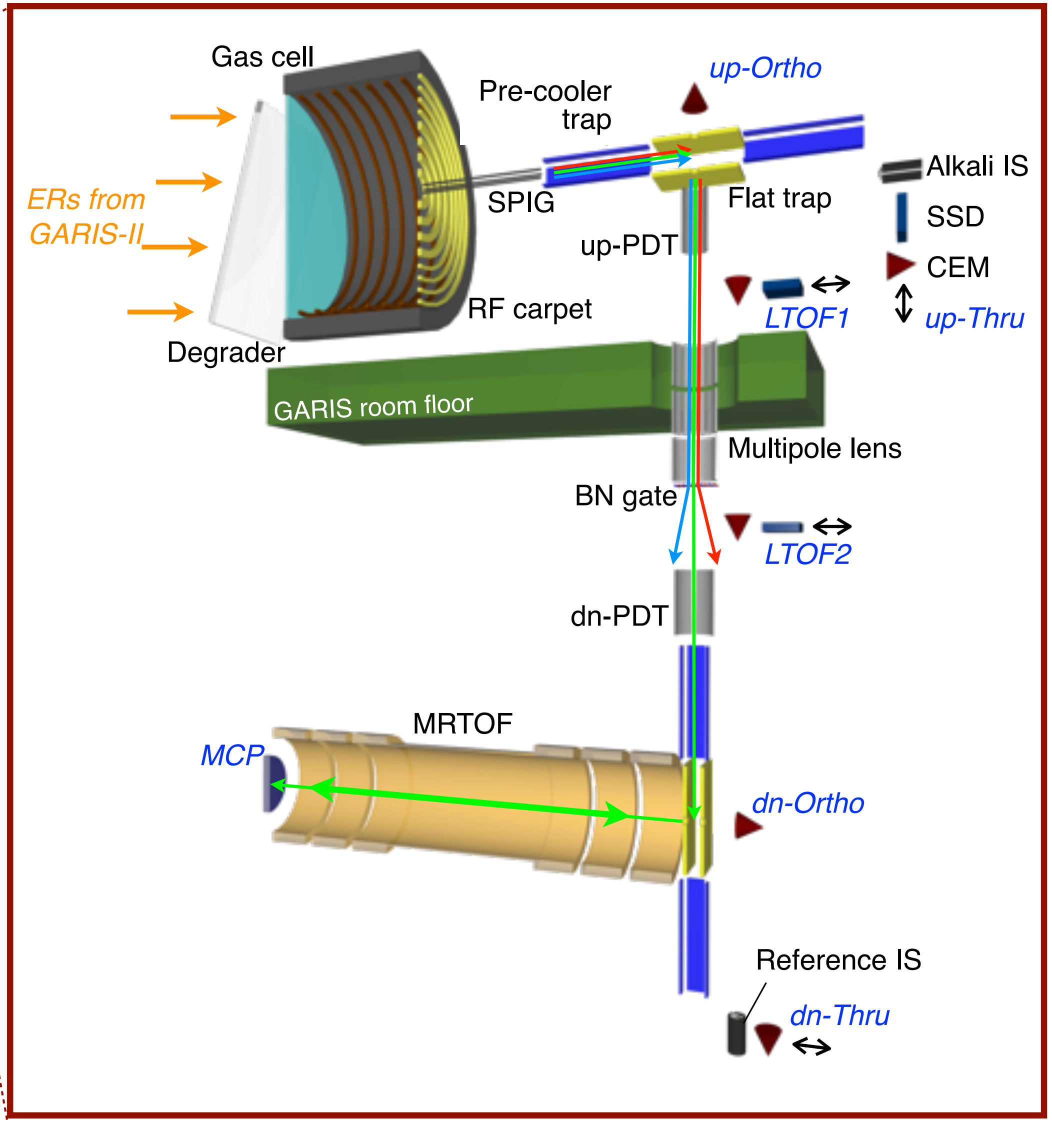
SHE-Mass Setup @GARIS-II

GARIS-II (by GARIS team)



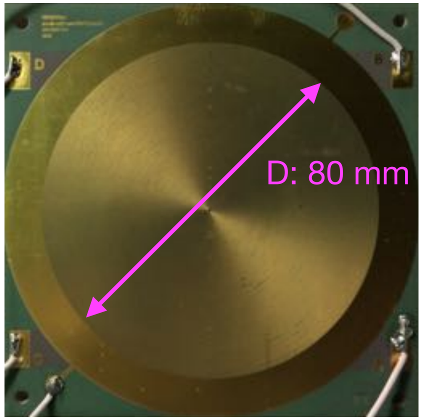


Cryogenic He gas cell + MRTOF

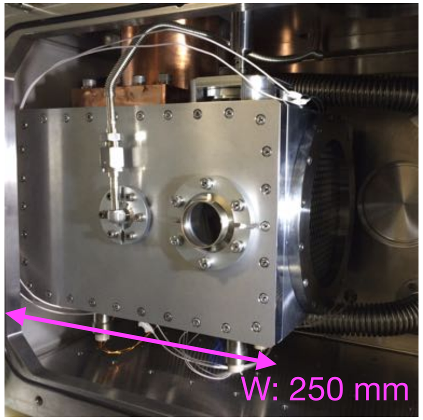


Overall system efficiency ~ 2%
(MRTOF detection rate / Gas-cell incoming rate)

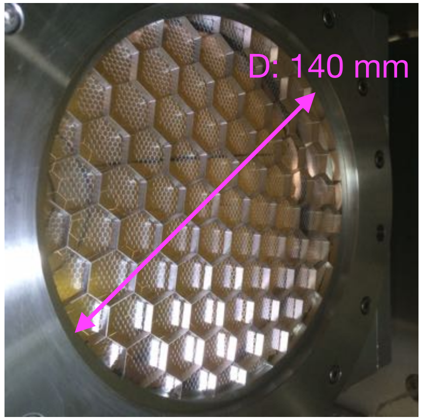
SHE-Mass Setup @GARIS-II



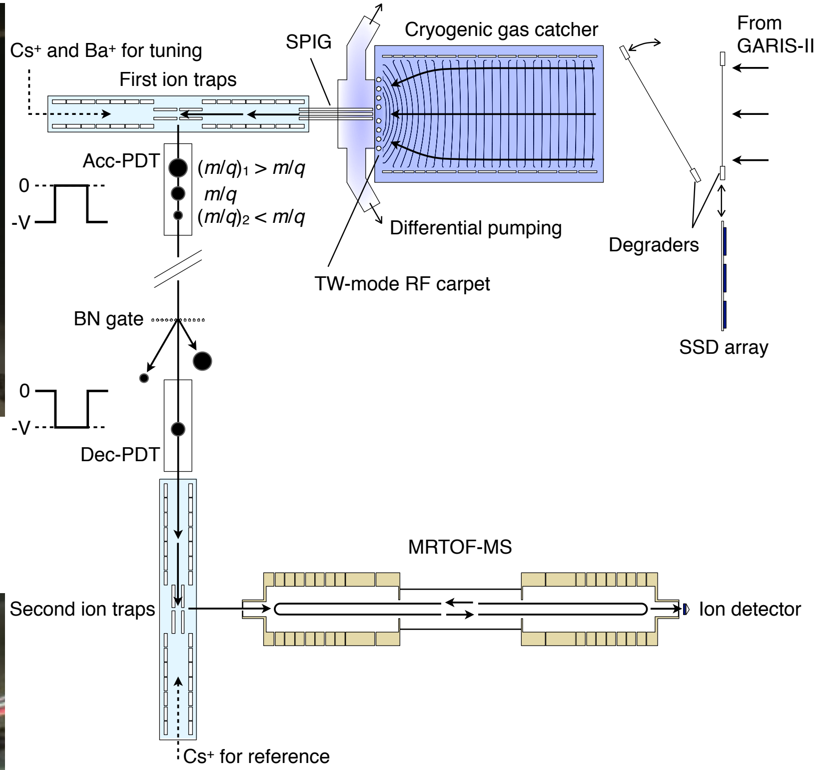
Traveling-wave RF carpet
Kapton PCB: t40 μm
width: 80 μm, pitch: 160 μm, exit: I.D. = 320 μm

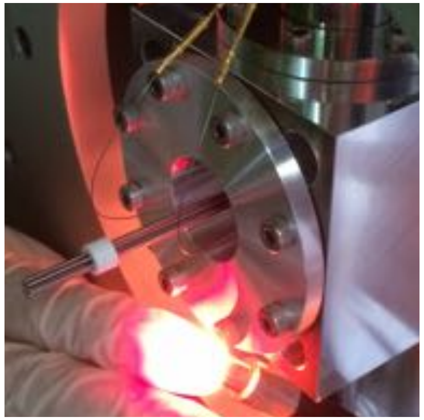


Cryogenic He gas catcher
pressure: <250 mbar
temperature: ~80 K (in operation)

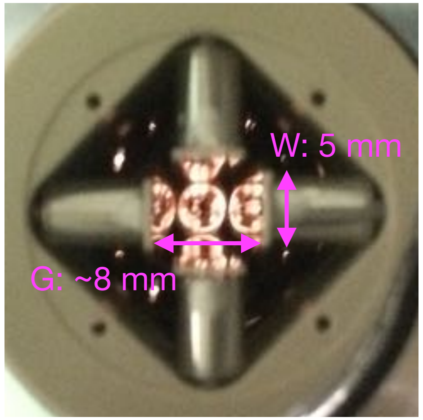


Mylar + Honeycomb
transmission: 0.88
Mylar thickness: 0.5 μm

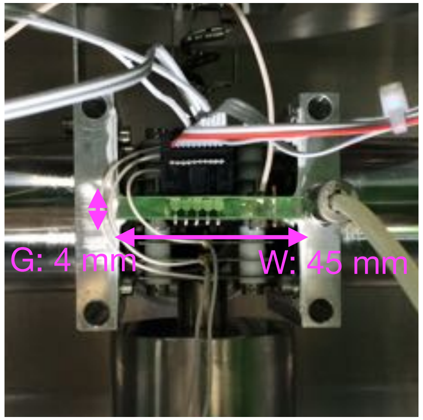




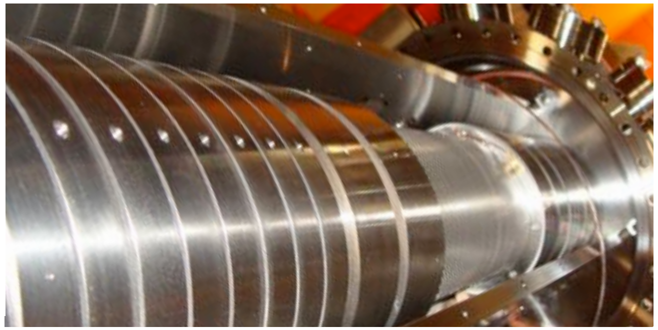
Sextupole ion guide
Mo rods: 126 mm, Φ1 mm
inter-rod radius: 1.1 mm



RFQ pre-cooler trap
resistive-divided PCB strips



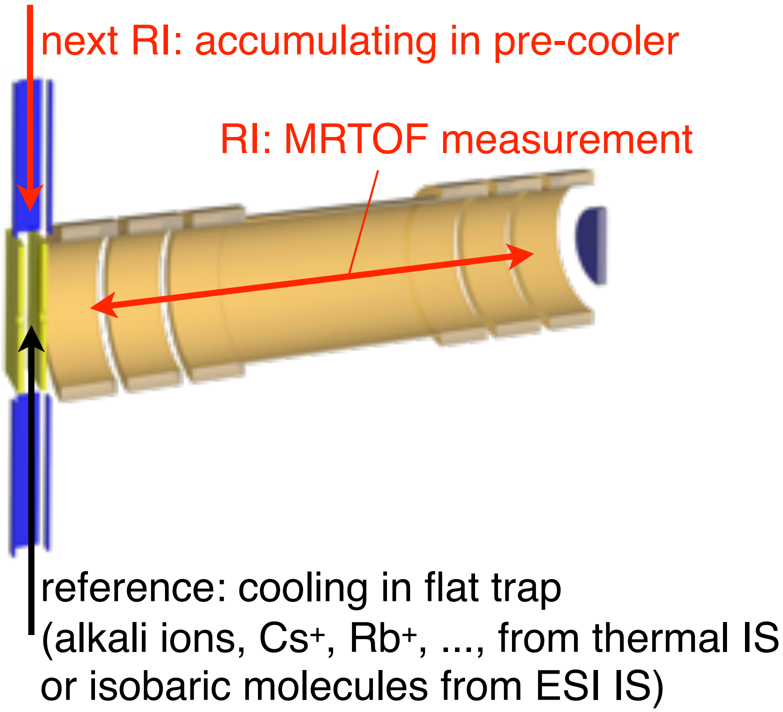
Flat trap
pulse width: ~ns
multi-injection, orthogonal ejection

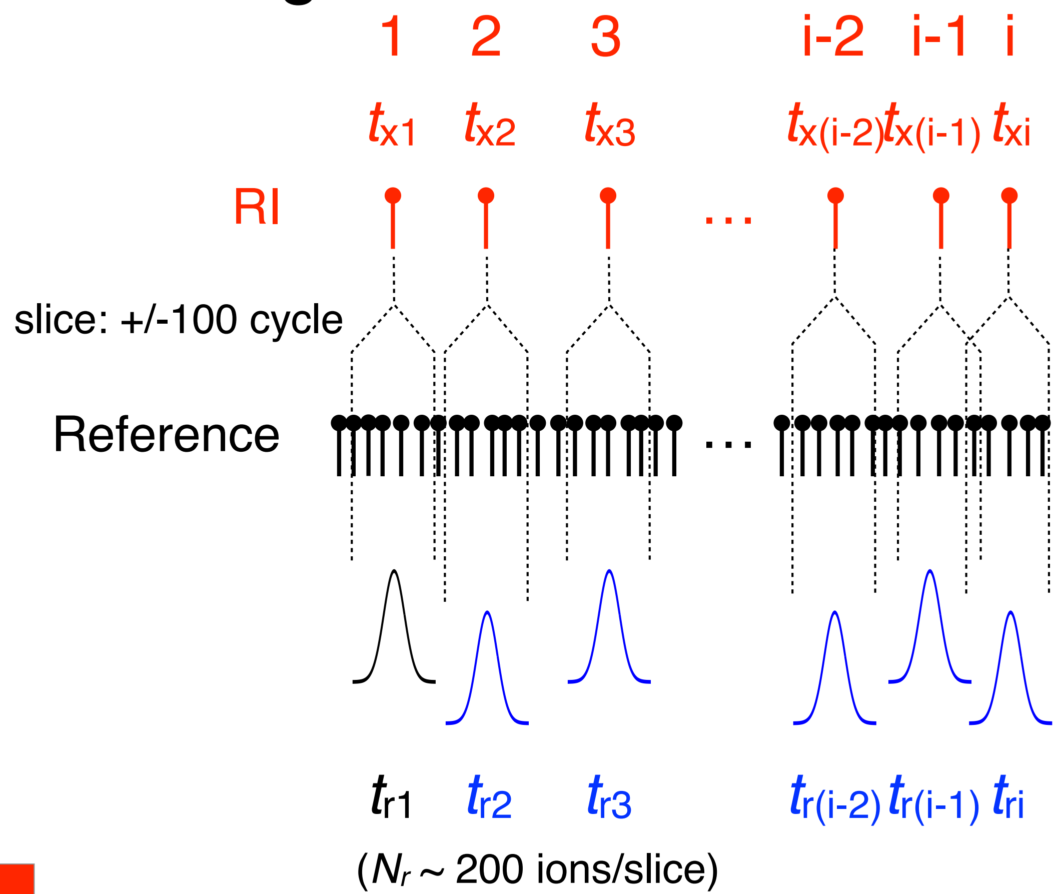


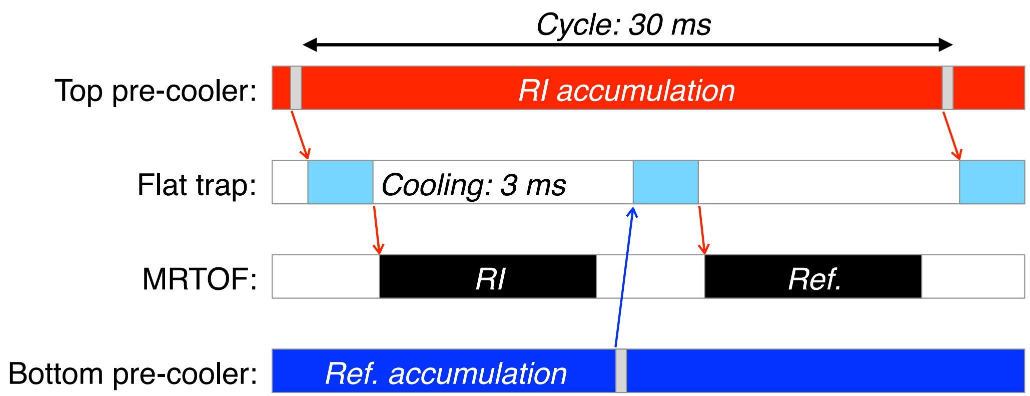
MRTOF
mass resolving power: >150,000 (<10 ms)
mass precision/accuracy: $<10^{-7}/\ll 10^{-7}$
system efficiency: 80%

Y.I. et al., PRL 120 (2018) 152501
P. Schury et al., NIMB 335, 39 (2014)
Y.I. et al., NIMB 317 (2013) 544

Concomitant Referencing Method







More accurate & precise
Easy drift compensation
(almost) No duty loss

Drift compensation: $t_i^{cor} = (t_{r1}/t_{ri}) \times t_i$ (i > 1)

↓

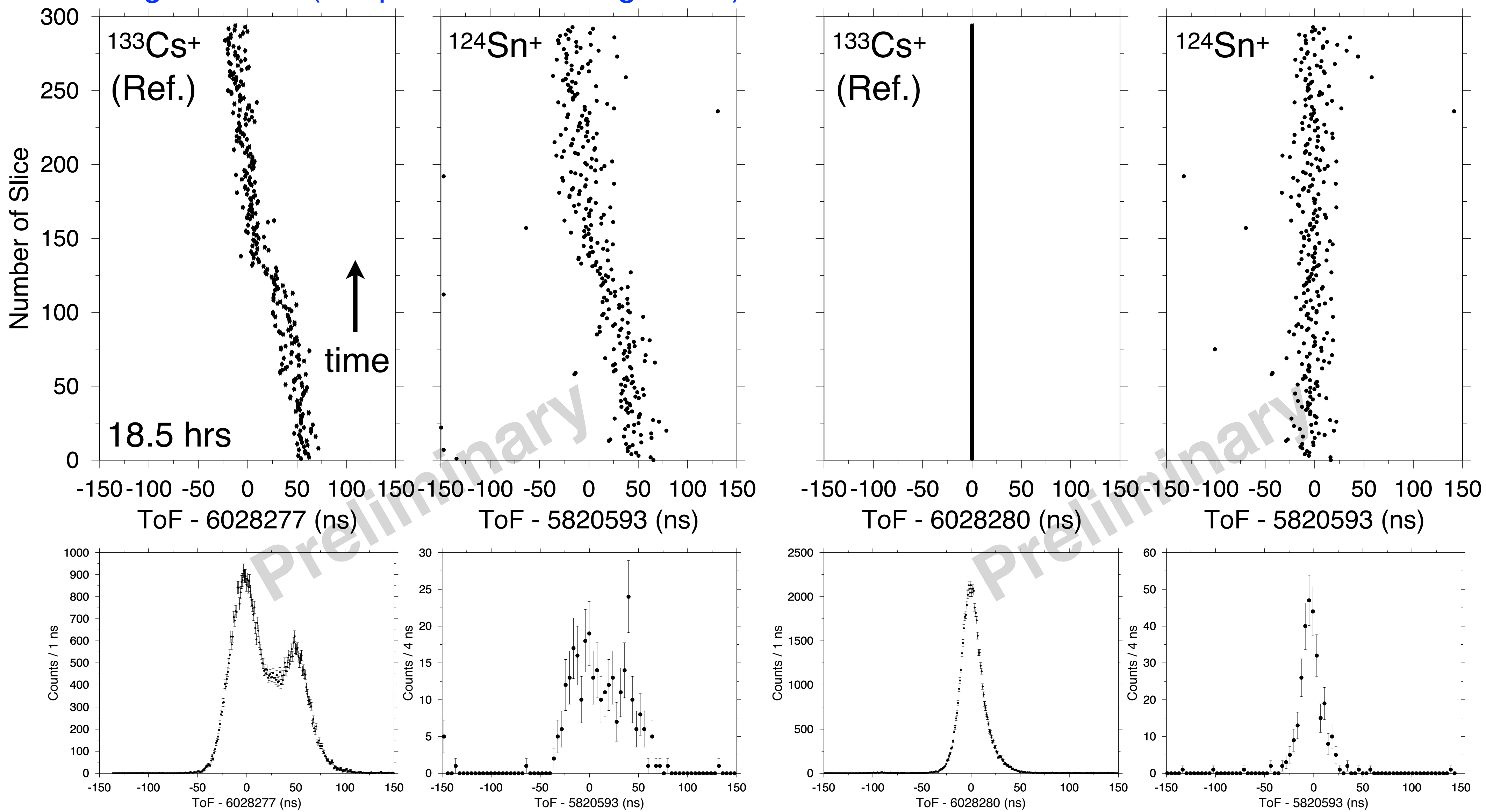
Sum up all events used for compensation

↓

Obtain corrected ToFs for mass determination

Drift Correction with Concomitant Referencing

Original Data (temperature non-regulated) | Drift corrected Data



peak splitting, fitting never work

$\Delta m(^{124}\mathrm{Sn}) = 8(28)$ keV

$\delta m/m = 2.4 \times 10^{-7}$

$R_m \sim 200{,}000$, $N(^{124}\mathrm{Sn}^+) = 244$

Multi-Steps Confirmation for Rare Events

- nature of MRTOF
  - only TOF for identification (no decay info.)
  - “spectrograph-like” nature, conversely, all ions are recorded in a spectrum
- possible contaminations
  - isobaric ions: same number of laps
  - non-isobaric ions (target recoils, other reaction channels, molecular ions, ...) : different number of laps
  - detector background: random
- 3-steps confirmation/identification

  1. TOF expected @ *N* laps
  2. TOF expected @ *N’* laps (typ. *N*±1) with similar rate
  3. dummy (lighter) target run : Au (Z = 79) target instead of Tl (Z = 81) target → no chance to produce ion of interest, while other conditions should be similar

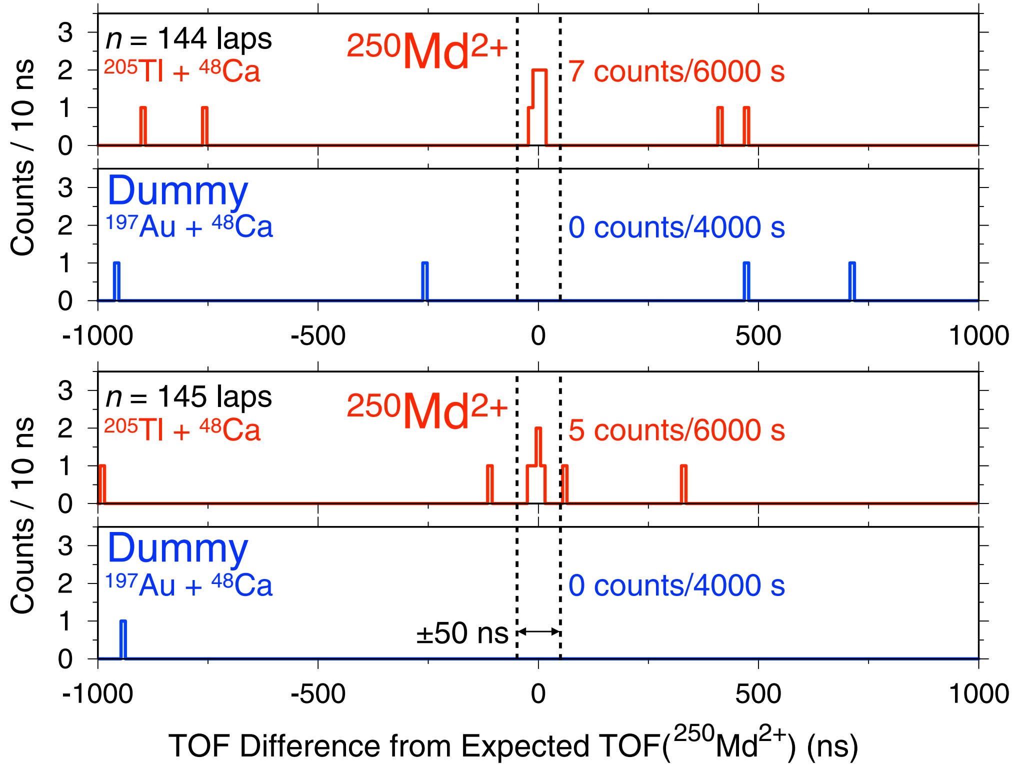
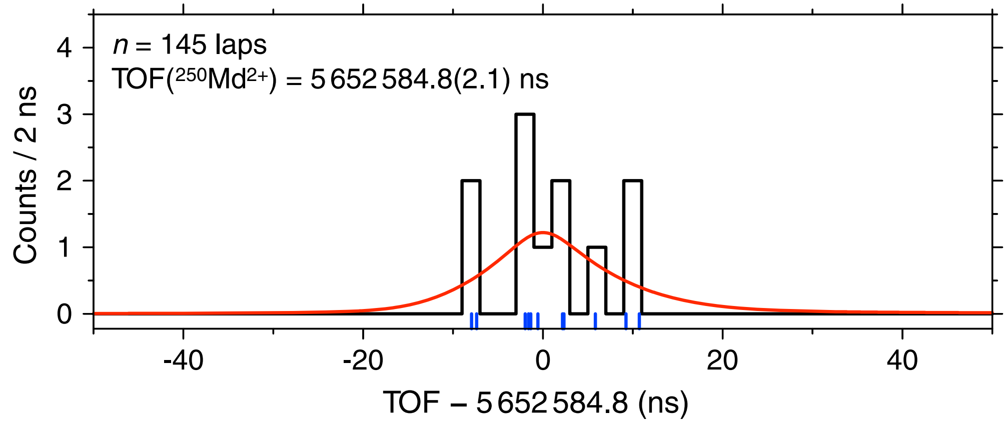


FIG. 4. TOF spectra in the anticipated vicinity of $^{250}\mathrm{Md}^{2+}$ at n = 144 and 145 laps for $^{\mathrm{nat}}\mathrm{Tl}$ and $^{197}\mathrm{Au}$ targets.



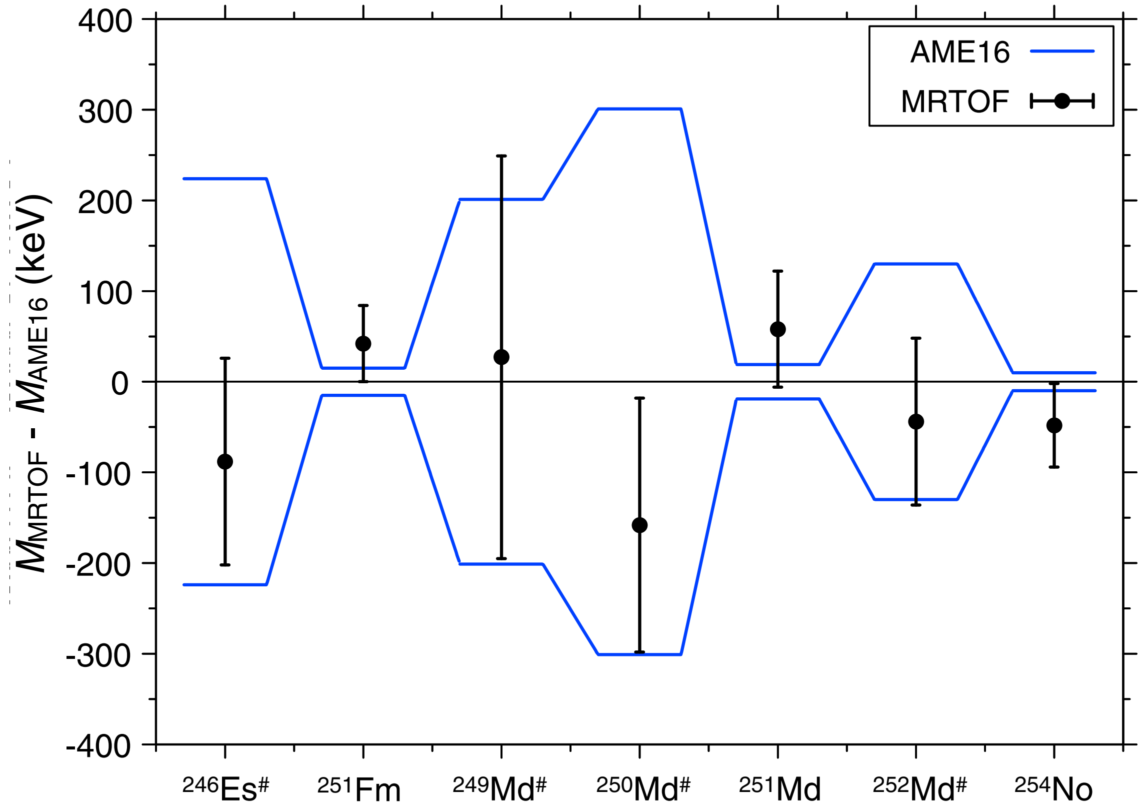
Mass Determinations

Isotope	Reaction	E_{lab} (MeV)	E_{recoil} (MeV)	σ_{ER} (nb)	ρ^2	$\mathrm{ME}_{\mathrm{MRTOF}}$ (keV/c^2)	$\mathrm{ME}_{\mathrm{AME16}}$ (keV/c^2)	Δm (keV/c^2)	N_{ion} (counts)
^{246}Es	^{232}Th(^{19}F, 5n)	99.6, 103	7.5, 7.8	(800) [29]	0.925 743 51(44)	67 812(109)(32)	67 900#(224#)	−88(109)(32)	33
^{251}Fm	^{238}U(^{18}O, 5n)	93.9	6.9	4000 [30]	0.944 587 00(14)	75 996(34)(25)	75 954(15)	42(34)(25)	397
^{249}Md	^{203}Tl(^{48}Ca, 2n)	215	41.1	(40) [29]	0.937 067 92(89)	77 259(221)(26)	77 232#(205#)	27(221)(26)	14
^{250}Md	^{205}Tl(^{48}Ca, 3n)	223	42.3	(200) [29]	0.940 834 91(56)	78 472(138)(25)	78 630#(298#)	−158(138)(25)	29
^{251}Md	^{205}Tl(^{48}Ca, 2n)	215	40.8	760 [31]	0.944 599 23(24)	79 025(60)(23)	78 967(19)	58(60)(23)	173
^{252}Md	^{238}U(^{19}F, 5n)	98.6	7.3	(500) [29]	0.948 367 15(36)	80 467(89)(22)	80 511#(130#)	−44(89)(22)	63
^{254g}No	^{208}Pb(^{48}Ca, 2n)	219	41.1	2000 [32]	0.955 908 32(17)	84 675(42)(19)	84 723.4(9.3)	−48(42)(19)	398

New masses

<100 nb

14 counts in 6 hrs, $\delta m/m \sim 10^{-6}$



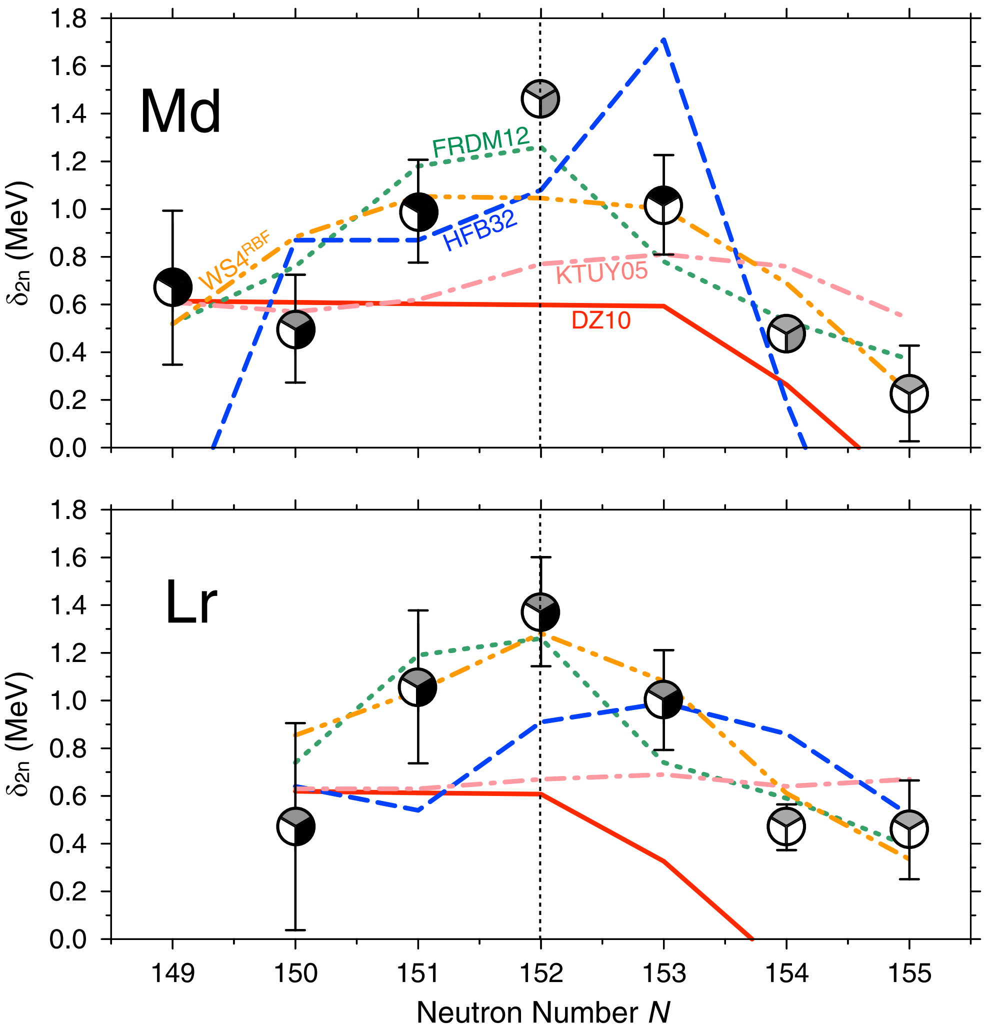
- good agreement with AME16: extrapolation in this region is still quite valid

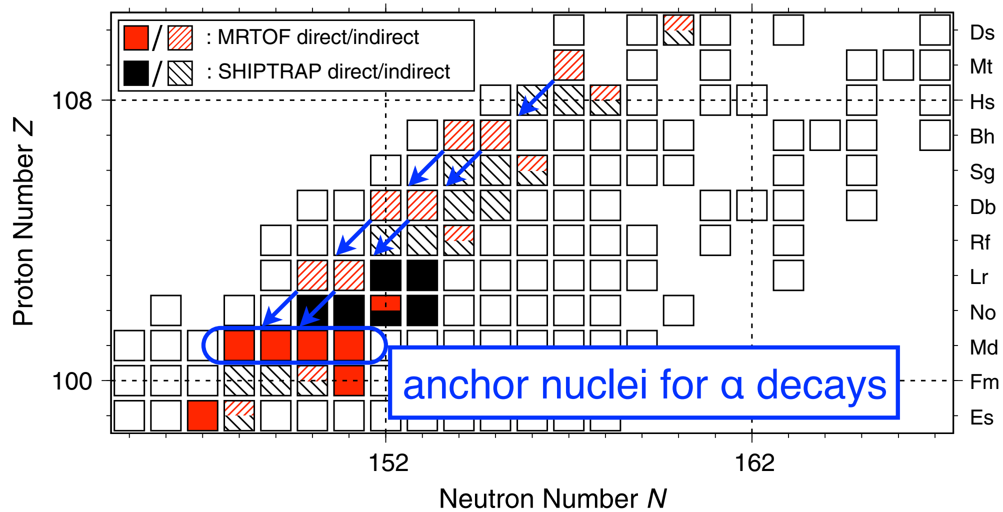
Nuclear Structure at $N = 152$ and Mass Predictions

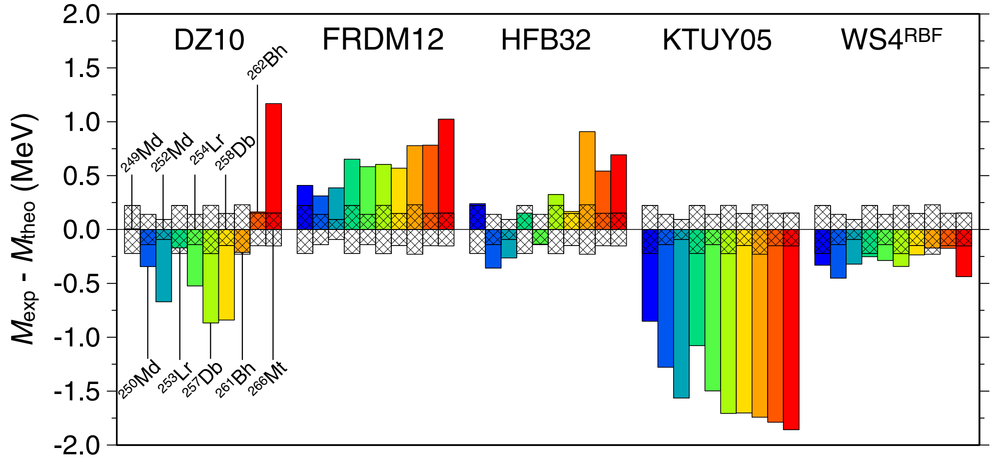
- Shell gap parameter δ_{2n}

$$\delta_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N+2,Z)$$
$$= 2B(N,Z) - B(N-2,Z) - B(N+2,Z)$$

■ : this work ■ : experimental in AME16 □ : extrapolated in AME16

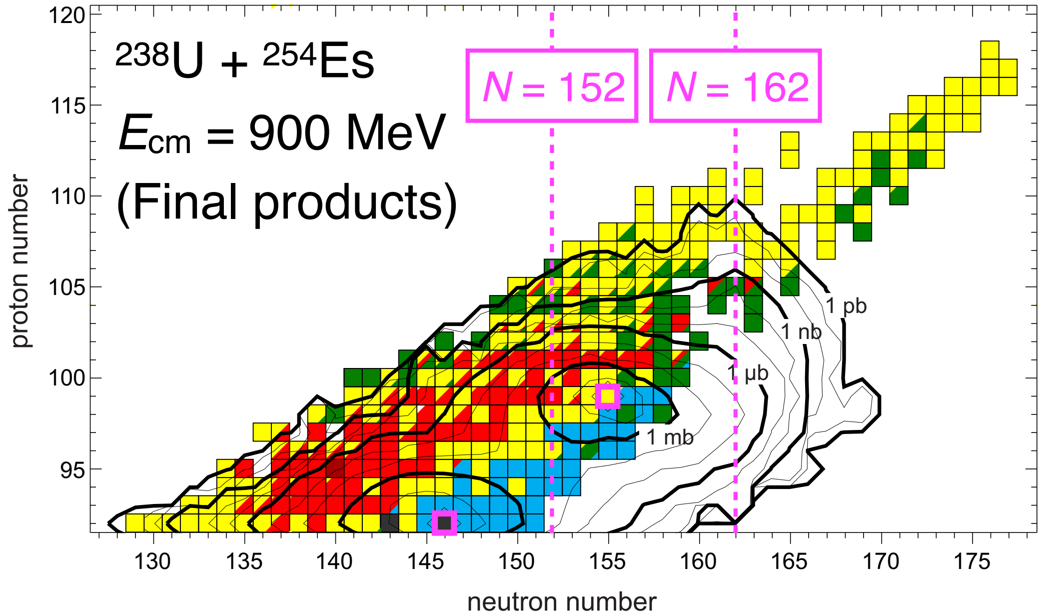




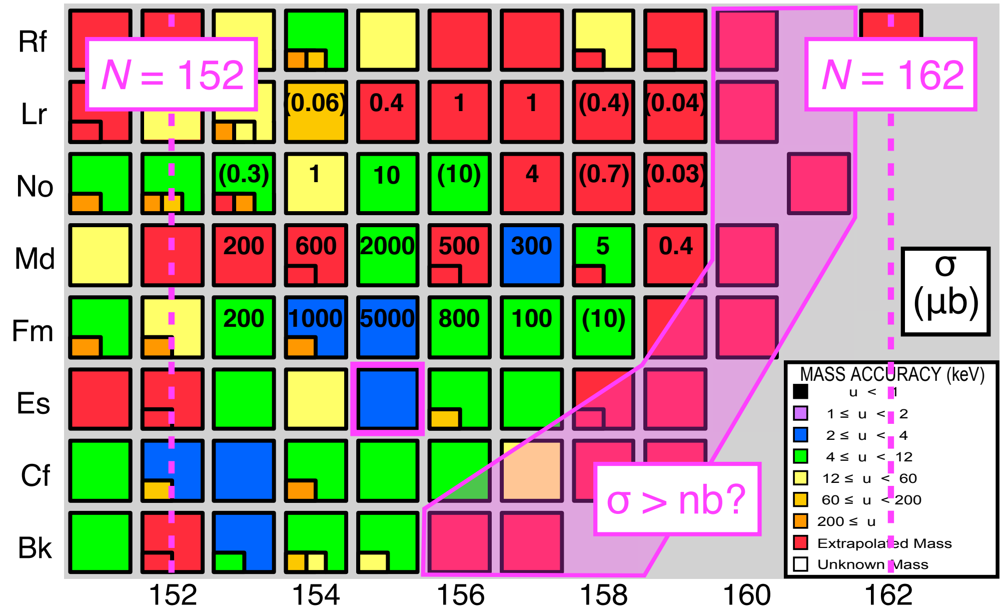


Isotope	Q_α (keV/c^2)	$\mathrm{ME}^{\mathrm{Indirect}}_{\mathrm{MRTOF}}$ (keV/c^2)	$\mathrm{ME}_{\mathrm{AME16}}$ (keV/c^2)	Δm (keV)
^{253}Lr	8918(20)	88 602(222)	88 575#(202#)	27(222)
^{254}Lr	8816(12)	89 713(141)	89 871#(301#)	−158(141)
^{257}Db	9207(20)	100 234(224)	100 206#(203#)	28(224)
^{258}Db	9500(50)	101 638(149)	101 797#(306#)	−159(149)
^{261}Bh	10 500(50)	113 158(229)	113 134#(209#)	25(229)
^{262}Bh	10 319(15)	114 382(150)	114 541#(306#)	−159(150)
^{266}Mt	10 996(25)	127 803(152)	127 962#(306#)	−159(152)

Mass Measurement Plan for MNT Products @JAEA

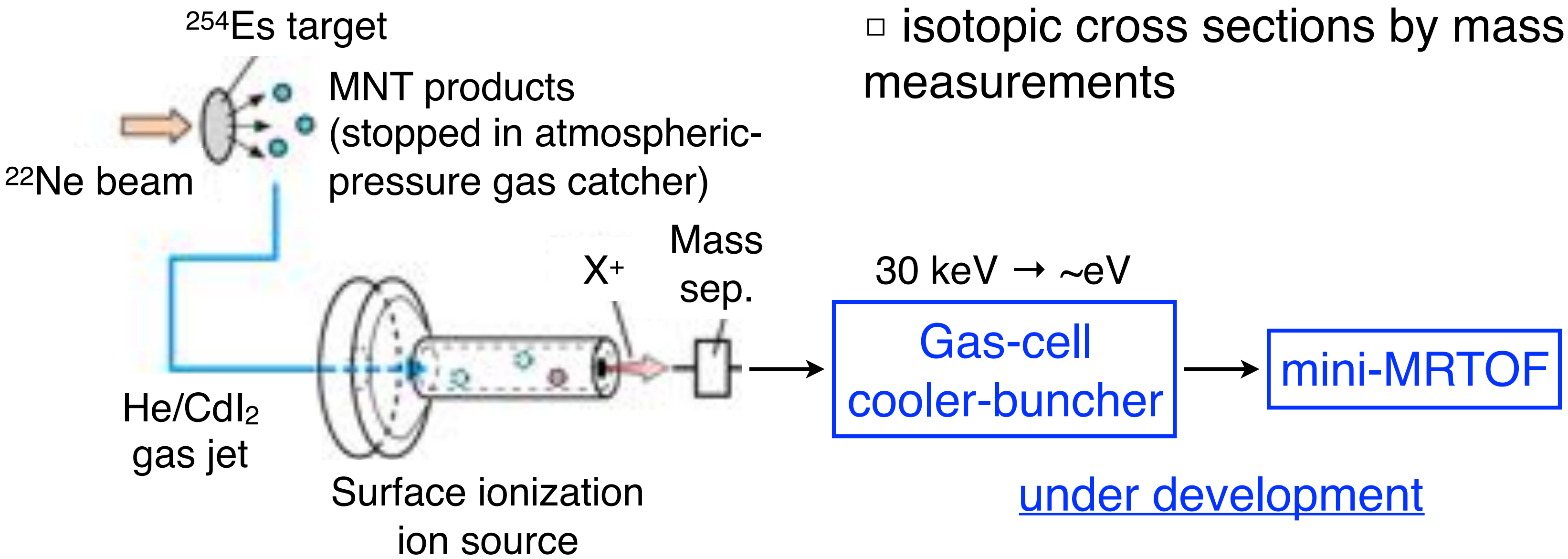


V.V. Saiko and A.V. Karpov, PRC 99, 014613 (2019)



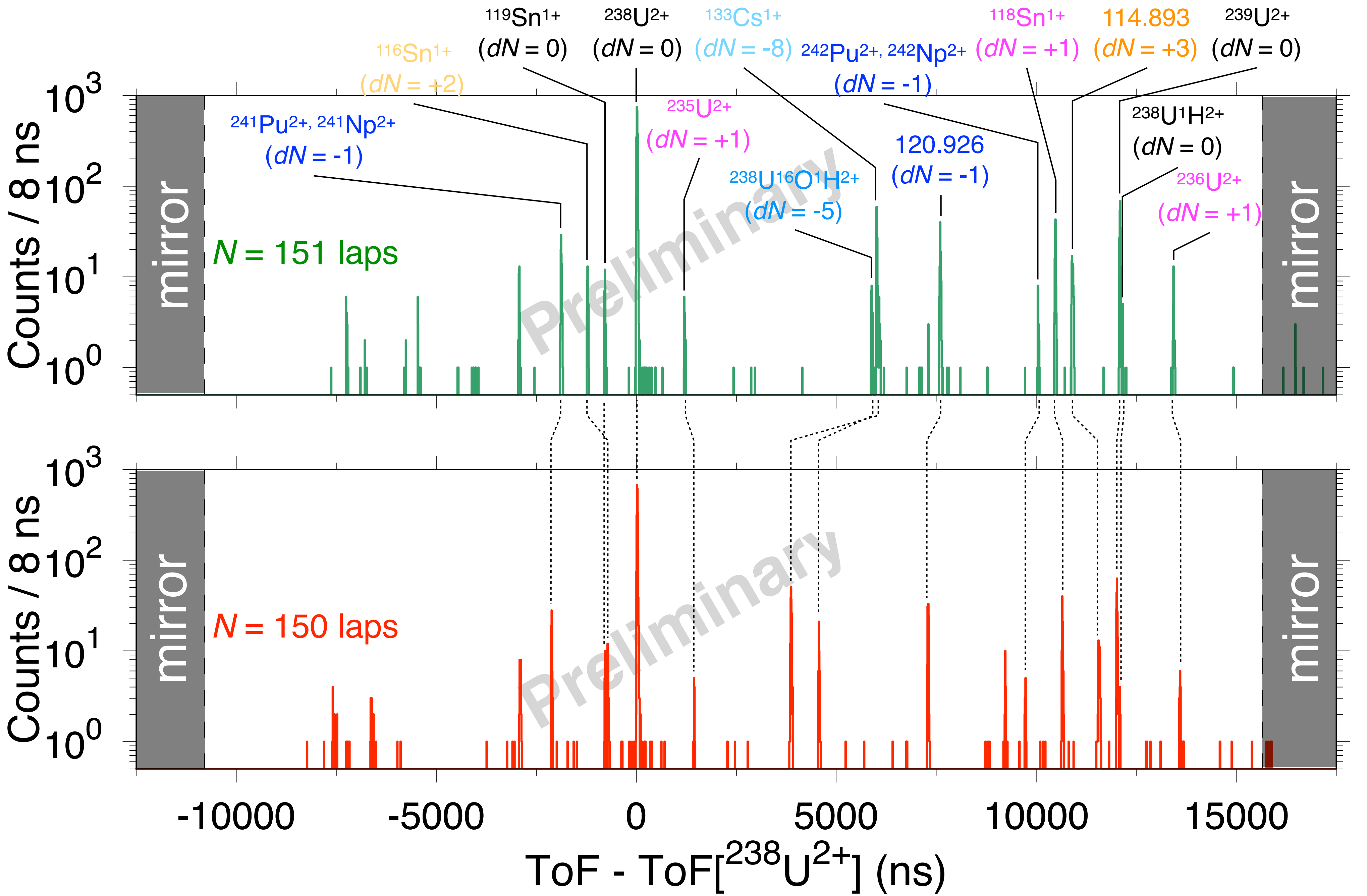
M. Schadel et al., PRC 33, 1547 (1986)

- MNT reactions with ^{238}U + ^{248}Cm/^{254}Es
  - σ > nb over N = 162
- MNT reactions with ^{22}Ne + ^{254}Es @JAEA
  - expect σ > nb in the vicinity of N = 162
  - isotopic cross sections by mass measurements



under development

MNT Spectra with $^{nat}U + {}^{18}O$ @GARIS-II



Summary

- Systematic mass information is indispensable to understand nuclear structure and to inspect nuclear mass models for exploring "Island of Stability"
- SHE-mass setup offers fast, efficient, and wide-band high-precision mass measurements
- Concomitant referencing enables drift correction and low count rate measurement
- Masses of ^{249,250,252}Md and ^{246}Es were newly measured in this work and extended mass determination up to ^{266}Mt
- WS4^{RBF} has relatively good prediction power even for heavier nuclei
- Macro-micro models, FRDM12 and WS4^{RBF}, reproduce the trend of δ_{2n} @ $N = 152$ well