Preparation for precise mass measurements using MMS at RAON

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Outline

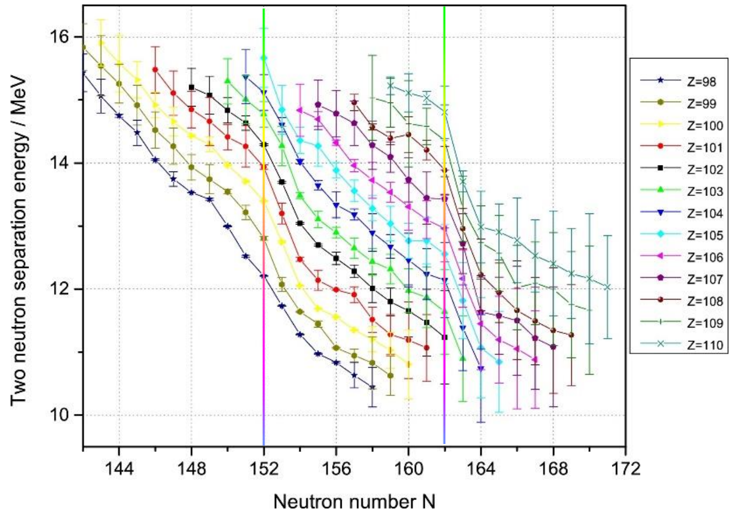
I. Introduction

❑ Nuclear structure

- Tracking shell closure

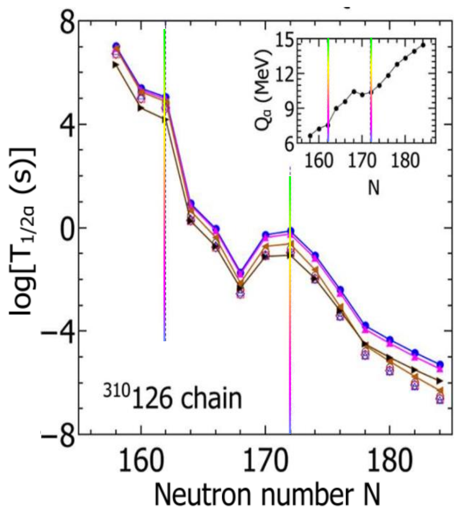
2n-separation energy: $S_{2n} = M(Z, N) - M(Z, N+2) - 2m_n$

Shell gap energy: $\delta_{2n} = S_{2n}(Z, N) - S_{2n}(Z, N+2)$



M. Block, NPA 944 (2015) 471-491.
Q. Mo et al., PRC90, 024320 (2014)

- α-cluster in SHN & α-decay



N.D. Ly et al., Phys.Scr. 96 (2021) 035301.

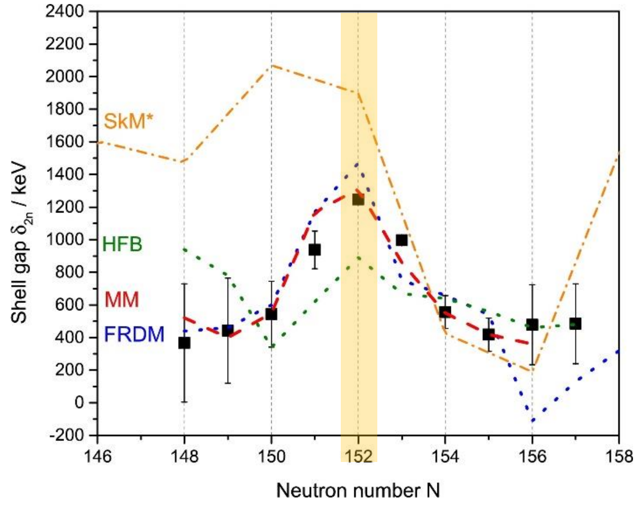
α-preformation: $S_\alpha = \dfrac{\ln 2}{\nu T_{1/2} P}$

$$P = exp\{-\frac{2}{\hbar}\int_{r_a}^{r_b}\sqrt{2\mu(V_T(r) - Q_\alpha)}\,dr\}$$

$$\nu = \omega/2\pi = 2E_\nu/h$$

$$E_\nu = Q_\alpha\left[0.056 + 0.039\exp\left(\frac{4 - A_2}{2.5}\right)\right];$$

$$Q_\alpha = M(Z,N) - M(A\text{-}4,Z\text{-}2) - M_\alpha$$



M. Block, NPA 944 (2015) 471-491.

I. Introduction

❑ Astrophysical implications

- Beta-decay rates

$$\ln T_{1/2} = a_6 + \left(\alpha^2 Z^2 - 5 - a_7 \frac{N-Z}{A}\right) \ln(Q - a_8\delta) + a_9\alpha^2 Z^2 + \frac{1}{3}\alpha^2 Z^2 \ln(A) - \alpha Z\pi + S(Z,N)$$

[Zhou et al. (2017)]

$$Q_{\beta^-} = M(Z,N) - M(Z+1,N-1)$$
$$= E_{\text{bind}}(Z+1,N-1) - E_{\text{bind}}(Z,N) + M_n - M_H$$

- Capture rates

$$N_A\langle\sigma v\rangle = 1.54\times10^{11}(\mu T_9)^{-3/2}\sum_i(\omega\gamma)_i \exp\left(\frac{-11.605 E_i}{T_9}\right)$$

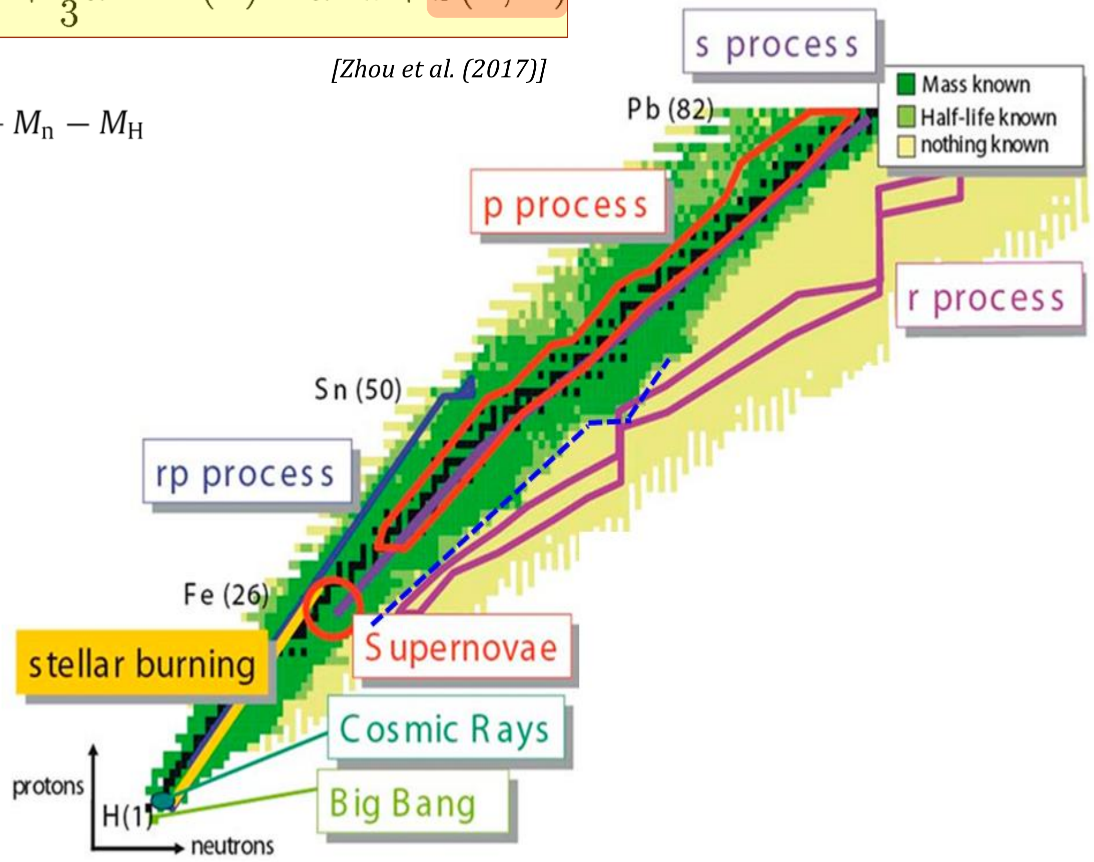
$$E_i = E_{cm} + Q \longrightarrow Q = (m_I - m_O)\times 931.5\ \text{MeV}$$

- Photodissociation rate in r-process

$$\lambda_\gamma(Z,A) \propto \exp\left[-\frac{S_n(Z,A)}{kT}\right]\langle\sigma v\rangle_{(Z,A-1)}$$

- Saha Equation

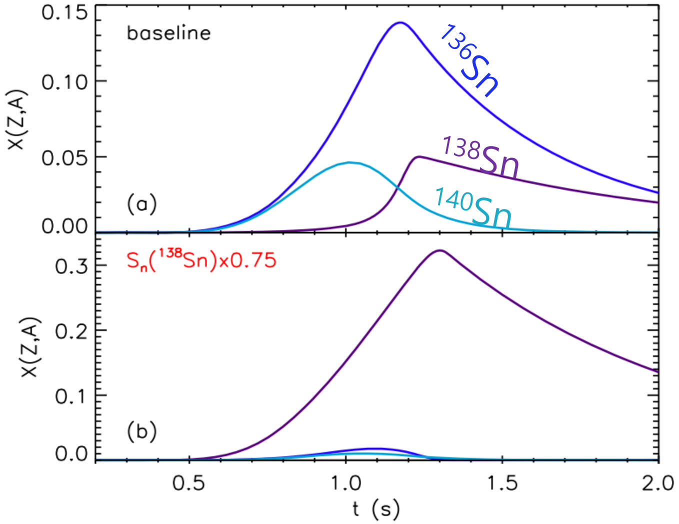
$$\frac{Y(Z,A+1)}{Y(Z,A)} \propto \exp\left[-\frac{S_n(Z,A+1)}{kT}\right]$$



*Particles **2020**, 3(2), 320-335*

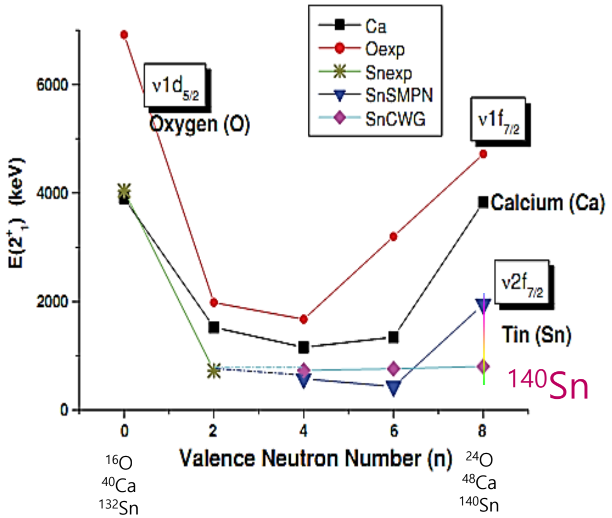
II. Proposed mass measurements at RAON

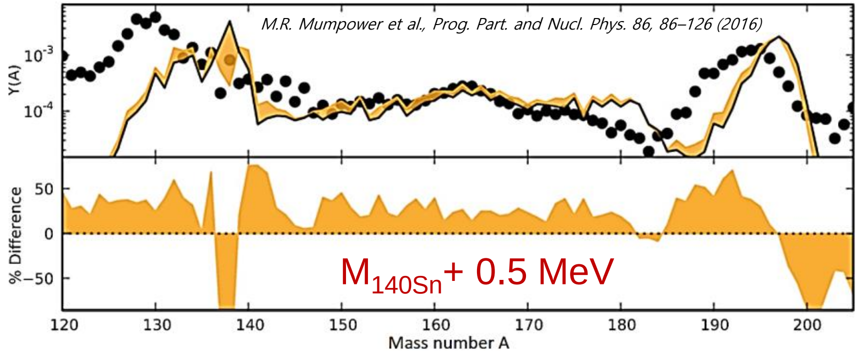
❖ **Isotopes of interest (neutron-rich $^{136\text{-}140}$Sn)**



S. Brett et al., Eur. Phys. J. A 48, 184 (2012)

S. Sarkar et al., Phys. Rev. C 81, 064328 (2010)





- M(^{A}Sn) are essential for nuclear structure & astrophysics
- M(^{140}Sn) is important for:
  - Shell closure at N = 82+8 ?
  - r-process abundance

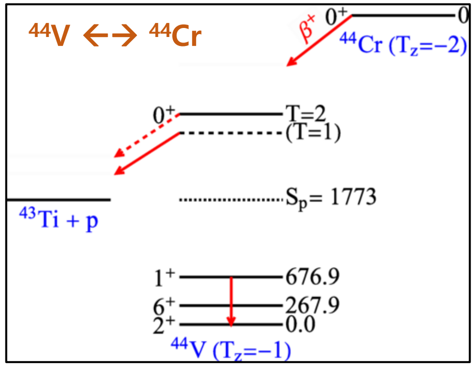
Isotope	m (u)	Δm (μu)	$T_{1/2}$ (ms)
^{136}Sn	135.939990	320	355
^{137}Sn	136.946550	430	249
^{138}Sn	137.951840	430	148
^{139}Sn	138.958730	430	120
^{140}Sn	139.962970	320	50

AME2020

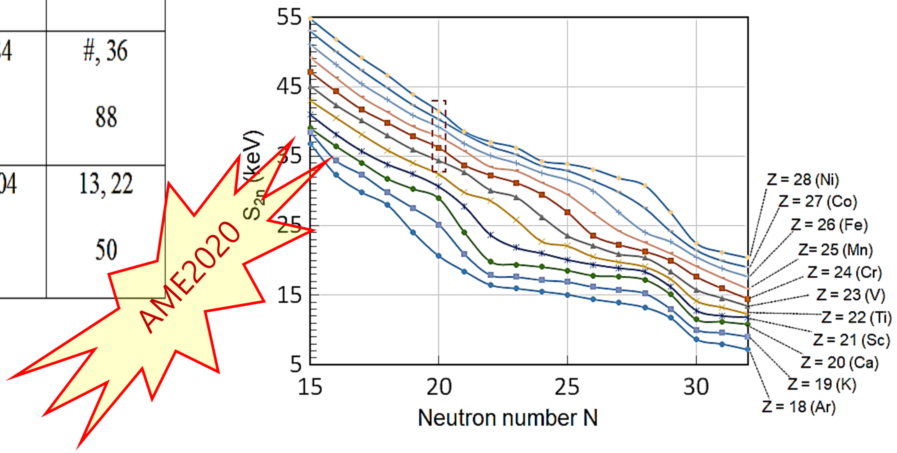
II. Proposed mass measurements at RAON

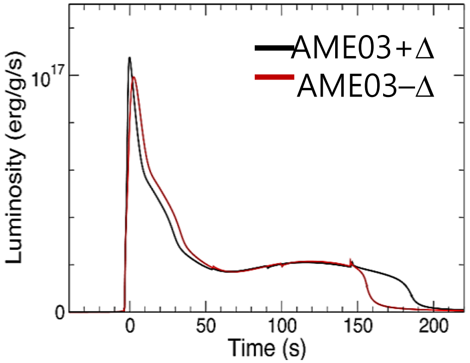
❖ **Isotopes of interest (proton-rich Ti – Fe)**

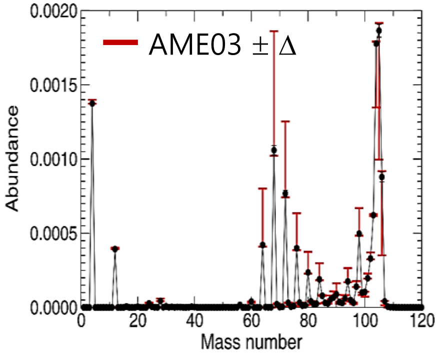
Isotope	Implications	Δm (keV)	$T_{1/2}$ (ms)
^{41}Ti	^{40}Sc(p, γ)^{41}Ti	28	82
^{43}V	^{42}Ti(p,γ)^{43}V & N = 20	43	80
^{44}V	^{44}V(p,γ)^{45}Cr ^{43}Ti(p,γ)^{44}V	80	111
^{44}Cr	N = 20	56	43
^{45}Cr	^{44}V(p,γ)^{45}Cr	37	61
^{45,46}Mn	N = 20	298, 84	#, 36
^{47}Mn	^{46}Cr(p,γ)^{47}Mn	28	88
^{46,47}Fe	N = 20	298, 504	13, 22
^{48}Fe	^{47}Mn(p,γ)^{48}Fe	94	50

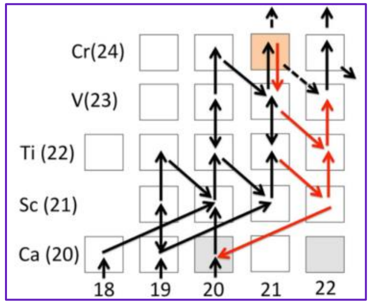


D. Puentes et al, Phys. Rev. C 101, (2020) 064309









➔ $S_p(^{45}Cr)$ = 2.139 MeV (AME03)

➔ $S_p(^{45}Cr)$ = 2.684 MeV
$\Delta m(^{45}Cr)$ = 35 keV

(Yan et al., Astrophys.J.Lett.766, L8)

II. Proposed mass measurements at RAON

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❖ Beam productions

Proton beam

- Intensity: 1 eμA
- Energy: 70 MeV

Target

- Materials: UC_x
- Thickness: 18g/cm^2
- Melting point: 2350 ^{o}C

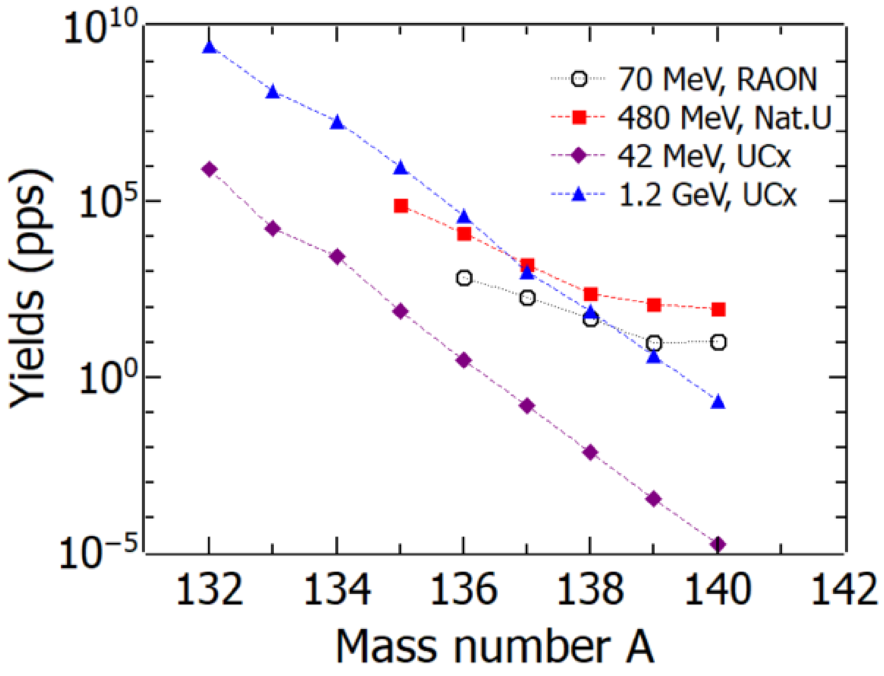
Driver: SC (**S**uperconductive **C**yclotron)

Ion Source: RILIS

(**R**esonance **I**onization **L**aser **I**on **S**ource)

S.J. Park & J.B. Kim, Hyper. Inter. 241 (2020) 39

Neutron-rich $^{132\text{-}140}$Sn isotopes



Estimated production yields of Tin isotopes using proton beams at 70 MeV (opened circles) based on p+U reactions with projectile at 42 MeV (diamonds - HRIBF), 1.2 GeV (triangles - CERN), 480 MeV (squares – TRIUMF).

A	Yields
136	~750
137	~ 300
138	~ 80
139	~ 10
140	~ 10

Contaminants

I, Sb & Te

Requirement

UC_x targets !

II. Proposed mass measurements at RAON

❖ Beam productions

Proton-rich isotopes

Proton beam
- Intensity: 1 eμA
- Energy: 70 MeV

Target for Z = 22 – 24
- Materials: Ti
- Thickness: 0.05 mol/cm^2
- Melting point: ~1660 °C

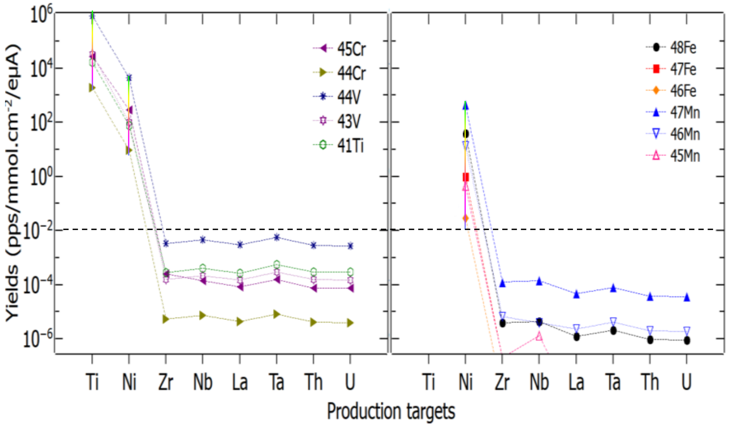
- Materials: Ni
- Thickness: 0.05 mol/cm^2
- Melting point: ~1455 °C

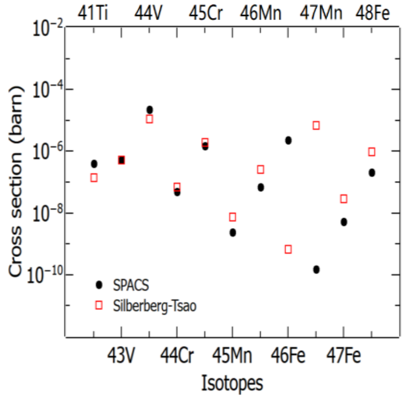
- Max Yields: 10 – 10^4 (pps/mmol.cm^{-2}/μA)

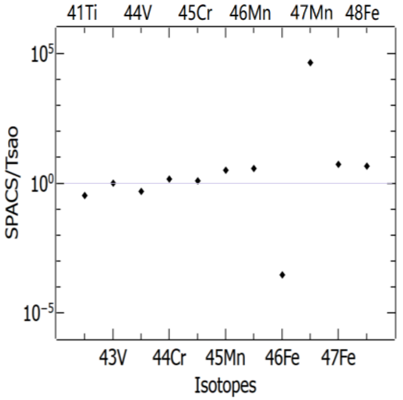
Driver: SC (**S**uperconductive **C**yclotron)

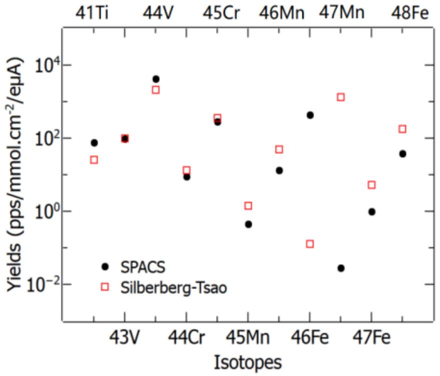
Ion Source: RILIS
(**R**esonance **I**onization **L**aser **I**on **S**ource)
S.J. Park & J.B. Kim, Hyper. Inter. 241 (2020) 39

SPACS code *[C. Schmitt et al. Phys. Rev. C 94, 039901 (2016)*









^{46}Fe Min: 0.13 pps (Tsao)
Max: 435 pps (SPACS)

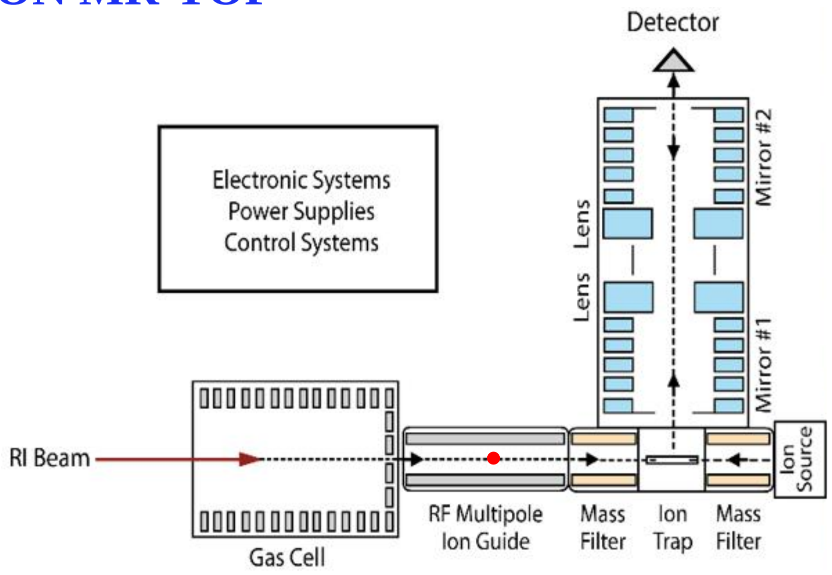
^{47}Mn Min: 0.03 pps (SPACS)
Yield$_{max}$: 1320 pps (Tsao)

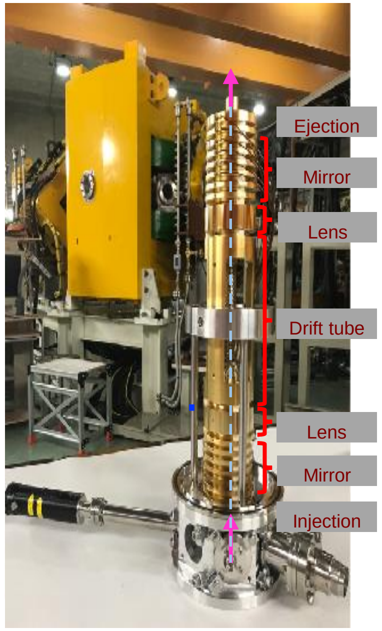
Nuclei	^{45}Mn	^{46}Mn	^{47}Mn	^{46}Fe	^{47}Fe	^{48}Fe
mol/cm^2	Ni	Ni	Ni	Ni	Ni	Ni
Yields	4×10^{-1}	~10	4×10^2	3 x 10^{-2}	~1	~40

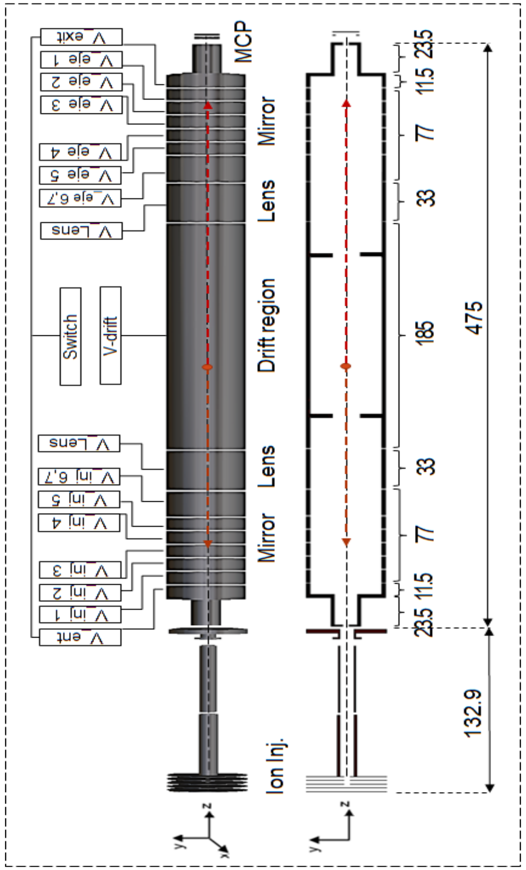
Requirement: Ni targets !

II. Proposed mass measurements at RAON

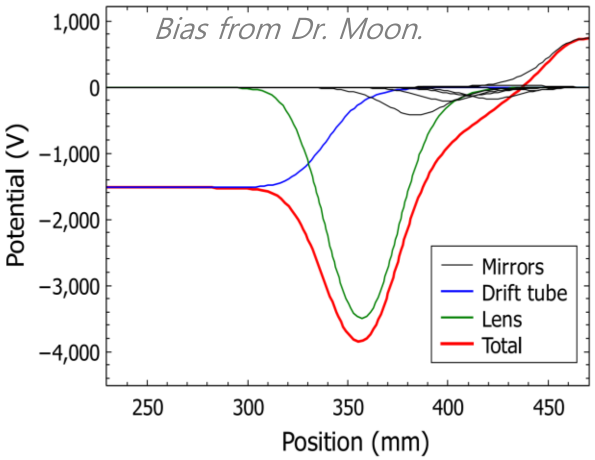
❖ RAON MR-TOF

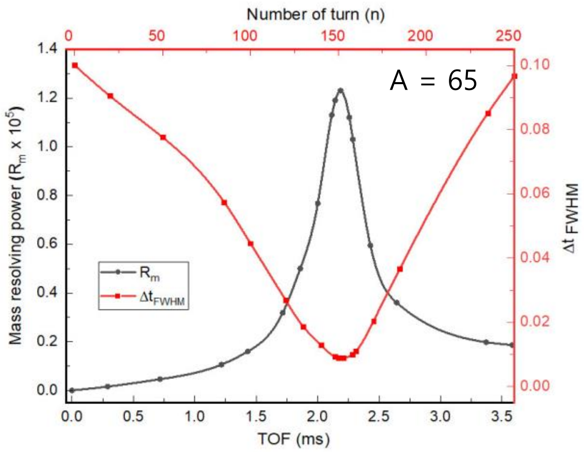






Dimension from Dr. Moon.





Resolving power:

R_m = ~1.2 x 10^5

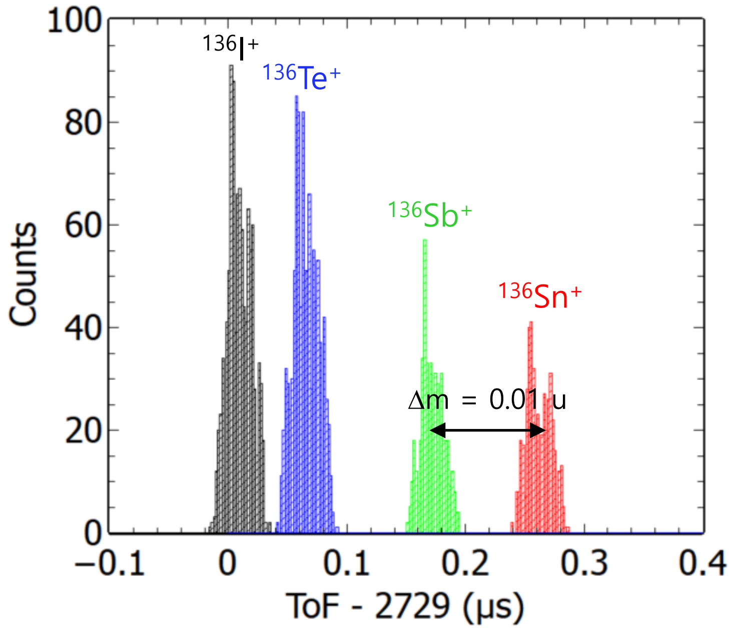
FWHM = ~10 ns

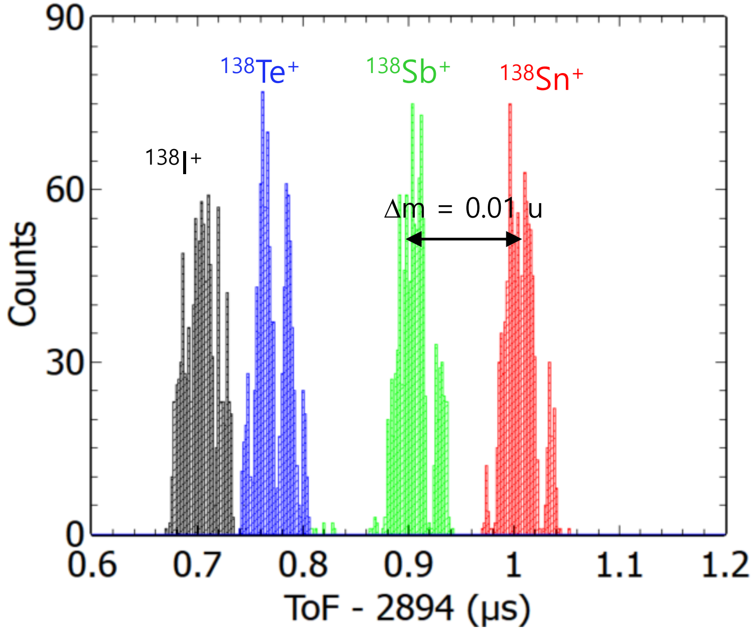
II. Proposed mass measurements at RAON

❖ Separability

Ions	Mass (u)	$T_{1/2}$ (s)
^{136}Sn	135.93970	0.350
^{136}I	135.91460	83.400
^{136}Sb	135.93075	0.923
$^{136}Te^+$	135.92010	17.630

Ions	Mass (u)	$T_{1/2}$ (s)
^{138}Sn	137.95114	0.150
^{138}I	137.92273	6.230
^{138}Sb	137.94133	0.380
$^{138}Te^+$	137.92947	1.400





- $R_m = 1.2 \times 10^5$

  with

  N = 134 turns

  Sn^+ & Sb^+ ions can be separated.

- ToF = ~3 ms << 150 ms

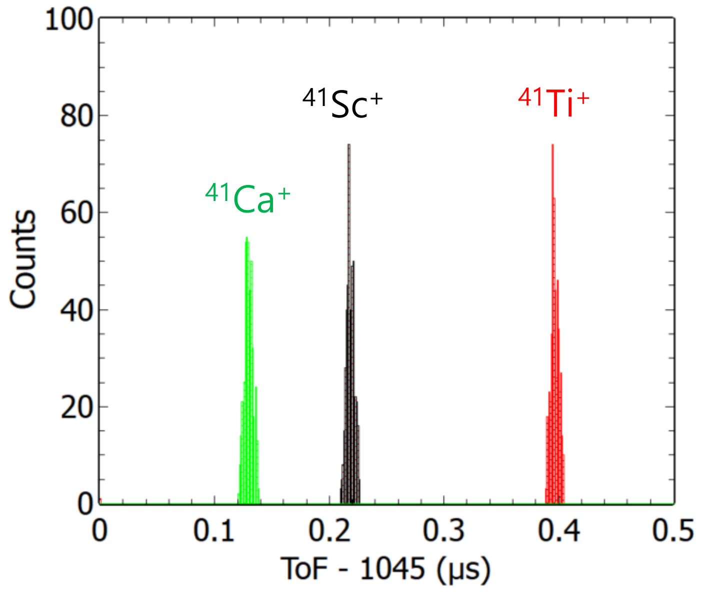
→ possible for measuring $^{136,138}Sn$.

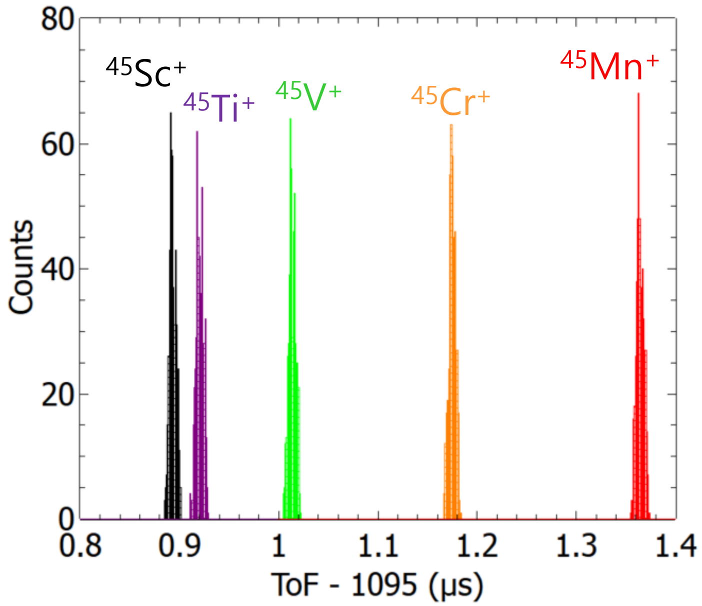
II. Proposed mass measurements at RAON

❖ Separability

Nuclide	Mass (u)	$T_{1/2}$
^{41}Ti	40.98315	**82 ms**
^{41}Sc	40.96925	596.3 ms
^{41}Ca	40.96228	99.4 ky

Nuclide	Mass (u)	$T_{1/2}$
^{45}Sc	44.95591	Stable
^{45}Ti	44.95812	184.8 m
^{45}V	44.96577	547 ms
^{45}Cr	44.97905	60.9 ms
^{45}Mn	44.99461	**18 ms***





II. Proposed mass measurements at RAON

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2 Letters of Intent

LOI 1: Neutron-rich nuclei

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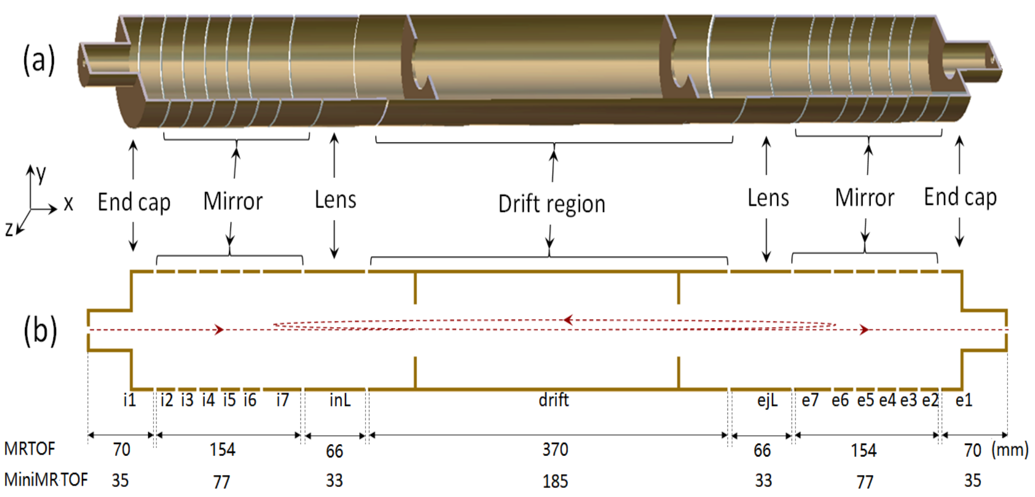
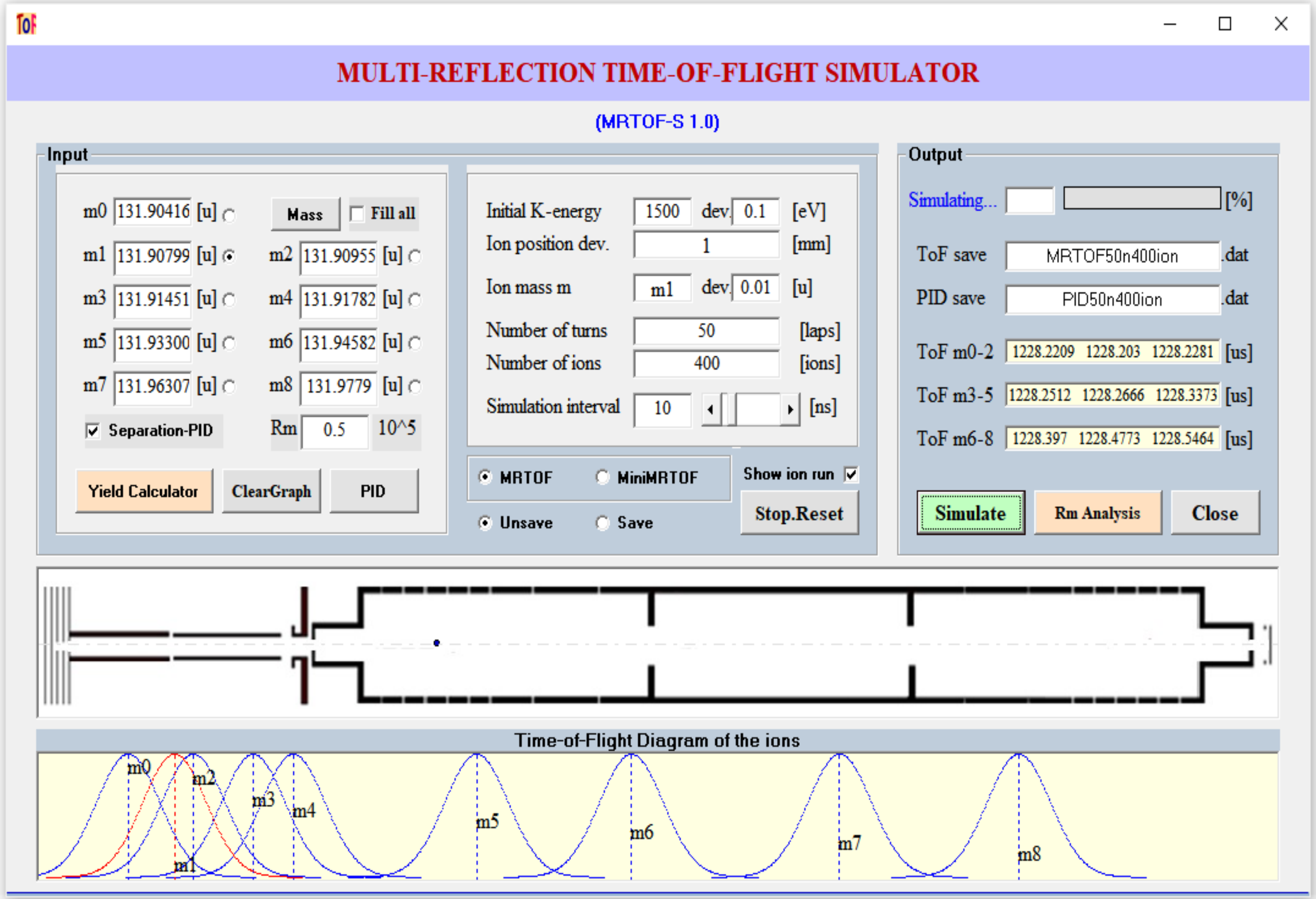
^{44}Cr ^{45}Cr	N = 20 ^{44}V(p,γ)^{45}Cr	56 37	43 61
^{45,46}Mn ^{47}Mn	N = 20 ^{46}Cr(p,γ)^{47}Mn	298, 84 28	#, 36 88
^{46,47}Fe ^{48}Fe	N = 20 ^{47}Mn(p,γ)^{48}Fe	298, 504 94	13, 22 50

III. MRTOF Simulator



P. Schury *et al.*, Nucl. Instr. Meth. B **335**, 39 (2014)

J. Y. Moon *et al.*, Private communication.



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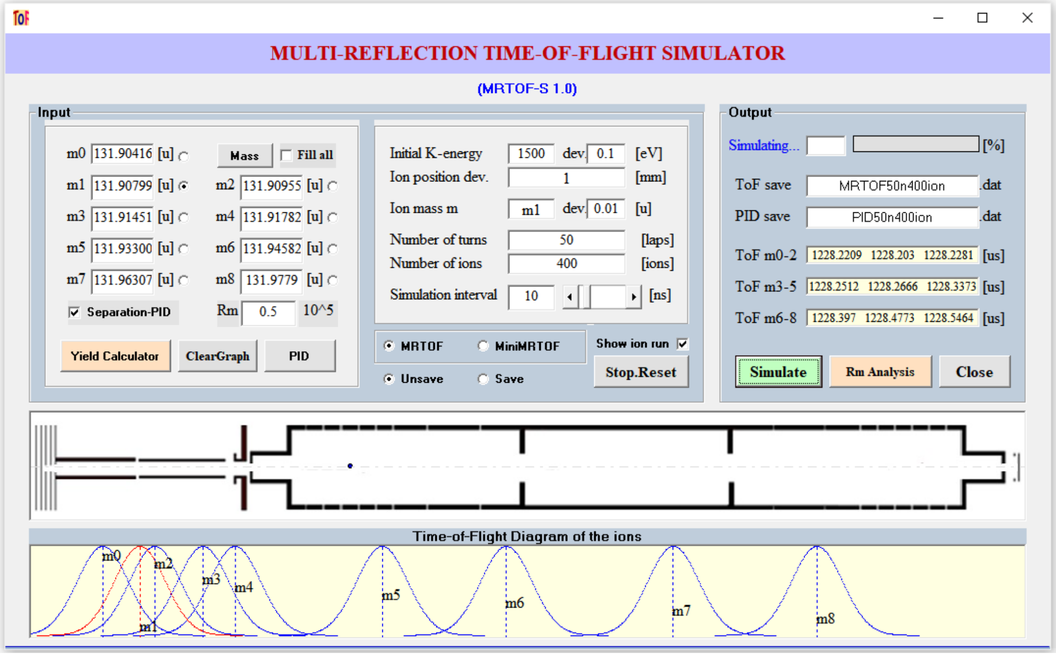

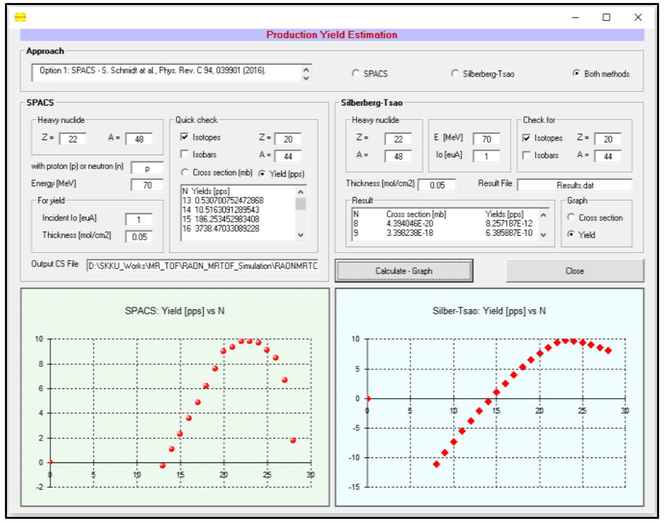

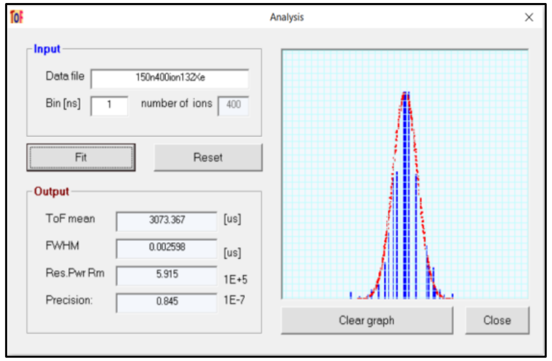

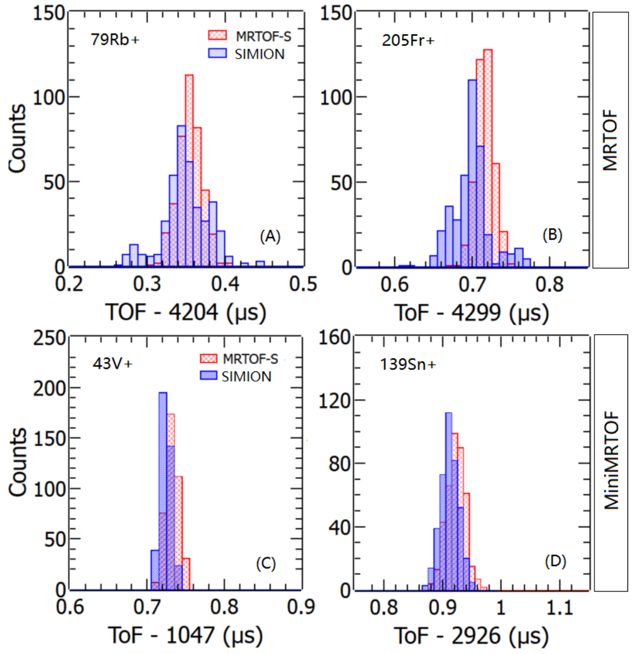

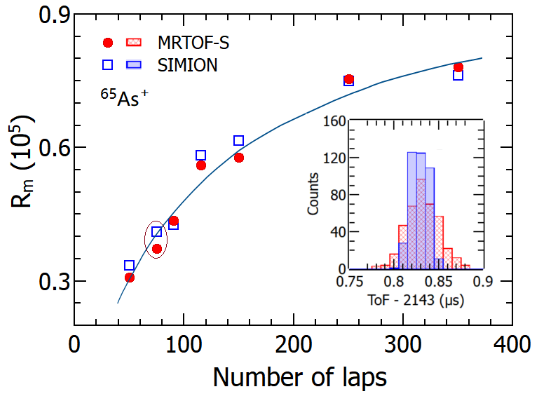

IV. Summary

- Large uncertainty in nuclear mass of the ^{41}Ti, ^{43,44}V, ^{44,45}Cr, $^{45\text{-}47}$Mn, $^{46\text{-}48}$Fe (proton-rich) and $^{136\text{-}140}$Sn (neutron-rich) isotopes

- Precise masses of ^{41}Ti, ^{43,44}V, ^{44,45}Cr, $^{45\text{-}47}$Mn, $^{46\text{-}48}$Fe (proton-rich) and $^{136\text{-}140}$Sn (neutron-rich) isotopes are important for astrophysical calculations and shell closures.

- Ni target for 10^4 pps of Ti-Cr and UC_x target for 10 – 750 pps of $^{136\text{-}140}$Sn.

- RI beam production is necessary for the measurements.

- Mass resolving power of MR-TOF at RAON is about 10^5 → uncertainty is better than 10 keV.

- Precise mass measurements at RAON are feasible.

- MRTOF Simulator is useful for pre-estimating parameters before experiments.

Thank you for your attention !