Nuclear spectroscopy of the nuclei in the vicinity of N = 126 at KISS

(KEK Isotope Separation System : KISS)

KEK Isotope Separation System (KISS)
for the study of nuclear properties from astrophysical interest

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KEK Wako Nuclear Science Center

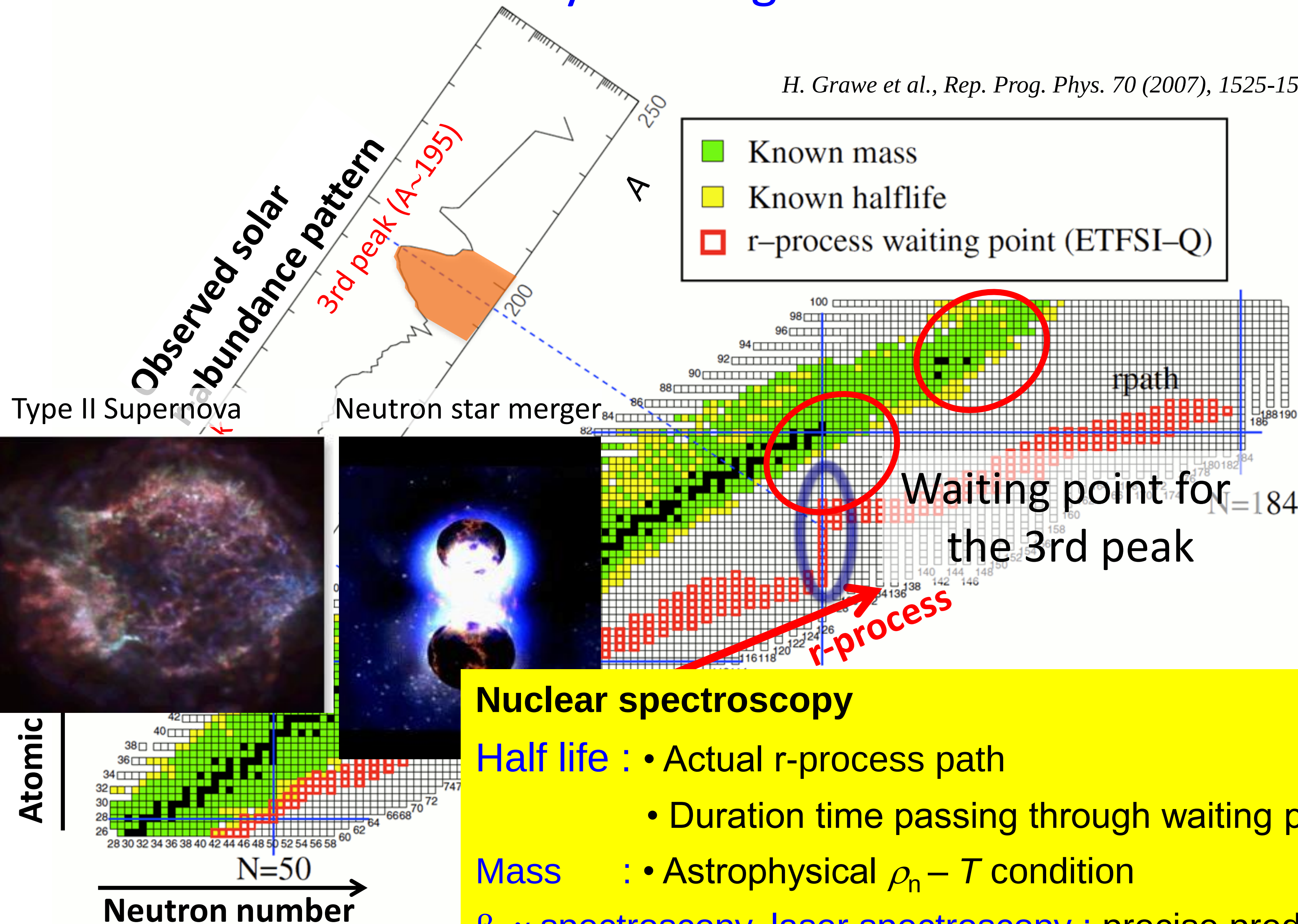
Outline :

1. Physics motivation
2. KISS
3. Experimental results
4. KISS upgrade
5. Summary

"Structure of neutron-rich matter revealed by beta decay"
29-30th July 2024, Nishina hall, RIKEN

Physics motivation

Identification of astrophysical site for r-process and study the origin of uranium



Nuclear spectroscopy

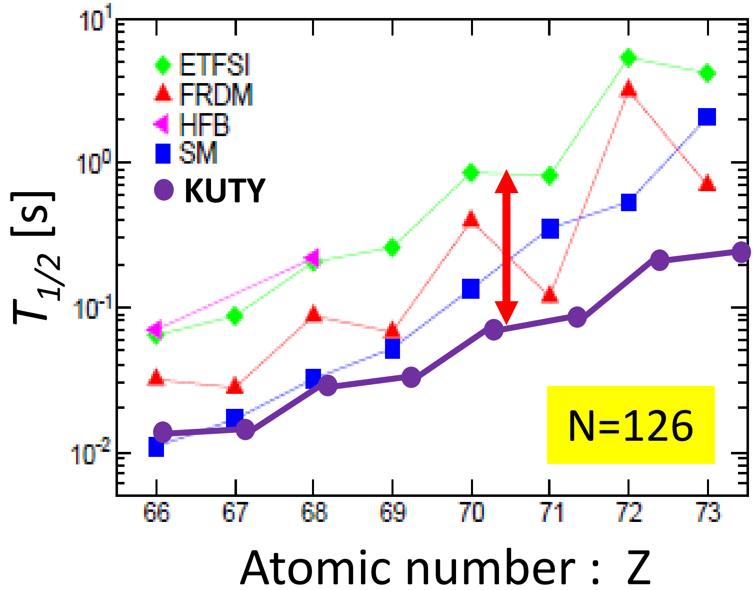
Half life : • Actual r-process path

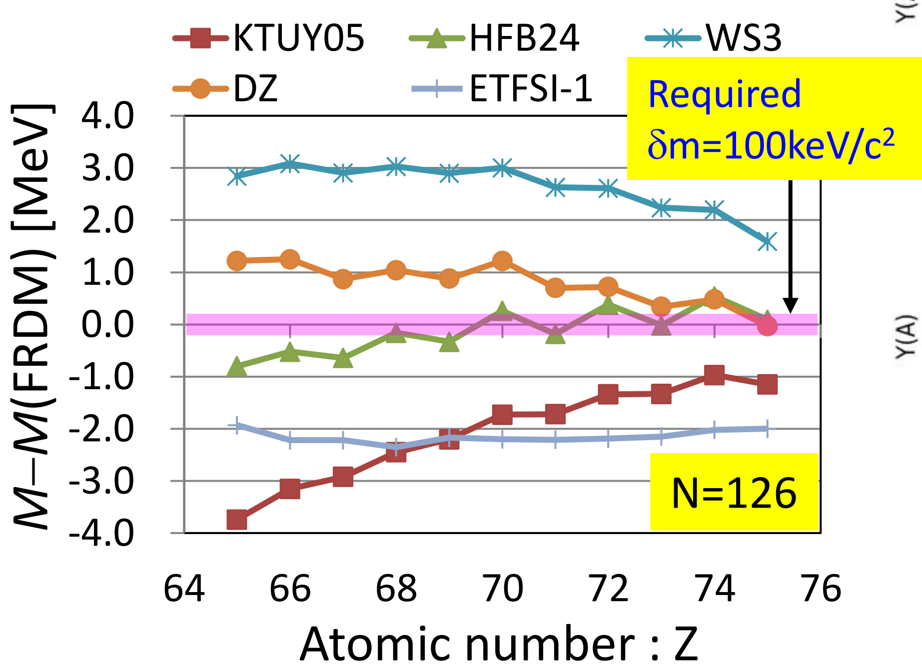
• Duration time passing through waiting point

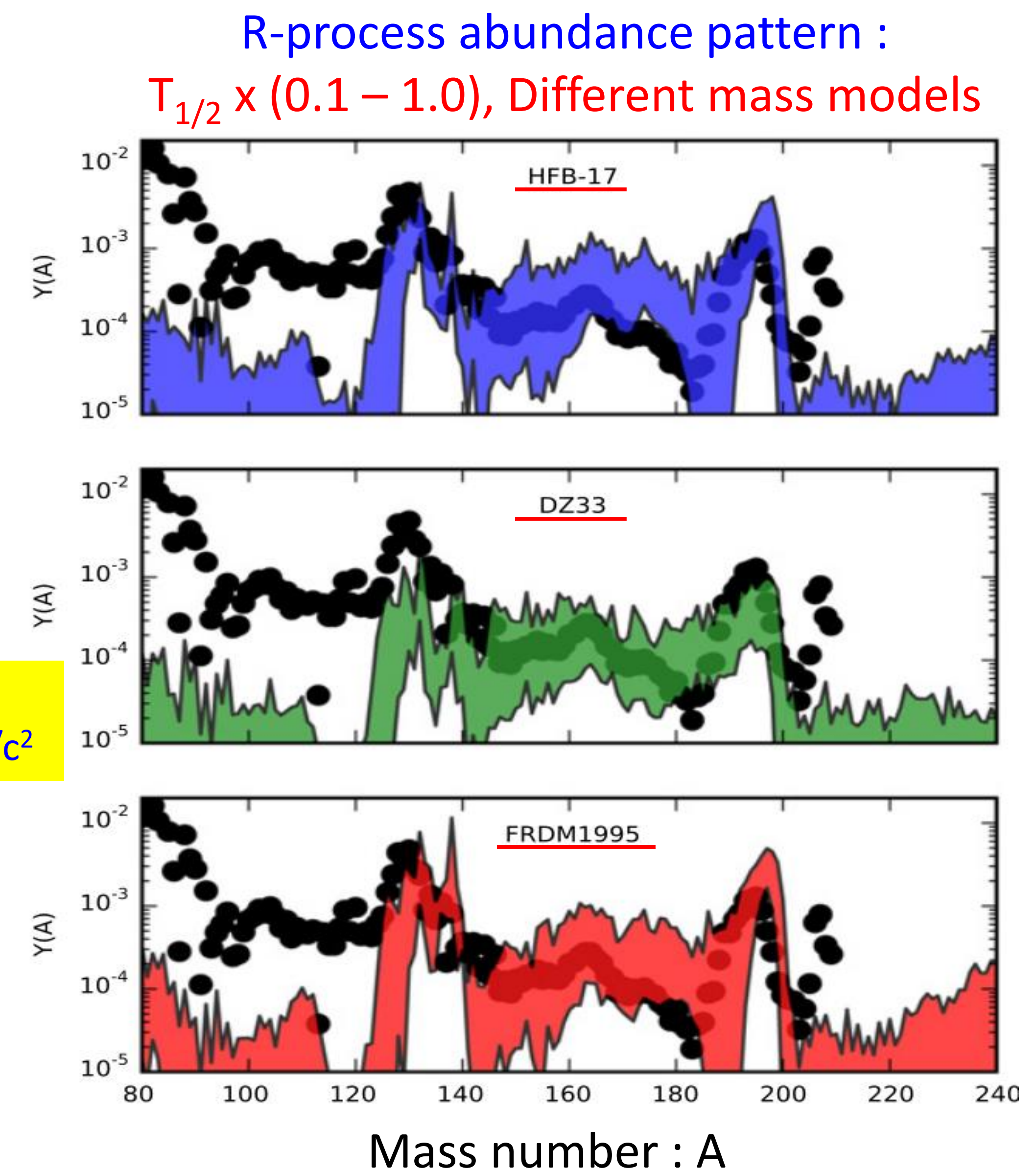
Mass : • Astrophysical $\rho_n - T$ condition

β–γ spectroscopy, laser spectroscopy : precise predictions

Importance of $T_{1/2}$ and mass

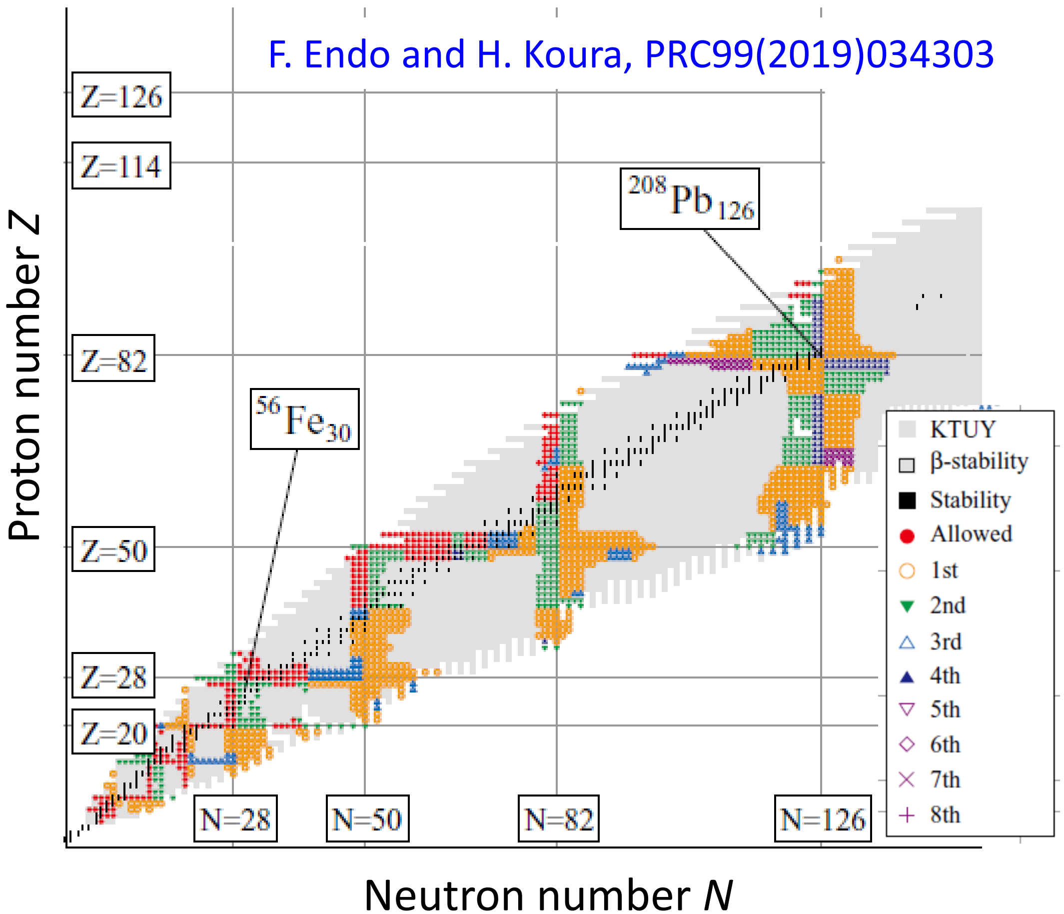


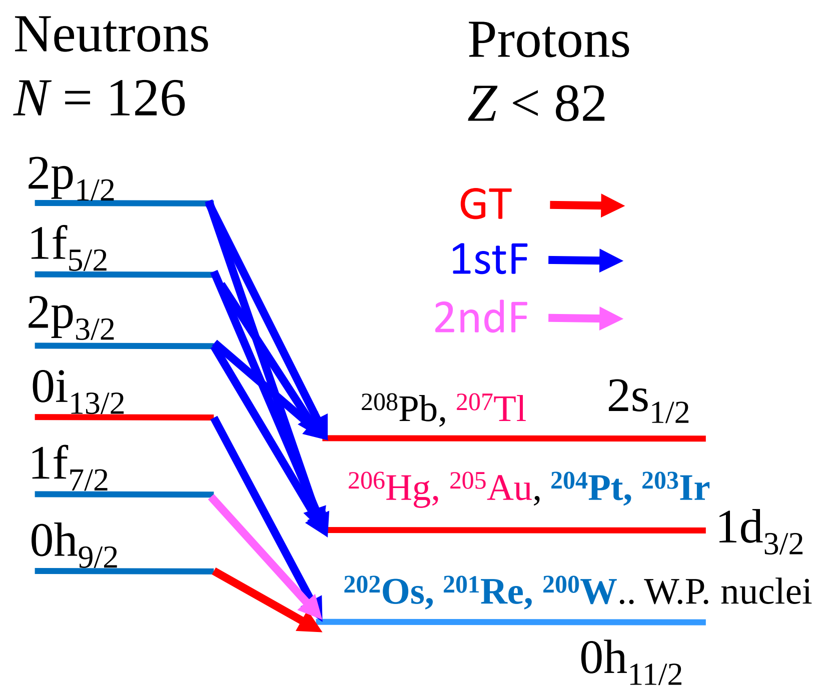




M.R. Mumpower *et al.*, Prog. Part. Nucl. Phys. 86 (2016) 86.

Competition between allowed Gamow-Taller (GT) and 1st forbidden (FF) beta-decay transitions





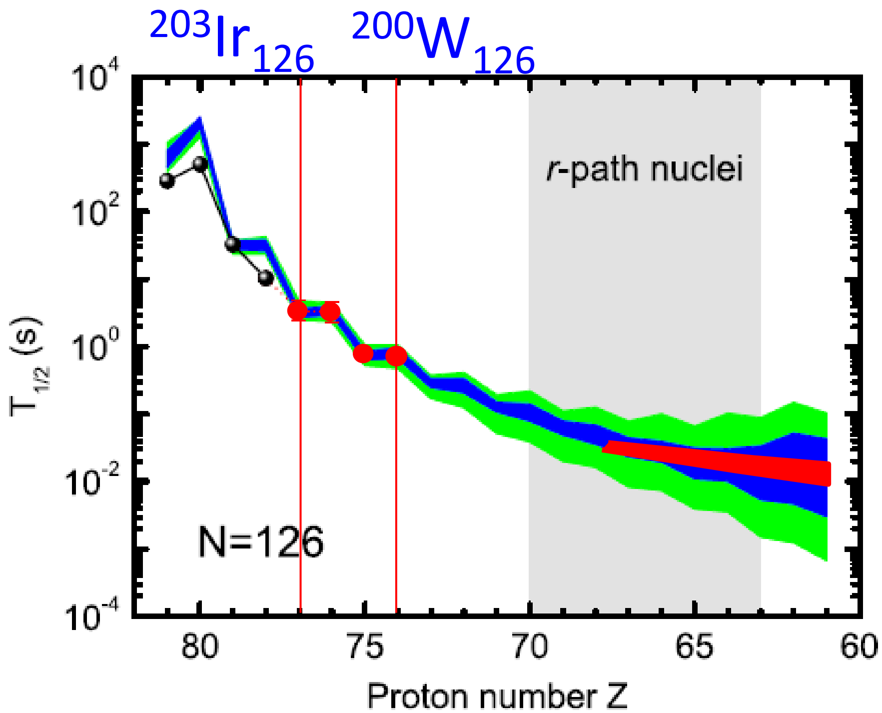
$T_{1/2} \propto 1/E^5$

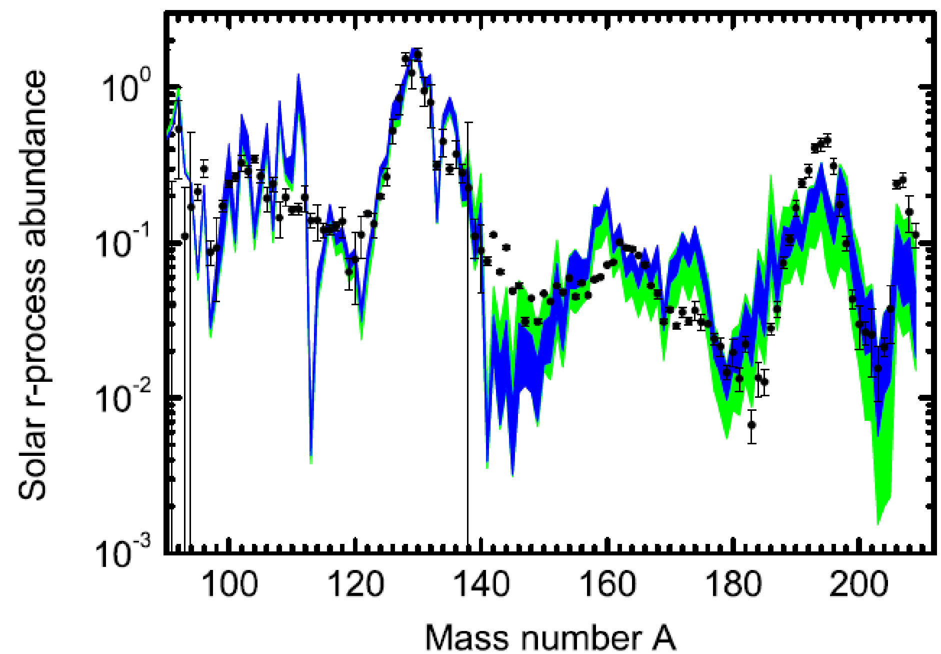
Large Q_β for FF → competition with GT

Mass measurements and βγ-decay spectroscopy (level schemes including spin-parity)

➡ feedback to theoretical models to predict them of waiting point nuclei

Half-lives predictions





Machine learning based on the Bayesian neural network

➡ Machine learning : masses of the N=126 isotones ??

Experimental data

⬇

Nuclear models (How about are the accuracies?)

⬇

Astrophysical calculation

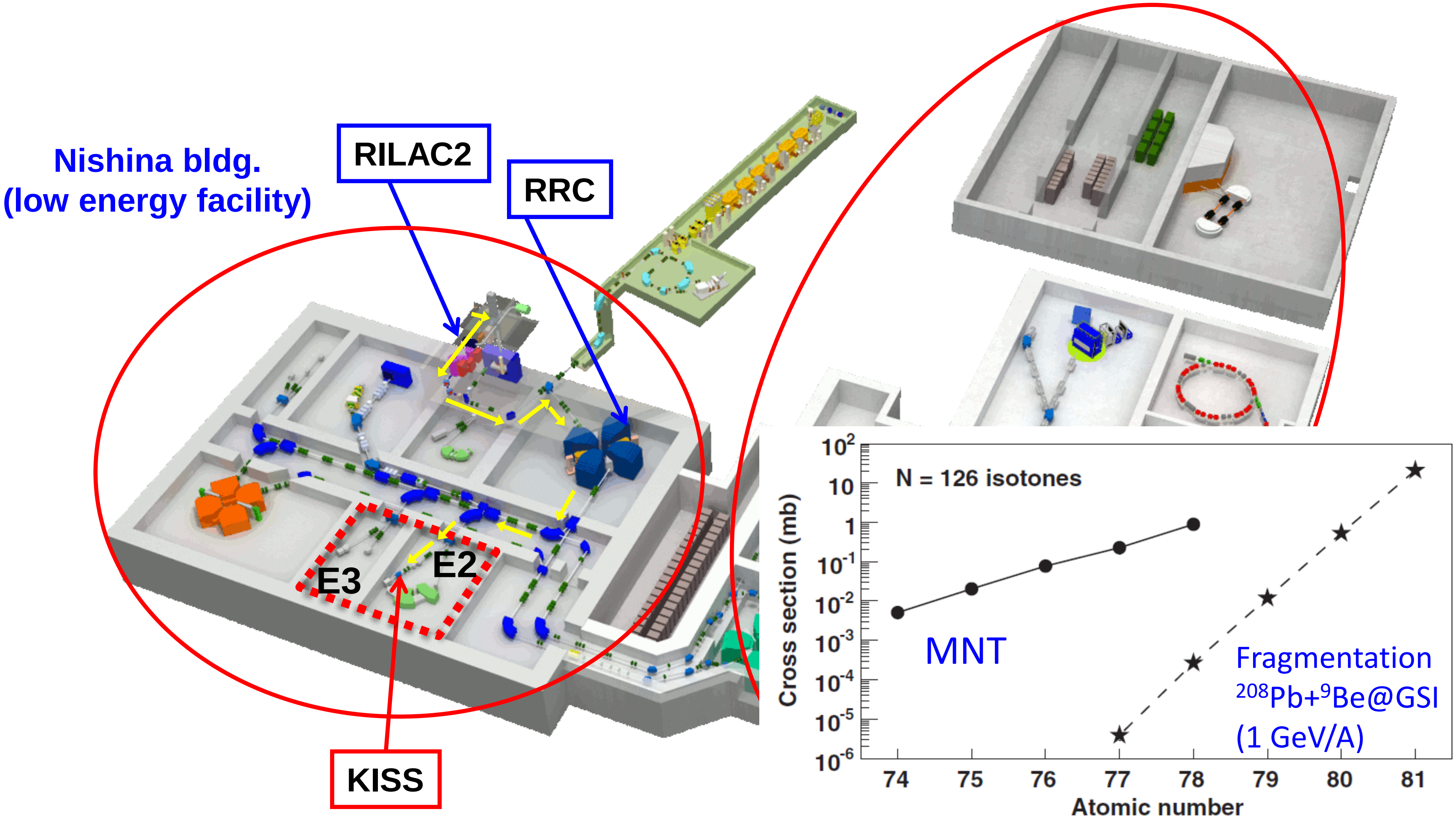
Z.M. Niu et al., Phys. Rev. C 99, 064307 (2019).

KISS

KEK Isotope Separation System

Production (MNT reactions)
Separation (KISS)
of the nuclei around N = 126

RIKEN RIBF (RI Beam Factory)



KEK Isotope Separation System

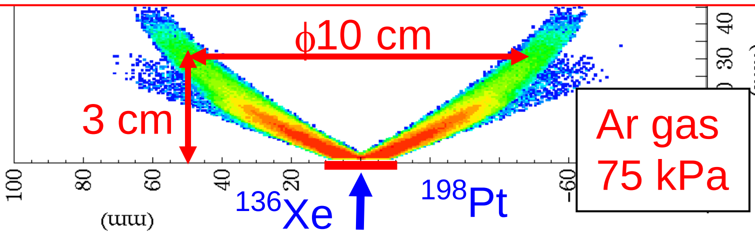
^{136}Xe and ^{238}U beams @ E = 10.75 MeV/A

Multi-nucleon transfer reactions

Y.X. Watanabe et al., PRL 115 (2015) 172503.

KEK Isotope Separation System (KISS)

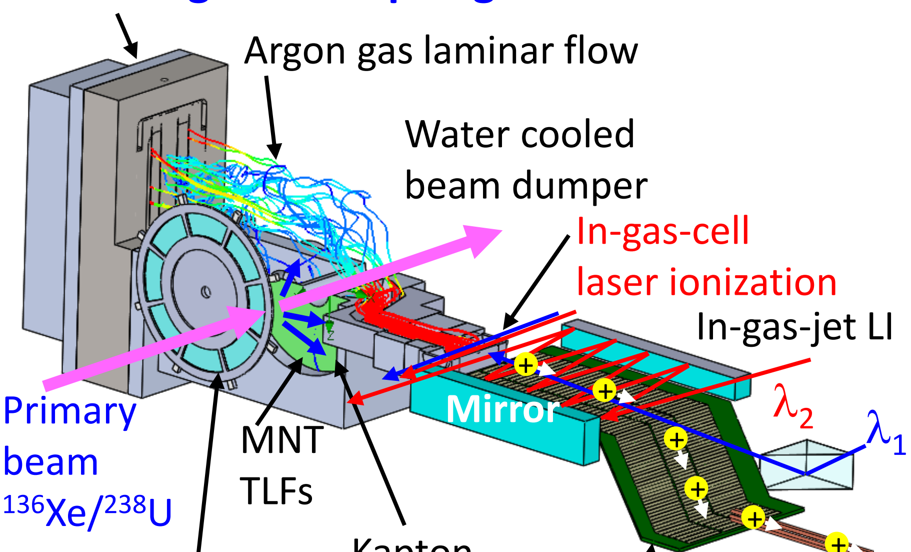
Stopping distribution of MNT products



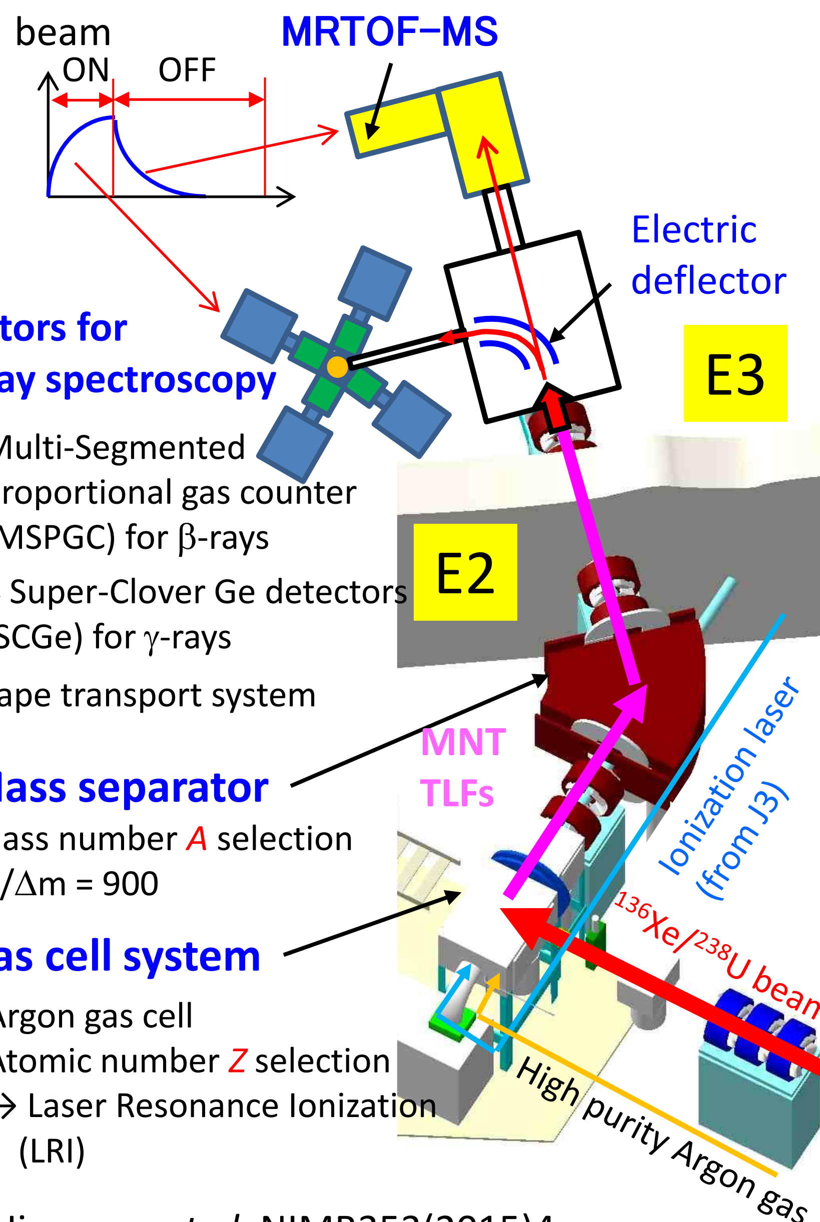
Angles ~ 60°
Energy : 0-1 MeV/A

Refractory elements (Z = 73-78)
By ^{136}Xe beam + ^{198}Pt target

Doughnut-shaped gas cell



Y.Hirayama *et al.* NIMB 412(2017)11



Detectors for β-decay spectroscopy

- Multi-Segmented Proportional gas counter (MSPGC) for β-rays
- 4 Super-Clover Ge detectors (SCGe) for γ-rays
- Tape transport system

Mass separator

Mass number *A* selection
m/Δm = 900

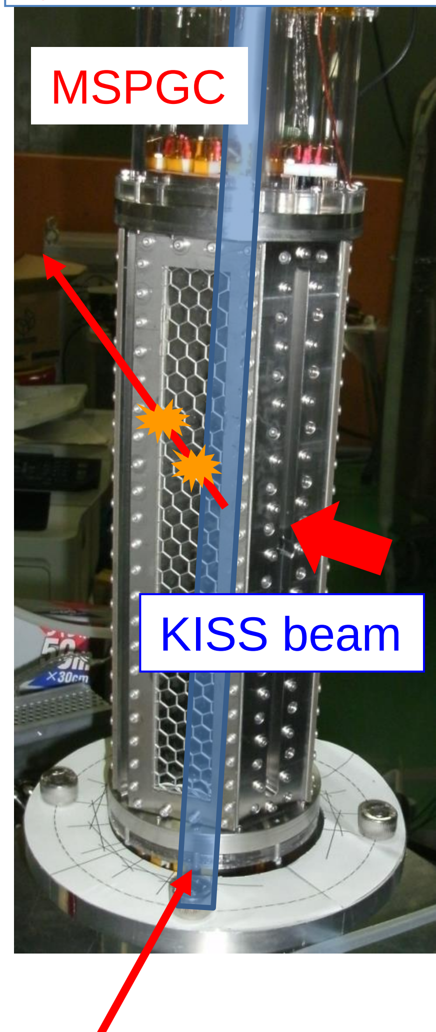
Gas cell system

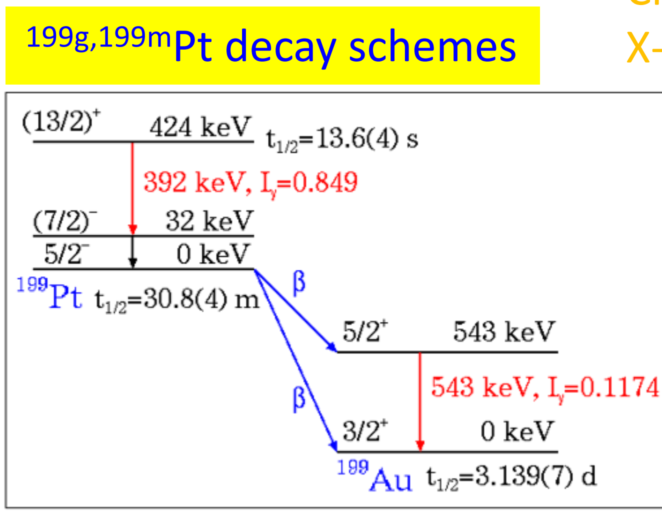
Argon gas cell
Atomic number *Z* selection
→ Laser Resonance Ionization (LRI)

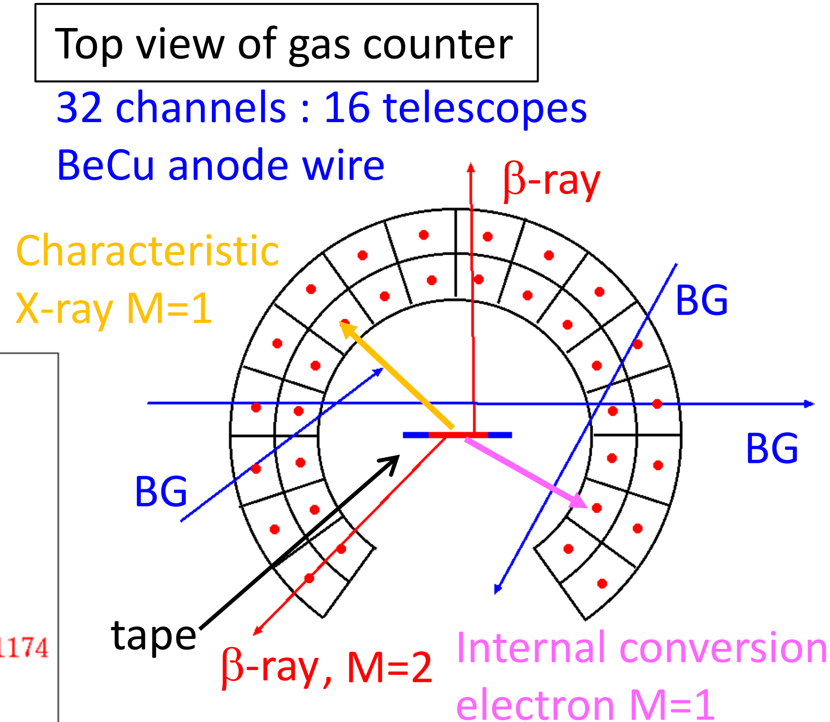
Y.Hirayama *et al.* NIMB353(2015)4

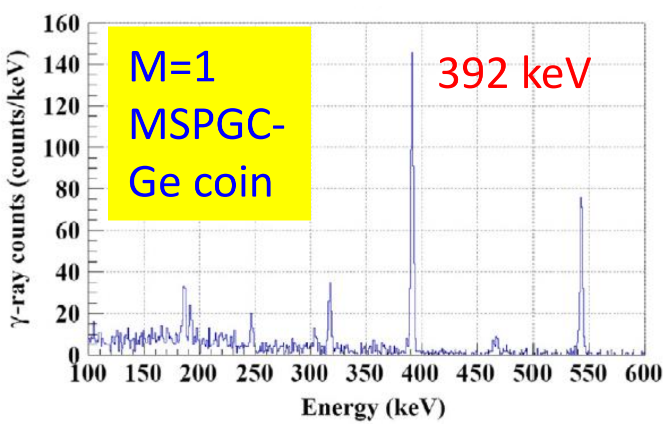
KISS detector system : 2DT-MSPGC

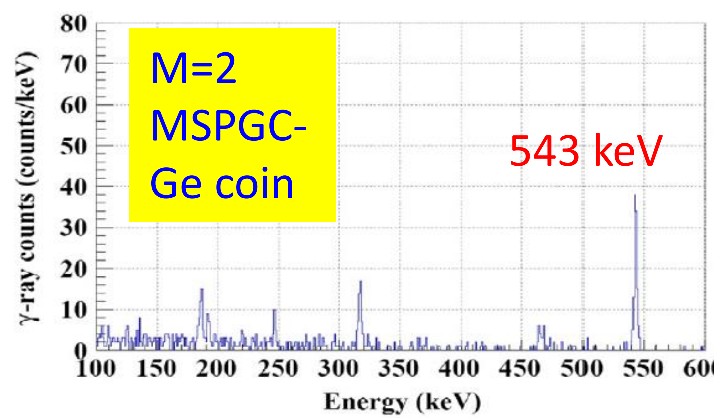
Beta-ray counter：
High-efficiency and low-background gas counter
(Multi-segmented proportional gas counter : MSPGC)
ε_β=40%@Q_β=1MeV, BG rate : 0.1 cps









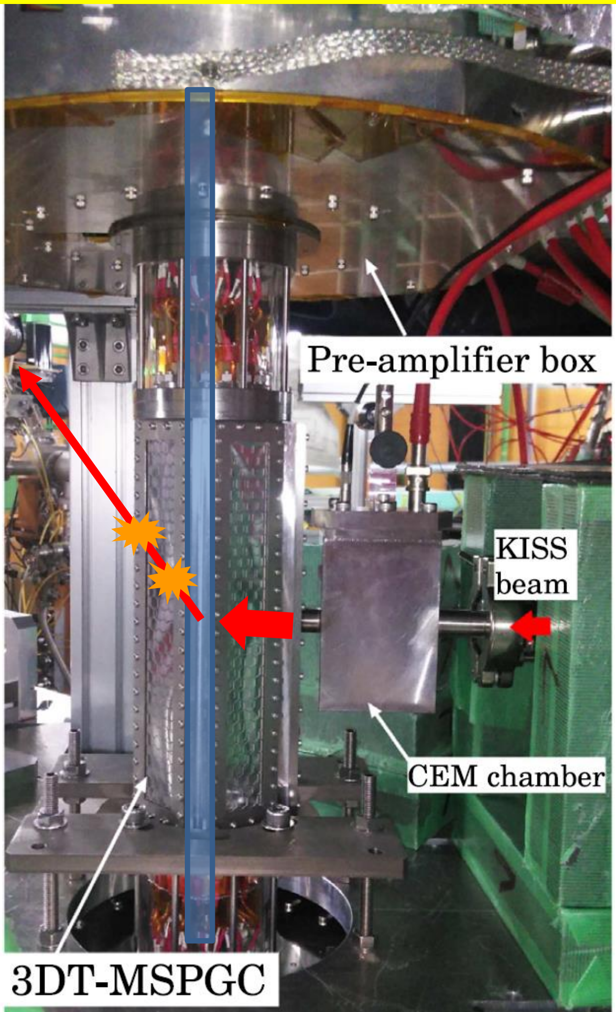


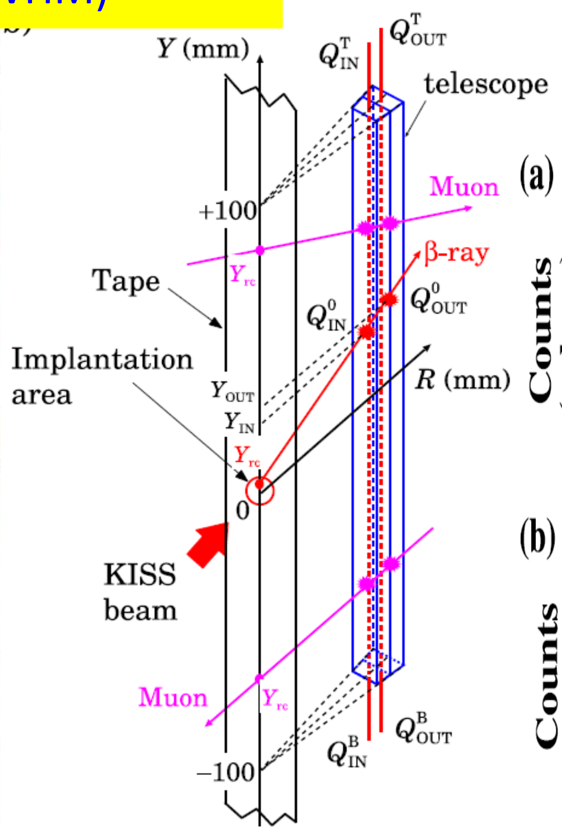
M. Mukai *et al.*, NIM A884 (2018) 1.

KISS detector system : 3DT-MSPGC

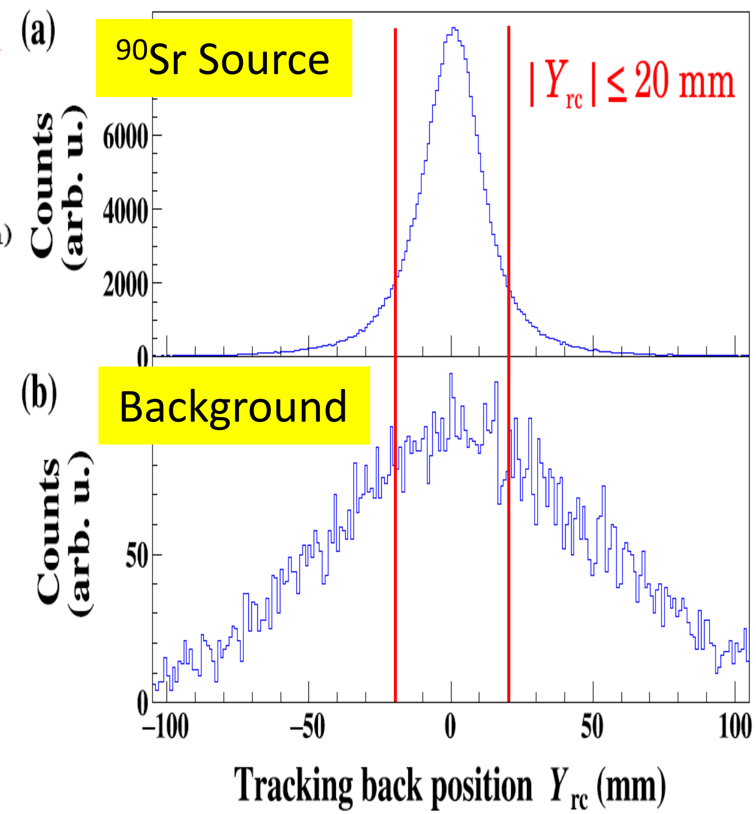
For the nuclear spectroscopy of rare isotopes
➡ lower background rate
➡ 3D tracking gas counter (3DT-MSPGC)
High resistive carbon wires (100 kΩ/200 mm)
→position resolution 3.5mm (FWHM)

ε_β=30%@Q_β=1MeV
BG rate : 0.03 cps
→ S/N > 2.5





$$Y_j = \frac{Q^T_j - Q^B_j}{Q^T_j + Q^B_j} \cdot L$$

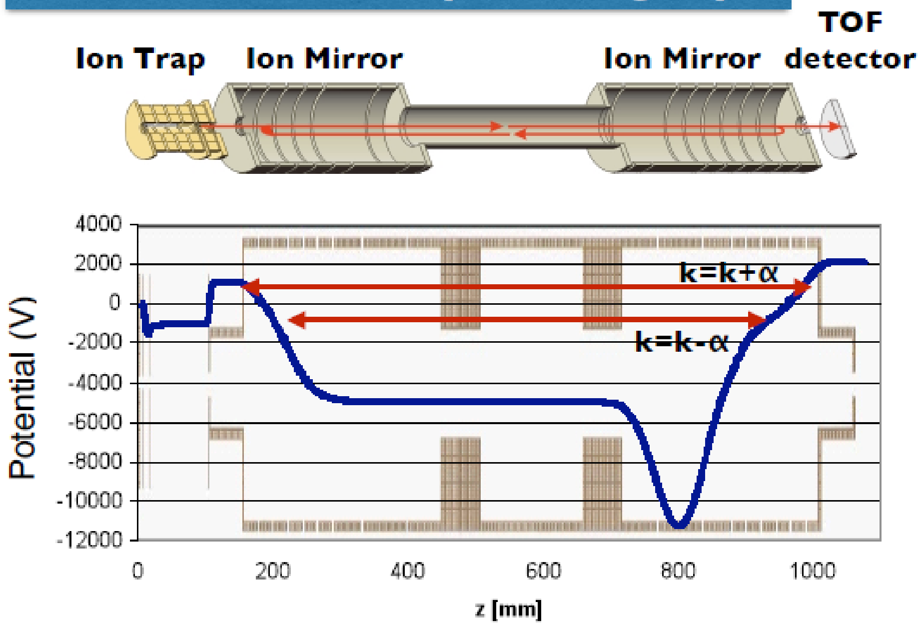


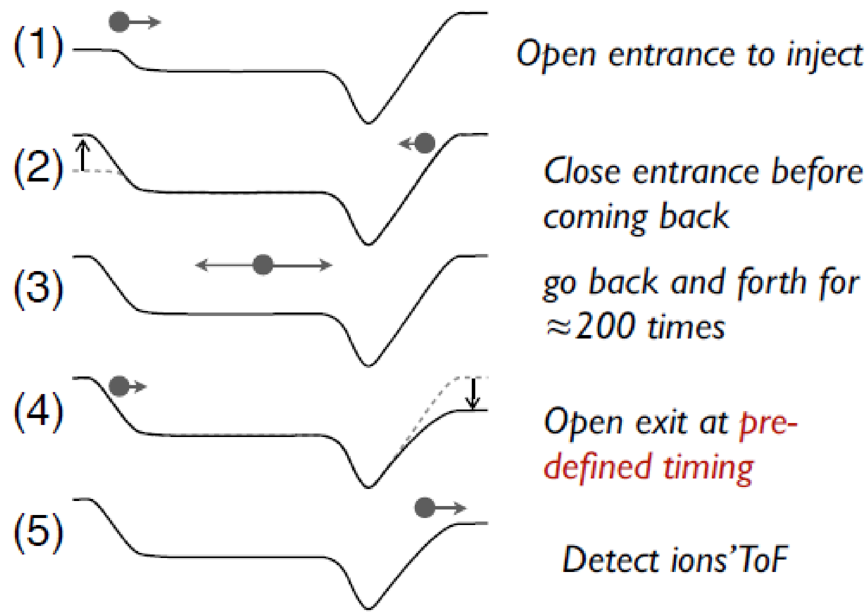
Y. Hirayama et al. NIM A997, 165152 (2021)

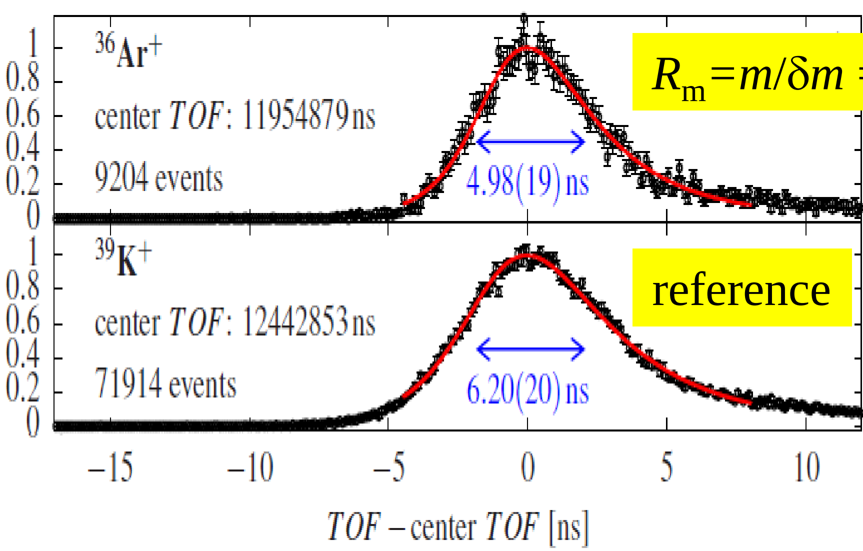
Multi-Reflection Time of Flight Mass Spectrograph

MRTOF Mass Spectrograph

(Multi Reflection Time of Flight…)







$R_m = m/\delta m$ = 1.2 M

reference

$$m_x = \left(\frac{TOF_x}{TOF_{ref}}\right)^2 m_{ref}$$

MR-TOF : R_m=500,000

20 ions sufficient

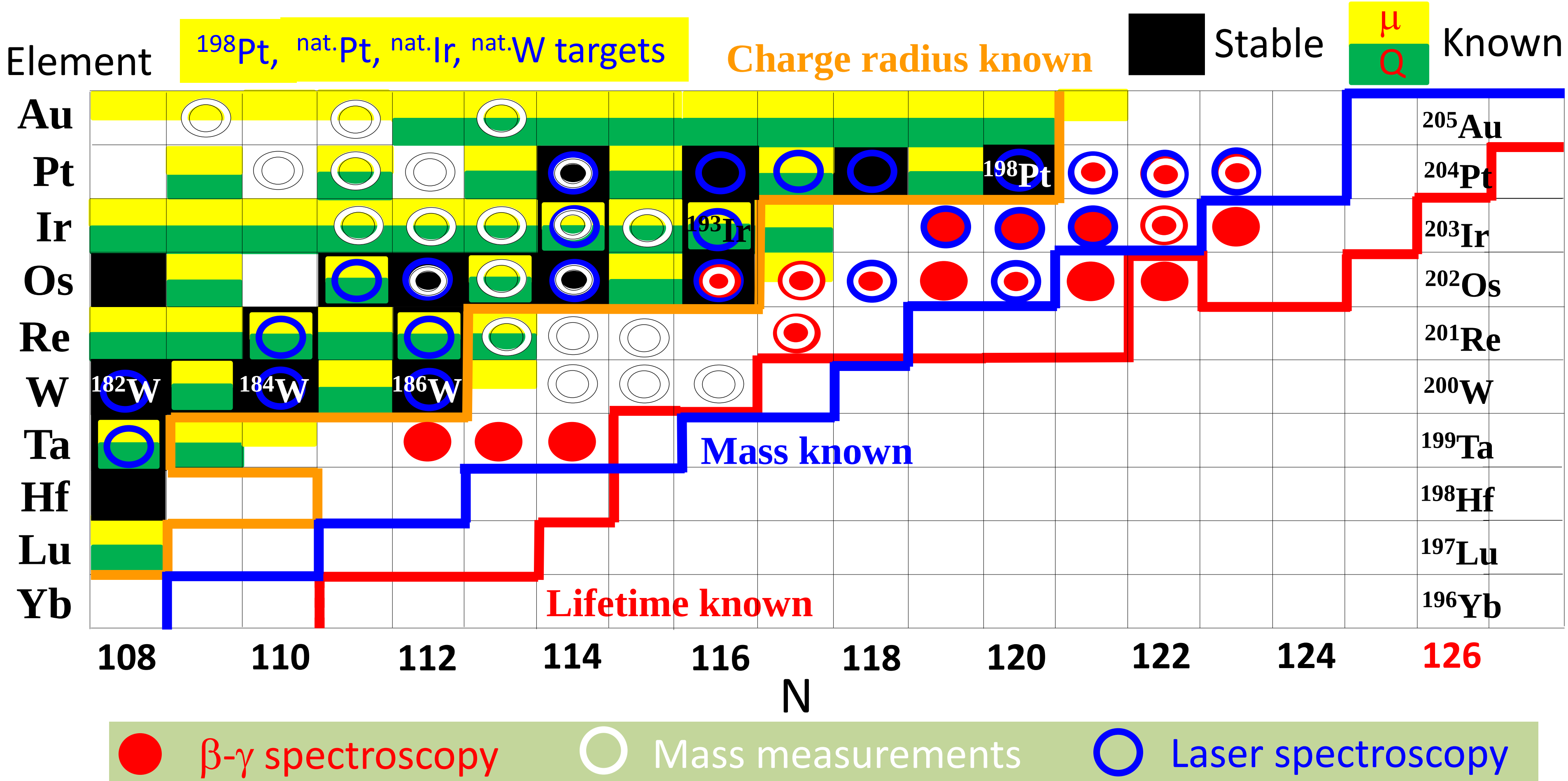
→ $\delta m/m = 1/(R_m \sqrt{20})$

~ 5×10^{-7}

20 detected ions

→ δm ~100 keV/c^2@A=200

Nuclear spectroscopy around *N* = 126 at KISS



^{197,198}Os : Y.H. et al., PRC 98 (2018) 014321

^{195m}Os : Y.X. Watanabe et al., PRC 101 (2020) 041305(R)

^{187m}Ta : P. Walker et al., PRL 125 (2020) 192505

^{195g}Os : M. Ahmed et al., PRC 103 (2021) 054312

^{192g}Re : H. Watanabe et al., PLB 814 (2021) 136088

^{186m}Ta : Y.X. Watanabe et al., PRC 104 (2021) 024330

^{187g}Ta : M. Mukai et al, PRC 105 (2022) 034331

^{199g}Pt, ^{199m}Pt : Y.H. et al, PRC 96 (2017) 014307

^{194,196}Os : H. Choi et al, PRC 102 (2020) 034309

$^{196-198}$Ir : M. Mukai et al, PRC 102 (2020) 054307

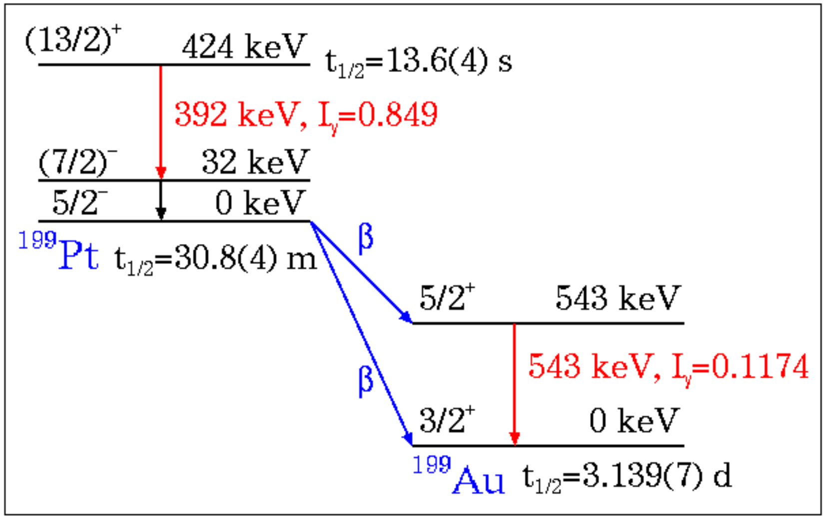
$^{200-201}$Pt: Y.H. et al., PRC 106 (2022) 034326

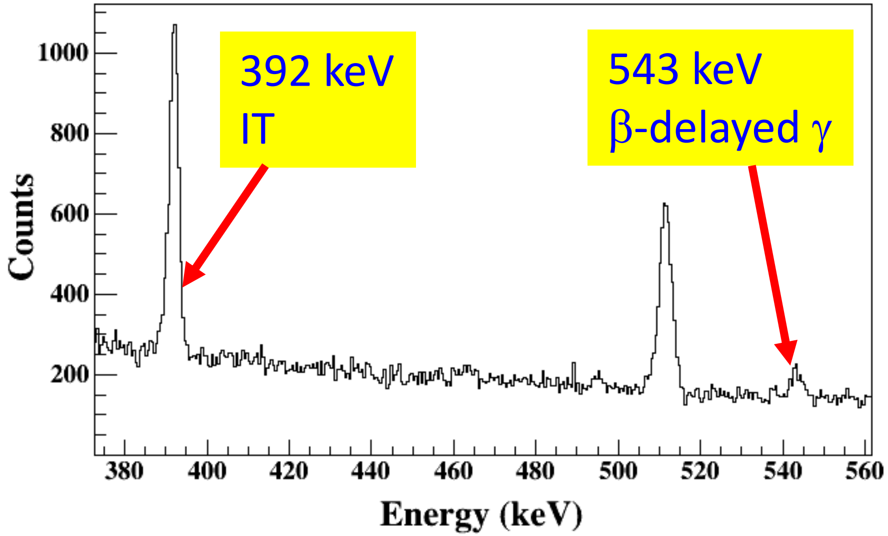
^{189g}W : M. Mukai et al., in preparation

Experimental results

β-γ spectroscopy

Isomer production by MNT reactions : ^{199g}Pt and ^{199m}Pt



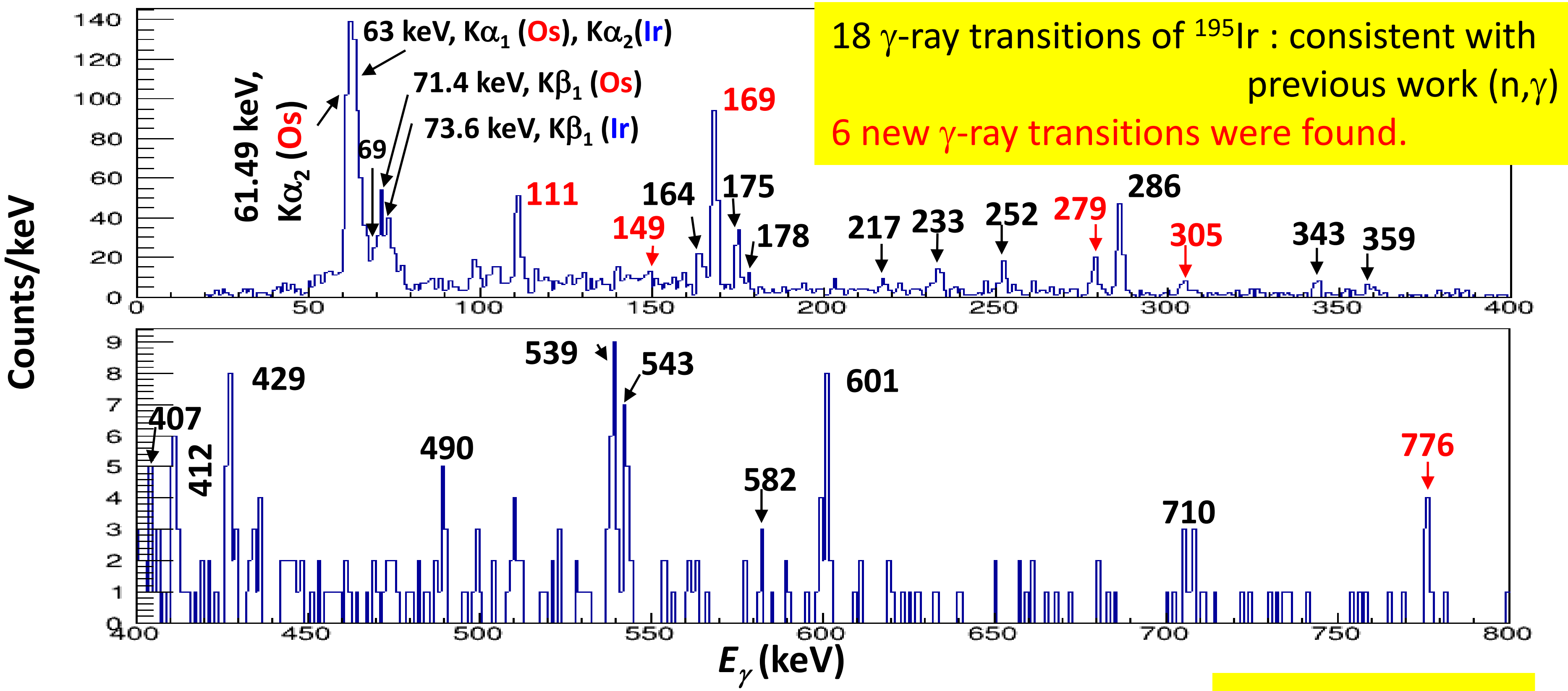


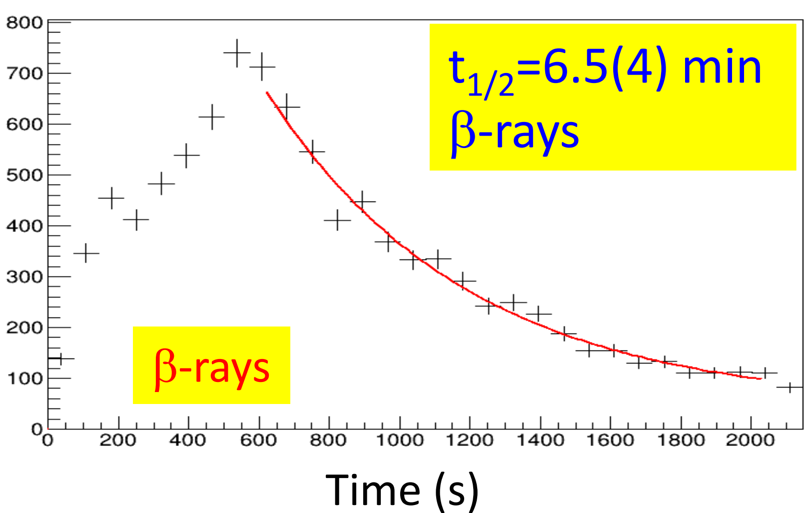
ν(*i*13/2⁺) π(*h*11/2⁻) states : Isomer

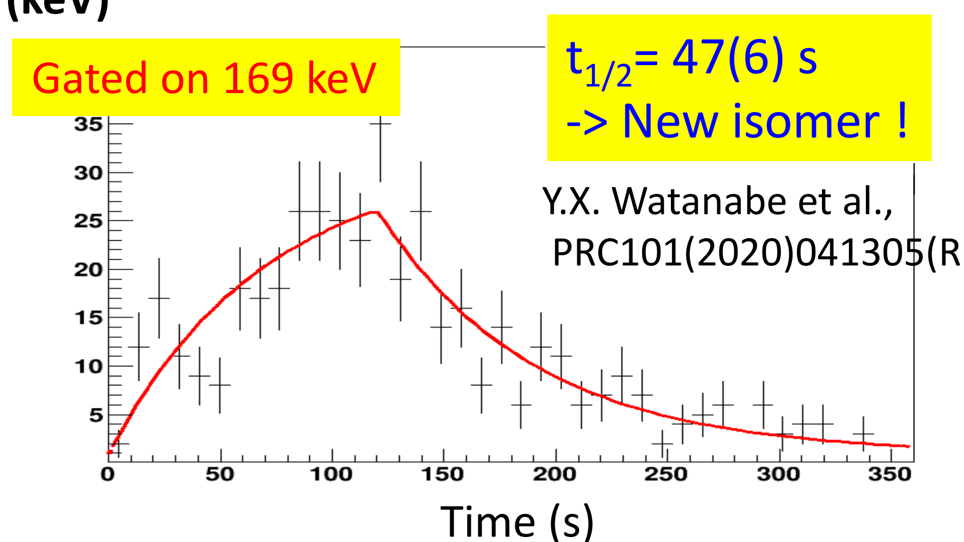
Yield(gs) : Yield(Isomer) ～ 3: 2
Isomer ratio = 40(5) %

MNT reactions can produce isomers with nice probability
→ Studies of isomeric states by detecting characteristic X-rays internal conversion electrons in 3DT-MSPGC

^{195}Os ($t_{1/2}$=6.5(11)min) : unknown β-decay scheme

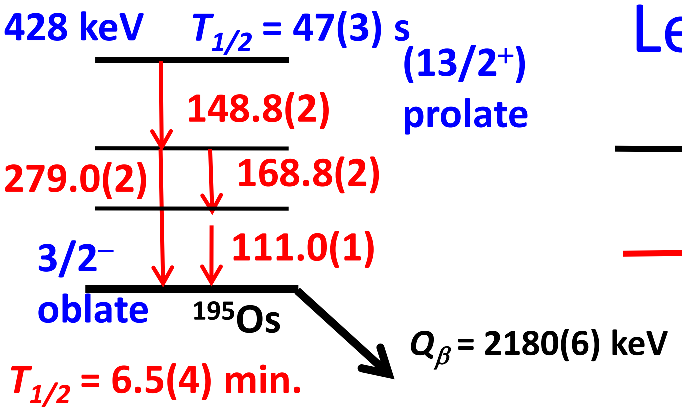






Y.X. Watanabe et al., PRC101(2020)041305(R)

Level scheme of ^{195}Os

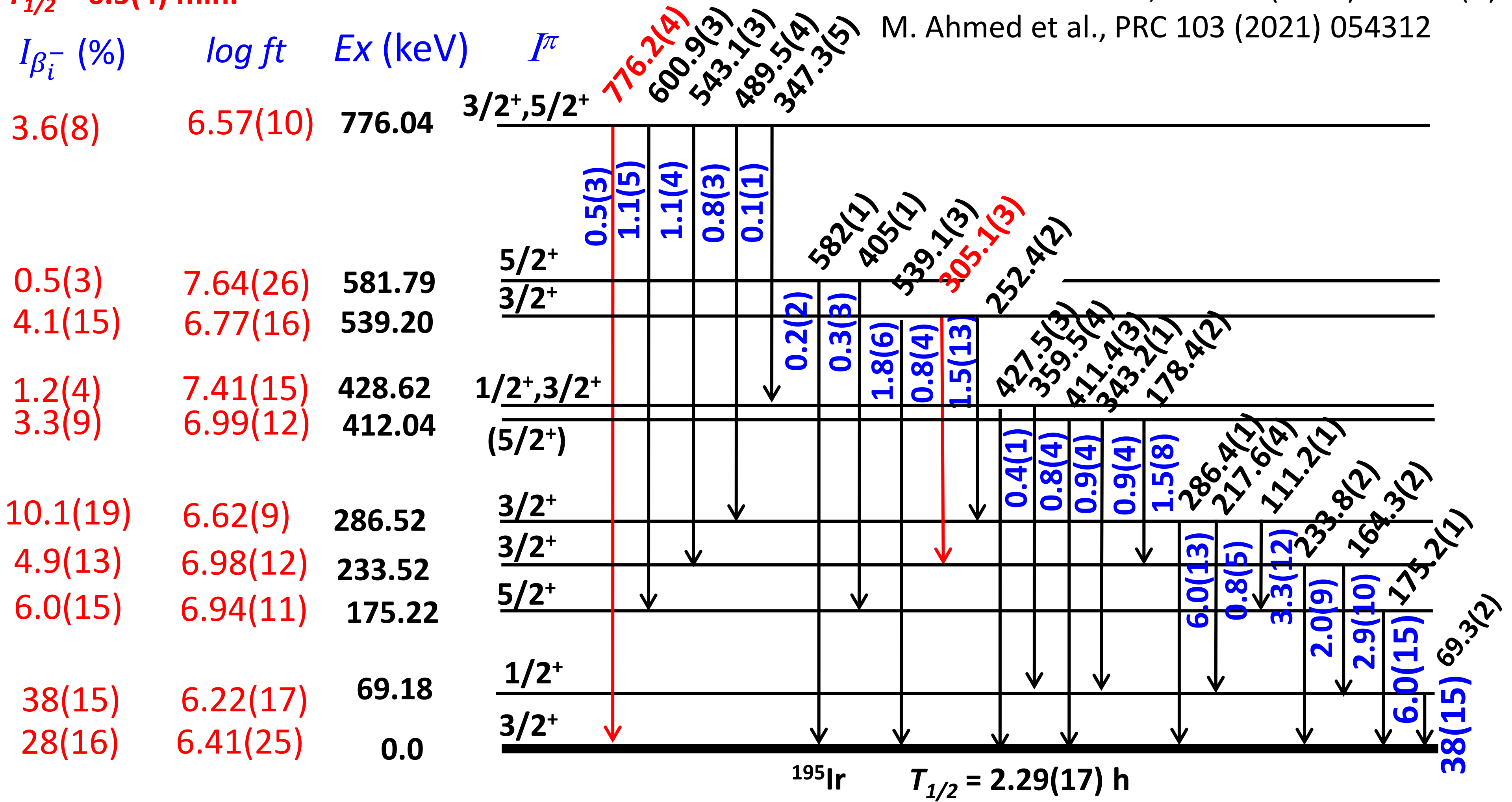


→ **Previously reported γ transitions : (n,γ), not β-decay**
H. Xiaolong and K. Mengxiao, Nuclear Data Sheets **121**, 395 (2014)

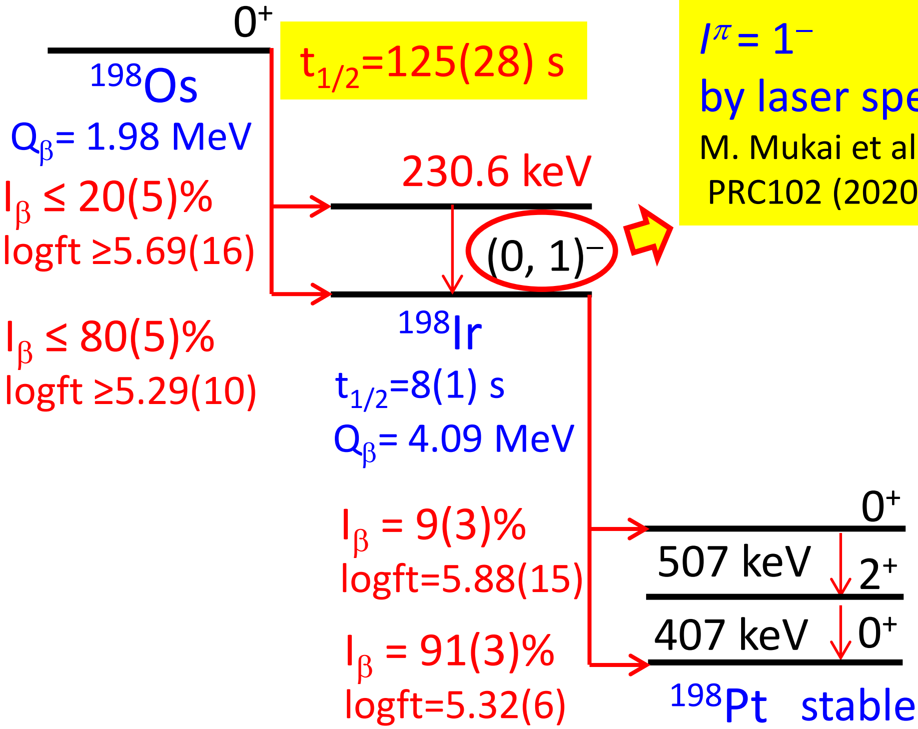
→ **Newly observed γ transitions**

Transition intensities : $I_{(\gamma + c.e)}$

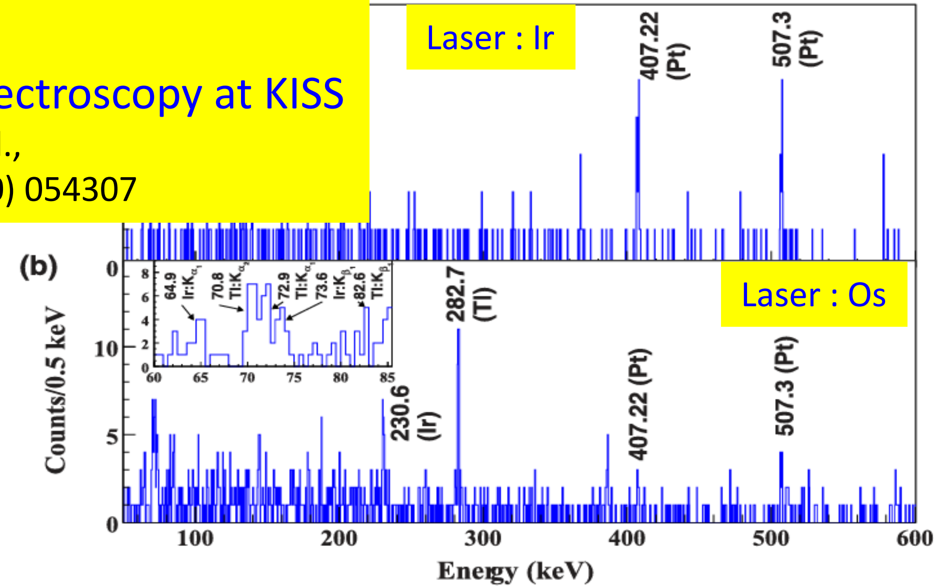
M. Ahmed, doctor work , Univ. of Tsukuba (2019)
Y.X. Watanabe et al., PRC101(2020)041305(R)
M. Ahmed et al., PRC 103 (2021) 054312

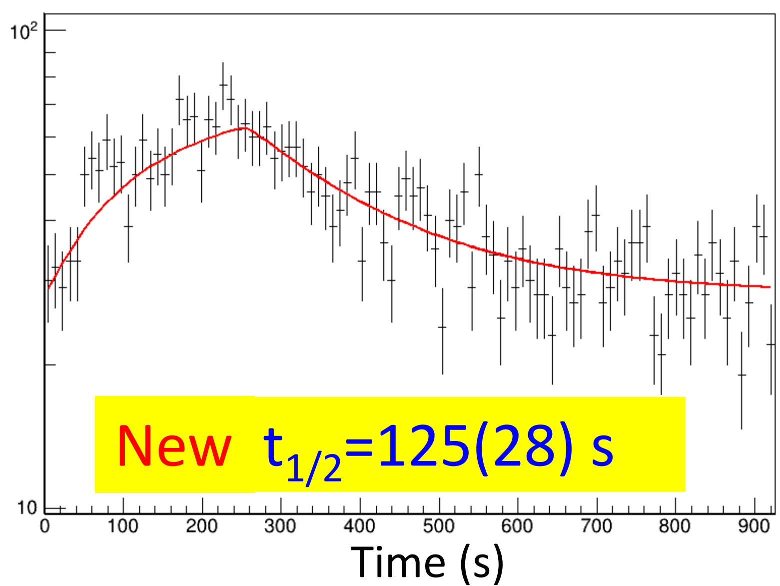


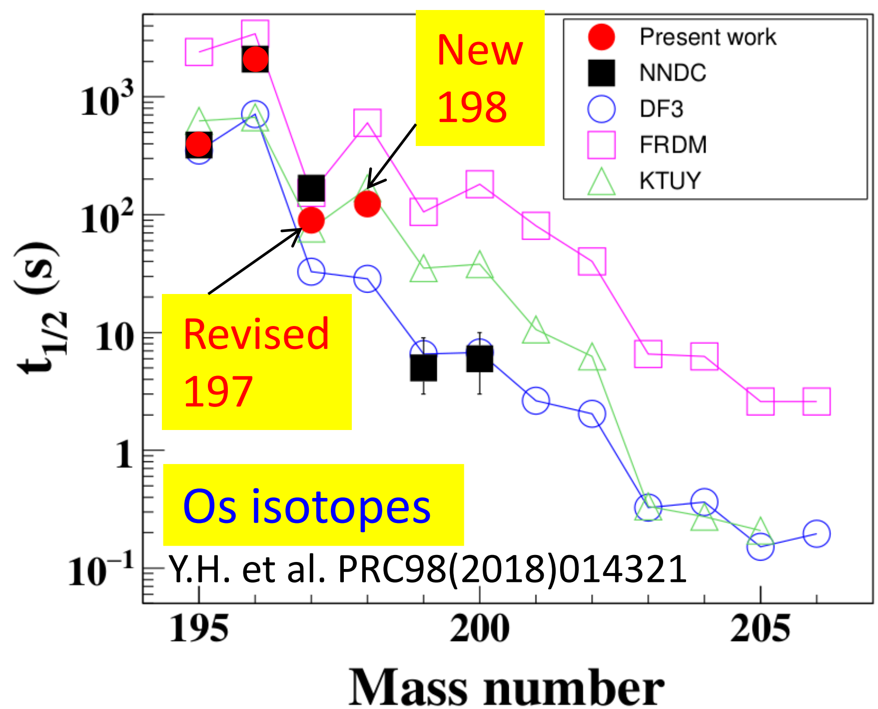
β-γ spectroscopy of ^{198}Os ($t_{1/2}$= unknown)



$I^{\pi} = 1^{-}$
by laser spectroscopy at KISS
M. Mukai et al.,
PRC102 (2020) 054307

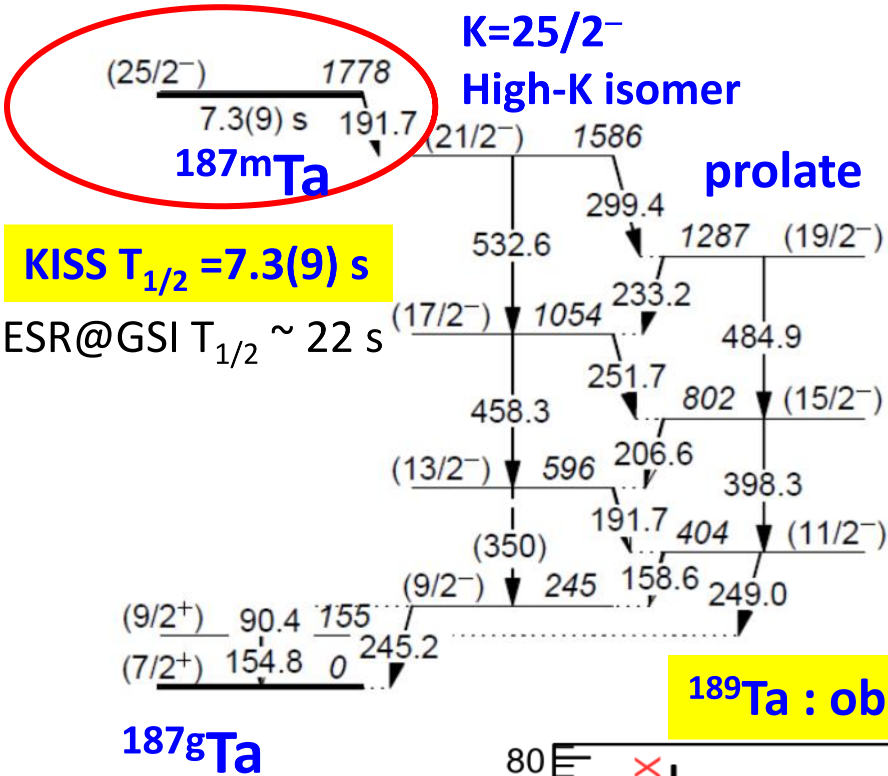






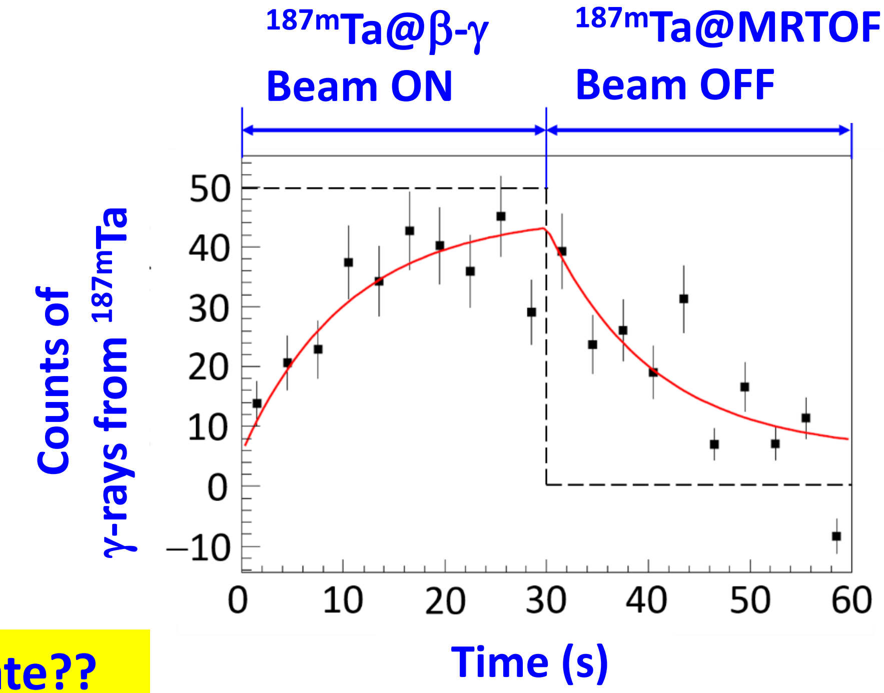
^{187m}Ta High K-isomer (P. Walker)

K=25/2⁻
High-K isomer

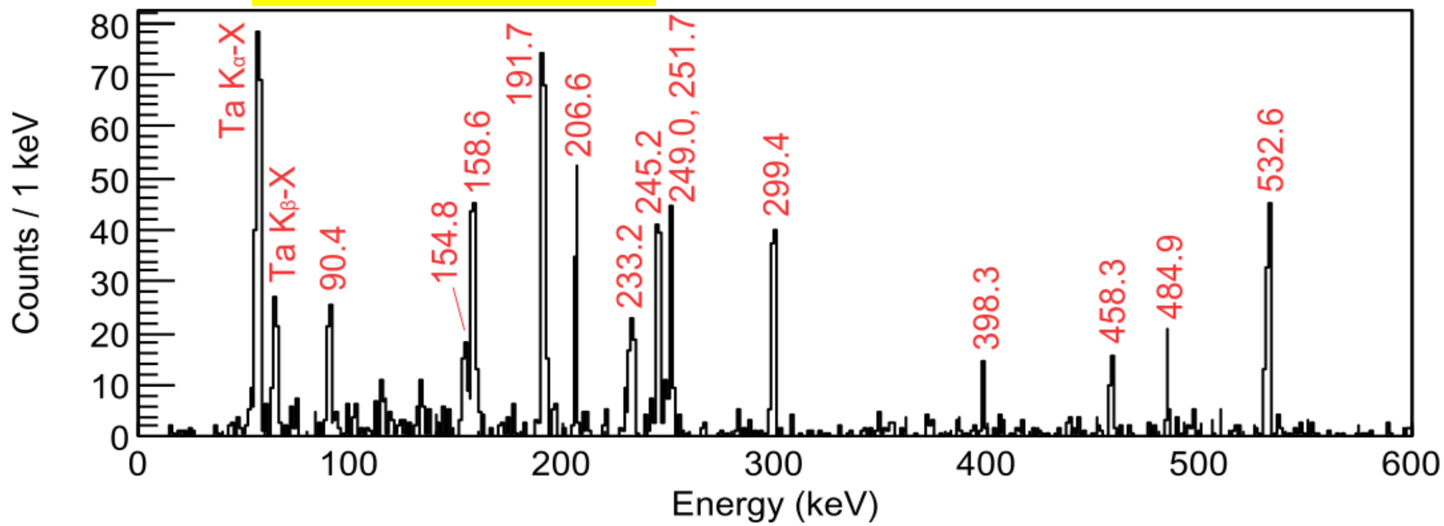


KISS $T_{1/2}$ =7.3(9) s

ESR@GSI $T_{1/2}$ ~ 22 s



^{189}Ta : oblate??

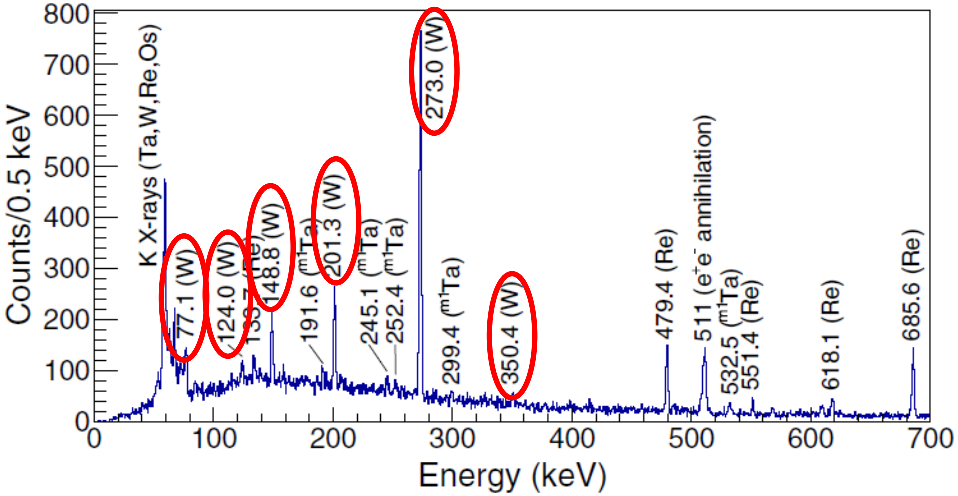


P. Walker et al., PRL 125(2020)192505

β–γ spectroscopy of ^{187g}Ta

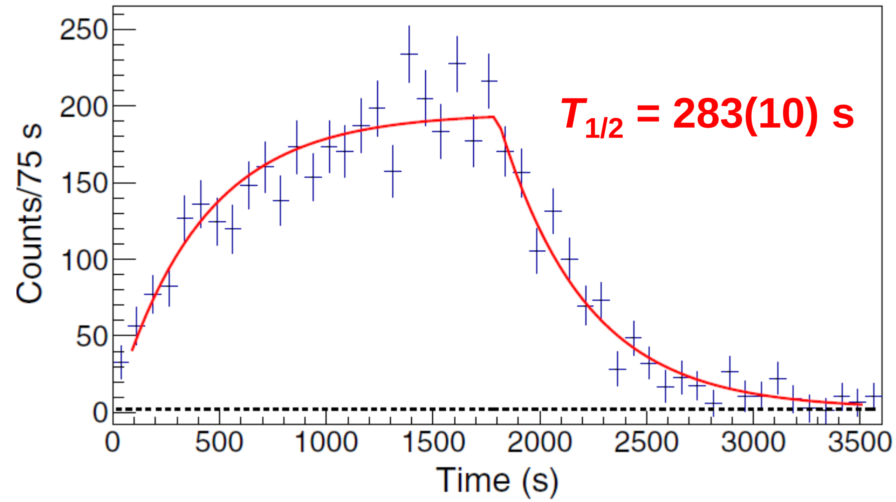
M. Mukai et al., Phys. Rev. C 105, 034331 (2022).

γ-ray energy spectrum in coincidence with MSPGC (M=2)



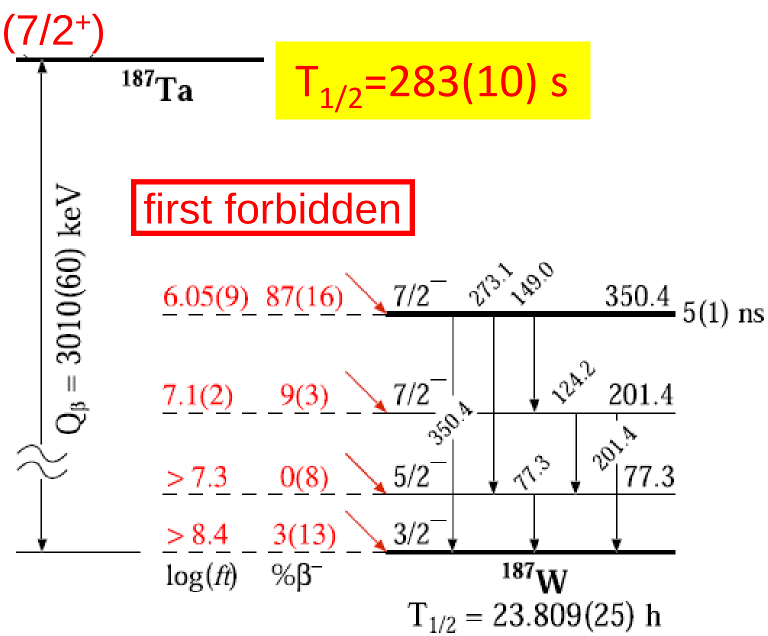
6 β-delayed transitions were observed

Growth-decay curve of *β*-delayed *γ*-ray counts

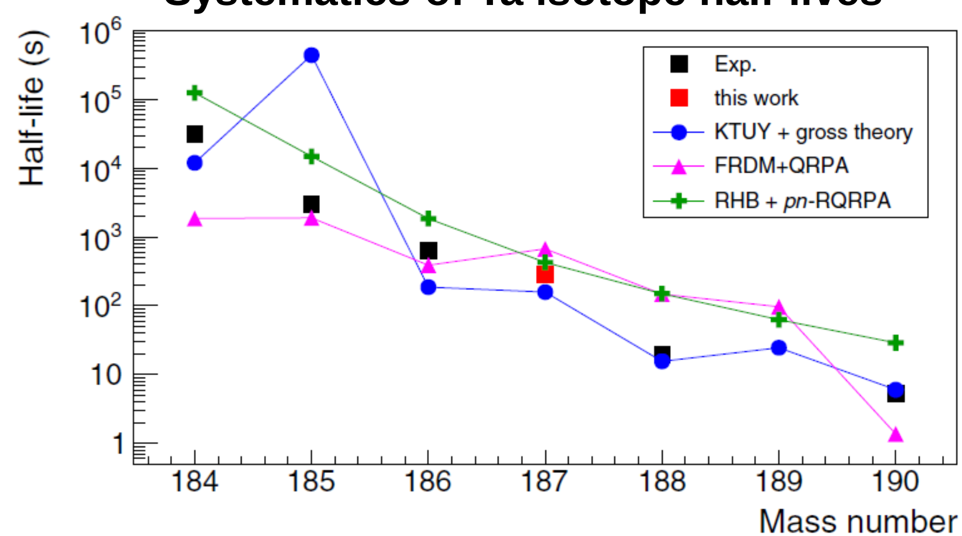


c.f. $T_{1/2}$ = 138(36) s for $^{187}Ta^{73+}$ at ESR GSI

M.W. Reed et al., Phys. Rev. Lett. 105, 172501 (2010).



Systematics of Ta isotope half-lives

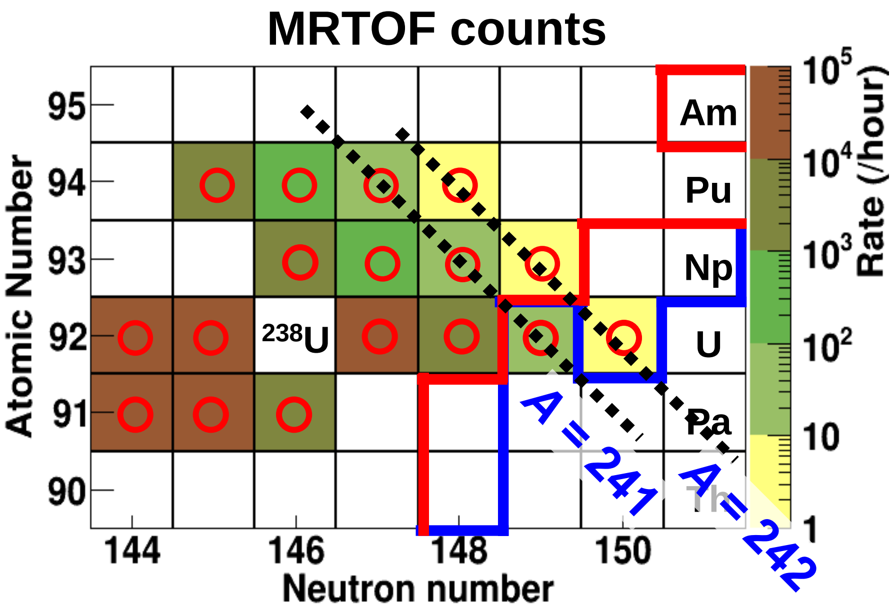


Experimental results

Mass measurement

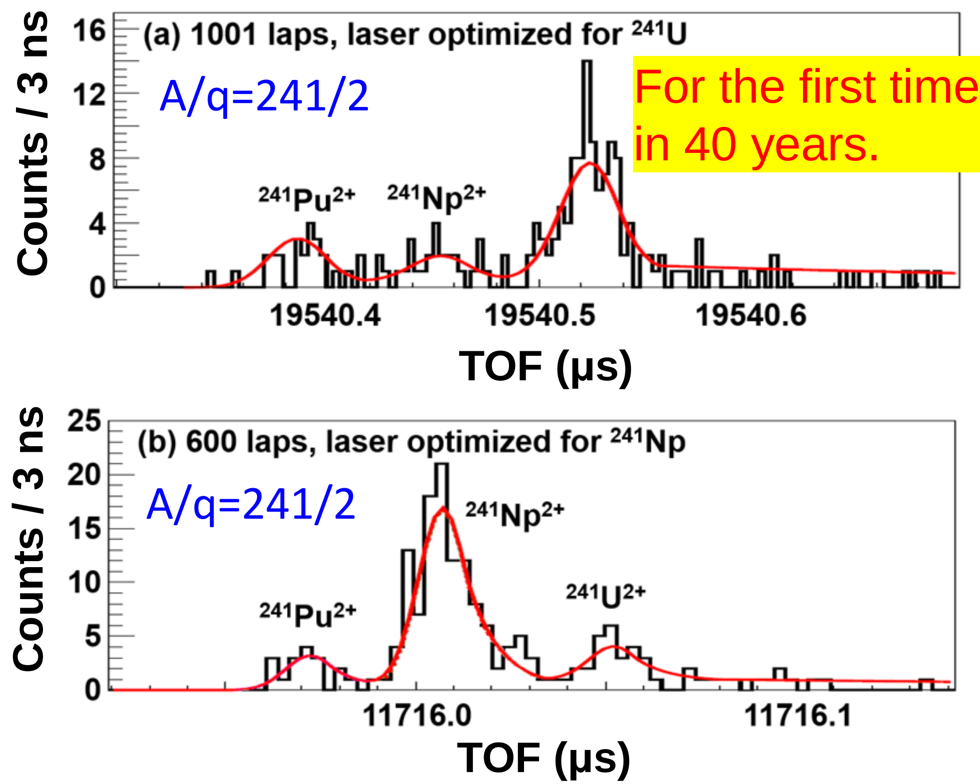
Discovery of ^{241}U and precise mass measurements

^{238}U beam + ^{198}Pt target

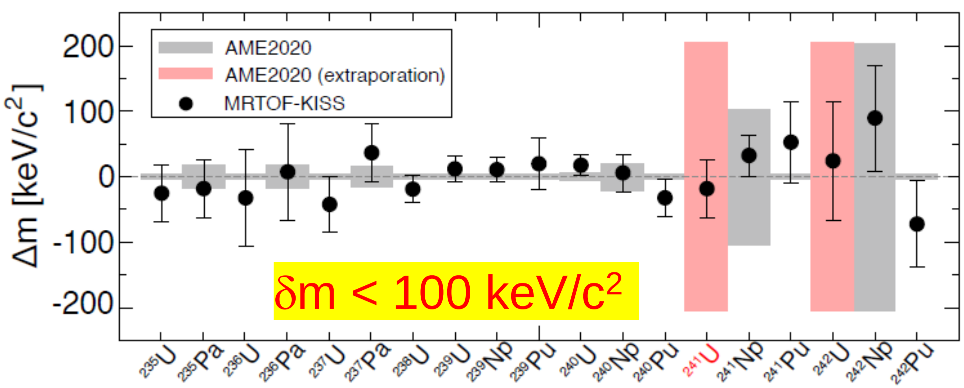


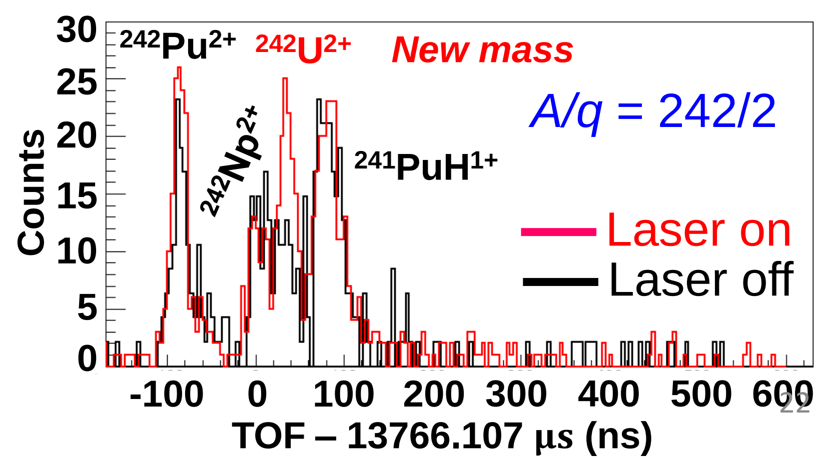
Mass frontier Lifetime frontier

MRTOF-MS spectra



Mass difference from AME2020





T. Niwase et al., PRL 130 (2023) 132502

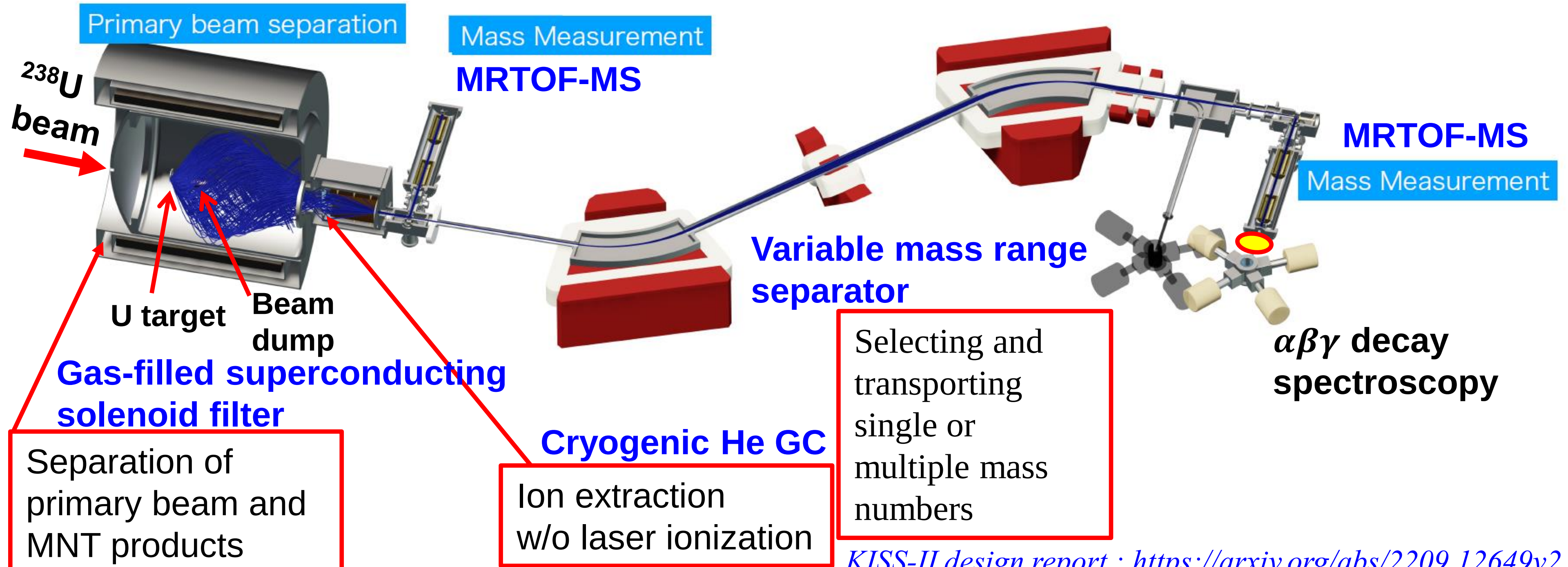
KISS upgrade plan
and
R&D work

KISS-II

Concept :「No separation」for efficient nuclear spectroscopy of multiple nuclides

- Primary beam separator ： Intense primary beam and primary beam rejection
- Cryogenic He gas catcher : Efficient ion accumulation and extraction
- New separator + MRTOF-MS : Transport multiple nuclides for precise mass measurements and particle identifications for spectroscopy

	Primary bema intensity	Extraction efficiency	Efficacy	Total gain
KISS	10 pnA	<0.1%	1	1
KISS-II	1000 pnA	>1%	> 10	> 10 000
	Primary beam separator	Cryogenic He GC	MRTOF-MS	

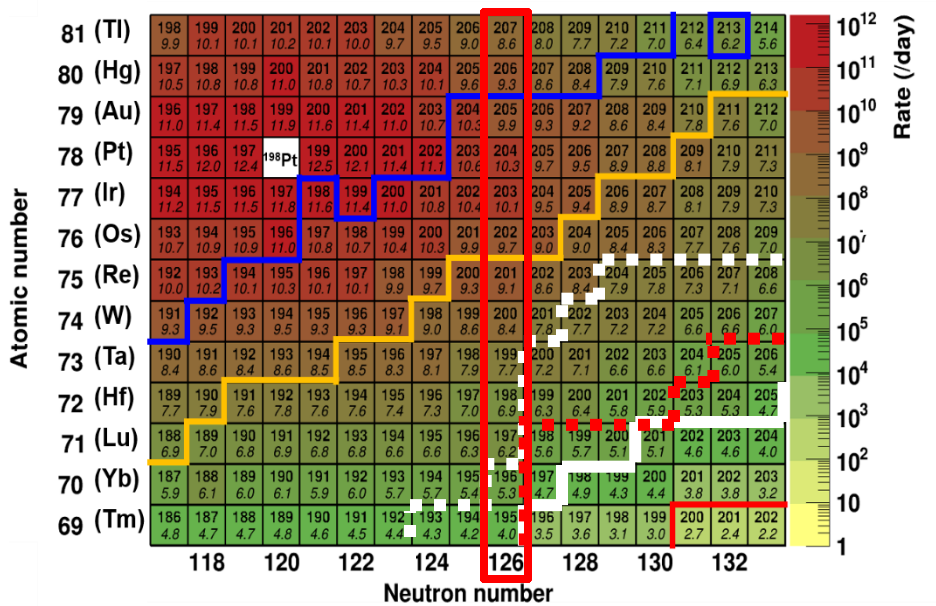


KISS-II design report : https://arxiv.org/abs/2209.12649v2

Expected yields of nuclei at KISS-II

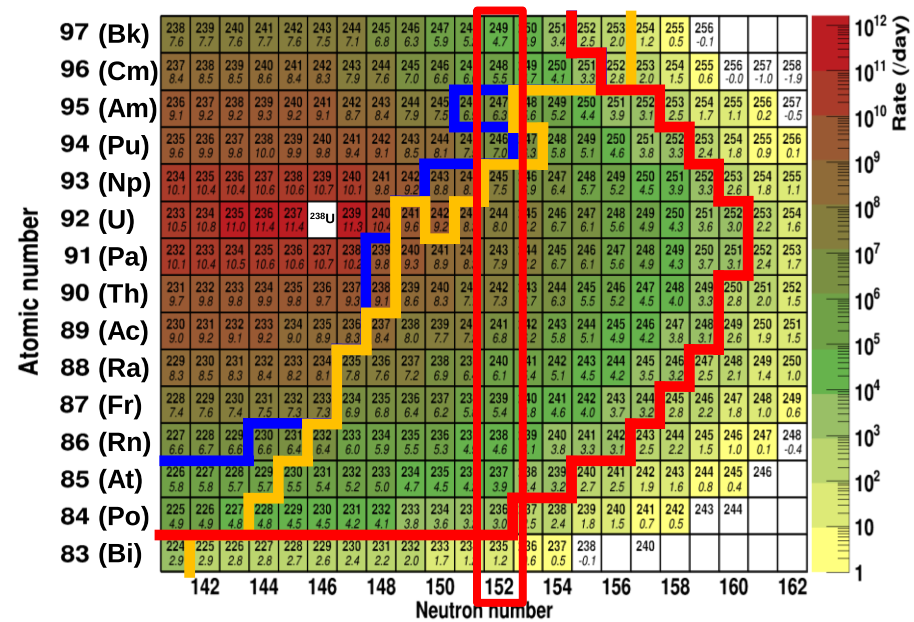
N = 126 region

^{238}U (9.0*A* MeV, 1 pμA) + ^{198}Pt (13 mg/cm^2)



Actinide region

^{238}U (9.4*A* MeV, 1 pμA) + ^{238}U (13 mg/cm^2)



Fission probability of 90% was assumed.

KUTY model prediction
White line : $T_{1/2}$>20ms
Red dotted line : $T_{1/2}$>30ms
White dotted line : $T_{1/2}$>100ms

- Mass frontier (blue line)
- Experimentally known frontier (orange line)
- Yield limit (Rate > 1 k/day) (red line)

248 — Mass number
5.7 — $\log_{10}$(Rate [/day])

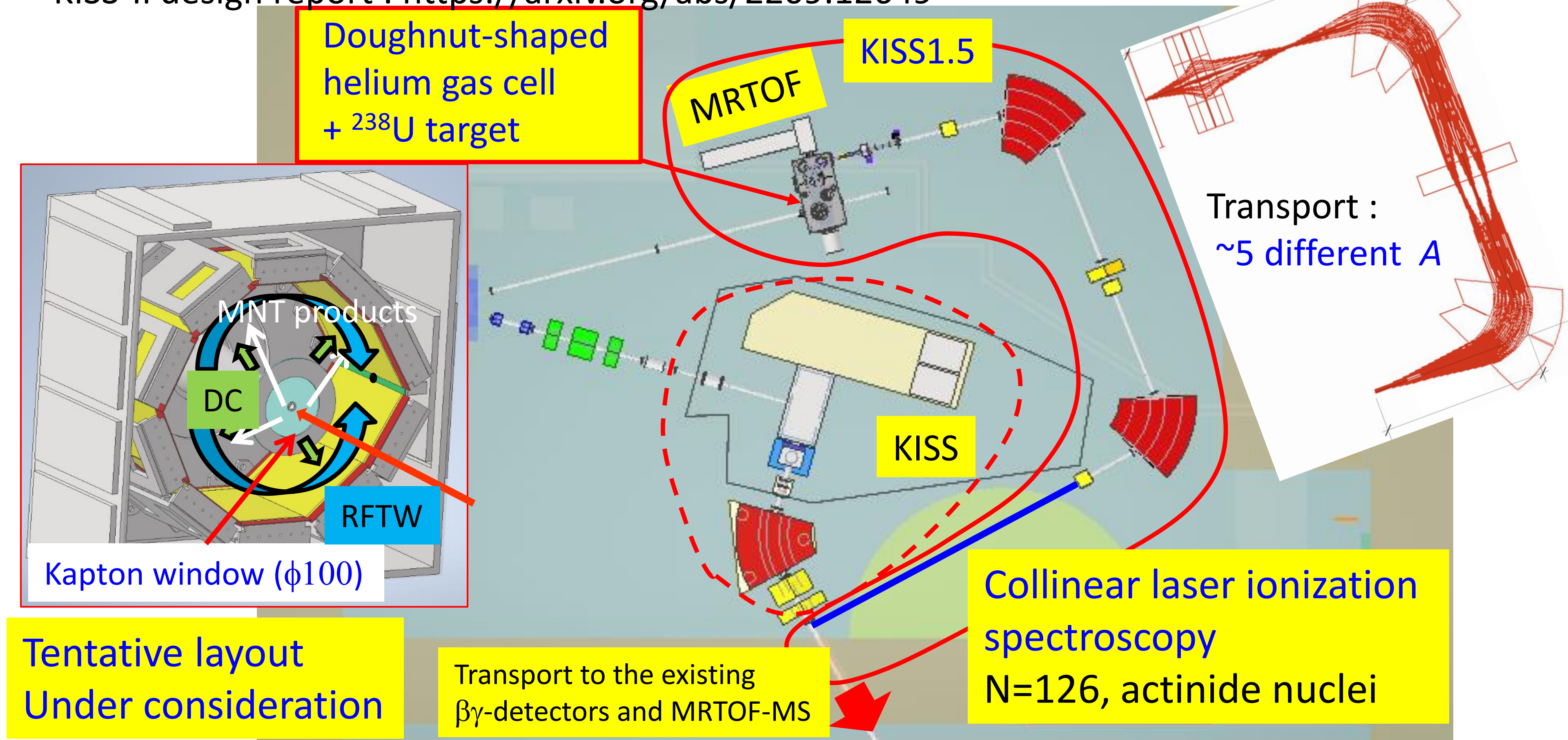
70 new isotopes

110 new isotopes

Near future plan : KISS−1.5

	Primary beam intensity	Extraction efficiency	Efficacy	Total gain
KISS	10 pnA	<0.1%	1	1
KISS-1.5	50 pnA Doughnut-shaped He GC	>1% RF He gas cell	> 10 MRTOF	> 500
KISS-II	1000 pnA Solenoid magnet	>1% RF He gas cell	> 10 MRTOF	> 10 000

KISS-II design report : https://arxiv.org/abs/2209.12649



Summary

To characterize *3rd peak of* abundance pattern and explore the origin of U and Th from nuclear physics perspective, nuclear spectroscopy in the vicinity of N=126 and actinide region is essential.

- Installation of KISS was completed.
- Lifetime measurements and β-γ spectroscopy
- Laser spectroscopy for g-factor and charge radius
- Mass measurement by using MRTOF-MS

➡ Proceed further nuclear spectroscopy of nuclei around N=126 and around ^{238}U (n-rich actinide)

➡ R&D of doughnut-shaped helium gas cell

➡ KISS1.5/2

Strong collaboration with theorists (nuclear physics and astrophysics)