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19th July, 2019

Recent experimental results of KEK Isotope Separation System (KISS)

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KEK Wako Nuclear Science Center (WNSC)

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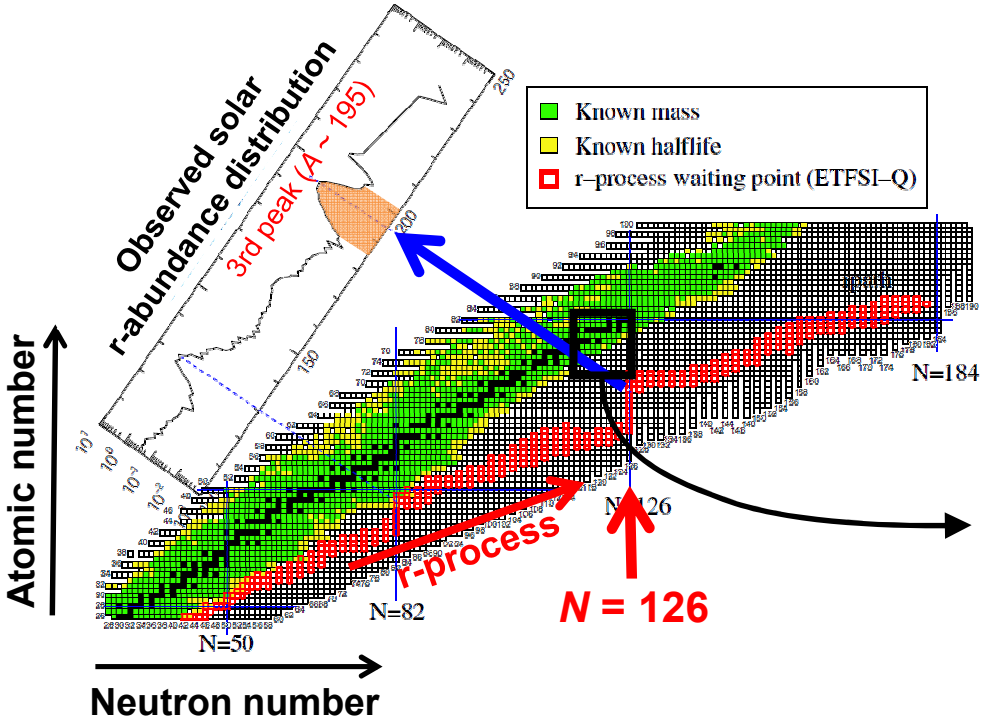
1. Introduction: astrophysical motivation
2. Nuclear production around *N* = 126 by MNT reactions
3. KISS facility and recent experimental results
4. R&D and future plan of KISS
5. Summary

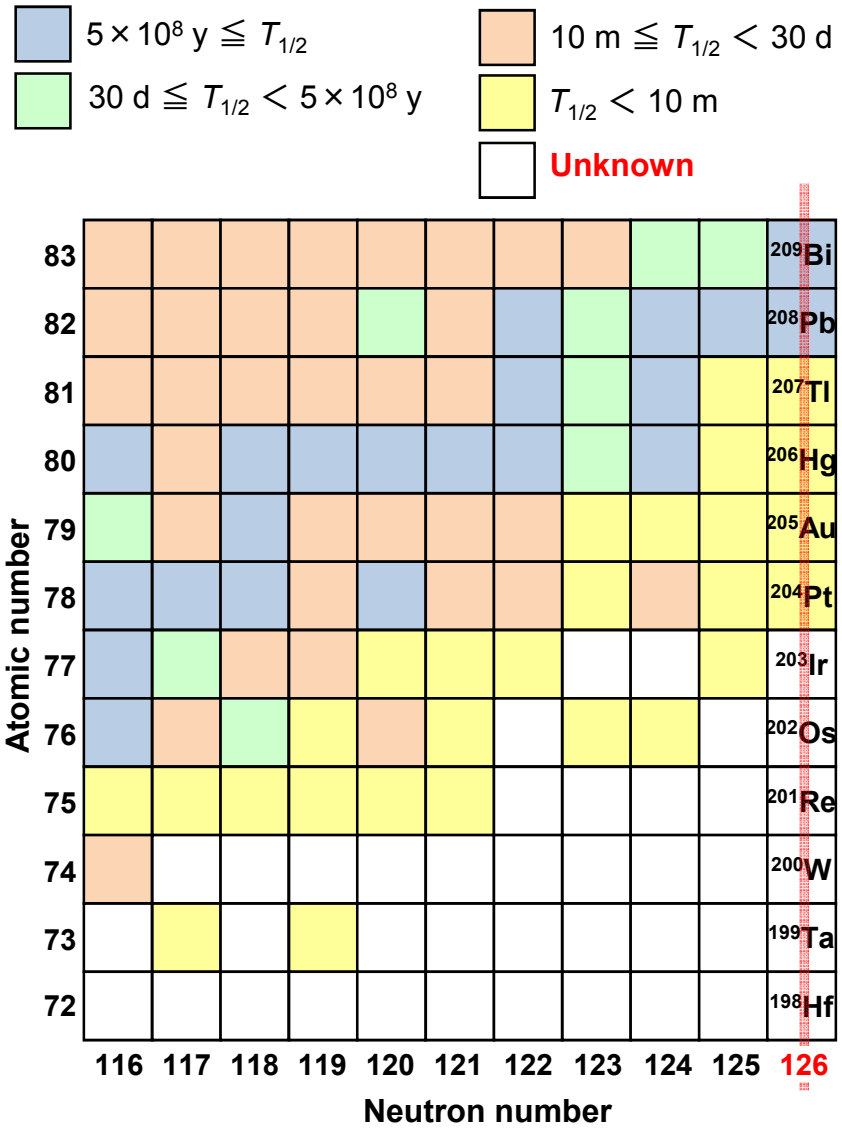
r-process nucleosynthesis and *N* = 126 neutron-rich nuclei

Nuclear properties of neutron closed shell *N* = 126 nuclei

→ r-process in astrophysical nucleosynthesis



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



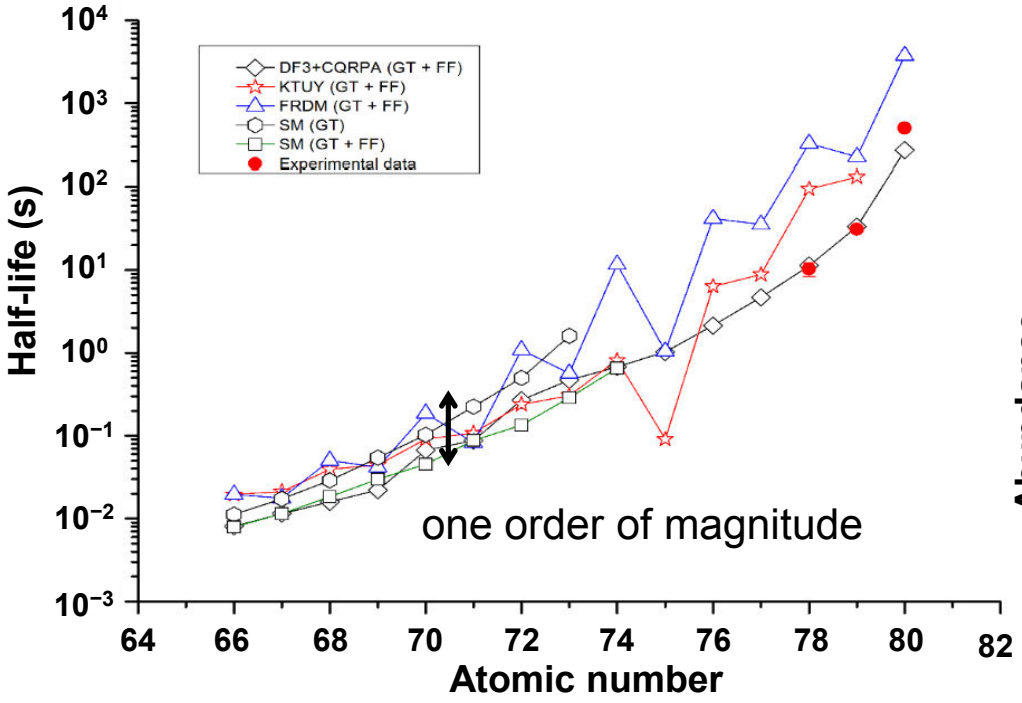
Lifetime and mass of waiting point nuclei

→ Astrophysical environments of r-process

Uncertainties of r-process abundance pattern: half-life

Theoretical nuclear models play crucial roles in the simulation of the r-process nucleosysnthesis.

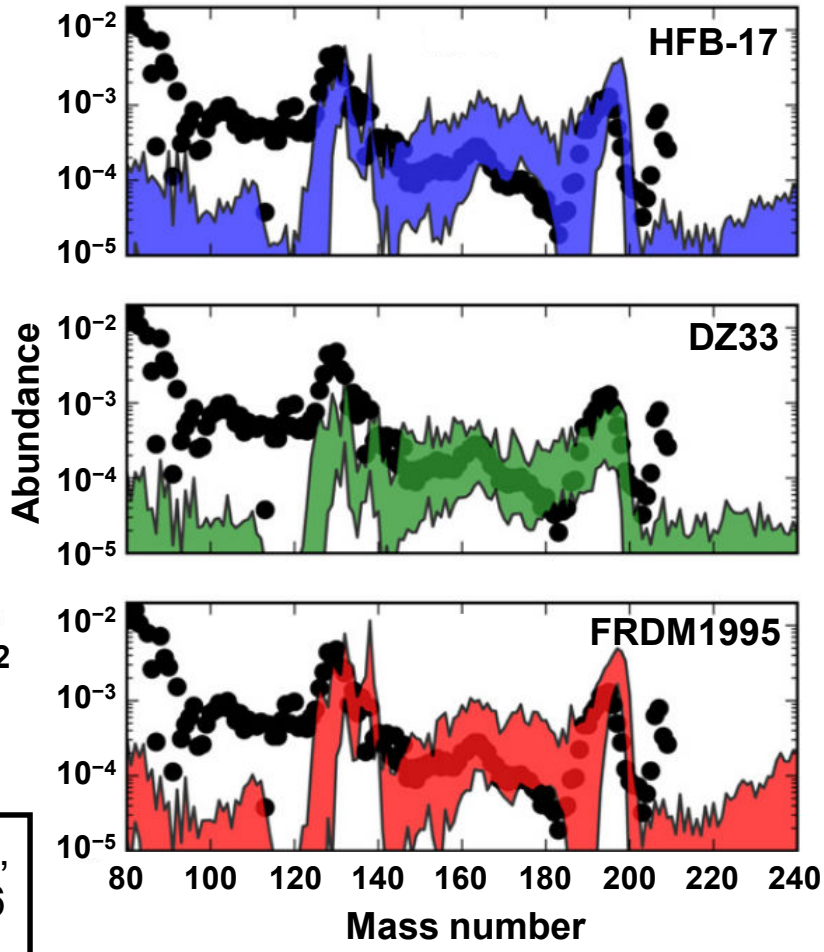
Half-lives of N = 126 isotones



KISS project

Systematic nuclear spectroscopy (lifetime, mass, β-γ spectroscopy, laser spectroscopy) around N = 126
→ Astrophysical environments of r-process

Isotopic abundance pattern variance from uncertain β-decay half-lives (0.1 ~ 10 × $T_{1/2}$)



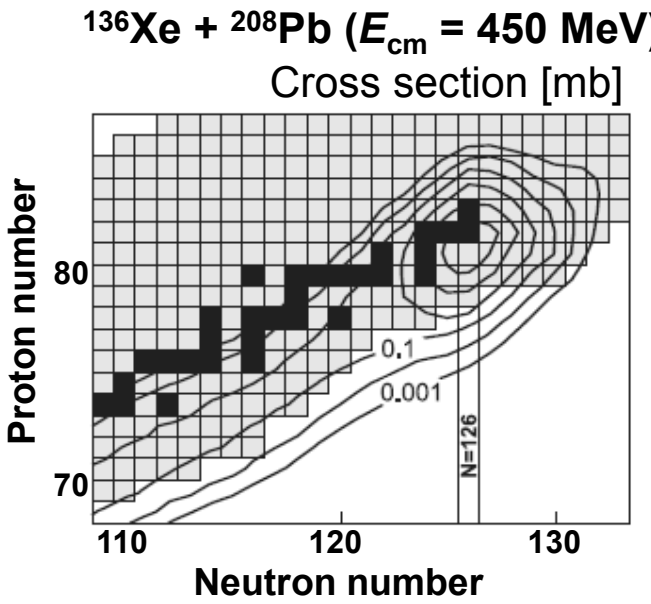
M.R. Mumpower et al., Prog. Part. Nucl. Phys. 86, 86 (2016).

Nuclear production around $N = 126$ by MNT reaction

Macroscopic approach

(Langevin-type dynamical equation of motion)

^{136}Xe + ^{208}Pb (E_{cm} = 450 MeV)

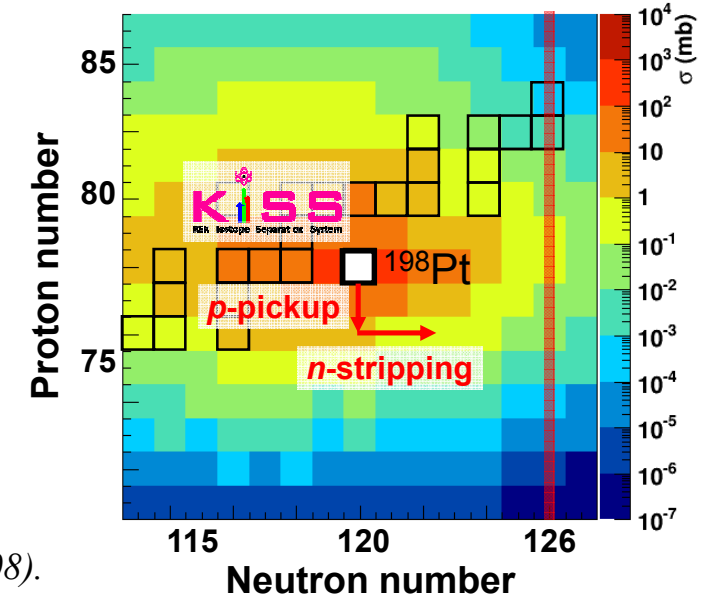


V. Zagrebaev and W. Greiner, Phys. Rev. Lett. 101, 122701 (2008).

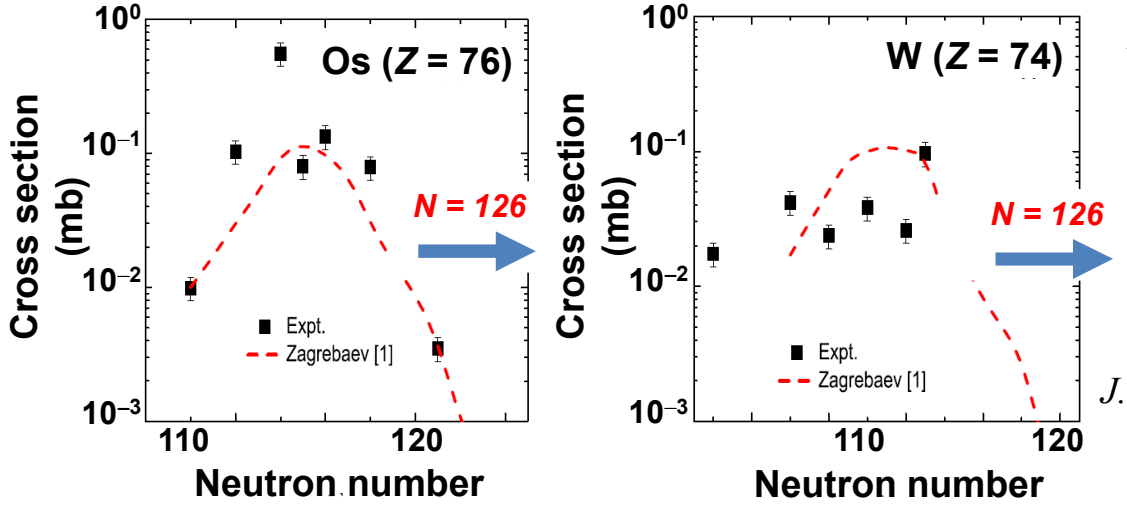
Semi-classical approach

(Single-particle transfer probability)

^{136}Xe + ^{198}Pt (E_{cm} = 645 MeV)



^{136}Xe + ^{208}Pb (5.8 MeV/A) at ANL



GRAZING calculation

A. Winther, Nucl. Phys. A 572, 191 – 235 (1994); 594, 203 – 245 (1995).

J.S. Barrett et al., Phys. Rev. C 91, 064615 (2015).

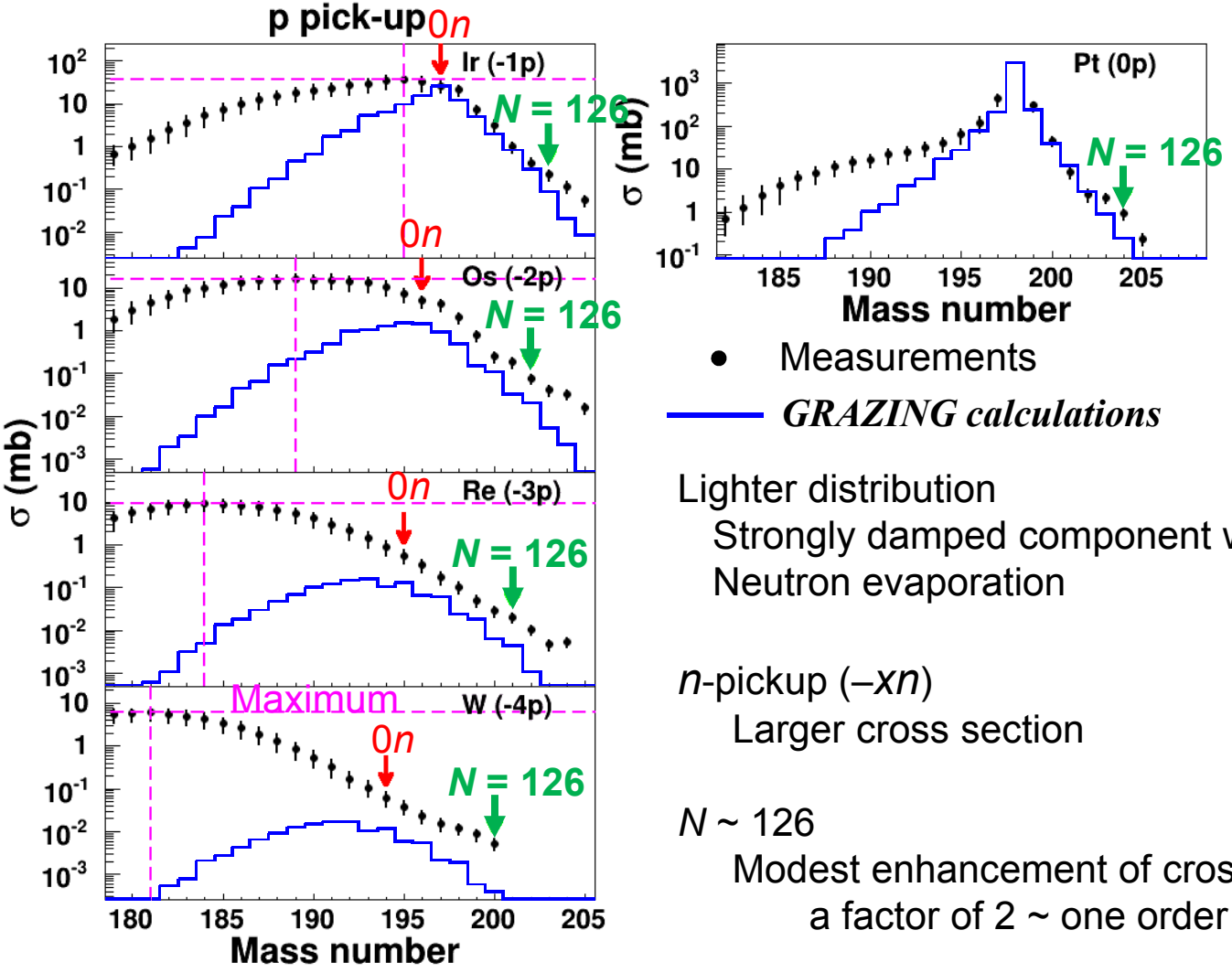
Experimental study for MNT reactions of ^{136}Xe + ^{198}Pt

^{136}Xe (8 MeV/nucleon) + ^{198}Pt (1.3 mg/cm^2)

Projectile-like fragments (PLFs) were detected by large acceptance magnetic spectrometer VAMOS++ at GANIL, and target-like fragment (TLF) distributions were deduced.

Y.X. Watanabe et al., Phys. Rev. Lett. 115, 172503 (2015).

Isotopic distributions of target-like fragments (TLFs)



Lighter distribution
- Strongly damped component with *N*/*Z* equilibration
- Neutron evaporation

n-pickup (–*xn*)
- Larger cross section

N ~ 126
- Modest enhancement of cross sections
  - a factor of 2 ~ one order of magnitude

Experimental study for MNT reactions of ^{136}Xe + ^{198}Pt

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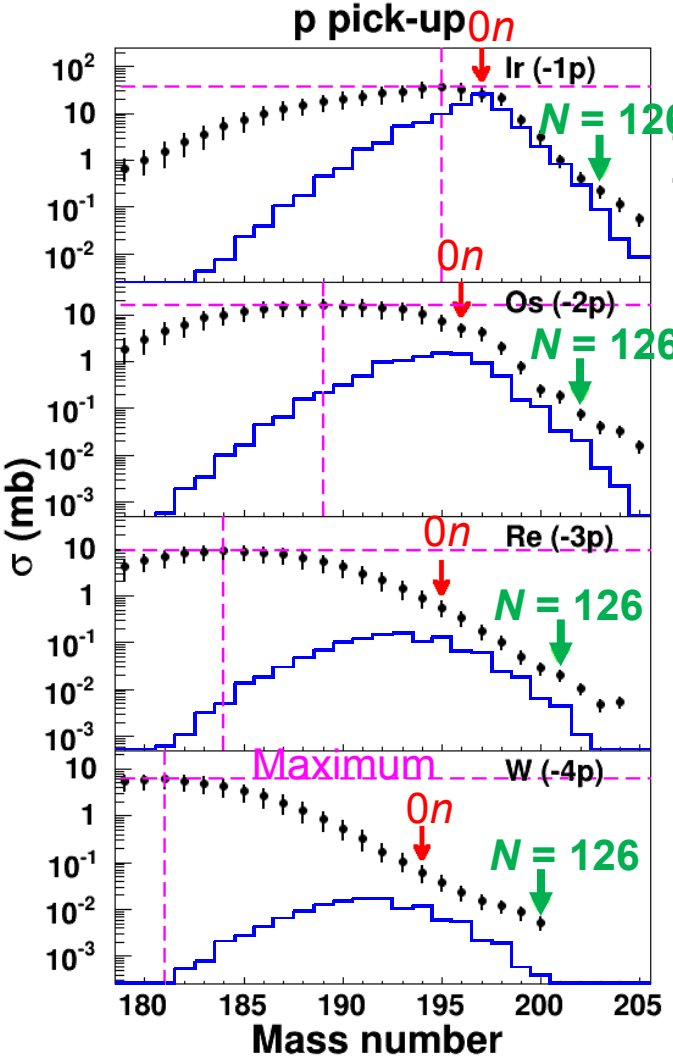
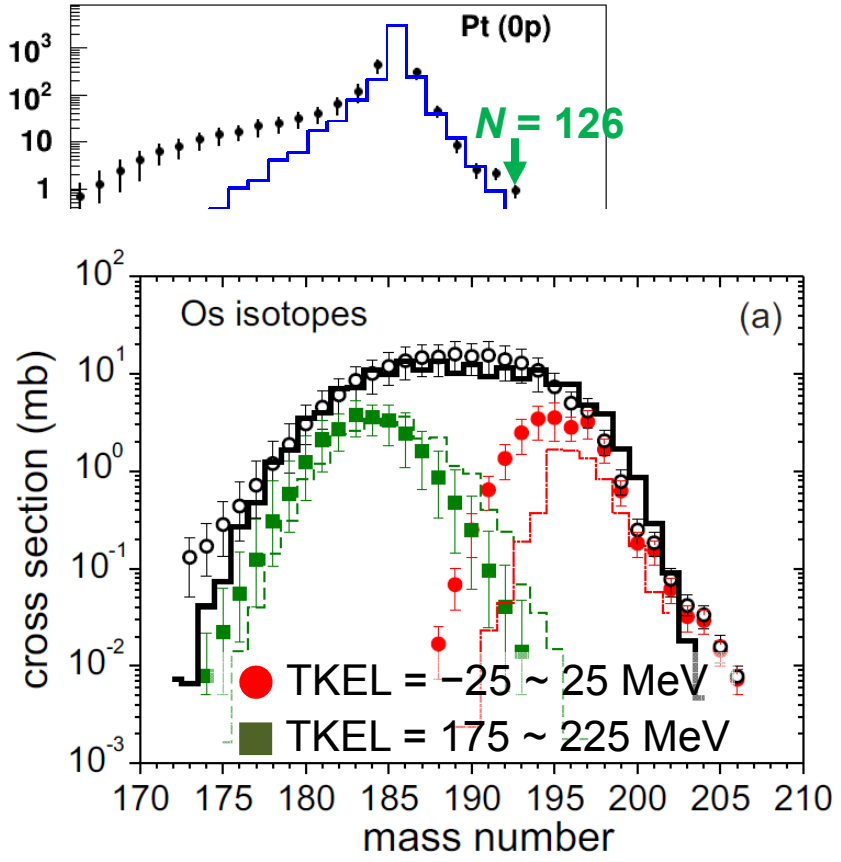
Isotopic distributions of target-like fragments (TLFs)



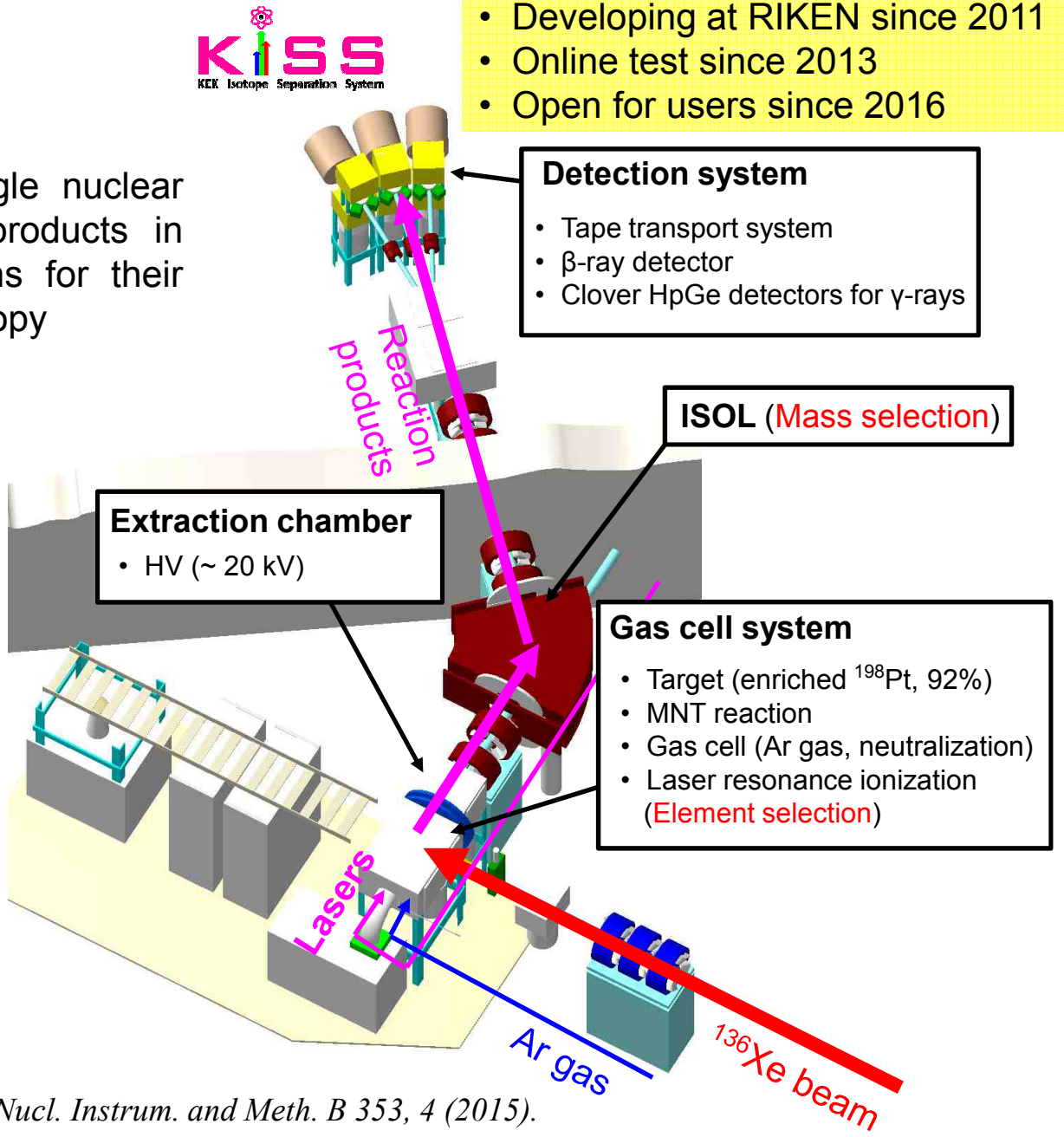


A.V. Karpov and V.V. Saiko, Phys. Rev. C 96, 024618 (2017).

KEK Isotope Separation System (KISS)

- Developing at RIKEN since 2011
- Online test since 2013
- Open for users since 2016

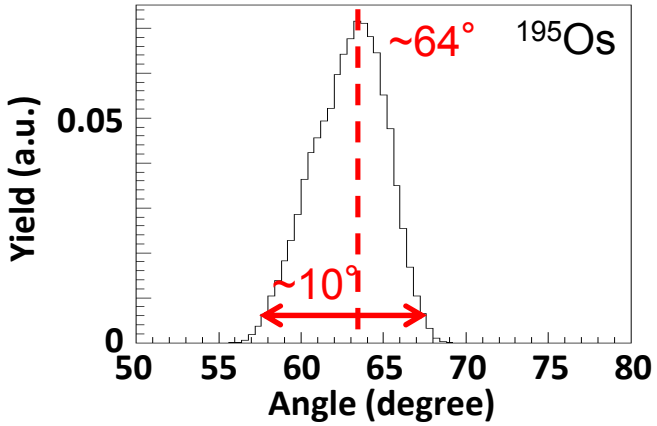
Separation a single nuclear species among products in the MNT reactions for their nuclear spectroscopy

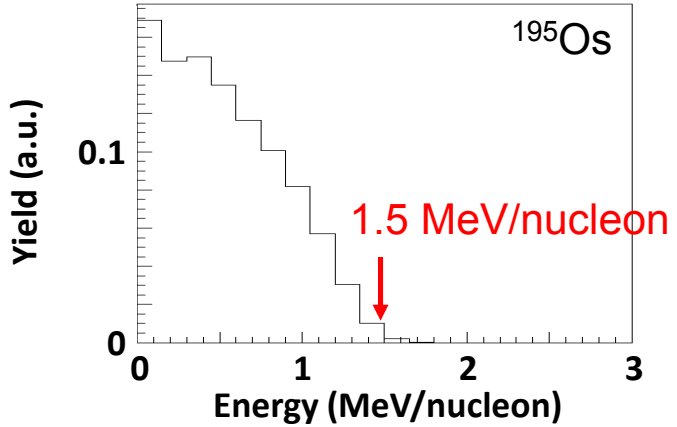


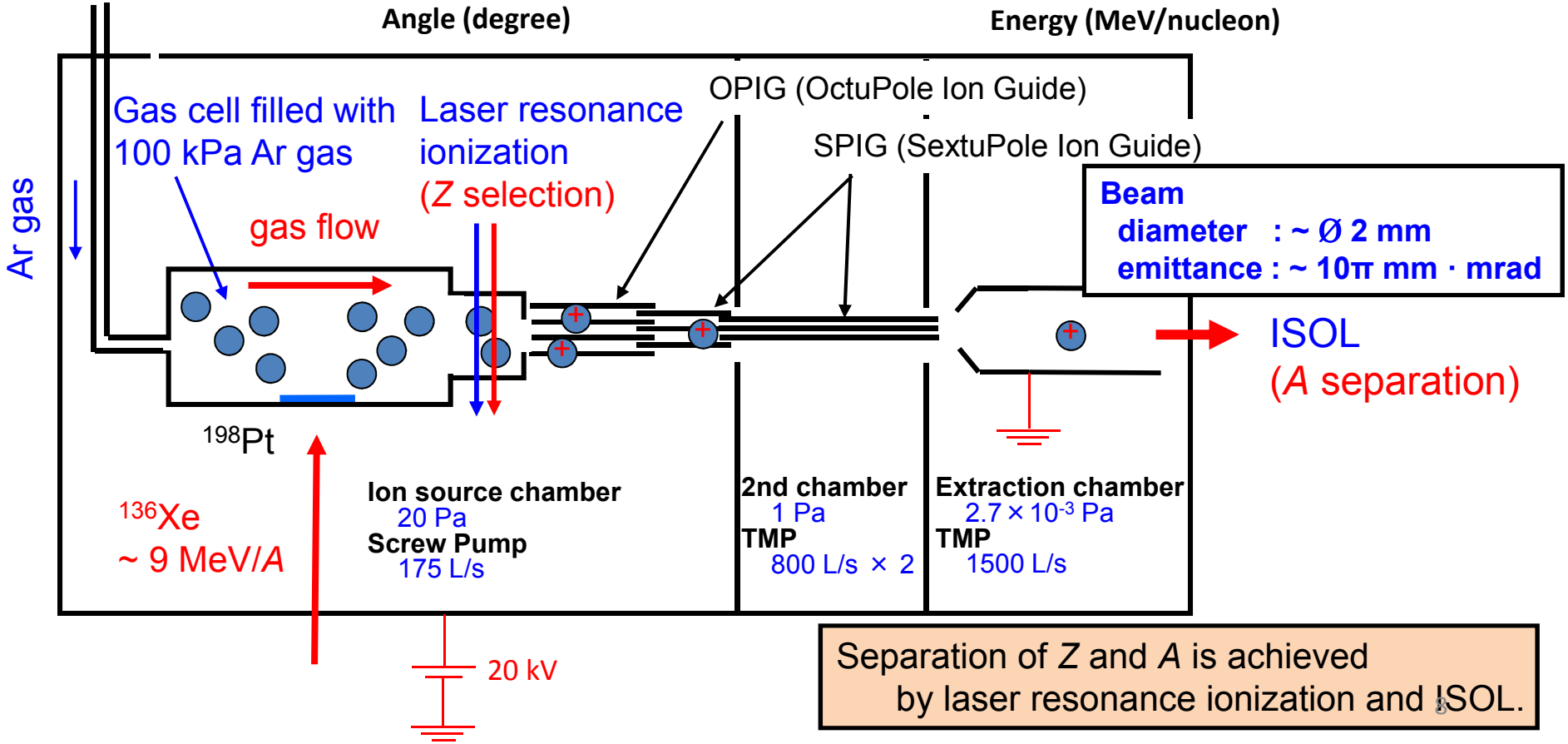
Y. Hirayama et al., Nucl. Instrum. and Meth. B 353, 4 (2015).

Gas cell system

^{136}Xe (9.4 MeV/nucleon) + ^{198}Pt (12.5 mg/cm^2)

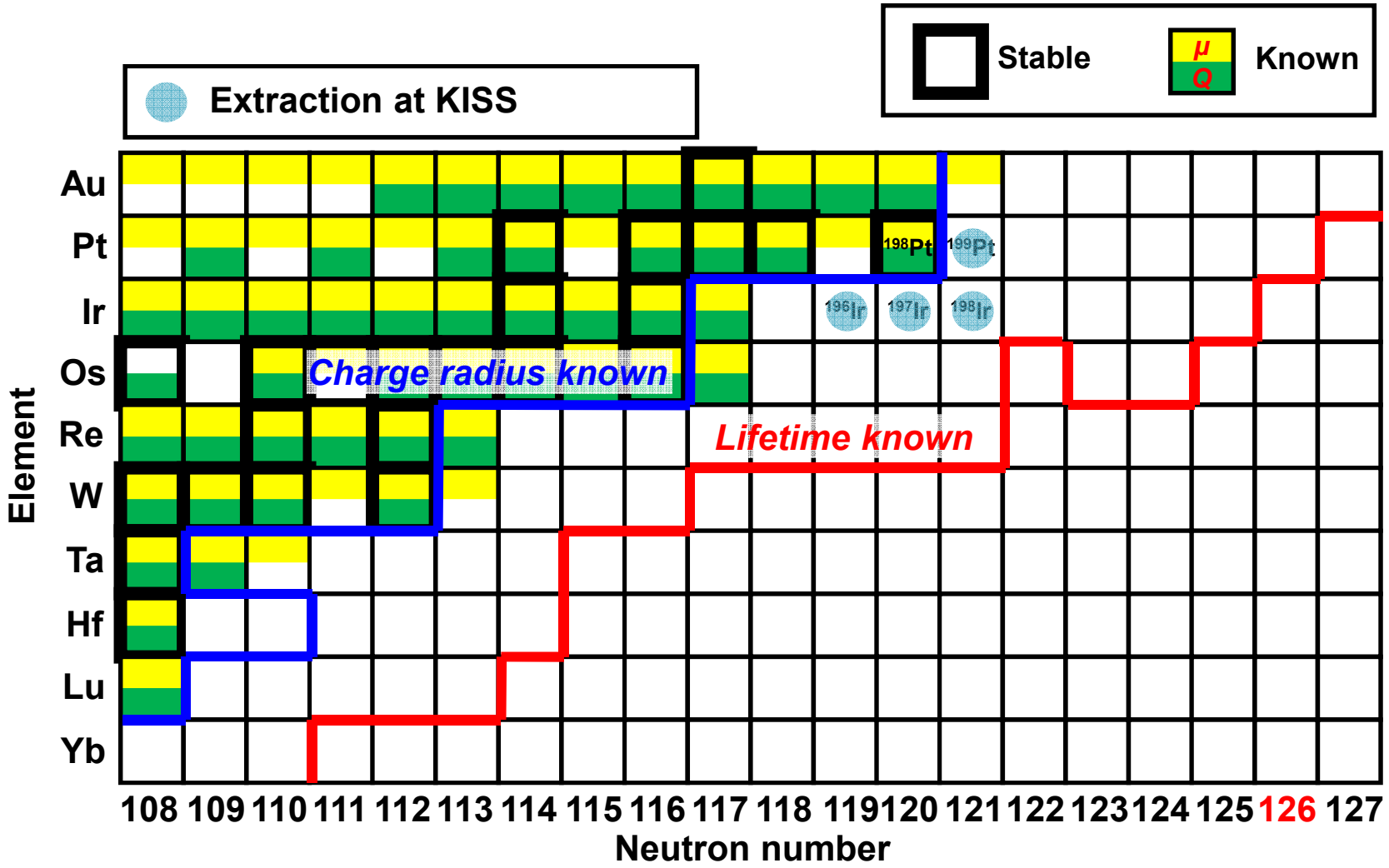






Separation of *Z* and *A* is achieved by laser resonance ionization and ISOL.

Experimental results (– 2016)



Extraction efficiency : 0.15% for $^{198}Pt^{+}$

0.01% for unstable nuclei

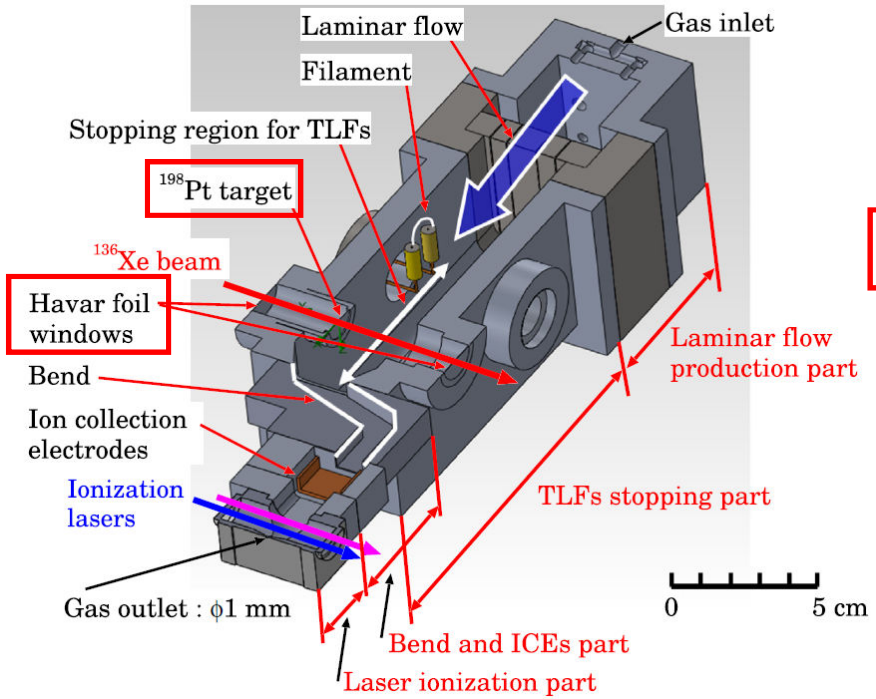
Primary beam : < 20 pnA (thermal damage of several window foils)

Rotating target and doughnut-shaped gas cell

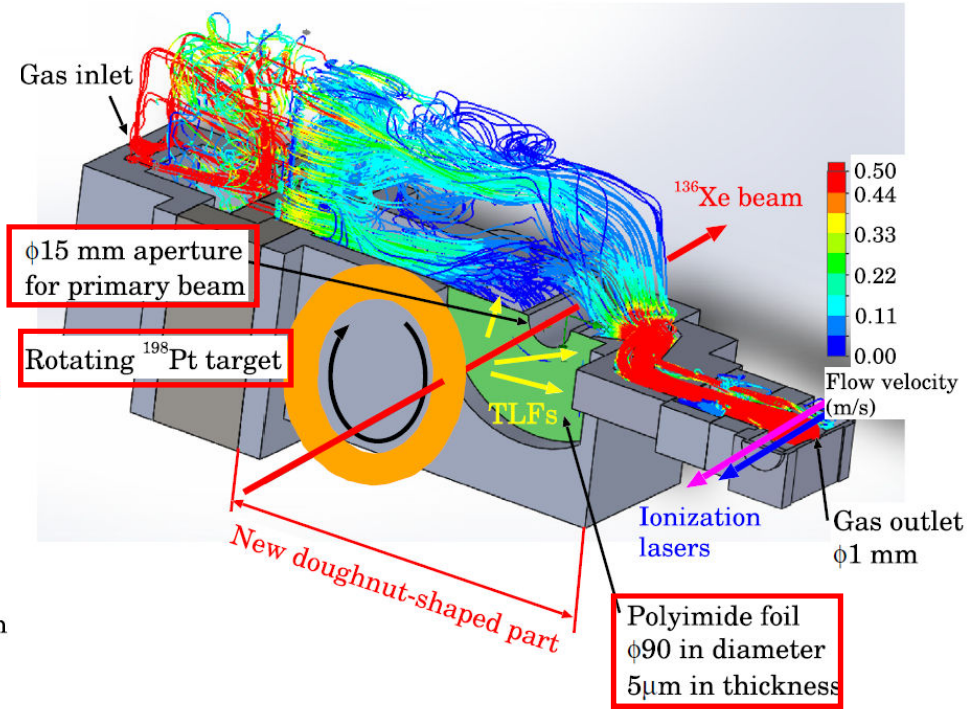
Rotating target → **High beam intensity**

Doughnut-shaped gas cell → **Reduction of induced plasma**

Original gas cell



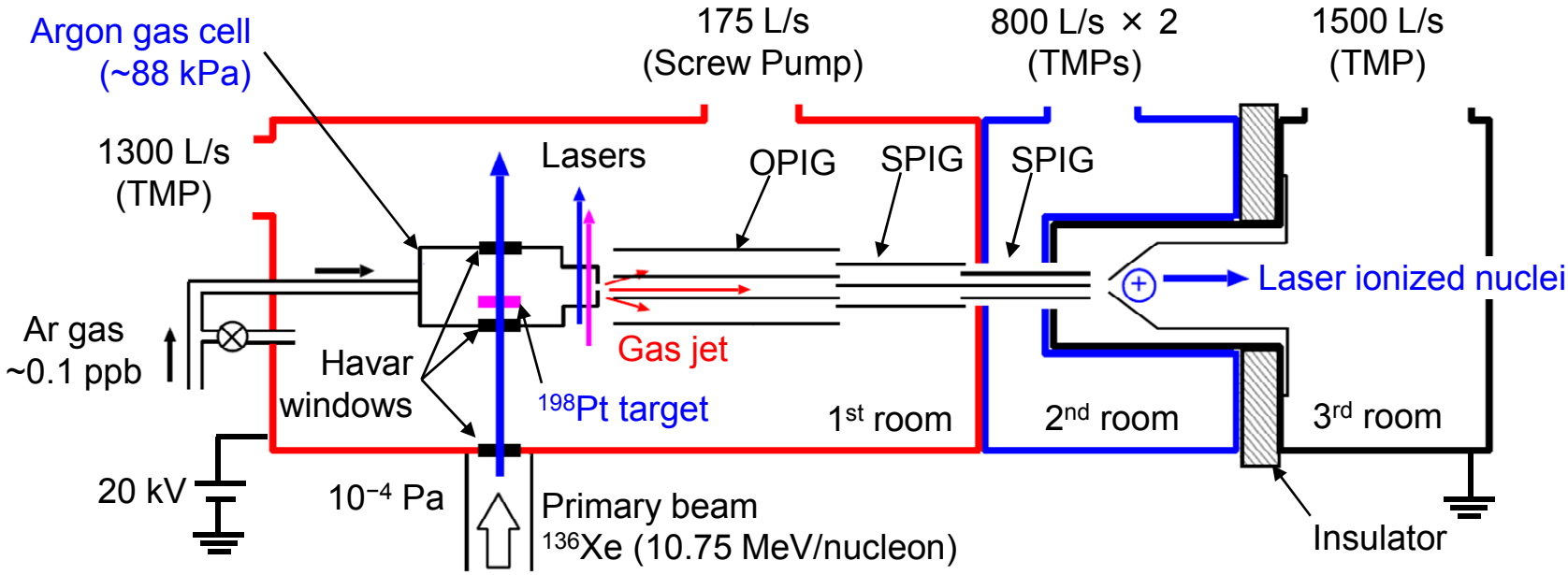
Doughnut-shaped gas cell

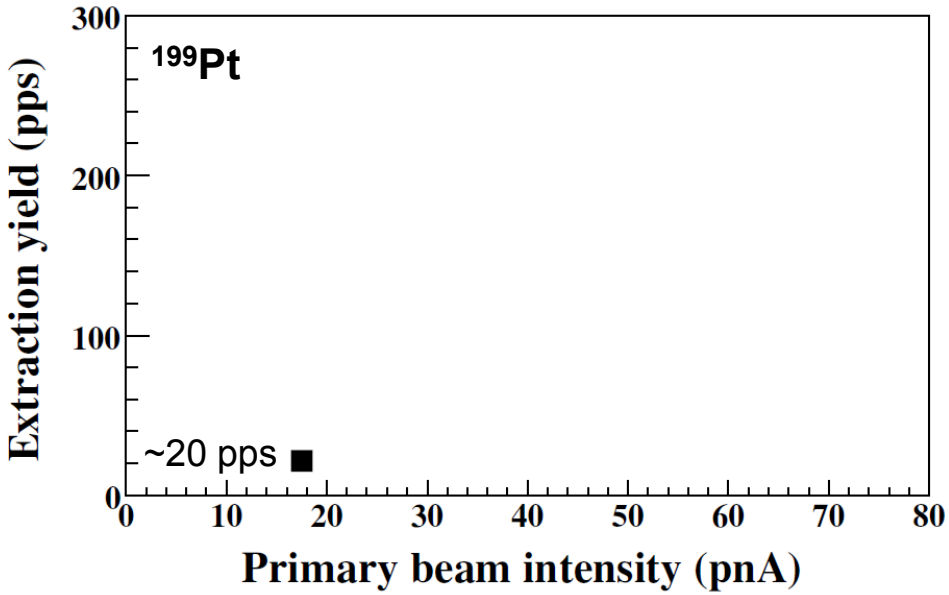


Y. Hirayama et al., Nucl. Instrum. and Meth. B 412, 11 – 18 (2017).

$\varepsilon_{implant}$	=	1.00	0.71
$\varepsilon_{stopping}$	=	0.86	0.82
$\varepsilon_{transport}$	=	0.40	0.36
ε_{total}	=	0.34	0.21

Configuration I

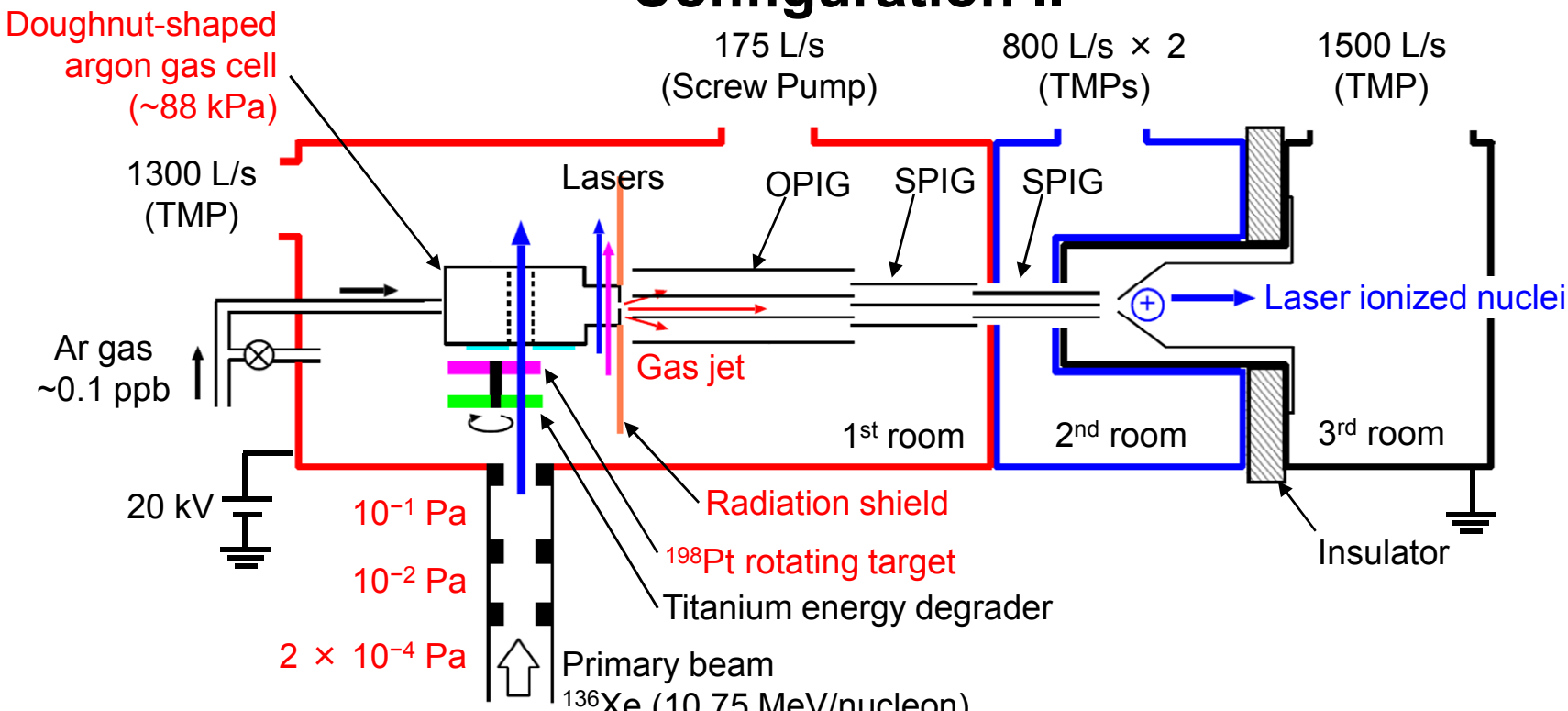


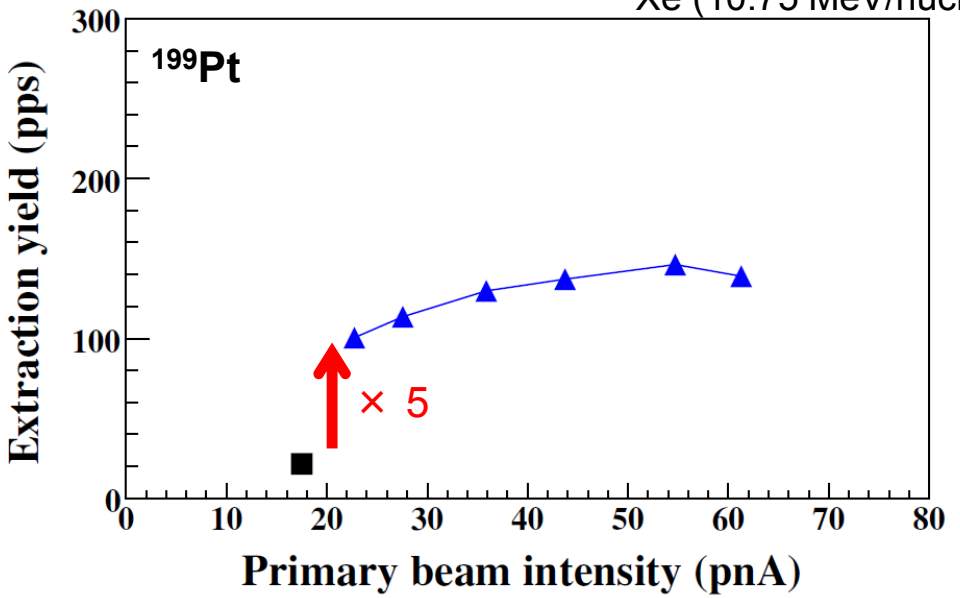


- Original gas cell
- Fixed target
- Havar windows for primary beam

- Efficiency ~0.01%
- Beam limit < 20 pnA

Configuration II

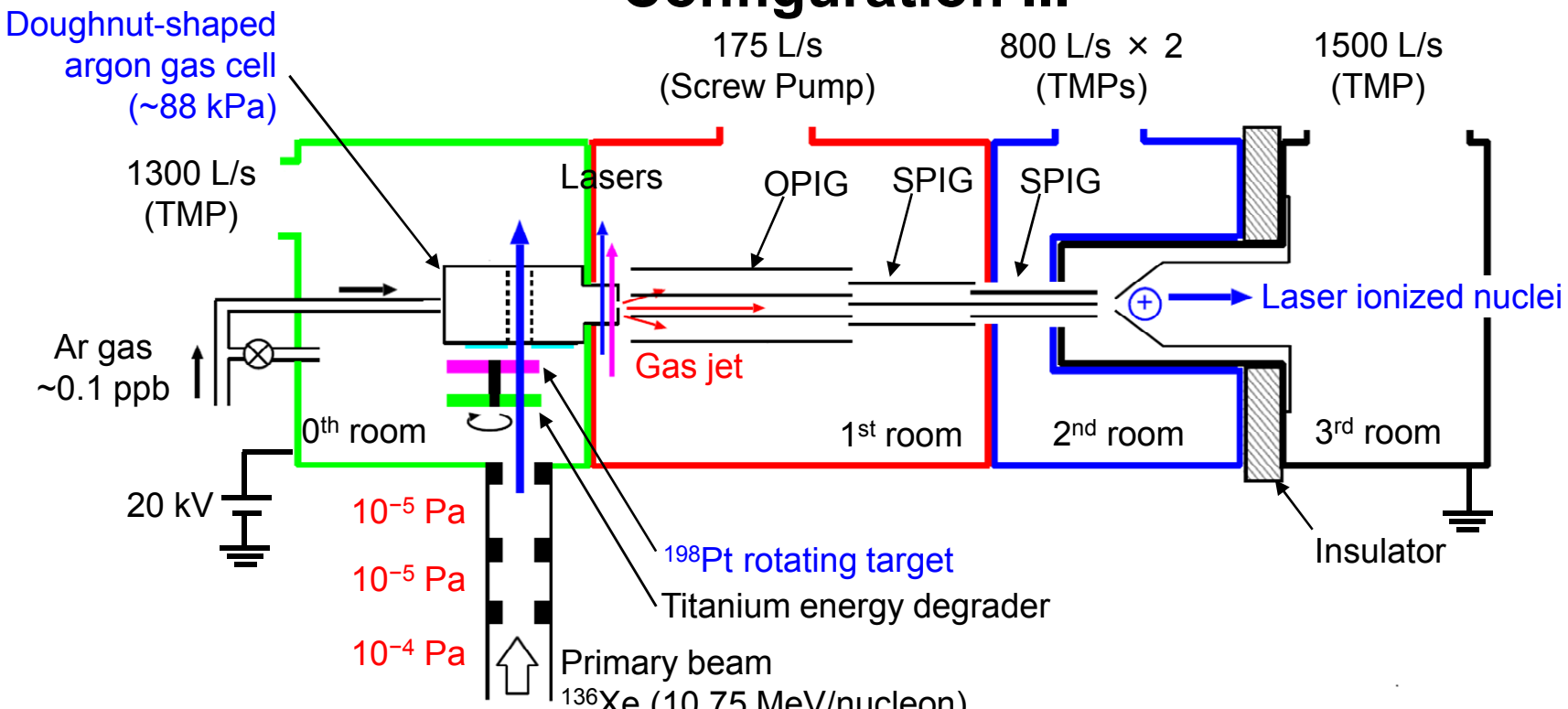


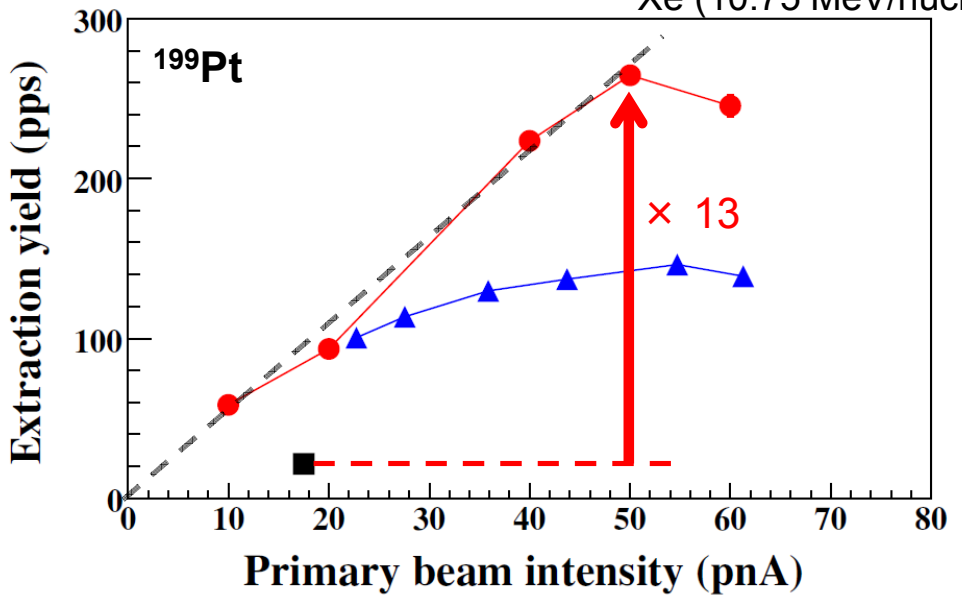


- Doughnut-shaped gas cell
- Rotating target
- Differential pumping for primary beam
- Radiation shield

- Extraction yield × 5
- Not linear to the primary beam intensity
- Saturation > 50 pnA
- Insufficient radiation shield

Configuration III

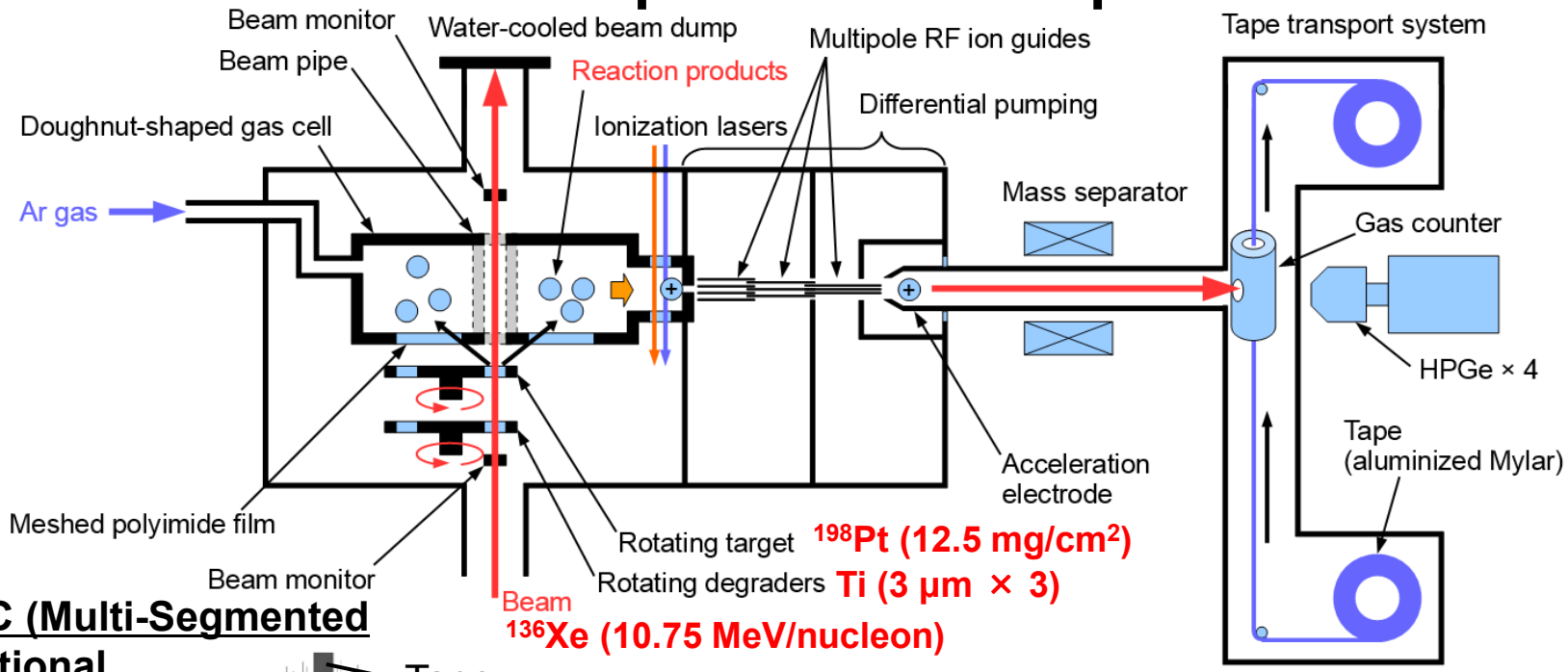




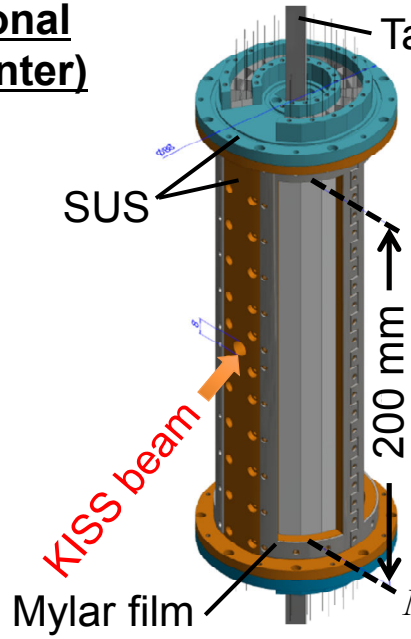
- Doughnut-shaped gas cell
- Rotating target
- High vacuum chamber for primary beam

- Extraction yield increases linearly until 50 pnA
- Peak at ~50 pnA

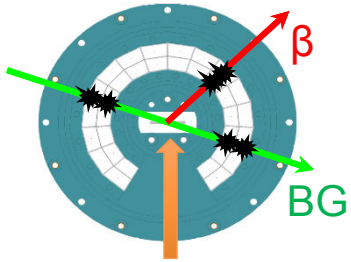
KISS experimental setup



MSPGC (Multi-Segmented Proportional Gas Counter)



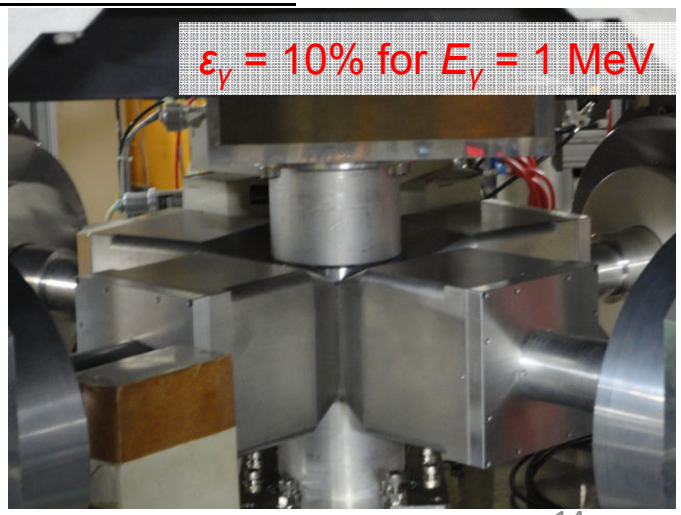
2-layered 16-segmented proportional gas counter



ε_β = 40% for Q_β = 1 MeV
B.G. rate = 0.1 cps

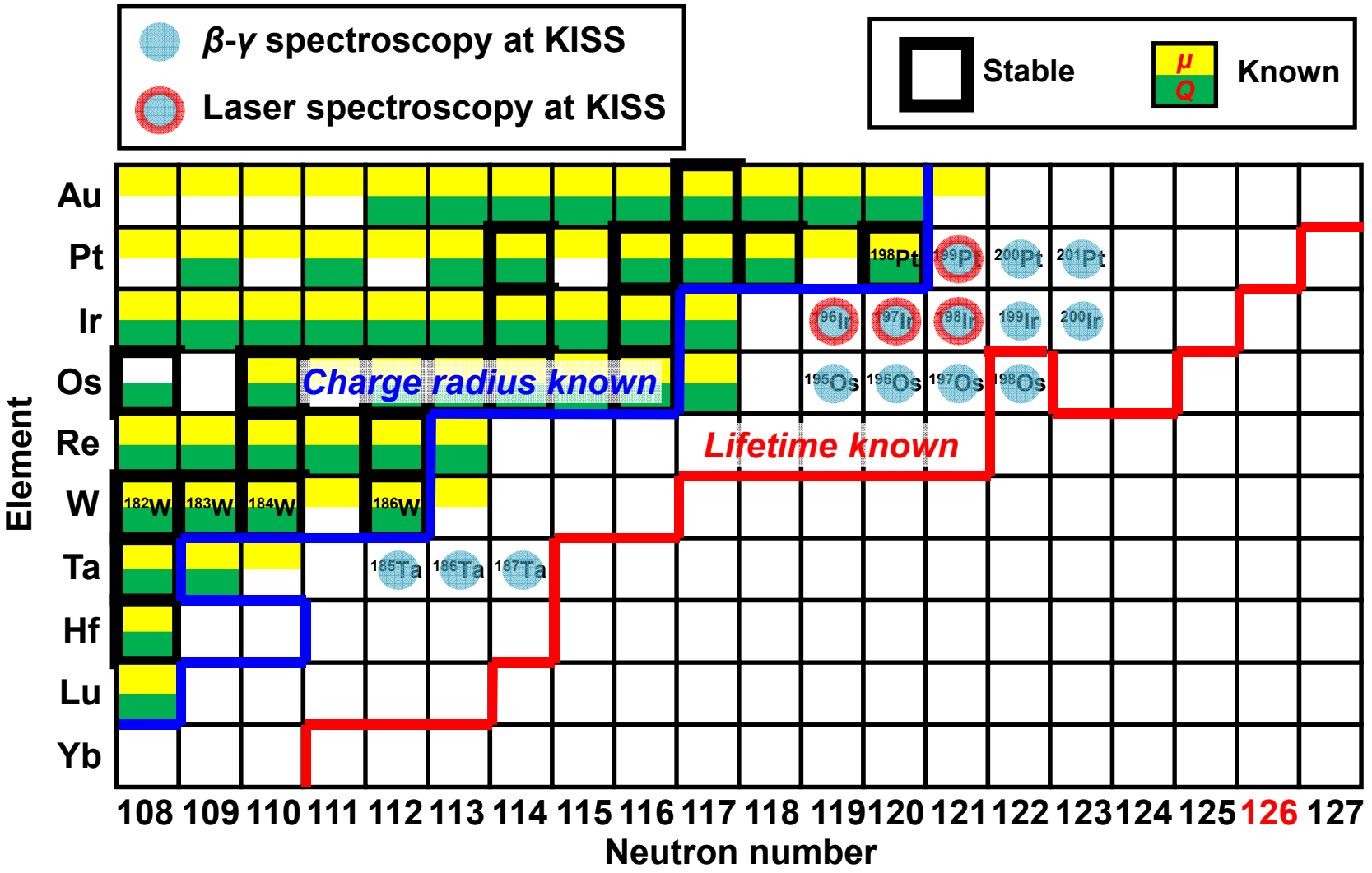
M. Mukai et al., Nucl. Instrum. and Methods A 884, 1–10 (2018).

Four HPGe (High-Purity Germanium) clover detectors



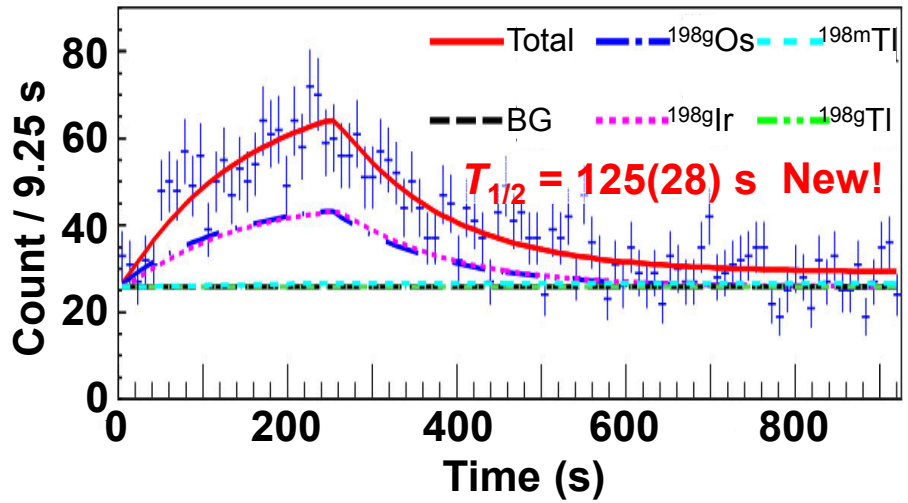
Collaboration with IBS (Korea)

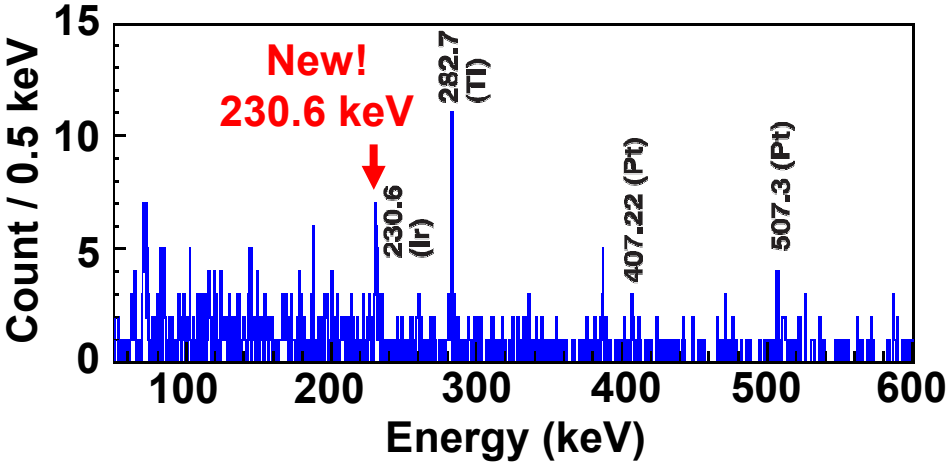
Experimental results

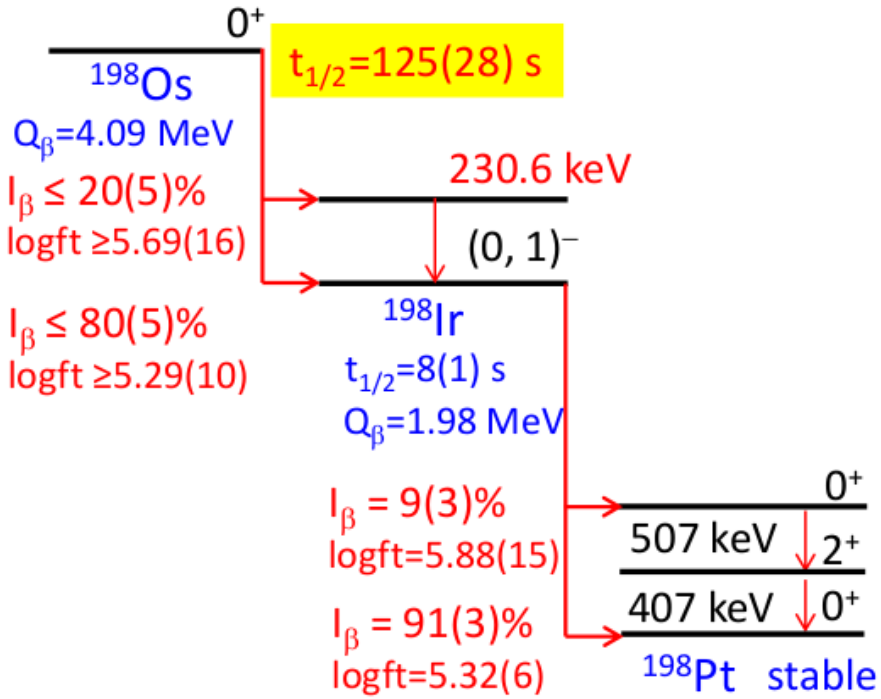


β-γ spectroscopy of ^{198}Os

Y. Hirayama et al., Phys. Rev. C 98, 014321 (2018).

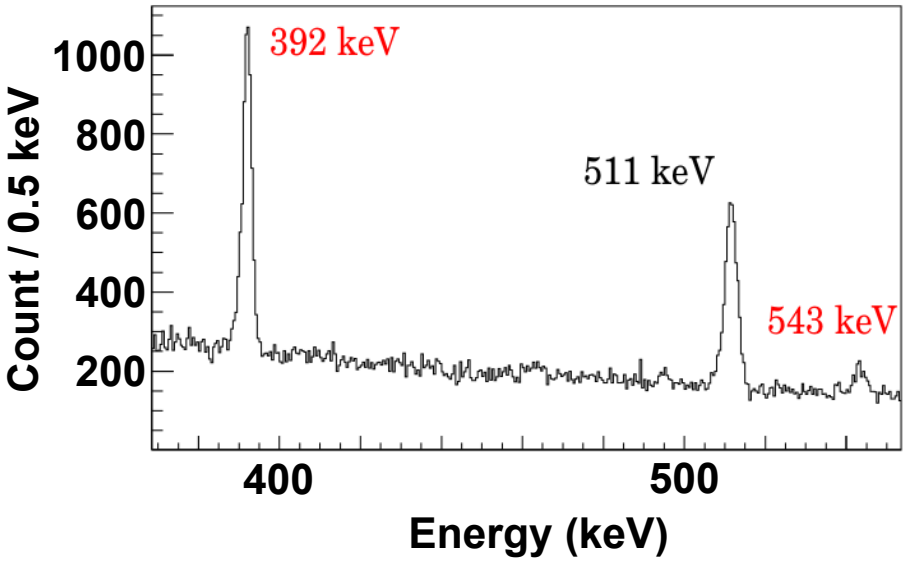


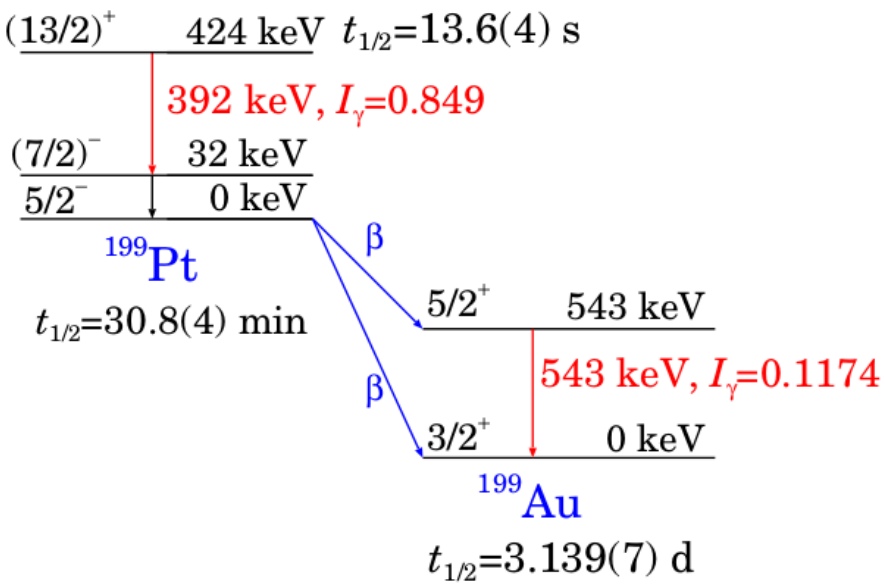


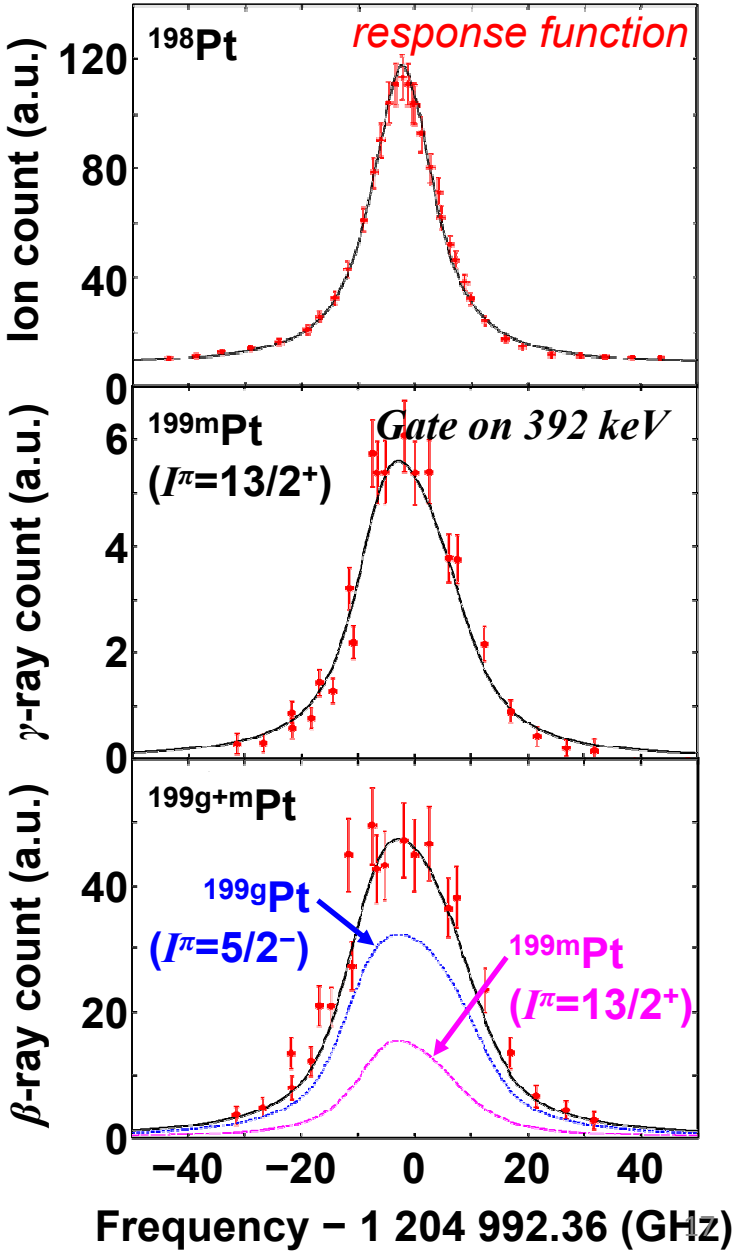


HFS measurement for ground and isomeric states of ^{199}Pt

Y. Hirayama et al., Phys. Rev. C 96, 014307 (2017).

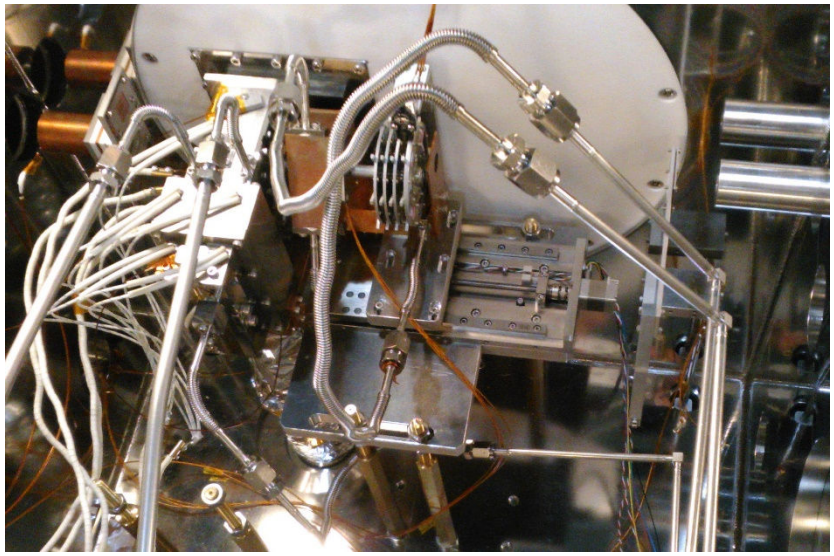




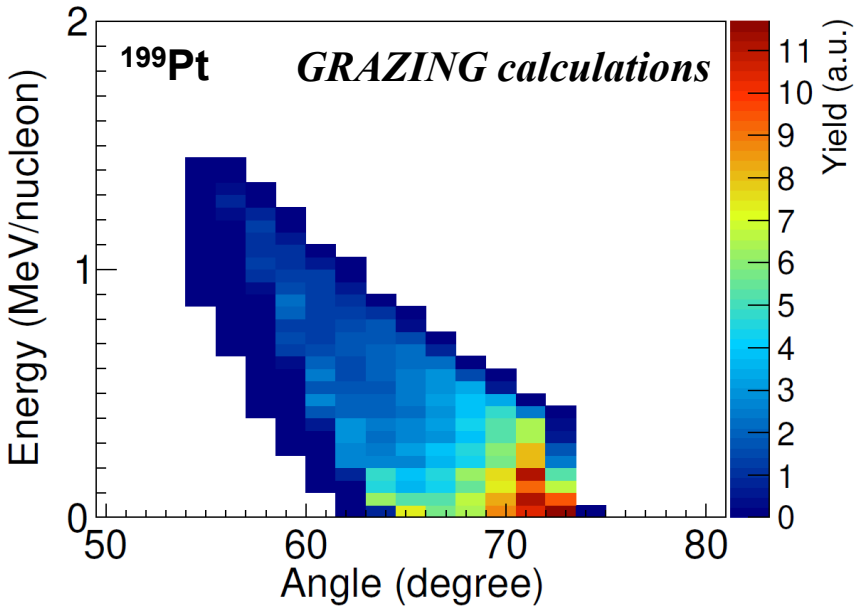


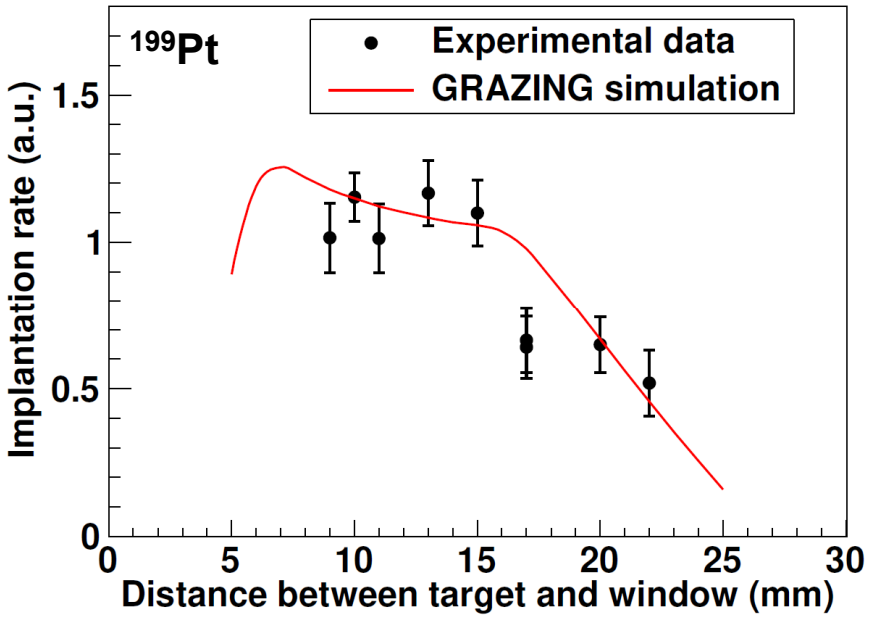
Target position dependence

Target sliding system



Correlation between energies and angles

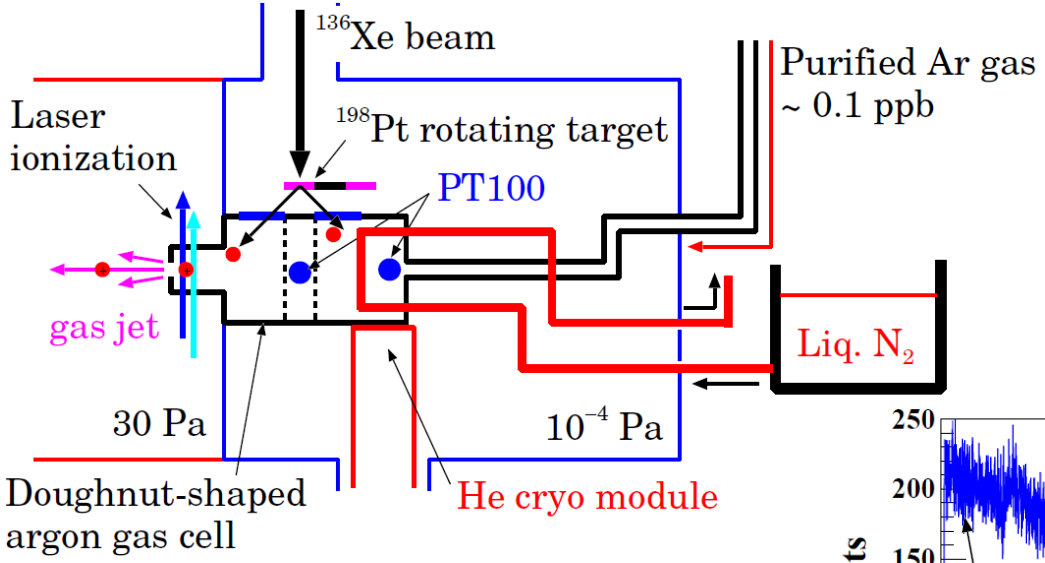




- Good consistency between measurements and calculations.

Gas cell cooling

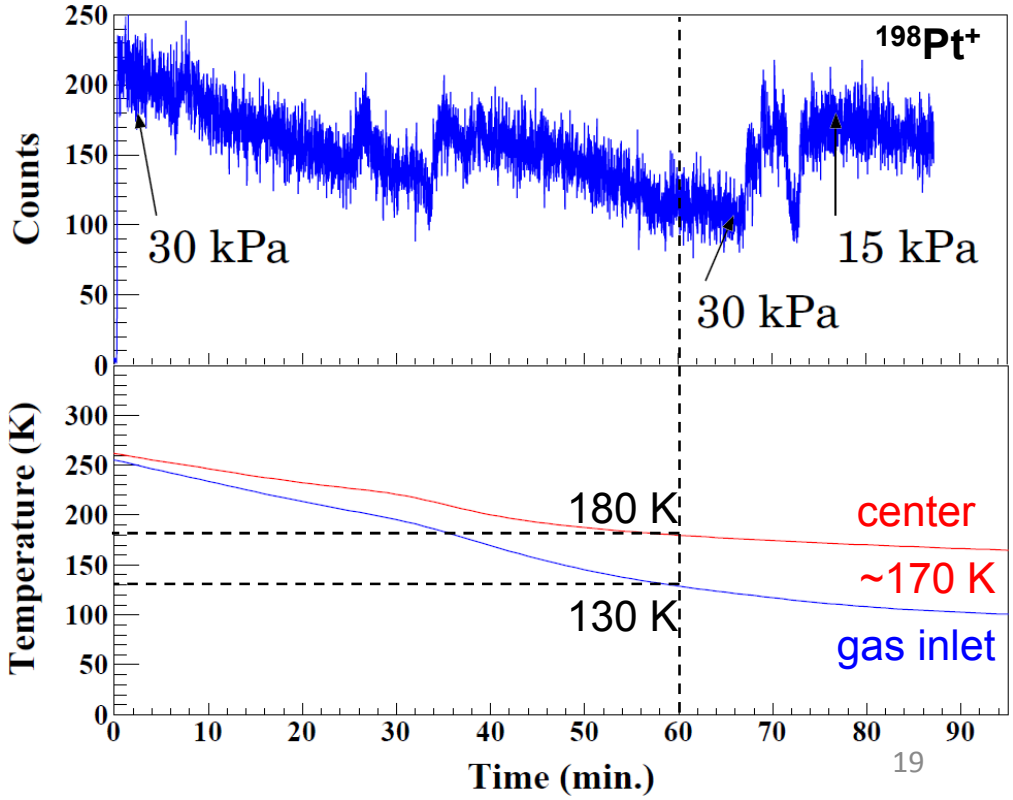
Freezing impurities → Suppression of molecule formation with impurities



- Liquid nitrogen flow
- He cryogenic cooler

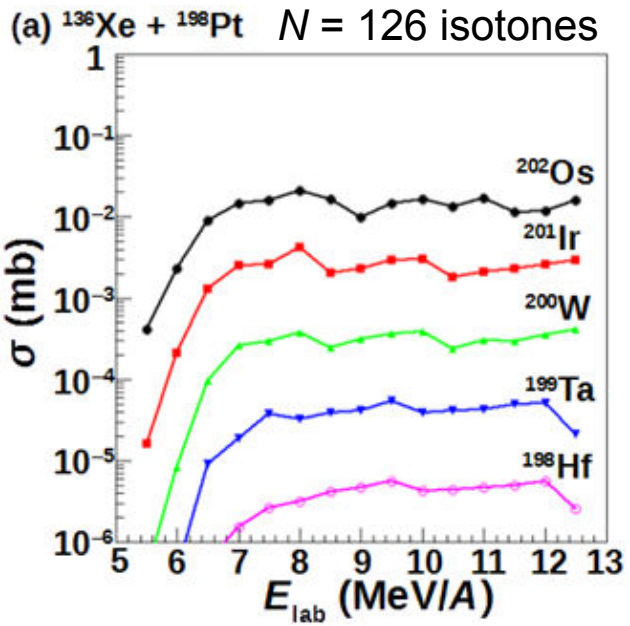
- Extraction yields are comparative at the same gas densities of 170 K and 310 K.

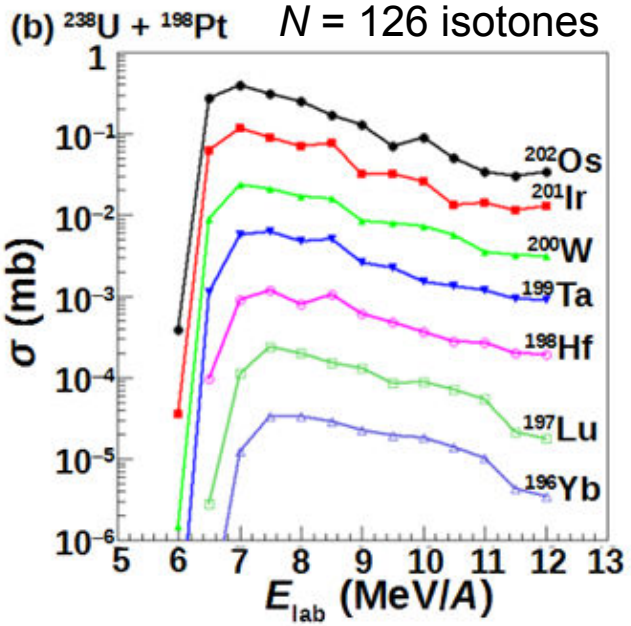
- Molecular formation is not dominant for low extraction efficiency.

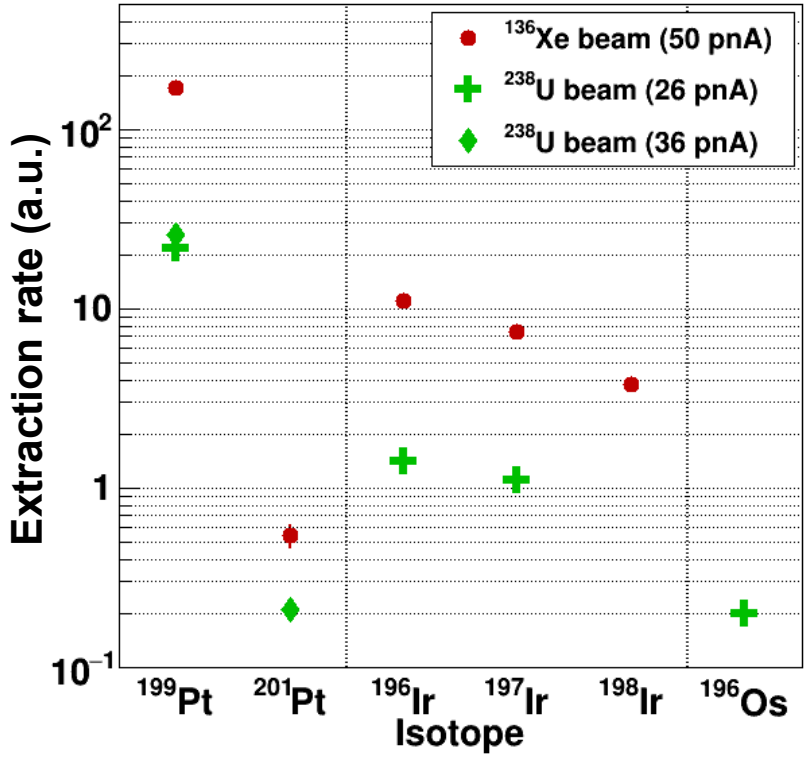


More yields of neutron-rich isotopes: ^{238}U beam

Excitation functions (*GRAZING calculations*)







^{136}Xe (9.40 MeV/A) + ^{198}Pt (12.5 mg/cm^2)

^{238}U (8.90 MeV/A) + ^{198}Pt (12.5 mg/cm^2)

- Extraction yields with ^{238}U beam is one order of magnitude smaller than ^{136}Xe beam.

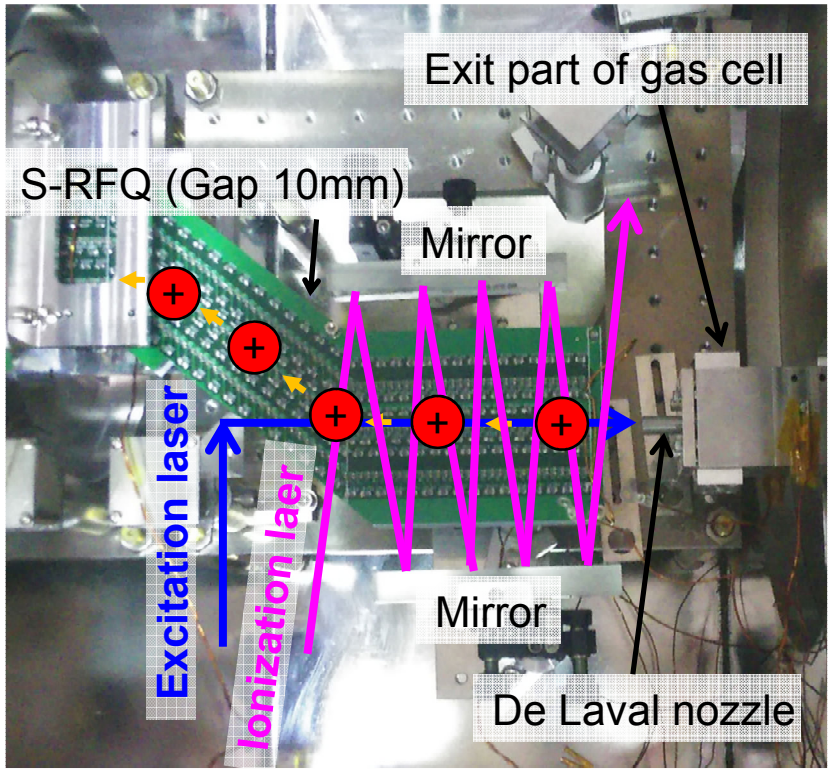
- Systematic study with lighter projectile.

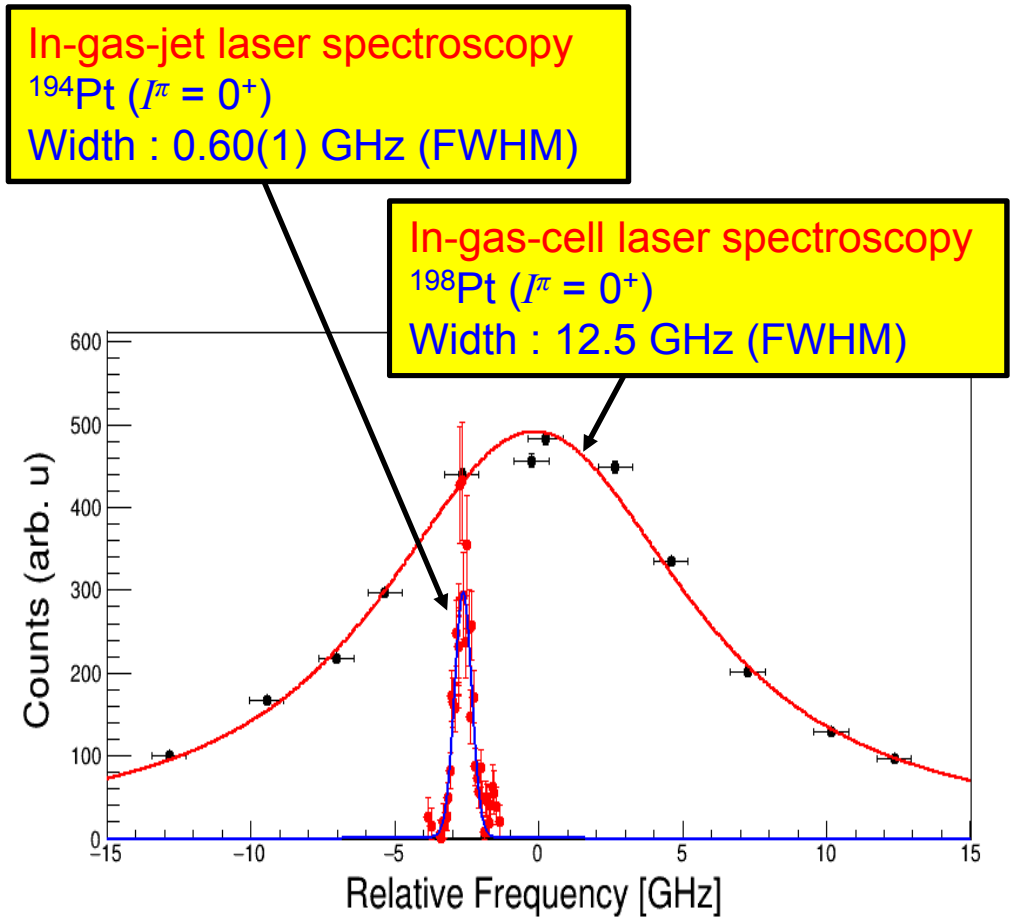
High-precision In-gas-jet laser spectroscopy

More precise study of wave-function and deformation

← High-precision laser spectroscopy

Narrow-band LD laser + Dye amplifier + Intense YAG laser





Ar gas cell: 80 kPa, $P_{B.G.}$ ~ 50 Pa

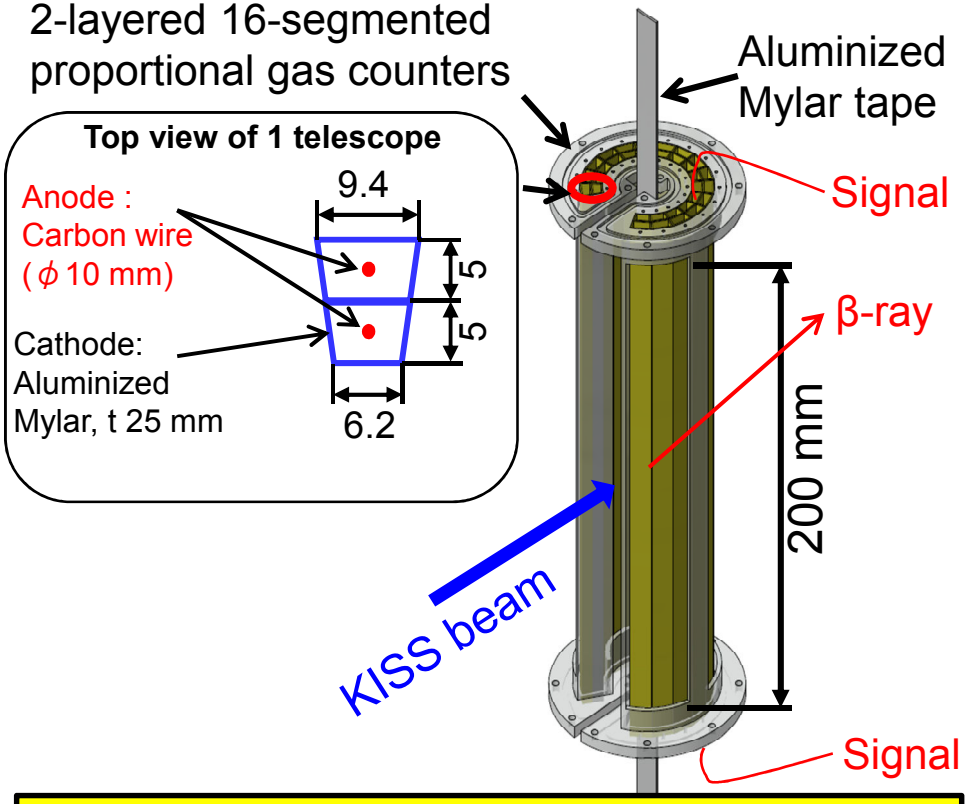
3D tracking gas counter for low-background rate of 0.01 cps

To go further to lifetime measurements of more neutron-rich nuclei, lower background rate of the gas counter is necessary (~0.01 cps)

Proportional gas counter: Ar + CH_4(10%), 0.1 MPa

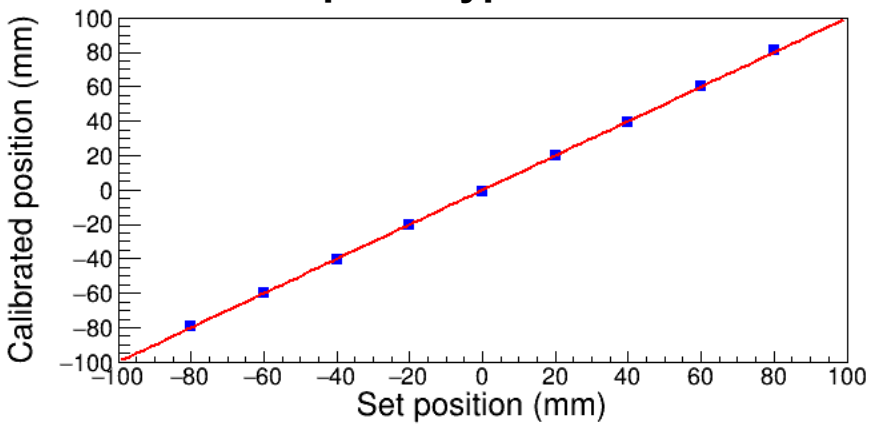
2D tracking : $\Delta\Omega$ = 80%, background rate 0.1 cps

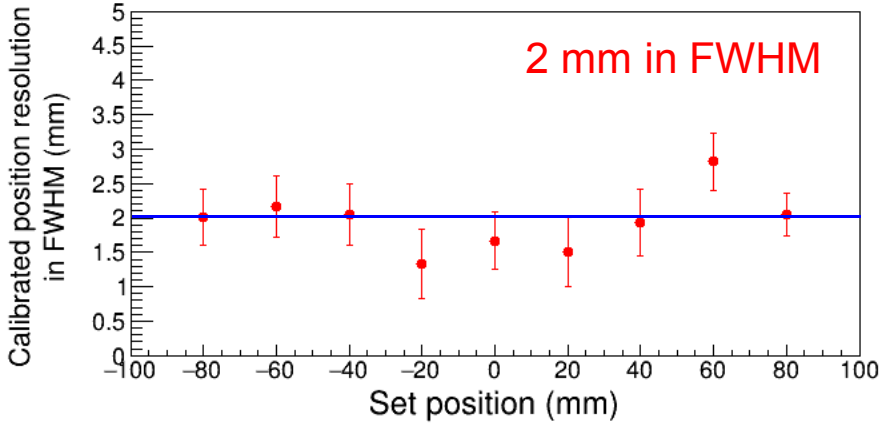
2-layered 16-segmented proportional gas counters



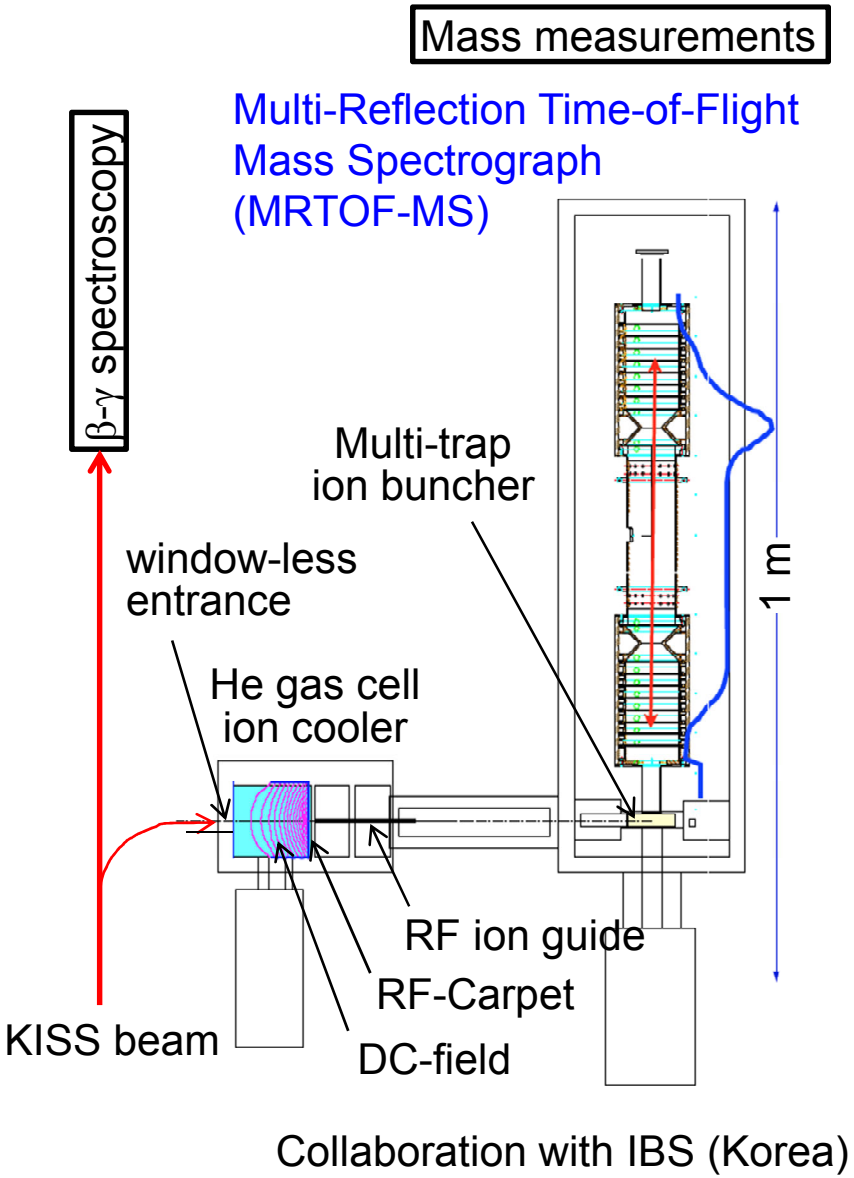
Anode wire: Carbon wire (φ 10 mm, 3 kΩ/cm)
→ Longitudinal hit-positions of β-rays can be identified.
→ Better separation from the B.G.

One proto-type counter

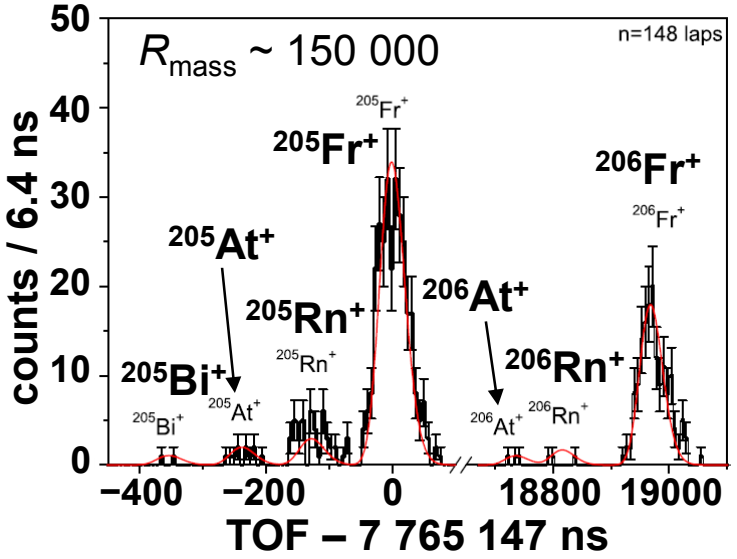




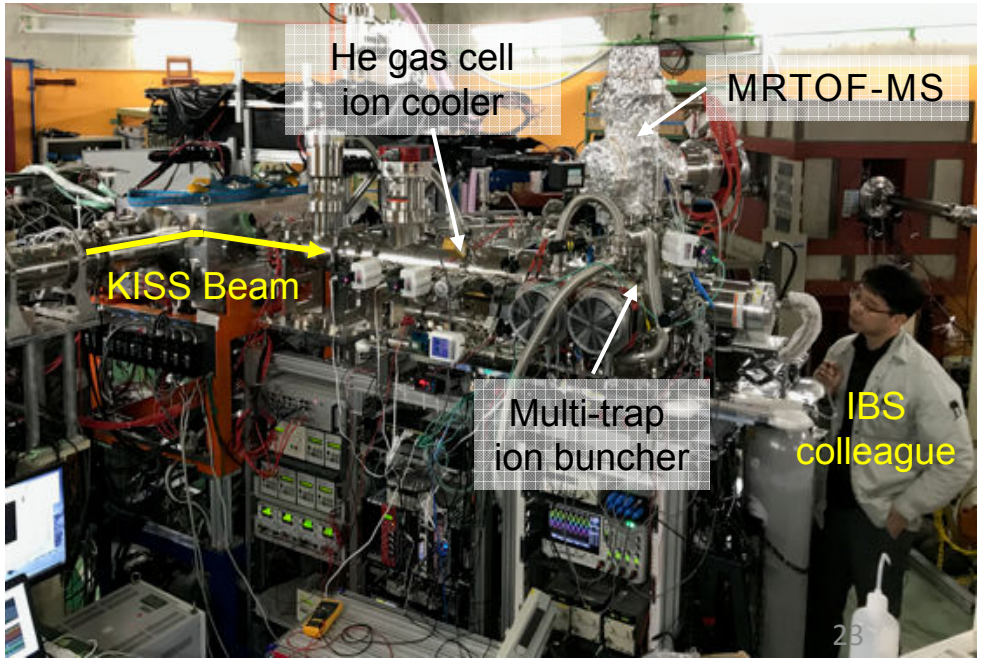
Mass measurements at KISS



Collaboration with IBS (Korea)



P. Schury et al., Phys. Rev. C 95, 011305(R) (2017).



Collaboration

KISS project

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MNT measurements at GANIL

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Summary

- Systematic nuclear spectroscopy (lifetime, mass, β-γ spectroscopy, laser spectroscopy) around neutron magic number 126 are important for identification of astrophysical environments of r-process.

- MNT reactions are promising for production of neutron-rich nuclei around $N = 126$.

- KEK Isotope Separation System (KISS)
  - MNT reactions of ^{136}Xe + ^{198}Pt
  - Gas cell + Laser resonance ionization + ISOL
    Efficient collection and separation of MNT reaction products
  - Lifetime measurements & β-γ spectroscopy
    $^{199\text{-}201}$Pt, $^{196\text{-}200}$Ir, $^{195\text{-}198}$Os (^{136}Xe + ^{198}Pt), $^{185\text{-}187}$Ta (^{136}Xe + $^{nat.}$W)
  - Laser spectroscopy
    ^{199}Pt, $^{196\text{-}198}$Ir
  - High-precision in-gas-jet laser spectroscopy was prepared
  - 3D tracking gas counter is under development
  - Mass measurements with MRTOF-MS is planned

KISS is open for external user programs

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THANK YOU FOR YOUR ATTENTION