

Nuclear Spectroscopy at KISS/KISS-1.5

KEK Isotope Separation System (KISS)

to study nuclear properties from astrophysical interest

- Multi-nucleon transfer reactions to produce neutron-rich nuclei
- Ar gas-cell combined with laser ionization
- Mass separator (ISOL)

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Ph.D. exp. at ISAC, 2002

Nuclear structure of ^{11}Be

from beta-decay spectroscopy with polarized ^{11}Li



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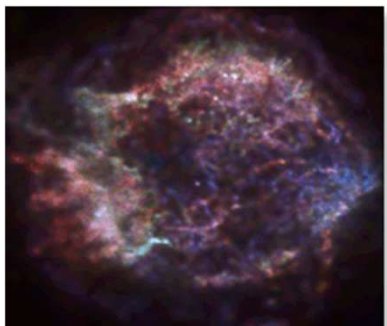
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2026 TRIUMF-KEK Symposium
28-29th September 2026, Vancouver, Canada

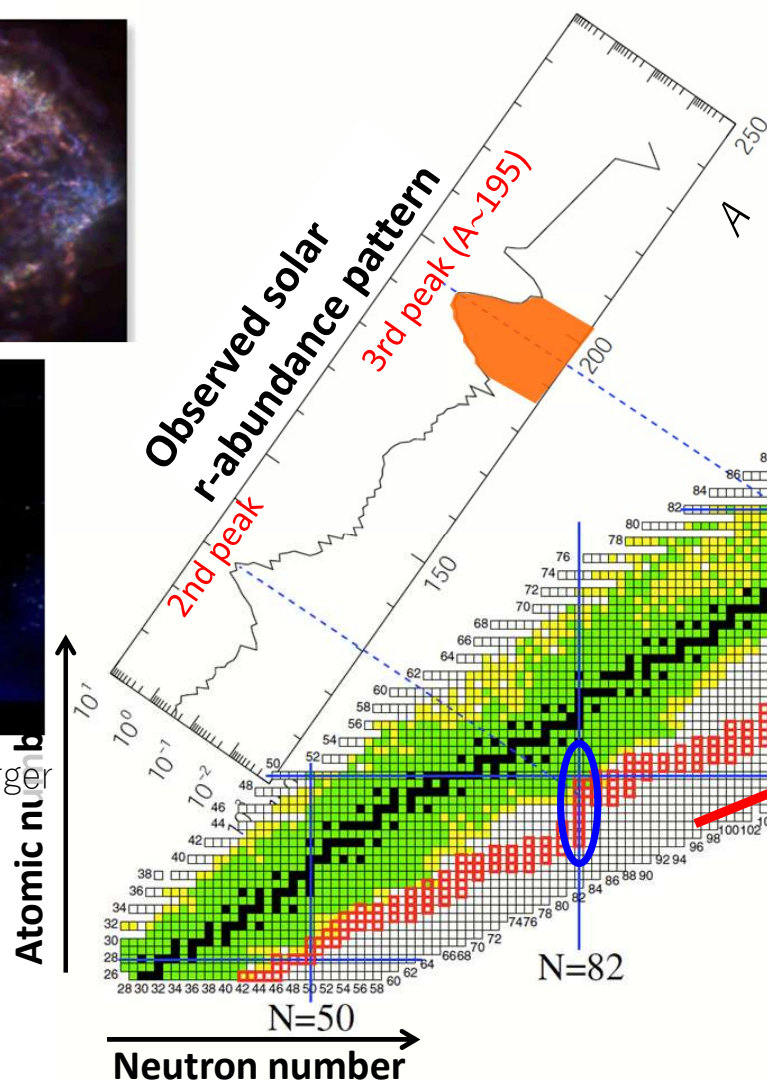
Physics motivation and KISS/KISS-1.5

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

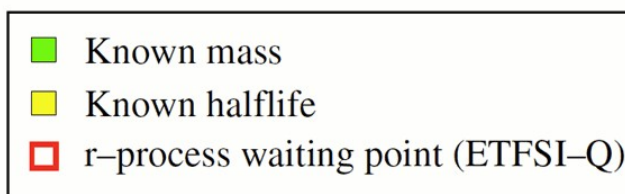
Type II Supernova



Neutron star merger



H. Grawe et al., Rep. Prog. Phys. 70 (2007), 1525-1582.



KISS/KISS-1.5
MNT combined with
gas cell system

Waiting point for
the 3rd peak

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

Collinear LAser Resonance Ionization Spectroscopy (CLARIS) project at KISS for the accurate and precise predictions of nuclear data

- To understand the astrophysical environment of the r-process → nuclear data of very neutron-rich nuclei
- **Density functional theory (DFT)**

$$E_{\text{Sky}} = \int dr \sum_{t=0,1} [\overset{\text{Time-even}}{\mathcal{H}_t^{\text{even}}(\mathbf{r})} + \overset{\text{Time-odd}}{\mathcal{H}_t^{\text{odd}}(\mathbf{r})}]$$

Well evaluated from
mass and radius of even-even nuclei

- **Strong dependence on spin s_t**
- **Essential for the understanding of wave-fuction and prediction of odd-odd nuclei and odd-A nuclei**
→ **Not evaluated**
→ **Large uncertainty for C_t^i**

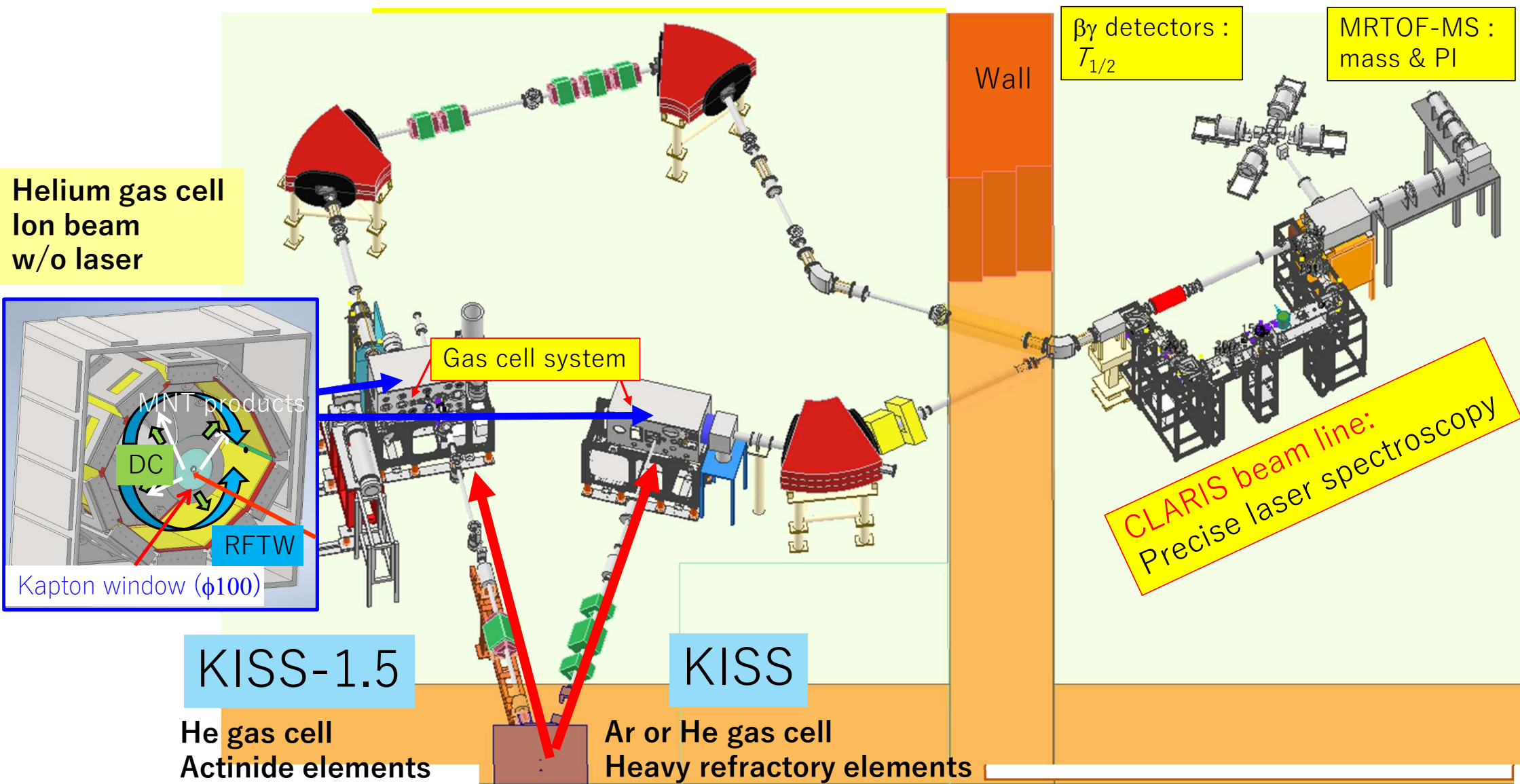
$$\mathcal{H}_t^{\text{odd}} = C_t^s[\rho_0]s_t^2 + C_t^{\Delta s}s_t \cdot \Delta s_t + C_t^T s_t \cdot T_t + C_t^j j_t^2 + C_t^{\nabla j} s_t \cdot (\nabla \times j_t)$$

Magnetic dipole moment : Sensitive to time-odd term (Only C_t^s verified so far)

A.R. Vernon et al., Nature 607 (2022) 260. J. Bonnard et al., Phys. Lett. B843(2023)138014. R.P. de Groote et al., Phys. Lett. B 848 (2024) 138352.

- **Precise laser ionization spectroscopy of the nuclei in the vicinity of $N = 126$**
magnetic moments, electric-quadrupole moments (deformation), $T_{1/2}$, and mass
- Determine $\mathcal{H}_t^{\text{odd}}$ term and evaluate EDF(E_{Sky}) → **Wave-function**
- Precise prediction of nuclear data on the r-process
→ **input**
- Study r-process through astrophysical network calculations

KISS/KISS-1.5



Laser Spectroscopy at KISS

- Neutron-rich Re isotopes
- Neutron-deficient Ir isotopes
- CLARIS

Laser spectroscopy of unstable nuclei

Hyperfine splitting (HFS) measurements

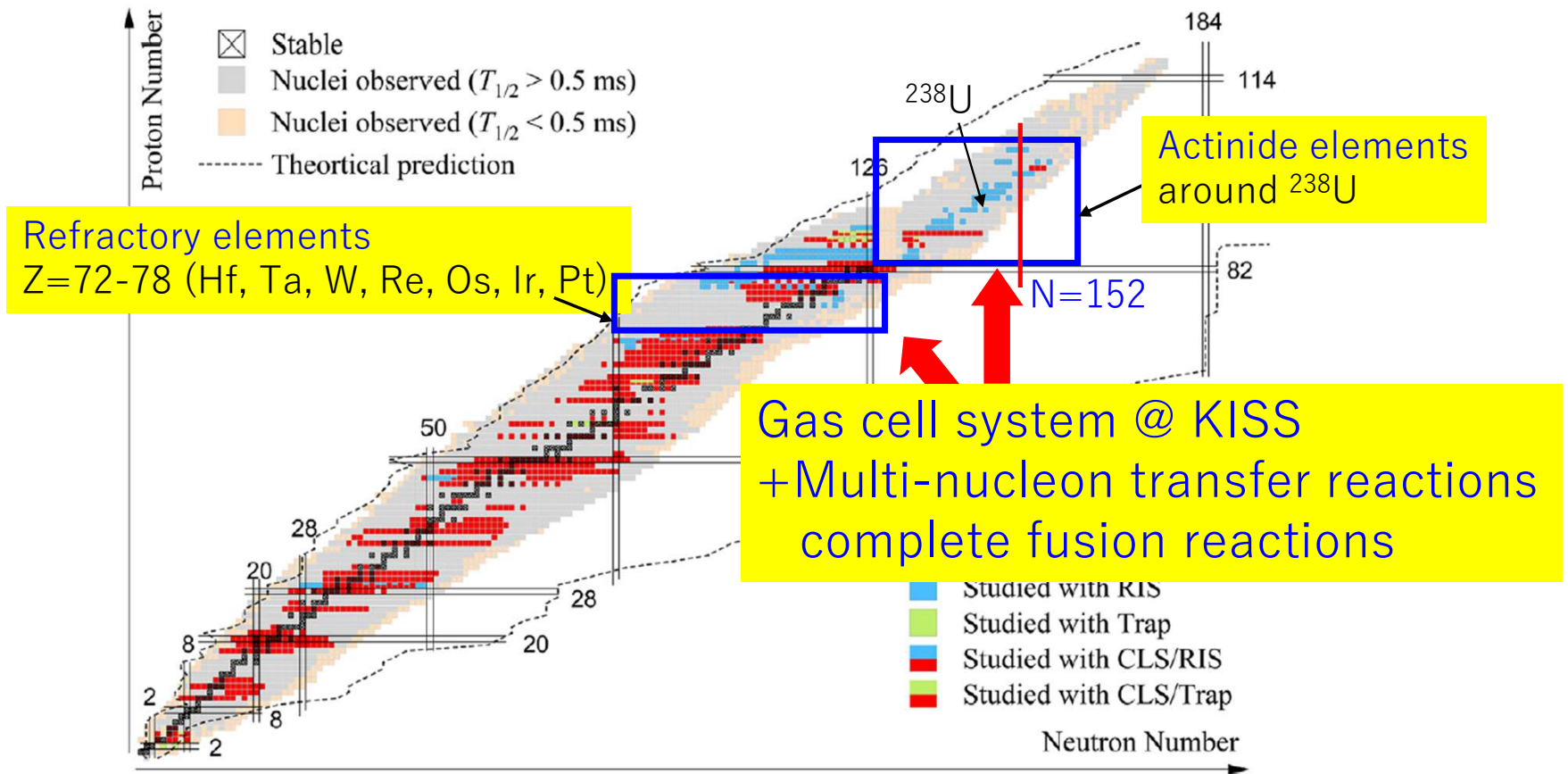
Nuclear electro-magnetic moments : μ_I, Q

→ Nuclear structure (wave function, deformation)

Isotope shift : $\delta\nu$

→ $\delta\langle r^2 \rangle$

→ nuclear deformation parameter $|\beta_2^2|^{1/2}$
for the nuclei with $I = 0, 1/2$

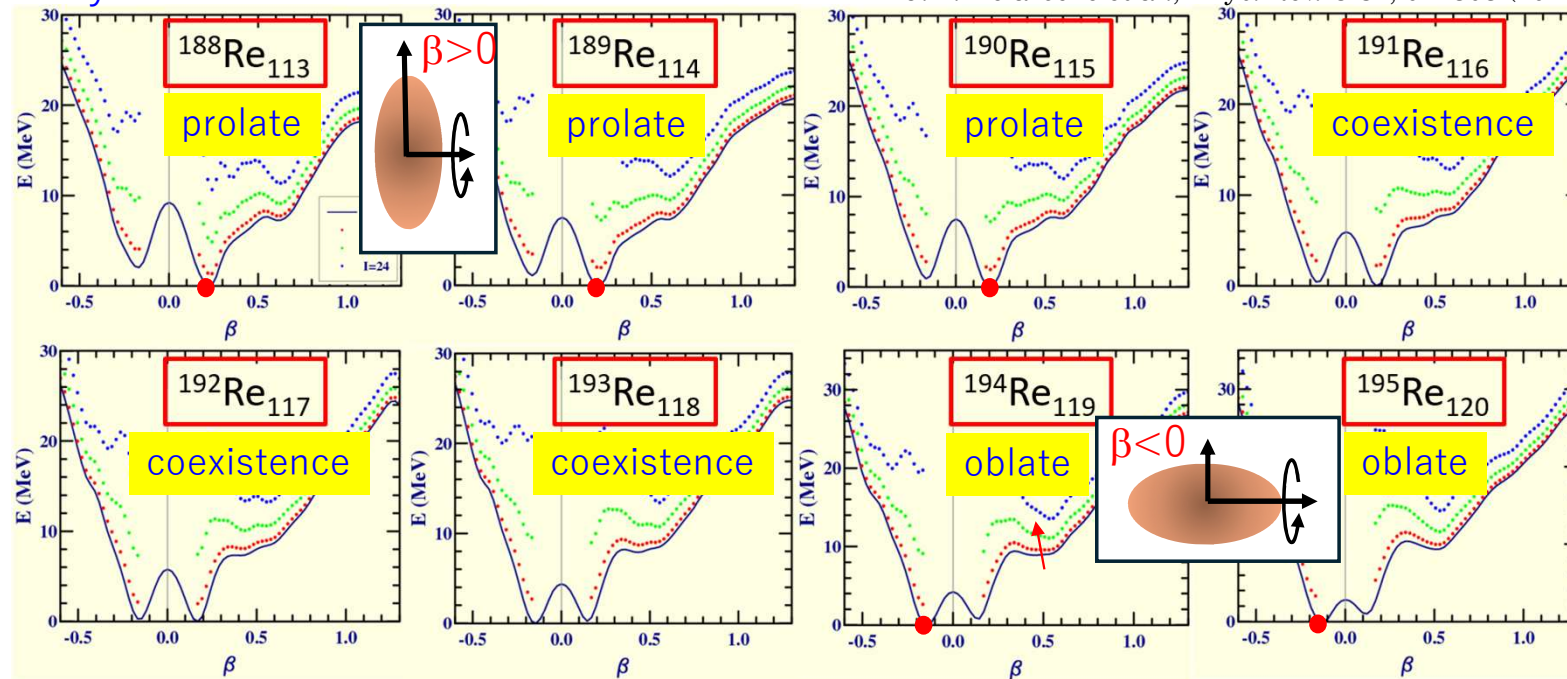


In-gas-cell laser spectroscopy of $^{188-193}\text{Re}$

Shape transition at $N = 116 - 118$, $Z = 72 \sim 76$

- PES calculated by CHFB+5DCH

J.-P. Delaroche et al., Phys. Rev. C 81, 014303 (2010).

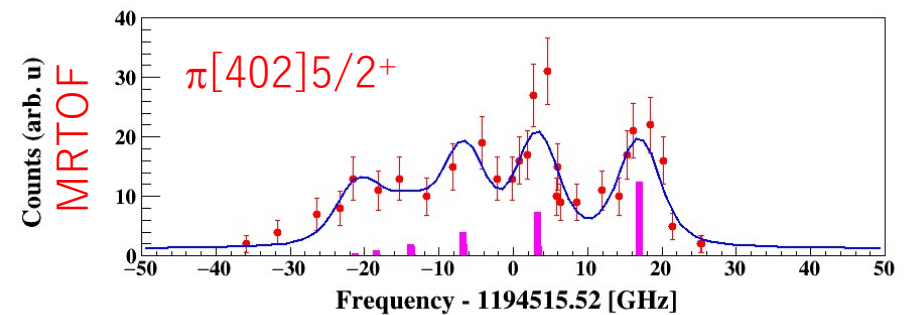
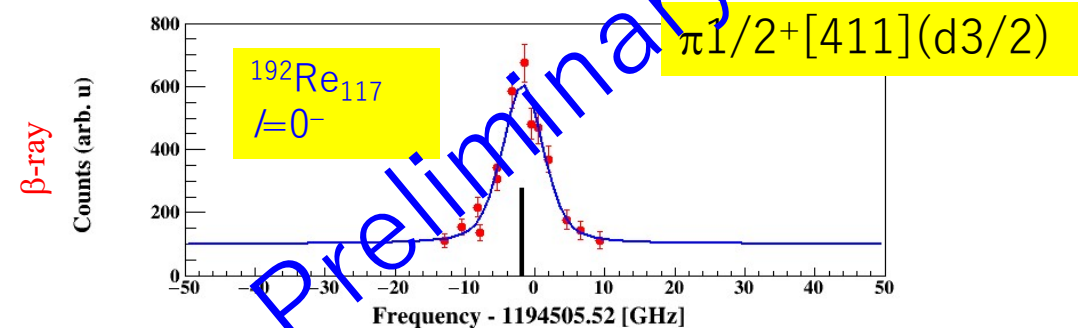
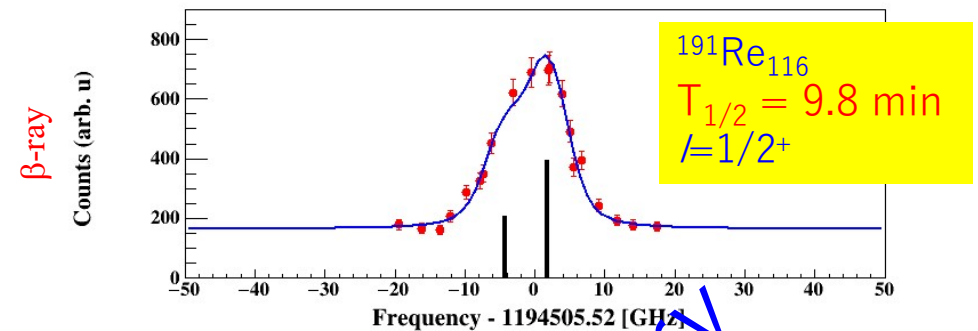
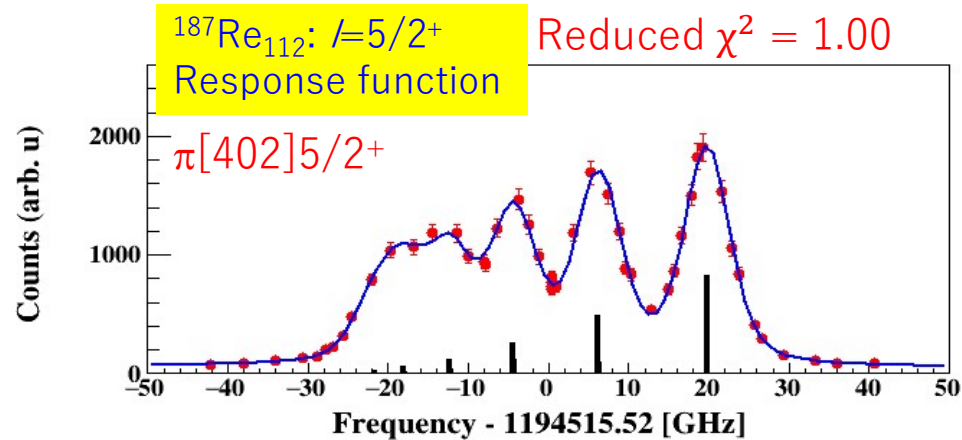


- Change of the proton orbit from $[402]5/2^+$ to $[411]1/2^+$ at $N = 116$ from the β -decay study of ^{192}Re at KISS H. Watanabe et al., Phys. Lett. B 814, 136088 (2021).

➡ Suggested $\pi = 1/2^+$ for ^{191}Re , 0^- for ^{192}Re , and $1/2^+$ for ^{193}Re

in-gas-cell laser spectroscopy of $^{188-193}\text{Re}$ ➡ μ_I sensitive to π

HFS of Re isotopes



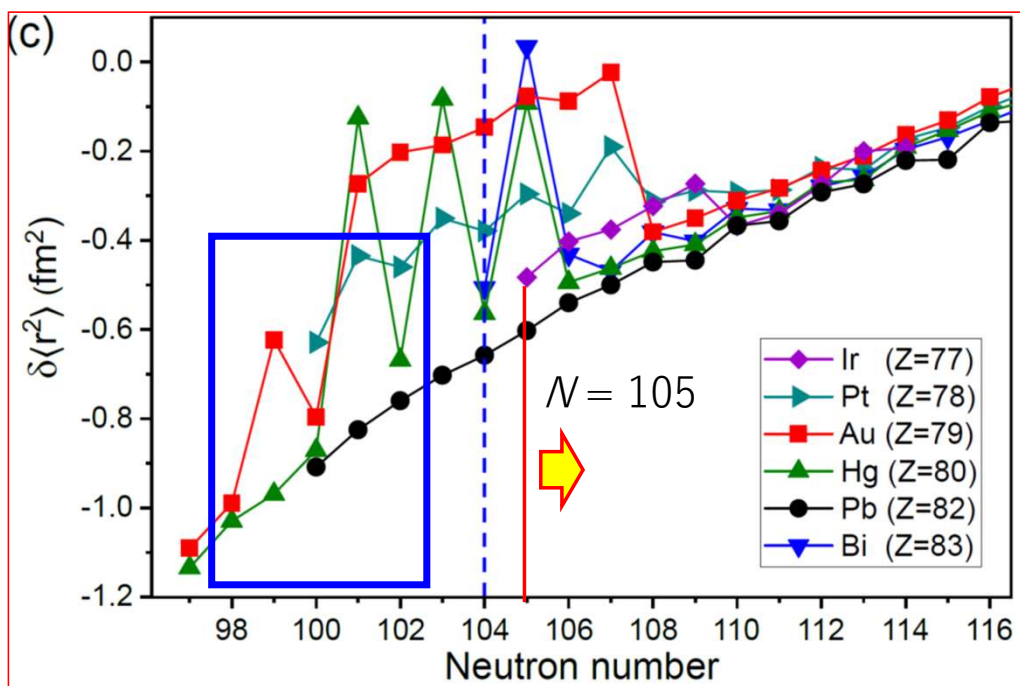
$^{193}\text{Re}_{118}$: I^π , $T_{1/2}$ =unknown

What drives the changes
in shape and proton orbit?

In-gas-cell laser ionization spectroscopy of neutron-deficient nuclei

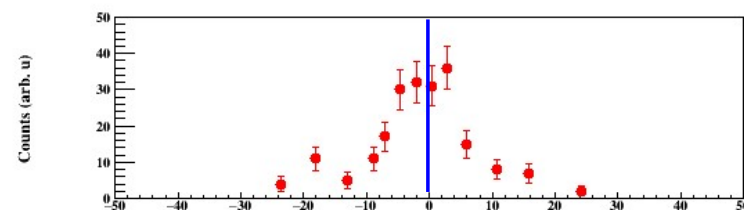
$^{175, 176, 177, 178, 179}\text{Ir}$ ($Z=77$, $N=98, 99, 100, 101, 102$)

Complete fusion reactions : $^{40}\text{Ar} + ^{141}\text{Pr} \rightarrow ^{181}\text{Ir}^*$

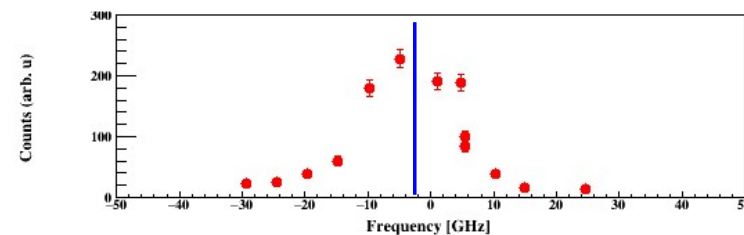


J. Cubiss, A. Andreyev et al., PRL131 (2023) 202501.

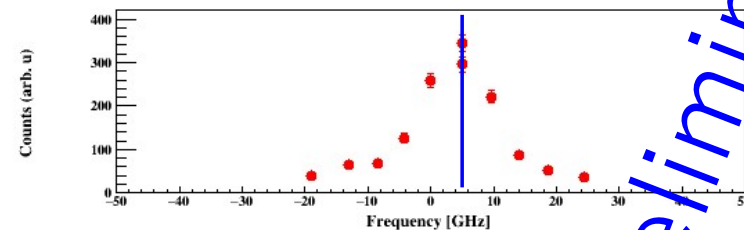
^{179}Ir
 $N = 102$



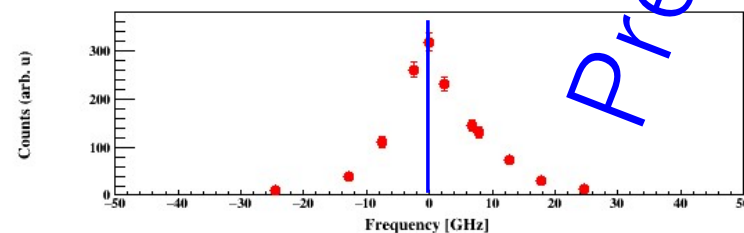
^{178}Ir
 $N = 101$



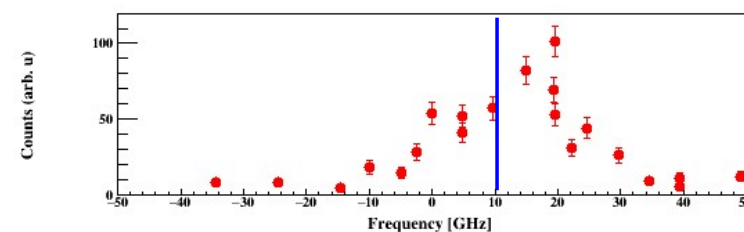
^{177}Ir
 $N = 100$



^{176}Ir
 $N = 99$



^{175}Ir
 $N = 98$



Preliminary

Collinear LAsER Resonance Ionization Spectroscopy (CLARIS) since 2025

Narrow-band pulsed UV laser :
Injection-locked TiSa

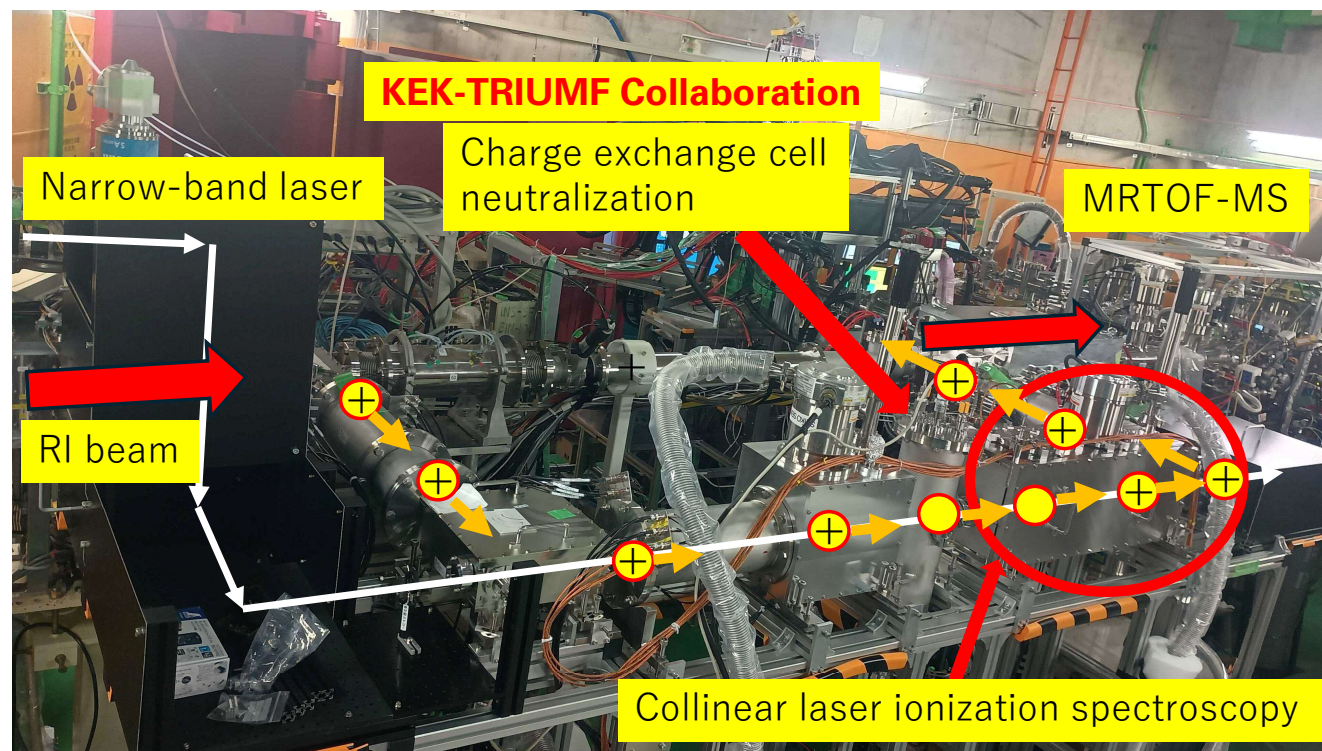
Narrow-band
CW seed laser
780 nm

Pulsed green laser
1kHz

Injection-locked
TiSa

THG out :
Pulsed 260 nm

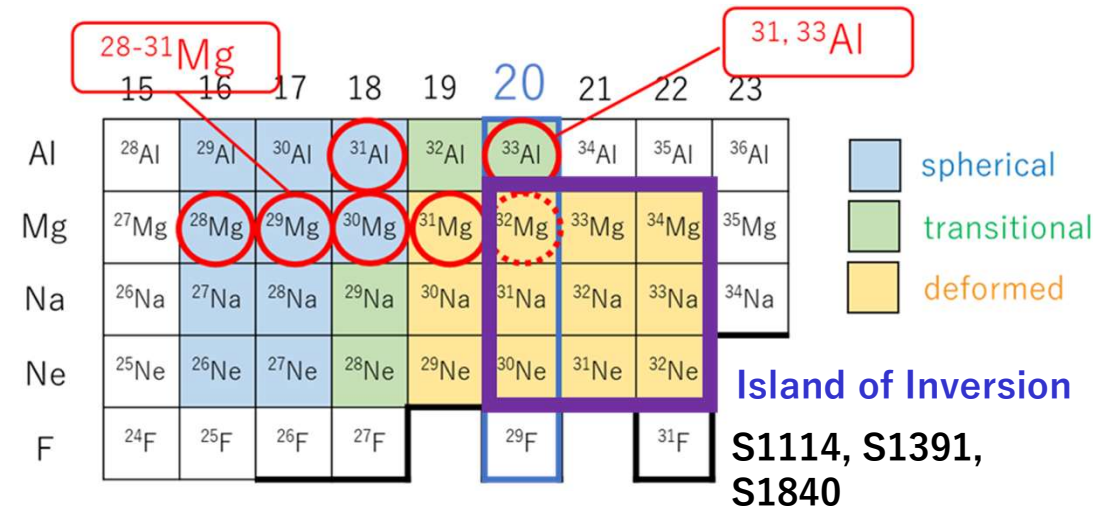
CLARIS beamline
ion and laser transports were done.



Societal applications by using laser spectroscopy and MRTOF-MS

- Purification of medical RI
- Ultra-Trace Analysis of Actinide Isotopes for Fukushima Daiichi Decommissioning

Studies of nuclear structure of neutron-rich Mg isotopes by using spin-polarized Na isotopes (Odahara@Osaka Univ.) @TRIUMF-ISAC



- Systematic studies have been performed for neutron-rich nuclei near and inside the $N = 20$ island of inversion. ($N=20$ magic number disappears.)
- By using spin-polarized nuclei, we can determine the nuclear-spin values of excited states of daughter nuclei

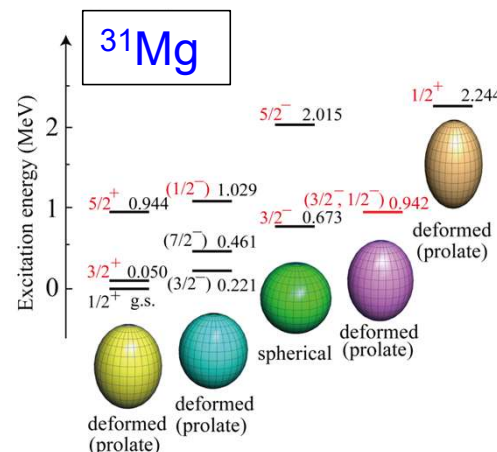
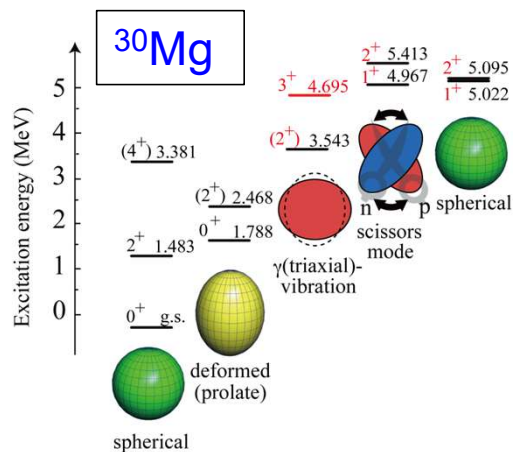


Next step : $^{32}\text{Na} \rightarrow ^{32}\text{Mg}$

To produce spin-polarized ^{32}Na , we need to determine nuclear spin of ^{32}Na at first.

➔ **HFS measurement**
by laser ionization spectroscopy
in the collaboration with Jens and Ruohong.

New collaboration with TITAN Gr.
for bunched RI beam to Polarizer.



H. Nishibata et al. Phys. Lett. B 767, 81 (2017).
H. Nishibata et al. Phys. Rev. C 99, 024322 (2019).

H. Nishibata et al. Phys. Rev. C 102, 054327 (2020).

Summary

KISS/KISS-1.5 : MNT reactions + Gas cell system

⇒ Access blank spots on the nuclear chart and
Perform laser ionization spectroscopy
for the studies of nuclear structure

- In-gas-cell laser ionization spectroscopy of heavy refractory nuclei
 - ➡ Systematic studies of Pt, Ir, Os, Re, W, Ta, and Hf isotopes
- Precise laser ionization spectroscopy for actinide nuclei
 - ➡ Collinear resonant ionization spectroscopy beam line at KISS
Offline studies will start soon.

TRIUMF-KEK Collaboration

for complementary laser spectroscopy and mass measurements across the nuclear chart