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)

Yoshikazu HIRAYAMA (Wako Nuclear Science Center, IPNS, KEK)

Ph.D. exp. at ISAC, 2002
Nuclear structure of ^{11}Be
from beta-decay spectroscopy with polarized ^{11}Li

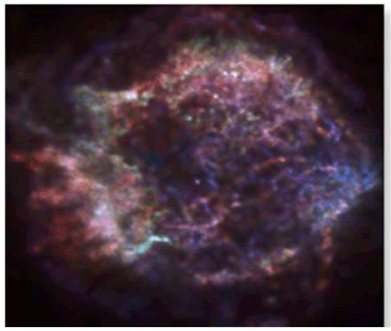
Contents :

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

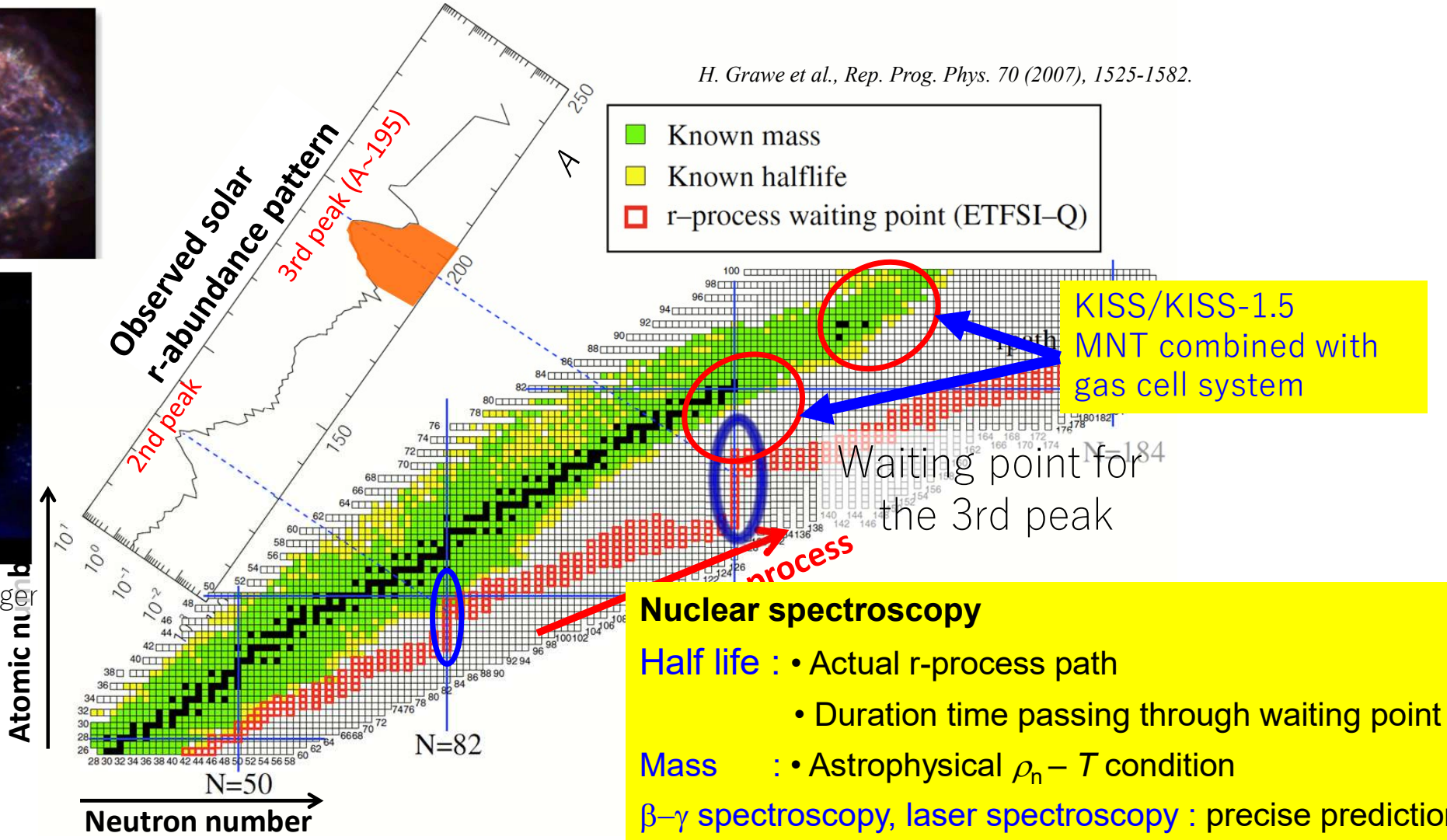
Physics motivation and KISS/KISS-1.5

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.

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 Resonant 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)**

Time-even Time-odd

$$E_{\mathrm{Sky}} = \int dr \sum_{t=0,1} \left[\mathcal{H}_t^{\mathrm{even}}(\boldsymbol{r}) + \mathcal{H}_t^{\mathrm{odd}}(\boldsymbol{r}) \right]$$

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

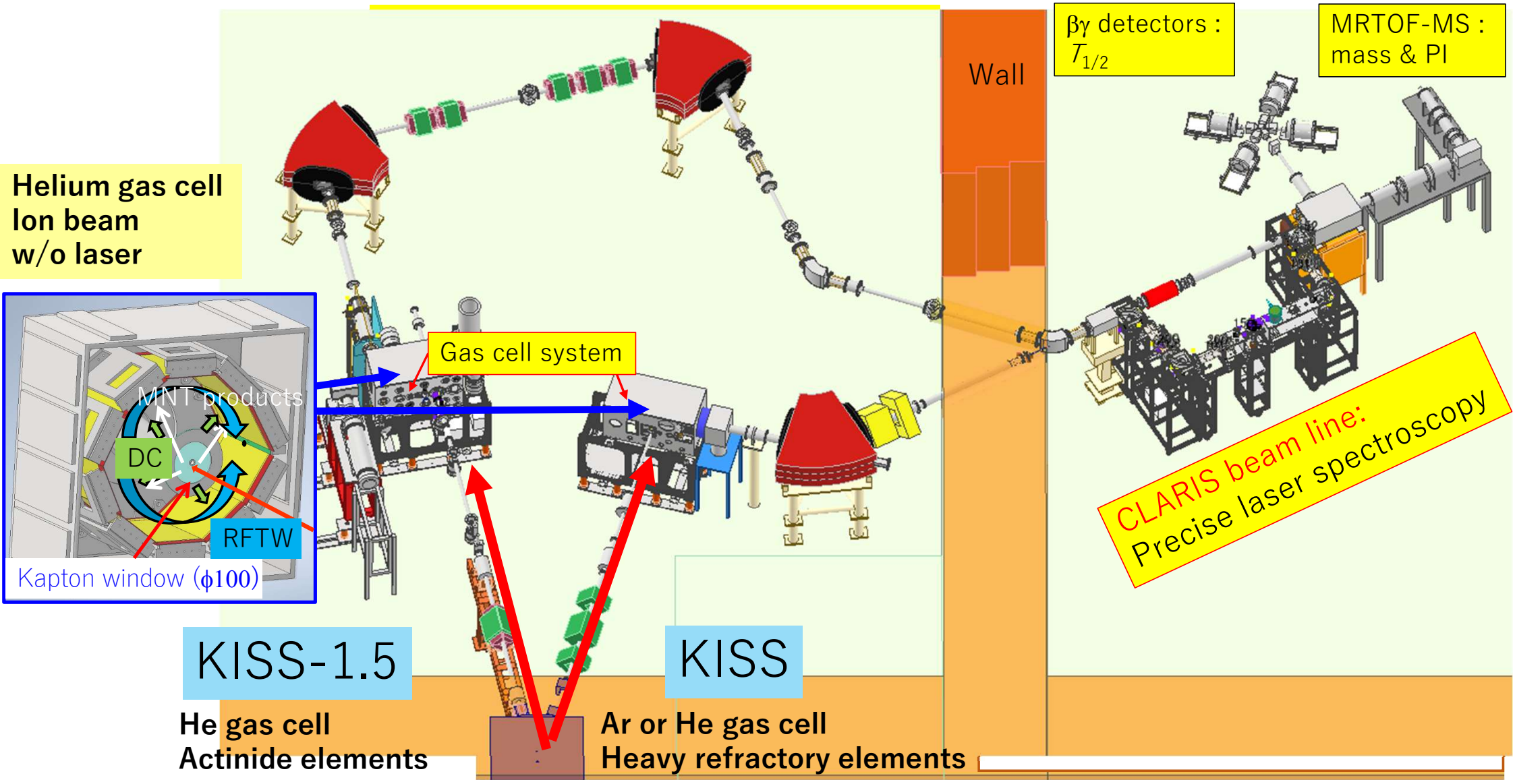
$$\mathcal{H}_t^{\mathrm{odd}} = C_t^s[\rho_0]\boldsymbol{s}_t^2 + C_t^{\Delta s}\boldsymbol{s}_t \cdot \boldsymbol{\Delta s}_t + C_t^T \boldsymbol{s}_t \cdot \boldsymbol{T}_t + C_t^j \boldsymbol{j}_t^2 + C_t^{\nabla j}\boldsymbol{s}_t \cdot (\boldsymbol{\nabla} \times \boldsymbol{j}_t)$$

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 $\mathcal{H}_t^{\mathrm{odd}}$ 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


Helium gas cell
Ion beam
w/o laser
MNT products
DC
RFTW
Kapton window (ϕ100)
Gas cell system
Wall
βγ detectors :
$T_{1/2}$
MRTOF-MS :
mass & PI
CLARIS beam line:
Precise laser spectroscopy
KISS-1.5
He gas cell
Actinide elements
KISS
Ar or He gas cell
Heavy refractory elements

Laser Spectroscopy at KISS

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

Laser spectroscopy of unstable nuclei

Hyperfine splitting (HFS) measurements

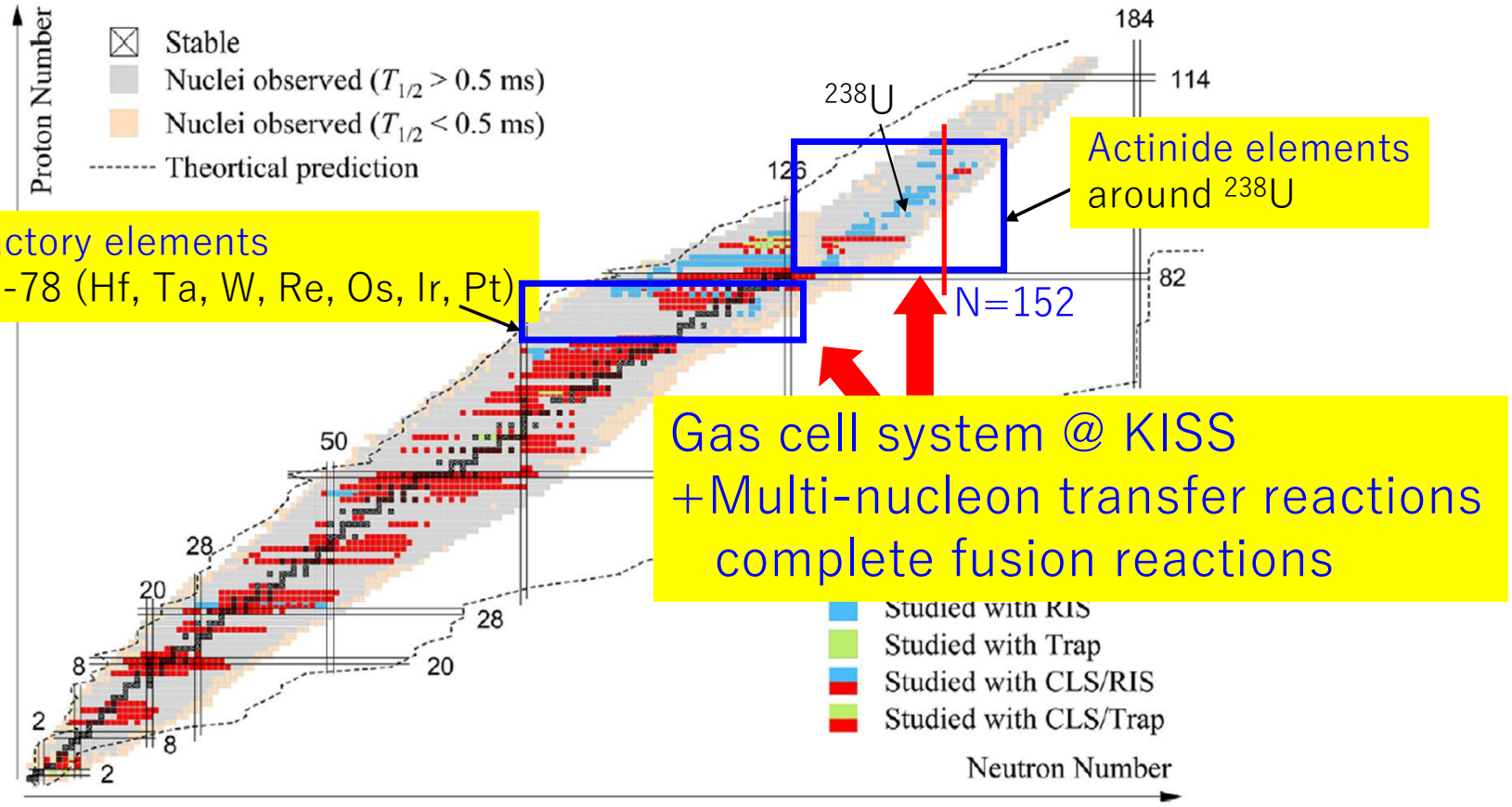
Nuclear electro-magnetic moments : μ_I, Q

→ 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 $I = 0, 1/2$



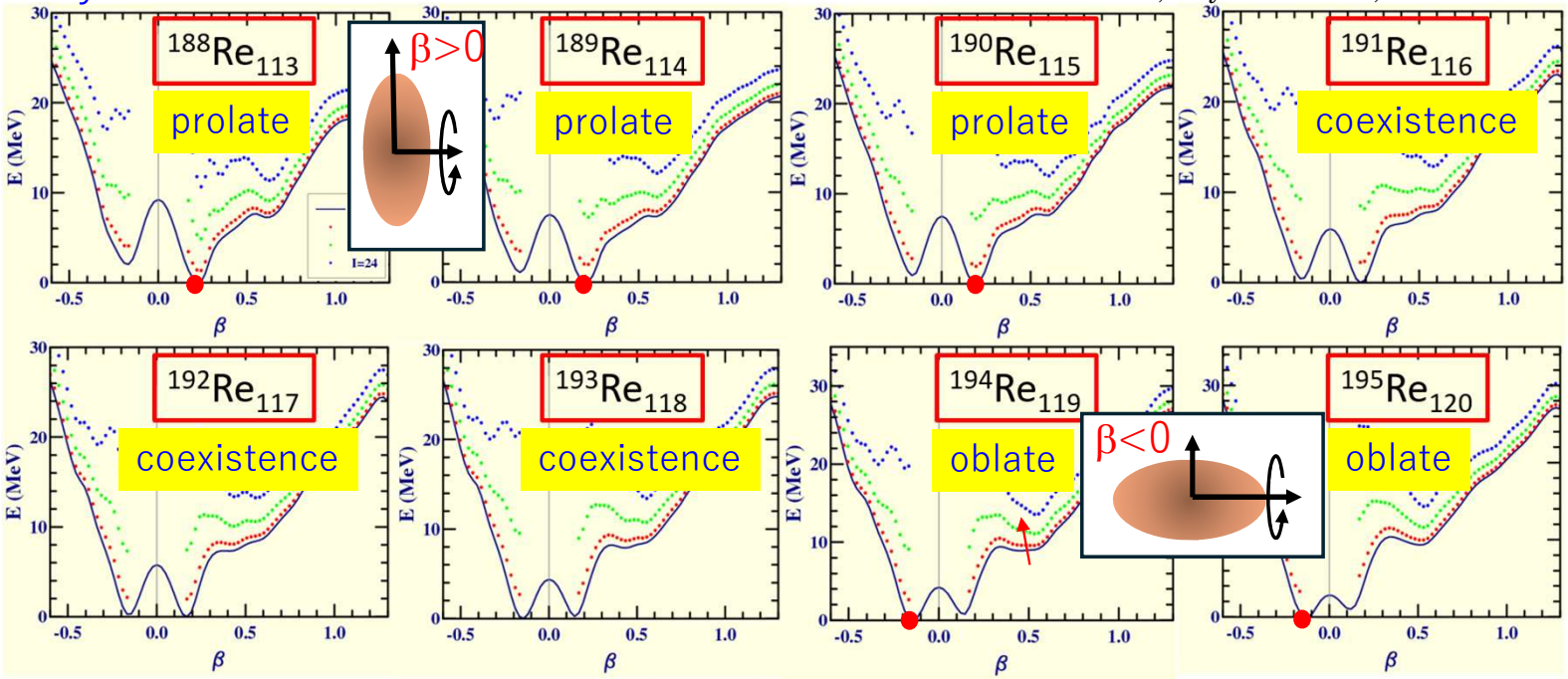
X.F. Yang et al., Prog. Part. Nucl.Phys. 129 (2023) 104005.

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

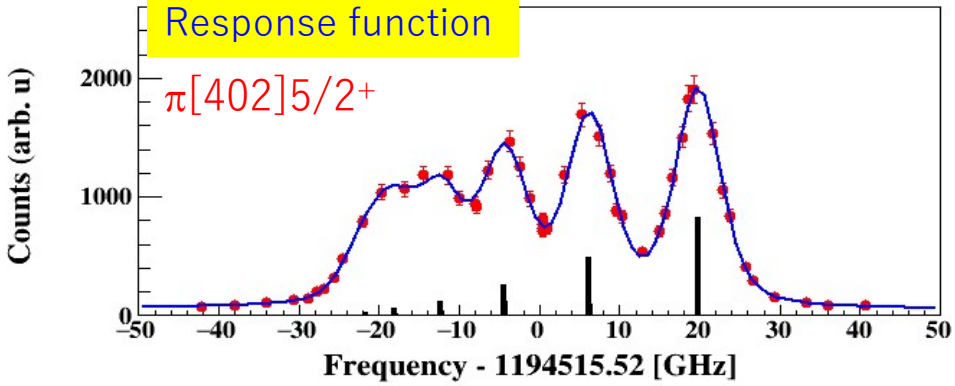
➡ Suggested $I^\pi = 1/2^+$ for ^{191}Re, 0^- for ^{192}Re, and $1/2^+$ for ^{193}Re

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

HFS of Re isotopes

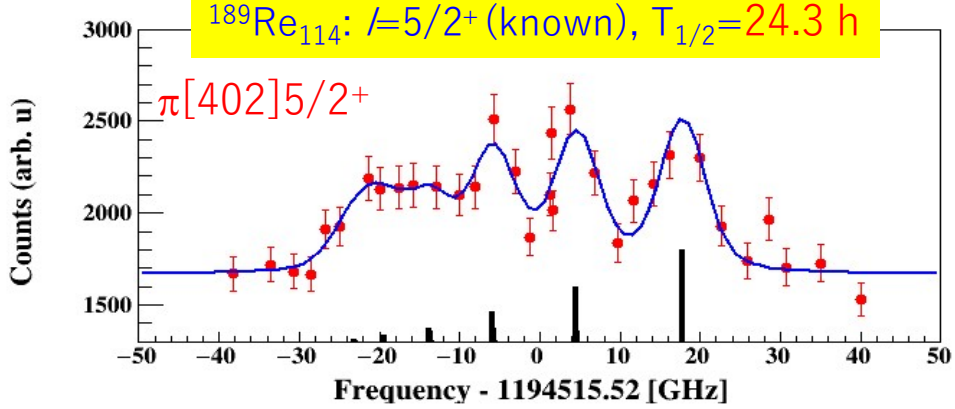
$^{187}Re_{112}$: I=5/2$^+$
Response function

Reduced χ^2 = 1.00



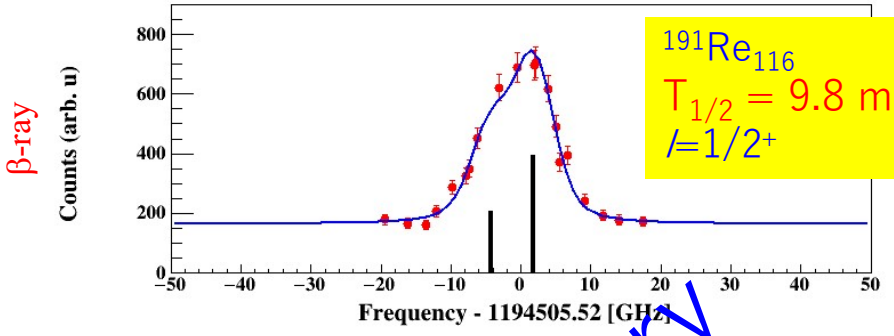
$^{189}Re_{114}$: I=5/2$^+$ (known), $T_{1/2}$=24.3 h

MRTOF



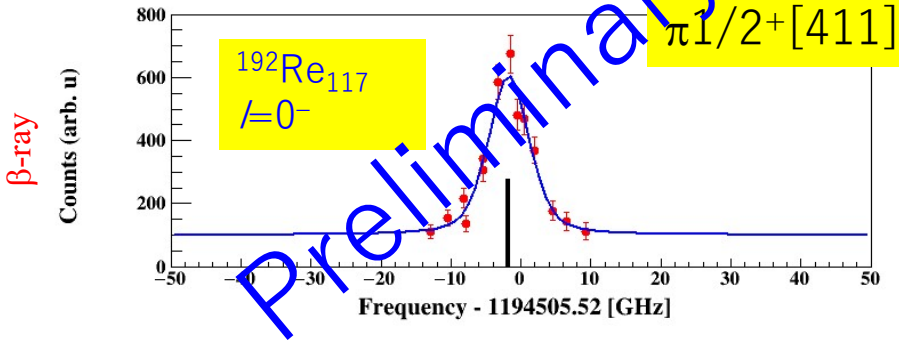
What drives the changes
in shape and proton orbit?

β-ray



$^{191}Re_{116}$
$T_{1/2}$ = 9.8 min
I=1/2$^+$

β-ray

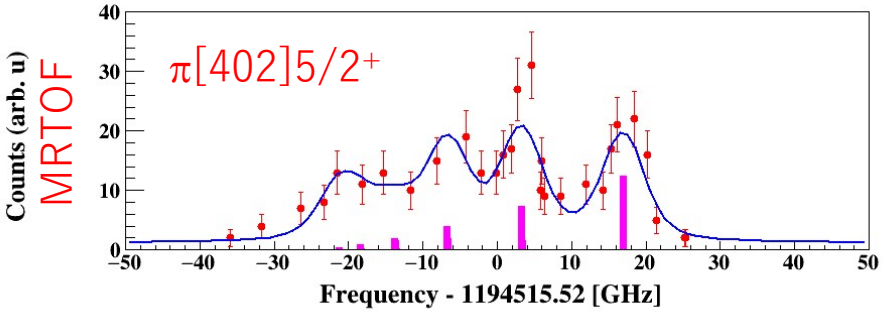


$^{192}Re_{117}$
I=0$^-$

π1/2$^+$[411](d3/2)

Preliminary

MRTOF

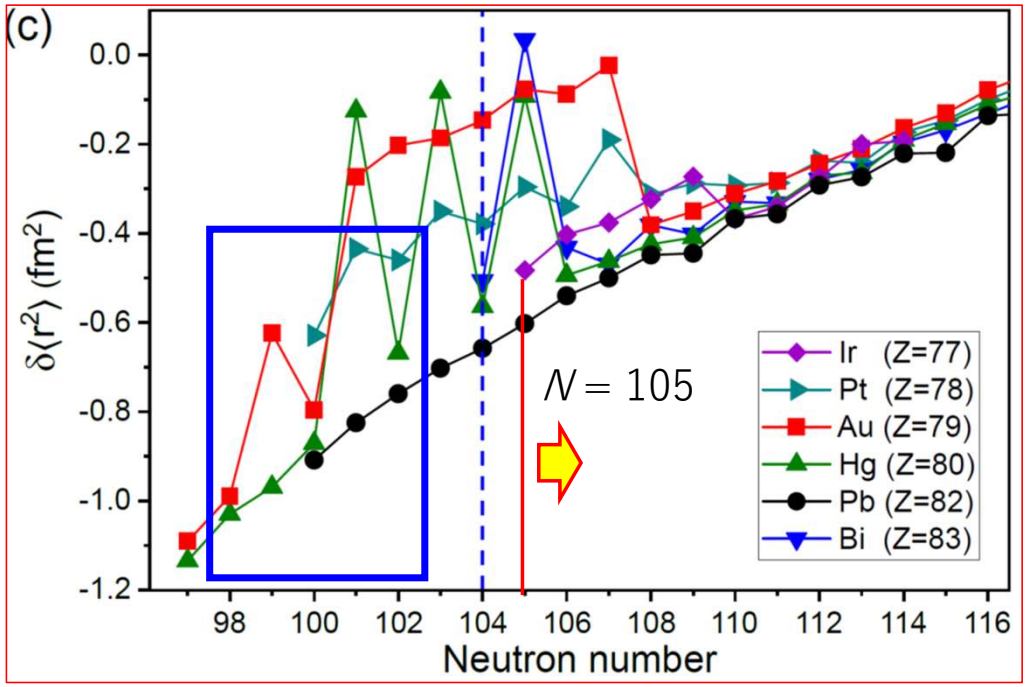


$^{193}Re_{118}$: I, $T_{1/2}$=unknown

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

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

Complete fusion reactions : ^{40}Ar+^{141}Pr ➔ ^{181}Ir*



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

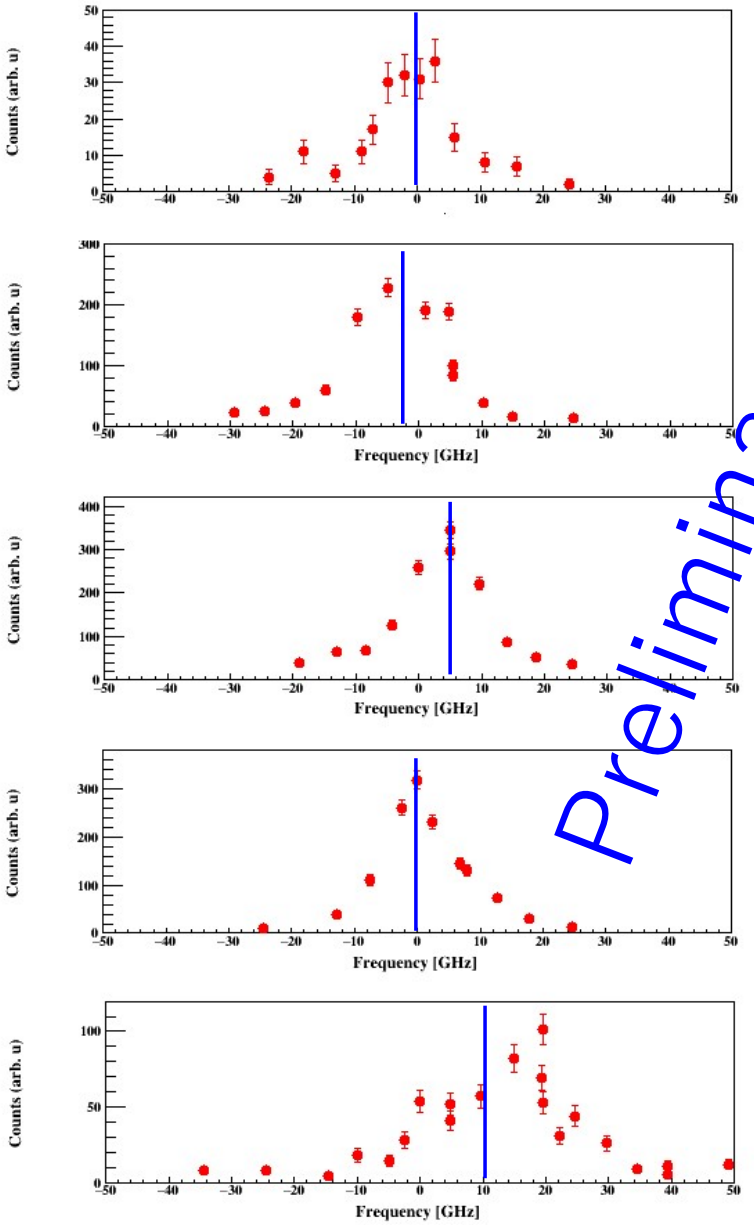
^{179}Ir
N = 102

^{178}Ir
N = 101

^{177}Ir
N = 100

^{176}Ir
N = 99

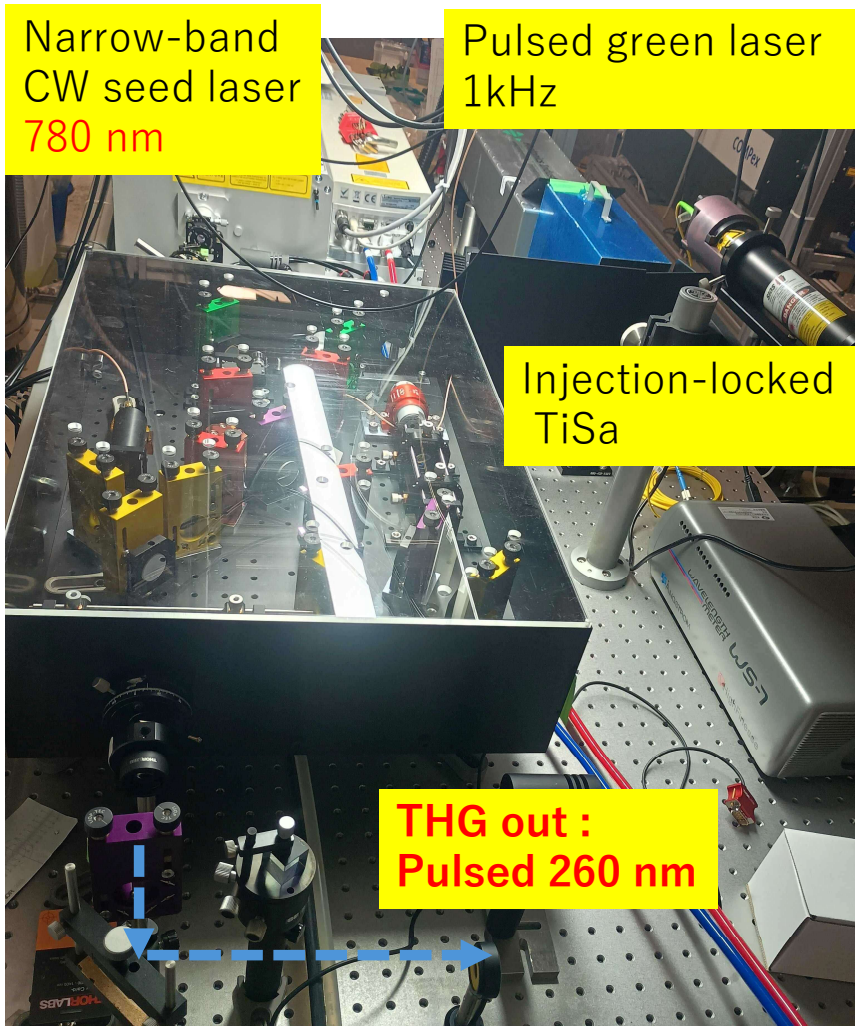
^{175}Ir
N = 98



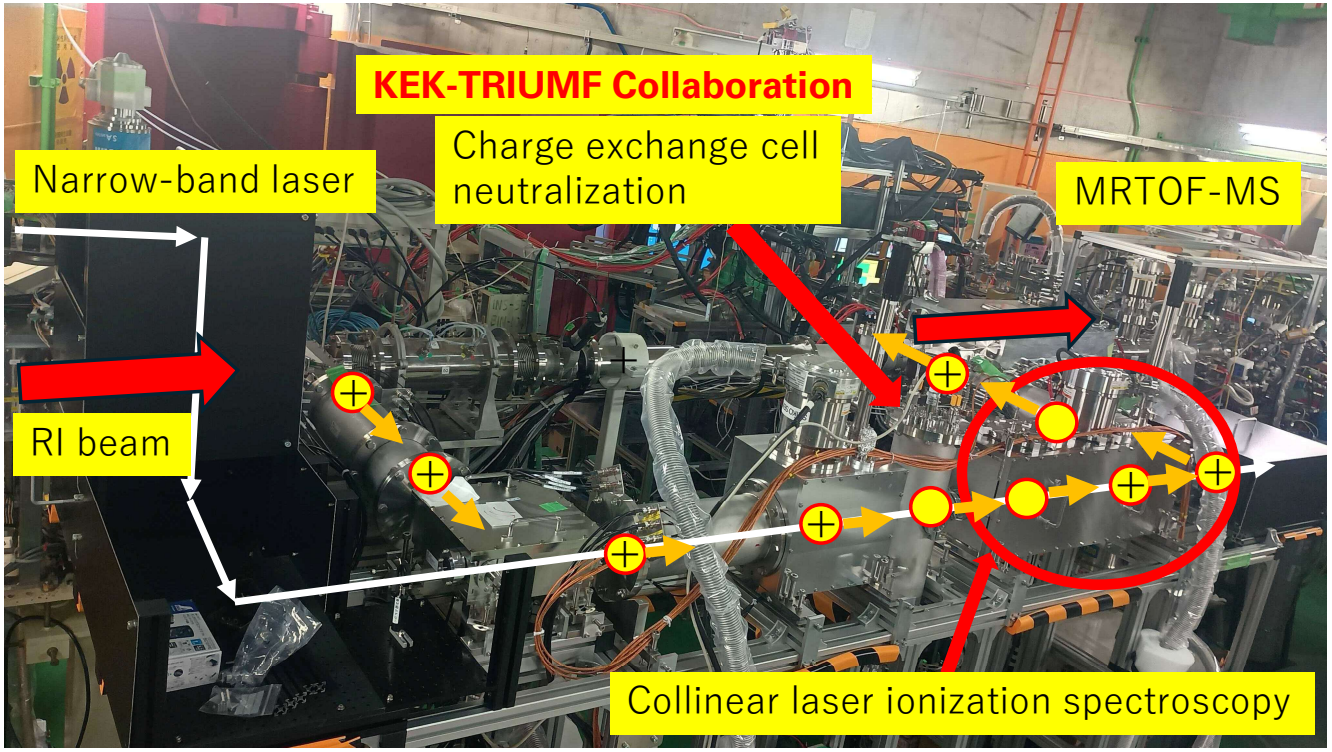
Preliminary

Collinear LAser Resonance Ionization Spectroscopy (CLARIS)

Narrow-band pulsed UV laser : Injection-locked TiSa



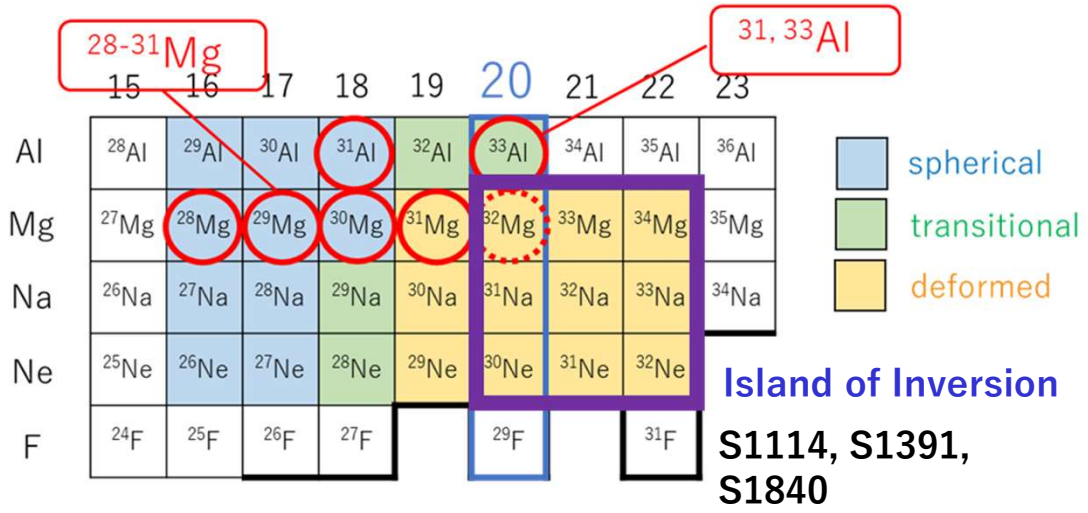
CLARIS beamline ion and laser transports were done.

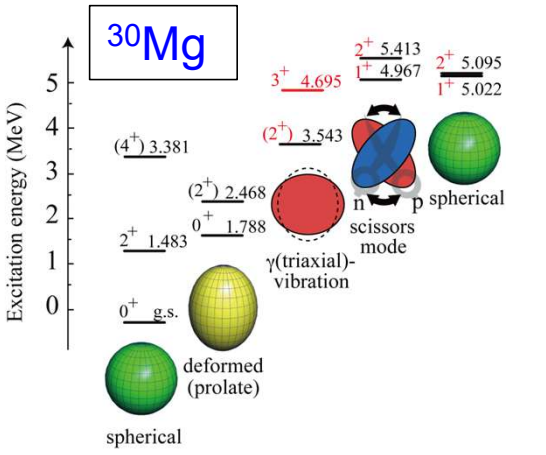


Societal applications by using laser spectroscopy and MRTOF-MS

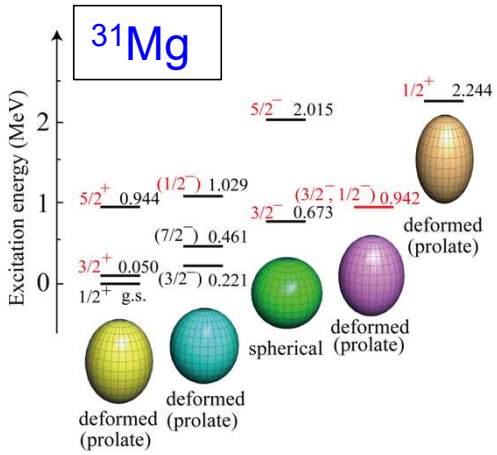
- Purification of medical RI
- Ultra-Trace Analysis of Actinide Isotopes for Fukushima Daiichi Decommissioning

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





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).

- 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}Na → ^{32}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.

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 Across the Nuclear Chart