Experimental studies of neutron-rich nuclei around $N = 126$ at KEK isotope separation system

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

Nuclear properties of neutron closed shell $N = 126$ nuclei
→ r-process in astrophysical nucleosynthesis

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 nucleosynthesis.

Half-lives of $N = 126$ isotones

Isotopic abundance pattern variance from uncertain $\beta$-decay half-lives $(0.1 \sim 10 \times T_{1/2})$

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Systematic nuclear spectroscopy (lifetime, mass, $\beta$-$\gamma$ spectroscopy, laser spectroscopy) around $N = 126$ → Astrophysical environments of r-process

Nuclear production around $N = 126$ by MNT reaction

**Macroscopic approach**
(Langevin-type dynamical equation of motion)

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

Cross section [mb]

![Graph showing cross section vs. neutron and proton numbers for $^{136}\text{Xe} + ^{208}\text{Pb}$ reaction.]

**Semi-classical approach**
(Single-particle transfer probability)

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

![Graph showing cross section vs. neutron and proton numbers for $^{136}\text{Xe} + ^{198}\text{Pt}$ reaction.]

**GRAZING calculation**


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.


Isotopic distributions of target-like fragments (TLFs)

- Measurements
- GRAZING calculations

Lighter distribution $N/Z$ equilibration & evaporation

$n$-pickup ($-xn$)

Larger cross section

$N \sim 126$

Modest enhancement of cross sections a factor of 2 ~ one order of magnitude
TKEL dependence of isotopic distribution

TKEL: Total Kinetic Energy Loss

- Total
- TKEL = -25 ~ 25 MeV
- TKEL = 25 ~ 75 MeV
- TKEL = 75 ~ 125 MeV
- TKEL = 125 ~ 175 MeV

**GRAZING calculations**

KEK Isotope Separation System (KISS)

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

Detection system
- Tape transport system
- β-ray detector
- Clover HpGe detectors for γ-rays

Doughnut-shaped Gas cell

Extraction chamber
- HV (~ 20 kV)

Gas cell system
- Target (enriched $^{198}$Pt, 92%)
- MNT reaction
- Gas cell (Ar gas, neutralization)
- Laser resonance ionization (Element selection)

KISS experimental setup

- Four HPGe (High-Purity Germanium) clover detectors
- Collaboration with IBS (Korea)
- KISS beam
- $\beta$ BG
- $\varepsilon_{\beta} = 40\%$ for $Q_{\beta} = 1$ MeV
- B.G. rate $= 0.1$ cps

MSPGC (Multi-Segmented Proportional Gas Counter)

- 2-layered 16-segmented proportional gas counter
- Beam $^{136}$Xe (10.75 MeV/nucleon)
- Beam $^{198}$Pt (12.5 mg/cm$^2$) Ti (3 μm × 3)


Collaboration with IBS (Korea)
Experimental results

- β-γ spectroscopy at KISS
- Laser spectroscopy at KISS

Element

- Au
- Pt
- Ir
- Os
- Re
- W
- Ta
- Hf
- Lu
- Yb

Charge radius known
Lifetime known

Stable
 Known

Neutron number

108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127
$\beta-\gamma$ spectroscopy of $^{198}\text{Os}$


$T_{1/2} = 125(28)$ s  New!

$^{198}\text{Os}$

$Q_\beta = 4.09$ MeV

$I_\beta \leq 20(5)\%$

$logf_t \geq 5.69(16)$

$^{198}\text{Ir}$

$t_{1/2} = 8(1)$ s

$Q_\beta = 1.98$ MeV

$I_\beta = 9(3)\%$

$logf_t = 5.88(15)$

$^{198}\text{Pt}$  stable

New! $230.6$ keV

Count / 0.5 keV

Energy (keV)

Count / 9.25 s

Time (s)

New! $230.6$ keV

230.6 keV
Systematics of osmium isotopes

Single-particle levels of $^{200}_{74}$W

Half-lives of osmium isotopes

Laser spectroscopy of nuclei around $N = 126$

Laser spectroscopy $\rightarrow$ Hyperfine structure
- $\mu, Q \rightarrow$ Wave-function
- Isotope shift $\rightarrow$ Charge radius $\rightarrow$ Nuclear deformation

In-gas-cell laser ionization spectroscopy at KISS for study of nuclear structure

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


$^{199m}$Pt ($I^\pi=13/2^+$)

$^{199g}$Pt ($I^\pi=5/2^-$)

$^{199}$Pt

$^{199}$Au

$^{199m}$Pt ($I^\pi=13/2^+$)
HFS measurement for ground and isomeric states of $^{199}$Pt


| Nuclide | $I^\pi$ | $\mu$ ($\mu_N$) | $\delta(r^2)^{194.4A}$ (fm$^2$) | $|\langle \beta_2^2 \rangle |^{1/2}$ |
|---------|---------|-----------------|-------------------------------|-------------------------------|
| $^{199m}$Pt | $(13/2)^+$ | $-0.57(5)$ | $0.166(30)$ | $0.110(12)$ |
| $^{199g}$Pt | $5/2^-$ | $+0.75(8)$ | $0.268(34)$ | $0.144(10)$ |
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

In-gas-jet laser spectroscopy
$^{194}\text{Pt} (\pi^+ = 0^+)$
Width: 0.60(1) GHz (FWHM)

In-gas-cell laser spectroscopy
$^{198}\text{Pt} (\pi^+ = 0^+)$
Width: 12.5 GHz (FWHM)

Ar gas cell: 80 kPa, $P_{\text{B.G.}} \sim 50$ Pa
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.
Mass measurements at KISS

Mass measurements

Multi-Reflection Time-of-Flight Mass Spectrograph (MRTOF-MS)

β-γ spectroscopy

Multi-trap ion buncher

window-less entrance

He gas cell ion cooler

RF ion guide

RF-Carpet

DC-field

KISS beam

Collaboration with IBS (Korea)

He gas cell ion cooler

MRTOF-MS

KISSL Beam

Multi-trap ion buncher

IBS colleague

Summary

- Systematic nuclear spectroscopy (lifetime, mass, $\beta$-$\gamma$ 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 ionization + ISOL
    - Efficient collection and separation of MNT reaction products
  - Lifetime measurements & $\beta$-$\gamma$ spectroscopy
    - $^{199-201}$Pt, $^{196-200}$Ir, $^{195-198}$Os ($^{136}$Xe + $^{198}$Pt), $^{185-187}$Ta ($^{136}$Xe + nat. W)
  - Laser spectroscopy
    - $^{199}$Pt, $^{196-198}$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
Pre-proposals will be discussed in the SSRI-PNS collaboration meeting (September)

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THANK YOU FOR YOUR ATTENTION
Collaboration

**KISS project**

KEK  Y. Hirayama, Y. Kakiguchi, H. Miyatake, M. Oyaizu, P.H. Schury, M. Wada, Y.X. Watanabe
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