Recent experimental results of KEK Isotope Separation System (KISS)

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

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

Lifetime and mass of waiting point nuclei
$\rightarrow$ 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 $(0.1 \sim 10 \times T_{1/2})$

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]

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

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


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

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

- Strongly damped component with $N/Z$ equilibration
- Neutron evaporation

$n$-pickup ($-xn$)

- Larger cross section

$N \sim 126$

- 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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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)

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

Gas cell system

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

- Gas cell filled with 100 kPa Ar gas
- Laser resonance ionization (Z selection)
- SPIG (SextuPole Ion Guide) + ISOL (A separation)
- Beam diameter: ~ $\sigma$ 2 mm
- Emittance: ~ $10\pi$ mm · mrad
- 20 kV

Ion source chamber: 20 Pa, Screw Pump 175 L/s
2nd chamber: 1 Pa, TMP 800 L/s × 2
Extraction chamber: 2.7 × 10$^{-3}$ Pa, TMP 1500 L/s

Separation of Z and A is achieved by laser resonance ionization and ISOL.
Experimental results (– 2016)

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

0.01% for unstable nuclei

Primary beam: < 20 pnA (thermal damage of several window foils)
Rotating target and doughnut-shaped gas cell

Original gas cell

Doughnut-shaped gas cell


$\varepsilon_{\text{implant}} = 1.00$
$\varepsilon_{\text{stopping}} = 0.86$
$\varepsilon_{\text{transport}} = 0.40$
$\varepsilon_{\text{total}} = 0.34$

$\varepsilon_{\text{implant}} = 0.71$
$\varepsilon_{\text{stopping}} = 0.82$
$\varepsilon_{\text{transport}} = 0.36$
$\varepsilon_{\text{total}} = 0.21$
Configuration I

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

- Efficiency ~0.01%
- Beam limit < 20 pnA

Primary beam intensity (pnA) vs. Extraction yield (pps)
Configuration II

- Doughnut-shaped argon gas cell (~88 kPa)
- Ar gas ~0.1 ppb
- 20 kV
- 10^{-1} Pa
- 10^{-2} Pa
- 2 \times 10^{-4} Pa
- Primary beam
  - 136Xe (10.75 MeV/nucleon)
  - 199Pt rotating target

1st room
- Lasers
- OPIG
- SPIG
- Gas jet

2nd room

3rd room

- Laser ionized nuclei
- Primary beam intensity (pnA)
- Extraction yield (ppps)

Graph:
- Extraction yield \times 5
- Not linear to the primary beam intensity
- Saturation > 50 pnA
- Insufficient radiation shield
Configuration III

Doughnut-shaped argon gas cell (~88 kPa)

Ar gas ~0.1 ppb

20 kV

175 L/s (Screw Pump)

800 L/s x 2 (TMPs)

1500 L/s (TMP)

Laser ionized nuclei

1st room

2nd room

3rd room

198Pt rotating target

Titanium energy degrader

Primary beam 136Xe (10.75 MeV/nucleon)

10^-5 Pa

10^-5 Pa

10^-4 Pa

Primary beam intensity (pnA)

Extraction yield (pps)

199Pt

Extraction yield increases linearly until 50 pnA

Peak at ~50 pnA

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

Four HPGe (High-Purity Germanium) clover detectors

MSPGC (Multi-Segmented Proportional Gas Counter)


Collaboration with IBS (Korea)
Experimental results

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

Stable

Lifetime known

Charge radius known

Experimental results

- 15
$\beta$-$\gamma$ spectroscopy of $^{198}$Os


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

$^{198}$Os
$Q_\beta = 4.09$ MeV
$I_\beta \leq 20(5)$%
$log t \geq 5.69(16)$

$^{198}$Ir
$t_{1/2} = 8(1)$ s
$Q_\beta = 1.98$ MeV
$I_\beta = 9(3)$%
$log t = 5.88(15)$

New! 230.6 keV

$^{198}$Pt stable
HFS measurement for ground and isomeric states of $^{199}$Pt


199Pt

199mPt ($I^\pi=13/2^+$)

199g+Pt

response function

Gate on 392 keV

198Pt

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

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

Frequency − 1 204 992.36 (GHz)

(13/2)$^+$ 424 keV $t_{1/2}=13.6(4)$ s

(7/2)$^-$ 32 keV

5/2$^-$ 0 keV

$^{199}$Pt $t_{1/2}=30.8(4)$ min

5/2$^+$ 543 keV $I_\gamma=0.1174$

3/2$^+$ 0 keV

$^{199}$Au $t_{1/2}=3.139(7)$ d

$^{199}$Pt

392 keV $I_\gamma=0.849$

511 keV

543 keV

400 500

200

800

1000

Energy (keV)

Count / 0.5 keV

Frequency − 1 204 992.36 (GHz)

$^{199}$Pt

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

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

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

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

(a) $^{136}$Xe + $^{198}$Pt $\ N = 126$ isotones

(b) $^{238}$U + $^{198}$Pt $\ N = 126$ isotones

$^{136}$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

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

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

Ar gas cell: 80 kPa, $P_{B.G.} \sim 50$ 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 + CH₄(10%), 0.1 MPa
2D tracking: ΔΩ = 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

Mass measurements

Multi-trap ion buncher

window-less entrance

He gas cell ion cooler

RF ion guide

RF-Carpet

DC-field

1 m

KISS beam

He gas cell

ion cooler

MRTOF-MS

KISS Beam

Multi-trap ion buncher

IBS colleague

Collaboration with IBS (Korea)
### Collaboration

**KISS project**

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**MNT measurements at GANIL**

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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 resonance 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
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Thank you for your attention