KEK isotope separation system for $\beta$-decay spectroscopy of r-process nuclei

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2. Multinucleon transfer reaction of $^{136}$Xe+$^{198}$Pt
3. Gas catcher system for collection and separation
4. Detection system for lifetime measurements
5. Summary
Lifetime measurements around $N=126$ nuclei

- Lifetime measurements of $N=126$ nuclei in our 5-year project since 2010
- Multinucleon transfer (MNT) reaction to access $N=126$ nuclei
  
  \[ \text{C.H. Dasso et al., Phys. Rev. Lett. 73 (1994) 1907.} \]
- From $^{204}$Pt down to $^{200}$W by $^{136}$Xe+$^{198}$Pt MNT reaction
KEK isotope separation system

Focusing chamber
- Electric-Q Triplet
- Electric Deflector
- Slit, Monitors

Detection system
- 3 detector stations
  : tape-transport system
  : Multi-layered plastic scintillators
  : Ge detectors
- β-decay spectroscopy

Mass separator
- Magnetic-Q Doublet
- Magnetic Dipole
- Magnetic-Q Doublet

Extraction chamber
- Electric lens
- Monitors

Gas catcher system
- Target (198Pt)
- Gas cell
- Laser resonance ionization
- SextuPole Ion-Guide

Coolant inlet & outlet
Stopping gas-inlet

MNT reactions of $^{136}$Xe+$^{198}$Pt

Excitation functions for the production of $N = 126$ isotones

<table>
<thead>
<tr>
<th>Mass A</th>
<th>Yield (pps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{202}$Os</td>
<td>$5.0$ pps</td>
</tr>
<tr>
<td>$^{200}$W</td>
<td>$0.1$ pps</td>
</tr>
</tbody>
</table>

$E_{\text{lab}}$ (MeV/A)

$\sigma \sim 10^{-1}$ mb for $^{202}$Os
$\sigma \sim 10^{-3}$ mb for $^{200}$W

Expected yields for $N = 126$ isotones

calculated by GRAZING code
(http://personalpages.to.infn.it/~nanni/grazing)
Isobaric distribution ($A=202$) 

- $\sigma (\text{mb}) \approx 0.3\%$
- $^{202}\text{Os}$ atomic number $\approx 99.7\%$ contaminations
- $^{198}\text{Pt}$ neutron number

$^{136}\text{Xe} + ^{198}\text{Pt}$

$Z$ and $A$ separations are essential for the lifetime measurements of rare channel products.
Kinematic condition for $^{202}$Os

$^{136}$Xe 9 MeV/A → $^{198}$Pt

$^{202}$Os

Angular distribution

Energy distribution

Large and wide emission angle

Low energy, wide energy spread

Efficient collection and separation

Gas catcher system
Gas catcher system
- Laser resonance ionization + ISOL -

Schematic view of gas catcher system

- Gas cell filled with 500 mbar Ar gas
- Laser for ionization (Z selection)
- Ion source chamber (<0.1 mbar)
- Extraction chamber (10^{-2} mbar)
- SPIG (SextuPole Ion Guide)

- Beam diameter: \(\sim \phi 1 \text{ mm}\)
- Emittance: \(\sim 10\pi \text{ mm-mrad}\)

- ISOL
- \(^{198}\text{Pt}\)
- \(^{136}\text{Xe} 9 \text{ MeV/A}\)

- V\(_{0}\) \(\sim 60 \text{ kV}\)
- V\(_{\text{RF}}\)
- V\(_{\text{SPIG}}\)
- V\(_{\text{end}}\)
- V\(_{\text{ext}}\)

Z and A separations are achieved by laser resonance ionization and ISOL.
Cross-sectional view of stopping distribution (\(^{202}\)Os fragments)

- **Transport time profile**
  - Mean-time = 253 ms
  - Transport efficiency: \(\varepsilon_{\text{tra}} = 56\%\)

- **Survival probability of radioactive nuclei**
  - Survival probability: \(\varepsilon_{\text{sur}} = 72\%\)
  - \((T_{1/2} = 500\, \text{msec})\)

**Simulation by hydrodynamic calculations**

- **Stopping efficiency**: \(\varepsilon_{\text{stop}} = 87\%\)

**Top view of gas cell**

- Laser
- Ar gas
- \(^{198}\)Pt target
- \(^{136}\)Xe beam
- \(^{136}\)Xe ion collector electrode
- Exit hole (\(\phi 1\, \text{mm}\))

**Gas cell design**

- **Laminar flow**
Laser resonance ionization

Schematic diagram of atomic level

- Autoionizing state
- 2nd laser pulse
- Intermediate state
- 1st laser pulse
- λ₁ and λ₂ are intrinsic to each element

Laser wavelength for ionization of stable isotopes (Z=69~78)

- λ₁ : 250 – 590 nm
- λ₂ : 220 – 460 nm

λ₁ and λ₂ are known, but we need to confirm and search the most efficient ionization schemes

Excimer laser LPX204i

Dye laser ScanMate2E

Dye laser FL3001

Gas cell

Frequency tunable dye lasers
Total efficiency of gas catcher system

Total efficiency = \( \varepsilon_{\text{stop}} \times \varepsilon_{\text{trans}} \times \varepsilon_{\text{surv}} \times \varepsilon_{\text{LIS}} \times \varepsilon_{\text{SPIG}} \)

- 6.8% for \(^{202}\text{Os}\)  
  \( T_{1/2} = 2.38 \text{ s} \) \(\text{predicted by KUTY}\)

- 5.0% for \(^{200}\text{W}\)  
  \( T_{1/2} = 423 \text{ ms} \) \(\text{predicted by KUTY}\)

Detection system

Tape transport system

Plastic scintillators for $\beta$ rays

two-layer 1 mm$^t$ and 2 mm$^t$
back: 10 cm wide 20 cm height
front: 4 cm radius 20 cm height
$\varepsilon_\beta = 80\%$ (for $Q_\beta = 4.5$ MeV)

Detection efficiency $\beta$-ray energy spectrum

Ge detectors for X rays

10 cm x 10 cm x 5 mm thick
$\varepsilon_X = 60\%$ (for 70 keV X-ray)

Ge detectors for $\gamma$ rays (option)

10 cm x 10 cm x 10 cm long
$\varepsilon_\gamma = 20\%$ (for 500 keV $\gamma$-ray)
Beam-on/off time-sequence

- Beam-on time (s): 1.0 s
- Beam-off time (s): 1.5 s
- Survival probability (%): \( \sim 40\% \)

Three detection stations (1st, 2nd, 3rd)

- Switching box

Diagram shows
- Beam switching
- Tape movement (50cm)
- Survival probability over beam-on time

Equation:
\[ T_{on} = T_{1/2} \times 2, \quad T_{off} = T_{1/2} \times 3 \]
Statistical estimation

**200W**: production rate = 0.11 pps $\rightarrow$ $\sim 1 \times 10^4$ particles/day

Good Z separation by laser resonance ionization (isobaric contaminations $\sim 0.1\%$)

<table>
<thead>
<tr>
<th>Collection efficiency</th>
<th>Survival probability during beam-on</th>
<th>Detection efficiency of $\beta$ ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0%</td>
<td>$\sim 40%$</td>
<td>80%</td>
</tr>
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</table>

$\beta$-decay detection: $\sim 160$ counts/day

Additional X-ray detection

<table>
<thead>
<tr>
<th>Emission probability of $K\alpha_2$ X ray</th>
<th>Detection efficiency of X ray</th>
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<tbody>
<tr>
<td>16 %</td>
<td>60 %</td>
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</table>

Detection: $\sim 16$ counts/day

Lifetime with 10% error

Region down to the red line could be accessed
Summary

- **Lifetime measurements for unstable nuclei produced by MNT reactions of** $^{136}\text{Xe} + ^{198}\text{Pt}$ in 5 years: $^{204}\text{Pt} \sim ^{200}\text{W}$ ($N=126$)

- **Gas cell + laser resonance ionization + ISOL**
  - rapid & efficient collection with laminar flow
  - $Z$ & $A$ separation with laser resonance ionization & ISOL
  - efficiency = 5.0% for $^{200}\text{W}$ ($T_{1/2} \sim 423 \text{ ms}$)

- **Tape transport + $\beta$-decay measurements**
  - Three detection stations $\rightarrow$ suppression of decay loss
  - 160 counts/day for $^{200}\text{W}$ $\rightarrow$ lifetime is determined with 10% error

- **Research & Development in 2 years**
  - Multi-nucleon transfer reaction: feasibility
  - Gas cell design: transport efficiency, transport time profile
  - Laser resonance ionization: wavelength tuning for most efficient ionization-scheme

- **Studies toward waiting nuclei**
  - Low-energy intense neutron-rich RIBs such as $^{140}\text{Xe}$
Collaboration

- **KEK**

- **RIKEN**
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- **TITech**
  T. Furukawa

- **K.U. Leuven**
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