First results of $\beta-\gamma$ spectroscopy for neutron-rich nuclei around $A=110$ at RIBF

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  + Detectors for $\beta-\gamma$ spectroscopy
  + 100MHz Time stamp DAQ system
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  + Shape evolution of neutron-rich even-even Zr isotopes
  + A possible oblate-shape isomer in $^{109}$Nb
  + $\beta$-decay half-lives of neutron-rich Kr to Tc isotopes
- Summary
Motivation
Motivation

A drastic shape evolution is predicted in neutron-rich nuclei around $A=110$. For the Zr isotopes, a deformation may reach a maximum by a deformed shell-closure. However, the maximization of the deformation has not been observed as a function of neutron numbers.

Blue: Measurement Region @ Decay Exp.
Green: T.Ohnishi, JPSJ 79 (2010).. 45 new isotopes

$$R_{4/2} = \frac{E(4^+_1)}{E(2^+_1)}$$
Nucleosynthesis on r-Process

B. Pfeiffer et al. ZPA 357 (1997)
Nucleosynthesis on R-Process

- Half-lives ($T_{1/2}$) → abundance → process speed
- Masses ($A, Q_\beta, S_n$) → location of the path
- β-delayed neutron ($P_n$) → final abundances
- ν ($\overline{\nu}$) captures

Purpose: To study the low-lying excited state of such nuclei, and β-decay half-life measurement
1. β–γ spectroscopy at RIBF
2. Beam production
3. Detectors for β–γ spectroscopy
4. 100MHz Time stamp DAQ system
5. Data analysis with Time-Stamp
β–γ spectroscopy at RIBF

- Beam time: Dec., 2009. 3 days
  (T_{1/2} measurement: 8 hours)
- Primary beam: \(^{238}\)U at 345 MeV/A
  \sim 0.3 \text{ pnA on average}
- Objective isotopes:
  Neutron-rich A = 110 nuclei
- Experimental method:
  Decay spectroscopy with stopped beam
**Beam production**

- **$^{238}$U @ 345 MeV/u → Be target (thickness: 3 mm)**
- **STOP Detector (Decay experiment)**

**Beam production details**:
- **Wedge Al degrader @ F1**
- **Charge stripper @ F5**
- **Al Degrader @ F11**

**Double sided Silicon strip detector (DSSD)**
- **Sensitive area**: 50 x 50 mm
- **Strip**: 16 x 16
- **Strip width**: 3 mm
- **Thickness**: 1000 μm
Detectors for $\beta-\gamma$ spectroscopy

- RI & $\beta$-ray detection
  - 9 DSSDs
  - ~ 2000 pixels in total
  - Implant rate ~ 100 cps
  - $T_{1/2}$ measurement: ~ 10 cps

• The implantation of an identified RI is associated with the following $\beta$-decay events that are detected in the same DSSD pixel

Y. Miyashita, Master thesis (2011)
Compton-suppressed Clover-type Ge detector

Sum of 4 crystals
(P/T ~ 0.1)

Add-back
(P/T ~ 0.2)

Add-back + Suppression
(P/T ~ 0.3)
100MHz Time stamp DAQ system

Each event build using 100MHz Time stamp

- **BEAM**
  - BigRIPS, ZDS
  - DSSDs (for RI)

- **β-decay half-life**
  - DSSDs (β)

- **Isomeric decay of RI**
  - Clovers, BGO,
  - β-Veto, LaBr3

- **β-γ spectroscopy of RI**
Particle identification (PID)

- ΔE-TOF-β method using the focal plane detectors in BigRIPS and ZDS

Isomeric decay of RI

- Delayed coincidence (up to 50 μs) between
  - F11 plastic: Identified RI (time zero)
  - Clover Ge: γ rays

β-decay half-life  β-γ spectroscopy

The implantation of an identified RI is associated with the following β-decay events that are detected in the same DSSD pixel:

- DSSD strip → X, Y
- DSSD layer → Z
Particle Identification

<table>
<thead>
<tr>
<th>RI</th>
<th>Yield [count]</th>
<th>Purity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{106}\text{Y}$</td>
<td>$6.8 \times 10^3$</td>
<td>0.11</td>
</tr>
<tr>
<td>$^{108}\text{Zr}$</td>
<td>$2.9 \times 10^4$</td>
<td>0.45</td>
</tr>
<tr>
<td>$^{109}\text{Zr}$</td>
<td>$2.1 \times 10^3$</td>
<td>0.03</td>
</tr>
<tr>
<td>$^{109}\text{Nb}$</td>
<td>$2.3 \times 10^5$</td>
<td>3.02</td>
</tr>
</tbody>
</table>

Total count : $6.3 \times 10^6$
1. Shape evolution of neutron-rich even-even Zr isotopes
2. Possible oblate-shape isomer in $^{109}$Nb
3. $\beta$-decay half-lives of neutron-rich Kr to Tc isotopes
1. Shape evolution of neutron-rich even-even Zr isotopes
2. Possible oblate-shape isomer in $^{109}$Nb
3. $\beta$-decay half-lives of neutron-rich Kr to Tc isotopes
In coincidence with $\beta$-decay of $^{106}$Y, 
- new 3 peaks observed

In coincidence with isomeric-decay of $^{108}$Zr, 
- new 5 peaks observed

Detail of these results is going to be shown in Dr. Sumikama’s talk.

T. Sumikama et. al.,
PRL 106, 202501 (2011)
1. Shape evolution of neutron-rich even-even Zr isotopes
2. Possible oblate-shape isomer in $^{109}$Nb
3. $\beta$-decay half-lives of neutron-rich Kr to Tc isotopes
Possible oblate-shape isomer in $^{109}$Nb

$^{109}$Nb isomeric decay

$^{109}$Zr $\beta$-decay

$\beta$-decay half-life: $T_{1/2} = 63^{+38}_{-17}$ ms
S. Nishimura et al., PRL 106, 052502 (2011)

H. Watanabe et al., PLB 696, 186 (2011)
Single-proton levels calculated for the $^{110}$Zr region

- $\pi E_{ex} = 313$ keV much below the pairing gap energies
- Single-quasiproton configuration
- Isomeric ratio $\sim 10\%$
- Yrast trap $\Rightarrow$ Spin$^{\text{isomer}} >$ Spin$^{\text{g.s.}}$

- $T_{1/2} = 150(30)$ ns
- $2\Delta n = 2.1$ MeV
- $2\Delta p = 2.5$ MeV

Properties of the $T_{1/2} = 150$ ns isomer

- $[303] 5/2^-$
- $[301] 3/2^-$
- $[422] 5/2^+$
<table>
<thead>
<tr>
<th>E\textsubscript{\gamma} [keV]</th>
<th>Transition</th>
<th>B(E1) [W.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>205.3</td>
<td>3/2\textsuperscript{-} \rightarrow 5/2\textsuperscript{+}</td>
<td>1.9\times10^{-5}</td>
</tr>
<tr>
<td>208.4</td>
<td>5/2\textsuperscript{-} \rightarrow 5/2\textsuperscript{+}</td>
<td>4.2\times10^{-5}</td>
</tr>
<tr>
<td>164.1</td>
<td>5/2\textsuperscript{-} \rightarrow 5/2\textsuperscript{+}</td>
<td>1.3\times10^{-5}</td>
</tr>
<tr>
<td>247.6</td>
<td>3/2\textsuperscript{-} \rightarrow 5/2\textsuperscript{+}</td>
<td>1.6\times10^{-5}</td>
</tr>
</tbody>
</table>

\[ ^{101}\text{Nb} \]

\[ ^{103}\text{Nb} \]

\[ ^{205.3}\text{Nb} \]

\[ ^{208.4}\text{Nb} \]

\[ ^{164.1}\text{Nb} \]

\[ ^{247.6}\text{Nb} \]

\[ ^{3/2}[303] \]

\[ ^{5/2}[301] \]

\[ ^{5/2}[422] \]

\[ ^{3/2}[422] \]

\[ ^{5/2}[303] \]

\[ ^{3/2}[303] \]

\[ ^{3/2}[301] \]

\[ ^{5/2}[301] \]

\[ ^{3/2}[422] \]

\[ ^{5/2}[422] \]

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\[ ^{3/2}[422] \]

\[ ^{5/2}[422] \]

\[ ^{3/2}[303] \]

\[ ^{5/2}[303] \]

\[ ^{3/2}[301] \]

\[ ^{5/2}[301] \]

\[ ^{3/2}[422] \]
Isomeric decays in $^{109}\text{Nb}$

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$I_{\gamma} [%]$ (relative)</th>
<th>$B(\sigma\lambda) [W.u.]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>313.1</td>
<td>62 (20)</td>
<td>$E1$: 3.9\times 10^{-8}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M1$: 2.9\times 10^{-6}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E2$: 2.4\times 10^{-2}</td>
</tr>
<tr>
<td>196.3</td>
<td>38 (14)</td>
<td>$E1$: 1.0\times 10^{-7}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M1$: 7.2\times 10^{-6}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E2$: 1.5\times 10^{-1}</td>
</tr>
</tbody>
</table>

Prolate
- [303] 5/2$^-$
- [301] 3/2$^-$
- [422] 5/2$^+$

Strongly hindered

$^{109}\text{Nb}$

Single-proton levels calculated for the $^{110}\text{Zr}$ region

$T_{1/2} = 150(30) \text{ ns}$

Diagram showing the levels of $^{110}\text{Zr}$ with transitions to the ground state.
Another possible explanation for this strong hindrance is Prolate-oblate shape coexistence.

\[ K^\Pi = 3/2^- \quad K^\Pi = 7/2^+ \]

courtesy of Y. Shi and F.R. Xu, Peking University Gr.

<table>
<thead>
<tr>
<th></th>
<th>( K^\Pi )</th>
<th>( \Omega[\text{Nn}_z\Lambda] )</th>
<th>( \beta_2 )</th>
<th>( \beta_4 )</th>
<th>( \gamma )</th>
<th>( E_{ex} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prolate</td>
<td>3/2^-</td>
<td>3/2[301]</td>
<td>0.324</td>
<td>-0.030</td>
<td>0°</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1/2^+</td>
<td>1/2[431]</td>
<td>0.364</td>
<td>-0.028</td>
<td>0°</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>5/2^-</td>
<td>5/2[303]</td>
<td>0.313</td>
<td>-0.026</td>
<td>0°</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>7/2^+</td>
<td>7/2[413]</td>
<td>0.339</td>
<td>-0.046</td>
<td>0°</td>
<td>388</td>
</tr>
<tr>
<td></td>
<td>5/2^+</td>
<td>5/2[422]</td>
<td>0.312</td>
<td>-0.023</td>
<td>0°</td>
<td>398</td>
</tr>
<tr>
<td>Oblate</td>
<td>7/2^+</td>
<td>7/2[413]</td>
<td>0.219</td>
<td>-0.035</td>
<td>-60°</td>
<td>301</td>
</tr>
<tr>
<td></td>
<td>1/2^-</td>
<td>1/2[321]</td>
<td>0.251</td>
<td>-0.031</td>
<td>-51°</td>
<td>554</td>
</tr>
<tr>
<td></td>
<td>3/2^-</td>
<td>3/2[321]</td>
<td>0.247</td>
<td>-0.030</td>
<td>-61°</td>
<td>804</td>
</tr>
<tr>
<td></td>
<td>9/2^+</td>
<td>9/2[404]</td>
<td>0.211</td>
<td>-0.043</td>
<td>-60°</td>
<td>1051</td>
</tr>
</tbody>
</table>

\( T_{1/2} = 150(30) \text{ ns} \)

H. Watanabe et al., PLB 696, 186 (2011)
1. Shape evolution of neutron-rich even-even Zr isotopes
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3. $\beta$-decay half-lives of neutron-rich Kr to Tc isotopes
Decay curves

S. Nishimura et al., PRL 106, 052502 (2011)
Zr and Nb decay faster than expected by FRDM+QRPA \((T_{1/2} : 1/2 \sim 1/3 \sim)\)

S. Nishimura et al.,
PRL 106, 052502 (2011)
Summary

- First $\beta-\gamma$ spectroscopy experiment with 345 MeV/A U-beam at RIBF

Results

- Shape evolution of neutron-rich even-even Zr isotopes
- Oblate shape isomer of $^{109}$Nb isotopes
- The half-lives of 18 nuclei are newly obtained.

In progress

- Analysis and study for neutron-rich Sr, Y, Zr, Mo isotopes
Thank you for your attention