Precision optical spectroscopy of radioactive Be isotopes produced in projectile fragmentation

Michiharu Wada and SLOWRI Collaboration
RIKEN

1. Optical Spectroscopy of Be
2. Mass Spectrograph for short-lived nuclei
3. New Facility at RIKEN
A goal of Nuclear Physics:

THE Nuclear Model uniquely describes all properties of all nuclides

Static Properties
- Mass
- Size
- Moments
- Spin
- Parity
- \( T_{1/2} \)

Dynamic Properties
- Cross Sections
- \( P_{n,p,\gamma} \)
- Level Scheme

We know only a few of them for radioactive nuclei

Optical spectroscopy
model independent manner

stable: \( \sim 250 \)
discovered: \( \sim 3000 \)
expected: \( \sim 10000 \)
Optical Spectroscopy Applied Nuclides

Proton ($Z$)

Z=50

Z=28

Z=82

N=50

N=82

N=126

Neutron ($N$)

Nuclides Optically Measured
($\approx$46 element、$\approx$600 Nuclei)

10^7 cps

1 cps

Expected Yields at SLOWRI
Mass: known: 2000

- Mass Known (Accuracy)
- T1/2 Known
- Mass to be measured

- 1 ppm
- 1 ppb

- Mass Known: 2000
- Mass to be measured: MRTOF@SLOWRI
- Mass to be measured: mass-ring

- N=28
- Z=28
- N=50
- Z=50
- N=82
- Z=82
- N=126
Penning Trap Performance

6 Major Penning Trap Facilities (20 years)
~500 nuclides were measured relatively close to stability line

A. Jokinen
Comprehensive Measurements of All Nuclides

Universal Methods to Produce Unstable Nuclei

*In-flight Separators, Gas catcher cooler, ...*

Efficient & Quick Methods to Measure the Properties

*Ion Traps, Lasers, MRTOF Mass Spectrograph*

More Beam Time

*Parasitic Beam*
Optical Spectroscopy of Be Isotopes

$^{11}\text{Be}$

$Z=4$
$N=7$
(T1/2=13s)

$^{10}\text{Be}$

$Z=4$
$N=6$

Core + One loosely bound Neutron

Charge Radius

$IS\,(E0)$

Volume without Charge-less Neutron

Magnetization Radius

$IS\,(M1)$

Single Valence Neutron carries most of Magnetization of Nucleus

Cancelled in the Core (core polarization still exist)

proposed: M. Wada et al, NPA (1997) 356c
Experimental Setup: SLOWRI prototype @ RIBF, RIKEN

High Energy RI Beam ~1 GeV

Low Energy RI Beam ~2 eV

RF Ion Guide

Carbon-OPIG

Qmass Ion Trap

Laser Cooled $^{7}\text{Be}$

Time of Flight - 957,347 GHz

$T_\text{ion} < 10 \text{ mK}$

10$^{-15}$ fold reduction of kinetic energy!

M. Wada et al., NIM B 204,570 (2003)
A. Takamine et al., RSI 76,103503 (2005)

T. Nakamura et al., PRA 74, 052503 (2004)
Finite Mass and Volume of a Nucleus cause a Shift in Optical Transition Energy

Atomic Energy Level

\[ \varepsilon_A = \varepsilon_\infty - \frac{\mu_A}{M_A} \varepsilon_\infty + \frac{\mu_A}{M_A} \frac{1}{m_e} \sum_{i<j}^N \mathbf{p}_i \cdot \mathbf{p}_j + \frac{2\pi}{3} Z |\psi(0)|^2 \langle r_c^2 \rangle \]

Mass Dependent

Normal Mass Shift (easy to calculate)

Specific Mass Shift (difficult to calculate)

Volume Dependent

Shallower Coulomb potential for electrons in a nucleus

for Be\(^{+} 2^2S \rightarrow 2^2P\)

Absolute transition frequency \(\sim 1 000 000 000\) MHz

Isotope Shift \(\sim 10 000\) MHz

Mass Shift \(\sim 10 000\) MHz

Field Shift \(\sim 10\) MHz

\[ F = \frac{2\pi}{3} Z \Delta |\psi(0)|^2 = -16.912 \text{ MHz/fm}^2 \]

\(1\% \text{ of } r_c \rightarrow 2\text{ MHz}\)

Yan et al, PRL\(^{100}, 243002\) (2008)

requires an accuracy of \(10^{-9}\)
$2^2S_{1/2} - 2^2P_{3/2}$ Transition Measurement

$^{11}\text{Be}^+$

$2^2P_{3/2}$

\begin{align*}
F = 2 & \quad m_F = +3 \\
F = 0 & \quad m_F = 0
\end{align*}

Cooling laser $\sigma^+$

Probe Laser

$2^2S_{1/2}$

\begin{align*}
F = 1 & \quad m_F = +1 \\
F = 0 & \quad m_F = -1
\end{align*}

$^{11}\text{Be}$

\[ 957,428,1 (3.0) \text{ MHz} \]

$^{9}\text{Be}$

\[ 957,396,6 (1.6) \text{ MHz} \]

Isotope Shift

\[ 31,570.2 \text{ MHz} \]

Mass Shift

\[ 31,563.9 \text{ MHz} \]

Field Shift

\[ 3.0 \text{ MHz} \]

\textbf{Shift of Charge Radii}

\[ \delta \langle r_c^2 \rangle_{A,A'} = \frac{\text{Field Shift}}{-16.912 \text{ MHz}} \]

A. Takamine et al., to be submitted
Hyperfine Constant (S-state)

Different Quantities, Comparison provide magnetic radius

\[ A = A_{\text{point}} (1 + \epsilon) \]

\[ ^{11}\Delta^9 = \epsilon_{11} - \epsilon_9 \approx \frac{A_{11}/(\mu_{11}/I_{11})}{A_9/(\mu_9/I_9)} - 1 \]

Nuclear Magnetization probed by strongly inhomogeneous magnetic field due to s-electron

Nuclear g-factor

Observation from \( \infty \)

Nuclear Magnetization probed by very homogeneous external magnetic field
theoretical prediction of HFA for Be isotopes

Large $\varepsilon_{BW}$ is expected for $^{11}$Be, due to extended halo neutron.

FIS: Fujita Ito Suzuki, PRC59(1999)210
HFS Spectroscopy of $^7\text{Be}^+$

Laser-Microwave Double Resonance

1. **Optical Pumping to Recyclable State by**
   - $\sigma^+$ or $\sigma^-$ Laser
2. **Laser Cooling**
3. **Microwave induces hf transition**
4. **Fluorescence detects population**

$\nu^+, \nu^- \Rightarrow A = -742.77228(43) \text{ MHz (5 \cdot 10^{-7})}$

$$\frac{d\nu}{dB} = \mu_B \frac{4I}{2I+1} = 21 \text{ MHz/mT} \Rightarrow I = 3/2$$

$$A \Rightarrow \mu_I = -1.39928(1) \quad |^7\Delta^9| < 10^{-5}$$

**HFS Spectroscopy of $^{11}\text{Be}^+$ ($T_{1/2}=13.8\text{s}$)**

$2^2P_{3/2}$ to $2^2S_{1/2}$

- $F=2$  
  - $m_F=+2$
  - $m_F=-2$

- $F=1$
  - $m_F=+1$
  - $m_F=0$
  - $m_F=-1$

- $F=0$
  - $m_F=0$

- Laser $\sigma^+$

- Microwave

Fitted to Breit-Rabi formula:

$$\nu^0 = \sqrt{A^2 + B^2 g^2 J^2 (1 - \gamma)^2}$$

- $A_{11} = -2677.30$ MHz ($3 \cdot 10^{-8}$)
- $A \Rightarrow \mu_1 = -1.6812(2)$
- $|^9\Delta^{11}| < 10^{-4}$
- $\frac{d\nu}{dB} = \mu_B \frac{4I}{2I+1} = 14$ MHz/mT $\Rightarrow I = 1/2$

A. Takamine et al., to be submitted
## Results of Be HFS Spectroscopy

<table>
<thead>
<tr>
<th></th>
<th>Be-7</th>
<th>Be-9</th>
<th>Be-11</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HFS constant $A$ [MHz]</strong></td>
<td>-742.77228(43)</td>
<td>-625.0088370529(11)**</td>
<td>-2677.3**</td>
</tr>
<tr>
<td><strong>Nuclear Mag. Moment [n.m]</strong></td>
<td>{-1.39928(2)}</td>
<td>-1.177432(3)</td>
<td>(-)1.6816(8)*</td>
</tr>
<tr>
<td><strong>{deduced from $A$}</strong></td>
<td>{-1.39928(2)}</td>
<td></td>
<td>{ -1.6812(2) }</td>
</tr>
</tbody>
</table>

* W. Geithner et al., PRL 83(1999)3792
** J. Bollinger et al.,

\[ 9 \Delta^{11} = \frac{A_9/\mu_9}{A_{11}/\mu_{11}} - 1 = 2.2(48) \times 10^{-4} \]

- More than one order of magnitude better accuracy for $\mu_I$ is required.
  → **Planning to remeasure @RIKEN**

- More seriously, $\beta$-NMR method cannot be applied for Be-7.
  → **How to measure it?**

* A. Takamine et al., to be submitted
Accurate and Independent Measurement of $\mu_I$ and $A$

Zeeman Splittings of the Ground-State Hyperfine Structure of $^9\text{Be}$

Breit-Rabi's Formula:

$$ W_F(m_J, m_I, b) = -\frac{A}{4} - (m_J + m_I)\gamma b $$

$$ + m_J \sqrt{A^2 \left(\frac{1}{2} + I\right)^2 + 2A(m_J + m_I)(\gamma - 1)b + (\gamma - 1)^2 b^2} $$

$$ b = g_I \mu_B B_0 / h, \quad \gamma = g'_I / g_J $$

$$ A = -625\,008\,835.23\,(75)\,\text{Hz} $$

$$ g'_I / g_J = 2.134\,780\,33\,(28) \times 10^{-4} $$


$\rightarrow ^7\text{Be}^+, ^{11}\text{Be}^+$
$\rightarrow$ B-W effect
Is a HFS constant a constant?

\[ ^9\text{Be}^+ \]

<table>
<thead>
<tr>
<th>A</th>
<th>( \text{gi/gj \times 10^{-4}} )</th>
<th>Magnetic field</th>
<th>Clock condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>-625 008 837.053(11) Hz</td>
<td>2.134 779 852(3)</td>
<td>6.8 / 8.2 kG</td>
<td></td>
</tr>
<tr>
<td>-625 008 835.23(75) Hz</td>
<td>2.134 780 33(28)</td>
<td>4.7 kG</td>
<td></td>
</tr>
</tbody>
</table>

J.J. Bollinger et al., PRL 54, 1000 (1985)


2\sigma discrepancy

\[ A \propto B^2 \]

* measurement at B=0
(0-0 transition in \(^{11}\text{Be}^+)\)

* measurement for isotopes (gi, ml)

High field correction (by W.M. Itano)

\[ \mathbf{p}_i \rightarrow \mathbf{p}_i + \frac{e}{c} \mathbf{A}(\mathbf{r}_i) \]

\[ T = \sum_i \frac{p_i^2}{2m} \rightarrow \sum_i \left( \mathbf{p}_i + \frac{e}{c} \mathbf{A}(\mathbf{r}_i) \right)^2 \]

**Quadratic corrections for each electrons**

\[ \frac{e^2}{8mc^2}(x_i^2 + y_i^2)B^2 \]

\[ \propto g_{I} m_{I} m_{J} B^2 \]
### Charge & Magnetization Radii of Be Isotopes

<table>
<thead>
<tr>
<th></th>
<th>Be7</th>
<th>Be9</th>
<th>Be10</th>
<th>Be11</th>
</tr>
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<tbody>
<tr>
<td><strong>HFS constant A (MHz)</strong></td>
<td>-742.77228(43)</td>
<td>-625.0088370529(11)</td>
<td>-</td>
<td>-2677.3(72)</td>
</tr>
<tr>
<td><strong>Nuclear Mag. Moment (n.m)</strong></td>
<td>[ -1.39928(2) ]</td>
<td>-1.177432(3)</td>
<td>-</td>
<td>[ -1.6812(5) ]</td>
</tr>
<tr>
<td><strong>by beta-NMR</strong></td>
<td></td>
<td></td>
<td></td>
<td>(-)1.6816(8)</td>
</tr>
<tr>
<td><strong>S1/2-P3/2 Opt. Transition (MHz)</strong></td>
<td>957347372(2.4)</td>
<td>957396618(0.6)</td>
<td>957413945.1(0.9)</td>
<td>957428188(2.9)</td>
</tr>
</tbody>
</table>

#### Differential hyperfine anomaly

- Theory FIS
- Theory FIS2
- Theory PL
- Theory PL2
- Exp

#### Be RMS Nuclear Charge Radii [fm]

- Laser-Cooled Trapped Ions @RIKEN
- Collinear Laser Spectroscopy @ ISOLDE

#### neutron halo of \(^{11}\text{Be}\)

\[ 9 \Delta^{11} = \frac{A_9/\mu_9}{A_{11}/\mu_{11}} - 1 = 2.2(48) \times 10^{-4} \]
Multi-Reflection TOF Mass Spectrograph

- Easy Calibration.
- No Scan, Higher Statistical Efficiency
- $\delta M \sim 10$ keV/c\(^2\) is achievable in short period (2 ms).

Test result with a small prototype

\[ A = 27.995 \] (CO)

\[ A = 28.006 \] (N\(_2\))

\[ 130 \text{ keV/c}^2 \]

\[ 10.46 \text{ MeV/c}^2 \]

All Isobars in Single Spectrum

Prototype MRTOF

\[ R(\text{FWHM}) \sim 200,000 \]

\[ \text{MBQ}_b \]

Y. Ishida et al., NIMB241 (2005) 983

Trap \hspace{1cm} Ion Mirror \hspace{1cm} Ion Mirror \hspace{1cm} Ion Detector
Penning Trap vs. MRTOF

MRP: Better MRP for Heavy, Short-lived Nuclei

\[ t_{\text{tof}} = L \sqrt{\frac{m}{2K}}, \quad \frac{\partial t_{\text{tof}}}{\partial K} \approx 0 \]

Energy Isochronous

\[ R_m \equiv \frac{m}{\Delta m} = \frac{1}{2} \frac{t_{\text{tof}}}{\Delta t} \propto \frac{1}{\sqrt{m}} \]

MRP: Better MRP for Heavy, Short-lived Nuclei

Heavy Molecule, too!

\[ \delta m \approx \frac{1}{R_m \sqrt{N}} \]

\[ \Delta \delta m \approx 0.1 \text{ ppm} \]

\[ R_m = 200,000 \]

\[ N = 3000 \]

\[ \delta M \approx 0.1 \text{ ppm} \]

New MRTOF: MRP $\approx 500,000$ expected
Cryo-Gas Cell

MRTOF trap

Portable MRTOF MS

Cryo-cooler

He gas cell (50cm)

RF-carpet

MR-TOF Mass Spectrograph

Cryo-cooler

SPIG Q-mass

TRAP

MRTOF trap made of PCB

trap

DC beam

~1 eV

Cooled Ion Bunch

Efficiency ~10%
First Test Results of new MRTOF

- **518 Laps, ~ 0.5 km, R ~ 82.000**
  - $R \approx 82000$ in 12 ms, equal to a 17.5 T Penning trap!
  - $^{39}K$
  - $t = 11935084.5 \text{ ns}$
  - $\Delta t = 72.5 \text{ ns}$
  - $R \approx 82.000$

- **1554 Laps, ~ 1.5 km, R ~ 122.000**
  - $R \approx 122000$ in 36 ms, equal to a 8.7 T Penning trap!
  - $^{39}K$
  - $t = 35740796.2 \text{ ns}$
  - $\Delta t = 146.7 \text{ ns}$
  - $R \approx 122.000$
mass uncertainty and half-life
SLOWRI facility

“Super ISOLDE”

Universal Slow RI-beam Facility: SLOWRI

RF Ion Guide
Gas Cell

RF-Carpet

Ion Trap

Laser Spectroscopy

Mass Measurement

Super Conducting Ring Cyclotron

Heavy ion beam 400 MeV/u

Target

Degraded

High Energy RI-Beam >200 MeV/u

High Energy RI-Beam >200 MeV/u

A/Z

A

ISOL 30 keV

~1 eV

30 keV

400 MeV/u

>200 MeV/u

300 MeV

all elements

high pure

low emittance

0-30 KeV

RI-Beam Factory

SLOWRI facility

“Super ISOLDE”
beam time issue

5 months/y
2 weeks/y for SLOWRI ??
5 mon./y for SLOWRI !!

power outage

SLOWRI
Projectile Fragmentation from, e.g., 350A MeV Xe136 0.5puA

Many nuclides are simultaneously produced from a single ion beam.

When other one plays with 78Ni, Many nuclides are freely available at F1
PALIS

PArasitic slow RI-beam with gas catcher Laser Ion Source

1) Stop & Neutralize in Ar (1 bar)
2) Extract by Gas Flow
3) Re-Ionize at Exit and SPIG

not universal, not very fast but
A/Z, Z, A separation
Yield at F1 (5cm cell, 105-155mm)

Pri. Beam: U 1000nA
Main Beam: Ni78
Overview of advanced SLOWRI facility
Collaborators
(Be spectroscopy)

RIKEN, Nishina Accelerator Center
A. Takamine, T. Sonoda, T. Kubo

RIKEN, Atomic Physics Lab.
T. Nakamura, Y. Yamazaki, T. Kojima, Y. Kanai

Sophia Univ.
K. Okada

Tsukuba Univ.
Peter Schury

JAEA
H. Iimura

KEK
I. Katayama

Univ. Electro-Comm., ILS
S. Ohtani

Justus-Liebig-Universitaet Giessen
H. Wollnik

Texas A&M University, USA
H. A. Schuessler