Properties of isomers measured by high resolution laser spectroscopy

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Properties of isomers measured by high resolution laser spectroscopy

1. Nuclear charge radii — measurement and interpretation
2. The 8⁻ isomers in $^{176}$Yb, $^{178}$Hf
3. Isomers and ground states of yttrium
4. Measurements by laser resonance ionization
Isotope Shift and Hyperfine Structure

Analysis yields the change in nuclear mean square charge radius

Nuclear size, static and dynamic deformations

Isotope shift of atomic transition

Hyperfine structure of atomic transition

(Isotope shift found using centroids of hyperfine multiplet)

Nuclear spin I
Magnetic moment $\mu$
Quadrupole moment $Q_s$
The laser/IGISOL facility at Jyväskylä

- Ion beam cooler
  - Reduces energy-spread of ion beam (<1 eV)
- Light collection region
  - (Laser resonance fluorescence)
  - Trap and accumulates ions – typically for 300 ms
  - Releases ions in a 15 µs bunch
Sensitivity gains using the RFQ ion-cooler

BEFORE

Photons from laser-excitation of radioactive $^{88}\text{Zr}$

AFTER

8000 ions/sec
5.3 hours
(Photon-ion coincidence method)

2000 ions/sec
48 minutes
(bunched beam method)
Isotope Shift

Isotope shift of atomic transition

Analysis yields the change in nuclear mean square charge radius

Nuclear size, static and dynamic deformations

Transition energy difference between isotopes A and A’

\[ \delta E = \frac{Ze^2}{6\varepsilon_0} \Delta \left| \psi(0) \right|^2 \delta \langle r^2 \rangle_{A,A'} \]

+ mass shift (zero for isomers)

Deformed nucleus

Spherical nucleus

\[ \langle r^2 \rangle = \langle r^2 \rangle_0 \left( 1 + \frac{5}{4\pi} \left( \langle \beta_2^2 \rangle + \langle \beta_3^2 \rangle + \ldots \right) \right) \]
Factors controlling $\delta < r^2>$

Volume change

Deformation change

Pairing change
Mean square charge radii

- NATURALLY ABUNDANT
- RADIOACTIVE
- ISOMER (EXCITED NUCLEAR STATE)

Volume

Deformation

Pairing effects?

Odd-even staggering

Radii of multi-quasiparticle isomers

$\delta \langle r^2 \rangle$ (fm$^2$)

$178^{16+}$ Hf
The K=8 isomers in $^{178}$Hf and $^{176}$Yb

Structure of $^{178}$Hf 16$^+$ (31 year) isomer

\[
[\nu \ 7/2 \ [514] \  \nu \ 9/2 \ [624] \ ]_{(8^-)} \ [\pi \ 7/2 \ [404] \ \pi \ 9/2 \ [514] \ ]_{(8^-)}
\]

\[
(\nu \ h_{9/2})(\nu \ i_{13/2}) \quad (\pi \ g_{7/2})(\pi \ h_{11/2})
\]

Structure of 2-neutron 8$^-$ state in $^{176}$Yb

Structure of 2-qp 8$^-$ state in $^{178}$Hf is 60$\%$(2\nu)+40$\%$(2\pi)

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>State</th>
<th>$Q_0$</th>
<th>$\langle r^2 \rangle_{isomer} - \langle r^2 \rangle_{g.s.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{178}$Hf</td>
<td>0$^+$ g.s.</td>
<td>6.961(43)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16$^+$ (4qp)</td>
<td>7.2(1)</td>
<td>-0.076(12) Boos et al (1994)</td>
</tr>
<tr>
<td>$^{177}$Lu</td>
<td>7/2$^+$ g.s.</td>
<td>7.26(6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23/2$^-$ (3qp)</td>
<td>7.33(6)</td>
<td>-0.035(4) Georg et al (1998)</td>
</tr>
</tbody>
</table>
The $^{176}\text{Yb}$ $8^-$ isomer

Production: (d,pn) at 13 MeV, 5.5 µA

Flux: 200 isomers/sec (total flux at A=176: 8,400 ions/sec)
$^{176, 176m}$Yb laser resonance spectrum

$\lambda = 328.9$ nm
## Experimental Deformation Parameters for Neighbouring Yb Isotopes

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>State</th>
<th>$Q_0$ (barns)</th>
<th>$\beta_2$</th>
<th>$\delta r^2_{176,176m\text{Yb}}$ (fm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{175}\text{Yb}$</td>
<td>$7/2^-$ g.s.</td>
<td>7.52(11)</td>
<td>0.286(4)</td>
<td></td>
</tr>
<tr>
<td>$^{176}\text{Yb}$</td>
<td>$0^+$ g.s.</td>
<td>7.40(5)</td>
<td>0.280(2)</td>
<td></td>
</tr>
<tr>
<td>$^{176}\text{Yb}$</td>
<td>$8^-$ (2qp)</td>
<td>7.54(11)</td>
<td>0.285(4)</td>
<td><strong>-0.0224(1)</strong></td>
</tr>
<tr>
<td>$^{177}\text{Yb}$</td>
<td>$9/2^+$ g.s.</td>
<td>7.37(11)</td>
<td>0.278(4)</td>
<td></td>
</tr>
</tbody>
</table>
The $^{178}$Hf $8^-$ isomer

Production: $^{176}$Yb (α, 2n) at 25 MeV, 5μA

Isomer beam: 3,000 per second
$8^- \quad \delta < r^2 >^{178,178 m1} = -0.0384(1) \text{ fm}^2$

$16^+ \quad \delta < r^2 >^{178,178 m2} = -0.0873(20) \text{ fm}^2$ (Boos et al.)
Negative isomer shifts in multi-quasiparticle isomers

Without pairing effects,
Isomer shift = +0.051 fm$^2$

Including pairing
Isomer shift = -0.033 fm$^2$

(Experiment: -0.087(2) fm$^2$)

$\langle r^2 \rangle$ for proton states

9/2$^+$ 36.097 fm$^2$

9/2$^-$

7/2$^-$ 28.888 fm$^2$

7/2$^+$

neutrons protons
3. Isomers and ground states of yttrium

Charge radii of Zr isotopes

\[ \langle r^2 \rangle = \langle r^2 \rangle_0 \left( 1 + \frac{5}{4\pi} (\langle \beta_2^2 \rangle + \langle \beta_3^2 \rangle + ...) \right) \]

\[ \langle r^2 \rangle = \langle r^2 \rangle_0 \left( 1 + \frac{5}{4\pi} (\langle \beta_2^2 \rangle + \langle \beta_3^2 \rangle + \ldots) \right) \]
Problem: charge radius increase inconsistent with deformation derived from $B(E2; 0^+ \rightarrow 2^+)$

$$40\text{Zr}$$

Lack of $Q_s$ data to investigate problem further…. but wealth of ground states and isomers with $I > \frac{1}{2}$ in neighbouring $^{39}\text{Y}$ chain

$$Q_0 = \left( \frac{16\pi}{5} \frac{B(E2) \uparrow}{e^2} \right)^{1/2}$$

$$Q_0 \approx \frac{3Z R_0^2}{\sqrt{5\pi}} \langle \beta_2 \rangle (1 + 0.36 \langle \beta_2 \rangle)$$
Yttrium atomic structure

\[ Y^+ \]

\[ \begin{align*}
& s^2 1S_0 \\
& s^2 + p^2 + d^2 \\
& dp^1P_1 \
\end{align*} \]

\[ \begin{align*}
& ds^3D_1 \\
& 224 \text{nm} \\
& 363 \text{nm} \\
& dp^3P_1 \\
& 311 \text{nm} \\
& dp^1P_1 \\
\end{align*} \]

\[ \begin{align*}
J = 0 \\
I = 0 \\
I \neq 0 \\
\text{Prolate} \\
\text{Hyperfine structure} \\
\end{align*} \]
Example of spectra for neutron-rich yttrium isotopes (production by proton-induced fission of uranium)

Shift to lower laser frequency indicates increase in the nuclear rms radius

Measured moment $Q_s$ is the projection of $Q_0$ on quantization axis:

$$Q_s = Q_0 \left[ \frac{3\Omega^2 - I(I + 1)}{(I + 1)(2I + 3)} \right]$$
Mean square radius predicted from spherical droplet model corrected for deformation deduced from measured quadrupole moment

\[ Q_s = Q_0 \left[ \frac{3\Omega^2 - I(I + 1)}{(I + 1)(2I + 3)} \right] \]

Mean square radius from isotope shift data
Charge radii of yttrium isotopes

Mean square charge radius (fm$^2$)

Neutron number

Isotope shift data (ground states)

Isotope shift data (isomers)

Spherical

Droplet model + deformation from $Q_s$
Ground state and two isomers in $^{97}$Y

(The smaller nucleus is shifted to higher frequency)
Results for $^{97}$Y isomers

$$9/2^+ (\pi g_{9/2}) Q_0 = -1.40(15) \text{ b}$$
$$\delta <r^2>^{97,97m1} = +0.122 \text{ fm}^2$$

$$27/2^- (\pi g_{9/2})(\nu g_{7/2})(\nu h_{11/2}) Q_0 = -1.50(17) \text{ b}$$
$$\delta <r^2>^{97m1,97m2} = -0.098(1) \text{ fm}^2$$

-Same effect in an oblate multi-quasiparticle state – the 3qp isomer is smaller than the 1qp isomer.

-Other isomers with same feature: $^{130}$Ba$(8^-)$, $^{202}$Pb$(9^-)$, $^{135}$Cs$(19/2^-)$

-Appears to be a common feature for multi-quasiparticle states
4. Measurements by laser resonance ionization

The collinear-beams resonance ionization method

- **5 µs**
- **10 ns**
- **50 Hz**
- repetition rate lasers

Atom bunch

50 Hz delivery rate, synchronized with laser pulse

- All atoms from the ion source have a chance to be ionized

- Resonance located by ion counting (not photon counting)

- Doppler-broadening free

Off-line tests with $^{27}$Al
Comparison with low-flux bunched beams

Photon counting (12 minutes)

Ion counting (4 minutes)

Sensitivity:
1 resonance ion per 30 atoms within 1 µs time window
(compared with 1 photon per 50,000 atoms)
In-source laser spectroscopy (Doppler broadened)

- Ti:Sapphire lasers
- Nd:YAG 100W, 10 kHz
- Pulsed dye lasers
- Copper vapour laser 45W, 10kHz
- cw dye laser
- cw pump laser
- Isotope separator
- Ion guide

Fast Universal Resonant laser IOn Source
FURIOS
LIST: Laser ion source trap
Method being developed by FURIOS collaboration at JYFL

Applications:
* Production of high isobaric purity isotope or isomer beams
* In-source laser spectroscopy
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Present work: Tantalum gs & isomers

![Diagram showing energy levels and transitions for Ta\(^{180}\) and Ta\(^{181}\).]

- **180\(^{Ta}\)**:
  - 7/2\(^+\) ground state
  - 9\(^-\) isomer (>1.2 x 10\(^{15}\) y)
  - 9\(^-\) transition: 75 keV, 8h

- **264 GHz** transition

- **296.5 nm** transition

- **Ta\(^+\) ion**