$g$-Factor measurements of high-spin isomers and condensed matter studies using spin-aligned isomeric beams

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Outline

• Introduction
• $g$-Factor measurements of the high-spin isomers in $N = 83$ isotones
• Condensed matter studies with spin-aligned isomeric beams
Overview of nuclear isomers presented over the chart of nuclei

A large number of isomeric states with various lifetimes and spins have been discovered so far!
Spin-oriented isomers as probes for studies of nuclear moments and solid-state physics

Larmor frequency
\[ \omega_L = \frac{g_N \mu_B B_{\text{ext}} \beta(T)}{\hbar} \]

Isomeric g-factor
\[ g \text{ known} \]

Local susceptibility
\[ \chi_{\text{loc}} = \beta(T) - 1 = \frac{g_s (J + 1) \mu_B B(0)}{3 k_B T} \]

Nuclear relaxation time
\[ \tau_{N^{-1}} = \frac{2(J + 1)\{g_s \mu_B B(0)\hbar\}^2}{J} \]

Oscillation curve

exp \((- t / \tau_N)\)

1 / \omega_L

\[ t [\text{ns}] \]

Nuclear structure
- Configuration of the isomer
- Effect of shell-closure

Material science
- Local moment
- Exchange interaction

4f electron spin fluctuation
\[ \tau_{\text{e}}^{-1} = \frac{4\pi}{\hbar} \{D_s (\epsilon_r) J_e(T)\}^2 k_B T \]
g-Factor measurements of the high-spin isomers in $N = 83$ isotones

Systematics of the high-spin isomers in $N = 83$ isotones

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Spin</th>
<th>Energy [MeV]</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{143}$Nd</td>
<td>$\frac{13}{2}^+$</td>
<td>$6.8$ ns</td>
<td>$&gt;2$ us</td>
</tr>
<tr>
<td>$^{144}$Pm</td>
<td>$\frac{13}{2}^+$</td>
<td>$12$ ns</td>
<td>$27/2^-$</td>
</tr>
<tr>
<td>$^{145}$Sm</td>
<td>$\frac{11}{2}^-$</td>
<td>$4.5$ us</td>
<td>$21/2^-$</td>
</tr>
<tr>
<td>$^{146}$Eu</td>
<td>$\frac{9}{2}^+$</td>
<td>$235$ us</td>
<td>$&lt;2$ m</td>
</tr>
<tr>
<td>$^{147}$Gd</td>
<td>$\frac{9}{2}^+$</td>
<td>$22$ ns</td>
<td>$13/2^+$</td>
</tr>
<tr>
<td>$^{149}$Tb</td>
<td>$\frac{9}{2}^+$</td>
<td>$12.5$ ns</td>
<td>$13/2^+$</td>
</tr>
<tr>
<td>$^{149}$Dy</td>
<td>$\frac{7}{2}^-$</td>
<td>$38$ h</td>
<td>$7/2^-$</td>
</tr>
</tbody>
</table>
Properties of the high-spin isomer in $^{147}\text{Gd}$


Isomeric configuration

$[\pi (h_{11/2}^2) \varphi (f_{7/2} h_{9/2} i_{13/2})]_{49/2}^+$

Experimental $g$-factor

Experimental $Q$-moment

Deformation $\beta = -0.19$

※ These properties are well reproduced by the DIPM calculation.

Does the other $N = 83$ high-spin isomers have the same properties as the $^{147m}\text{Gd}$?
$^{149}$Dy Level Structure

$E_{ex} = 8.52$ MeV, $T_{1/2} = 28$ ns High-Spin Isomer

Configuration predicted by the DIPM calc.

$I = \frac{47}{2} \hbar$

Z = 64 core excitation

Spherical shape
$\beta = -0.041$

$I = \frac{49}{2} \hbar$

N = 82 core excitation

Oblate shape
$\beta = -0.166$

Configuration predicted by the DIPM calc.

$Z = 64$ core excitation

$N = 82$ core excitation

$^{146}$Gd

2 proton

1 neutron

proton

proton hole

neutron
$^{143}$Nd Level Structure

Angular distribution
Linear polarization

$E_{ex} = 8.98\text{MeV}, T_{1/2} = 35\text{ns}, I^{\pi} = 49/2^+$

Configuration predicted by the DIPM calc.

$I = \frac{49}{2} \hbar$

$Z = 64, N = 82$ core excitation

Oblate shape
$\beta = -0.176$
Production of the high-spin isomer in $^{149}$Dy
✧ Projectile: $^{132}$Xe 7.0 MeV/u, $T = 1 \mu s$
✧ Target: natural Mg of 6.0 mg/cm$^2$ thickness

Production of the high-spin isomer in $^{143}$Nd
✧ Projectile: $^{136}$Xe 7.6 MeV/u $\rightarrow$ 6.5 MeV/u, $T = 1 \mu s$
✧ Target: $^{12}$C of 1.7 mg/cm$^2$ thickness
Experimental setup for the measurement of g-factors

**Inverse reaction & Recoil shadow method**

1. Only \( \gamma \) rays emitted through isomeric states can be detected

2. Spin relaxation control
   - (I) **Recoil into Gas**
     - Suppress the nuclear spin relaxation during the flight
   - (II) **Stopper heating system**
     - Make the relaxation time long after stopping
Experimental Technique

**γ-ray Time-Differential Perturbed Angular Distribution (TDPAD) technique**

Intensity of γ ray: \( N(t, \theta, B_{\text{eff}}) = N_0 \exp\left(-\frac{\ln 2}{T_{\text{1/2}}} \cdot t\right) W(t, \theta, B_{\text{eff}}) \)

Angular distribution: \( W(t, \theta, B_{\text{eff}}) = \sum_{k, \text{even}} B_k(I)A_k(\gamma)P_k[\cos(\theta - \omega_k \cdot t)] \)

\[ \star R(t, \theta, B_{\text{eff}}) = \frac{N(t, \theta, B_{\text{eff}}) - N(t, \theta, \pi/2, B_{\text{eff}})}{N(t, \theta, B_{\text{eff}}) + N(t, \theta, \pi/2, B_{\text{eff}})} \]

\[ \approx \frac{3A_{22}}{4 + A_{22}} \cos[2(\theta - \omega_k \cdot t)] \quad \text{for} \ k \leq 2 \]

\( \omega_k \): Larmor frequency

**g factor**: \( g = \frac{\hbar \omega_k}{\mu_B B_{\text{eff}}} \)

\( B_{\text{eff}} = B_{\text{cur}} + B_{\text{int}} = \beta(T)B_{\text{int}} \)

\( \beta(T) \): Paramagnetic Correction Factor

\( \beta(T) = 1 + \frac{g_J(J + 1)\mu_B B(0)}{3k_B T} \)
Calibration of the paramagnetic field

For Dy$^{3+}$ ion: $J = 15/2$, $g_J = 4/3$

calibrated with the known $g$-factor of the isomeric state in $^{152}$Dy (produced concurrently with the $^{149m}$Dy)

For Nd$^{3+}$ ion: $J = 9/2$, $g_J = 8/11$

calibrated with $B(0) = 3.51(10)$ MG
for Nd$^{3+}$ ion given by D.Riegel et al.
Result for the high-spin isomer in $^{149}$Dy

<table>
<thead>
<tr>
<th>$T$</th>
<th>$\omega_L$ [rad/ns]</th>
<th>$\beta$</th>
<th>$g_{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>328</td>
<td>0.19(2)</td>
<td>6.4(9)</td>
<td>0.41(7)</td>
</tr>
<tr>
<td>533</td>
<td>0.11(2)</td>
<td>3.6(5)</td>
<td>0.41(9)</td>
</tr>
</tbody>
</table>

$g_{exp} = 0.41(6)$

<table>
<thead>
<tr>
<th>$I^\pi$</th>
<th>Configuration (DIPM)</th>
<th>$g_{cal}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$47/2^-$</td>
<td>$\pi (h_{11/2}^3g_{7/2}^{-1}) \nu (i_{13/2})$</td>
<td>0.82</td>
</tr>
<tr>
<td>$49/2^+$</td>
<td>$\pi (h_{11/2}^2) \nu (f_{7/2} h_{9/2} i_{13/2})$</td>
<td>0.46</td>
</tr>
</tbody>
</table>

$^* g_\pi(\pi) = 1.1$, $g_\pi(\nu) = -0.03$, $g_\nu = 0.6g_s$(free)
Result for the high-spin isomer in $^{143}$Nd

$\omega_L = 0.082 \pm 0.006 \text{ rad/ns}$

$g_{\text{exp}} = 0.56 \pm 0.04$

Measured at $T = 302$ K
Experimental $g$-factors of the high-spin isomers in $N = 83$ isotones

$g$-factor

$\pi (h_{11/2}^2) \nu (f_{7/2} h_{9/2} i_{13/2})$

$Z = 64$ shell-gap energies which reproduce the experimental excitation energies of the high-spin isomers in $N = 83$ isotones
# Condensed matter studies with spin-aligned isomeric beams

## 4d atomic-shell

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$E_x$ [keV]</th>
<th>$T_1/2$</th>
<th>I</th>
<th>$\mu$ [nm]</th>
<th>Q[b]</th>
</tr>
</thead>
<tbody>
<tr>
<td>85Y</td>
<td>266</td>
<td>170 ns</td>
<td>5/2–</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td>88Zr</td>
<td>2889</td>
<td>1.32 μs</td>
<td>8+</td>
<td>−1.81</td>
<td>0.51</td>
</tr>
<tr>
<td>90Zr</td>
<td>3589</td>
<td>134 ns</td>
<td>8+</td>
<td>10.84</td>
<td>−0.51</td>
</tr>
<tr>
<td>91Zr</td>
<td>3167</td>
<td>3.6 μs</td>
<td>21/2+</td>
<td>9.82</td>
<td>−0.86</td>
</tr>
<tr>
<td>97Zr</td>
<td>1264</td>
<td>102 ns</td>
<td>7/2+</td>
<td>1.37</td>
<td></td>
</tr>
<tr>
<td>90Nb</td>
<td>1881</td>
<td>477 ns</td>
<td>11−</td>
<td>8.78</td>
<td></td>
</tr>
<tr>
<td>91Nb</td>
<td>2037</td>
<td>3.4 μs</td>
<td>17/2−</td>
<td>10.82</td>
<td></td>
</tr>
<tr>
<td>92Nb</td>
<td>2203</td>
<td>167 ns</td>
<td>11−</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td>90Mo</td>
<td>2875</td>
<td>1.1 μs</td>
<td>8+</td>
<td>−1.391</td>
<td>0.58</td>
</tr>
<tr>
<td>92Mo</td>
<td>2760</td>
<td>190 ns</td>
<td>8+</td>
<td>11.3</td>
<td>−0.34</td>
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<tr>
<td>94Mo</td>
<td>2956</td>
<td>98 ns</td>
<td>8+</td>
<td>10.46</td>
<td>0.47</td>
</tr>
<tr>
<td>93Tc</td>
<td>2186</td>
<td>10.1 μs</td>
<td>17/2–</td>
<td>10.46</td>
<td></td>
</tr>
<tr>
<td>93Ru</td>
<td>2082</td>
<td>2.4 μs</td>
<td>21/2+</td>
<td>8.97</td>
<td>0.04</td>
</tr>
<tr>
<td>100Rh</td>
<td>75</td>
<td>215 ns</td>
<td>2+</td>
<td>4.324</td>
<td></td>
</tr>
<tr>
<td></td>
<td>112+4+</td>
<td>140 ns</td>
<td>7+</td>
<td>4.69</td>
<td></td>
</tr>
<tr>
<td>104Rh</td>
<td>215.5+4+</td>
<td>47 ns</td>
<td>6−</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>96Pd</td>
<td>2532</td>
<td>2.22 μs</td>
<td>8+</td>
<td>10.97</td>
<td></td>
</tr>
</tbody>
</table>

## 4f atomic-shell

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$E_x$ [keV]</th>
<th>$T_1/2$</th>
<th>I</th>
<th>$\mu$ [nm]</th>
<th>Q[b]</th>
</tr>
</thead>
<tbody>
<tr>
<td>134Ce</td>
<td>3209</td>
<td>308 ns</td>
<td>10+</td>
<td>−1.87</td>
<td>1.32</td>
</tr>
<tr>
<td>136Ce</td>
<td>3096</td>
<td>2.2 μs</td>
<td>10+</td>
<td>−1.8</td>
<td></td>
</tr>
<tr>
<td>138Ce</td>
<td>3538</td>
<td>82 ns</td>
<td>10+</td>
<td>−1.7</td>
<td></td>
</tr>
<tr>
<td>139Ce</td>
<td>2632</td>
<td>70 ns</td>
<td>19/2–</td>
<td>3.99</td>
<td></td>
</tr>
<tr>
<td>136Pr</td>
<td>548</td>
<td>90 ns</td>
<td>4+</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>138Nd</td>
<td>3172</td>
<td>330 ns</td>
<td>10+</td>
<td>−1.74</td>
<td></td>
</tr>
<tr>
<td>148Nd</td>
<td>3621</td>
<td>330 ns</td>
<td>10+</td>
<td>−1.75</td>
<td></td>
</tr>
<tr>
<td>142Sm</td>
<td>2372</td>
<td>170 ns</td>
<td>7−</td>
<td>0.42</td>
<td>1.1</td>
</tr>
<tr>
<td>151Sm</td>
<td>92</td>
<td>77 ns</td>
<td>9/2+</td>
<td>−0.95</td>
<td></td>
</tr>
<tr>
<td>145Eu</td>
<td>716</td>
<td>0.49 μs</td>
<td>11/2–</td>
<td>7.46</td>
<td></td>
</tr>
<tr>
<td>147Eu</td>
<td>635</td>
<td>765 ns</td>
<td>11/2–</td>
<td>7.05</td>
<td></td>
</tr>
<tr>
<td>148Eu</td>
<td>720</td>
<td>235 ns</td>
<td>9+</td>
<td>6.12</td>
<td></td>
</tr>
<tr>
<td>144Gd</td>
<td>3433</td>
<td>130 ns</td>
<td>10+</td>
<td>12.76</td>
<td>−1.46</td>
</tr>
<tr>
<td>147Gd</td>
<td>8587</td>
<td>510 ns</td>
<td>49/2+</td>
<td>10.9</td>
<td>−3.24</td>
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<tr>
<td>158Dy</td>
<td>99</td>
<td>1.66 μs</td>
<td>2+</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>168Er</td>
<td>1094</td>
<td>112.5 ns</td>
<td>4−</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>169Tm</td>
<td>316</td>
<td>660 ns</td>
<td>7/2+</td>
<td>0.156</td>
<td></td>
</tr>
<tr>
<td>157Yb</td>
<td>494+4+</td>
<td>45 ns</td>
<td>13/2+</td>
<td>−0.75</td>
<td></td>
</tr>
</tbody>
</table>
Why Ce beam?

Many physical phenomena, such as ferro- and anti-ferromagnetism, Kondo effect, superconductivity, and heavy-fermion behavior can take place in Ce-based compounds and alloys.

The RKKY interaction gives rise to various kinds of magnetic ordering.

Demagnetization is caused by the Kondo effect.

Heavy fermion system

Properties of Ce-based systems

\[ \varepsilon_F \gg E_f \]

\[ \varepsilon_F \ll E_f \]

\[ k_B T_{RKKY} \sim J_{cf} D_c(\varepsilon_F) \]

\[ k_B T_K \sim \exp[-1/J_{cf} D_c(\varepsilon_F)] \]

\[ T \]

\[ J_{cf} D_c(\varepsilon_F) \]

CeIn₃, CeCu₂Si₂, CeCu₆, CeRu₂Si₂, CeNi, CeSn₃, CeAl₂, CeAl₃, CeB₆

\[ \text{A.F.} \]

\[ T_N \]

Quantum critical point

Heavy-fermion (Fermi liquid)

\[ T_k \]

\[ T_{RKKY} \]

\[ \varepsilon_F \approx E_f \]

Compete

localize around the atom

itinerate in the crystal

many physical phenomena, such as ferro- and anti-ferromagnetism, Kondo effect, superconductivity, and heavy-fermion behavior can take place in Ce-based compounds and alloys.
Anomalous ferromagnetism in CeRh$_3$B$_2$

- $T_c = 115 \text{ K}$ → the highest Curie temperature among known Ce-based compounds with nonmagnetic constituents
  [GdRh$_3$B$_2$ ($T_c = 90 \text{ K}$) → expected to be $T_c \sim 1 \text{ K}$]
  de Genne law

- Hexagonal ternary (CeCo$_3$B$_2$-type) structure
  Ce-Ce chain along the $c$-axis → very close Ce-Ce distance (3.09 Å)

- Small magnetic moments
  \[ \mu_{\text{bulk}} = 0.42 \mu_B / \text{f.u.} \]
  \[ \mu_{\text{Ce}} = 0.38 \mu_B / \text{Ce} \]

- Magnetic anisotropy
  \[ \mu_{(c\text{-plane})} / \mu_{(c\text{-axis})} = 2.5 \]
Production of the $^{134}\text{Ce}$ isomeric beam

Fusion reaction with inverse-kinematics

Low energy beam
Not-fully-stripped charge state

Very large hyperfine fields are produced by the atomic electrons

Keep the initial nuclear alignment by transporting only one charge state of Ce ions which have the Ne-like atomic shell

Optimal condition for the production of $^{134m}\text{Ce}^{48+}$

- Projectile: $^{131}\text{Xe}$, $E = 8$ MeV/u, $I = 5$ pnA ($T = 3\mu s$)
- Target: $^9\text{Be}$, 7.5 $\mu$ m
- Reaction: $^9\text{Be}(^{131}\text{Xe}, 6n)^{134m}\text{Ce}$ (Isomer ratio = 17 %)

$^{134m}\text{Ce}$ intensity @F3 $\cdots 6.9 \times 10^3 /s$
Summary

Spin-aligned isomers become excellent probes for studies of nuclear moments and condensed matter studies.

$g$-Factor measurements of high-spin isomers

$g^{(149m\text{Dy})} = 0.41 \pm 0.06$
$g^{(143m\text{Nd})} = 0.56 \pm 0.04$

Main configuration of the high-spin isomers in $N = 83$ isotones

$[\pi (h_{11/2}^2) \otimes \nu (f_{7/2} h_{9/2} i_{13/2})]$

The $g$-factors of these isomers gradually increase as the proton numbers decrease.

Condensed matter studies with spin-aligned isomeric beams

$^{134}\text{Ce}$ isomeric beam will be developed.

$\text{CeRh}_3\text{B}_2$ ($T_c = 115$ K) will be studied in near future.
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