Aspects of nuclear isomerism and shape coexistence

- historical introduction
- energy storage
- enhanced stability
- high-K isomers
- neutron-rich A≈190 isomers

Phil Walker
**Isomer prediction:** Soddy, *Nature* 99 (1917) 433

“We can have isotopes with identity of atomic weight, as well as of chemical character, which are different in their stability and mode of breaking up.”

**Explanation:** von Weizsäcker, *Naturwissenschaften* 24 (1936) 813

Isomer half-lives range from $10^{-9}$ seconds to $>10^{16}$ years
Historical background: isomers

1917: Soddy predicts existence of isomers
1921: Hahn observations: UZ, UX₂ (²³⁴Pa, 7 h; ²³⁴ᵐPa, 1 m)
1935: Kurtchatov observes bromine isomers
1936: von Weizsäcker explains isomers as spin traps
1938: Hahn identifies barium from neutrons on uranium
1939: Meitner and Frisch explain Hahn’s discovery: fission
1955: Alaga et al. explain K isomers
1962: Polikanov discovers fission isomers (²⁴²ᵐAm, 14 ms)

“The whole ‘fission’ process can thus be described in an essentially classical way …”
“… it might not be necessary to assume nuclear isomerism”.

Meitner and Frisch, Nature 3615 (Feb 1939) 239

Otto Hahn
discoverer of
isomers and fission

Lise Meitner
“mother of
nuclear structure”
Historical background: isomers

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Meitner and Frisch,
Nature 3615 (Feb 1939) 239
\( ^{180}\text{Hf} \) isomer decay: nuclear collective rotation

\[ K^{\pi} = I^{\pi} = 8^{-} : \text{broken-pair excitation} \]

\( K \) quantum number not yet recognised

\[ E(I) = \left( \frac{\hbar^2}{2\Sigma} \right) I(I+1) \]

\[ \Sigma \sim \frac{1}{3} \Sigma_{\text{rigid}} \Rightarrow \text{superfluidity} \]

\( ^{180}\text{Hf}: \frac{E(4^{+})}{E(2^{+})} = 3.30 \)

perfect rotor: \( \frac{E(4^{+})}{E(2^{+})} = 3.33 \)

interplay between individual-particle and collective degrees of freedom

Bohr and Mottelson, Phys. Rev. 90 (1953) 717
$^{180}$Hf isomer decay: nuclear collective rotation

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access to "exotic" nuclear states

interplay between individual-particle and collective degrees of freedom

Bohr and Mottelson, Phys. Rev. 90 (1953) 717
K-forbidden γ-ray transitions

degree of forbiddenness, \( \nu = \Delta K - \lambda \)

=> \( \lambda=1 \) transition is 7-fold K-forbidden (\( \nu = 7 \))
Extreme isomers

<table>
<thead>
<tr>
<th>Category</th>
<th>Isotope</th>
<th>Spin</th>
<th>Energy</th>
<th>Rate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>long half-life:</td>
<td>$^{180}$Ta</td>
<td>$9^-$</td>
<td>75 keV</td>
<td>$&gt;4.5 \times 10^{16}$ y</td>
<td>PRC 2017</td>
</tr>
<tr>
<td>high spin:</td>
<td>$^{212}$Rn</td>
<td>$38^+$</td>
<td>12.5 MeV*</td>
<td>8 ns</td>
<td>PLB 2008</td>
</tr>
<tr>
<td>high energy:</td>
<td>$^{152}$Er</td>
<td></td>
<td>13.4 MeV*</td>
<td>11 ns</td>
<td>PRC 1992</td>
</tr>
<tr>
<td>low energy:</td>
<td>$^{229}$Th</td>
<td>3/2$^+$</td>
<td>8 eV</td>
<td>7 μs</td>
<td>PRL 2017</td>
</tr>
<tr>
<td>low mass:</td>
<td>$^{12}$Be</td>
<td>0$^+$</td>
<td>2.2 MeV</td>
<td>230 ns</td>
<td>PLB 2010</td>
</tr>
<tr>
<td>high mass:</td>
<td>$^{270}$Ds</td>
<td>10$^-$</td>
<td>1 MeV</td>
<td>6 ms</td>
<td>EPJA 2001</td>
</tr>
</tbody>
</table>

* unbound to both p and n emission

decay rates vary over at least 32 orders of magnitude
$^{99m}$Tc: an isomer in the clinic

$^{99m}$Tc \quad 6 \text{ hours} \quad \frac{1}{2^+} - \frac{7}{2^+}

2 \text{ keV} \quad \alpha = 10^{10}

141 \text{ keV} \quad \alpha = 0.1

$^{99g}$Tc \quad 200,000 \text{ years} \quad \frac{9}{2^+}$
isomers as nuclear “batteries”?  
can isomer energy be released in a controlled manner?

conceptual picture:

energy axis

110 keV  
100 keV  
10 keV  
110 keV

intermediate state
long-lived isomer
ground state

energy release ~100 keV per atom

cf. chemical energy ~ 1 eV per atom
180\textsuperscript{Ta} photoexcitation and decay

nature's only "stable" isomer

astrophysical scenarios and role of K quantum number


Nuclear Excitation by Electron Capture: NEEC from $^{93m}$Mo

Chiara et al., Nature 554 (2018) 216

first observation
isomers in superheavy nuclei: $\alpha$ decay

$^{270}_{110}$Ds $\alpha$ decay

6 ms isomer at 1 MeV

$\alpha$ 100%?

$^{0+}$

0.1 ms ground state

$\alpha$ 100%


isomers can provide extra stability for superheavy nuclei
isomers in superheavy nuclei: fission

\[ ^{254}\text{Rf}_{104} \]


250 μs (<40% SF)

5 μs (<10% SF)

23 μs (100% SF)

Extra stability against fission: see also 250\textsuperscript{No}

\textbf{Rf} \textsuperscript{254}

\begin{align*}
23 \mu s \text{ (100\% SF)} & & 5 \mu s \text{ (<10\% SF)} & & 250 \mu s \text{ (<40\% SF)} \\
\end{align*}
nuclear chart with >1 MeV isomers

adapted from Walker and Dracoulis, Nature 399 (1999) 35

recent isomer reviews:

- high-K
  - Kondev et al., ADNDT 103-104 (2015) 50
- Dracoulis et al., Rep. Prog. Phys. 79 (2016) 076301
nuclear chart with >1 MeV isomers

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recent isomer reviews:
- high-K
  - Kondev et al., ADNDT 103-104 (2015) 50
- A ≥ 150
  - Dracoulis et al., Rep. Prog. Phys. 79 (2016) 076301
A~180 isomers with at least 2 broken pairs \((\geq 4 \text{ quasiparticles})\)

Walker, Prog. Part. Nucl. Phys. to be published
A~180 isomers with at least 2 broken pairs (≥4 quasiparticles)

Walker, Prog. Part. Nucl. Phys. to be published
178\text{Hf}^{106}_{72}

K and spin isomerism combined

495-keV gate

0.005%

data from the 8π spectrometer at TRIUMF

$^{178}$Hf has $N=106$, $Z=72$, $\beta_2 \sim 0.25$

Woods-Saxon potential

$^{178}$Hf has $N=106$, $Z=72$, $\beta_2 \sim 0.25$

$^{178}\text{W}$ energy vs. spin

Multi-quasiparticle states: Woods-Saxon-Strutinsky configuration-constrained calculations and exp.

rms deviation $\approx 1.7\%$

Walker, Prog. Part. Nucl. Phys. to be published
A≈180 multi-quasiparticle isomer half-lives

Limits to K isomerism

neutron-rich hafnium (Z = 72) region
hafnium (Z=72) 4-qp isomers

Walker and Dracoulis, Hyp. Int. 135 (2001) 83
prolate-oblate shape transition (ground states)

N = 114

HFB + SLy4

N = 116 critical point

$^{180}$Hf prolate $\rightarrow$ oblate \textit{at high spin}

the original rotor of Bohr and Mottelson, 1953

Giant backbending is predicted to occur in $^{180}$Hf at $J \approx 26\hbar$

prediction (HFB):
\textit{Hilton and Mang PRL43 (1979) 1979}
$^{180}$Hf prolate $\rightarrow$ oblate at high spin

the original rotor of Bohr and Mottelson, 1953

experiment (Gammasphere at ANL):
Tandel et al. PRL101 (2008) 182503

prediction (HFB):
Hilton and Mang PRL43 (1979) 1979
total Routhian surfaces (TRS): $^{182}$Hf


$\hbar\omega = 0.2$ MeV, $\hbar\omega = 0.3$ MeV, $\hbar\omega = 0.4$ MeV

prolate

oblate

$I \sim 20$
total Routhian surfaces (TRS): $^{182}$Hf


\[ \hbar \omega = 0.2 \text{ MeV} \]
\[ \hbar \omega = 0.3 \text{ MeV} \]
\[ \hbar \omega = 0.4 \text{ MeV} \]

but don’t forget the non-collective (m-p) minimum

prolate

oblative

I~20
TRS calculations  


\[ E (\text{MeV}) - 0.00501(I+1) \]
Nilsson single-particle diagram $\bullet N = 116 \ (^{188}\text{Hf}, \ ^{190}\text{W}, \ ^{192}\text{Os})$
Nilsson single-particle diagram  \( N = 116 \) \( (^{188}\text{Hf},\,^{190}\text{W},\,^{192}\text{Os}) \)

and similarly for protons \( (Z \sim 72) \)
Spins > 20 h possible

$^{136}$Xe on $^{192}$Os

$^{192}$Os on $^{116}$Sb

$^{192}$Os

200 ns isomer

$^{136}$Xe on $^{192}$Os

prolate $\rightarrow$ oblate bandcrossing

high-K isomer

6 s, 10 h

oblate isomer

20 h


(Gammasphere data)
Spins > 20 $\hbar$ possible

($^{136}$Xe on $^{192}$Os)

$^{192}_{76}$Os$_{116}$

issue of triaxiality

Gammasphere data

E(4$^+$)/E(2$^+$) = 2.82

prolate $\rightarrow$ oblate bandcrossing

high-K isomer
6 s, 10 $\hbar$

oblate
200 ns isomer
20 $\hbar$
A~180 isomers with at least 2 broken pairs

Walker, Prog. Part. Nucl. Phys. to be published
Summary – high-K isomers

superheavy nuclei – extra stability
A~190 neutron-rich – long-lived isomers, oblate coexistence

future challenges – n-rich Hf, Ta data, isomer manipulation

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Filip Kondev (Argonne)
George Dracoulis (ANU)
Yoshikazu Hirayama (KEK)
184Hf and 187Ta isomers seen in the ESR at GSI

A = 184, q = 72+

- Bare 184Hf72+
- T\(_{1/2}\) = 113 s
- E\(_x\) = 1264 keV

A = 187, q = 73+

- Bare 187Ta73+
- T\(_{1/2}\) > 5 min
- E\(_x\) = 2477 keV

197Au fragmentation

⇒ T\(_{1/2}\)(m1) = 22 s
⇒ E\(_x\) = 1789 keV
⇒ K^π=27/2^- (predicted)

⇒ T\(_{1/2}\)(m2) > 5 min
⇒ E\(_x\) = 2935 keV
⇒ K^π=41/2^+ (predicted)

new experimental programme at the KEK Isotope Separation System

KISS principles

now operating at RIKEN

KISS principles

186\text{W}

136\text{Xe}

7.2 \text{ A.MeV}

Ar gas 50 kPa

gas flow

Resonance Ionization (laser)

\approx 500 \text{ ms}

\beta and \gamma detection

tape transport

ISOL (A separation)

delete hole

decay station for spectroscopy

from Jeong et al., KEK Report 2010-2;
see also Hirayama et al., Phys. Rev. C96 (2017) 014307
new experimental programme at the KEK Isotope Separation System

known $\gamma$'s in $^{187}$W

see also Hirayama et al., Phys. Rev. C96 (2017) 014307
possibility of coherent $\gamma$-ray emission from a Bose-Einstein condensate of $^{135}\text{Cs}$ isomers at 100 nK