Spectroscopy of Very Heavy Elements

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What is the link?
Outline

1. Introduction
2. Experimental Approaches
3. Alpha Decay (Fine Structure) Spectroscopy
4. In-Beam Spectroscopy
5. Structure of High-K States
6. Future Perspectives
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What is the structure of SHE?
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Decay Spectroscopy - Case Study $^{255}$No

- **Target chamber**
- **He/KCl**
- **$^{251}$Cf target**
- **$^{12}$C beam (71 MeV)**

**JAEE Tandem accelerator**
- Beam intensity: ~600 pA
- Total beam time: 14 days

**Rotating wheel $\alpha$-\gamma detection system**
- **Gas-jet transport**
- **259Rf**
- **Vacuum chamber**
- **Catcher foils (x 40)**
  - 120 $\mu$g/cm$^2$ PET
- **Pb shield**
- **Ge**
- **Si PIN photodiodes**
  - 18 x 18 mm$^2$

**Detection efficiency**
- Si ($\alpha$): 87%
- Ge ($\gamma$): 30%
Decay Spectroscopy - Case Study $^{255}$No

M. Asai et al., PRC 83, 014315 (2011) and ARIS2011

FIG. 2. Two-dimensional plots of $\alpha$-$\gamma$ coincidence events: (a) prompt coincidence events detected within the time interval $0 < t < 22$ ns, (b) delayed coincidence events detected with the time interval $22 < t < 700$ ns.
Decay Spectroscopy - Case Study $^{255}$No

M. Asai et al., PRC 83, 014315 (2011) and ARIS2011

FIG. 6. $\alpha$ fine-structure spectrum of $^{255}$No measured during the period of 90–360 s after the ends of the source depositions.
Decay Spectroscopy - Case Study $^{255}\text{No}$

FIG. 6. $\alpha$ fine-structure spectrum of $^{255}\text{No}$ measured during the period of 90–360 s after the ends of the source depositions.
Decay Spectroscopy - Case Study $^{255}$No

TABLE III. Hindrance factors of $\alpha$ transitions from the $1/2^+ [620]$ ground states in the $N = 153$ isotones $^{253}$Cf, $^{253}$Fm, and $^{255}$No to excited states in the $N = 151$ daughters. They were calculated on the basis of the Preston's spin-independent theory [21] using the radius parameters given in Refs. [22,23].

<table>
<thead>
<tr>
<th>Nilsson orbital</th>
<th>Populated level</th>
<th>$^{253}$Cf $\rightarrow$ $^{247}$Cm</th>
<th>$^{253}$Fm $\rightarrow$ $^{249}$Cf</th>
<th>$^{255}$No $\rightarrow$ $^{253}$Fm</th>
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</thead>
<tbody>
<tr>
<td>$1/2^+[620]$</td>
<td>$5/2^+$</td>
<td>11</td>
<td>17</td>
<td>18</td>
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<tr>
<td></td>
<td>$3/2^+$</td>
<td>19</td>
<td>23</td>
<td>22</td>
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<tr>
<td></td>
<td>$1/2^+$</td>
<td>2.6</td>
<td>3.0</td>
<td>3.8</td>
</tr>
<tr>
<td>$1/2^+[631]$</td>
<td>$5/2^+$</td>
<td>32</td>
<td>31</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>$3/2^+$</td>
<td>11</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>$5/2^+[622]$</td>
<td>$9/2^+$</td>
<td>77</td>
<td>48</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>$7/2^+$</td>
<td>134</td>
<td>72</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>$5/2^+$</td>
<td>31</td>
<td>25</td>
<td>42</td>
</tr>
<tr>
<td>$9/2^-[734]$</td>
<td>$11/2^-$</td>
<td>512</td>
<td>350</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>$9/2^-$</td>
<td>5100</td>
<td>3200</td>
<td>4800</td>
</tr>
</tbody>
</table>

TABLE IV. $B(E2)$ values of $1/2^+ [631] \rightarrow 5/2^+[622]$ and $1/2^+[620] \rightarrow 5/2^+[622]$ transitions in various actinide nuclei.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$E_{level}$ (keV)</th>
<th>$\tau_{1/2}$</th>
<th>$E_{y}$ (keV)</th>
<th>$B(E2)$ (W.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{239}$U</td>
<td>133.7</td>
<td>0.78(4) $\mu$s</td>
<td>133.7</td>
<td>0.0404(21)</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>161.4</td>
<td>0.88(5) $\mu$s</td>
<td>161.4</td>
<td>0.0218(12)</td>
</tr>
<tr>
<td>$^{243}$Cm</td>
<td>87.4</td>
<td>1.08(3) $\mu$s</td>
<td>87.4</td>
<td>0.0313(9)</td>
</tr>
<tr>
<td>$^{249}$Pu</td>
<td>383.6</td>
<td>0.33(3) $\mu$s</td>
<td>96.2</td>
<td>0.114(10)</td>
</tr>
<tr>
<td>$^{251}$Cm</td>
<td>355.9</td>
<td>0.29(2) $\mu$s</td>
<td>103.0</td>
<td>0.105(7)</td>
</tr>
<tr>
<td></td>
<td>392.0</td>
<td>22(3) ns</td>
<td>191.9</td>
<td>0.41(6)</td>
</tr>
<tr>
<td>$^{251}$Fm</td>
<td>311</td>
<td>0.33(2) $\mu$s</td>
<td>47</td>
<td>0.139(8)</td>
</tr>
<tr>
<td>$^{243}$Pu</td>
<td>404.9</td>
<td>100.6(6) ns</td>
<td>177.5</td>
<td>0.1338(8)</td>
</tr>
<tr>
<td>$^{251}$Cm</td>
<td>311</td>
<td>0.33(2) $\mu$s</td>
<td>47</td>
<td>0.139(8)</td>
</tr>
<tr>
<td>$^{243}$Pu</td>
<td>404.9</td>
<td>100.6(6) ns</td>
<td>177.5</td>
<td>0.1338(8)</td>
</tr>
</tbody>
</table>
Decay Spectroscopy - Case Study $^{255}$No

(a) Exp. $N = 151$ systematics

(b) Calc. 1 (Present)

(c) Calc. 2 (Ref.)

Woods-Saxon $E_{sp}$

Paul Greenlees (JYFL, Finland)
Decay spectroscopy of $^{255}$Lr

A.Chatillon et al., EPJA 30 397 (2006)

![Image of spectrum and decay curves]

**Fig. 4.** Portion of the α-decay spectrum, resulting from recoil-α correlations, in the $^{255}$Lr region. Data are taken from the JYFL experiment.

**Fig. 5.** Decay curves corresponding to the 8365 keV (upper panel) and 8457 keV (lower panel) α-decay lines.

**Fig. 9.** Upper panel: matrix corresponding to prompt α-γ correlations. Lower panel: γ transition in coincidence with the $^{251}$Md α line. Data are taken from the GANIL experiment.

**Fig. 13.** Level scheme of $^{247}$Es $^{251}$Md and $^{255}$Lr deduced from experimental data. The tentative 8290 keV line from $^{255}$Lr is not shown.
Decay spectroscopy at SHIP

Trace separation of states from 4 spherical shells:

- $\pi[521]1/2^{-} (2f_5/2)$
- $\pi[514]7/2^{-} (1h_9/2)$
- $\pi[633]7/2^{+} (1i_{13}/2)$
- $\pi[521]3/2^{-} (2f_7/2)$
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Principles of Recoil- Decay Tagging

Tagging Techniques
Recoil, Recoil–Decay, Isomer

Time Line:

\[ \Delta t < \Delta T \]

Prompt \( \gamma \)'s

\( g.s. \)

Isomer

\( \tau \)

Delayed \( \gamma \)'s

\( g.s. \)

\( \tau \)

\( \alpha \)

\( R(x,y,t) \)

\( \alpha(x,y,t+\Delta t) \)

Paul Greenlees (JYFL, Finland)
Over a decade of in-beam studies in the region of $^{254}$No

P. Reiter et al., PRL 82, 509 (1999)

The ground-state band of the $\text{Z} = 12$ isotope $^{254}$No has been identified up to spin 14, indicating that the nucleus is deformed. The deduced quadrupole deformation, $\beta = 27^\circ$, is in agreement with theoretical predictions. These observations confirm that the shell-correction energy responsible for the stability of transfermium nuclei is partly derived from deformation. The survival of $^{254}$No up to spin 14 means that its fission barrier persists at least up to that spin. [S0031-9007(98)08223-4]
In-beam $\gamma$-ray Spectroscopy of $^{254}$No

Unpublished spectrum, see also S. Eeckhaudt, P.T. Greenlees et al., EPJA 26, 227 (2005)
Rotational Bands

Harris Fits

- $\mathcal{J}^{(1)} = \frac{\hbar^2}{\frac{2I-1}{E_\gamma}}$
- $\mathcal{J}^{(2)} = \frac{4\hbar^2}{\Delta E_\gamma}$
- $\mathcal{J}^{(1)} = \mathcal{J}_0 + \mathcal{J}_1 \omega^2$
- $\mathcal{J}^{(2)} = \mathcal{J}_0 + 3\mathcal{J}_1 \omega^2$
- $I = \mathcal{J}_0 \omega + \mathcal{J}_1 \omega^3 + 1/2$
Rotational Bands

$^{254}_{\text{No}}$

$J_0 = 68.20 \quad J_1 = 164.73$

Harris Fits

- $J^{(1)} = \hbar^2 \frac{2I-1}{E_{\gamma 1}}$
- $J^{(2)} = \frac{4\hbar^2}{\Delta E_{\gamma}}$
- $J^{(1)} = J_0 + J_1 \omega^2$
- $J^{(2)} = J_0 + 3J_1 \omega^2$
- $I = J_0 \omega + J_1 \omega^3 + 1/2$
Rotational Bands

$^{252}\text{No}$

$J_0 = 63.26, J_1 = 273.31$

Harris Fits

- $J^{(1)} = \frac{1}{E_{\gamma_1}}$
- $J^{(2)} = \frac{4\hbar^2}{\Delta E_{\gamma}}$
- $J^{(1)} = J_0 + J_1 \omega^2$
- $J^{(2)} = J_0 + 3J_1 \omega^2$
- $I = J_0 \omega + J_1 \omega^3 + 1/2$
In-beam studies in region of $^{254}$No

S. Eeckhaudt, P.T. Greenlees et al., EPJA 26, 227 (2005)

- Confirmed deformed nature of nuclei around $^{254}$No
- Showed fission barrier robust with spin ($>20\hbar$)
- Faster alignment at $N=150$ compared to $N=152$ ($\pi i_{13/2}, \nu j_{15/2}$)
- Excellent testing ground for theory; e.g. Duguet et al., NPA 679, 427 (2001), Bender et al., NPA 723, 354 (2003), Afanasjev et al., PRC 67, 024309 (2003), Egido and Robledo, PRL 85 1198 (2000)
Introduction

Experiments

Alpha Spec

In-Beam Spec

K-Isomerism

Future

Theory - $N=150$ vs. $N=152$

PHYSICAL REVIEW C 86, 011301(R) (2012)

Understanding the different rotational behaviors of $^{252}$No and $^{254}$No

H. L. Liu,¹,* F. R. Xu,² and P. M. Walker³,⁴

Paul Greenlees (JYFL, Finland)

Spectroscopy of VHE

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Recent history of JUROGAM

- Fifth and final campaign ended May 2008
- 2003 - 2008: 67 experiments, 11000 hours beam on target
- 2008: Fully instrumented with TNT2 digital electronics
- TNT2 cards in collaboration with CNRS/IN2P3 GABRIELA
- Superseded by JUROGAM II
The JUROGAM II Germanium Array

- 24 Clover and 15 Tapered Ge detectors - GAMMAPOOL resource
- Total Photopeak Efficiency \( \approx 6\% @ 1.3 \text{ MeV} \)
- Excellent \( \gamma-\gamma \) efficiency
- Autofill system built by University of York, part of GREAT
- Instrumented with TNT2 / Lyrtech digital electronics
- Higher counting rates, higher beam intensities
- 20,000 hours in-beam \( \gamma \)-ray spectroscopy passed in 2011
Next step - push to Rutherfordium $Z=104$

- Can produce $^{256}\text{Rf}$ using: $^{50}\text{Ti} + ^{208}\text{Pb} \rightarrow ^{256}\text{Rf} + 2\text{n}$
- Cross section below 20 nb
- Need high intensity $^{50}\text{Ti}$ beam
- Used up to 70 pnA in $^{246}\text{Fm}$ experiment
- Rotating target wheel built at IPHC Strasbourg

$^{50}\text{Ti}$ MIVOC beam development

- Metallic Ions from VOlatile Compounds
- Method developed at JYFL
- Synthesis of enriched $^{50}\text{Ti}$ compound led by IPHC Strasbourg
- Several years of hard work!
- 19 $\mu$A of $^{50}\text{Ti}^{11+}$ from ECR
- 490 enA on target
- Low consumption - 0.2 mg/hr
- See J.Rubert et al., NIMB 276, 33 (2012)
In-beam spectroscopy of SHE: $^{256}$Rf

**Experimental Details**

- $^{50}$Ti + $^{208}$Pb $\Rightarrow$ $^{256}$Rf + 2n
- JUROGAM II, RITU, GREAT
- Enriched $^{50}$Ti beam from MIVOC
- 450 hours, 29pnA beam, 2210 observed fissions
- Cross section 17 nb

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P.T. Greenlees, J. Rubert et al., PRL 109, 012501 (2012)
In-beam spectroscopy of SHE: $^{256}$Rf

Single-particle energies

Paul Greenlees, J. Rubert et al.,
PRL 109, 012501 (2012)
Experimental 2\(^+\) Energies

Harris Fits

\( \mathcal{J}^{(1)} = \hbar^2 \frac{2I-1}{E_\gamma 1} \)

\( \mathcal{J}^{(2)} = \frac{4\hbar^2}{\Delta E_\gamma} \)

\( \mathcal{J}^{(1)} = \mathcal{J}_0 + \mathcal{J}_1 \omega^2 \)

\( \mathcal{J}^{(2)} = \mathcal{J}_0 + 3 \mathcal{J}_1 \omega^2 \)

\( I = \mathcal{J}_0 \omega + \mathcal{J}_1 \omega^3 + 1/2 \)
Theoretical $2^+$ Energies

Sobiczewski, Muntian, Patyk. PRC 63, 034306 (2001)

(a)

(b)

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Spectroscopy of VHE

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Correlation to Masses - Isotopes

AME2003: \( S_{2n}(Z, N) = B(Z, N) - B(Z, N - 2) \), \( \delta_{2n}(Z, N) = S_{2n}(Z, N) - S_{2n}(Z, N + 2) \)
Correlation to Masses - Isotones

AME2003: $S_{2p}(Z, N) = B(Z, N) - B(Z - 2, N)$, $\delta_{2p}(Z, N) = S_{2p}(Z, N) - S_{2p}(Z + 2, N)$

(a)

(b)
Internal Conversion

- \( E_i = E_\gamma - B_i \);
- \( i = K, L_I, L_{II}, \ldots, M_V, \ldots \)
- \( \alpha_{tot} = \frac{N_e}{N_\gamma} = \alpha_K + \alpha_L + \ldots \)
- \( \alpha \propto \frac{Z^3}{n^3E_\gamma^{2.5}} \)
- \( \alpha \) increases strongly with multipolarity
- \( \alpha \) larger for magnetic transitions

![Diagram showing internal conversion process](image)

**Conversion coefficients for Z=103**

<table>
<thead>
<tr>
<th>E(\gamma) (MeV)</th>
<th>M1 (\alpha_{total})</th>
<th>M1 (\alpha_K)</th>
<th>E2 (\alpha_{total})</th>
<th>E2 (\alpha_K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>10^3</td>
<td>10^2</td>
<td>10^1</td>
<td>10^0</td>
</tr>
<tr>
<td>300</td>
<td>10^2</td>
<td></td>
<td>10^1</td>
<td>10^0</td>
</tr>
<tr>
<td>450</td>
<td>10^1</td>
<td></td>
<td>10^0</td>
<td>10^0</td>
</tr>
</tbody>
</table>

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Spectroscopy of VHE

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Internal Conversion

Fraction of 200 keV E2 converted

\[ f = \frac{\alpha}{1 + \alpha} \]

\[ Z \]

\[ 56 \ 58 \ 60 \ 62 \ 64 \ 66 \ 68 \ 70 \]

\[ \text{Fraction Converted (\%)} \]

\[ 200 \text{ keV E2} \]

\[ 70 \ 68 \ 66 \ 64 \ 62 \ 60 \ 58 \]

\[ 200 \text{ keV E2} \]

\[ Z \]

\[ 254 \text{ No} \]

\[ 102 \]

\[ \text{Electron} \  \text{Gamma} \]
Electromagnetic Properties

- Odd-proton orbitals in $^{251}\text{Md}$
- $B(\text{M1})/B(\text{E2})$ depends on $(g_K - g_R / Q_0)$
In-beam $\gamma$-ray Spectroscopy of $^{255}\text{Lr}$

$^{48}\text{Ca} + ^{209}\text{Bi} \rightarrow ^{255}\text{Lr} + 2\text{n}$, $\sigma \simeq 300$ nb, S. Ketelhut et al., PRL 102, 212501 (2009)
Spectrometer Design Considerations

**Efficiency**
- Broad Range
- Typically 0-1 MeV
- Backscattering - normal incidence

**Magnetic Field**
- Profile
- Strength

**Detector**
- Thickness
- Size
- Granularity

**Resolution**
- Intrinsic
- Doppler Broadening

**Delta Electron Suppression**
- Kinematics
- Biased Target
- Physical Block
- HV Barrier
- High Counting Rate Capability
- Tagging Techniques

**Combination with Ge**
- Maintain Ge Efficiency
- Maintain P/T
- Effect of stray field
The SACRED Electron Spectrometer

- Beam In
- Cold Finger
- 25 Element Annular Si Detector
- High Voltage Barrier
- Carbon He Containment Windows
- Target Chamber
- To RITU

P. A. Butler et al., NIM A381, 433 (1996)
Recoil-Decay Tagging with SACRED

$\delta$ electrons produced with atomic cross sections!

see also:
R.D. Humphreys et al., PRC69, 064324 (2004)
Conversion Electron Cascades in $^{254}_{102}$No

P. A. Butler,¹ R. D. Humphreys,¹ P. T. Greenlees,² R.-D. Herzberg,¹ D. G. Jenkins,¹ G. D. Jones,¹ H. Kankaanpää,² H. Kettunen,² P. Rahkila,² C. Scholey,¹,² J. Uusitalo,² N. Amzal,¹ J. E. Bastin,¹ P. M. T. Brew,¹ K. Eskola,³ J. Gerl,⁴ N. J. Hammond,¹ K. Hauschild,⁵ K. Helariutta,⁴ F.-P. Heßberger,⁴ A. Hürstel,⁵ P. M. Jones,² R. Julin,² S. Juutinen,² A. Keenan,² T.-L. Khoo,⁶ W. Korten,⁵ P. Kuusiniemi,² Y. Le Coz,⁵ M. Leino,² A.-P. Leppänen,² M. Muikkunen,² P. Nieminen,² S. W. Ødegård,⁷ T. Page,¹ J. Pakarinen,² P. Reiter,⁸ G. Sletten,⁹ Ch. Theisen,⁵ and H.-J. Wollersheim⁴

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Conversion-Electron Spectroscopy of $^{254}$No

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Spectroscopy of VHE

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The SAGE Spectrometer

SAGE - Silicon Detector

- 90 segments
- 51 mm diameter
- 1 mm thick

Simulated normalised count rate distribution using data from SACRED experiments

![Graph showing normalised count rate distribution](image)
SAGE - Silicon Detector

C.A.E.N. A1422 charge sensitive hybrid preamplifiers

- 400 mV/MeV
- Low noise
- Suitable for high count-rates
SAGE - Electronics

201 Fully digital channels
90 Si channels
111 Ge channels

Lyrtech VHS-ADC
SAGE - Shielding

- Photomultiplier tubes are sensitive to magnetic fields
- Shields: Weaken and redirect stray magnetic field
The SAGE Spectrometer

Full Geant4 Simulation
P.Papadakis, D.Cox, J.Konki, K.Hauschild, P. Rahkila

Figure 4.5: An example drawing of simulated events visualised in Geant4. Electrons are presented with red lines and gamma rays with blue. Only some of the electrons reach the detector while the others either interact with the surrounding materials (open circles) or are reflected back by the HV barrier. Note also the magnetic bottle effect of electrons being trapped in the magnetic field.
SAGE - Field Profile

**SAGE magnetic field profile**

Applied current 700 A

- **Measured**
- **Simulated**
ICC determination with SAGE-$^{133}\text{Ba}$
ICC determination with SAGE-\(^{177}\)Au Preliminary!

**177Au Gamma Spectrum**
Gamma-Gamma Gates on 160,289,453

**177Au Electron spectrum**
Gates on 160,453 gammas -> 160 electrons - > all subsequent gammas

<table>
<thead>
<tr>
<th>265 keV</th>
<th>9/2,11/2-&gt;9/2+</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICC</td>
<td>Value</td>
</tr>
<tr>
<td>K ICC Exp</td>
<td>0.132</td>
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<tr>
<td>K ICC BRICC</td>
<td>0.090</td>
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<tr>
<td>L ICC Exp</td>
<td>0.082</td>
</tr>
<tr>
<td>L ICC BRICC</td>
<td>0.050</td>
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<tr>
<td>K/L Exp</td>
<td>1.610</td>
</tr>
<tr>
<td>K/L BRICC</td>
<td>1.82</td>
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</table>

<table>
<thead>
<tr>
<th>257 keV</th>
<th>21/2-&gt;17/2+</th>
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</thead>
<tbody>
<tr>
<td>ICC</td>
<td>Value</td>
</tr>
<tr>
<td>K ICC Exp</td>
<td>0.088</td>
</tr>
<tr>
<td>K ICC Theo</td>
<td>0.091</td>
</tr>
<tr>
<td>L ICC Exp</td>
<td>0.062</td>
</tr>
<tr>
<td>L ICC BRICC</td>
<td>0.051</td>
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<tr>
<td>K/L Exp</td>
<td>1.421</td>
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<tr>
<td>K/L BRICC</td>
<td>1.644</td>
</tr>
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</table>
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K-Isomerism in $^{254}$No and $^{250}$Fm

- Transition forbidden if: $\Delta K \leq L$
- Degree of forbiddenness $\nu = \Delta K - L$
- Information on pairing gap, $\Delta$ and single-particle energies, $\epsilon_i$
- $E = \sqrt{(\epsilon_i - \lambda)^2 + \Delta^2} + \sqrt{(\epsilon_j - \lambda)^2 + \Delta^2}$
- Studies at focal plane - clean environment
- Often full decay path to ground state can be delineated
K-Isomerism in $^{254}$No and $^{250}$Fm

Isomeric states in $^{254}$No and $^{250}$Fm first postulated by Ghiorso et al., PRC7 (1973) 2032

The transfer of the $^{250}$Fm atoms from the wheel onto the movable detectors must then be caused by the feeble recoil resulting from the isomeric transition or other accompanying $\gamma$ rays and conversion electrons in the cascade that leads to the ground state. For a 500 keV $\gamma$ ray the recoil energy of a $^{250}$Fm atom is about 0.5 eV.
K-Isomerism in $^{254}$No


Determined Configurations:

3$^+$ - ($\pi [514]7/2^- \otimes \pi [521]1/2^-$)
8$^-$ - ($\pi [514]7/2^- \otimes \pi [624]9/2^+$)
53keV E1 $\Delta K=5$: $f_\nu = 804$
K-Isomerism in $^{254}$No

K-Isomerism in $^{254}$No

Determined Configurations:

$3^+ - (\pi[514]7/2^- \otimes \pi[521]1/2^-)$

$8^- - (\nu[734]9/2^- \otimes \nu[624]7/2^+)$

or $8^- - (\nu[734]9/2^- \otimes \nu[613]7/2^+)$

$10^+ - (\nu[734]9/2^- \otimes \nu[725]11/2^-)$

$16^+ - (\pi[514]7/2^- \otimes \pi[624]9/2^+) + (\nu[734]9/2^- \otimes \nu[613]7/2^+)$

R.M.Clarke et al., PLB 690, 19 (2010)
K-Isomerism in $^{250}$Fm

$^{48}$Ca + $^{204}$HgS $\Rightarrow$ $^{250}$Fm + 2n, JUROGAM+RITU+GREAT, P.T. Greenlees et al., PRC 78, 021301(R) (2008)

Focal Plane Gamma Rays

(a) Counts / keV vs. Energy [keV]
(b) Counts / 1.5keV vs. Energy [keV]
(c) Counts / 2keV vs. Energy [keV]
K-Isomerism in $^{250}$Fm

$^{48}$Ca + $^{204}$HgS $\rightarrow ^{250}$Fm + 2n, JUROGAM+RITU+GREAT, P.T. Greenlees et al., PRC 78, 021301(R) (2008)

**Ground State Band**

**Isomer-Tagged Transitions**
K-Isomerism in $^{250}$Fm

$^{250}$Fm: P.T. Greenlees et al. PRC 78, 021301(R) (2008)

- 8$^-$ - $\nu[624]7/2^+ \otimes \nu[734]9/2^-$ dominates
  - 682 keV E1 $\Delta K=8$: $f_\nu = 213$
  - 23.5 keV M1 $\Delta K=6$: $f_\nu = 192$

- 2$^-$ - $\nu[622]5/2^+ \otimes \nu[734]9/2^-$
## Known 2QP K-Isomers in Region

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$K^\pi$</th>
<th>$T_{1/2}$</th>
<th>$E_x$</th>
<th>Decay Mode</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{270}$Ds</td>
<td>$9^-,10^-$</td>
<td>6 ms</td>
<td>$\simeq 1.13$ MeV</td>
<td>$\alpha$</td>
<td>$9^- - \nu[725]11/2^- \otimes \nu[613]7/2^+$</td>
</tr>
<tr>
<td>$^{256}$Rf</td>
<td>6, 7?</td>
<td>25 $\mu$s</td>
<td>$\simeq 1.20$ MeV</td>
<td>$\gamma$</td>
<td>??</td>
</tr>
<tr>
<td>$^{256}$Rf</td>
<td>10 - 12?</td>
<td>17 $\mu$s</td>
<td>$\simeq 1.40$ MeV</td>
<td>$\gamma$</td>
<td>??</td>
</tr>
<tr>
<td>$^{254}$No</td>
<td>8$^-$</td>
<td>266 ms</td>
<td>1.293 MeV</td>
<td>$\gamma$</td>
<td>$8^- - \pi[514]7/2^- \otimes \pi[624]9/2^+$</td>
</tr>
<tr>
<td>$^{252}$No</td>
<td>8$^-$</td>
<td>110 ms</td>
<td>1.254 MeV</td>
<td>$\gamma$</td>
<td>$8^- - \nu[624]7/2^+ \otimes \nu[734]9/2^-$</td>
</tr>
<tr>
<td>$^{250}$No</td>
<td>6$^+$?</td>
<td>42 $\mu$s</td>
<td>??</td>
<td>SF, $\gamma$?</td>
<td>$6^+ - \nu[622]5/2^+ \otimes \nu[624]7/2^+$</td>
</tr>
<tr>
<td>$^{256}$Fm</td>
<td>7$^-$</td>
<td>70 ns</td>
<td>1.425 MeV</td>
<td>$\gamma, SF$</td>
<td>$7^- - \pi[633]7/2^+ \otimes \pi[514]7/2^-$</td>
</tr>
<tr>
<td>$^{250}$Fm</td>
<td>8$^-$</td>
<td>1.92 s</td>
<td>1.195 MeV</td>
<td>$\gamma$</td>
<td>$8^- - \nu[624]7/2^+ \otimes \nu[734]9/2^-$</td>
</tr>
<tr>
<td>$^{248}$Fm</td>
<td>??</td>
<td>$\simeq 8$ ms</td>
<td>??</td>
<td>??</td>
<td>??</td>
</tr>
<tr>
<td>$^{246}$Cm</td>
<td>8$^-$</td>
<td>??</td>
<td>1.179 MeV</td>
<td>$\gamma$</td>
<td>$8^- - \nu[624]7/2^+ \otimes \nu[734]9/2^-$</td>
</tr>
<tr>
<td>$^{244}$Cm</td>
<td>6$^+$</td>
<td>34 ms</td>
<td>1.040 MeV</td>
<td>$\gamma$</td>
<td>$6^+ - \nu[622]5/2^+ \otimes \nu[624]7/2^+$</td>
</tr>
</tbody>
</table>

- **References:** See R.-D. Herzberg and P.T. Greenlees, Prog. Part. Nuc. Phys. 61, 674 (2008)
- **$^{256}$Rf:** H.B. Jeppesen et al., PRC 79, 031303(R) (2009)
- **3QP isomer in $^{255}$Lr (Dubna/GSI/JYFL/Berkeley).** Also in $^{253}$No
**Systematics of 2 quasi-particle states**

N=150: A.Robinson et al., PRC 78, 034308 (2008)

N=150/152: P.T.Greenlees et al., PRC 78, 021303(R) (2008)
Self-Consistent Calculations

HFB Gogny D1S

HFB SLy4 - from A. Chatillon et al., EPJA 30 397 (2006)
Self-Consistent Calculations

Taken from Talk of Paul-Henri Heenen (http://nuclear1.paisley.ac.uk/SHEworkshop/)
Self-Consistent Calculations

Taken from Talk of Paul-Henri Heenen (http://nuclear1.paisley.ac.uk/SHEworkshop/)
Outline

1. Introduction
2. Experimental Approaches
3. Alpha Decay (Fine Structure) Spectroscopy
4. In-Beam Spectroscopy
5. Structure of High-K States
6. Future Perspectives
Future with Stable Beams: Upgrades / New Devices

IRiS
HEAVY ELEMENTS
TASiSpec

SHE study in RIBF (After 2011)
RILAC
for SHE study
RILAC-II
for RI beam study

Image 1
Highly selective beam rejection

Image 2
Extended drift to place detector arrays

Image 3
M/Q resolving power > 300

Image 4
M/Q resolving power > 300

M. Amthor (GANIL)

Spiral2

Mass separator

Argonne
NATIONAL LABORATORY
Optical spectroscopy of heaviest elements

- Sample of $^{255}$Fm produced at ORNL
- Breeding of $^{255}$Es from $^{246}$Cm
- Sample transported to Germany (about $10^{11}$ atoms)
- Two-step RIS, Fm confirmed with QMS
- Determined location of atomic levels for first time
- Heavily dependent on atomic theory

M. Sewtz et al., PRL 90, 163002 (2003)
Optical spectroscopy of heaviest elements

M. Amthor (GANIL)

Image 1
Highly selective
beam rejection

Image 2
Extended drift to
place detector arrays

Image 3
Mass separator

Image 4
M/Q resolving
power > 300

Spiral2

P. Van Duppen et al., LoI for SPIRAL2
Production of heavy radioactive "beams"

- Typical separator efficiency 50%
- Primary beam suppression e.g. $10^{12}$
- 10 pμA beam $^{48}$Ca
- 0.5 mg/cm$^2$ $^{208}$Pb target
- $\rightarrow$ 150pps $^{254}$No

- Only one reaction product
- Narrow excitation function (10 MeV in lab)
- No increase in yield with thick target
- Energy $\simeq 0.2$ MeV/u
- Could use inverse kinematics

Paul Greenlees (JYFL, Finland)  Spectroscopy of VHE  EJC2012 71 / 77
Possibilities with RIBs

Around N=152/162

90−94 Kr + 164 Dy → 254−258 No*
90−94 Kr + 160 Gd → 250−254 Fm*
132 Sn + 137 Cs → 267 Db*
132 Sn + 132,134,136 Xe → 264,266,268 Rf*
132 Sn + 138 Ba → 270 Sg*
132 Sn + 139 La → 271 Bh*
132 Sn + 140,142 Ce → 272,274 Hs*
132 Sn + 142−150 Nd → 274−282 Ds*
90−96 Kr + 181 Ta → 271−277 Mt*
90−96 Kr + 186 W → 276−282 Ds*
90−96 Kr + 180 Hf → 270−276 Hs*
90−96 Kr + 175,176 Lu → 265−272 Bh*
90−96 Kr + 176 Yb → 266−272 Sg*

Towards N=184?

Difficult even with radioactive beams
90−95 Kr + 208 Pb → 298−303 118*
132 Sn + 170 Er → 302 118*
132 Sn + 176 Yb → 308 120*

Paul Greenlees (JYFL, Finland)
Spectroscopy of VHE

EJC2012 72 / 77
SPIRAL2 Predicted Intensities

- Figures assume $5 \times 10^{13}$ fissions/sec
- Phase2 Day1, 50 kW d beam: e.g. $^{92}$Kr
  6.2MeV/u $2.6 \times 10^8$ pps
**EURISOL Predicted Intensities**

**Fig. 13: Predicted EURISOL intensities of several nuclides:**

- **Left:** Be (black open dots), Li (blue filled squares), Mg (open green triangles), Ar (red filled rhomboids), Ni (magenta open triangles), Ga (black filled dots), Kr (open blue squares);
- **Centre:** Zr (filled green triangles), Nb (open red diamonds), Mo (magenta filled triangles), Tc (black open dots), Ru (red filled dots), Rh (green open triangles), Pd (red filled diamonds), Ag (magenta open triangles), Cd (filled black dots);
- **Right:** Hg (squares), Fr (triangles)
Possibilities with RIBs

Atomic Physics and Chemistry of the Transactinides

>5 atom/day list

- $^{264}$Rf
- $^{265}$Db
- $^{268}$Sg
- $^{267}$Bh

$^{252}$Cf($^{16}$C, 4$n$)
$^{249}$Bk($^{20}$O, 4$n$)
$^{252}$Cf($^{20}$O, 4$n$)
$^{252}$Cf($^{21}$F, 6$n$)

What kind of reactions with RNBs are used to form n-rich nuclei?

<table>
<thead>
<tr>
<th>Reactants</th>
<th>Products</th>
<th>FRIB Beam Intensity (p/s)</th>
<th>Production Rate (atoms/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{26}$Ne + $^{248}$Cm</td>
<td>$^{271}$Sg + 4$n$</td>
<td>$2.2 \times 10^6$</td>
<td>0.004</td>
</tr>
<tr>
<td>$^{30}$Mg + $^{244}$Pu</td>
<td>$^{270}$Sg + 4$n$</td>
<td>$7.1 \times 10^6$</td>
<td>1</td>
</tr>
<tr>
<td>$^{29}$Mg + $^{244}$Pu</td>
<td>$^{269}$Sg + 4$n$</td>
<td>$3.6 \times 10^7$</td>
<td>0.2</td>
</tr>
<tr>
<td>$^{20}$O + $^{252}$Cf</td>
<td>$^{268}$Sg + 4$n$</td>
<td>$1.5 \times 10^8$</td>
<td>5</td>
</tr>
<tr>
<td>$^{23}$Ne + $^{248}$Cm</td>
<td>$^{267}$Sg + 4$n$</td>
<td>$1.6 \times 10^8$</td>
<td>1</td>
</tr>
</tbody>
</table>

W. Loveland, FUSHE2012
See also W.Loveland PRC 76 014612 (2007)
N.B. Does not include detection efficiency
The Limits

Minimum requirement for in-beam studies

Cross section required to accumulate 300 full-energy alpha decays

One week irradiation, target A=170, 0.5mgcm$^{-2}$, 50% transmission

Minimum requirement for decay/reaction mechanism studies

Beam time required to accumulate 10 full-energy alpha decays

Target A=170, 0.5mgcm$^{-2}$, 50% transmission, $I_{\text{beam}}=10^{10}$ pps

$10^{12}$ pps, XS 1pb $\rightarrow$ 0.3 events/week
Detailed spectroscopy of heavy elements can provide high quality data and level assignments

- In-beam spectroscopy at 10 nb level
- Decay spectroscopy at sub-nb level
- Data is providing challenges for theory
- Hopefully will lead to a better understanding of the structure of SHE
- Laser and Mass Measurements will bring much-needed new information
- Many new facilities being built and upgrades going on
- Some opportunities to produce new isotopes from secondary reactions with RIBs
- Still much to be done (for both experiment and theory)