Spectroscopy of heavy nuclei

R-D Herzberg

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Overview

- Introduction
- Isomer Spectroscopy
- Analysis Methods
- In-beam Spectroscopy
- Electron Spectroscopy: SAGE
- Summary
Data known today

<table>
<thead>
<tr>
<th>N Level</th>
<th>N Level</th>
<th>N Level</th>
<th>N Bands</th>
<th>Mass</th>
<th>Db</th>
<th>Rf</th>
<th>Lr</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>= 0</td>
<td>≤ 5</td>
<td>≤ 10</td>
<td></td>
<td></td>
<td>253</td>
<td>254</td>
<td>255</td>
<td>256</td>
</tr>
<tr>
<td>≤ 20</td>
<td>≤ 50</td>
<td>&gt; 50</td>
<td></td>
<td></td>
<td>256</td>
<td>257</td>
<td>258</td>
<td>259</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>260</td>
<td>261</td>
<td>262</td>
<td>263</td>
</tr>
</tbody>
</table>

Proton Number:

- **N Level**
  - 0
  - ≤ 5
  - ≤ 10

- **N Bands**
  - N

Neutron Number:

- **Rf**
  - 253
  - 254
  - 255
  - 256

- **Lr**
  - 256
  - 257
  - 258
  - 259

- **No**
  - 260
  - 261
  - 262
  - 263

**References**

- R-D Herzberg
Deformed Single Particle Orbitals

R. Chasman et al., Rev. Mod. Phys. 49, 833 (1977)

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Spin-Orbit Interaction

Strong

2g\(9/2\)  
3p\(1/2\)  
3p\(3/2\)  
2f\(5/2\)  
2f\(7/2\)  
1i\(13/2\)  
1h\(9/2\)

Weak

3s\(1/2\)

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Spin-Orbit

Phenomenological:

\[ V_{l.s}(r) = -\frac{1}{r} \frac{\partial V(r)}{\partial r} \]

Regardless of details, \( V_{l.s} \) is density dependent.

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Shell Positions for $^{298}_{114}$

From M. Bender et al., PRC 60 (1999) 034304

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HFB Gogny Calculation

J.P. Delaroche et al., NPA 771 (06) 103

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Deformed orbitals

Problems:
No gap at $Z=100$ or $102$
No gap at $N=152$

Trace to position of high-$l$ Orbitals?

$p\ i_{13/2} \ n\ j_{15/2}$

M Bender, e.g. in
A. Chatillon et al, EPJA30, 06, 397
Shape is important!

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Summary

• Structure is very important.

• Position of high-

• Isomer spectroscopy is ideal to locate these positions experimentally

• Systematic approach needed
Isomers

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Fission Barrier

Xu et al, PRL 92 (2004) 252501

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Isomer Hunting Grounds


Z=102  Fm + No

Hf – W

N=106

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Isomers

Longest lived isomeric state

RDH & DM Cox, RCA 99, 441, (2011)
Isomers $J \leq 8$

Longest lived isomeric state spin $\leq 8$

RDH & DM Cox, RCA 99, 441, (2011)
Isomers J>8

Longest lived isomeric state spin ≥17/2

RDH & DM Cox, RCA 99, 441, (2011)
- Greenlees et al, PRC78 (08) 021303R
- Delayed gamma rays leading to energies of $K=2$ and $K=8$ bands
- Half life of isomeric $K=8$ band head
Branching Ratios

\[ E2 \sim Q_o^2 \]

\[ M1 \sim (g_k - g_R)^2 \]

Stretched: E2 only

Interband: mixed E2 + M1

Branching ratios sensitive to \[ \left(\frac{g_k - g_R}{Q_o}\right)^2 \]
g-factors in $^{250}$Fm

Test:

pp:
$8\cdot\{9/2^+[624] \times 7/2^-[514]\}$
$g_K = 1.001$

nn:
$8\cdot\{7/2^+[624] \times 9/2^-[734]\}$
$g_K = -0.0225$

D. Rostron

Branching Ratio
If statistics is low:

Use Region 2 to predict counts in region 1.
In Practice: $^{250}$Fm

Expected Counts in Region 1 for different configurations

Observed Counts

E. Parr thesis & in prep.
A test case

E.Parr, in preparation
Quenching

\[ g_R = q \frac{Z}{A} \]

Typically used:
\[ q \sim 0.7 \]

We always test
\[ q = 1 \] and \[ q = 0.7 \]

From Bohr & Mottelson
$^{250}\text{Fm}$ 8$^-$ isomer
$^{250}\text{Fm} \ 8^- \ \text{isomer}$

$7/2^+ [624] \times 9/2^- [734] \ \text{nn}$

$7/2^- [514] \times 9/2^+ [624] \ \text{pp}$

Clearly a two-neutron state
$^{252}\text{No}$ 8$^-$ isomer

B Sulignano, E Parr, in preparation
$^{252}$No 8$^-$ isomer

$\frac{7}{2}^+[624] \times \frac{9}{2}^-[734]$ nn

$\frac{7}{2}^-[514] \times \frac{9}{2}^+[624]$ pp

Clearly a two-neutron state

B Sulignano, E Parr, in preparation
New Data:
F.P. Hessberger, EPJ43, 55 (10)
C Gray-Jones, thesis

R.M. Clark et al., PLB690, 610 (09)
$^{254}\text{No}$ $8^-$ isomer

Data:
F.P. Hessberger, EPJ43, 55 (10)
C Gray-Jones, thesis
$^{254}\text{No}$ 8$^-$ isomer

$7/2^+\{624\} \times 9/2^-\{734\}$ nn
$7/2^+\{613\} \times 9/2^-\{734\}$ nn
$7/2^-\{514\} \times 9/2^+\{624\}$ pp
$11/2^-\{725\} \times 9/2^-\{734\}$ nn

Depending on quenching, either configuration is possible.
Transitions

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Deformed gaps


Gap at \(N=152\)

Gap at \(Z=100\)

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Conclusions

• 8\(^{-}\) isomers in \(^{252}\)No and \(^{250}\)Fm are neutron states

• 3\(^{+}\) state in \(^{254}\)No is a proton state

• 8\(^{-}\) isomer in \(^{254}\)No needs more study

• What quenching is appropriate in this region?

We see many isomers – do we really understand their structure?
In-beam Spectroscopy
In-beam Spectroscopy

$^{48}\text{Ca} \text{ (}^{208}\text{Pb}, 2n) \text{ } ^{254}\text{No}$

Best Rotor Nucleus known

S. Eeckhautd et al
New record: $^{246}\text{Fm}$

J. Piot et al., to be published
Fm rotational bands

J. Piot et al., to be published

Excitation Energy (keV)

J=

This Work

Fm

Fm Isotopes (ref 1)
Alignment

From E.S. Paul et al.
PRL 98 (2007) 012501
Systematics

Bender et al, NPA723 (03) 354

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Internal Conversion

![Graph showing internal conversion coefficients vs transition energy]

- $e^-$ dominate
- $\gamma$ dominate

- E2 $\alpha_k$
- M1 $\alpha_k$
- E2 $\alpha_t$
- M1 $\alpha_t$
Conversion Coefficients

E = 200 keV   Z = 102   BrICCC   (T. Kibédi et al., NIMA 589 (2008) 202)

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SAGE

S(iliicon) A(nd) GE(rmanium) spectrometer

JUROGAM II

RITU

GREAT

Beam

Phase I

Si detector

Clovers

Fully instrumented with digital electronics

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SAGE

Detector

Beam

HV barrier

Target

C-foils

Ge opening angles

Solenoid coils

R-D Herzberg
SAGE

R-D Herzberg
SAGE Collaboration

University of Liverpool, UK
P. Papadakis, R.-D. Herzberg, J. Pakarinen, P.A. Butler, R.D. Page, J.R. Cresswell, D.A. Seddon, J. Thornhill, D. Wells

University of Jyväskylä, Finland
P.T. Greenlees, P. Jones, R. Julin, P. Rahkila, J. Sorri

STFC Daresbury Laboratory, UK
Summary

- A variety of experimental probes is available for structure investigations in heavy nuclei
- Study high-\(l\) orbitals, which pose a challenge to theory
- Isomers are great
- Need to reach more neutron rich systems
- Systematic studies under way in many places
- Combined Gamma and conversion electron spectroscopy is the next step

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Collaboration

UNIVERSITY OF JYVÄSKYLÄ

THE UNIVERSITY OF LIVERPOOL

CEA

IKP

ARGONNE NATIONAL LABORATORY

GSi

HELSINGIN YLIOPISTO

CCLRC

ISOLDE

CERN

Institut de Recherches Subatomiques