Spectroscopy of Very Heavy Elements

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What is the link?
Outline

1. Introduction
2. Experimental Approaches
3. Existing Facilities
Outline

1. Introduction
2. Experimental Approaches
3. Existing Facilities
What is the structure of the superheavy elements?

How can the study of transfermium nuclei inform the structure of the superheavy elements?

What is predictive power of theory for the transfemium nuclei and the superheavies? Are extrapolations reliable?

What are experimental uncertainties? What data can be safely used by theorists to benchmark modern density functionals?

What new experimental data are needed? Is there any guidance from theory in that respect?

What are the crucial questions regarding the structure of the transfermium nuclei?

http://nuclear1.paisley.ac.uk/SHEworkshop/

Ultimate goal of the work addressed here: To confront theoretical predictions of the structure of heavy nuclei with spectroscopic experimental data of the highest quality
What is a Superheavy Element?

Reminder - Nuclear Binding Energy:

\[ B = a_{\text{volume}}A - a_{\text{surface}}A^{2/3} - \frac{1}{2}a_{\text{symmetry}} \frac{(N - Z)^2}{A} - \frac{3}{5} \frac{Z^2e^2}{4\pi\varepsilon_0R_C} \]  

\( (1) \)
What is a Superheavy Element?

Liquid Drop Model and Fission Barrier:

\[ E(d) = E_C(d) + E_S(d) = a_C \frac{Z^2}{A^{1/3}} \left( \frac{E_C(d)}{E_C^0} \right) + a_S \left( 1 - \kappa_S \left( \frac{(N - Z)}{A} \right)^2 \right) A^{2/3} \left( \frac{E_S(d)}{E_S^0} \right) \]  

- \( E_C^0, E_S^0 \) - spherical shape
- Calculate for a sequence of nuclear shapes
- e.g. Expansion of nuclear radius in spherical harmonics

\[ R(\theta, \phi) = c (\beta_\lambda) R_0 \left[ 1 + \sum_{\lambda=2}^{\lambda_{\text{max}}} \beta_\lambda Y_{\lambda 0}(\theta, \phi) \right] \]
What is a Superheavy Element?

Fissility Parameter and Barrier Height

- Competition of Coulomb repulsion and surface tension
- Fissility Parameter, $x = \frac{E_C}{2E_S}$
- Barrier Height, $E_{\text{barrier}} = \frac{98}{15} \left(1-x\right)^3 \frac{E_S}{(1+2x)^2}$
- Superheavy Element - $E_{\text{barrier}} = 0, x > 1$
- Fuzzy definition - depends on parameterisation

Table 4.1. Height of fission barriers and $\beta_2$ $(a_2)$ deformations at the top of the barrier calculated in the liquid-drop model using a third-order expansion for different values of the fissility parameter $x$.

<table>
<thead>
<tr>
<th>$Z^2/A$</th>
<th>$x$</th>
<th>$E_{\text{bar}}$ (MeV)</th>
<th>$a_2^{\text{bar}}$</th>
<th>$\beta_2^{\text{bar}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{208}\text{Bi}$</td>
<td>32.96</td>
<td>0.700</td>
<td>17.9</td>
<td>0.88</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>34.91</td>
<td>0.753</td>
<td>9.7</td>
<td>0.69</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>35.56</td>
<td>0.769</td>
<td>7.8</td>
<td>0.64</td>
</tr>
<tr>
<td>$^{244}\text{Pu}$</td>
<td>36.51</td>
<td>0.787</td>
<td>6.0</td>
<td>0.58</td>
</tr>
<tr>
<td>$^{252}\text{Fm}$</td>
<td>39.37</td>
<td>0.841</td>
<td>2.4</td>
<td>0.41</td>
</tr>
<tr>
<td>$^{262}\text{X}$</td>
<td>41.16</td>
<td>0.912</td>
<td>0.4</td>
<td>0.22</td>
</tr>
</tbody>
</table>
What is a Superheavy Element?

Enhanced Stability - Shell Effects

- Nucleus not simply a liquid drop
- Evidence e.g. from masses
- Enhanced stability at 2, 8, 20, 28, 50, 82, (126)
- Confining potential - gaps in energy level spectrum
- Reproduction of Magic Numbers - \( l^2 \) and \( l.s \) terms
What is a Superheavy Element?

**Enhanced Stability - Shell Effects**

- Majority of nuclei not spherical
- Effect of deformation?
- Deformed shell gaps
- Enhanced stability e.g. at $N=142,152$
What is a Superheavy Element?

Enhanced Stability - Shell Effects

- Strutinsky Method
- \[ E = E_{LDM} + E_{SHELL} \]
- \[ E_{SHELL} = \sum_{i=1}^{A} \epsilon_i(\delta) - \tilde{E}_{SHELL} \]
- Calculate Potential Energy Surface

FIG. 8. Schematic diagram of Strutinsky shell-correction method illustrating the difference between bunched energy levels and a smooth level ordering. In practical calculations, actual energy levels are used.
What is a Superheavy Element?

Back to the Fission Barrier
The Island of Stability

An allegorical representation of the stability of nuclei showing a peninsula of known stable or nearly stable nuclei and a ridge of relatively stable nuclei around $Z = 108$ and $N = 162$ and a predicted Magic Superheavy Island around $Z = 114$ and $N = 184$. 

The Seaborg Archive, LBL
Next Spherical Shell Gap?

[Diagram of single-particle energy and quadrupole deformation]
Next Closed Shells? Where is the Island?

Extrapolation with Mass

- Gap at $Z=114$ sensitive to spin-orbit strength
- Splitting of $f_{5/2}$ and $f_{7/2}$
- Differences in level ordering/spacing
- Large uncertainties in extrapolation
Next Closed Shells? Where is the Island?

Fig. 37. The Gogny neutron and proton single-particle levels for \( Z = 114 \) as functions of the neutron number \( N \).

Extrapolation with Mass
- Proton shell gaps change with \( N \)
- \( Z=114,120 \) only for neutron-deficient isotopes?
- Evolution of shell structure
- c.f. light neutron-rich nuclei
Sensitivity to Deformation

R.R. Chasman et al., Rev. Mod. Phys. 49, 833 (1977)
Next Closed Shells? Where is the Island?

Self-Consistent Theories

- Calculations based on realistic effective nucleon-nucleon interaction
- e.g. Skyrme
- Allows results to be traced back to interaction
- Difficult in Macroscopic-Microscopic calculations
- Need experimental data to determine correct ordering
- Will provide better predictions of properties of SHE

M. Bender et al., PRC60, 034304 (1999)
How big is the Island?

M. Bender, W. Nazarewicz, P.-G. Reinhard, PLB 515, 42 (2001)
What is the structure of SHE?

**superheavy elements**

- Z=102 Nobelium
- Z=94 Plutonium
- Z=50 Tin
- Z=82 Lead

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Spectroscopy of VHE
Knowledge of the Region

### Introduction

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### Mass Levels

<table>
<thead>
<tr>
<th>N Level</th>
<th>N Level</th>
<th>N Level</th>
<th>N Level</th>
<th>N Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>= 0</td>
<td>≤ 5</td>
<td>≤ 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤ 20</td>
<td>≤ 50</td>
<td>&gt; 50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Experiments

R.-D.Herzberg and P.T.Greenlees, Prog. Part. Nuc. Phys. 61, 674 (2008)

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### Facilities

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What is the structure of SHE?

\[
\begin{array}{c}
\begin{align*}
184 & \quad 7/2+[613] \\
5/2 & \quad 1/2+[620] \\
15/2 & \quad 9/2+[734] \\
11/2 & \quad 7/2+[624] \\
114 & \quad 1/2+[514] \\
13/2 & \quad 9/2+[624] \\
82 & \quad 7/2+[633] \\
126 & \\
152 & \\
134 & \\
142 & \\
96 & \\
88 & 
\end{align*}
\end{array}
\]
Outline

1. Introduction
2. Experimental Approaches
3. Existing Facilities
Experimental Approaches

SHIP

Resonance Ionization Spectroscopy at Trans-Fermium Elements @ GSI MAFF

Buffer Gas Cell

Resonance Ionization Spectroscopy at Trans-Fermium Elements @ GSI MAFF
Recoil Separators - Velocity Filters

\[ F_B = qvB, \quad F_{el} = qE \]

\[ F_{tot} = (F_B - F_{el}) = q(vB - E) \rightarrow F_{tot} = 0 \quad \text{for} \quad v = -E/B \]
Recoil Separators - Velocity Filters

FLNR - JINR, Dubna

Vassilissa
Recoil Separators - Mass Spectrometers

Argonne National Laboratory
Argonne Tandem Linear Accelerator System (ATLAS)

Mass Separator (A/Q)

Fragment Mass Analyzer

Target

Q1 Q2 ED1 MD ED2 Q3 Q4

Different energies

Different masses

Quadrupole triplet
Electric dipole
Magnetic dipole

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Spectroscopy of VHE
EJC2012 27 / 49
Recoil Separators - Gas-Filled Separators

\[ B_\rho = \frac{mv}{q_{ave}} = \frac{mv}{[(v/v_0)eZ^{1/3}]} = \frac{0.0227A}{Z^{1/3}} \cdot Tm, \]  

(5)

RIKEN GARIS (Gas-filled Recoil Ion Separator)

D1 Q1 Q2 D2

He gas inlet

Mylar window (1 µm)

Evaporation residue

Primary beam

Beam stopper

Rotating target

Detector system

Differential pumping

Vacuum

He gas (0.1–1 torr)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification</td>
<td>X: 40, Y: 1.25</td>
</tr>
<tr>
<td>Expansion</td>
<td>±0.7% error</td>
</tr>
<tr>
<td>Total length</td>
<td>108 cm</td>
</tr>
<tr>
<td>Acceptance</td>
<td>±1 mrad</td>
</tr>
<tr>
<td>Acceptance</td>
<td>10.2 mrad</td>
</tr>
</tbody>
</table>

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Spectroscopy of VHE
Decay Spectroscopy

SHIP

- Alpha-Gamma/Electron Coincidences
- Excitation energies, spins, parities
- High beam intensities ($p\mu A$)
- Clean environment

- Distance in meters
- Rotating Target
- Beam Stop
- Magnetical Quadrupoles 1-3
- Magnetical Dipoles 1-4
- Magnetical Quadrupoles 4-6
- Electrical Deflector 1
- Electrical Deflector 2
- TOF System
- Magnetical Dipole 5
- Gamma Detectors
- Stop Detector
- CLOVER
- MWPC
- PIN-diode box
- PLANAR Ge
- DSSSD
- Recoil

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Spectroscopy of VHE
EJC2012 29 / 49
Genetic Correlations

- Search for pairs of events at same x,y position
- Search time $\Delta t$
- Based on assumption that paired events follow each other in time
- $P_{acc} = T_1 r_2 r_3 \Delta t_{1,2} \Delta t_{2,3}$

S. Antalic, Thesis 2005
The GREAT Spectrometer

- UK Universities + Daresbury
- $2 \times 60 \text{ mm} \times 40 \text{ mm}$ DSSSD
- $28 \times 28 \text{ mm} \times 28 \text{ mm}$ PIN Diodes
- $24 \times 12$ Segmented Planar Ge
- Compton-Suppressed 16-fold Segmented Clover Ge
- Position Sensitive MWPC
- Total Data Readout (TDR) Acquisition System

In-beam Spectroscopy

Observables

- Excitation energies, spins, parities
- Moments of Inertia, Alignments

Tagging Techniques
Recoil, Recoil–Decay, Isomer

Time Line:
\[ R(x,y,t) \rightarrow \alpha(x,y,t+\Delta t) \]

\[ \Delta T \]

\[ \Delta < \Delta T \]
Cross Sections

Paul Greenlees (JYFL, Finland) Spectroscopy of VHE EJC2012 33 / 49
Principles of Recoil-Decay Tagging

Tagging Techniques
Recoil, Recoil–Decay, Isomer

Time Line:
\[ \Delta T < \Delta t < R(x,y,t) \]

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

\[ \gamma \]

\[ g.s. \rightarrow \tau \rightarrow \text{Isomer} \rightarrow \text{Prompt } \gamma \text{'s} \]
Evidence for Nuclear Shape Coexistence in $^{180}$Hg

Gesellschaft für Schwerionenforschung, Darmstadt, Federal Republic of Germany

H.-G. Clerc, U. Gollerthan, and W. Schwab
Institut für Kernphysik, Technische Hochschule Darmstadt, Federal Republic of Germany

Received August 4, 1986

The $\gamma$ decay in the radiative fusion reaction $^{90}$Zr + $^{90}$Zr $\rightarrow$ $^{180}$Hg + $x\gamma$ has been observed in an array of NaI detectors. States up to $6^+$ in the yrast sequence of $^{180}$Hg are tentatively assigned and suggest the coexistence of weakly oblate and strongly prolate nuclear shapes. The difference in potential energy between the two inferred shapes has dropped to about 200 keV, continuing the downward trend observed in the heavier even isotopes $^{184-186}$Hg.
The JUROGAM Germanium Array

- 43 Phase I and GASP-type Ge detectors - EUROBALL and U.K.-France loan pool
- Total Photopeak Efficiency 4.2% @ 1.3 MeV
- Much improved (x10) $\gamma-\gamma$ efficiency
- Software Compton suppression
- Autofill system built by University of York, part of GREAT
- Target chamber built by IReS Strasbourg, allows use of rotating target wheel
- Modified EUROGAM support structure
Anatomy of Total Data Readout (TDR)

In-beam Spectroscopy: Recoil-Decay Tagging

- Typical beam intensity: $6.25 \times 10^{10}$ pps
- Total Gamma Ray Counting Rate: >1 MHz
- 10 nb - 3 reactions/hour
- 1 in $10^9$ selectivity
Experimental Data

- Is the data reliable?
- Do we get the full picture?
- Favoured ($\alpha$, $\beta$) decays connect states of similar structure
- Coincidence techniques give multipolarities (spin/parity changes)
- Very few reliable measurements of ground-state spins/parities
- Did we really see the ground state?
- Transfer reactions powerful tool - limited number of cases
- Complemented by in-beam studies ($MoI$, $B(M1)/B(E2)$, $g_K$, etc)
- K-isomers also give valuable information on location of s.p. states
Outline

1. Introduction
2. Experimental Approaches
3. Existing Facilities
Centres for study of SHE

- JYFL, Finland
- GSI
- DUBNA
- LANZHOU
- LBNL
- ANL
- GANIL
- JAEA/RIKEN

Spectroscopy of VHE
**GSI**

**SHIP**

- Renowned centre of SHE research
- New elements 107-112 (Bh-Cn)
- SHIP/TASCA
- Synthesis/Structure/Chemistry
- Intensities pµA range
- Radioactive Targets
**FLNR**

FLNR - JINR, Dubna

- Renowned centre of SHE research
- Large number of new elements (recently 114-118)
- GFRS/Vassilissa/MASHA
- Synthesis/Structure/Chemistry
- Intensities $\mu A$ range
- Radioactive Targets
- New dedicated facility under construction
RIKEN

RIKEN GARIS (Gas-filled Recoil Ion Separator)

- GARIS/GARIS2
- Synthesis/Structure/Chemistry
- Recently been studying 113
- Intensities pμA range
- Radioactive Targets
- New dedicated facility for SHE
Lawrence Berkeley Laboratory

- Historical centre of SHE research
- 88 inch cyclotron/BGS
- Synthesis/Structure/Chemistry
- Intensities 0.4\(\mu\)A range
- Radioactive Targets
- Recently hosted GRETINA
JYFL

- JGII/RITU/GREAT/SAGE
- Structure
- Specialist in in-beam work
- Intensities $0.1\,\mu A$ range
- Electron spectroscopy unique
- New Mass Spectrometer MARA
ANL

- GS/FMA
- Structure
- In-beam and decay spectroscopy
- Intensities 0.4pµA range
- Entry distribution measurements unique
- Intensity Upgrade
- Digitised GS
- Plans for new GFS
Fig. 2. $\gamma$-ray spectrum of $^{250}\text{Cm}$, obtained by setting the gate on indicated by the enclosed area in Fig. 1.

- **Tandem/Booster**
- **Structure/Chemistry**
- **In-beam and decay spectroscopy**
- **Intensities 0.4p\(\mu\)A range**
- **Radioactive Targets**
- **Transfer Reactions**
GANIL

- **LISE/VAMOS/EXOGAM**
- Structure
- In-beam and decay spectroscopy
- Intensities 0.4$\mu$A range
- VAMOS tested in GF mode
- S$^3$/LINAG under development