Paving the way to the island of stability
- superheavy element research at GSI and beyond

Dieter Ackermann
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Helmholtzzentrum für Schwerionenforschung GmbH

College Station, March 31st 2015
**SHE investigations – stable and exotic beams**

- **outline**

- intro – towards the island of stability
  - model predictions
- nuclear structure features of superheavy nuclei (decay spectroscopy after separation)
  - isotopic/isotonic trends of single particle levels
    → towards the next p/n shell gaps
  - quasi-particle excitations
    → deformation/K-isomers
- SHN studies at GANIL/S3/SPIRAL2
  - first experiments at LISE
  - perspectives
- alternative approaches/RIB
  → reaction studies
  - multi nucleon transfer
  - CN spin distributions

- SHN studies at GANIL/S3/SPIRAL2

- multi nucleon transfer
- CN spin distributions

- deformed shell-stabilised superheavy nuclei

- spherical shell-stabilised superheavy nuclei
SHE and the origin of the “island of stability”

- liquid drop limit and quantum mechanical extension

different Z predictions (120-126)
self-consistent models (relativistic meanfield RMF/
Hartree-Fock-Bogoliubov HFB)

existence only due to quantum mechanics and the strong nuclear interaction

spherical shell-stabilised superheavy nuclei

background:
$E_{\text{shell}}$
microscopic-macroscopic calculation (A. Sobiczewski)

deformed shell-stabilised superheavy nuclei
SHN in Nature (EOS calculations)

Superheavy nuclear clusters in core collapse super novae and the crust of neutron stars

- dense core of core collapse SN and low density outer crust of n-stars
- superheavy nuclei imbedded in neutron superfluid ($e^-$ screening)
  → increased lifetime

→ experimental input on nuclear structure features needed also for n-rich superheavy nuclei

Shell evolution in superheavy Z = 120 isotopes: QVC in relativistic framework - dominant n-states

PC+QVC: Formation of the „shell gap“!

Comparable Spectroscopic strengths

Elena Litvinova
PRC 85, 021303(R) 2012
Shell evolution in superheavy Z = 120 isotopes: QVC in relativistic framework

1. Relativistic Mean Field: spherical minima
2. Small amplitude vibrations: RQRPA
3. Very soft nuclei: large amount of low-lying collective vibrational modes (~100 phonons below 15 MeV)

Vibration corrections to alpha decay energies $Q_\alpha$ [MeV]

- Impact on the shell gaps
- Smearing of the shell effects

Shell stabilization & vibration stabilization/destabilization (?)

E.L., arXiv:1108.3508
Decay spectroscopy
- access to a wide variety of nuclear structure features in SHN

K isomerism, mass measurements
EDF calculations
PES, $Q_\alpha$, sps

$\text{sf}/\alpha$ branching ratios - specific for g.s. and excited states
sf barriers

transition to spherical
fission competition
deformation
single particle states (sps)
transition energies

Nuclides discovered at SHIP
New or improved decay data

Calc.: A. Sobszewiski

Dieter Ackermann
**Nuclear Structure of the Heaviest Nuclei:**

**- Production Rates**

<table>
<thead>
<tr>
<th>UNILAC intensities</th>
<th>reaction</th>
<th>σ/nbarn</th>
<th>countrate</th>
<th>countrate</th>
<th>countrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>≈ 1 pμA/10^{12} particles/s</td>
<td>→ SPIRAL2 day 1</td>
<td>→ phase 1++</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Reaction</th>
<th>UNILAC intensity</th>
<th>SPIRAL2 day 1</th>
<th>Phase 1++</th>
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</thead>
<tbody>
<tr>
<td>208Pb(48Ca,2n)(^{254})No</td>
<td>2000</td>
<td>15000/h</td>
<td>40000/h</td>
</tr>
<tr>
<td>206Pb(48Ca,2n)(^{252})No</td>
<td>430</td>
<td>3300/h</td>
<td>8000/h</td>
</tr>
<tr>
<td>206Pb(48Ca,3n)(^{251})No</td>
<td>25</td>
<td>200/h</td>
<td>500/h</td>
</tr>
<tr>
<td>209Bi(40Ar,2n)(^{247})Md</td>
<td>7</td>
<td>80/h</td>
<td>300/h</td>
</tr>
<tr>
<td>208Pb(54Cr,1n)(^{261})Sg</td>
<td>2</td>
<td>15/h</td>
<td>30/h</td>
</tr>
<tr>
<td>207Pb(64Ni,1n)(^{270})Ds</td>
<td>0.013</td>
<td>1/d</td>
<td>2/d</td>
</tr>
</tbody>
</table>
\[ \alpha - \alpha - \text{correlations} \quad ^{209}\text{Bi}(^{50}\text{Ti},n)^{258}\text{Db}, \Delta t(\alpha-\alpha) < 400 \text{ s} \]

- corr. \(^{254}\text{Lr} (\Delta t < 400 \text{ s})
- corr. \(^{254}\text{No} (\Delta t < 400 \text{ s})
- \text{delayed coinc. to } (\text{CE},\gamma) (\Delta t < 40 \text{ ms})

**SHIP**

*spring 2015 under analysis*  
F.P. Heßberger
- News – $^{266}$Hs sf-branch - $^{262}$Sg $\alpha$-branch $\rightarrow$ link to $^{254}$No

- 26 decay chains ($^{270}$Ds: 25, $^{271}$Ds: 1)
- new spectroscopic data

**SHIP spring 2015 under analysis F.P. Heßberger**
**270Ds Decay Scheme**

**270Ds:**
- 12 g.s. decays
- 13 isomer decays - 2 γ’s: 175/741 keV (in 2000: 3:3 + 1 γ)

**Chain 8:**
- $E_\alpha$ 200-300 keV lower

**266Hs:**
- 16 g.s. decays
- 1 isomer decay with a 332 keV γ-ray

**Chain 8:**
- $E_\alpha \approx$ 200 keV higher
- $E_\gamma = 332$ keV

**262Sg:**
- α decay observed for the first time (1 full E, 1 escape)

Calculations:
- HFB: S. Cwiok, et al.
Ds: 12 g.s. decays
13 isomer decays - 2 γ's: 175/241 keV
(in 2000: 3:3 + 1 γ)

Hs: 16 g.s. decays

Sg: α decay observed for the first time
(1 full E, 1 escape)
Energy Density Functional Calculations
- Dario Vretenar, Vaia Prassa et al.
Energy Density Functional Calculations
- Dario Vretenar, Vaia Prassa et al.

S. Ćwiok et al., NATURE, 433 (2005)
HFB + SLy4
16 nuclides with K-isomeric states known for $Z = 96$ to 110

→ tool to map deformation towards spherical SHE
Potential E surface Calculations (rel. HFB)

- Bingnan Lu, Dario Vretenar et al.

Rel. Hartree Bogoliubov PES $E(\beta_{20};\beta_{30})$

- axial symmetry
- $\Delta E = 1$ MeV.
Potential E surface Calculations (rel. HFB)

- g.s. deformation varies slowly from \( Z = 100 \) to 112
- wide octupole range for minimum for Fm and No isotopes
- minimum decreases \( \rightarrow \) K-isomer in \( ^{276}\text{Cn} \)?
- \( Z = 112 \): at the edge of the spherical shell stabilized region - “island of stability”?

Rel. Hartree Bogoliubov PES \( E(\beta_{20};\beta_{30}) \)
- axial symmetry
- \( \Delta E = 1 \text{ MeV.} \)
High-K isomers in trans-actinide nuclei close to $N=162$

- Energy Density Functional Calculations, Vaia Prassa et al.

Vaia Prassa et al.
PRC 91, 034324 (2015)

Selfconsistent constraint triaxial HFB calculations based on the DD-PC1 functional (PRC 88, 044324 (2013))

- Proton single particle states elevated to higher excitation energies for $N=162$
  - $^{270}\text{Hs} \rightarrow ^{248}\text{Cm}(^{26}\text{Mg}, 4n)$
    J. Dvorak et al., PRL 97, 242501 (2006)
  - $^{272}\text{Ds} \rightarrow \alpha$- daughter of $^{207}\text{Pb}(^{70}\text{Zn}, 1n)^{276}\text{Cn}$
    $\rightarrow \text{HI-LiNAC}$
    (e.g. GSI cw-Linac, FLNR SHE-factory, SPIRAL2 LINAG, ...)

College Station, March 31st 2015
Day 1 SPIRAL2 Phase 1
- SHE LoI(s)

LoI 2009:
“Production and spectroscopy of heavy and superheavy elements using $S^3$ and LINAG”
- Neutron deficient nuclei around Z=92 N=126
- $K$-isomerism studies in the Z=100-110 region
- study of neutron rich isotopes produced by asymmetric reactions
- Production of SHE with Z=106-108-112 with Uranium target

Addendum 2012:
“Detailed spectroscopy of high-$K$ states in $^{254}$No and $^{256}$Rf: location of single--particle states close to the Z=100 and N=152 deformed shell gaps”

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Christophe Theisen, IfNu/SPhN
Stodel Christelle, GANIL

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N. Redon et O. Stezowski (IPN Lyon, France)
# Beam intensities

- SPIRAL2 day 1/phase 1+

<table>
<thead>
<tr>
<th>Ion</th>
<th>$I_{\text{max}}$ [$\mu$A]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPIRAL 2 day 1</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>30</td>
</tr>
<tr>
<td>$^{18}$O</td>
<td>30</td>
</tr>
<tr>
<td>$^{19}$F</td>
<td>30</td>
</tr>
<tr>
<td>$^{24}$Mg</td>
<td>25</td>
</tr>
<tr>
<td>$^{22}$Ne</td>
<td>25</td>
</tr>
<tr>
<td>$^{28}$Si</td>
<td>25</td>
</tr>
<tr>
<td>$^{36}$Ar</td>
<td>20</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>5.8</td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>14.6</td>
</tr>
<tr>
<td>$^{36}$S</td>
<td>9.2</td>
</tr>
<tr>
<td>$^{40}$Ca</td>
<td>6</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>2.5</td>
</tr>
<tr>
<td>$^{50}$Cr</td>
<td>4</td>
</tr>
<tr>
<td>$^{46}$Ti</td>
<td>5</td>
</tr>
<tr>
<td>$^{58}$Ni</td>
<td>2.2</td>
</tr>
</tbody>
</table>

SPIRAL2 day 1:
- injector A/Q=3
- conventional phoenix ECR

SPIRAL2 phase 1++ (not funded so far):
- injector A/Q=6-7
- new ECR supra conducting source
### Day 1 experiments at S³ (SPIRAL2/GANIL)

- **rate summary**

<table>
<thead>
<tr>
<th>nuclide</th>
<th>reaction</th>
<th>feature</th>
<th>X-section [pbarn]</th>
<th>rate [Hz]</th>
<th>integral counts(21UT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>day 1</td>
</tr>
<tr>
<td>²⁵⁴No</td>
<td>⁴⁸Ca+²⁰⁸Pb</td>
<td>K-isomer</td>
<td>2000×10³</td>
<td>60.000</td>
<td>1×10⁷</td>
</tr>
<tr>
<td>²⁵⁶Rf</td>
<td>⁵⁰Ti+²⁰⁸Pb</td>
<td>K-isomer</td>
<td>17×10³</td>
<td>550</td>
<td>90.000</td>
</tr>
<tr>
<td>²⁶⁶Hs</td>
<td>⁶⁴Ni+²⁰⁷Pb</td>
<td>ER</td>
<td>15 (²⁷⁰Ds)</td>
<td>0.34</td>
<td>57</td>
</tr>
<tr>
<td>²⁶⁶mHs</td>
<td>⁶⁴Ni+²⁰⁷Pb</td>
<td>K-isomer</td>
<td>15 (²⁷⁰Ds)</td>
<td>0.01</td>
<td>2.5</td>
</tr>
<tr>
<td>²⁷⁰Ds</td>
<td>⁶⁴Ni+²⁰⁷Pb</td>
<td>ER</td>
<td>15</td>
<td>0.45</td>
<td>76</td>
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<tr>
<td>²⁷⁰mDs</td>
<td>⁶⁴Ni+²⁰⁷Pb</td>
<td>K-isomer</td>
<td>15 (²⁷⁰Ds)</td>
<td>0.22</td>
<td>38</td>
</tr>
<tr>
<td>²⁶²Sg</td>
<td>⁶⁴Ni+²⁰⁷Pb</td>
<td>α-decay</td>
<td>15 (²⁷⁰Ds)</td>
<td>0.02</td>
<td>5</td>
</tr>
<tr>
<td>²⁷⁶Cn</td>
<td>⁷⁰Zn+²⁰⁷Pb</td>
<td>K-Isomer search</td>
<td>0.5 (²⁷⁷Cn)</td>
<td>0.01</td>
<td>2.5</td>
</tr>
<tr>
<td>²⁸⁸115</td>
<td>⁴⁸Ca+²⁴³Am</td>
<td>ER</td>
<td>10</td>
<td>0.3</td>
<td>50</td>
</tr>
<tr>
<td>²⁸⁸115</td>
<td>⁴⁸Ca+²⁴³Am</td>
<td>L X-rays</td>
<td>10</td>
<td>1.8</td>
<td>300</td>
</tr>
</tbody>
</table>
SHN research at SPIRAL2/GANIL
- decay spectroscopy at S³

- comprehensive focal plane detector setup SIRIUS
  - trackers for ToF and veto
  - Si detector array for charged particle detection
    - ER, α’s, e⁻
  - photon detector array
    - γ’s, X-rays
SHN research at SPIRAL2/GANIL
- decay spectroscopy at $S^3$

**comprehensive focal plane detector setup SIRIUS**
- trackers for ToF and veto
- Si detector array for charged particle detection
  - ER, $\alpha$’s, $e^-$
- photon detector array
  - $\gamma$’s, X-rays
**Mobile Decay Spectroscopy Set-up – MoDSS for SHE research**

- Si stop+box (DSSD+SSSD) combined with large volume Ge-detectors

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**First $\alpha$ spectrum (test run at LISE/GANIL)**

$\Delta E$: 20 keV

**Typical $\alpha$-decay trace (FEBEX)**

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**Configuration (similar to TASiSpec, L. Andersson et al.)**

- **Stop detector**: 1 × DSSD (60×60 strips)
- **Box detectors**: 4 × SSSD (32 strips)
- **$\gamma$ efficiency**: $\approx 40\%$

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**Chamber**

- **Compact (overall length 35 cm)**
- **Al-cap with thin $\gamma$ window (1.5 mm)**
- **Compatible due to 150 mm standard flange**

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**DSSD**

- **Integrated cooling (Cu-frame) and connection (flex-PCB)**
- **60×60 strips/mm (pitch 1 mm)**
- **300 $\mu$m**

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**Electronics (partly integrated in the vacuum)**

- **Analog and digital (FEBEX) options**
Mobile Decay Spectroscopy Set-up – MoDSS for SHE research
- starting from Sunday, March 29th in operation at GANIL/LISE for $^{50}$Ti + $^{209}$Bi

compact electronics: FEBEX3A flash ADC’s

compact configuration: MoDSS + EXOGAM clovers

first Th-α’s from $^{50}$Ti+$^{170}$Er:
March 30th 2015 at 4:30 a.m.

the night shift
SHE research at S³/SPIRAL2

- physics and requirements

- nuclear structure features of SHN
  - quasi-particle excitations → deformation/K-isomers
  - X-ray Z-identification (LoI GANIL-FLNR for Z=115)
  - in-beam studies/in-beam X-rays?

- reaction studies
  - isospin dependent investigations

- instrumentation
  - GSI Si-array MoDSS → SIRIUS

- accelerator and targets
  - A/q = 6-7 (SPIRAL2 phase 1+)
  - actinide target technology

Nuclides discovered at SHIP
New or improved detectors

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Dieter Ackermann

See contribution of Christelle Stodel on Thursday
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