Superheavy nuclei @ RIKEN, Dubna and JYFL

CSNSM – IPHC – GANIL
Motivations

How many elements?

Properties of matter in extreme conditions of mass & charge?
Limits of the nuclear chart?
Theoretical challenge

- Large density of states
- Strong Coulomb field

Total spin-orbit splitting depends on the location of the radial wavefunctions

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

Unreacted beam
Scattered beam
Transfer: beamlike
Transfer: targetlike
Coullex
Fusion - Fission

Survival of nucleus of interest: $\sigma < 1 \mu b$

Making the heaviest elements

28/11/2016: IUPAC approves the names of the 4 new elements!

30/12/2015: IUPAC announces that the 7th period of the periodic table is complete!
What next?


Cross sections (broad range of predictions) ?
Excitation functions: Optimal beam energy ?
Intense heavy-ion beams via the Metal Ions from VOlatile Compounds method


$^{50}$Ti beam out of source on target trans. cons.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Current (μA)</th>
<th>Charge State</th>
<th>Current (μA)</th>
<th>Transmission (%)</th>
<th>Consum. (mge/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JYFL ECRIS2</td>
<td>19 (11+)</td>
<td>1.7</td>
<td>0.044</td>
<td>2.6</td>
<td>~0.6</td>
</tr>
<tr>
<td>GANIL ECR4</td>
<td>28 (10+)</td>
<td>2.8</td>
<td>0.450</td>
<td>16.0</td>
<td>~0.2</td>
</tr>
<tr>
<td>DUBNA ECR4M</td>
<td>55 (5+)</td>
<td>11.0</td>
<td>0.490</td>
<td>4.5</td>
<td>~0.6</td>
</tr>
<tr>
<td>RIKEN RILAC</td>
<td>15 (11+)</td>
<td>1.6</td>
<td>0.500</td>
<td>30.0</td>
<td>~0.5</td>
</tr>
</tbody>
</table>

MIVOC method:
Intensity, stability, reliability & low material consumption

$^{51}$V beam sucessfully tested in RIKEN 2017
$^{46}$ & $^{47}$Ti isotopic MIVOC beams since 2017
$^{54}$Cr beam sucessfully tested in Dubna 2018

Metallic beams for next generation of SHE!
Beams for synthesis, spectroscopy & chemistry


First prompt spectroscopy of a superheavy nucleus $^{256}$Rf @ JYFL

$^{46}$Ti beam to prepare the chemistry of Nh (113) @ FLNR:

$^{46}$Ti + $^{141}$Pr -> Thallium
(Nh homologue)
Synthesis program @ RIKEN (2014-)

$^{50}\text{Ti} + ^{248}\text{Cm} \rightarrow ^{295}\text{Og} + 3n$

$^{50}\text{Ti}$ from IPHC, accelerated by RILAC (0.5 pμA)

No events – upper limit unpublished

$^{51}\text{V} + ^{248}\text{Cm} \rightarrow ^{299-\chi}\text{Uue} + \chi n$

$^{51}\text{V}$ from IPHC, beam accelerated by RRC cyclotron

Optimal beam energy determined by barrier distribution run

Several campaigns since 2017, ongoing

T. Tanaka et al., Journal of the Physical Society of Japan 87 (2018) 014201
Perspectives

2020: Start of the SHE Factory @ DUBNA & new RILAC @ RIKEN

Metallic ions beams of $^{50}$Ti, $^{51}$V & $^{54}$Cr (MIVOC + Inductive oven)
-=> up to 10 µA on target!

Unique $^{248}$Cm, $^{249}$Bk & $^{249-251}$Cf targets

-=> two parallel programs in Dubna and RIKEN (with IN2P3 teams)

    E119, E120 campaigns ...

R&D to enable the use of an $^{254}$Es target for synthesis

Ongoing R&D on Uranocene for multinucleon transfer

Reach more neutron-rich SHE with Multinucleon transfer
-=> potential discovery and study or many tens of new SHE
Spectroscopy of super heavy nuclei

Beam Filter ERs Focal Plane
Target Beam dump Time-of-Flight

\[ ^{256}\text{Rf} \at \text{JYFL} \]

\[ ^{256}\text{Rf} \at \text{FLNR (2018)} \]

\[ \gamma, e^- \]

\[ ^{5}\text{isomer} \]

\[ ^{0+} \]

\[ ^{2+} \]

\[ ^{4+} \]

\[ ^{6+} \]

\[ ^{8+} \]

\[ ^{10+} \]

\[ ^{12+} \]

\[ ^{14+} \]

\[ ^{16+} \]

\[ ^{18+} \]

\[ ^{20+} \]

\[ ^{22+} \]

\[ ^{24+} \]

\[ ^{26+} \]

\[ ^{28+} \]

\[ ^{30+} \]

J. Rubert, PhD thesis, Université de Strasbourg (2013)

K. Hauschild et al., in preparation
Prompt spectroscopy @ JYFL

$^{208}\text{Pb}(^{40}\text{Ar},2n)^{246}\text{Fm}$ up to 71 pnA, 40 kHz $\sigma=11$ nb


Perspectives

AGATA (3-4\pi) @ RITU (also VAMOSGF) -> increased $\gamma^n$

Calorimetric efficiency: fission barriers


Polarization capabilities: search for M1 resonances in superheavy nuclei
Decay spectroscopy at FLNR

2004: **Gamma Alpha Beta Recoil Investigations with the ELECTromagnetic Analyser (CSNSM-FLNR-IPHC)**

- Intense beams
- Dedicated beam time
- Availability of exotic targets
SHELS@Dubna

VASSILISSA (Energy filter) → SHELS (velocity filter)

Gain in transmission, especially for asymmetric reactions

GABRIELA@SHELS

Rotating target

Intense beam

SHELS

Concrete wall

ToF

Focal plane

8° magnet

Triggerless detector array

fission

α

γ

ICE

8ommagnet
Structure & reaction studies

$\gamma$ and ICE decay of an isomer in $^{251}$Fm: evidence for octupole collectivity

PhD thesis (Université Paris Saclay)

$^{50}$Ti + $^{209}$Bi $\rightarrow$ $^{259}$-xnDb

$^{256}$Db $\quad 1.6$ s
$^{257}$Db $\quad 2.3$ s
$^{258}$Db $\quad 4.2$ s
$^{259}$Db

$^{256}$Rf $\quad 6.9$ ms
$^{257}$Rf $\quad 4.4$ s
$^{258}$Rf $\quad 4.7$-$10$ ms

B(E3) = 18(6) W.u

$^{50}$Ti + $^{209}$Bi $\rightarrow$ $^{258,256}$Rf: 5 events observed
$\sigma \sim 5$ pb
K-isomer studies

Best examples of K-conserving decays In the nuclear chart
Excellent probes of shell structure
Enhanced stability with respect to fission?

$^{50}\text{Ti} + ^{207}\text{Pb} \rightarrow ^{255}\text{Rf} + 2n$ (2017)

$^{22}\text{Ne} + ^{238}\text{U} \rightarrow ^{256}\text{No} + 4n$ (2019)

R. Chakma, PhD thesis (Université Paris Saclay)
K. Kessaci, PhD thesis (Université de Strasbourg)

$\Delta t(\text{recoil-isomer})$ vs subsequent $\alpha$ Energy

$\gamma$ decay of new isomer in $^{255}\text{Rf}$

preliminary
**Perspectives**

- Search for rare decay modes
  - e.g. fission branch from K isomers
- Detailed (high statistics) spectroscopic studies
  - from Fm up to Sg using heavy and light beams

\[ \sigma \geq 0.1 \text{ nb for decay} \]

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<tr>
<th>90\text{Th}, 92\text{U}, 94\text{Pu}, 95\text{Am}, 96\text{Cm}, 98\text{Cf} targets</th>
<th>80\text{Hg}, 81\text{TI}, 82\text{Pb}, 83\text{Bi} targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>253 Bh</td>
<td>254 Bh</td>
</tr>
<tr>
<td>252 Db</td>
<td>253 Db</td>
</tr>
<tr>
<td>251 Rf</td>
<td>252 Rf</td>
</tr>
<tr>
<td>250 Lr</td>
<td>251 Lr</td>
</tr>
<tr>
<td>249 No</td>
<td>250 No</td>
</tr>
<tr>
<td>247 Fm</td>
<td>248 Fm</td>
</tr>
</tbody>
</table>

\[ 78\text{Pt}, 79\text{Au}, 80\text{Hg}, 81\text{TI}, 82\text{Pb}, 83\text{Bi} \text{ targets} \]

\[ 90\text{Th}, 92\text{U}, 94\text{Pu}, 95\text{Am}, 96\text{Cm}, 98\text{Cf} \text{ targets} \]
Perspectives

- Upgrade of GABRIELA to digital GABRIELA with enhanced Xray & ICE sensitivity

\[ ^{251}\text{Fm isomer decay} \]

Simulations: 60-day \( ^{48}\text{Ca} + ^{243}\text{Am} \) run (5 p\( \mu \text{A} \))

Conclusions & Outlook

- SHE research is a challenging field requiring long beam times, intense beams and technological innovations (chemistry, detectors, electronics, targets...)
- Longstanding in2p3 research programs in the field
- Experience & expertise, which has been/will be applied to other projects (S3 and SIRIUS @ SPIRAL2)
- Successful collaborations in Dubna, JYFL and RIKEN
- New results & discoveries are foreseen