Study of very Heavy Nuclei at GANIL-SPIRAL2 facilities

Super Heavy Nuclei International Symposium
Texas A & M University, College Station TX, USA
March 31 - April 02, 2015

Christelle Stodel (GANIL)
Study of very Heavy Nuclei at GANIL-SPIRAL2 facilities

- **SPIRAL 2 Facility**
  - LINAG
  - NFS
  - Physics cases
  - Technical description
  - Targets issues

- **GANIL**
  - decay spectroscopy of $^{257}$Db
  - AGATA campaign

- Conclusions and Perspectives
Study of very Heavy Nuclei at GANIL-SPIRAL2 facilities

• SPIRAL 2 Facility
  ✓ LINAG
  ✓ NFS
  ✓
    Physics cases
    Technical description
    Targets issues

• GANIL
  ✓ decay spectroscopy of $^{257}$Db
  ✓ AGATA campaign

• Conclusions and Perspectives
mid term roadmap

**Phase1 (2015-)**
Increase the intensity of stable beams
High intense neutron source
\(HI \leq 10^{15} \text{ pps, p-Ni}\)

**Phase1++ (2021-)**
High Intensity
\(HI \leq 10^{15} \text{ pps, p-U}\)

**Phase2**
Expand the range and the intensity of exotic nuclei

**DESIR Phase1+ (2019-)**
Low energy facility

**AGATA (2015-2018)**
New light RIBs from beam/target fragmentation

**SPIRAL1 Upgrade (2016-)**
A National & EU priority

**GANIL (HI \leq 10^{13} \text{ pps})**
Production up to \(10^{14} \text{ FF/s}\)

**LINAG**
33 MeV p, 40 MeV d (5mA)
A/q=3 - 14.5 A.MeV HI (1mA)

**SPIRAL1 upgrade**
CME: 1-20 A.MeV (9 A.MeV pour FF)

**LISE RIBs**
High Intensity Project (SPIRAL2 Phase 1++)

- Reference project $\leq 10^{15}$ pps, p-Ni, 0.75 MeV/n – 14.5 MeV/n
- Phase 1++ $\leq 10^{15}$ pps, p-U, 0.75 MeV/n – 10 MeV/n

- Strengthen the phase 1+ scientific program
- Open new perspectives (Pb, U heavy beams)

<table>
<thead>
<tr>
<th>Ions</th>
<th>Intensity (pµA)) [A/Q=3]</th>
<th>High Intensity [A/Q=6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}$O</td>
<td>216</td>
<td>375</td>
</tr>
<tr>
<td>$^{19}$F</td>
<td>28.6</td>
<td>50</td>
</tr>
<tr>
<td>$^{36}$Ar</td>
<td>17.5</td>
<td>40</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>2.9</td>
<td>30</td>
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<tr>
<td>$^{36}$S</td>
<td>4.6</td>
<td>30</td>
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<tr>
<td>$^{40}$Ca</td>
<td>3</td>
<td>20</td>
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<tr>
<td>$^{48}$Ca</td>
<td>1.25</td>
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<tr>
<td>$^{58}$Ni</td>
<td>1.1</td>
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<tr>
<td>$^{84}$Kr</td>
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<td>20</td>
</tr>
<tr>
<td>$^{124}$Sn</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>$^{139}$Xe</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>0</td>
<td>2.5</td>
</tr>
</tbody>
</table>
SPIRAL2 Phase 1++ civil construction is finished

September 2014
Installation

LINAC beams in 2015
SPIRAL2 - LINAG

December 19th-22nd 2015: 7.7mA H⁺ on CF11

90% of equipments installed
Objectif ambitieux de démarrer la source protons et LBE2 avant Noël 2014

http://pro.ganil-spiral2.eu/events/weeks/ganil-spiral2-week-2014
Neutrons For Science

Physics cases (19 LOIs):
- Neutron induced reactions studies (n, xlcp) (n,xn)
- Fission studies
- Cross-section reaction measurements by activation technique
- Biology
- Detector development

- Beam at 0°
- Collimator ↔ beam quality
- Size (L x l) ≈ (28m x 6m)
  - TOF measurements
  - free flight path

Use of radioactive samples
A< 1 GBq for thin layers
A< 10 GBq for thick samples

I < 50 µA
P < 2 kW

Most of the detection systems setups already exist

High impact day 1 experiments for first SPIRAL2 beams (PAC October 2015)

R&D for the production of radioisotopes (211At & 64Cu)

By courtesy of X. Ledoux
Super Separator Spectrometer

The project & the physics opportunities

*S3 Collaboration* (Loi signed by 28 laboratoires)

ANL (US), CENBG, CSNSM, JINR-FLNR, (Russia), GANIL, France, GSI (Germany), INFN Legnaro, (Italy), IPHC, France, IPNL, , Irfu CEA Saclay, IPNO, France, JYFL (Finland), K.U. Leuven (Belgium), Liverpool-U, (UK), LNS (Italy), LPSC, MSU (US), LMU, (Germany), Nanjing-U (China), Northern Illinois University (US), SAS Bratislava, (Slovaquia), IFJ PAN Cracow (Poland), Smoluchowski Institute (Poland), CEA-DAM; SUBATECH, TAMU (US), U. Mainz (Germany), York-U (UK), Vinca Institute (Serbia)

http://pro.ganil-spiral2.eu/spiral2/instrumentation/s3
Physics goals

Study of rare events in nuclear and atomic physics

\[ ^{58}\text{Ni}+^{46}\text{Ti} \rightarrow ^{100}\text{Sn} +4\text{n} \]
\[ (I=10\mu\text{A}) \rightarrow 3\text{evt/s} @ \sigma_{\text{th}}=5\text{nb} \]

Proton Dripline & N=Z nuclei
- Tests of Shell Model
- Shapes of nuclei
- Exotic decay
- Ground-State Properties

Nuclei produced by Fusion-Evaporation

\[ ^{48}\text{Ca}+^{238}\text{U} \rightarrow ^{283}112 +3,4\text{n} \]
\[ (I=10\mu\text{A}) \rightarrow 20\text{evt/week/pb} \]

Neutron-Rich Nuclei
- Single-Particle structure
- Quenching of Shell Gaps

High Resolution and High Transmission versatile separator-spectrometer

Ion-Ion interactions

Atomic physics
FISIC project

→ test nuclear and atomic models and guide new theoretical development
Day 1 experiments: VHE - SHE

© SHE Synthesis
I = 10 pμA
⇒ 1 evt/month @ σ ~ 10 fb

© Reaction studies
Isospin dependent investigation

© Nuclear structure
Quasi-particle excitations ⇒ deformation/K-isomers
Alpha/gamma/electron spectroscopy
X ray spectroscopy
### Day 1 experiments: VHE - SHE

<table>
<thead>
<tr>
<th>nuclide</th>
<th>feature</th>
<th>X-section [nb]</th>
<th>rate [h⁻¹]</th>
<th>21UT integral</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>day 1</td>
<td>phase 1++</td>
</tr>
<tr>
<td>254No</td>
<td>ER</td>
<td>2000</td>
<td>60.000</td>
<td>1×10⁷</td>
</tr>
<tr>
<td>256Rf</td>
<td>ER</td>
<td>17</td>
<td>550</td>
<td>90.000</td>
</tr>
<tr>
<td>266Hs</td>
<td>ER</td>
<td>15 (²⁷⁰Ds)</td>
<td>0.34</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>K-isomer</td>
<td>15 (²⁷⁰Ds)</td>
<td>0.01</td>
<td>2.5</td>
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<tr>
<td>270Ds</td>
<td>ER</td>
<td>15</td>
<td>0.45</td>
<td>76</td>
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<td>270mDs</td>
<td>K-isomer</td>
<td>15 (²⁷⁰Ds)</td>
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<tr>
<td>262Sg</td>
<td>α-decay</td>
<td>15 (²⁷⁰Ds)</td>
<td>0.02</td>
<td>5</td>
</tr>
<tr>
<td>276Cn</td>
<td>ER</td>
<td>0.5 (²⁷⁷Cn)</td>
<td>0.01</td>
<td>2.5</td>
</tr>
<tr>
<td>²⁸⁸115</td>
<td>ER</td>
<td>10</td>
<td>0.3</td>
<td>50</td>
</tr>
<tr>
<td>²⁸⁸115</td>
<td>L X-rays</td>
<td>10</td>
<td>1.8</td>
<td>300</td>
</tr>
</tbody>
</table>

### Lol 2009:

“Production and spectroscopy of heavy and superheavy elements using S³ 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 ²⁵⁴No and ²⁵⁶Rf: location of single--particle states close to the Z=100 and N=152 deformed shell gaps”
(Univ Jyvaskyla, CSNSM, GANIL, IRFU and S3 coll)

“Towards the study of Z=115 via the reaction ⁴⁸Ca + ²⁴³Am”
(JINR, GANIL and S3 coll)

Talk of J. Gates on Tuesday

**SIRIUS needed**

Z > 112 ➔ Actinide targets
Optics

- Multistep separation
- Large acceptance
- Mass resolution ($\Delta M/M = 460$)

Image 1: Highly selective beam rejection

Image 2: Achromat selection
Extended drift to place detector arrays

Image 3: TKE selection

Image 4: Mass selection

Tracewin simulation code (Irfu):
Full raytracing in the multipole 3D field maps
Automatic optimisation of 80 fields

$\Delta (M/Q) \approx 460$

$A = 101, 100, 99$

$22, 23, 24, 25, 26$
Beam spot: $\sigma_x = 0.5\text{mm}, \sigma_y [0.5-2.5\text{mm}]

Energy precision $\approx 5 \times 10^{-3}$

All hardware components are under final construction

Installation completed by September 2016
Experimental Techniques

**Ground state properties**
(mass, size, moments, spins)

**REGLIS\(^3\) setup**
Low Energy Branch
Funded

**Atomic physics**

**FISIC setup**
Fast Ion Slow Ion Collisions Electron exchange

**Partially Funded**
INSPI-CIMAP-JENA/GSI + new CPIER

**In-beam spectroscopy**
Two step reactions
EXOGAM2
PARIS-AGATA
MUST2/GASPARD
Not in the scope of the project

**Delayed spectroscopy**
SIRIUS setup
Implantation-decay station at the mass dispersive plan
Funded by new CPIER

**Phase 1a**
GANIL, IPHC, CSNSM, CEA/Irfu/SPhN

**Phase 1b**

**Phase 2**

**Phase 3**
REGLIS$^3$ day 1 experiments

215$^{Ac}$ ($N=126$)

May 2014 5GHz

Dec 2014 S3-like
Target stations for $S^3$

- Prototype Actinide target station
  - Design & Conception
  - Target irradiations
- First stable target station
**Requirements**

**Stable**

\(^{208}\text{Pb}, ^{209}\text{Bi}, \text{Ni}, \text{Ca}, \text{C}..., 0.3 - 2 \text{ mg/cm}^2 \)  
\( (R \approx 35 \text{ cm}) \)

**Actinides**

\(^{232}\text{Th}, ^{238}\text{U}, ^{239}\text{Pu}, ^{242}\text{Pu}, ^{244}\text{Pu}, ^{243}\text{Am}, ^{248}\text{Cm} \)

\( 0.3 - 0.5 \text{ mg/cm}^2 \approx 25 \text{ mg} \approx 10^2 - 10^8 \text{ Bq} \)  
\( (R \approx 7 \text{ cm}) \)

**Stripper**

C, Al

30-100 \( \mu \text{g/cm}^2 \)

<table>
<thead>
<tr>
<th>beam</th>
<th>(^{70}\text{Zn})</th>
<th>(^{48}\text{Ca})</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(MeV/u)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>target</td>
<td>C/Pb/C</td>
<td>Ti/Cm/C</td>
</tr>
<tr>
<td>thickness (( \mu \text{g/cm}^2 ))</td>
<td>10/450/10</td>
<td>2( \mu \text{m}/450/10</td>
</tr>
<tr>
<td>w (rpm)</td>
<td>3000</td>
<td>5000</td>
</tr>
<tr>
<td>R(cm)</td>
<td>33.5</td>
<td>7</td>
</tr>
<tr>
<td>( T_{max} &lt; T_{fus} )</td>
<td>Pb ou PbS</td>
<td>U ou Cm(_2)O(_3)</td>
</tr>
<tr>
<td>( I_{max} (\mu\text{Ae}) )</td>
<td>90-800</td>
<td>100-400</td>
</tr>
<tr>
<td>DT ( \pm 50^\circ \text{C} )</td>
<td>(Ti)</td>
<td>(Ti)</td>
</tr>
<tr>
<td>( I_{max} (\mu\text{Ae}) )</td>
<td>60-80</td>
<td>30-70</td>
</tr>
<tr>
<td>( dP (w) )</td>
<td>35-50</td>
<td>15-35 (*3 Ti)</td>
</tr>
</tbody>
</table>

**48Ca (10p\mu\text{A}) + ^{248}\text{Cm} \rightarrow ^{296}\text{Zn}^{116*} 70\text{Zn} (10p\mu\text{A}) + ^{208}\text{Pb} \rightarrow ^{278}\text{Zn}^{112*}**

oxidation of backings, irradiation modification, sputtering....???
Prototype Actinide Target Station

- Reliability tests
- Instrumentation of the dedicated electronics for target control (e-beam, silicons...)

2009

- Command/control of target wheel
- GANIL beam tests ($^{129}$Xe @ 8 MeV/A, 250 pnA)

S³ target monitoring with an electron gun

Test at LISE 2000 in 2014

Automated Scanning of the e-Gun using Raspberry Pi and digital Potentiometer

- Online 3D imaging of each target is possible
- We observed some degradation according to the material and the dose

Jinesh Kallunkathariyil et al, Institute of Physics, Jagiellonian University, Krakow
Carbon – 500 µg/cm²

Before irradiation (R5)

10 Multilayer

4.4E16 part (R60)

5 Multilayer

DLC

4 Multilayer

C Targets from W. Mittig, F. Pellemeoine, MSU
Upstream beam line

Collimator with beam current measurement

F. Lutton, P. Gangnant, C. Marry, J.F. Libin, P. Lecomte …
Conclusions - Perspectives - SPIRAL2

- LINAC under test
- First LINAC Beams end 2015-2016
- “Actinide test bench” available

- **1st S3 stable target station:**
  - Manufacture et receipt
  - Integration of instrumentation
  - Mechanical tests
  - Development of the Command/control
  - Pyrometer / thermal camera

- Installation
- Off-beam Tests
- commissioning

- Design + manufacture of **actinide station** + Glove box
- Tests with actinides targets

- R&D target technologies
  - Cacao/GSI/MAINZ/Dubna...
  - backings
  - fabrication methods
  - FISIC strippers
  - Characterization
Study of very Heavy Nuclei at GANIL-SPIRAL2 facilities

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  - Physics cases
  - Technical description
  - Targets issues

- **GANIL**
  - decay spectroscopy of $^{257}$Db
  - AGATA campaign

- Conclusions and Perspectives
Spectroscopy of $^{257}$Db

J. Piot, M. Vostinar et al, (GANIL, IPHC, Dpt of Physics, Jyväskylä, GSI, DNPB, Bratislava, CEA, IRFU, LPC, CNSNSM, Dpt of Physics, Liverpool, JINR Dubna)

Measure new electromagnetic transitions in $^{257}$Db, $^{253}$Lr and $^{249}$Md

$^{209}$Bi($^{50}$Ti,2n)$^{257}$Db $\sigma$=2.4 nb

- Isomeric levels in $^{255}$Lr [Hauschild et al. PRC, 2008.]
- and $^{256}$Rf [Jeppesen et al. PRC, 2009.]
- $^{257}$Db, $^{258}$Sg?
Synthesis of $^{257}\text{Db} @ \text{GANIL}$, LISE in FULIS MODE

First experiment using $^{50}\text{Ti}$ GANIL - up to 0.5 $\mu\text{A}$ on target
 Separation by LISE velocity filter Rejection : $3 \times 10^{10}$
 Transmission : 15% (→ Gain factor 15-20 with S$^3$)

E656, E686 experiments : J. Piot & M. Vostinar (GANIL)
Mobile Decay Spectroscopy Set-up - MoDSS for SHE research
- Si stop+box (DSSD+SSSD) combined with large volume Ge-detectors

configuration
- stop detector: 1 × DSSD (60×60 strips)
- box detectors: 4 × SSSD (32 strips)
- γ efficiency ≈ 40%

chamber
- compact (overall length 35 cm)
- Al-cap with thin γ window (1.5 mm)
- compatible due to 150 mm standard flange

DSSD
- integrated cooling (Cu-frame) and connection (flex-PCB)
- 60×60 strips/mm (pitch 1 mm)
- 300 µm

electronics (partly integrated in the vacuum)
- analog and digital (FEBEX) options

first α spectrum (test run at LISE/GANIL 2014)
(ΔE: 20 keV)

typical α-decay trace (FEBEX)
2010 → 2011
LNL : 5TC

AGATA D.+PRISMA
Total Eff Nominal ~ 2.6%

2012 → 2014
GSI/FRS : 6TC+3 DC

AGATA @ FRS
Total Eff. (β=0.5) ~ 10%

2014 → 2018
GANIL/SPIRAL2 : 15TC

AGATA @G1 (→ π)
Total Eff ~ 8% to 14%

E. Clément, A. Lemasson, et al
Physics cases for the AGATA campaign in GANIL

- 46, 48Ca
- S, Cl, Ar, K
- 46Ti
- 77Y
- 132In
- 80Zr
- 68Ni, Fe, Co, Cu
- 194Pb
- Sm, Pm
- 78Ni
- Zr, Mo
- Ru, Pd
- Xe, Te

SPIRAL1

- 38K
- 63Ge
- 75Sr
- 80Zr
- 100In
- 176Hg
- 194Pb
- Sm, Pm

58Ni, 40Ca → N=Z

- 48Ca, 50Ti → SHE

254No

- 256Rf

Cm, Bk, Cf, Es

- 238U, 208Pb → 235U

- 47 Letters of Intents
- The equivalent of ~2006 UT are proposed → 16048 hours of beam on target (669 days)
- 4 main setups
  - Vamos in magnetic spectrometer
  - Vamos in gas-filled
  - Nwall + Diamant
  - DSSSD (SPIRAL1)
Physics cases for the 1st AGATA run at GANIL: nuclear structure in the vicinity of doubly magic nuclei

- $^{238}U, ^{208}Pb \rightarrow n$-rich

J. Ljungvall et al: 2+, 4+ 6+ lifetime and $g$-factor in $^{62,64,66}$Fe;

C. Domingo-Pardo et al: 4+, 2+ lifetime in $^{94}$Ru and $^{96}$Pd;

J. J. Valiente Dobon et al: 4+, 2+ lifetime in $^{106,108}$Sn;

G. Georgiev et al: 2+ lifetimes and $g$ factor in $^{204,206,208}$Hg;

D. Verney et al: lifetime measurement in $^{83}$Ge;

A. Navin et al: $i_{13/2}$ single particle state in $^{133}$Sn and high spin in $^{108}$Zr;

G. Duchêne et al: 80Zn and 82Ge highest spin structures;

A. Lemasson et al: spectroscopy of $^{39,41,43}$S;

P. R. John et al: Shape transition in W isotopes: 190W and 192W spectroscopy and fast timing;

S. Leoni et al: Lifetime in n-rich C and O isotopes: test of the three body forces.
In-beam test VAMOS-AGATA

$^{238}$U beam for the commissioning of the AGATA-VAMOS coupling.
27 November: 17 UT
8 December: 19 UT
NOW DATA TAKING !
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• GANIL
  ✓ decay spectroscopy of $^{257}$Db
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• Conclusions and Perspectives
SPIRAL2/GANIL Road map

2016: Start of the scientific program of SPIRAL2
- 2015: Commissioning and exploitation of SPIRAL2-Phase 1
- Beginning of 2016: First NFS beams
- End 2016-2017: First $S^3$ beams

2015 - …. GANIL Scientific program
- AGATA Campaigns 2015-2018 - PARIS, NEDA, GASPARD
- LISE & new SPIRAL1 beams (end 2016) – ACTAR-TPC
- FAZIA-INDRA campaigns, …
- France-hadron, industrial applications

2019- … Start of DESIR Scientific program
- Low energy $S^3$ beams (ANR REGLIS$^3$)
- SPIRAL1 new beams

2015- … study of the new injector $A/Q=1-7$

Next steps:
- Long-range strategy for GANIL/SPIRAL2: Working group GANIL/SP2 2025
- Final report on a long-range strategy for GANIL/SPIRAL2, XIX$^{th}$ COLLOQUE GANIL (12th-16th October, 2015 Anglet (Aquitaine))