Super Separator Spectrometer

The project & the physics opportunities

Hervé Savajols

on behalf of the $S^3$ collaboration

$S^3$ 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, (Slovakia), 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
Overview

✓ Status of SPIRAL2 phase 1

✓ Separator Spectrometer

✓ Experimental techniques

✓ Physics opportunities

  Spiral2 Ph1 physics WS – March 2014 – 165 participants

✓ Outlook and conclusions
SPIRAL2 under construction

Phase 1: High intensity stable beams + Experimental rooms (NFS + S\(^3\) + DESIR) (2015)
Phase 2: High-intensity low-energy & post-accelerated Radioactive Ion Beam facility

SPIRAL2 is on the list of the European Strategy Forum on Research Infrastructures (ESFRI)
Phase 1 (2015-)
Increase the intensity of stable beams
High intense neutron source
\( (HI \leq 10^{15} \text{ pps, p-Ni}) \)

Phase 1++ (2020-)
High Intensity
\( (HI \leq 10^{15} \text{ pps, p-U}) \)

Phase 2
Expand the range and the intensity of exotic nuclei

Desir Phase 1+ (2019-)
Low energy facility

Agata (2015-2018)

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

Spiral 1 upgrade
Production up to \( 10^{14} \text{ FF/s} \)
CME: 1-20 AMeV (9 AMeV pour FF)

Spiral 1 Upgrade (2016-)
New light RIBs from beam/target fragmentation

A National & EU priority
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 (µA) [A/Q=3]</th>
<th>High Intensity [A/Q=6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{O}$</td>
<td>216</td>
<td>375</td>
</tr>
<tr>
<td>$^{19}\text{F}$</td>
<td>28.6</td>
<td>50</td>
</tr>
<tr>
<td>$^{36}\text{Ar}$</td>
<td>17.5</td>
<td>40</td>
</tr>
<tr>
<td>$^{40}\text{Ar}$</td>
<td>2.9</td>
<td>30</td>
</tr>
<tr>
<td>$^{36}\text{S}$</td>
<td>4.6</td>
<td>30</td>
</tr>
<tr>
<td>$^{40}\text{Ca}$</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>1.25</td>
<td>15</td>
</tr>
<tr>
<td>$^{58}\text{Ni}$</td>
<td>1.1</td>
<td>10</td>
</tr>
<tr>
<td>$^{84}\text{Kr}$</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>$^{124}\text{Sn}$</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>$^{139}\text{Xe}$</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>0</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Neutron-rich VHE-SHE

New perspectives with the phase1++ high intensity heavy beams (Xe, Pb, U)

I=1μA $\rightarrow$ 15evt/s@$\sigma$~1μb
Take into account fission / 1000
$\rightarrow$ 50 evt/hour

SPIRAL2 Phase 1++ civil construction is finished

September 2014
Installation

LINAC beams in 2015
“First generation of ECOS facility”
Physics goals

Study of rare events in nuclear and atomic physics

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

Proton Dripline & N=Z nuclei
Shell correction effects
Study the role of \( \pi-\nu \) correlations
Deformation – shape coexistence
Exotic decay
Astrophysics rp-process
Fundamental interaction

High Resolution and High Transmission versatile separator-spectrometer

Nuclei produced by Fusion-Evaporation

Nuclei produced by nucleon transfer reaction

Neutron-rich Nuclei
Evolution of shell closure
(Tensor, 3-body forces …)

\[ ^{48}\text{Ca} + ^{238}\text{U} \rightarrow ^{283}\text{112} + 3,4n \]  
(\( I = 10\,\mu\text{A} \))  \Rightarrow 30\text{evt/week/pb}

Limit of the nuclear existence
Reaction mechanism
Shell correction effects
Atomic properties

Ion-Ion interactions

Atomic physics
FISIC project

\( \Rightarrow \) test nuclear and atomic models and guide new theoretical development
Technical challenges

- **High Beam intensity** (10µA = 6.10^{13} p/s or more)
  - High power loss density in target and beam dump
  - Rejection of the beam: >10^{13}

- **Reactions at Low Energy** (fusion-evaporation residues)
  - Large solid angle: +/- 80 mrad X and +/- 80 mrad Y
  - Charge state acceptance of +/- 10% (q=20^+)
  - Momentum acceptance for each charge state Bρ: +/- 10%

- **Many reaction channels** (evaporation channels)
  - M/q selection: 1/350 (FWHM) resolution
  - Identification in Z when possible

- **Versatility** (transfer reactions & ion-ion collisions)
  - High range in energy [Bρ_{max} = 1.8Tm]
  - Secondary reactions
Optics

Image 1
Highly selective beam rejection

Image 2
Achromat selection
Extended drift to place detector arrays

Image 3
TKE selection

Image 4
Mass selection

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

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

Momentum Achromat
Mass spectrometer

Horizontal
Vertical

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

$A=101, 100, 99$
Operational modes & performances

- **High Resolution mode**
  - Designed for maximum selection
  - Weighted mass resolution: $\Delta M/M = 460$
  - Folded transmission: 50% for $^{58}\text{Ni} + ^{46}\text{Ti} \rightarrow ^{100}\text{Sn}^{24+} + 4n$

- **High Transmission mode**
  - Designed for very asymmetric reactions
  - Weighted mass resolution: $\Delta M/M = 260$
  - Folded transmission: 15-20% for $^{22}\text{Ne} + ^{238}\text{U} \rightarrow ^{255}\text{No} + 5n$

- **Converging mode**
  - Designed for gas cell – Laser spectroscopy
  - Folded transmission: 68% for $^{58}\text{Ni} + ^{40}\text{Ca} \rightarrow ^{94}\text{Ag} + p3n$

1) High resolution  
2) High transmission  
3) Converging  

$\varphi=5cm$
Technical highlight

Beam spot:
$\sigma_x=0.5\text{mm}, \sigma_y[0.5-2.5\text{mm}]$
Energy precision $\approx 5 \times 10^{-3}$

3 x M-dipoles
Large H & V gaps

Dispersive zone
(beam dump & Movable fingers)

tested for $5\text{kW/cm}^2$

Target system
High power rotating targets (3000-5000 rpm)
Stable & Actinide systems

3 x M-dipoles
Large H & V gaps

E-Dipole
20 cm gap & +/- 350 kV
$E_{\text{max}}: 12-14 \text{ MeV}$
Open slit in the anode

SC Multipoles
Q+S+O fields

All hardware components are under final construction
Installation completed by September 2016
Experimental Techniques

**In-beam spectroscopy**
Two step reactions  
EXOGAM2  
PARIS  
AGATA  
MUST2/GASPARD

**S3 Physics case** (16 Lols)
- VHE – SHE elements
- Proton drip-line and N=Z
- Nuclear astrophysics
- Atomic physics

**Delayed spectroscopy**

**SIRIUS setup**
Implantation-decay station at the mass dispersive plan

**Atomic physics**

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

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

**REGLIS³ setup**
Low Energy Branch

**DESIR**
SIRIUS (Spectroscopy & Identification of Rare Ions Using S$^3$)

- Recoil-decay tagging
- Short decay times
- High Resolution, High efficiency
- Mass separation

**Germanium detector**
- e.g., Exogam2, CLODETTE

**Time of flight + tracking detector**
- Large size (200x150 mm$^2$)
- Time Resolution < 1ns
- Position resolution = 1mm
- Very low thickness

**Tunnel detector for escaped e$^-$ and $\alpha$**
- Conversion electrons FWHM <5 keV
- Escaped alpha FWHM 15 keV

**Implantation detector**
- (HI, $\alpha$ and e$^-$ decay)
- Large detector size 10x10 cm$^2$
- High resolution FWHM
- **Ability to detect large > 50 MeV pulse**
  Followed ($\approx$ 10$\mu$s) by a weak (<15 MeV) pulse.
- No Dead time

(GANIL, IPHC, CSNSM, CEA/IRFU/SPhN)
Day 1 experiments: N=Z

100Sn region experimental status

- 112Ba-108Xe-104Te super-allowed α decay and search for cluster radioactivity
- Exotic decays from the 21+ isomer in 94Ag

Excited states
Fusion-evaporation
Decay properties
Fusion-evaporation
Existence
Fragmentation
α decay
proton decay
β-delayed protons with sizeable branch
Observed/expected
Day1 experiments: VHE - SHE

- **Nuclear structure**
  Quasi-particle excitations ➔ deformation/K-isomers

- **Reaction studies**
  Isospin dependent investigation

- **SHE Synthesis**
  I=10µA ➔ 1evt/month@σ~10fb

<table>
<thead>
<tr>
<th>nuclide</th>
<th>feature</th>
<th>X-section [nb]</th>
<th>rate [h⁻¹]</th>
<th>21UT integral day 1</th>
<th>21UT integral 15-20</th>
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</thead>
<tbody>
<tr>
<td>$^{254}$No</td>
<td>ER</td>
<td>2000</td>
<td>60.000</td>
<td>$6\times10^7$</td>
<td>$1\times10^7$</td>
</tr>
<tr>
<td>$^{256}$Rf</td>
<td>ER</td>
<td>17</td>
<td>550</td>
<td>$90.000$</td>
<td>$5.4\times10^5$</td>
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<tr>
<td>$^{266}$Hs</td>
<td>ER</td>
<td>15 ($^{270}$Ds)</td>
<td>0.34</td>
<td>57</td>
<td>285</td>
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<tr>
<td>$^{266m}$Hs</td>
<td>K-isomer</td>
<td>15 ($^{270}$Ds)</td>
<td>0.01</td>
<td>2.5</td>
<td>12.5</td>
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<tr>
<td>$^{270}$Ds</td>
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<td>190</td>
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<tr>
<td>$^{262}$Sg</td>
<td>α-decay</td>
<td>15 ($^{270}$Ds)</td>
<td>0.02</td>
<td>5</td>
<td>25</td>
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<tr>
<td>$^{276}$Cn</td>
<td>ER</td>
<td>0.5 ($^{277}$Cn)</td>
<td>0.01</td>
<td>2.5</td>
<td>12.5</td>
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<tr>
<td>$^{288}$115</td>
<td>ER</td>
<td>10</td>
<td>0.3</td>
<td>50</td>
<td>300</td>
</tr>
<tr>
<td>$^{288}$115</td>
<td>L X-rays</td>
<td>10</td>
<td>1.8</td>
<td>300</td>
<td>1800</td>
</tr>
</tbody>
</table>

Rate summary vs GSI UNILAC
× 2-4 [A/Q=3]
× 15-20 [A/Q=6]
Synthesis of $^{257}$Db @ GANIL

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

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

First experiment using $^{50}$Ti GANIL - up to 0.5 $\mu$A on target
Separation by LISE velocity filter Rejection : $3.10^{10}$
Transmission : 15% (Gain factor 15-20 with S$^3$)

Set the course for the S$^3$ VHE-SHE researchs

E656 experiment : J. Piot & M. Vostinar (GANIL)
Low energy branch

(Some experiments require higher purity, low energy ions in vacuum, …)

**REGLIS³**: In-gas cell laser ionization and spectroscopy

- Pre-selection by S³ in-flight separator
- Products thermalized and neutralized in a buffer gas
- Re-ionization of stopped reaction products
- Selective ionization for decay spectroscopy, mass measurements, DESIR
- High resolution laser spectroscopy in gas jet
Laser systems for in gas ionization: Dye laser (HELIOS) and Ti:Sa laser (GISELE2)

MAJOR ATTRIBUTES OF THE DEVICE

- **Efficient**: produced in very small quantities (→ ~ 1 pps)
- **Selective (isotopic & isobaric selections)**: suppression of unwanted isotopes (1/10 000 lower limit demonstrated)
- **Relatively fast**: short life time (up to ~ 100 ms)
- **Sufficient spectral resolution** (→ few hundred MHz): determine the isotope/isomer shift and hyperfine structure, spin, moments...

=> 2 in 1: Laser spectroscopy + Laser Ion Source (pure (isomeric) beams)

**Expected performances**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission through $S^3$</td>
<td>40-50 %</td>
</tr>
<tr>
<td>Thermalization, diffusion and transport through the exit hole</td>
<td>50-90 %</td>
</tr>
<tr>
<td>Neutralization</td>
<td>50-100 %</td>
</tr>
<tr>
<td>Laser ionization</td>
<td>50-60 %</td>
</tr>
<tr>
<td>Transport efficiency</td>
<td>80-90 %</td>
</tr>
<tr>
<td><strong>Total efficiency</strong></td>
<td>4-24 %</td>
</tr>
</tbody>
</table>
Low energy platform

- Collinear laser spectroscopy
- $\beta$-delayed $\gamma$ spectroscopy (laser)
- $\beta-\nu$ angular correlation: LPCtrap
- Mass measurements: MLLTrap
- $\beta$-delayed charge part. Emission
- (Trap-assisted) $\beta$-decay, TAS
**REGLIS³ day 1 experiments**

- **Red boxes:** Laser (optical) spectroscopy data available
- **Empty 'gaps':** Beams are not available at high temperature ISOL systems (refractory or above uranium)

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**"Day 1" experiments**

- commissioning
- laser and decay spectroscopy - mass measurements MR-TOF
  - N=Z region around and below 100Sn: shell evolution, astrophysics
  - heavy element region: shapes, stability
  - $^{254}\text{No}$: atomic physics ("Day 2" experiment)
UNIQUE Opportunities:
SPIRAL2 Phase 1 + - GANIL (AGATA, …)

Probing nuclei properties with unique complementarity techniques

SIRIUS

Ground State properties

S³-SIRIUS/DESIR
(Mass – Size – $J^\pi$ – Moments)

Decay spectroscopy
S³-SIRIUS/DESIR

In-Beam spectroscopy
AGATA-VAMOS@GANIL
S³

Excited state properties

SIRIUS

REGIS³

DE$\ddagger$IR

Ground State properties
Détermination de $V_{ud}$ depuis les transitions $0^+ \rightarrow 0^+$ et miroirs

$V_{ud} = 0.97425 (22)$

Hardy J C and Towner I S 2009 Nucl. Phys. A 254 221

MLLTrap

LPCTrap

CENBG tape station

Tape system

Phase 1++

$T_z = 0, -1, -2$ decays

$T_z = -1/2$ mirror decays

$V_{ud} = 0.97425 (22)$

Détermination de $V_{ud}$ à une précision équivalente des $0^+$ $0^+$ depuis les transitions miroirs
Conclusions

- SPIRAL2 phase 1 under final construction: “First generation ECOS accelerator”
  - Commissioning of the accelerator will start in 2015

- SPIRAL2 phase 1++ (new injector A/Q=7) design will start 2015

- S$^3$ is a low energy in-flight separator for the Spiral2 stable beams
  - Fusion-evaporation, two-step reactions, rare channels, electron exchange…
  - Designed for the selection and identification of rare events
    - 2 steps rejection and >350 Mass resolution
    - High transmission of evaporation residues
    - High versatility

- Two basic detection set-ups
  - Implantation-decay spectroscopy station
  - In gas cell laser ionization & spec.
  - First beam in 2016

You are welcome to join the collaboration