Towards the superheavy elements:

MNT experiment carried out at Argonne: $^{136}\text{Xe}+^{238}\text{U}$ at $0^\circ$
Towards the synthesis and spectroscopy of superheavy elements: proposal and analysis of the Multi-Nucleon Transfer reactions \((^{136}\text{Xe}\text{+}^{238}\text{U})\) and characterization of the new SIRIUS implantation detector (DSSD)
Towards the synthesis and spectroscopy of superheavy elements: proposal and analysis of the Multi-Nucleon Transfer reactions ($^{136}\text{Xe} + ^{238}\text{U}$) and characterization of the new SIRIUS implantation detector (DSSD)
Towards the synthesis and spectroscopy of superheavy elements: proposal and analysis of the Multi-Nucleon Transfer reactions ($^{136}\text{Xe} + ^{238}\text{U}$) and characterization of the new SIRIUS implantation detector (DSSD)
SIRIUS decay station

SIRIUS: System for the Investigation of Recoiling Ions Using S3

Tracker | Tunnel | DSSD | Ge-array
---|---|---|---
Recoils

**Time of Flight:**
- Emissive foil
- Thin windows
- High Time resolution
- Mass Identification
  A/ΔA ~300

**Silicon detectors:**
- Charged particle discrimination for recoil, beta and decay alpha
- High resolution alpha and conversion electron spectroscopy
- Measurement of TKE for spontaneous fission
- Access to short decay times

**Digital electronics:**
Digital signal processing

**γ-ray detection :**
- 5 EXOGAM clover detectors
- Efficiency of 40% at 121 keV

See Rikel Chakma’s talk
**SIRIUS decay station**

**SIRIUS: System for the Investigation of Recoiling Ions Using S3**

**Tracker**
- Recoils

**Tunnel**
- Time of Flight:
  - Emissive foil
  - Thin windows
  - High Time resolution
  - Mass Identification
  - $A/\Delta A \sim 300$

**DSSD**
- Silicon detectors:
  - Charged particle discrimination for recoil, beta and decay alpha
  - High resolution alpha and conversion electron spectroscopy
  - Measurement of TKE for spontaneous fission
  - Access to short decay times

**Ge-array**
- $\gamma$-ray detection:
  - 5 EXOGAM clover detectors
  - Efficiency of 40% at 121 keV

**Digital electronics:**
- Digital signal processing

See Rikel Chakma’s talk
Decay station

SIRIUS

Delayed spectroscopy

Since July 2020 at CEA/Irfu

Complete chamber from Strasbourg.

Tunnels from IJClab.

DSSD and electronics from CEA/Irfu.

Offline commissioning (sources $\alpha$, $\beta^-$)
Decay station

SIRIUS

Delayed spectroscopy

Since March 2021 at GANIL

Complete chamber from Strasbourg.
Tunnels from IJClab.
DSSD and electronics from CEA/Irfu.
Offline commissioning (sources $\alpha$, $\beta^-$)
SIRIUS Collaboration


IPHC : P. Brionnet, O. Dorvaux, B. Gall, Th. Goeltzenlichter, C. Mathieu
Towards SHE using MNT reactions

- Physics motivations
- #1786 experiment at Argonne: $^{136}$Xe+$^{238}$U at 0°
- First results
- Limits, perspectives and outlooks
Towards SHE using MNT reactions

- Physics motivations
- #1786 experiment at Argonne: $^{136}\text{Xe}+^{238}\text{U}$ at 0°
- First results
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Physics objectives: SHE, a perfect laboratory
Physics objectives: SHE, a perfect laboratory

Spherical superheavy nuclei?
Island of stability?
Limits of existence of the matter

Nuclear chart from l’Édition n°13 - June 2020
Physics objectives: SHE, a perfect laboratory

Spherical superheavy nuclei?
Island of stability?
Limits of existence of the matter

<table>
<thead>
<tr>
<th>Model</th>
<th>Z</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>W.S.</td>
<td>114</td>
<td>184</td>
</tr>
<tr>
<td>F.R.D.M</td>
<td>114</td>
<td>178</td>
</tr>
<tr>
<td>H.F.B.</td>
<td>126</td>
<td>184</td>
</tr>
<tr>
<td>R.M.F.</td>
<td>120</td>
<td>172</td>
</tr>
</tbody>
</table>

Expected magic numbers for SHE
Physics objectives: SHE, a perfect laboratory

Very Heavy and Super Heavy Elements
- Limit of the nuclear existence
- Shell correction effects
- Strong Coulomb forces
- Study nuclear structure
- Basic nuclear properties (masses, ionization potential, quadrupole moments, radii...)
- Single particle states
- K-isomers
- New isotopes
- Odd-Z nuclei
- N=152, 162 ...

Spherical superheavy nuclei? Island of stability?
Limits of existence of the matter

<table>
<thead>
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<td>184</td>
</tr>
<tr>
<td>R.M.F.</td>
<td>120</td>
<td>172</td>
</tr>
</tbody>
</table>

Expected magic numbers for SHE

Detection of evaporation residues
Reaction mechanisms to produce SHE?

1) Fusion-evaporation
2) MultiNucleon Transfer (MNT)

SHE

\[ \text{Beam} \rightarrow \text{Target} \]
Reaction mechanisms to produce SHE?

1. Fusion-evaporation
2. MultiNucleon Transfer (MNT)

\[ \text{SHE} + n \rightarrow \text{Exchange} n, p \]
Reaction mechanisms to produce SHE?

1) Fusion-evaporation
2) MultiNucleon Transfer (MNT)

\[ \text{SHE} + n \]
Reaction mechanisms to produce SHE?

1) Fusion-evaporation
2) MultiNucleon Transfer (MNT)

Deep Inelastic Transfer

Primary Transfer Products

Evaporation Residue (ER)

Fission Fragments

Exchange n, p

SHE

Compound Nucleus

Fission Fragments

Evaporation Residue (ER)

Fusion-Fission
Reaction mechanisms to produce SHE?

1) Fusion-evaporation
2) Multi-Nucleon Transfer (MNT)
Physics objectives: VHE and SHE

Superheavy nuclei? Island of stability?

Limits of the fusion-evaporation method
- Superheavy nuclei up to Z=118
- GSI, Dubna, RIKEN: Z = 119 or 120?
- Very low cross-sections
- Limited due to beam-target combination

New separators -> $S^3$/SIRIUS, SHE factory...
**Physics objectives: VHE and SHE**

- Production of Heavy and Superheavy Elements

**Limits of the fusion-evaporation method**
- Superheavy nuclei up to Z=118
- GSI, Dubna, RIKEN: Z = 119 or 120?
- Very low cross-sections
- Limited due to beam-target combination

**New separators -> S³/SIRIUS, SHE factory...**

**Multi-Nucleon Transfer (MNT) reactions**
- Heavy and superheavy nuclei?
- More neutron-rich nuclei
- Not limited to beam-target combination

"New" reaction mechanisms -> MNT

(Nuclear chart from l’Édition n°13 - June 2020)
Towards superheavy elements

### 136Xe + 248Cm @ 5 MeV/n around 0°

**σ≈ 1-10 μb**

- 244Es
- 246Es
- 248Es
- 250Es
- 252Es
- 254Es
- 256Es
- 258Es

**σ≈ 0.1-10 mb**

- 248Bk
- 250Bk
- 252Bk
- 254Bk
- 256Bk
- 258Bk

Prompt spectroscopy allows to measure:

- Highly excited states not populated via fusion-evaporation reaction
- γ-rays spectroscopy will provide crucial information for theoretical models

E.g.: Via measurement of excitation energy and spin distribution

---

Zoé Favier – CEA Saclay/Irfu
Towards SHE using MNT reactions

- Physics motivations

- **#1786 experiment at Argonne:** $^{136}\text{Xe} + ^{238}\text{U}$ at 0°
  - Theoretical computations
  - Simulations
  - Experimental set-up

- First results

- Limits, perspectives and outlooks
The experiment:
ZF, D. Seweryniak et al: « Synthesis of heavy and superheavy neutron-rich nuclei in multinucleon transfer reactions close to 0° »

The reaction:
$^{136}$Xe$+^{238}$U at 0°
@3.6, 4.4 and 5.9MeV/u, 20 pnA
Gammasphere-AGFA-XArray
The reaction: \( ^{136}\text{Xe} + ^{238}\text{U} \text{ at } 0^\circ \)

@ 3.6, 4.4 and 5.9 MeV/u, 20 pnA
Gammasphere-AGFA-XArray

\[ \text{Courtesy of A. Karpov} \]

(using the Langevin’s model)

\[ E_{\text{cm}} = \sim 490 \text{ MeV} \]

Integrated between 0-5°
Kinetic simulations (VGFS code)

- Schiwietz - Grande
- Ghiorso
- Betz
- Gregorich

Beam-like

MNT products
Target-like

Ghiorso

Developed by Ch. Theisen
Optical simulations (transmission of AGFA)

Generate the input files

Semi-classical model
(generates diff. xsec at grazing angle)

GRAZING

Generates the events

PartGen

AGFA MC optical simulations

Monte-Carlo

92 ≤ Z ≤ 98
136 ≤ N ≤ 153

Grazing Code:
- Aim: to produce an event generator to feed the AGFA MC simulation
- Estimates the Q-value (with ame2012.cal)
- Generates the output files of the event generator

\[ Z \quad A \quad Q \quad \bar{Q} \quad E \quad \vec{x} \quad \frac{\vec{p}}{||\vec{p}||} \quad B\rho \]

AGFA Monte-Carlo simulation:
- Charge state model: A. Ghiorso et al. NIM in PRA 269 (1988) 192-201
- Optical simulations of AGFA (greetings to D.H. Potterveld)
AGFA Monte-Carlo simulations

for 100 random Uranium-like recoils

Top view

Side view
AGFA Monte-Carlo simulations

1 Torr  4 Torr  8 Torr

DSSD cuts
recoils

<table>
<thead>
<tr>
<th>Pressure (Torr)</th>
<th>(N_{AGFA})</th>
<th>(N_{DSSD})</th>
<th>Transmission to the DSSD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>4735</td>
<td>1275</td>
<td>13.6</td>
</tr>
<tr>
<td>1.0</td>
<td>5159</td>
<td>1936</td>
<td>20.7</td>
</tr>
<tr>
<td>2.0</td>
<td>5215</td>
<td>2229</td>
<td>23.8</td>
</tr>
<tr>
<td>4.0</td>
<td>5384</td>
<td>3106</td>
<td>33.2</td>
</tr>
<tr>
<td>8.0</td>
<td>5114</td>
<td>3827</td>
<td>40.9</td>
</tr>
</tbody>
</table>

\(~28\% \text{ at } 3 \text{ Torr}\)
ATLAS at Argonne

ATLAS
ARGONNE TANDEM LINEAR ACCELERATOR SYSTEM
Multinucleon transfer reactions (MNT) at Argonne
Multinucleon transfer reactions (MNT) at Argonne

$^{136}$Xe beam from ATLAS
Multinucleon transfer reactions (MNT) at Argonne

$^{136}$Xe beam from ATLAS

$^{238}$U target
Multinucleon transfer reactions (MNT) at Argonne

$^{136}\text{Xe}$ beam from ATLAS

$^{238}\text{U}$ target

Target wheel

Target chamber

$Q_v$

$D_m$

$Q_v$

$D_m$

Scattered beam

Focal plane

MNT products

AGFA gas-filled recoil separator
Multinucleon transfer reactions (MNT) at Argonne

136Xe beam from ATLAS

Target-like products identification
(coincidences)

Scattered beam

Focal plane

238U target

MNT products

Q

D

m

AGFA gas-filled recoil separator

Target wheel

Target chamber

Q

D

m

\[ \text{products} \]
Multinucleon transfer reactions (MNT) at Argonne

$^{136}$Xe beam from ATLAS

$^{238}$U target

$\gamma$, Xrays

Target-like products identification (coincidences)

MNT products

Scattered beam

Focal plane

GammaSphere

Prompt spectroscopy

Target chamber

$Q_e$

$D_m$

AGFA gas-filled recoil separator

$1^{st}$ Colloque GANIL – Autrans-Méaudre en Vercors, France – Sept. 27, 2021

Zoe Favier – CEA Saclay/Irfu
Multinucleon transfer reactions (MNT) at Argonne

Zoé Favier – CEA Saclay/Irfu

XXII 1nd Colloque GANIL – Autrans-Méaudre en Vercors, France – Sept. 27, 2021

136Xe beam from ATLAS

Scattered beam

Target-like products identification (coincidences)

Xarray

Focal plane

Target chamber

Gammasphere

Prompt spectroscopy

Target-like products identification

MNT products

X, Xrays

238U target

Q_v

D_m

Scattered beam

Fast isomers

Recoils

Decay spectroscopy

Gammasphere

Target wheel

AGFA gas-filled recoil separator

Focal plane

DSSD

PPAC

Si Tunnels

Fast isomers

Recoils

Gammasphere

Target wheel
Multinucleon transfer reactions (MNT) at Argonne

- Proof-of-principle experiment to study neutron-rich heavy nuclei using MNT reactions
- 1\textsuperscript{st} MNT reaction using AGFA @ANL to produce heavy nuclei
- **Beam:** $^{136}$Xe @605, 705 and 809MeV
- **Target:** $^{238}$U (UF$_4$ 300µg/cm$^2$ + C 40µg/cm$^2$)
- Innovative solutions to increase AGFA helium pressure up to 3Torr (Ti window after the target chamber)

**Prompt spectroscopy**

$^{136}$Xe beam from ATLAS

$^{238}$U target

$\gamma$, Xrays

Target-like products identification (coincidences)

MNT products

D$_m$

Fast isomers recoils

Target-like products identification

Focal plane

Decay spectroscopy

$eta$

Fast isomers recoils

Focal plane

DSSD

Si Tunnels

PPAC

CloverA

CloverB

CloverC

CloverD

Xarray

Gammasphere

Target wheel

Target chamber

AGFA gas-filled recoil separator

Zoé Favier – CEA Saclay/Irfu
Towards SHE using MNT reactions

- Physics motivations

- #1786 experiment at Argonne: $^{136}\text{Xe} + ^{238}\text{U}$ at $0^\circ$

- First results

- Limits, perspectives and outlooks
### Experimental conditions

#### 3 energies

<table>
<thead>
<tr>
<th>Beam energy (MeV)</th>
<th>Run numbers</th>
<th>Theor. $\beta = v/c$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No beam</td>
<td>1–19 ans 117–129</td>
<td>0</td>
</tr>
<tr>
<td>605</td>
<td>20–50</td>
<td>6.91</td>
</tr>
<tr>
<td>705</td>
<td>73–116</td>
<td>7.55</td>
</tr>
<tr>
<td>809</td>
<td>51–72</td>
<td>8.16</td>
</tr>
</tbody>
</table>

#### 5 $B_\rho$

<table>
<thead>
<tr>
<th>Beam energy (MeV)</th>
<th>Run numbers</th>
<th>$B_\rho$ (Tm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>605</td>
<td>20</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>21–27</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>2.2</td>
</tr>
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<td></td>
<td>30</td>
<td>2.4</td>
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<td></td>
<td>21–50</td>
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</tr>
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<td>705</td>
<td>73–116</td>
<td>1.8</td>
</tr>
<tr>
<td>809</td>
<td>51–66</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>67–72</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Identification of neutron-rich nuclei (recoils)

Preliminary

With TOF conditions
Identification of neutron-rich nuclei (recoils)

Preliminary with TOF conditions
Identification of neutron-rich nuclei (recoils)
Identification of neutron-rich nuclei (recoils)

Correlations in time and position

Ebeam = 705 MeV, BRho = 1.8 Tm
Duration: 38h
Number of recoils: 786430

Ebeam = 705 MeV, BRho = 1.8 Tm
Duration: 38h
Number of recoils: 786430
Identification of neutron-rich nuclei (recoils)

- $\gamma - \gamma$ correlations
- Transfer of 2n ($^{240}$U)
- Xrays of Am, Np, U (transfer of 1p, 3p)?
- Correlations with GS and XArray
- New accepted experiment at PAC2021 to get more statistics!
Towards SHE using MNT reactions

- Physics motivations
- #1786 experiment at Argonne: $^{136}\text{Xe} + ^{238}\text{U}$ at $0^\circ$
- First results
- Limits, perspectives and outlooks
Main limits of the #1786 experiment

Lack of statistics

6.5 Shift losses due to:

- DAQ issues (reboot IOTs)
- broken targets (mechanical constraints)

had to vent, open the target chamber...

Limitations :

- APEX UF₄ targets, lots of fission events... had to decrease the beam intensity
- Frequency in the GS crystals
- 70/110 working detectors of GS
- bad resolution of the GS crystals
- can not rely on alphas
- no mass identification
GS Calibration with a $^{152}\text{Eu}$ source

\[ \text{FWHM} = \sqrt{a + bE_\gamma + cE_\gamma^2} \]

- $a = 1.111 \pm 0.002975$
- $b = 0.005366 \pm 5.43e^{-06}$
- $c = 1.183e^{-05} \pm 2.239e^{-09}$
New #1930 experiment accepted PAC 2021

- $^{136}\text{Xe} + ^{238}\text{U}$ at 0°
- New metallic targets manufactured at GSI
  (thanks to B. Lomel, B. Kindler, and their team)
  Not the old APEC UF$_4$ ones
- Annealing of some GS detectors: 70 → 110°?
- More beam intensity (from 2.25 to 20 pnA)
- More gas pressure from 3 to 5 Torr in AGFA

- PAC2019 (#1786) For the $E_{\text{beam}}=705$ MeV:
  We collected 786 430 recoils, within 38h at 2.25 pnA
  i.e a rate of 20755 recoils/h
  These recoils emitted $4.7 \times 10^7$ single-gammas.

- PAC 2021 (#1930) For the $E_{\text{beam}}=705$ MeV:
  Running at 20 pnA with the same beam for 110 working detectors in Gammasphere (instead of 70), during 4 days (96 hours)
  we expect $1.7 \times 10^7$ recoils (gain of factor 20)
  emitting $1.7 \times 10^8$ single-gammas (gain of factor 35).
Conclusions and perspectives

- **Simulations and particle generator**
  - Kinetic and optical simulations
  - Helped us predict the separation power of AGFA for MNT reactions

- **MNT at Argonne**
  - First proof-of-principle experiment of MNT using AGFA
  - Good separation of the BLFs and TLFs with AGFA
  - First transfers observed to be confirmed with the new experiment (PAC2021)

- **MNT at GSI/FAIR**
  - First experiments with TASCA and SHIP for SHE with MNT
  - See the talk of Timo Dickel

- **MNT for VHE and SHE**
  - A new path for neutron-rich VHE and SHE
  - Towards the “Island of Stability”? Mass identifications with gas-cells?
Thank you for your kind attention
Backup slides on MNT #1786 experiment
Production of neutron-rich Os isotopes

Cross section, mb

Mass

$N=126$

$^{136}\text{Xe} + ^{198}\text{Pt}$

Multinucleon transfer

fragmentation of $^{208}\text{Pb}$

$T.\ Kurtukian-Nieto\ et\ al\ (2014)$

Fragmentation of $^{238}\text{U}$

$J.\ Kurcewicz\ et\ al.,(2012)$
Deep-inelastic studies at $0^\circ$

V.I. Zagrebaev and W. Greiner, PRC 83 (2011) 044618

The angular distribution of the superheavy nuclei does not reveal any grazing feature, it is forward directed.
First MNT studies in the SHE region at 0°

The nuclei observed in the $^{50}\text{Ti}+^{249}\text{Cf}$ and $^{48}\text{Ca}+^{248}\text{Cm}$ reactions originate from a process where a large number of nucleons flow in the direction of the projectile nucleus with cross-sections significantly higher than the fusion-evaporation ones.\footnote{A. Di Nitto, et al. PLB 784 (2018)199–205}
MNT 136Xe+238U at 1GeV and $\theta_{\text{lab}} \sim 50^\circ$

Cross sections of GRAZING calculations and experimental yields (histogram bars) normalized to the calculated cross section of the +1 channel of $^{137}$Xe.

AGFA Monte-Carlo simulations

Particles reaching the focal plane

At 2 Torr

Counts

Entries 10000
Mean 24.57
Std Dev 4.108

X (cm)

DSSD
MNT products
Beam
AGFA Monte-Carlo simulations

DSSD
6.4 x 6.4 cm²

At 2 Torr

Entries 10000
Mean x -0.2331
Mean y 239.7
Std Dev x 5.412
Std Dev y 5.18

Zoé Favier – CEA Saclay/Irfu
From the particle generator

**Beam**

- U (Z=92)
- Np (Z=93)
- Pu (Z=94)
- Am (Z=95)
- Cm (Z=96)
- Bk (Z=97)
- Cf (Z=98)

**Target-like products**

- Xe (Z=54)
- Ba (Z=56)
- La (Z=57)
- Ce (Z=58)
- Pr (Z=59)
- Nd (Z=60)
- Sm (Z=62)
- Eu (Z=63)
- Gd (Z=64)
- Tb (Z=65)
- Dy (Z=66)
- Ho (Z=67)
- Er (Z=68)
- Tm (Z=69)
- Yb (Z=70)
- Lu (Z=71)

**Q-value (MeV)**

- 228 to 260
- A (mass number)

**Counts / 0.05 Tm**

- Bρ (Tm)
- 1.0 to 2.4
Angular distribution $\theta_{\text{lab}}$ (deg) of the differential cross-sections (mbar/sr) of the target-like nuclei generated by GRAZING.

At the grazing angle, GRAZING is giving the nice reproduction of the reactions but between 0 and 5° we are above the limits of the model.
Monte-Carlo AGFA simulations

X (at the DSSD, in cm) of the 136Xe beam

If the beam misses the target, there is significant amount that will hit the DSSD.
Monte-Carlo AGFA simulations

Charge states distributions

It starts with $Q=24$, and evolves upwards towards the equilibrium distribution in the gas as it travels.

It starts slightly higher than the equilibrium charge state in the gas, and so moves to lower $Q$ as it moves through the gas.
$^{238}\text{U}$ Targets

Zoé Favier – CEA Saclay/Irfu

XXII$^\text{nd}$ Colloque GANIL – Autrans-Méaudre en Vercors, France – Sept. 27, 2021
238U Targets

- **Up-to-now targets**
  - John P. Greene and his team have been striving on the preparation of the targets.
  - Old UF₄ thin targets are the target lab: 300 µg/cm² UF₄ prepared by vacuum evaporation onto 40 µg/cm² carbon slides
    - from the APEX¹ experiment in the 90s
    - they also prepared many slides from this era as well. All these slides are now exhausted and are floated in the Hot Lab.

- **Wheel with slits**
  - Small target wheel quadrants

Windows and degraders

- **Windows**
  - John P. Greene made a Titanium Window
  - Thickness is 0.451 mg/cm²

- **Degraders for the DSSD**
  - Different thicknesses of Aluminum foils

<table>
<thead>
<tr>
<th>E_{beam} (MeV)</th>
<th>Al degrader thickness (mg/cm²)</th>
<th>E_{remain} (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>605</td>
<td>4.26</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td>5.42</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>6.44</td>
<td>30</td>
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<tr>
<td></td>
<td>7.36</td>
<td>5</td>
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<tr>
<td>809</td>
<td>4.26</td>
<td>130</td>
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<td></td>
<td>5.42</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>6.44</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>7.36</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>all energies +/- 15 MeV</td>
<td></td>
</tr>
</tbody>
</table>
Gammasphere

XXII\textsuperscript{nd} Colloque GANIL - Autrans-Méaudre en Vercors, France – Sept. 27, 2021
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>$Q, D_m$</td>
</tr>
<tr>
<td>Maximum bending power, $B_{\rho}$</td>
<td>2.5 Tesla-m</td>
</tr>
<tr>
<td>Maximum field at $Q_v$ pole tip</td>
<td>1.24 Tesla</td>
</tr>
<tr>
<td>Maximum field at $D_m$ pole tip</td>
<td>1.7 Tesla</td>
</tr>
<tr>
<td>Bend angle</td>
<td>38 degrees</td>
</tr>
<tr>
<td>Target to $Q_v$ distance</td>
<td>40 cm 84 cm</td>
</tr>
<tr>
<td>Solid angle, $\Omega$</td>
<td>44 msr 22 msr</td>
</tr>
<tr>
<td>Target to focal plane distance</td>
<td>3.7 m 4.3 m</td>
</tr>
</tbody>
</table>

B.B. Black. EPJ Web of Conferences 163, 00003 (2017)
DSSD, PPAC and Si tunnels

DSSD mounting frame

Si tunnels

PPAC plates

Focal plane

6.4 x 6.4 cm²
EXOGAM
Germanium clovers

Clover B was missing
Digital electronics

DETECTORS

Gammasphere (up to 110 GeHP)

Focal plane

XArray (4 Clovers GeHP)

Analogic signals

Analogic signals

Numeric signals

Numeric signals

start run 1
stop run

DIGITAL ELECTRONICS

DGS digitizers

DFMA digitizers

XArray digitizers

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Presorting scheme

DGS digitizers

DFMA digitizers

XArray digitizers

RAW DATA

dgsdata
run_1.save

DFMA data
run_1.save

XArray data
run_1.save

Numeric signals

Numeric signals

start run 1
stop run

MERGED DATA

Merged
GEBMerged_run1.gtd

PreSorted
TREE1

ROOTFILES/run1.root (online)
TREETEILES/new_presort_run1.root

bin_dfma.C

gebmerge.sh

GEBMerge.chat

gebsort.sh

GEBSort.chat

beta ; dgs_m ;
dgs_PZ ; dgs_ecal

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Sorting and analysis scheme

PreSorted
ROOTFILES/run1.root (online)
TREEFILES/new_presort.run1.root

Sorted
output_sorted_beta_run1.root

Analysis
analyse_output_beta_run1.root

Merged data
bin_dfma.C

Correction
beta ;
dgs_ecal;
doppler_corr

SelectorArg.C

Sorted
output_sorted_beta_run1.root

SelectorAnalysis.C

Analysis
analyse_output_beta_run1.root

PreSorted
ROOTFILES/run1.root (online)

Sorted
output_sorted_beta_run1.root

Analysis
analyse_output_beta_run1.root

Histograms and matrices
## Calibrations

<table>
<thead>
<tr>
<th>Detector</th>
<th>Source</th>
<th>Energy range [keV]</th>
<th>Activity [kBq]</th>
<th>Run number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gammasphere</td>
<td>$^{182}$Ta</td>
<td>0-2000</td>
<td>85 (17/09/18)</td>
<td>127</td>
</tr>
<tr>
<td>Gammasphere</td>
<td>$^{152}$Eu</td>
<td>121-1410</td>
<td>?</td>
<td>126</td>
</tr>
<tr>
<td>Gammasphere</td>
<td>Mixed gamma</td>
<td>0-2000</td>
<td>115 (01/10/09)</td>
<td>125</td>
</tr>
<tr>
<td>Xarray</td>
<td>$^{182}$Ta</td>
<td>0-2000</td>
<td>85 (17/09/18)</td>
<td>123</td>
</tr>
<tr>
<td>Xarray</td>
<td>$^{152}$Eu</td>
<td>121-1410</td>
<td>?</td>
<td>124</td>
</tr>
<tr>
<td>Xarray</td>
<td>Mixed gamma</td>
<td>0-2000</td>
<td>115 (01/10/09)</td>
<td>129</td>
</tr>
<tr>
<td>Xarray</td>
<td>$^{243}$Am</td>
<td>5000-5400</td>
<td>148 (15/03/06)</td>
<td>128</td>
</tr>
<tr>
<td>DSSD</td>
<td>$^{239}$Pu, $^{244}$Cm, ($^{241}$Am)</td>
<td>5000-6000</td>
<td>?</td>
<td>120</td>
</tr>
</tbody>
</table>
Without Doppler correction / Calibration
Doppler correction (7.55% at $E_{\text{beam}}=705$ MeV)

Doppler correction function:

$$E_\gamma = E_0 \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \theta}$$
Doppler correction (7.55\% at $E_{\text{beam}}=705$ MeV)

With cuts on the recoils

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Graph showing HPGe GS id vs GS Energy (keV) with cuts on the recoils.}
\end{figure}

\begin{table}
\centering
\begin{tabular}{|c|c|}
\hline
Entry & 786430 \\
\hline
Mean x & 266.3 \\
\hline
Mean y & 61.15 \\
\hline
RMS x & 109.6 \\
\hline
RMS y & 30.47 \\
\hline
\end{tabular}
\caption{Summary statistics for the mGS_gammaE_id_with_cuts dataset.}
\end{table}
Backup slides on SIRIUS
**S³ in the SPIRAL2 project**

**Very high intensity beams (LINAG)**
- Deuterons and stable heavy beams
- $E_{\text{beam}}$ = up to 14.5 MeV/u
- Intensity $10^{14}$ ion/s beyond 1µA ($\geq 10^{13}$pps)

A/Q=3
NEWGAIN A/Q=7

**S³: Exceptional transmission/selection combination**
- High rejection $> 10^{13}$
- High transmission 50%
- Mass resolution $> 1/350$
A cutting-edge instrumentation for S³ (SIRIUS, LEB, FISIC...)

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**S³: Super Separator Spectrometer**

Beam → **Magnetic Achromat** → Target → **Achromatic point** → **Mass Spectrometer** → Final focal plane

**S3: Super Separator Spectrometer**

- Magnetic rigidity acceptance of ±7%
- Charge state acceptance of ±10%
- Angular acceptance of ±50 mrad
- Max. magnetic rigidity: $B\rho_{\text{max}} = 1.8\text{Tm}$
- Max. electric rigidity: $E\rho_{\text{max}} = 12\text{MV}$

**Decay station SIRIUS**

Delayed spectroscopy
Isomeric/decay spectroscopy at the mass dispersive focal plane ($\alpha$, e-, fission, $\gamma$)

**Structure and reaction mechanism for heavy and super-heavy nuclei**
DSSD test bench @CEA/Irfu

- Testing of DSSD, full electronics chain, with tri-alpha and electron sources
- Digital Signal Processing with Jordanov Filters (optimization of m and k)
- Characterization of the DSSD front-end electronics
- Write online and offline codes for data acquisition (NUMEXO2 cards)
- Different temperatures (-20, 0, +20°C)
- Test of low gain and high gain (0.5pF/1pF and 9pF)

992 samples
Sampling period 5ns

DSSD
128 strips x
128 strips y

Conditions:
U=55V
I=1.4µA
Temp. 20°C

Trace_spectrum

18 keV resolution

Tri alpha (239Pu, 241Am, 244Cm)

Jordanov Filter
DSSD test bench @CEA/Irfu

- Testing of DSSD, full electronics chain, with tri-alpha and electron sources
- Digital Signal Processing with Jordanov Filters (optimization of m and k)
- Characterization of the DSSD front-end electronics
- Write online and offline codes for data acquisition (NUMEXO2 cards)
- Different temperatures (-20, 0, +20°C)
- Test of low gain and high gain (0.5pF/1pF and 9pF)

First tests on the DSSD inside the MUSSETT’s chamber at CEA/Irfu
Tunnels test bench @IPHC/IJClab

Still waiting for tests with the Numexo2 electronics, it will be finished at IJClab/GANIL

Courtesy of O. Dorvaux

With CREMAT electronics

©P. Brionnet

~ 15 keV resolution
Objectives:
Testing the rejection of the line LISE2000 @GANIL with a small DSSD to study the feasibility of the SIRIUS commissioning at LISE2000.

Chosen reaction:
$^{40}\text{Ar} + ^{174}\text{Yb} \rightarrow ^{209,210}\text{Ra}$. 4.62 MeV/u
Cross section: 1.4 mb

Set-up:
- 1 DSSD 16x16 strips 300 µm (50x50 mm² active area with PAC 15mV/MeV)
- 2 amplifiers CAEN N568B
  (OUT1: GANIL ADC, FOUT1: 16 strips CFD CAEN N843)
- 1 MWPC (50x50 mm²) for TOF measurements

Work has been done to improve the transmission of LISE2000!
The selection of day one experiments for S³ was made to determine out the list of pre-proposals with “high impact” (discovery & unique proposals for S³) and feasibility.

- Identification of $^{252}\text{Rf}$ (GS & Isomeric state) and isomeric states of $^{254}\text{Rf}$
- Identification of $^{248}\text{No}$ which needs the in-flight mass-resolution that is unique to S3.
- Isomeric state in $^{250}\text{No}$
- High-K isomeric states in $^{260}\text{Sg}$
Conclusions and perspectives

- **Developing a cutting-edge technology**
  - SIRIUS in the SPIRAL2/S³ framework
  - SIRIUS: “Spectroscopy and Identification of Rare Isotopes Using S3”
  - All the different parts of SIRIUS have been tested offline @IPHC, IJClab, GANIL and IRFU test benches
  - Since July 2020, SIRIUS @CEA/Irfu (DSSD+Tunnels)
  - Offline commissioning and tests of the complete acquisition chain!

- **March 23-24, 2021:**
  - Move SIRIUS from CEA-Saclay to GANIL!

- **March-April 2021:**
  - Continuation of the tests of SIRIUS @GANIL (Trackers, HPGe, electronics...)

- **April 23, 2021:**
  - T21-01 new test with LISE2000
    - $^{40}\text{Ar}^6+$ 4.6 MeV/u
    - $^{40}\text{Ar}^+ + ^{174}\text{Yb} \rightarrow ^{209,210}\text{Ra}$
  - Online commissioning of SIRIUS with LISE2000?