PARIS
(Photon Array for studies with Radioactive Ions and Stable beams)
Physics for PARIS

- **Reaction Mechanism**
- **Hot Rotating Nuclei**
- **Collective Modes**
- **Shell Structure**

(Reviewed in O. Sorlin’s talk)
Jacobi and Poincare shape transitions (+AGATA)
Studies of shape phase diagrams of hot nuclei – GDR
differential methods
Hot GDR in neutron-rich nuclei
Isospin mixing at finite temperatures
Links between GDR emission and SD/HD structure (+AGATA)
GDR and PDR built on isomeric states
Onset of chaotic regime (+AGATA)

Onset of multifragmentation and GDR (+FAZIA)
Reaction mechanism studied via gamma-rays
Heavy ion radiative capture
Nuclear astrophysics

PDR in neutron-rich and proton-rich nuclei
(+GASPARD, NEDA)
Gamma -decay of GDR and GQR built on ground states

Multiple Coulex of SD bands in light nuclei
Relativistic coulex
Shell structure at intermediate energies (+LISE, S3, ACTAR)
Near barrier resonances
<table>
<thead>
<tr>
<th>Physics Case</th>
<th>Recoil mass</th>
<th>v/c [%]</th>
<th>$E_\gamma$ range [MeV]</th>
<th>$\Delta E_\gamma/E_\gamma$ [%]</th>
<th>$\Delta E_{\text{sum}}/E_{\text{sum}}$ [%]</th>
<th>$\Delta M_\gamma$ coverage</th>
<th>$\Delta T$ [ns]</th>
<th>Ancillaries</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacobi transition</td>
<td>40-150</td>
<td>&lt;10</td>
<td>0.1-30</td>
<td>4</td>
<td>&lt;5</td>
<td>4</td>
<td>2$\pi$-4$\pi$</td>
<td>&lt;1</td>
<td>AGATA HI det.</td>
</tr>
<tr>
<td>Shape Phase Diagram</td>
<td>160-180</td>
<td>&lt;10</td>
<td>0.1-30</td>
<td>6</td>
<td>&lt;5</td>
<td>4</td>
<td>2$\pi$-4$\pi$</td>
<td>&lt;1</td>
<td>HI det.</td>
</tr>
<tr>
<td>Hot GDR in n-rich nuclei</td>
<td>120-140</td>
<td>&lt;11</td>
<td>0.1-30</td>
<td>6</td>
<td>&lt;8</td>
<td>4</td>
<td>2$\pi$-4$\pi$</td>
<td>&lt;1</td>
<td>HI det.</td>
</tr>
<tr>
<td>Isospin mixing</td>
<td>60-100</td>
<td>&lt;7</td>
<td>5-30</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>4$\pi$</td>
<td>&lt;1</td>
<td>HI det.</td>
</tr>
<tr>
<td>Reaction dynamics</td>
<td>160-220</td>
<td>&lt;7</td>
<td>0.1-25</td>
<td>6-8</td>
<td>&lt;8</td>
<td>4</td>
<td>2$\pi$</td>
<td>&lt;1</td>
<td>n-det. FF det.</td>
</tr>
<tr>
<td>Collectivity vs. multi-fragmentation</td>
<td>120-200</td>
<td>&lt;8</td>
<td>5-25</td>
<td>5-10</td>
<td>-</td>
<td>-</td>
<td>4$\pi$</td>
<td>&lt;1</td>
<td>LCP det. HI det.</td>
</tr>
<tr>
<td>Radiative capture</td>
<td>20-30</td>
<td>&lt;3</td>
<td>1-5</td>
<td>2-5</td>
<td>-</td>
<td>-</td>
<td>2$\pi$</td>
<td>&lt;1</td>
<td>HI det.</td>
</tr>
<tr>
<td>Multiple Coulex</td>
<td>40-60</td>
<td>&lt;7</td>
<td>2-5</td>
<td>2-4</td>
<td>-</td>
<td>-</td>
<td>2$\pi$</td>
<td>&lt;1</td>
<td>AGATA CD det.</td>
</tr>
<tr>
<td>Astrophysics</td>
<td>16-90</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Outer PARIS shell as active shield</td>
</tr>
<tr>
<td>Shell structure at intermediate energies (SISSI/LISE)</td>
<td>16-40</td>
<td>20-40</td>
<td>0.5-4</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>3$\pi$</td>
<td>&lt;&lt;1</td>
<td>SPEG or VAMOS</td>
</tr>
<tr>
<td>Shell structure at low energies (separator part of $S^3$)</td>
<td>30-150</td>
<td>10-15</td>
<td>0.3-3</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>3$\pi$</td>
<td>&lt;&lt;1</td>
<td>Spectrometer part of $S^3$</td>
</tr>
<tr>
<td>Relativistic Coulex</td>
<td>40-60</td>
<td>50-60</td>
<td>1-4</td>
<td>4</td>
<td>-</td>
<td>1</td>
<td>Forward 3$\pi$</td>
<td>&lt;&lt;1</td>
<td>AGATA HI analyzer</td>
</tr>
</tbody>
</table>

**Beta \approx 10\% and DM/M < 4**

**DT < 1 ns**

**DEg/Eg: \sim 4-5 \%**

**High efficiency up to 15 MeV**
PARIS: two shells design

- **inner shell**, highly granular, for use as multiplicity filter, sum-energy, medium energy resolution, fast timing, Doppler correction ...

- **outer shell** for high energy gamma detection

- two shells for efficient add-back reconstruction

This project was developed jointly by physicists from France, Poland and Italy.
Phoswich/cluster concept

Interaction only in NaI:Tl

Interaction only in LaBr₃:Ce or CeBr₃

τ = 16 ns

Mixed interaction

1⁰⁰  6.13 MeV
<table>
<thead>
<tr>
<th>Phase 4</th>
<th>2025 ?</th>
<th>PARIS $4\pi$</th>
<th>2500 k€</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 3</td>
<td>2022</td>
<td>PARIS $2\pi$</td>
<td>2500 k€</td>
</tr>
<tr>
<td>Phase 2</td>
<td>2015</td>
<td>PARIS Demonstrator</td>
<td>1900 k€</td>
</tr>
<tr>
<td>Phase 1</td>
<td>2011/2012</td>
<td>PARIS Prototype</td>
<td>250 k€</td>
</tr>
<tr>
<td>1 cluster: 9 phoswiches</td>
<td>(ANR PROVA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~ 9 clusters (81 phoswichs)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 clusters: 108 phoswiches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\geq$24 clusters: $\geq$216 phoswiches</td>
<td>5000 k€</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PARIS organisation
PARIS Steering Committee
(nominated by the MoU partners):
IN2P3 France: O. Dorvaux
GANIL France: M. Lewitowicz
COPIN Poland: B. Fornal (dep.chair)
India: V. Nanal (chair)
Italy: A. Bracco
Romania: M. Stanoiu
UK: W. Catford
Turkey: S. Erturk

PARIS Project Manager
(nominated by PSC)
A. Maj (Poland)

PARIS Collaboration Council
(nominated by the MoU institutions)
Franco Camera (INFN, Italy) - chair and PARIS spokesman
Chandana Bhattacharya (VECC Kolkata, India)
Wilton N. Catford (University of Surrey, UK)
Marco Cinausero (LNL Legnaro, Italy)
Sandrine Courtin (IPHC Strasbourg, France)
Zsolt Dombradi (ATOMKI Debrecen, Hungary)
Camille Ducoin (IPN Lyon, France)
Sefa Ertuerk (Nigde, Turkey)
Juergen Gerl (GSI, Germany)
Anil K. Gourishetty (IIT Roorkee, India)
David Jenkins (University of York, UK)
Maria Kmiecik (IFJ PAN Krakow, Poland)
Basant Kumar Nayak (BARC Mumbai, India)
Marc Labiche (STFC Daresbury, UK)
Vandana Nanal (TIFR Mumbai, India)
Pawel Napiorkowski (HLL Warsaw, Poland)
Marek Ploszajczak (GANIL, France)
Mihai Stanoiu (IFIN-HH Bucharest, Romania)
Jonathan Wilson (IPN Orsay, France)

Working Groups and their Coordinators
(proposed by PPM and approved by PSC):
Geant4 simulation: O. Stezowski
Detectors: O. Dorvaux
Electronics and DAQ: P. Bednarczyk
Mechanical integrations: I. Matea
Data analysis: S. Leoni
New materials: F. Camera
New Physics case: I. Mazumdar

PARIS Management Board:
PARIS Project Manager + WG coordinators
PARIS

Photon Array for studies with Radioactive Ions and Stable beams

Memorandum of Understanding

AMENDMENT n°1

TO
Memorandum of Understanding

PARIS

Photon Array for studies with Radioactive

GOAL: Phase 2

GOAL: Phase 2 ++

(2013 - 2021)
Table 5.1 Summary table of the proposed capital investment, personnel resources for PARIS system and the planned sharing between the participating collaborating institutions of each Party (extracted from the amendment to the PARIS Demonstrator MoU).

<table>
<thead>
<tr>
<th>Party or Country</th>
<th>Funds committed (before December 2017) (k€)</th>
<th>Personnel resources committed (before December 2017) (person-month)</th>
<th>Planned (2018-2021) new capital investment (k€)</th>
<th>Planned (2018-2021) Personnel resources (person-month)</th>
<th>Total capital investment (k€)</th>
<th>Total personnel resources (person-month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRANCE-IN2P3</td>
<td>292</td>
<td>36</td>
<td>200</td>
<td>48</td>
<td>492</td>
<td>84</td>
</tr>
<tr>
<td>FRANCE-GANIL</td>
<td>64</td>
<td>12</td>
<td>80</td>
<td>3</td>
<td>144</td>
<td>15</td>
</tr>
<tr>
<td>POLAND</td>
<td>300</td>
<td>30</td>
<td>160</td>
<td>40</td>
<td>460</td>
<td>70</td>
</tr>
<tr>
<td>INDIA</td>
<td>217</td>
<td>36</td>
<td>103</td>
<td>36</td>
<td>320</td>
<td>72</td>
</tr>
<tr>
<td>UK</td>
<td>42</td>
<td>11</td>
<td>21</td>
<td>11</td>
<td>63</td>
<td>22</td>
</tr>
<tr>
<td>ITALY</td>
<td>64</td>
<td>20</td>
<td>170</td>
<td>20</td>
<td>234</td>
<td>40</td>
</tr>
<tr>
<td>TURKEY</td>
<td>27</td>
<td>10</td>
<td>40</td>
<td>10</td>
<td>67</td>
<td>20</td>
</tr>
<tr>
<td>ROMANIA</td>
<td>64</td>
<td>5</td>
<td>36</td>
<td>10</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>DUBNA</td>
<td>85'</td>
<td>10</td>
<td>85'</td>
<td>10</td>
<td>85'</td>
<td>10</td>
</tr>
<tr>
<td>GSI</td>
<td>25</td>
<td>9</td>
<td>25</td>
<td>9</td>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>1070</td>
<td>920</td>
<td>1990</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Under financial support by grant of Plenipotentiary of the Government of the Poland Republic to JINR.
Detector ownership (past, present and future projections)
(PARIS MoU and MoU amendment)
Manpower:
IN2P3 et GANIL

(based of 2018 NSIP declaration)
(only most active persons are mentioned)

PARIS is in a construction phase: manpower investment at the lowest!
Physics with PARIS: highlights

“GDR emission from $^{192}$Pt* CN decay leading to $^{188}$Pt”
(nuball + PARIS → talk Wilson)

“Statistical study of the prompt fission gamma ray spectrum for 238U(n,f)”

“Features of the fission fragments formed in the heavy ion induced 32S+197Au reaction near the interaction barrier”

“Testing of the Brink-Axel hypothesis with the HECTOR+PARIS+KRATTA set-up”

“Lifetime measurements of excited states in neutron-rich C and O isotopes”
(PARIS + AGATA → talk Araceli-Lopez)
(paper under revision by the collaborations)
PARIS strong points:

- high efficiency over a wide range of energies (~100 keV to 30 MeV)
- good energy resolution
- granularity (for use as multiplicity filter, Doppler correction ...)
- sub-nanosecond timing resolution (neutron – gamma discrimination)
- stand high count rates (~MHz)
- some depth granularity (gain in the add-back reconstruction)
- modularity (to facilitate the integration with other detectors)
- mobility (for experimental campaign in other facilities)
Two-fold motivation:

1. **Reactor Physics**
   - 5% release in fission is done through PFG and $\gamma$-heating can be underestimated by up to 28%
   - design of Gen. IV reactors: fast neutron reactors – nuclear data are scarce out of thermal regime

2. **Fundamental Physics**
   - understanding the fission process, like energy partition in fission or generation of $\vec{J}$
   - study of level density function, $\gamma$-strength function, competition between $n$ and $\gamma$ emission (needed for validation of different competing codes like GEF, FREYA, CGMF, FIFRELIN)

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**Prompt gamma and neutron emission for $^{238}$U induced fission with fast neutrons at different energies (ALTO)**

Courtesy of L. Qi
Prompt gamma and neutron emission for $^{238}$U induced fission with fast neutrons at different energies (ALTO)

Courtesy of L. Qi

→ aiming at measuring spectral characteristics ($M_\gamma, E_\gamma \text{ tot}$ and $\varepsilon_{\text{ph}}$) for different fissioning systems

→ $^{252}$Cf source measurements (test data)

→ $E_n = (1.9; 4.8)$ MeV – induced fission on $^{238}$U

($\rightarrow$ also studied induced fission of fast n on $^{239}$Pu)
Conclusions:

→ low energy PFGS different for different energies: change in fragment population

→ softening of the HE part of PFGS suggests that the increased total excitation energy goes to the heavy fragments: hints on the excitation energy sharing mechanism...

→ spectral characteristics stay constant with increased neutron energy: extra excitation energy is mainly evacuated by prompt neutron evaporation. As a consequence, the fast reactors in Generation-IV don’t need significant changes in the modeling of gamma heating transportation

<table>
<thead>
<tr>
<th>$E_n$ (MeV)</th>
<th>$M_γ$ (MeV/fission)</th>
<th>$E_{γ, tot}$ (MeV)</th>
<th>$ε_γ$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>1.9</td>
<td>6.54±0.19</td>
<td>5.25±0.20</td>
</tr>
<tr>
<td></td>
<td>4.8</td>
<td>7.31±0.46</td>
<td>6.18±0.65</td>
</tr>
<tr>
<td>J-M.Laborie et al. [7]</td>
<td>1.7</td>
<td>7.05±0.20</td>
<td>5.92±0.24</td>
</tr>
<tr>
<td>M.Lebois et al. [8]</td>
<td>3.3</td>
<td>10.08±0.14</td>
<td>7.55±0.15</td>
</tr>
</tbody>
</table>

Second paper under prep.
Motivation and Goal:
Challenging fission around the interaction barrier

$^{32}\text{S} + ^{197}\text{Au} \rightarrow ^{229}\text{Am}^*, \ E^* \approx 43 \text{ MeV}$

- Coupling of 3 detection systems: CORSET + ORGAM + PARIS;
- Extracting details on the shell effects characterizing two competing processes fusion-fission (CNF) and quasi-fission (QF): (A, TKE) correlation;
- Measurement of prompt $\gamma$-rays in coincidence with binary reaction fragments obtained in the reactions: low and high energy $\gamma$-rays for further insight.

- Are population and feedings of specific isotopes preferred in different mechanisms or CNF modes?
- How does the $\gamma$-ray multiplicity or the sum energy evolve with fragment mass A, TKE or their variances?
Prompt gamma rays as a probe of nuclear dynamics (ALTO)

Experimental Setup: CORSET

$^{32}\text{S} + ^{197}\text{Au} \rightarrow ^{229}\text{Am}^*, E^* \approx 43 \text{ MeV}$

- CORSET:
  - Measured parameters:
    - ToF, X, Y
  - Extracted parameters:
    - Velocity, energy, angles
    - mass of fission fragments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Coulomb barrier (in lab. sys)</td>
<td>167 MeV</td>
</tr>
<tr>
<td>Irradiation time</td>
<td>(~4 \text{ days})</td>
</tr>
<tr>
<td>Beam current</td>
<td>(~90 \text{ nA})</td>
</tr>
<tr>
<td>Collected statistics for fission fragments</td>
<td>274448</td>
</tr>
<tr>
<td>Excitation energy of the CN</td>
<td>(~43 \text{ MeV})</td>
</tr>
</tbody>
</table>

Courtesy of I.M. Harca
Experimental Setup: Coincident FF - γ-rays

- ORGAM: Prompt γ–rays coincident with FF
- PARIS: Prompt γ–rays (HE part) coincident with FF.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ORGAM</th>
<th>PARIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number and type of Detectors</td>
<td>10 x Ge + BGO shielding</td>
<td>10 x LaBr3(Ce)-NaI(Tl) (phoswich)</td>
</tr>
<tr>
<td>Photo-peak Efficiency</td>
<td>~1%</td>
<td>~1%</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>2.6(3.4)keV @121(1408)keV</td>
<td>62keV @1332keV</td>
</tr>
<tr>
<td>Dynamical range</td>
<td>$E_\gamma &lt; 2.5$MeV</td>
<td>$E_\gamma &lt; 15$MeV</td>
</tr>
</tbody>
</table>
Hundreds of cases of nuclear fission have been explored in the past. The fission process is complex and involves the release of large amounts of energy and the formation of two or more new nuclei. Prompt gamma rays are a probe of nuclear dynamics that can provide valuable insights into the fission process. A recent study by I. Harca et al. titled “Features of the fission-like fragments following the heavy ion induced 32S+197Au reaction near the interaction barrier” is in progress for publication in PRC (2019).

- Unique investigation tool (using PARIS) of the energy deformation at different stages of fusion-fission and quasi-fission processes
- First measurement of the nuclei spin as function of the fission fragment mass distribution for different selection in the total kinetic energy of the considered system
- Opportunity to develop a program around this topic
Testing the Brink-Axel hypothesis (CCB IFJ PAN)

Courtesy of A. Maj

→ GDR build on GS and excited states are equivalent. What about the PDR?

Axel-Brink Hypothesis doesn’t seem to hold for PDR

PDR along closed neutron shell isotonic chains

“Can pygmy GT be a doorway to pymy DR?”

(I. Matea et al. - experiment ongoing)

Decay spectroscopy with high and low gamma transitions

A. Gottardo et al., PLB772 (2017)

Waiting for beam
Past/Present/Future “séjours” of PARIS

GANIL/SPRAL2 (France)  →  LoIs & Experiments
IPN/ALTO (France)  →  LoIs & Experiments
CCB IFJ PAN Krakow (Poland)  →  Experiments
SPES/LNL Legnaro (Italy)  →  LoIs
HISPEC/DESPEC FAIR (Germany)  →  LoIs
JINR/Dubna (Russia)  →  (future) Experiments
TIFR/BARC (India)  →  (future) Experiments

There will be a PARIS collaboration meeting in 2019 (autumn) (organized by F. Camera and A. Maj) with the goal to discuss new/updated PARIS physics
<table>
<thead>
<tr>
<th><strong>Strengths</strong></th>
<th><strong>Weakness</strong></th>
</tr>
</thead>
</table>
| High performances detection system in terms of:  
- efficiency in wide photon energy range  
- energy and timing resolutions  
- modularity and granularity  
- mobility  
- simultaneously sensitivity to photons and neutrons  
- easy to integrate with other detectors | - no home-base of detectors  
- limited fund to complete Phase4 (4pi)  
- PARIS standard electronic still not defined  
- limited numbers of FTE, but ... |

<table>
<thead>
<tr>
<th><strong>Opportunities</strong></th>
<th><strong>Threats</strong></th>
</tr>
</thead>
</table>
| Nice opportunities for synergies with different partners  
Readiness for physics with new facilities | - Unknown crystal ageing  
- not many provider for phoswich like for PARIS crystals (Saint Gobain/Scionix) |