PARIS

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Executive summary

PARIS array is a powerful photons detection system based on a state-of-the-art phoswich assembly of two crystal layers. The request was based on a wide physics program in nuclear physics and close to many different facilities. The PARIS concept detector was unique and very challenging at the beginning of the international collaboration. French laboratories from IN2P3 were in charge of the PARIS detector design based on GEANT simulations, the follow-up of the manufacturing process and the qualification of detectors. Ten years later, PARIS is a worldwide reference in the detection of high-energy photons and will be concerned by many physics cases as evidenced by the very long list of LoIs cited in Section 2.

1. Introduction

The worldwide offer of radioactive ion beam facilities being either in operation or under construction (SPIRAL1 and 2, SPES, HIE-ISOLDE, GSI-FAIR, RIKEN …) has opened the possibility of studying structure and dynamics of (very) exotic nuclei. Furthermore, in-flight or post-accelerated ISOL radioactive beams interacting on different targets allow for the production of even more exotic systems. But in all these cases, the nuclei or the reaction channels to be studied are often at the limits of the detection. This requires the use of extremely efficient detection systems with properties that can profit from the use of novel, advanced materials.

The **P**hoton **A**rray for studies with **R**adioactive **I**on and **S**table beams – PARIS – [PA_web] is an array intended for the efficient detection of gamma-rays over a wide energy and multiplicity range as emitted in fusion-evaporation, fusion-fission, deep-inelastic or transfer reactions. The device is devoted to both nuclear structure and reaction dynamics studies and was designed to simultaneously act as a calorimeter for high energy gamma-rays, a spin spectrometer and a medium energy resolution detector. PARIS collaboration gathers physicists working in ~40 institutions, from 19 countries. The project was initiated in the context of SPIRAL2 project, but the detector array is meant to travel to different other facilities in the world.

France, represented by IN2P3 and GANIL, is one of the major partners in the PARIS collaboration that was initiated jointly with researchers from Poland and Italy. Physicists and engineers from IN2P3 and GANIL were also involved at all levels in the R&D phase of the PARIS project.

Now, PARIS is in construction phase, and the objective is to reach the 2pi and 4pi phases of the project (see Figure 4.1). France, Poland and India are the major contributors to the construction of the PARIS array. It is worth mentioning that their involvement is realised in close collaboration, within the COPIN-CNRS and LIA COPIGAL projects (Poland), and LIA (India).

2. Scientific Program and genesis of PARIS array design

A) GANIL/SPIRAL2 Letter(s) of Intent

The initial PARIS project was put forward by groups of physicists interested in performing gamma-ray measurements using stable and radioactive beams from GANIL/SPIRAL2 facilities [GaSP2_web]. Future availability of intense stable beams (LINAG/SPIRAL2 Phase1) or neutron rich radioactive beams (SPIRAL2 Phase2) opens the possibility for the study of the properties and dynamics of hot exotic nuclei by measuring the high-energy gamma-rays associated with the Giant Dipole Resonance (GDR).

Fusion-evaporation reactions allow for the population of very high angular momentum states in the compound nucleus. A number of effects may appear in this regime including Jacobi or other shape transitions. The evolution of the GDR strength towards neutron rich systems as well as its temperature and spin-dependence will greatly benefit from future radioactive beams. Access to intense N~Z nuclei with SPIRAL2 Phase 1 can significantly deepen our understanding on isospin mixing in N=Z heavy systems. The GDR is also an useful tool for study of reaction mechanisms. In particular, it can probe the onset of multi-fragmentation like phenomena, nuclear viscosity and fusion-quasifission dynamics.

Heavy ion radiative capture is a rare process that can be studied using intense LINAG beams coupled with high efficiency gamma-ray detection system. Neutron-rich species can be populated efficiently in multi-nucleon transfer and deep inelastic reactions using either LINAG+S3 or GANIL+VAMOS spectrometers, allowing for gamma-spectroscopy studies.

This scientific program is detailed in the Letter of Intent for SPIRAL2 submitted in 2006 [LoI8] and in [Maj2009].

LoI	Nuclei/Region of interest	Spokes-person
Jacobi and Poincaré shape transitions (+AGATA)	130-142Ba, 116-120Cd, 88-98Mo, 71Zn	A. Maj et al.
Studies of shape phase diagrams of hot nuclei – GDR differential methodes	186-193Os, 190-197Pt	I. Mazumdar et al.
Hot GDR studies in neutron rich nuclei		D.R. Chakrabarty et al.
Isospin mixing at finite temperature	68Se, 80Zr, 84Mo, 96Cd, 112Ba	M. Kicinska-Habior et al.
Onset of the multifragmentation and the GDR (+FAZIA)	120<A<140, 180<A<200	**J.P. Wieleczko** et al.
Reaction dynamics by means of gamma-ray measurements	214-222Ra, 118-226Th, 229-234U	**Ch. Schmitt** et al.
Heavy ion radiative capture	24Mg, 28Si	**S. Courtin** et al.
Multiple coulex and SD bands	36<A<50	P. Napiorkowski et al.
Relativistic Coulex (after post-acceleration)	40<A<90	P. Bednarczyk et al.
Nuclear astrophysics (p,gamma)	90Zn	S. Harissopulos et al.
Shell structure at intermediate energies (LISE)	20<A<40	Z. Dombradi et al
Shell structure at low energies (separator part of S3)	30 < A < 150	**F. Azaiez** et al.
PDR studies with GASPARD and PARIS		**D. Beaumel** et al.
PDR in proton rich nuclei with NEDA and PARIS		G. de Angelis et al.
Onset of chaotic regime : PARIS + AGATA		S. Leoni et al.
Evolution of nuclear structure around 78Ni and 132Sn with PARIS and ACTAR		**G.F. Grinyer** et al.
Study of giant and pygmy resonances in exotic nuclei at LISE (PARIS + ACTAR)	neutron rich Ni isotopes	**M. Vanderbrouck** et al.
The 79Se(n,gamma) capture cross section via the surrogate 79Se(d,p)80Se reaction		G. de Angelis et al.

Table 2.1: GANIL/SPIRAL2 LoIs for PARIS (in yellow are the physics cases presented in [LoI8] and in bold are indicated the spokespersons from IN2P3/French community).

Synergies with parallel instrumental projects for GANIL/SPIRAL2 facilities, like ACTAR-TPC, FAZIA, GASPARD, NEDA etc, or with AGATA were put forward through Letters of Intent that enriched the initial physics program to be performed with PARIS array.

The list of the proposed LoIs using PARIS at GANIL/SPIRAL2 facilities is given in Table 2.1.

A summary of the technical requirements for the PARIS array as they are imposed by the above LoIs is given in Table 2.2, extracted from the PARIS theory Working Group report [WG_th1].

Physics Case	Recoil mass	v/c [%]	E_γ range [MeV]	$\Delta E_\gamma/E_\gamma$ [%]	$\Delta E_{sum}/E_{sum}$ [%]	ΔM_γ	Ω coverage	ΔT [ns]	Ancillaries	Comments
Jacobi transition	40-150	<10	0.1-30	4	<5	4	2π-4π	<1	AGATA HI det.	High eff. Beam rej.
Shape Phase Diagram	160-180	<10	0.1-30	6	<5	4	2π-4π	<1	HI det.	High eff. Differential method Beam rej.
Hot GDR in n-rich nuclei	120-140	<11	0.1-30	6	<8	4	2π-4π	<1	HI det.	Beam re.
Isospin mixing	60-100	<7	5-30	6	-	-	4π	<1	HI det.	High eff. Beam rej.
Reaction dynamics	160-220	<7	0.1-25	6-8	<8	4	2π	<1	n-det. FF det.	Complex coupling
Collectivity vs. multi-fragmentation	120-200	<8	5-30	5	-	-	2π	<1	LCP det. HI det.	Complex coupling
Radiative capture	20-30	<3	1-30	<4	5	-	4π	<1	HI det.	High eff.
Multiple Coulex	40-60	<7	2-6	5	-	-	2π	<5	AGATA CD det.	Complex coupling
Astrophysics	16-90	0.1	0.1-6	6	5	-	4π	<1	Outer PARIS shell as active shield	High eff. Back-ground
Shell structure at intermediate energies (SISSI/LISE)	16-40	20-40	0.5-4	3	-	-	3π	<<1	SPEG or VAMOS	High eff. Low I_{beam} γ–γ coinc
Shell structure at low energies (separator part of S^3)	30-150	10-15	0.3-3	3	-	-	3π	<<1	Spectrometer part of S^3	High eff. Low I_{beam} γ–γ coinc
Relativistic Coulex	40-60	50-60	1-4	4	-	1	Forward 3π	<<1	AGATA HI analyzer	Ang. Distr. Lorentz boost
Nuclear Moments	30-15-	0	0.1 - 4	3	-	4	3π – 4π	<1	Permanent magnet, particle det.	Stopped ion

Table 2.2: List of requirements related to the different physics cases to be addressed with PARIS

The study summarized in Table 2.2, puts forward the following requirements for the design of PARIS array:

– **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

– stand **high count rates** (~MHz)

– some depth granularity (to distinguish single high-energy gamma-ray from cascade of low energy gamma-rays)

– **modularity** (to facilitate the integration with other detectors)

– **mobility** (for experimental campaign in other facilities)

Quite early in the genesis of the design, the concept of two layers array appeared as the best solution: i. an inner layer, highly granular, based on new crystals, acting as gamma-ray multiplicity filter and sum-energy detector, with good timing performances and relative good resolution for low energy gamma-rays; ii. an outer layer composed of high volume conventional crystals, efficient for high energy gamma-ray detection and possibly acting as active shield for the inner layer.

An important R&D program was developed by the collaboration in order to answer to the physics requirements put forward in the LoIs.

The collaboration R&D work was involved in the selection of the type of crystals to be coupled with LaBr3(Ce) [Hull2012], in the simulations performed to define the best geometry for the array [PA_preTDR], in electronic readout performance studies and in source and beam measurements to characterize the prototype.

As part of this program, the French community involved in PARIS was granted by an ANR (Agence Nationale de Recherche) funding (600 k€ over 4 years, 2009 - 2012) for R&D work on a "Prototype for a versatile gamma-array" [PROVA] based on phoswich-like design and developed in collaboration with Saint Gobain, the owner of the B380 (LaBr3(Ce) crystals) patent.

The R&D program resulted in a design based on phoswich-like detectors made of new generation LaBr3(Ce) scintillators, 2x2x2 inches, coupled with more conventional NaI(Tl) scintillators, 2x2x6 inches (see Figure 2.1, a). The phoswich is read by one PM Tube, the discrimination between interactions of gamma-rays in LaBr3(Ce) or NaI(Tl) is based on the difference between the scintillation constants of the two crystals. The phoswiches are assembled 3x3 units in clusters (see Figure 2.1, b).

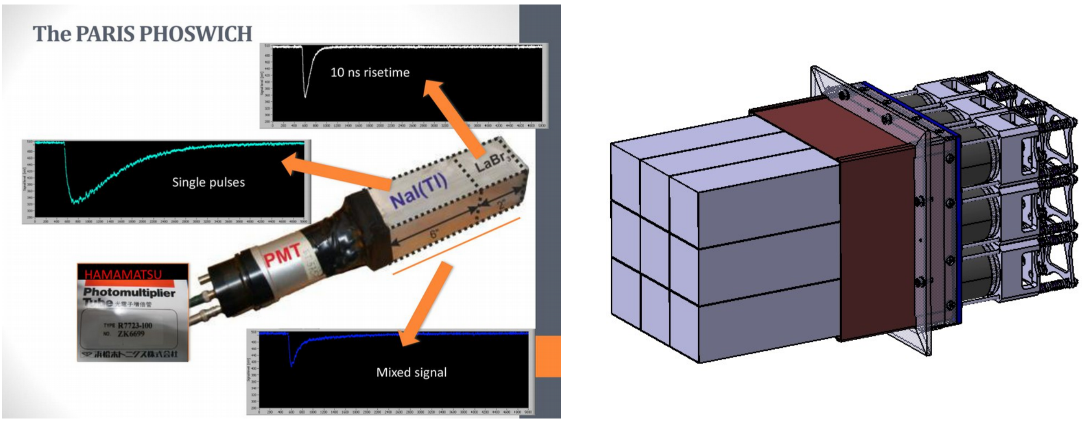

Figure 2.1: PARIS a) phoswich and b) cluster designs

Comparing PARIS present design with existing or under construction gamma-ray arrays for the field of nuclear physics underlines very well its unique performances:

– PARIS has a higher efficiency for high energy gamma-rays as the **AGATA/GRETA** arrays, state of art high resolution spectrometers.

– PARIS is transportable, efficient for detection of single gamma-rays with energies higher than 10 MeV, when compared with the **CALIFA/R3B** calorimeter.

– PARIS has higher granularity, higher efficiency than the existing arrays based on single LaBr3(Ce) crystals, like **HECTOR+** or the **Oslo array**.

– if PARIS is used as a Total Absorption Spectrometer (**TAS**), it has the advantage of granularity to measure both the total and single gamma-ray energies. Existing TAS devices, some based on LaBr3(Ce) technology, are optimized for total energy measurements.

B) Letters of Intent – other facilities

As explained above, PARIS array was designed such that it can travel to different facilities and can, a priori, easily be integrated with other detectors and, as such, profit from complementarity between beams and experimental set-ups these facilities may have. PARIS collaboration is very active in the proposed physics program for SPES radioactive beam facility [SPES_web]. The Letters of Intent submitted at SPES in 2016 and 2019 are listed in Table 2.3.

LoI	Spokes-person
Gamma and Particle Decay of Giant Resonances Excited by Inelastic Scattering of 17O ions at 20 MeV/A	F. Crespi et al.
Measurement of isospin mixing in N=Z medium mass nuclei	F. Camera et al.
GDR feeding of SD states	G. Benzoni et al.
Onset of colectivization/clusterization in Oxygen neutron-rich isotopes	S. Leoni et al.
Lifetimes measurements of excited states in neutron-rich C isotopes: a test of the three-body forces	M. Ciemala et al.
The search of Jacobi shape transitions in hot rotating nuclei from the Mo-Ba region	M. Kmiecik et al.
Study of single particle structure of Pygmy Dipole Resonance	M. Krzysiek et al.
Investigation of high spin structure in the vicinity of 44Ti via discrete and continuum gamma-spectroscopy with AGATA+EUCLIDES+RFD and PARIS	P. Bednarczyck et al.
Coulomb excitation of the super-deformed structures in A ~ 40 mass region (AGATA+SPIDER+PARIS)	K. Hadynska-Klek et al.
Study of IV-GDR in hot super-heavy nuclei	M. Vanderbrouck et al.

Table 2.3: SPES LoIs for PARIS

Different other experimental campaigns are under discussion, the targeted facilities being: TIFR Mumbai (India), JINR Dubna (Russia), HISPEC/DESPEC at FAIR-GSI (Germany).

3. Project Organization

PARIS collaboration is organized under a Memorandum of Understanding [MoU1]. The purpose of the [MoU1] is the construction of the PARIS Demonstrator. The extension (amendment) of the MoU is in the process of collecting signatures from the partners (as for today, six partners already signed the MoU extension: Poland, GANIL, INFN Italy, IFIN-HH Romania, GSI Darmstadt, JINR Dubna).

The management structure of PARIS is composed of :

- PARIS Steering Committee (PSC) – acting on behalf of the Parties defined in the MoU and responsible for the project coordination and the science policy of the collaboration.

- PARIS Collaboration Council (PCC) – representing all the institutions collaborating under the PARIS project, advises the PSC on scientific matters.

- PARIS Project Manager (PPM) and PARIS Management Board (PMB) – responsible for the execution of the project along the lines defined by PSC. The PMB is composed by the coordinators of PARIS Working Groups and the PPM, who is nominated by PSC.

The present organisation chart is displayed below (IN2P3 scientists are underlined).

PARIS Steering Committee
(nominated by the MoU partners):
IN2P3 France: <u>O. Dorvaux</u>
GANIL France: <u>M. Lewitowicz</u>
COPIN Poland: B. Fornal (dep.chair)
India: V. Nanal (chair)
Italy: A. Bracco
Romania: M. Stanoiu
UK: W. Catford
Turkey: S. Erturk

Working Groups and their Coordinators
(proposed by PPM and aproved by PSC):

Geant4 simulation: **<u>O. Stezowski</u>**
Detectors: **<u>O. Dorvaux</u>**
Electronics and DAQ: **P. Bednarczyk**
Mechanical integrations: **<u>I. Matea</u>**
Data analysis: **S. Leoni**
New materials: **F. Camera**
New Physics case: **I. Mazumdar**

PARIS Management Board: PARIS Project Manager + WG coordinators

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)
<u>Sandrine Courtin</u> (IPHC Strasbourg, France)
Zsolt Dombradi (ATOMKI Debrecen, Hungary)
<u>Camille Ducoin</u> (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 (HIL Warsaw, Poland)
<u>Marek Ploszajczak</u> (GANIL, France)
Mihai Stanoiu (IFIN-HH Bucharest, Romania)
<u>Jonathan Wilson</u> (IPN Orsay, France)

In 2018, JINR Dubna (Russia), and GSI Darmstadt (Germany), joined the PARIS Demonstrator MoU.

As underlined in the organizational chart, IN2P3 researchers are involved at different levels in the decisional process.

At the level of Working Groups, IN2P3 physicists play an important and visible role that is declined as follows :

– <u>WG (New) Physics cases</u> – in charge of the group for the first ~6 years. The work of this group was crucial for the construction of the PARIS community. Collaboration with theoretical physicists triggered new ideas that were submitted as Letters of Intent or proposals for experiments in different facilities in the world. The document synthesising the technical requests for the PARIS array [WG_th1] guided the simulations and detector performance testing.

– <u>WG Simulations</u> – in charge of this group and with a leading role in the simulations for PARIS design and for different physics cases involving PARIS. The neutron interactions in PARIS simulations were also performed by the French collaborators.

– <u>WG Detectors</u> – in charge of this group and also in charge of the relations with Saint Gobain. Homogeneity measurements of all PARIS phoswichs are done at IPHC Strasbourg, using the AGATA scanning table. A data base with these information and detector references is available for the collaboration and is hosted at IPHC.

– <u>WG Mechanical integration</u> – in charge of this group. Solutions for the cluster mechanical design and for a PARIS holding structure were proposed by engineers from IPN Orsay. The PARIS holding structure is under construction.

4. Project schedule

The different phases in the construction of PARIS are indicated in Figure 4.1.

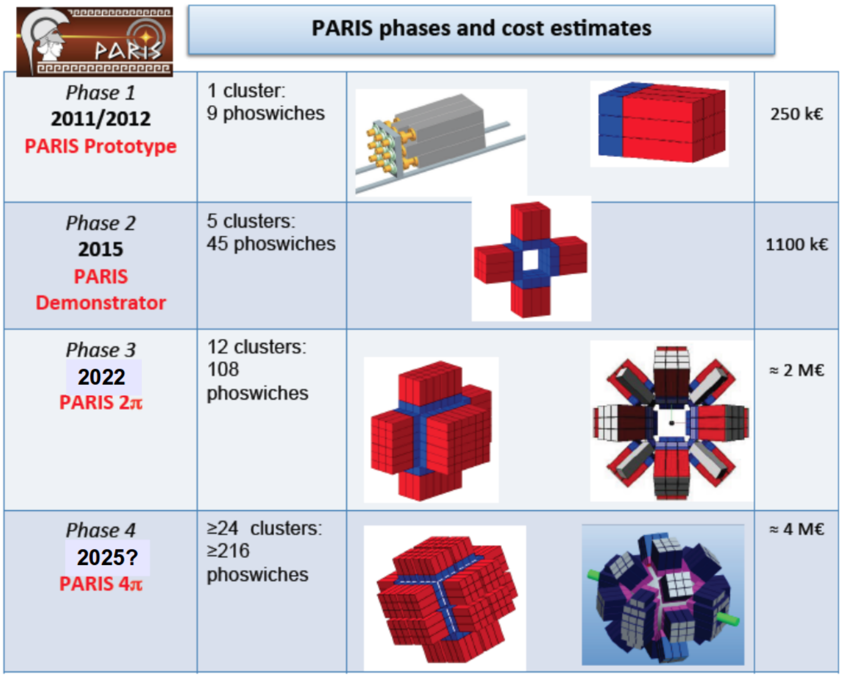

Figure 4.1: PARIS construction phases (cost estimates for Demonstrator phase changed to 1.9 M€ – see text for explanations)

The initial time-line established for the construction of PARIS Demonstrator (2012 – 2015) was perturbed by failures in the production of the phoswiches by Saint-Gobain. Several PARIS Prototype phoswichs showed ageing signs (principally, energy resolution deterioration) and between 2012 and 2015, Saint Gobain changed several times the phoswich design (presently there are 4 designs for PARIS phoswich) and finally also the manufacturing site (from France to US). As a result of these delays, several experiments proposed at ALTO facility were either delayed or cancelled, as for these experiments PARIS did not have the necessary efficiency.

Since 2016, Saint-Gobain restarted the production of detectors for PARIS. While interacting with Saint-Gobain in order to solve the fabrication problems, the PARIS collaboration continued an R&D program to search for other types of new scintillators with properties comparable with the LaBr3(Ce) crystals. As a result of tests performed within the collaboration on CeBr3+NaI(Tl) phoswichs, it was decided to start the acquisition of phoswiches based on CeBr3 (2x2x2 inches crystals) coupled with NaI(Tl) (2x2x6 inches) produced by Scionix.

Recently, saint-Gobain proposed to the PARIS collaboration a new enhanced version of LaBr3(Ce) detectors, labelled B390, which are co-doped with Ce and Sr. The main enhancement of B390 type compared to B380 type is the improvement of the energy resolution of about 10% @ 662 keV with a very slightly degradation of the rise time signal [B390]. The PARIS collaboration already acquired two phoswiches equipped with B390 crystals and confirmed this energy resolution improvement.

PARIS Demonstrator will thus be hybrid, 50% based on LaBr3(Ce) and 50% on CeBr3 phoswiches.

The Demonstrator Phase is ongoing and it will end in 2021 as stated in the amendment to the MoU. The prolongation of this phase will also result in the acquisition of ~ 9 clusters (instead of the 5 initially scheduled, see Figure 4.1), resulting in a total cost of the Demonstrator of 1.9 M€.

As part of the SPIRAL2 Instruments for physics, PARIS was annually evaluated by the SPIRAL2 SAC between 2006 and 2011 (see reports of SAC on the PARIS webpage [PA_web]). The overall conclusion of the evaluation is very favourable to the project. PARIS was also evaluated by the Scientific and Technical Council (CST) of IPN Orsay in 2015.

5. Project resources

An overview of the resources invested or planned to be invested by the Parties, as defined in the amendment to the PARIS Demonstrator MoU, is given in Table 5.1.

The objective is for IN2P3 to contribute with funds for 2 clusters over the PARIS Demonstrator phase. The capital already invested by IN2P3 includes the ANR PROVA funds used for PARIS Prototype construction.

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

* Under financial support by grant of Plenipotentiary of the Government of the Poland Republic to JINR

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).

In France, the laboratories/people involved in PARIS are :

– GANIL (~2.5 persons-month) : M. Lewitowicz

– IPN Orsay (~ 4.5 persons-month) : I. Matea, J. Wilson, G. Hull, L. Vatrinet, C. Le Galliard, J. Bettane, M. Josselin

– IPN Lyon (~ 4 persons-month) : O. Stezowski, C. Ducoin, C. Aufranc

– IPHC Strasbourg (~ 3 persons-month) : O. Dorvaux, C. Schmitt, S. Kihel, C. Mathieu

In green are listed the permanent researchers and in red, the engineers.

A summary of the ownership of the acquired detectors for PARIS is given in Table 5.2.

Partner	2012-2017		2018-2021		Whole period of MoU	
	$LaBr_3$_NaI	$CeBr_3$_NaI	$LaBr_3$_NaI	$CeBr_3$_NaI	$LaBr_3$_NaI	$CeBr_3$_NaI
FRANCE–IN2P3	10		8		18	0
FRANCE-GANIL	2	1	2	3	4	3
POLAND	6	4	3	5	9	9
INDIA	2	4	4	5	6	9
UK	2		1		3	
ITALY	2		7		9	
TURKEY	1			2	1	2
ROMANIA		4		2		6
DUBNA				6*		6*
Total	**25**	**13**	**23**	**23**	**48**	**36**

* Under financial support by grant of Plenipotentiary of the Government of the Poland Republic to JINR

Table 5.2: National summary table of the PARIS detectors (extracted from the amendment to the PARIS Demonstrator MoU).

6. Highlights

General PARIS

a) Phoswich concept validation

Different measurements with single phoswichs (with standard sources or using radiative capture reactions) were performed in IFJ-PAN Krakow, TIFR Mumbai, ALTO Orsay, IPHC Strasbourg and INFN Milano. The phoswich+PMT output charge was integrated over a short (Qfast) and a long (Qslow) time interval, allowing for the separation of gamma-ray interactions in NaI(Tl) and LaBr3(Ce) crystals.

As an example, the global phoswich response to a 6.13 MeV gamma-ray source is given in Figure 6.1. The characteristic signals/spectra for gamma-ray interaction exclusively in the LaBr3(Ce) and NaI(Tl) layers and also for interaction in both layers are given in Figure 6.2. The results are extracted from [Zieb2013].

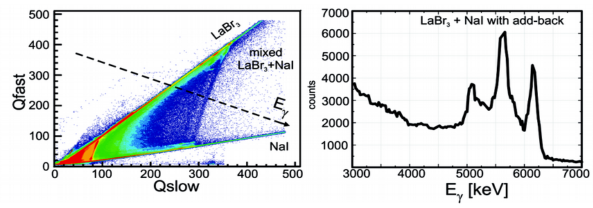

Figure 6.1: Left: the 2D plot of charges collected in fast (Qfast) and slow (Qslow) gates by a phoswich detector for 6.13 MeV gamma-rays. Right: the corresponding add-back spectrum, obtained as the projection on the energy axis E, indicated by the dashed line.

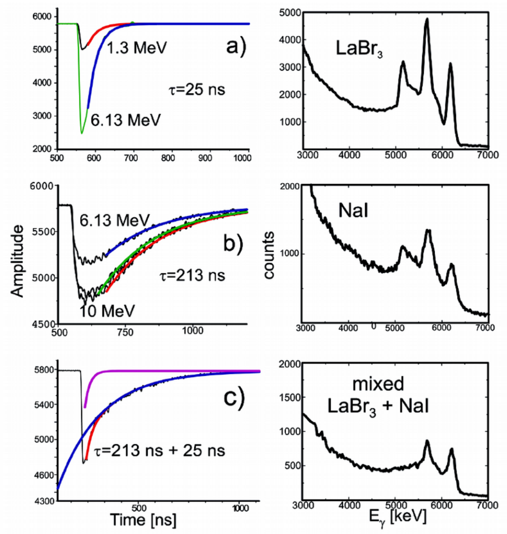

Figure 6.2: Left: the analytical function fit to signal shapes associated with different regions of the Qfast–Qslow matrix, as indicated in Fig. 6.1 (left). Calculated decay times are shown. Right: the 6.13 MeV gamma line and the escape peaks reconstructed by charge integration of the filtered detector pulses

b) High energy gamma-ray detection within one PARIS cluster

Cluster response to high energy gamma-rays was investigated at ALTO Orsay, ELBE Dresden, ATOMKI Debrecen. An example of the cluster response to a 17.6 MeV gamma-ray emitted from the radiative capture reaction ^{7}Li(p,gamma)^{8}Be is given in Figure 6.3.

The response of PARIS phoswich/cluster to neutrons was also investigated using both standard neutron sources (Am-Be, ^{252}Cf) and LICORNE [LIC]. A paper is in preparation.

Further investigation of the PARIS cluster response to neutrons is planed by end of 2019 in FLNR Dubna laboratory using an intense 252Cf fission source. The fission fragments will be tagged using the CORSET set-up and the measurements of gamma-rays and neutrons will be ensure by PARIS detectors. The main goal will be to get a full function response of PARIS to neutrons in the energy range 0.5-10 MeV.

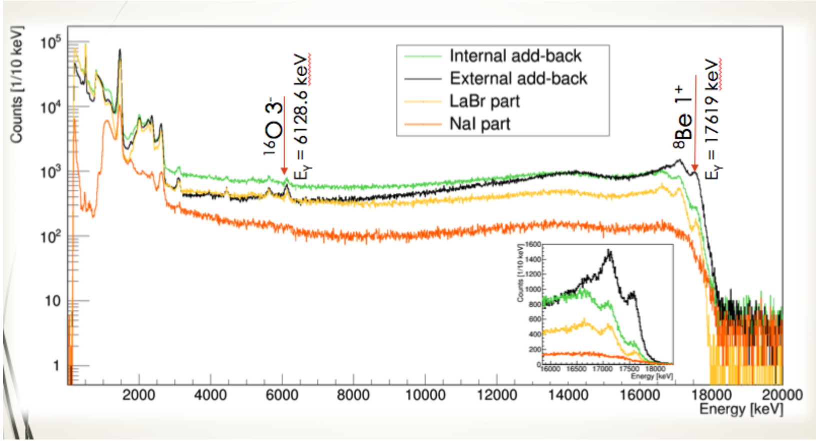

Figure 6.3: Cluster response to 17.6 MeV gamma-ray. Internal add-back refers to the energy deposited in one phoswich (summing of LaBr3(Ce) and NaI(Tl) responses. External add-back refers to the total energy measured in the cluster.

GANIL experiments

In order to take advantage from the installation of AGATA in GANIL, several experiments were proposed with PARIS coupled with the AGATA array, as listed in Table 6.1.

Accepted Experiments at GANIL	Spokes-person
Lifetime measurements of excited states in neutron-rich C and O isotopes (2017)	S. Leoni et al.
Gamma decay from near-threshold states in 14C: a probe of clusterization phenomena in open quantum systems (TBD)	B. Fornal et al.
Investigation of a high spin structure in 44Ti via discrete and continuum gamma-spectroscopy with AGATA, PARIS Demonstrator and DIAMANT (TBD)	P. Bednarczyck et al.

Table 6.1: Accepted experiments with PARIS at GANIL (the year the experiment was performed is given in brackets, TBD stands for "To Be Decided")

The first one was successfully performed in 2017, but with a reduced number of PARIS clusters that was initially requested.

The main experimental goal of the performed experiment was the measurement of the lifetime of the second 2^+ states in ^{20}O and ^{16}C using the Doppler Shift Attenuation Method (DSAM). For these nuclei, ab initio calculations predict a strong sensitivity of selected electromagnetic transition probabilities to the details of the nucleon–nucleon interactions, especially to the three-body term. Preliminary results are presented in [Ciem2019]. PARIS role in the detection set-up (see Figure 6.4) was triple: i. efficient detection of gamma-ray for 2_2^+ branching ratio measurements; ii. around 90° coverage for gamma-ray angular distributions; iii. correction for the residual nucleus velocity measured in VAMOS.

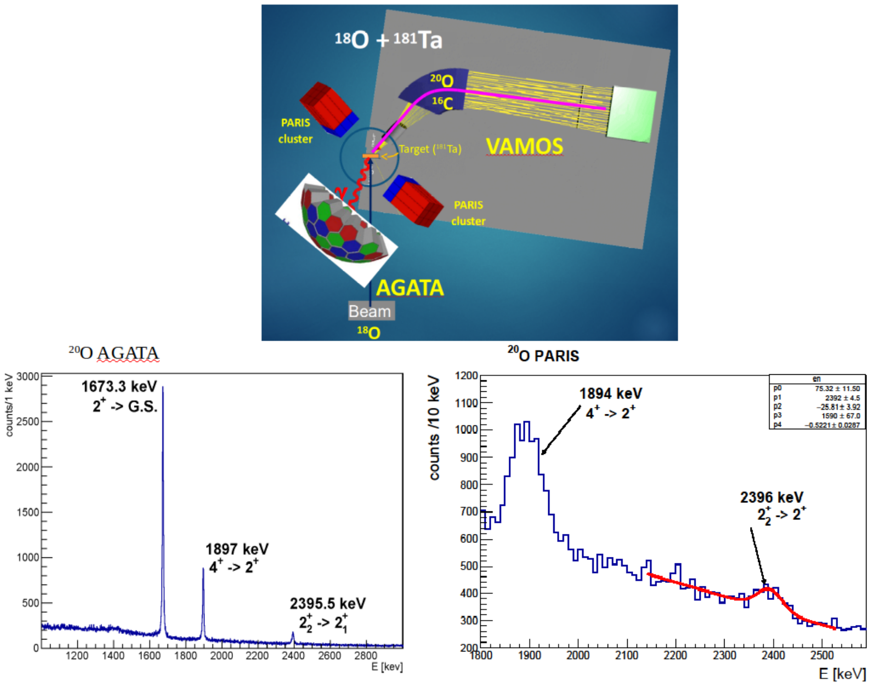

Figure 6.4 : AGATA+PARIS+VAMOS experimental set-up. Preliminary low energy spectra measured with AGATA (left) and PARIS (right) in coincidence with ^{20}O detection in VAMOS. The data analysis is in progress.

ALTO experiments

In November 2014, PARIS collaboration organized a Workshop dedicated to preparation of proposals for an experimental campaign to be performed in 2015-2016 at the ALTO facility [ALTO_web] (https://indico.in2p3.fr/event/10381/). The ALTO facility can provide stable beams with energies around the Coulomb barrier from light nuclei to I, neutron beams using the LICORNE setup and 30 keV radioactive beams obtained by photo-fission of Uranium [ALTO_web].

The ALTO PAC accepted a number of 6 experiments, the first six lines in Table 6.2. The asterisk indicates the experiments that could not be performed because of the limited availability of PARIS clusters due to Saint-Gobain manufacturing problems (see Section 4 of this document).

One specificity of the ALTO performed experiments is the use of FASTER digital electronics [FASTER], developed at LPC Caen. The data acquisition system based on FASTER readout performed very well with PARIS.

We highlight here two experiments already performed at ALTO with stable beams.

"Prompt gamma and neutron emission for 238-U fast neutron induced fission as a function of incident neutron energy" (L. Qi et al.)

In this experiment, prompt-fission gamma-ray spectra (PFGS) have been measured for the ^{238}U(n,f) reaction using fast neutrons produced by the LICORNE [LIC] directional neutron source. Fission events were detected with an ionization chamber containing actinide samples placed in the neutron beam, and the coincident prompt-fission gamma-rays were measured using a number of LaBr3 scintillation detectors and a cluster of nine phoswichs detectors from the PARIS array.

Prompt-fission gamma-rays (PFGs) were discriminated from prompt-fission neutrons using the time-of-flight technique over distances of around 35 cm. PFG emission spectra were measured at two incident neutron energies of 1.9 and 4.8 MeV for ^{238}U(n,f) and also for ^{252}Cf(sf) as a reference. Spectral characteristics of PFG emission, such as mean gamma multiplicity and average total gamma-ray energy per fission, as well as the average gamma-ray energy, were extracted [Qi2018].

Accepted Experiments at ALTO	Spokes-person
Coulomb excitation of 14C*	M. Wiedeking et al.
Measurement of the super-allowed branching ratio of ^{10}C (2018, without PARIS)	B. Blank et al.
Coulomb excitation of super-deformed band in ^{40}Ca (TBD)	P.J. Napiorkowski et al.
Prompt gamma and neutron emission for ^{238}U/^{239}Pu fast neutron induced fission as a function of incident neutron energy (2016/2017)	M. Lebois et al.
A new probe of alpha-cluster structure in ^{12}C*	O. Kirsebom et al.
Prompt γ-rays as a probe of nucleardynamics (2016)	A. Kozulin et al.
Feeding of low-energy structures in 188Pt of different deformations by the GDR decay: the NuBall array coupled to PARIS (2018)	M. Kmiecik et al.
Measurement of prompt gamma-ray spectra from the reaction 233U(n,f) (TBD)	A. Oberstedt et al.
81Zn ground-state spin determination from pandemonium free beta-delayed spectroscopy of 81Ga (TBD)	M. Babo et al.
PDR studies in very neutron rich nuclei around N=50 shell closure through beta-decay (2019)	I. Matea et al.

Table 6.2: Experiments performed or to be performed at the ALTO facility, with stable or radioactive beams. The asterisk indicates the experiments that were not scheduled due to lack of gamma efficiency. (the year the experiment was performed is given in brackets, TBD stands for "To Be Decided")

In Figure 6.5 the average unfolded prompt gamma-ray spectra for the ^{238}U(n,f) reaction is represented for single LaBr3(Ce) detectors and for one PARIS cluster (named "PARIS phoswich" in the figure). A very good agreement is obtained between the two spectra, despite the very different gamma-ray responses.

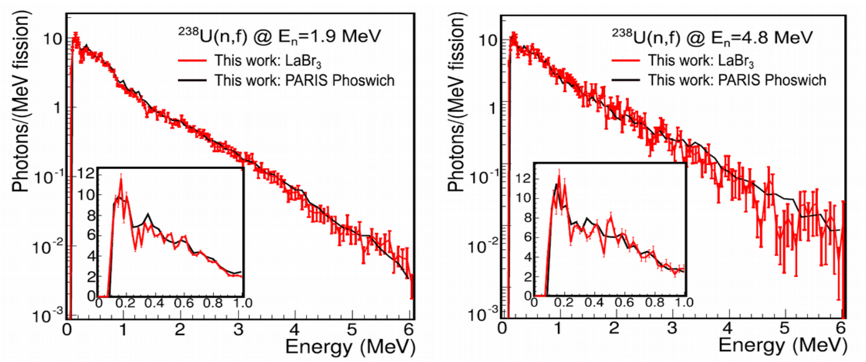

Figure 6.5: Averaged unfolded spectra with the time window ± 2.5 ns for the 238U(n,f) reaction in logarithmic scale, as obtained for two different types of γ detectors. The error bar of PARIS is omitted for better visibility. The inset shows the region below 900 keV in linear scale.

"Prompt gamma-rays as a probe of nuclear dynamics" (E. Kozulin et al.)

Even if fission is a physics phenomenon studied since rather long time, we still do not understand the processes involved during the collision of two massive heavy ions, Understanding this fusion-fission is of the utmost importance for the synthesis of new superheavy elements. Thus, it is crucial to investigate what will be predominant to form a evaporation residue after the collision of two nuclei instead of the system will undergo to a fission or a (faster) quasi-fission process. To investigate this question, a PARIS+ORGAM+CORSET setups combination has been performed at the ALTO facility. This experiment was considered as a "test" experiment of only 3 days of beamtime investigating the 32S + 197Au reaction system. Some really interesting results have shown, that measuring the characteristics of the fission event with the CORSET device and gamma rays with one PARIS cluster coupled to 11 ORGAM detectors, it has been possible to get a measure of the nuclei spin has function of the fission fragment mass distribution for different selection in the total kinetic energy of the system (see Figure 6.6).

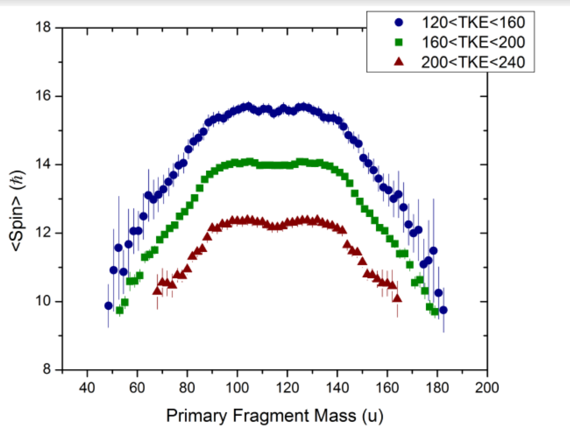

Figure 6.6 : Measurement spin from gamma detection as function of primary fission fragment mass for three different Total Kinetic Energy (TKE) selections.

It is the first time such result is made possible. Since the beam time period was short, the accumulated statistics was low. Then it has not been possible to fully conclude on this physics case but this experiment gave indication of having an unique investigation tool using PARIS of the energy deformation at different stages of fusion-fission and quasi-fission processes [Har2019].

IFJ-PAN Krakow experiments

Inelastic proton scattering experiments can be performed at the CCB facility in Krakow, Poland, using the medical cyclotron IBA Proteus C-235 that can produce proton beams with energies between 70 and 230 MeV. In Table 6.3, the list of performed and "to be done" (TBD) experiments is given.

Accepted Experiments at CCB (IFJ-PAN, Krakow)	Spokes-person
Studies of resonance states in nuclei using high-energy proton beam in p,p' reactions at forward angles with HECTOR, PARIS, KRATTA (2017, 2018, 2019)	M. Kmiecik et al.
Study of M4 resonance decay in 13C (TBD)	S. Leoni et al.
Investigations of (p,2p) reactions in order to identify deep single particle proton-hole states (TBD)	A. Bracco et al.
Investigation of proton induced spallation with HECTOR, PARIS and KRATTA (TBD)	Ch. Schmitt et al.

Table 6.3: Experiments performed or to be performed at the CCB facility. (the year the experiment was performed is given in brackets, TBD stands for "To Be Decided")

First experiments of Giant and Pygmy resonances in 208Pb using PARIS clusters were already performed. Interesting findings concerning the Axel-Bring hypothesis were found [Was2019], namely that although the GDR in 208Pb fulfils this hypothesis, the Pygmy resonances seems not to obey to it.

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1) A.Maj, et al. "The Paris Project" Acta Physica Polonica B 40 (2009) 565

2) S. Erturk et al. "Energy Response of LaBr3" RUTHERFORD CENTENNIAL CONFERENCE ON NUCLEAR PHYSICS, 2011 Book Series: Journal of Physics Conference Series Volume: 381 Article Number: 012134 Published: 2012

3) G. Hull et al. "Energy resolution of LaBr3:Ce in a phoswich configuration with CsI:Na and NaI:Tl scintillators" NIMA695, p350 (2012)

4) Zieblinski et al. "TESTING OF THE PARIS LaBr3-NaI PHOSWICH DETECTOR WITH HIGH ENERGY GAMMA-RAYS" ACTA PHYSICA POLONICA B Volume: 44 Issue: 3 Pages: 651-656 Published: MAR 2013

5) B. Wasilewska et al., "The PARIS cluster coupled to the BaFPro electronic module: data analysis from the NRF experiment at the gamma ELBE facility" In: "APPLICATIONS OF NOVEL SCINTILLATORS FOR RESEARCH AND INDUSTRY (ANSRI 2015)", Journal of Physic Conference Series 620, Eds Roberts O., Hanlon L., McBreen S., 012006, 2015.

6) C. Ghosh, et al. " Characterization of PARIS LaBr3(Ce)-NaI(Tl) phoswich detectors up to Egamma~22 MeV", Journal of Instrumentation 11 (2016) art. number P05023

7) I.M. Harca et al, "The reaction 32S + 197Au near the interaction barrier", Worls Scientific Publishing Company Proceedings (2016)

8) B. Wasilewska et al., "The First Results from Studies of Gamma Decay of Proton-induced Excitations at the CCB Facility", Acta Phys. Pol. B48, 415 (2017)

9) L. Qi et al. "Statistical study of the prompt fission gamma ray spectrum for 238U(n,f) in the fast-neutron region" PRC 98, 014612 (2018)

10) A.Pulcini et al. "Gamma rays as probe of fission and quasi-fission dynamics in the reaction S-32+Au-197 near the Coulomb barrier", INTERNATIONAL WORKSHOP NUCLEAR REACTIONS ON NUCLEONS AND NUCLEI Book Series: Journal of Physics Conference Series Volume: 1014 Article Number: UNSP 012013 Published: 2018

11) B. Wasilewska et al., "Testing of the Brink–Axel Hypothesis with the HECTOR+PARIS+KRATTA Set-up", Acta Phys. Pol. B50, 469 (2019)

12) M. Ciemala et al., "Determination of lifetimes of excited states in neutron rich ^{20}O isotope from experiment with AGATA, PARIS and VAMOS", Acta Phys. Pol. B50, 615 (2019)

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C. Gosh, "Characterization of PARIS LaBr3(Ce)-NaI(Tl) phoswich detectors up to Egamma~22 MeV", **Ph.D. Thesis**, TIFR Mumbai, 2016

L. Qi, **Ph.D. Thesis**, IPN Orsay (2018) "Measurements of prompt gamma rays emitted in fission of 238U and 239Pu induced by fast neutrons from the LICORNE neutron source"

B. Wasilewska, **Ph.D. Thesis**, IFJ PAN Krakow (2018), "Study of the decay of collective states induced by protons" (in Polish)

A. Mentana, **Ph.D. Thesis**, INFN Milano (2018), "Experimental study of isospin symetry in N=Z nuclei"

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