PHOTON ARRAY FOR STUDIES WITH RADIOACTIVE ION AND STABLE BEAMS

PARIS detector – progress report

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on behalf of the PARIS collaboration

LoI title: High-energy γ-rays as a probe of hot nuclei and reaction mechanisms

Abstract:
This report presents recent milestones in the progress of the PARIS project, achieved since the previous SAC meeting in September 2009. More complete information may be found on the PARIS website [i] which is regularly updated.

1. Introduction

The September 2009 PARIS progress report was evaluated by the SAC and the following recommendation was given:

It would be strongly recommended that in the next status report both the GASPARD and PARIS collaborations should work out one or more experiments where the integrated GASPARD and PARIS detectors are used.

2. Progress with elaborating the key physics cases

a) Possible physics case with integrated GASPARD and PARIS: Study Pygmy Dipole Resonances excited in direct reactions

In a recent work at GSI (with LAND and RISING arrays) and in RIKEN a clear evidence of pygmy dipole resonance (PDR) states in ^{130}-^{132}Sn [ii], ^{68}Ni [iii] and ^{26}Ni [iv] has been obtained below 10 MeV excitation energy, i.e. around and below the neutron binding energy. While mean field calculations essentially agree on the excitation energy of the PDR in both nuclei, they provide contradictory predictions on their microscopic structure. In ^{132}Sn, for example, the Relativistic RPA approach predicts a relatively collective state involving a sizeable number of particle-hole configuration, while the non-relativistic suggests one or two *p-h* configurations contributing significantly.

SPIRAL2 beams provide new opportunities to investigate the microscopic structure of Pygmy Dipole states. By using the *(d,p)* reaction in inverse kinematics, one could investigate whether these states involve only a few neutron excitations coupled to the A-1 core. For example, by using intense ^{129}Sn and ^{131}Sn beams, one could selectively populate the pygmy states observed already in ^{130}Sn and ^{132}Sn.

GASPARD is the ideal device to perform such study, allowing to detect the low energy recoiling protons with maximum efficiency. The coupling with the PARIS array would allow the detection of the relatively high energy E1 gamma-rays from the decay of the pygmy states, providing an additional strong filter, as well as structure information. This technique could be applied in quite a number of cases. A detailed common GASPARD-PARIS LoI for such experiments is under preparation.

b) Jacobi and Poincare shape transitions in neutron-rich nuclei – work on feasibility issues

Fusion-evaporation reactions permit probing nuclear structure and dynamics under extreme conditions of angular momentum and/or temperature. The advent of heavy-ion neutron-rich beams

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with high intensity will allow to populate exotic compound nuclei at high angular angular momentum (up to ~100ħ). This will make possible the study of collective phenomena in neutron-rich nuclei at finite temperature, and namely exotic shape changes induced by fast rotation. The present proposal is intended to address two instabilities of this kind – referred hereafter as the Jacobi and the Poincaré transitions - taking profit from the performance of the new γ-array PARIS [v].

At high angular momentum, due to the combined effects of the Coulomb repulsion and the centrifugal force, the excited nucleus can become instable. The Jacobi instability leads to a gradual transition with increasing spin from an initially oblate to a triaxial and finally very elongated prolate nucleus. Left-right symmetry is preserved. As for the Poincaré transition, predicted at even higher angular momentum, the elongated axial or triaxial left-right symmetric system evolves towards an octupole (left-right asymmetric) shape. More details about these phenomena and the related physics can be found in Ref. [vi]. Here we focus on the feasibility of experiments dedicated to the investigation of these phenomena.

We propose to synthesize ^{120}Cd and ^{142}Ba nuclei, in which the Jacobi and Poincare phenomena are expected to happen, using the following projectile-target combinations at energies well above the barrier: ^{94}Kr (900MeV) + ^{26}Mg → ^{120}Cd*, ^{94}Kr (430MeV) + ^{48}Ca → ^{142}Ba*.

The angular momentum induced in the compound nucleus for the above reactions reaches up to ~98ħ and ~100ħ for ^{120}Cd and ^{142}Ba, respectively. The excitation energies are high: E* ~ 200MeV for ^{120}Cd and E* ~ 118MeV for ^{142}Ba. The fusion cross section predicted by statistical model calculations [vii] amounts to about 1500mbarn for both systems.

The detection of the heavy residue with a heavy-ion spectrograph is presently proposed as the most direct way to select fusion-evaporation events. Since the product goes at 0°, in addition to efficiently detect the residue, the device must reject the intense incoming beam which would damage – if not destroy – the detectors. To do so, one can profit from the difference between projectiles and fusion residues in either velocity V or magnetic rigidity $B\rho \sim A \cdot V/Q$ or a combination of both. The velocity filter FULIS at Ganil is not suited since the acceptance (and consequently, efficiency) is small and no prompt γ-spectroscopy is possible (no room for a γ-array around the target). Selection in $B\rho$ is feasible with the large-acceptance spectrometer VAMOS operated in vacuum [viii]. Yet, magnetic rigidity in vacuum is not selective enough for the present reactions, yielding a poor beam rejection. We therefore propose to use the new gas-filled mode of VAMOS which has been recently successfully tested[2] [ix]. High rejection of the direct beam and very large transmission of the heavy recoil are expected as shown in Fig.3 for the ^{94}Kr (900MeV) + ^{26}Mg collision. The focal plane of the gas-filled VAMOS would be equipped with two drift chambers, a Si wall and a Plastic scintillator. This combination of detectors will permit a very clean selection of fusion-evaporation events: Un-wanted particles entering VAMOS (scattered beam, target-like nuclei, fission fragments) can be tagged. Furthermore, the velocity reconstruction available at the gas-filled VAMOS will provide the suited correction for the Doppler effect in the γ-ray spectrum on an event by event basis [viii, ix].

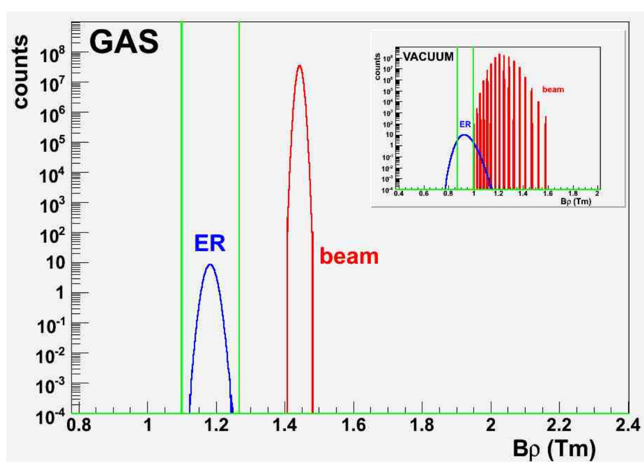

Fig.1: Magnetic rigidity Bρ distribution of beam (red) and typical evaporation-residue (blue) particles at the gas-filled VAMOS focal plane for the ^{94}Kr+^{26}Mg collision. The inset shows, for comparison, the Bρ distribution with VAMOS used in the vacuum mode. Vertical lines delineate the acceptance of the spectrometer centred on fusion-evaporation residues.

[2] The gas-filled mode of VAMOS has been successfully used in a test-experiment. It is not available yet for physics measurements. Modifications of the set-up should be performed in near future.

The beam rejection achieved with VAMOS is less good for the ^{94}Kr (430MeV) + ^{48}Ca collision. The use of a full intensity beams seems excluded. An alternative solution for tagging fusion-evaporation in this system consists in the use of the Krakow Recoil Filter Detector (RFD). The rejection capability of this device for the incoming beam and the fission fragments in this reaction will be studied. Apart from the selection of the events of interest, the RFD would provide as well the suited Doppler correction of the γ-ray spectrum. As compared to the gas-filled VAMOS the detection efficiency might be slightly less. An alternative solution to the spectrometer and velocity filter for tagging fusion-evaporation events would be to use a light-charged particle detector. This option is under investigation.

In complement to PARIS, a part of a high-resolution γ-array (e.g. AGATA demonstrator, EXOGAM2) might be used. This coupling will further increase the selectivity of the set-up.

The work on preparing the LoI and final proposal for "Day2"-experiment with this physics case is ongoing.

3. Detector tests

a) Testing the PARIS crystals with radioactive sources

The table below is a summary of the different tests done with the three basic configurations for PARIS: phoswich LaBr3+CsI, long LaBr3, 2-shells: Labr3 and CsI.

	Configuration 1 Phoswich	Configuration2 Long LaBr3:Ce	Configuration 3 «Two shells»
Concept	1x1x2 LaBr3(Ce)+1x1x6 CsI(Na) 2x2x2 LaBr3(Ce)+2x2x6 CsI(Na) or other shape/size ?	1x1x4 (6) 2x2x4 (6) or other shape/size?	1x1x2 LaBr3(Ce) + APD/SiPM and 1x1x6 CsI(Na) + PM/SiPM 2x2x2 LaBr3 or other shape/size?
Energy Resolution **<3% @ 662keV**	LaBr3 : 4,0% - CsI(Na) : 13,1%	3,08 %	1x1x2 LaBr3 +PM :2.5% + APD : 6% Resolution remains constant with the detector size
Time Resolution **< 1 ns**	not done yet	< 1ns	< 1ns
n/γ discrimination	by time of flight	by time of flight	by time of flight
Pileup	Just started - need more investigation	not done yet	not done yet
Cross-talk	not done yet	not done yet	not done yet

Configuration 1: The phoswich concept has been successfully tested with a 1''x1''x2'' LaBr3 coupled to 1''x1''x6'' Csi(Na) and different phototubes. The analysis was based on a pulse shape analysis with 120 ns for the fast component and 3500 ns for the slow one. We got 4% resolution @ 662 keV from the ^{137}Cs source) with the signal coming out from the LaBr3(Ce) and 13.1% from the signal coming out of the CsI(Na) crystal while the Saint-Gobain characteristics were 3.1% for the LaBr3 crystal and 10.1% for the CsI(Na). We noticed a relative small degradation of the rise-time and real effect of sensitivity with the optical coupling.

Configuration 2: A full set of data has been measured with a 2''x2''x4'' LaBr3(Ce) stand alone detector and gave some nice performances of 3% resolution @ 662 keV.

Configuration 3: A full set of data has been analyzed using a 10x10 mm2 large area APD in function of high voltage and temperature. We succeeded to obtain a 5.5% resolution @ 662 keV at room temperature.

Some timing tests have been done for timing measurements only for configuration 2 with different crystal sizes and configuration 3. The configuration 3 did not give promising results while a time resolution of less than 1 ns has been obtained for configuration 2. A slight increase of the resolution has been noticed for low gamma-ray energies. Further tests will have to be done.

A large set of data has been taken for testing the linearity of different PM tubes. Some modifications have been made especially on HV divider from Hamamatsu and Photonis to correct the linearity up to high gamma-ray energies.

The simulation study on light collection started. Te first results show a rather good agreement with experiment, but a poor capacity to localize the interaction point for bigger detectors.

An AmBe source has been used to discriminate between neutrons and gamma-rays using a LaBr3(Ce) crystal. Such a neutron-gamma discrimination is unsuccessful with a 1,5”x1,5” LaBr3:Ce crystal essentially due to La and Br excited state gamma emission after neutron activation.

Two options are thus retained in priority for the choice of the detector type: the phoswich configuration and a long LaBr3:Ce crystal. The option consisting in two shells (small LaBr3:Ce + APM/SiPM and CsI(Na)/PMT) is put on standby. This last solution will only be a backup solution if the next results on the two first options do not match the specifications of the project.

b) In-beam tests of PARIS crystals

Investigation of the LaBr3 detectors in-beam properties were carried out in the experiments held in Heavy Ion Laboratory, University of Warsaw. The experimental set-up consisted of a cubic 2”x2”x2” LaBr3 detector, two 1”x1” cylindrical detectors and 6 HPGe detectors in anticompton shields (spectrometer EAGLE, Heavy Ion Laboratory, University of Warsaw). The gamma-rays emitted in the reaction ^{14}N(75 and 80 MeV)+^{12}C $\rightarrow$ ^{26}Al* $\rightarrow$ 2n + ^{24}Al were measured (see Fig.2). Similar energy resolution as in the source measurements and good in-beam performance was obtained.

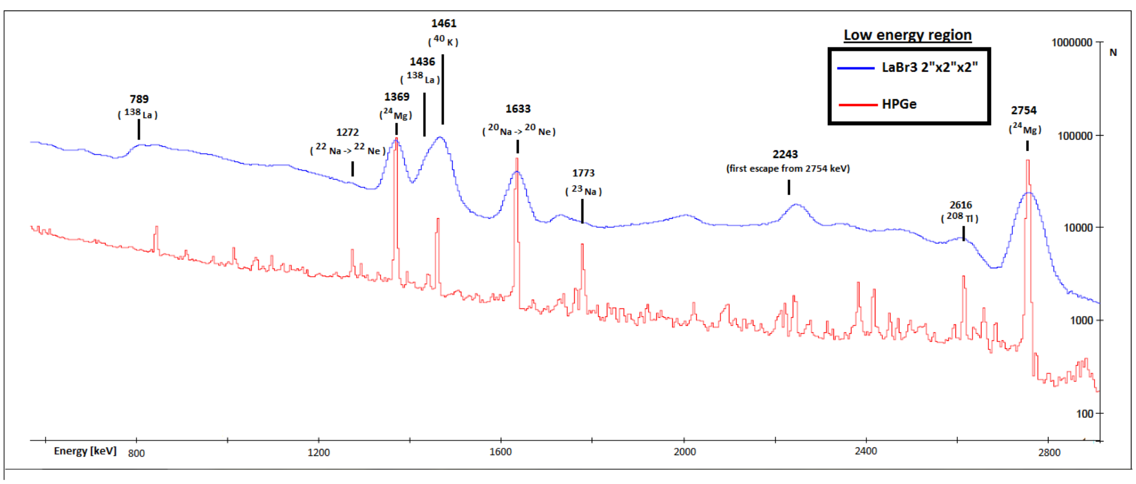

Fig. 2: Comparison of the spectra from cubic LaBr3 crystal (blue) and from the HPGe detector (red).

c) Planned detector tests

A major effort will be put on the configuration 1. A second phoswich detector has been ordered from Saint-Gobain by IPN Orsay in December 2009. It will be a 1’’x’’x2’’ LaBr3 coupled with a 1’’x1’’x6’’ NaI. A full test of different phototubes coupled with different (standard and home made) HV dividers for single LaBr3 crystals has started. Additional in-beam experiments in Orsay, Strasbourg and Warsaw are planned to be performed.

4. Mechanical design and GEANT4 simulations

At the PARIS collaboration meeting in Krakow it was decided that the general shape of the PARIS module will be rectangular and that few crystals (4 or 9) will be packed together in a single “cluster”. This will allow, depending on the physics case, to arrange the clusters in a close-packed quasi-cubic or in quasi-spherical array (see Fig.3). The quasi-spherical geometry is presently investigated intensively both from mechanical and simulation point of view in connection to the Day1-Phase1 PARIS@S3 proposal (cf. LoI_Day1_7: “In-beam gamma spectroscopy of neutron-rich nuclei studied with PARIS at the intermediate focal plane of S3”, I. Stefan, B. Fornal et al.), where the PARIS array will be located at the mid-focal plane of S^3 spectrometer. Simulations on the reconstruction of energy, multiplicity (see Fig. 4) and sum-energy for both geometries are in progress. In addition, from the point of view of the work achieved, extensive and more complex simulations, using realistic generators and reconstruction algorithms, start to be available to compare the different configurations for the main PARIS physics cases.

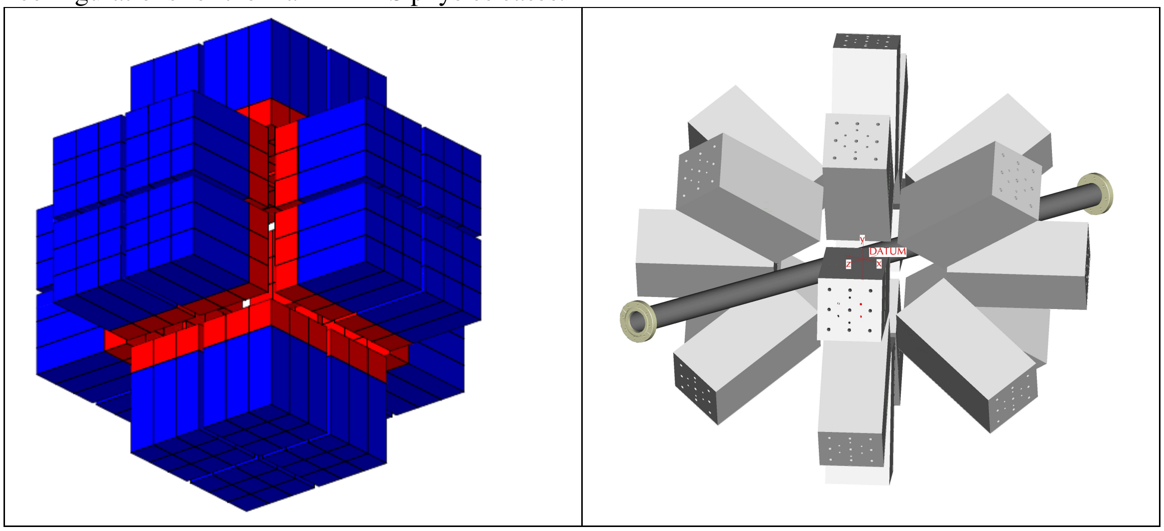

Fig. 3: Quasi-cubic (left) and quasi-spherical (right) PARIS geometry, made of 9-module clusters of phoswich (Labr3+CsI) detectors.

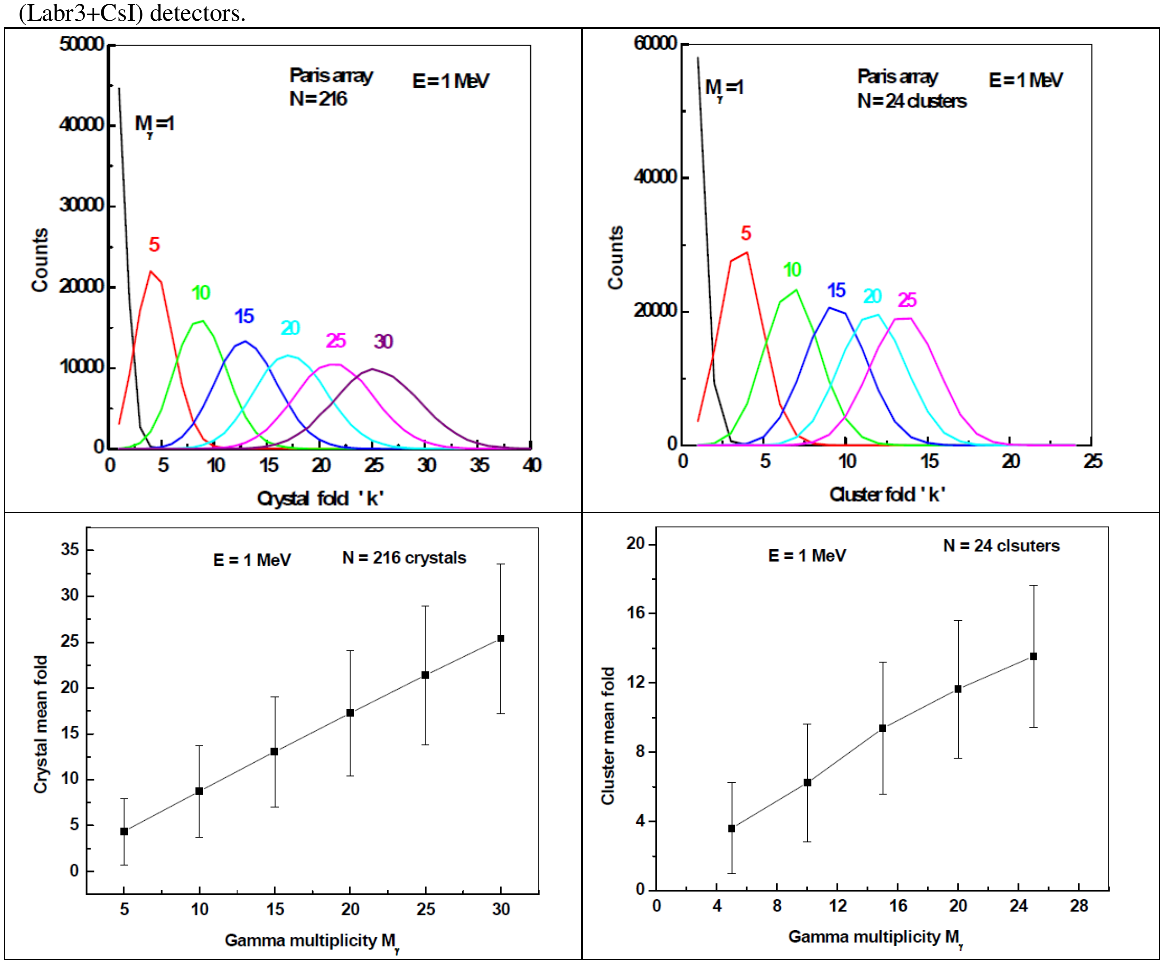

Fig. 4: Simulation of the multiplicity response of the quasi-cubic array (see Fig.3, left), consisting of 216 phoswich detectors arranged in 24 clusters of 9 crystals each.

The main questions to be solved and presented in the next report are: How to build a cluster? How to build spherical-like and cubic-like arrays? How to integrate PARIS within S3? How to integrate PARIS with GASPARD? What will be the efficiency and response function of PARIS in all of the geometries.

5. Conclusion and collaboration issues

The PARIS collaboration meeting was held from October 14-16 (2009) in Krakow. It gathered 50 physicists, engineers and Ph.D. students from many countries. One day was devoted to the PARIS mini-Worshop, where many interesting scientific contributions, concerning PARIS and associated or similar projects (GASPARD, S^3, TAS, SHOGUN) were presented. Another day was devoted to parallel working group meetings. The third day was devoted to a general discussion on various aspects related to experiments with PARIS (e.g. beam rejection). Finally the conclusions from the meeting and possible next steps were discussed. The next collaboration meeting was decided to be in May or June 2010 in Strasbourg. The information about the collaboration meeting and the talks presented can be found at http://paris.ifj.edu.pl/Paris_Krakow_2009/.

The main conclusions are that the rectangular crystal shape is the optimal one for the PARIS physics cases. The possibility of packing few (4 or 9) crystals into one cluster has to be investigated, in close contact with Saint Gobain. This will allow to have a particularly versatile PARIS array witth variable geometries (quasi-cubic, quasi-sperical, wall-like,…) to be chosen for different physics cases. From 3 possibilities of obtaining the 2-shell spectrometer: phoswich LaBr3+CsI (or LaBr3+NaI), long LaBr3 single crystals and separated inner and outer detectors, the first 2 shall be intensively investigated and compared to each other.

The discussion between potential partners in the PARIS MoU, concerning the funds that can be assigned to build the whole PARIS array, has started.

[i] http://paris.ifj.edu.pl
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[vii] A. Gavron et al., Phys. Rev. C 20 (1980) 230.
[viii] S. Pullanhiotan et al., Nucl. Inst. Meth. A 593 (2008) 343.
[ix] C. Schmitt et al., submitted to Nucl. Inst. Meth. A.