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 January 2009. More complete information may be found on the PARIS website [2] which is regularly updated, and in Ref. [3]

1. Introduction

The preliminary technical proposal, submitted to the previous SAC meeting, was evaluated by the SAC and the following recommendations were given:
1- The PARIS collaboration should finalise the simulations and choose the final geometry in close consultation with the GASPARD collaboration to ensure complete synergy of the geometries.
2- Both PARIS and GASPARD collaborations need to develop their electronics and therefore this necessary further development should be pursued jointly by both collaborations aiming at synergies where possible.
3- The PARIS collaboration should present in the next status report the programme focussed at SPIRAL2 (and not the full PARIS programme), i.e. the most important topics for SPIRAL2 Physics with PARIS, with a worked out physics case for "day-one" experiment with SPIRAL2.

2. Most important topics for SPIRAL2 Physics with PARIS

There are three most important topics of the PARIS physics case, which are planned to be studied at various stages of the PARIS and SPIRAL2 construction. Each of them makes use of different main characteristics of PARIS: a) good energy resolution up to 10 MeV, b) medium energy resolution for discrete lines associated with very high efficiency, and c) very good efficiency for high energy gamma rays associated with a highly resolved gamma-ray multiplicity.

a) Heavy-ion radiative capture *(to be done before SPIRAL2, with early PARIS implementation)*

Heavy-ion radiative capture is a rare process due to the high Coulomb barriers and overwhelming competition from fusion-evaporation channels. Surprisingly, however, large cross sections have been observed in the $^{12}C(^{12}C,\gamma)^{24}Mg$ and $^{12}C(^{16}O,\gamma)^{28}Si$ resonant reactions. This has been attributed to enhanced population of ^{24}Mg / ^{28}Si "doorway states" with special structure, for example,

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[3] A. Maj et al., Acta Phys. Pol B40, 565 (2009)

highly deformed rotational bands in ^{24}Mg for the ^{12}C+^{12}C reaction. A connection has been drawn with the molecular picture previously elaborated for these nuclei with the suggestion that the entry capture states correspond to molecular resonances. Microscopic cluster approaches based on a many-body Hamiltonian and the Generator Coordinate Method have been employed in studying this phenomenon. They predict bands based on a ^{12}C-^{12}C “molecular” configuration whose wave-function has a sizeable overlap with those of highly deformed states in ^{24}Mg. To obtain more information about specific decay pathways, both the energy and angular distribution of the high-energy capture γ-rays need to be measured with good energy resolution and efficiency. In addition, to determine the position and width the capture states, measurement of the sum energy is highly desirable.

Figure 1a shows the ^{24}Mg decay scheme assuming the entrance capture state is a 2^+ resonance (consistent with our previous radiative capture studies). Figure 1b shows a GEANT4 simulated γ spectrum for the ^{12}C(^{12}C,γ)^{24}Mg reaction as would be obtained using the PARIS array in a 200 $LaBr_3$ modules (2" by 2" by 2") spherical configuration. Experimental resolution for the $LaBr_3$ modules has been taken into account. The gray curve shows the spectrum obtained if PARIS is used in a calorimeter mode to tag the radiative capture events.

Interestingly, the simulation shows that individual discrete lines - γ-peaks, first and second escape peaks (colour lines at the bottom of the spectrum to guide the eyes) - would be identified in the PARIS array showing the decay path for the resonant radiative capture reaction. Such a measurement would allow us to conclude on the nature of the entrance capture state and to eventually draw the link between molecular states and capture resonances in ^{24}Mg which is a highly debated question.

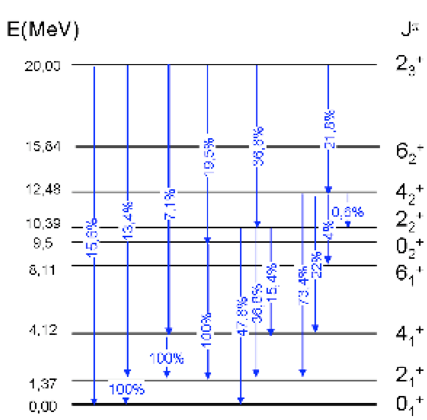

Fig. 1a: Decay scheme of ^{24}Mg, inserted into the event generator

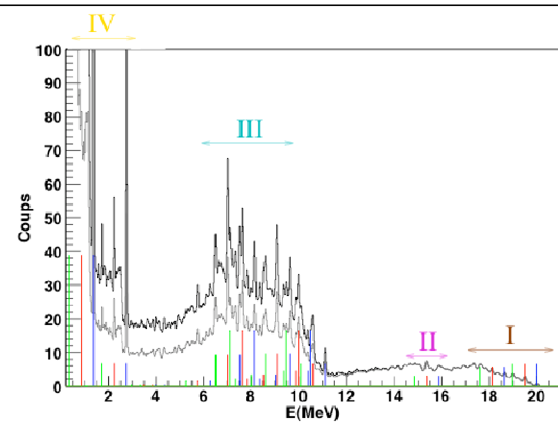

Fig. 1b: GEANT4 simulated spectrum for PARIS.

b) In-beam gamma spectroscopy of neutron-rich nuclei studied at the intermediate focal plane of S^3*(to be done in Day 1 of SPIRAL2 phase 1, with PARIS-Demonstrator implementation)*

The basic idea, put forward as the **LoI for Day-1 experiment with S^3**, is to use the deep-inelastic or quasi-fission reaction mechanism in order to produce neutron-rich secondary beams, employing high intensity stable beams from LINAG and the high power rotating target. The secondary beams will be separated from the primary stable beam and selected in-flight using the first half of S^3. Secondary reactions will be subsequently induced at the mid-point focal plane of the S^3 spectrometer in order to populate excited states in even more neutron rich nuclei and measure their gamma-decay using the PARIS array combined with EXOGAM2 or AGATA in its GANIL-phase. The final products, for which gamma spectroscopy will be performed, are going to have one or two neutrons more than the secondary beam nuclei – they will be identified in the second half of the S^3 spectrometer.

The aim for the LoI is two-fold:

i) To request beam time at LINAG to use the $^{48}Ca+^{238}U$ reaction, with a high intensity ^{48}Ca beam in order to study how far it will be possible for S^3 to produce secondary beams of neutron-rich nuclei in the vicinity of ^{44}S. It will be essential to achieve a sufficiently high degree of rejection of the primary beam. The overall intensity should not exceed 10^{10} particles/second on the secondary target;

ii) To use the obtained secondary beam to induce secondary reactions at the mid-point of S^3 in order to produce nuclei around ^{42}Si and perform gamma-ray spectroscopy studies on them using the early implementation of PARIS – the PARIS Demonstrator. In addition, the high-resolution germanium arrays, EXOGAM2 and/or AGATA in its GANIL-phase, will be used. The spectroscopic studies should be done through an event-by-event identification of the final fragments using the second half of the S^3 target and recording coincidences with gamma-rays emitted from the secondary reaction products. To identify the final fragments a magnetic dipole is necessary. This will require modifications of S^3 between experiments, i.e. interchanging electrostatic and magnetic components of the mass separator.

In the proposed studies, fragments produced in the secondary reactions will be magic or close-to-magic light nuclei. Since the majority of gamma rays emitted from such products are of relatively high energy, i.e. above 2 MeV, it is essential to use a detection system with high efficiency for high energy transitions. The PARIS array will have appropriate characteristics. The early implementation of the PARIS array (PARIS demonstrator) will cover about 1π solid angle, which corresponds to more than 15% of the full peak efficiency for gamma-rays up to 5 MeV. This will permit medium energy-resolution spectroscopic studies of weakly populated, light, exotic secondary reaction products, which emit relatively high energy gamma rays with rather low multiplicity. In turn, the germanium arrays, EXOGAM2 and the AGATA GANIL-phase, will make it possible to perform high-resolution spectroscopy of the heavier secondary reaction products, for which the gamma-ray spectra are more complicated. EXOGAM2 and/or AGATA (GANIL-phase) will be located around 90 degree while the PARIS Demonstrator will be at backward and forward angles. This experiment will require a 10 MeV/u ^{48}Ca beam from LINAG. The primary target will be a 1 mg/cm^2 foil of pure ^{238}U. As the secondary target we will plan to use ^{208}Pb with thickness of 0.5 mg/cm^2. (See the LoI by I. Stefan, B. Fornal et al. for more information).

c) Jacobi and Poincare transitions in neutron rich nuclei at highest spins *(to be done in SPIRAL2 phase 2, with 2π PARIS implementation)*

At sufficiently high temperatures the quantum shell effects in atomic nuclei gradually decrease and eventually vanish and the stability of the corresponding system can be described using the classical notions of the surface tension that keeps nucleons together and the competing Coulomb repulsion. However, when the angular momentum of such a system increases, the Coriolis effects become more and more active so that at certain critical spin (or the corresponding critical classical frequency) the combined effects of the Coulomb repulsion and centrifugal stretching win the competition with the surface tension and the system becomes quickly unstable.

There are two types of instabilities of this kind discussed already in the previous centuries in relation to rotating stellar objects. One of the instabilities that preserves the `left-right symmetry' is referred to as the Jacobi instability. Historically independent type of transitions, leading to a loss of stability, do break the `left-right symmetry'. They are referred to as Poincare instability. An example of the corresponding shapes in nuclear physics is provided by octupole deformations possibly superposed with other shapes.

The Jacobi shape transition corresponds to a shape change of hot nucleus at high angular momenta from oblate to triaxial and very elongated prolate configurations. The name "Jacobi shape change" is related to the C.G.J. Jacobi predictions (1834 year) for a gravitating rotating object. It has been predicted also to appear in many nuclei[4] in the liquid drop regime and is considered as a gateway to hyper-deformed shapes. The giant dipole resonance (GDR) line-shape is a very sensitive signature of this phenomenon: its strength function gets split according to the deformation of the system and a

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[4] K. Pomorski, J. Dudek, Phys. Rev. C67, 044316 (2003); J. Dudek, N. Schunck, N. Dubray, Acta Phys. Pol. B36, 975 (2005).

"giant back-bend" in the rotational frequency occurs at the highest spins. The newest theoretical calculations based on the LSD model predicted also another shape change in very neutron rich nuclei at spins close to the fission limit[5], the nuclei which encounter the Jacobi minima may, when the spin is still increasing, change the form from very elongated triaxial configuration to very elongated left-right asymmetric configurations (see Figure 2a and 2b). Such a phenomenon is related to the predictions of H. Poincare (in 1885) for very fast rotating gravitating body. A signatures of such a exotic shapes will be, for example, highly fragmented GDR strength function or highly mass asymmetric fission that strongly increases with an increase in angular momentum.

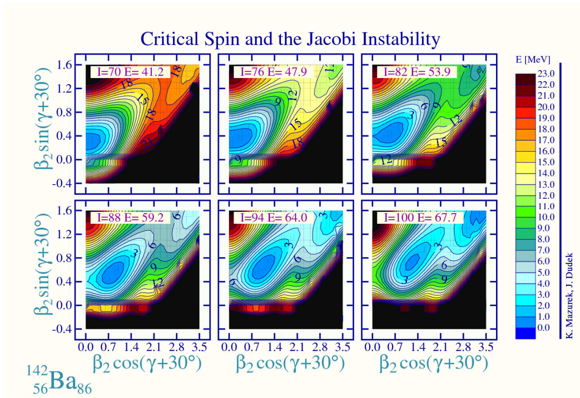

Fig. 2a: The LSD energy surfaces for ^{142}Ba for Jacobi transition, calculated for spins 70, 76, 82, 88, 94 and 100 ħ.

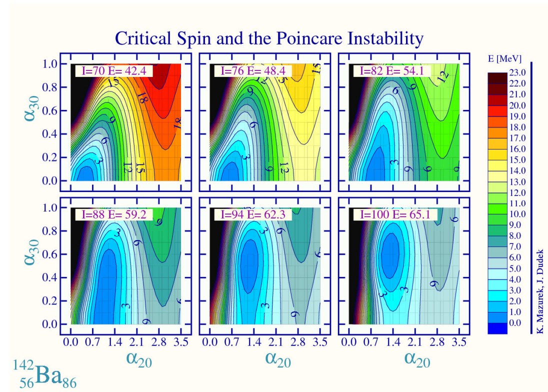

Fig. 2b: Same as in 2a, but for Poincare transition.

The difficulty inherent to the experimental study of these phenomena is related to the rather narrow spin window covered by the oblate-triaxial Jacobi shape change or triaxial-octupole Poincare shape change and the proximity of the fission limit. Favourable conditions are expected to be met in exotic, neutron-rich nuclei, accessible via fusion-evaporation with the advent of SPIRAL2 beams. Therefore we consider some of the best options to be the compound nuclei ^{120}Cd and ^{142}Ba, which can be produced at very high angular momentum, almost reaching 100ħ, in inverse kinematics by a ^{94}Kr beam, available at SPIRAL2, impinging on ^{26}Mg and ^{48}Ca, respectively. This will require a coupling of the 2π PARIS array to the AGATA Demonstrator or EXOGAM2, and to a recoil detector.

[5] K. Mazurek, J. Dudek and A. Maj, to be published

3. Detector tests

a) Test of the energy resolution of the cubic 2"x2"x2" and cubic 2"x2"x4" LaBr3 crystals

The cubic 2"x2"x4" crystal was tested by the IPN Orsay group using standard analogue electronics with CAMAC readout. A Photonis XP3292 photomultiplier tube perfectly matching the size of the crystal was used. The PM signal was read by a 571 Ortec Amplifier (after going through a Charge Preamplifier with gain 1) and digitized with a Ortec ADC (ADC811). The resulting energy spectrum for e.g., ^{137}Cs with ^{60}Co sources is presented in Figure 3a. For the resolution measurements we have used standard calibration sources: ^{22}Na, ^{57}Co, ^{60}Co, ^{137}Cs, ^{154}Eu, ^{207}Bi. It allowed us to cover an energy range from 0.1 to 3.2 MeV. We obtained 3.31(1) % resolution for 0.661 MeV. The results are presented in Figure 3b. Because the light output of the LaBr3(Ce) crystal is very high, care should be taken to insure the output linearity of the anode current of the PM. The linearity is insured by the constructor within 2% only for currents less than 10mA. Accordingly, the Voltage divider was modified and the signal was collected on the 5th dynode instead of the anode.

Similar tests, with almost the same standard electronics were performed for the 2"x2"x2" crystal by the Krakow and Warsaw groups. Here in additions a measurement for the 6.13 MeV gamma ray was performed (see Figure 3c). Here also non-linerity problems were noticed, and the voltage divider will be modified.

The main conclusion from tests of the cubic detectors is that their resolution is as good as the one of cylindrical one of similar size[6].

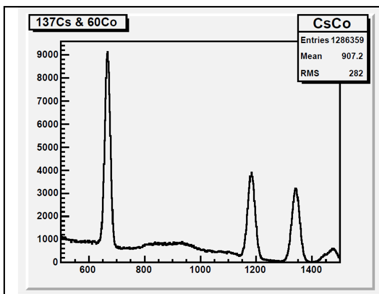

Fig. 3a: Energy spectrum (counts/1 keV) for the 4 inch long LaBr3(Ce) cubic crystal

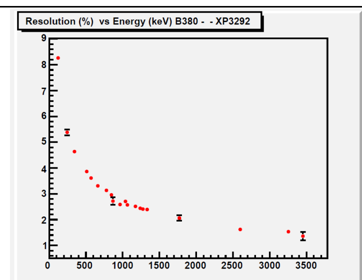

Fig. 3b: Energy resolution (%) as a function of energy (keV) for the 4 inch long LaBr3(Ce) cubic crystal.

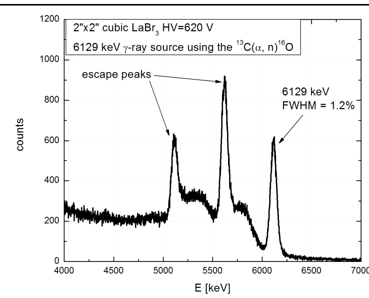

Fig. 3c: Energy spectrum for the 2 inch long LaBr3(Ce) cubic crystal

b) Test of the phoswich detector

First tests of the phoswich detector, consisting of 1"x1"x2" LaBr3(Ce) coupled to the 1"x1"x6" CsI(Na), specially manufactured for the PARIS collaboration by Saint Gobain, were performed by the Strasbourg and York groups. Signals from both crystals were collected by a common photomultiplier attach to the CsI(Na). Figures 4a,b,c shows snapshots of the signals related to the ^{60}Co source, recorded by the oscilloscope. Clearly one can distinguished the signals coming from both crystals (fast signal from $LaBr_3$, slow – from CsI) even in the case when the gamma energy was shared between both crystals.

Fast and slow signals, properly gated, were digitized and the corresponding 2D correlations are plotted in Fig. 5b, while the projections on LaBr3 and CsI axis are shown in Fig. 5a. The resolution for the 661 keV line in the CsI crystal is 11%, while for the LaBr3 case - 5.5%. This latter

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[6] M. Ciemala et al., Nuclear Instruments and Methods in Physics Research A608, 76 (2009)

value, which is very preliminary, seem to be slightly worse than the one obtained by single 2”x2”x2” cubic crystal (cf. Fig. 3b).

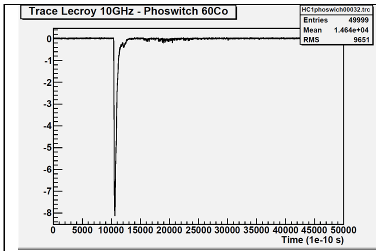


Fig. 4a: Signal corresponding to the event which deposited energy only in LaBr3

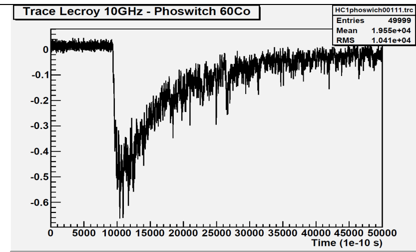


Fig. 4b: Signal corresponding to the event which deposited energy only in CsI(Na)

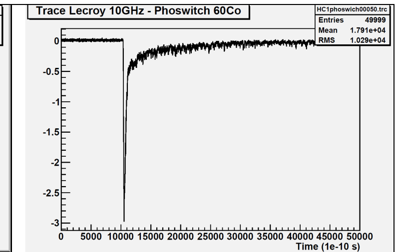


Fig. 4c: Signal corresponding to the event which deposited energy in both crystals

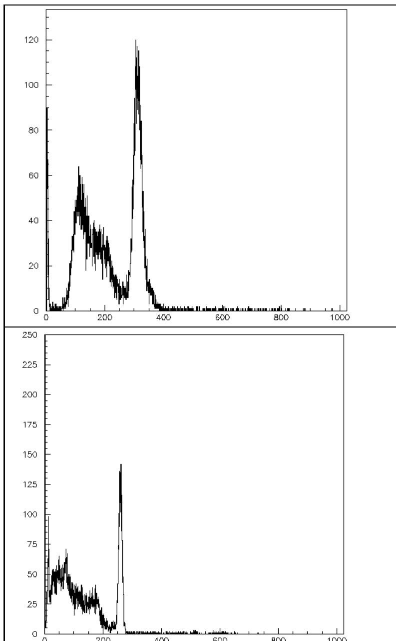


Fig. 5a: Spectra for ^{137}Cs for the events, when the whole energy is deposited in LaBr3 (bottom) and in CsI (top).

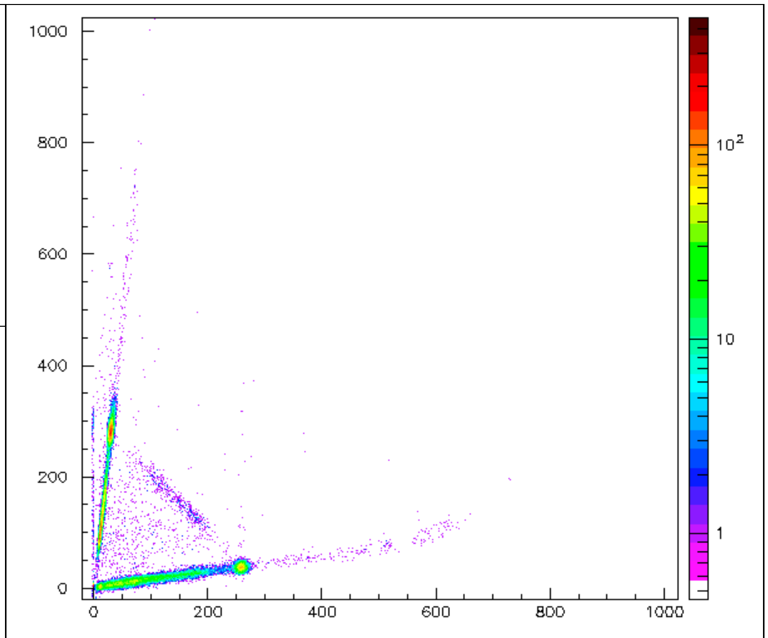
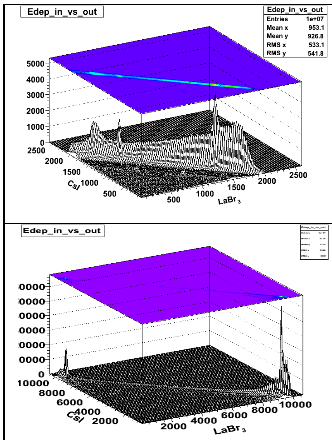
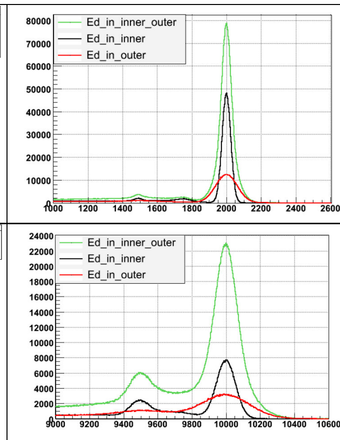


Fig.5b: Correlation plot between events deposited in LaBr3 (x-axis) and CsI (y-axis), when the detector was exposed to 661 keV gamma radiation from ^{137}Cs source

4. GEANT4 simulations for phoswich detector type

As the tests of the phoswich type of detector ($LaBr_3$(Ce)+CsI(Na)) gave rather optimistic results, a simulations of the resolutions of the PARIS array cubic array (see the Figures 6a, b, c) were performed to see what we may expect for the energy resolution of the reconstructed spectra from the $LaBr_3$ (having good resolution) and CsI(Na) (possessing rather poor resolution) in the case of a cubic geometry made of such phoswich detectors. The results are presented in figure. As can be seen, the excellent resolution of $LaBr_3$ crystal is only slightly destroyed, even at high energies, providing the 2'' long $LaBr_3$ is used. In case of replacing it 1" $LaBr_3$, the resolution is significantly worse.





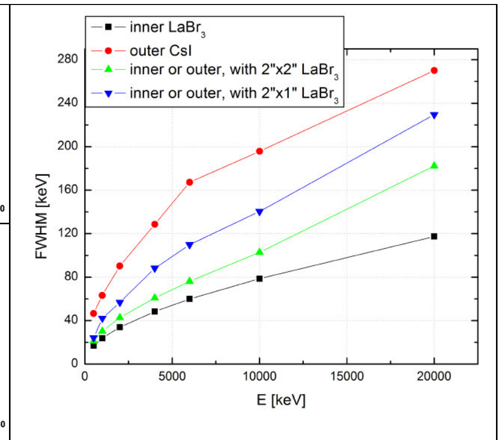


Fig. 6a: Distribution of events sharing their energies between LaBr3 and CsI for 2 MeV (top) and 10 MeV (bottom). Events having the full energy deposit in one of the crystals only are not shown for better visibility.	*Fig. 6b: Spectra for only LaBr3 events (black), only CsI events (red) and for all reconstructed events (green). Top: 2 MeV, Bottom: 10 MeV.*	*Fig. 6c: FWHM for only LaBr3 events (black), only CsI events (red) and for all reconstructed events (green). For comparison FWHM for reconstructed events in case when LaBr3 has 1" length.*

5. Conclusions

Since the energy resolution of the cubic type of the $LaBr_3$ is the same as for the cylindrical one, this shape will be most probably chose for the final version. Also the rectangular phoswich simulations and first tests give very promising results. If this will be confirmed in forthcoming tests and in-beam experiments (the first at the Heavy Ion Cyclotron in Warsaw is scheduled for October thos year), this type will be consider with highest priority.

A decision of such a rectangular shape will exclude the truly spherical geometry, and enables to decide on two possible final geometries of the whole PARIS: *a cubic-like* one (Fig. 7a), offering the highest efficiency, and the *radial* one (Fig. 7b), offering the good angular resolution and response function. Cubic shaped detectors can be mounted either in one geometry, or the other, depending of the physics case. Such a solution will be proposed by the PARIS management board and the project leader. The final decision is expected to be taken during the PARIS collaboration meeting in October 2009.

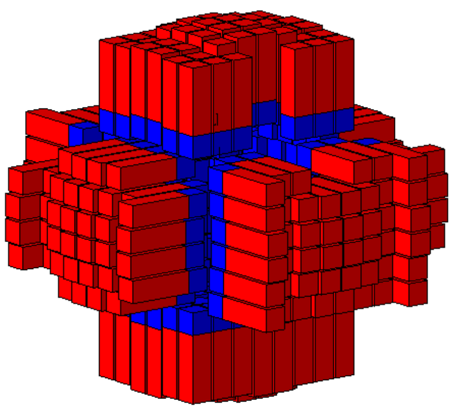
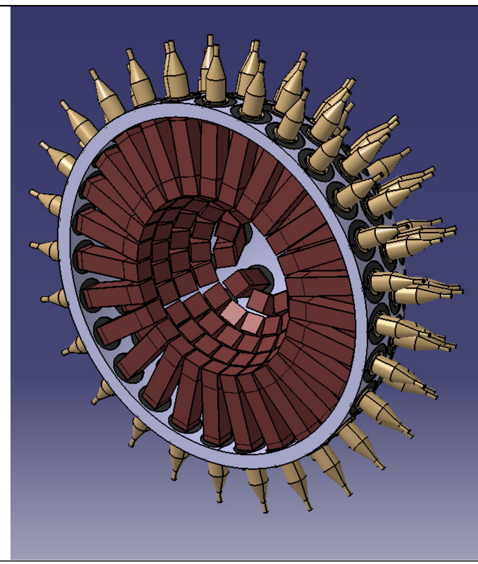
	

Fig. 7a: Cubic-like geometry of PARIS consisting of 220 rectangular phoswiches	*Fig. 7b: Radial geometry of PARIS consisting of 200 rectangular phoswiches*

Such proposed variable geometry of PARIS will also have very positive impact on the further synergy with GASPARD concerning the integration of both detectors. This and other synergy aspects, will also be discussed during next PARIS collaboration meeting, to which GASPARD project leader was invited.