# GEANT4 Simulations for a 4π array of LaBr:Ce scintillators for the PARIS collaboration

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The PARIS collaboration is in the process of arriving at a best possible design for an array of gamma detectors that can optimally serve as a sum-spin spectrometer and also as a calorimeter for high energy gamma rays using both stable and high energy radioactive ion beams. The primary requisites for such an array are high efficiency, energy and timing resolutions and granularity. While high granularity is a must for the array to serve as a multiplicity filter the effect of cross talks between contiguous detectors puts a limit on reducing the sizes of the detectors and thereby on high granularity for a given volume. The most widely used scintillators for such arrays have been the NaI(Tl), BGO and $BaF_2$ crystals. The time tested NaI(Tl) crystals provide better energy resolutions than the other two with a relatively good efficiency. However, NaI(Tl) has large neutron absorption cross section and being a slow detector the crystals are to be kept at a considerable distance from the target for neutron-gamma separation by time-of-flight. In comparison the much faster timing of $BaF_2$ allows it to be kept much closer to the target and it has a much weaker response to neutrons. However, the energy resolution of $BaF_2$ is much poorer than NaI(Tl). In addition the strong temperature dependence of the pulse height in $BaF_2$ crystals demand a steady and constant temperature environment for the detectors. In light of these shortcomings an ideal gamma ray detector would have good energy and timing resolutions, less neutron absorption cross section and little or no dependence on temperature over a sufficiently long range of temperature. The recently developed LaBr:Ce scintillators seem to satisfy most of the requirements for an ideal spectroscopic detector. The energy resolution of these crystals are significantly better than NaI(Tl) with a very fast timing comparable to $BaF_2$. In addition, unlike $BaF_2$, the performance of LaBr:Ce crystals show very little dependence on temperature. The high Z of Lanthanum and high density of the crystal also allows the efficient detection of high energy gamma rays (~10-20 MeV) in a crystal of relatively smaller volume compared to a large volume NaI detector. In this report we present our results of exhaustive GEANT4 simulations for the performance of an array of LaBr:Ce detectors in a complete 4π configuration. As mentioned in the beginning the PARIS array is expected to serve the dual purpose of both a sum-spin spectrometer and also a calorimeter for high energy gamma rays. The configuration of such an array is driven by the desire to cover as much solid angle as possible with the best possible response to the gamma rays over a wide range of energy. Ideally, the arrangement of the detectors in a "soccer ball' configuration covering the entire $4_p$ solid angle surrounding the target would result in a much better response of the array over other configurations. An often used configuration is the so called castle geometry with straight crystals of hexagonal cross sections in a close packed honeycomb structure below and above the scattering chamber. However, in such a configuration the solid angles covered by the central detector is different from detectors in the successive rings surrounding it. The response of the array also gets spoilt by the possibility of the gamma rays going into the outer rings having first interacted with the inner rings. This problem is circumvented in the soccer ball geometry with the faces of the detectors perpendicular to the gamma rays emitted radially outwards.

In our simulations we have considered an array of 32 tapering conical detectors of both pentagonal and hexagonal cross sections. Once arranged in a close packed geometry the array covers complete 4π solid angle surrounding the target forming a spherical shell with inner diameter of 10.0 cm. We have also considered a cylindrical aluminium scattering chamber of 8 cm diameter and wall thickness of 3 mm placed centrally inside the spherical shell created by the detectors. The source of the gamma rays is from the centre of the scattering chamber. The Figure 1. shows the drawings for both the pentagonal and hexagonal detectors. The dimensions of the detectors are given below.

| | Pentagon | Hexagon |
|---|---|---|
| Length | 76.2 mm | 76.2 mm |
| Side (front face) | 44.14 mm | 44.14 mm |
| Side (back face) | 81.0 mm | 81.0 mm |
| Area (front face) | 3300 mm2 | 5016 mm2 |
| Area (back face) | 11340 mm2 | 17010 mm2 |

We consider the crystals to be encased in 1 mm thick Al casings. The 3-d picture for such array as generated by GEANT4 is shown in Figure 2. The blown up pictures of the proposed array of 32 detectors showing the two halves with 16 detectors each are provided in Fig.3. Figure 4 shows the beam axis going through the spherical array by removing two of the pentagonal detectors placed $180^{o}$ apart. Figure 4 shows the possible mechanical arrangement for the array.

Having frozen the geometry of the array we calculate the efficiencies and response of the array and also the individual detectors. The Tables 1-3 present the efficiencies for the individual detectors, the full array of 32 detectors and also the array with two and three detectors removed for the beam inlet, outlet and for another ancillary detector at a distance from the target outside the array. We also provide tables for corresponding values of efficiencies for a similar array of NaI(Tl) detectors for comparison.

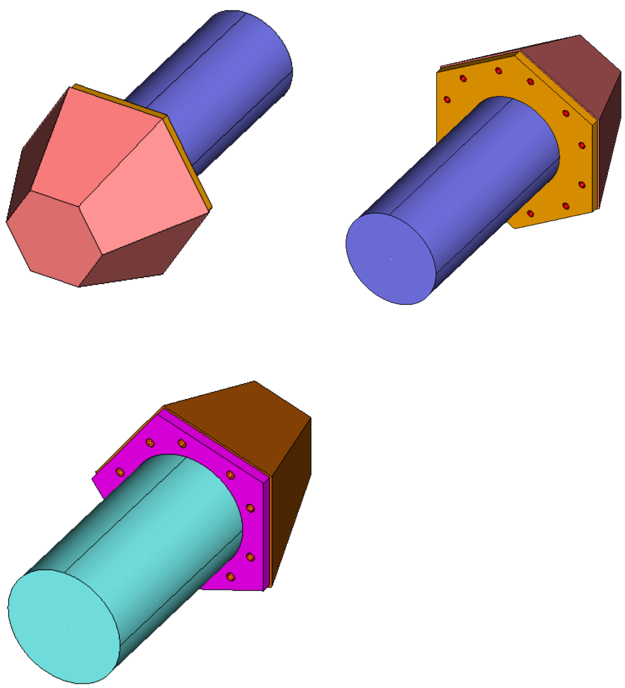


**Figure 1 : Conical hexagon and Pentagon**

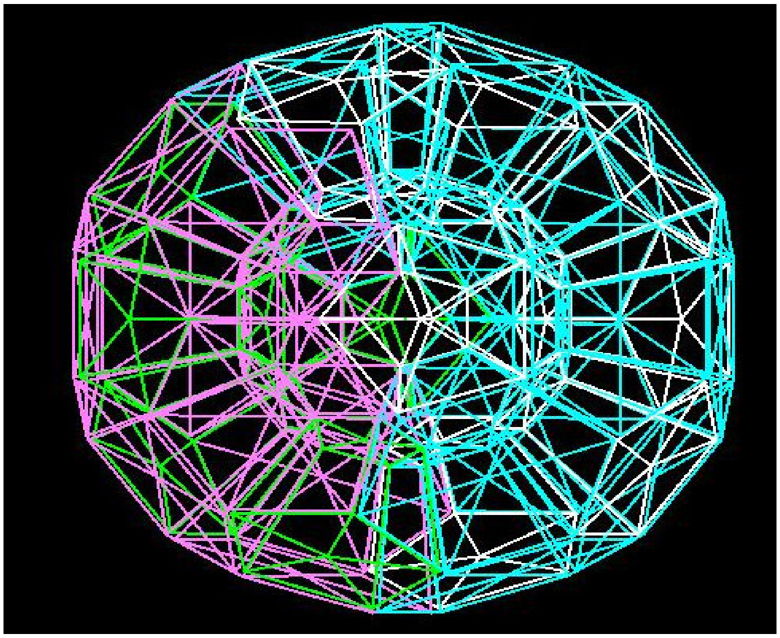


**Figure 2**

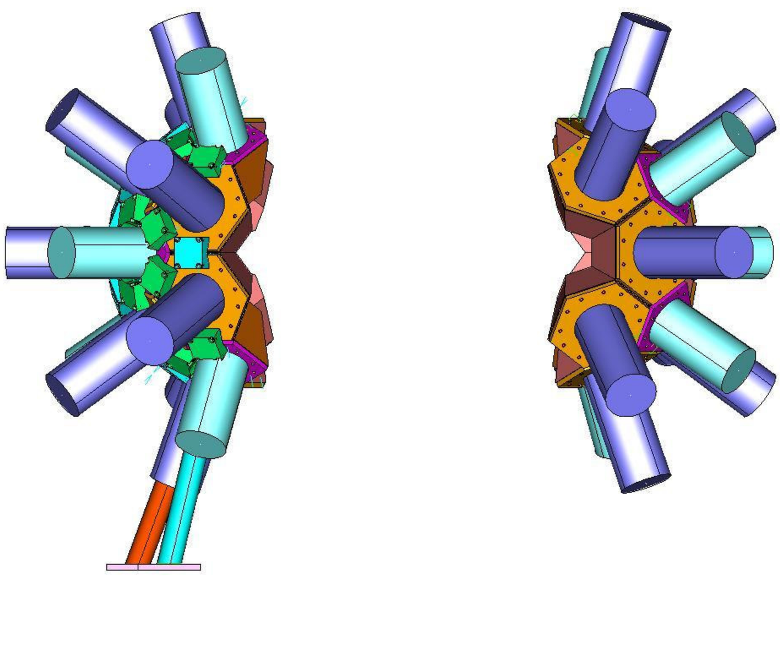
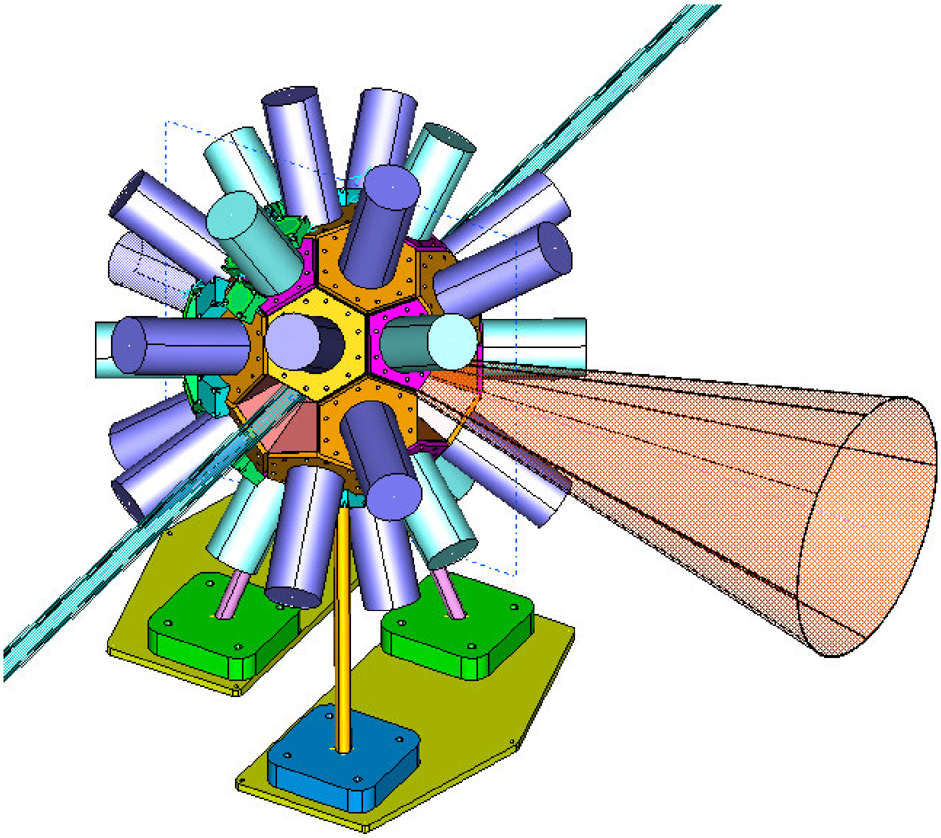


**Figure 3**



# Figure 4

# Tables:

**$LaBr_3$ Conical Hexagon**

| Energy (MeV) | Absolute efficiency (in %) | Photo peak efficiency (in %) |
|---|---|---|
| 0.662 | 3.21 | 2.20 |
| 1.173 | 2.93 | 1.55 |
| 1.132 | 2.89 | 1.45 |

**$LaBr_3$ Conical Pentagon**

| Energy (MeV) | Absolute efficiency (in %) | Photo peak efficiency (in %) |
|---|---|---|
| 0.662 | 2.26 | 1.37 |
| 1.173 | 2.10 | 1.00 |
| 1.132 | 2.02 | 0.90 |

**$LaBr_3$ 4π □array (full, 32 detetctors)**

| E (MeV) | Absolute Efficiency (in %) | Photo peak efficiency (in %) |
|---|---|---|
| 0.662 | 90.00 | 71.00 |
| 1.173 | 82.60 | 55.63 |
| 1.332 | 81.00 | 52.75 |
| 5 | 68.42 | 32.63 |
| 10 | 71.25 | 25.64 |
| 15 | 72.70 | 18.38 |
| 20 | 75.03 | 11.37 |
| 30 | 78.31 | 4.41 |
| 40 | 79.73 | 1.56 |
| 50 | 81.56 | 0.55 |

**$LaBr_3$ 4π array with different configurations for 662 keV**

| Configuration | Absolute Efficiency | Photo peak efficiency |
|---|---|---|
| 32 (12 P + 20H) | 90.0 | 71.0 |
| 30 (10 P + 20H) | 85.7 | 66.4 |
| 29 (10 P + 19H) | 82.4 | 63.4 |
| 29 ( 9 P + 20H) | 83.5 | 64.5 |

**NaI Conical Hexagon**

| Energy (MeV) | Absolute efficiency (in %) | Photo peak efficiency (in %) |
|---|---|---|
| 0.662 | 3.05 | 1.81 |

**NaI Conical Pentagon**

| Energy (MeV) | Absolute efficiency (in %) | Photo peak efficiency (in %) |
|---|---|---|
| 0.662 | 2.08 | 1.12 |

**NaI 4π □array (full)**

| **E (MeV)** | **Absolute Efficiency (in %)** | **Photo peak efficiency (in %)** |
|---|---|---|
| 0.662 | 83.40 | 60.02 |
| 1 | 76.13 | 47.91 |
| 5 | 59.32 | 22.82 |
| 10 | 62.02 | 16.98 |
| 15 | 64.21 | 10.80 |
| 20 | 66.33 | 6.00 |
| 25 | 68.15 | 3.32 |
| 30 | 69.33 | 1.84 |
| 35 | 70.87 | 0.81 |
| 40 | 71.83 | 0.46 |
| 45 | 72.23 | 0.23 |
| 50 | 73.41 | 0.10 |

**NaI 4π array with different configurations for 662 keV**

| **Configuration** | **Absolute Efficiency** | **Photo peak efficiency** |
|---|---|---|
| 32 (12 P + 20H) | 83.40 | 60.02 |
| 30 (10 P + 20H) | 80.13 | 58.06 |
| 29 (10 P + 19H) | 77.55 | 55.91 |
| 29 ( 9 P + 20H) | 78.26 | 56.70 |