

A report on the possible experiments to characterise the PARIS array

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Abstract

In this report we discuss the calibration and determination of the response function of the PARIS detectors, individually, and as an array of multiple closed packed detectors. The primary aim is to tabulate the radioactive sources and the in-beam reactions necessary to characterise PARIS and study its performance. We also discuss and list the specific accelerator facilities where the experiments can be carried out.

1. Introduction

A host of major experimental detection systems are currently under construction for the upcoming SPIRAL2 project at GANIL. The proposed Photon Array for Studies with Radioactive Ion and Stable Beams (PARIS) is one of them. PARIS is a large array of phoswich detectors expected to measure gamma rays over a wide range of energy from few hundred keV to 40 MeV. It is envisaged to serve the dual purpose of a high-energy gamma ray spectrometer and a spin-spectrometer, capable of determining the multiplicity of low energy (~ 100 keV to few MeV) discrete gamma rays associated with a specific reaction.

The simulations and mechanical studies performed over the last few years by the collaborating groups have resulted in zeroing upon the final design of PARIS. Upon completion PARIS is envisaged to be an array of 216 phoswich detectors. The front section of each of the phoswich detectors is a cubic (2''x2''x2'') Lanthanum Bromide crystal optically coupled to a 6'' long square bar of NaI(Tl) of matching cross section. Each of these detectors is to be viewed by a single photo multiplier tube (PMT) of 2'' diameter that would allow close packing of such detectors. It is planned to combine 9 phoswich detectors in a

square (3X3) close packed geometry forming a PARIS cluster. The project is to be executed in a phased manner with the completion of one cluster in the first phase (PARIS prototype) and five clusters by the end of the second phase (PARIS demonstrator). The third phases will see the completion of 12 clusters. In its final configuration, commissioned by the end of the fourth phase, PARIS is envisaged to have clusters covering 4π solid angle around the target.

A variety of experiments in nuclear structure and reaction dynamics are foreseen to be pursued with PARIS using both stable and radioactive ion beams. The various physics cases include studies of giant dipole resonances (GDR) in excited nuclei, exotic shape-phase transitions, Coulomb excitation, heavy ion radiative capture, reaction dynamics around and above the barrier etc. For a fuller discussion of all aspects of the project we refer to the PARIS web page <http://paris.ifj.edu.pl>.

The primary objective of this report is to work out a strategy for the 1) calibration and 2) determination of the response function of the whole array and also the individual detectors for a wide range of photon energy from around hundred keV to tens of MeV. There are a large number of radioactive isotopes producing gamma rays from as low as tens of keV to few MeV. A combination of alpha emitters and stable isotopes can produce higher energy gamma rays up to 4.43 and 6.13 MeV. However, the dearth of radioactive sources producing gamma rays beyond 6.13 MeV makes it imperative to consider in-beam reactions producing higher energy, monochromatic gamma rays. A complete mapping of the response of the individual detector and also an ensemble of detectors to gamma rays beyond 10 MeV is crucially required for the experiments to be performed with PARIS.

In this report we have tried to compile a set of essential gamma ray sources and a set of nuclear reactions producing high-energy monochromatic gamma rays for the characterisation of PARIS. As mentioned previously by characterization we mean the determination of energy and timing resolutions, efficiencies, linearity, uniformity and determination of response function of the individual detectors and the whole array. The tests to study the performance of the array as a spin spectrometer is not the focus of this report. Finally, we provide a list of accelerator facilities where these measurements can be carried out.

2. Calibration and determination of Response function of PARIS

It has been mentioned in the introduction that PARIS is to be used both as a high-energy calorimeter requiring efficient absorption of gamma rays up to around 40 MeV and also as a low energy sum-spin spectrometer. It is, therefore, absolutely essential to determine and estimate the overall performance of the array over the entire range of energy of interest. The performance is to be judged in terms of efficient absorption of high-energy photons (4 – 40 MeV) and determination of the sum-energy and the multiplicity of the low energy discrete gamma rays. The determination of the multiplicity and the segregation of energy deposited in the different sections (of the phoswich) is intimately coupled to the extraction and processing of the signals involving both electronics and related software.

The primary properties characterizing a single or an array of gamma detectors are 1) energy resolution and its variation with energy, 2) linearity, 3) efficiencies of gamma absorption (both total and photo peak), 4) uniformity of the crystal and 5) timing resolution. These properties along with the optimum granularity of the array would determine the overall performance of the array in terms of photon absorption and determination of the multiplicity.

While Photo Electric Effect and Compton Scattering are the inelastic interaction processes for gamma rays up to $\sim 1\text{MeV}$ the dominant process of interaction for a higher energy photon in the detector material is by e^+e^- pair production that develops into an electromagnetic shower. A certain fraction of the total shower may escape out of the finite volume of the detector, resulting in reduced full energy peak efficiency and a low energy tail. This response of the detector is energy dependent and it is required to determine the full energy dependent detector response over the entire range of interest. The energy response matrix of the detector or the detector array is convoluted with the calculated spectrum for comparison with the measured spectrum. While the response matrix is calculated using detailed simulation packages it requires experimental inputs from measured spectra of **monochromatic** gamma rays. It is essential to measure the spectra over the entire range of energy of interest for as many monochromatic gamma rays as experimentally feasible to provide realistic inputs to the simulations.

All the properties, like linearity, efficiency (total and photo peak) etc. can be measured easily for low energy gamma rays using radioactive sources producing monoenergetic gamma rays. Using calibrated sources of gamma rays the detection efficiencies can be measured even at an absolute scale. However, the highest available energy from radioactive sources is 6.13 MeV ($^{244}\text{Cm}-^{13}\text{C}$ or $^{238}\text{Pu}-^{13}\text{C}$). The response of the detector array cannot be interpolated from the measurements at lower energies as the pair production cross-section increases drastically with energy. The calibration of the gamma ray spectrum up to 40 MeV also requires higher energy lines. The possible non-linearity present in the system does not allow a linear calibration over the entire energy range up to 40 MeV or beyond. The calibration of the array over the Giant Dipole Resonance (GDR) region requires high-energy monochromatic gamma rays between 10 to 20 MeV. In-beam studies of nuclear reactions in which gamma rays are produced by well isolated transitions are used for this purpose.

Another important issue for the PARIS array is the determination of the Multiplicity and Sum-Energy response matrices. The gamma-multiplicity response, i.e. the conversion of measured fold to multiplicity of low energy gamma-rays can be established (see [35, 36]) by recording event-by-event gamma-rays from a radioactive source emitting two gamma rays in cascade (^{60}Co , ^{88}Y , ^{207}Bi) An external gamma detector can be used as a trigger detecting one of the gamma rays, while the other gamma-ray is detected in the PARIS array, and the number of folds (i.e. number of detectors fired) is stored. This will define the response to multiplicity $M=1$. The response to multiplicity $M=k$ is generated in the off-line analysis by randomly selecting k events and adding up the resulting folds. In an analogous way one can determine the partial, for some of the energies, sum-energy response matrix.

In this report we discuss some of the sources and in-beam reactions that we propose to use. The measurements for individual detectors and the clusters can be performed at specific laboratories listed in this report and decided by the collaboration.

3. Measurements using radioactive sources

Before embarking upon the discussions on the in-beam reactions we summarise the measurements with radioactive sources. While a host of gamma ray sources are available in the energy range of few tens of keV to few MeV our selection is guided by the ease of availability and reasonably long lifetime of the source. The sources we suggest are mostly available with researchers involved in gamma ray spectroscopy in different laboratories. The most widely used low energy calibration sources are ^{137}Cs (661.6 keV) and ^{60}Co (1173.2 and 1332.5 keV). The much short-lived isotope of ^{88}Y ($T_{1/2}=100$ d) is also a very useful source with two widely separated lines of 897 and 1832 keV. The simultaneous detection and summing of the two gamma rays from ^{60}Co in the same detector provides an extra point for calibration at 2505 keV. For calibration of the fold-multiplicity response one uses sources having two gamma transitions in cascade, such as, ^{207}Bi (1770 and 570 keV), or the above-mentioned ^{60}Co or ^{88}Y .

A neutron source like ^{252}Cf can provide a gamma line of 2.22 MeV due to capture of the neutrons by protons. The emitted neutrons from ^{252}Cf can be thermalized by paraffin blocks before they are captured by protons to yield 2.22 MeV gamma rays. Combined radioactive sources containing a mixture of an α emitter and ^{13}C and ^9Be emit neutrons and γ -rays of 6.13 and 4.43 MeV from the de-excitation of the second excited state of ^{16}O and the first excited state of ^{12}C respectively. Sources like ^{241}Am - ^9Be and ^{244}Cm - ^{13}C (or ^{238}Pu - ^{13}C) produce 4.433 and 6.13 MeV respectively. The alpha particles from ^{241}Am and ^{244}Cm (or ^{238}Pu) induce $^9\text{Be}(\alpha, n-\gamma)^{12}\text{C}$ and $^{13}\text{C}(\alpha, n-\gamma)^{16}\text{O}$ reactions to produce 4.43 and 6.13 MeV gamma rays respectively [1-4]. The neutron spectra and the gamma to neutron ratio from such combined sources have been discussed in references [2-4]. The composite source of ^{226}Ra - ^9Be also produces 4.433 MeV gamma rays using the $^9\text{Be}(\alpha, n-\gamma)^{12}\text{C}$ reaction. Fig. 1) shows a typical 4.433 MeV γ -ray spectrum recorded in a large volume cylindrical Lanthanum Bromide crystal using a ^{241}Am - ^9Be source. The solid line in the figure is a GEANT4 simulation that adequately reproduces the experimental spectrum.

Table I summarises the radioactive sources with the corresponding gamma rays useful for calibration and other necessary tests up to 6.13 MeV.

Table I.

Source	E _{gamma} (keV)	Half-Life
¹³⁷ Cs	661.6 keV	30.08 y
⁶⁰ Co	1173 keV, 1332 keV	1925 d
⁸⁸ Y	897 keV, 1832 keV	106.6 d
²⁰⁷ Bi	1770 keV, 570 keV	31.5 y
²⁵² Cf	2224 keV	2.645 y
²⁴¹ Am- ⁹ Be	4433 keV	432.6 y
²²⁶ Ra- ⁹ Be	4433 keV	1600 y
²⁴⁴ Cm- ¹³ C	6129 keV	18.1 y
²³⁸ Pu- ¹³ C		87.7 y

The neutron emitting sources mentioned above can also be used to check the neutron response of the detectors and also the n- γ separation. This would further provide information about the timing response of the crystals by setting up a coincidence circuit using two detector assemblies. A typical n- γ time spectrum measured with a neutron source and one large volume LaBr₃:Ce detector is shown in Fig.2. The start signal was taken from a small cylindrical (1" X 1") Lanthanum Bromide crystal kept very close (~ 5cm) to the source. The large volume crystal was kept around 30 cm from the source resulting in clear n- γ separation as seen in the spectrum.

In addition to energy calibration, the low energy gamma ray sources are ideal for checking the uniformity of the detector. A collimated source of Cs or Co can be made to shine over the entire surface area of the crystal to check for any appreciable change in pulse height due to non-uniformity of the crystal. Fig.3. shows the results of measurements using a collimated ⁶⁰Co source to check the uniformity of a large volume cylindrical Lanthanum Bromide crystal of 3.5" diameter and 6" length. We refer to Appendix II for further discussion on scanning of the detectors.

The tests discussed so far with radioactive sources can be carried out at all the laboratories belonging to the different collaborative groups.

At this stage it is worth mentioning that it is possible to generate higher energy monochromatic gamma rays beyond 6.13 MeV in the lab by (n, γ) reactions using thermal neutrons. Thermal neutrons can be generated using sufficient volume of paraffin or borated

paraffin around a typical neutron-emitting source, namely, Am-Be. A thick chemically pure Ni plate can be used to generate monochromatic high energy gamma rays from the (n, γ) reaction on Ni [5]. Fig. 4) shows a gamma ray spectrum recorded in a large volume cylindrical Lanthanum Bromide detector. The mono-energetic high-energy gamma rays up to ~ 8 MeV were generated using (n, γ) reactions on Ni

Since PARIS is also a sum-spin spectrometer detecting low energy gamma rays from few tens of keV to few MeV it is necessary to check the performance using gamma ray sources for energies lower than Cs energy (662 keV). The table below provides a list of low energy gamma rays and the corresponding isotopes.

Table II

Source	E_{gamma} (keV)	Half-life
^{88}Y	14.14	106.6 d
^{241}Am	17.54	432.6 y
^{241}Am	26.34	432.6 y
^{133}Ba	30.85	10.551 y
^{137}Cs	32.06	30.08 y
^{152}Eu	39.91	13.52 y
^{241}Am	59.54	432.6 y
^{133}Ba	81.0	10.551 y
^{57}Co	122.06	271.74 d
^{152}Eu	244.7	13.52 y
^{133}Ba	276.4	10.551 y
^{133}Ba	302.85	10.551 y
^{133}Ba	356.02	10.551 y
^{22}Na	511.0	2.602 y

4. In-beam measurements

We now discuss some in-beam reactions to produce high-energy monochromatic gamma rays for characterizing the PARIS detectors. There has been a very large body of work carried over many decades for production of high-energy monochromatic gamma rays. These reactions are either low energy proton capture reactions or inelastic scattering reactions. The primary criteria for the selection of such reactions are the yield of the gamma rays of interest, well-known relative intensities of cascades, availability of low energy high current light ion (primarily proton) accelerators, and the ease of target preparation.

Over the decades many experiments have been done and reported for efficiency calibration of Germanium detectors [6-10] using proton capture reactions. In recent times several authors have reported about characterizations of small volume Lanthanum Bromide detectors using low energy sources [11-12]. Few authors have also reported about the performance of phoswich of Lanthanum Bromide and NaI(Tl) using low energy sources [13,14]. Fig. 12 shows gamma-rays spectra recorded in a phoswich of LaBr and NaI(Tl) for ^{137}Cs and ^{60}Co sources. The very different time response of the two crystals allow complete segregation of the energy deposited in the two sections by pulse shape discrimination [13]. Figure 13 shows the measurements carried out in Krakow for a phoswich of LaBr and NaI(Tl) for 6.13 MeV gamma rays. Figure 14 shows similar measurements from Strasbourg using ^{137}Cs source. Only a few measurements have so far been carried out up to higher energies for Lanthanum Bromide detectors, using either proton capture reactions [15] or high-energy photon beams [16]. We summarise below some of these reactions which can be chosen for calibration and determination of efficiency of PARIS.

4.1. $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ reaction

This reaction has been studied and reported by many workers for calibration and efficiency measurements and also for practical applications. The excited states of the compound nucleus ^{20}Ne de-excite by α -particle emission to populate excited states of ^{16}O . The excited states of ^{16}O de-excite by emitting 6.129, 6.917 and 7.116 MeV gamma rays. The absolute yield of these photons have been reported by Fessler *et. al.* from thick target measurements using NaI(Tl) detector and proton beams from 1.5 to 4.0 MeV. [17]. Excitation

functions using thin target have been measured by other authors using Ge detectors with proton beam ranging from 1.0 to 3.8 MeV [18,19]. The yield of $8.72 \times 10^4 \gamma/\mu\text{C}/\text{Sr}$ for proton energy of 340 keV has been reported by Croft [20]. The target in all these measurements has either been thick pellet of CaF_2 or thin layer of CaF_2 evaporated on thick Ta backing.

4.2. $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ reaction

The $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ reaction has been very well studied by several workers at different resonance energies. We refer to some of them in this report [6-10]. The measurements have been carried out with targets ranging from $10 \mu\text{g}/\text{cm}^2$ to $40 \mu\text{g}/\text{cm}^2$ with beam energies (E_p) from 760 to 2489 keV. The relative intensities of the prominent gamma rays, produced up to 11.6 MeV at these beam energies are now well known and tabulated. The disadvantages of certain beam energies at which gamma ray yields from strong ($p, p'\gamma$) and ($p, \alpha\gamma$) channels start dominating have been discussed in more recent works [9,10]. Based upon their observations we feel the best possible beam energies would be $E_p = 767, 992, 1317$ and 2046 keV for the testing of PARIS. The prominent high-energy gamma rays produced in this reaction at the beam energies, which are particularly useful for calibrating PARIS, are 6.57, 7.7 and 10.76 MeV. A recent spectrum recorded in a 2''X2''X2'' cubic Lanthanum Bromide detector for the $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ reaction at $E_p = 770$ keV is shown in Fig.5.

4.5. $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction

There are many resonances below $E_p = 2$ MeV for the $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction. This reaction has been studied and the prominent resonances have been tabulated in [9,10]. Zijderhand *et. al.* [9] have pointed out that the resonances at $E_p = 1318$ and 1417 keV are ideally suited for efficiency calibration of gamma detectors. Based upon the observations in [9,10] we suggest $E_p = 1020, 1318,$ and 1417 keV for this reaction. The prominent gamma rays produced are 1.37, 2.75, 4.24, 8.43, 8.92 and 11.58 MeV. In a very recent work Ciemala *et. al.* [15] have carried out this reaction for full-energy peak efficiency calibration of a 2''X2'' cylindrical Lanthanum Bromide detector. In all these measurements [9,10,15] the target thickness varies between 5 to $30 \mu\text{g}/\text{cm}^2$.

4.6. $^{39}\text{K}(p,\gamma)^{40}\text{Ca}$ reaction

This reaction was tabulated and discussed by Singh and Evans [21]. In more recent times Elekes *et. al.* [10] has used this reaction for full-energy peak efficiency calibration of a Clover-BGO detector system. This reaction produces two gamma rays of 3.904MeV and 5.736MeV at $E_p = 1347$ keV. Kikstra *et. al.* have reported about the parameters of this 1347 keV resonance [22]. This reaction has also been used by Ciemala *et. al.* to study a 2"X2" Lanthanum Bromide detector. The target thickness used in all these measurements has varied from 10 to 20 $\mu\text{g}/\text{cm}^2$.

4.7. $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction

This very well known (p, γ) capture reaction has been studied for last several decades and is a very important reaction for nuclear structure studies, nuclear astrophysics and practical applications. Early measurements reported about the resonances for proton energy varying from 200 to 1100 keV [23,24, 25]. More recent measurements by Cecil *et.al.* report about γ to charged particle branching ratio for $E_p = 40$ to 170 keV [26]. Measurements at very low energies 80 – 0 keV using polarized protons and thick target have been reported by Chasteler *et. al.* [27]. For our purpose of calibration and efficiency measurements the important gamma rays are the 17.64, 18.15, 19.1 and 22.6 MeV because of capture to ground and first excited states of ^8Be at 441 and 1030 keV resonances. Ciemala *et.al.* have measured the 17.6 MeV gamma ray using a 2"X2" cylindrical Lanthanum Bromide detector using a thin LiBO_2 target [15].

4.3. $^{11}\text{B}(p,\gamma)^{12}\text{C}$ reaction

This reaction has well known isolated transitions populating the ground state and the first excited state of ^{12}C . The attractive feature of this reaction is that the energy of the produced gamma rays is in the GDR energy range for medium mass nuclei. The radiative capture of proton by Boron in this reaction produces two gamma rays of energies 22.5 MeV and 18.1 MeV by decay to the ground state and first excited state of ^{12}C respectively. The cross section for the decay to the ground state shows a broad peak with a maximum at $E_p=7.2$ MeV, whereas it is more or less constant for decay to the first excited state. Due to energy conservation the gamma ray energies are related to the proton energy according to $E_{\gamma 0} = (0.92)E_p + 15.957$ MeV; $E_{\gamma 1} = (0.92)E_p + 11.518$ MeV

The only difficult part in this measurement is to have a self-supporting Boron target of thickness beyond $250 \mu\text{g}/\text{cm}^2$. This can be circumvented by depositing the Boron on a thick backing. In addition to the high-energy lines of 22.5 and 18.1 MeV the first excited state of ^{12}C (4.44 MeV) is also produced copiously in this reaction. The 22.5 MeV gamma ray spectrum measured using a large volume cylindrical Lanthanum Bromide detector is shown in Fig. 6. The first escape peak is much more dominant than the photo-peak owing to the relatively smaller volume of the crystal for the rather high energy gamma rays of 22.5 MeV. Fig.7. shows the same gamma ray spectrum from this reaction recorded in a much larger volume (10" diameter and 12" length) cylindrical NaI(Tl) detector [28]. Two more high energy gamma rays can be produced from this reaction at much lower beam energy of $E_p = 163 \text{ keV}$ [29].

Having discussed some of the important capture reactions for efficiency calibration at high energies we mention below an inelastic scattering reaction heavily used for detector calibration at high energies not accessible by radioactive sources.

4.4. $^{12}\text{C}(\text{p},\text{p}')\gamma$ and $^2\text{H}(^{11}\text{B},\text{n})\gamma$ reactions

The inelastic scattering of 22 MeV proton off ^{12}C produces 15.1 MeV gamma-rays from the decay of the 1^+ state ($T=1$) in ^{12}C and is, therefore, another very useful reaction for calibration of the PARIS array. A reasonably thick Mylar target, say 5 to $6 \mu\text{g}/\text{cm}^2$ is to be bombarded with the proton beam for this reaction. The first excited state of ^{12}C populated in this reaction adds the 4.43 MeV line in the spectrum. The presence of Oxygen in the mylar also helps in providing a richer spectrum (6.13 MeV) than that of a pure Carbon target. Fig. 8) shows the spectrum recorded in a very large volume cylindrical NaI(Tl) detector [28].

The 15.1 MeV line can also be populated by the fusion reaction of 19.1 MeV ^{11}B beam on deuteron target and evaporation of a neutron [$d(^{11}\text{B},n\gamma)^{12}\text{C}$] [30,31,36]. This reaction is particularly useful as ^{11}B beam can be delivered in accelerator facilities like, GANIL, LNL Legnaro, ALTO Orsay, HIL Warsaw, where PARIS is planned to be used. For this reaction the target is generally a $\text{C}_{32}\text{D}_{66}$ foil ($0.5 \text{ mg}/\text{cm}^2$) on thick tantalum backing. In facilities like LNL Legnaro where the energy of the ^{11}B beam is higher than 19 MeV a gold foil of appropriate thickness can degrade the beam energy to the required value. Figures 9 and 10 show two typical high-energy gamma rays spectra produced from

this reaction and measured in a Lanthanum Bromide detector and in a large volume BaF₂ detector respectively.

We tabulate below the reactions discussed so far with the important parameters.

Table III

<i>Reaction</i>	<i>E_{beam} (keV)</i>	<i>E_{gamma} (MeV)</i>	<i>Target</i>
$^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$	340 – 4000	6129, 6917, 7116	thick, thin
$^{27}\text{Al}(p, \gamma)^{28}\text{Si}$	767, 992, 1317, 2046	6570, 7700, 10760	thin (10-40 $\mu\text{g}/\text{cm}^2$)
$^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$	1020, 1318, 1417	1.37, 2.75, 4.24, 8.43, 8.92, 11.58	thin, 5-30 $\mu\text{g}/\text{cm}^2$
$^{39}\text{K}(p, \gamma)^{40}\text{Ca}$	1347	3.904, 5.736	thin, 10-20 $\mu\text{g}/\text{cm}^2$
$^7\text{Li}(p, \gamma)^8\text{Be}$	441, 1030	17.64, 18.15, 19.1, 22.6	thin
$^{11}\text{B}(p, \gamma)^{12}\text{C}$	163, 7200	11.67, 16.11, 18.1, 22.5	thick, $\sim 1\text{mg}/\text{cm}^2$
$^{12}\text{C}(p, p')\gamma$	22000	15.1	thick foil
$^2\text{H}(^{11}\text{B}, n)\gamma$	19100	15.1	$\text{C}_{32}\text{D}_{66}$ thin foil on Ta backing

While it may not be practically feasible to carry out all these reactions in any particular accelerator laboratory, it is expected that the collaboration will eventually identify suitable places where such reactions can be carried out. In the following section (Appendix A) we list some of the suitable accelerator facilities for testing of PARIS. It is also to be noted that the discussions so far have centred around light ion capture and inelastic scattering reactions. However, the testing of PARIS can also be carried out at high-energy photon facilities. One such facility is discussed in brief in Appendix A.

Appendix A:

Facilities for in-beam experiments

(The laboratories listed below are not in order of preference)

I. Ion beam facilities:

IPNO, Orsay:

Can provide high intensity proton beam up to 25MeV.

Heavy ions (e.g. C, Mg, Ni) with suitable energies for the commissioning of the demonstrator can also be provided (see http://ipnweb.in2p3.fr/tandem-alto/usersguide/ions_E.html)

ATOMKI, Debrecen:

Can deliver high intensity proton beams of several micro amp from ~150keV up to 5 MeV.

Can also provide targets which are not readily available at other places

see also http://www.atomki.hu/atomki/Accelerators/VDG/vdg5_en.html and <http://www.atomki.hu/atomki/Accelerators/Cyclotron/beams-en.html>

IFJ PAN, Krakow:

Can deliver protons beams from ~500keV up to ~2.5MeV.

(see: http://www.ifj.edu.pl/dev/akcel_mik.php?lang=en)

GANIL, Caen:

Can deliver heavy ion beams from C up to U (including Mg, O, Sn, etc) at suitable energies and intensities.

see also <http://pro.ganil-spiral2.eu/users-guide/accelerators/available-stable-ion-beams-at-ganil/view>

HIL, Warsaw University, Warsaw:

Can deliver heavy ion beams between B up to Ar (including C, Ne, etc) at suitable energies and intensities.

see also <http://www.slcyj.uw.edu.pl/en/48.html>

India: Two heavy ion laboratories in Mumbai(TIFR-BARC) and Delhi (IUAC) can provide protons beam of 7 MeV and 22 MeV for reaction 3 and 4 (see list above). In addition a newly installed low energy facility in the Delhi lab can also provide low energy (< 2 MeV) proton beams.

II. High energy gamma ray facilities:

FZ Rossendorf, Germany

The bremsstrahlung facility at the superconducting electron accelerator ELBE [32] of HZDR delivers γ rays with end energies of up to about 18 MeV. The integral flux is about 10^9 /s on a target of about 3 cm^2 . The experimental area is designed in particular for experiments with high electron energies such that the production of neutrons and the scattering of γ rays from surrounding materials are strongly reduced. The sensitive detector setup is well shielded against background radiation. ELBE is a user facility open to external experimenters. Submission of proposals is possible each semester. A typical spectrum measured at ELBE facility using (γ, γ') reaction [33] is shown in Fig.11.

HI γ S Facility at Duke Free Energy Laser Laboratory

The HI γ S facility at Duke University, North Carolina, provides high intensity and high energy photon beam up to 60 MeV [34]. The facility is being upgraded to increase the beam energy up to 100 MeV in near future. The maximum intensity of the beam can reach up to 10^9 photons/s at 10 MeV.

Appendix B: Scanning of the detectors

Scanning of the detector is important for determining the uniformity of the detector volume and also to arrive at the best suited reconstruction algorithm. The sources to be used for lapping the surface of the crystal are necessarily to be collimated. The primary reasons for scanning are two-fold;

1) Determine the uniformity of the crystal for checking the pulse height and resolution as function of the point of interaction.

Remark: In Orsay, during the testing of small phoswiches, it was noted that CsI has more inhomogeneities than NaI (this was one of the reasons for the selection of NaI(Tl) over CsI(Na) for the PARIS phoswich).

2) Determine the detector response in order to digitize the signal.

The point is to determine the profile/shape of the signal depending upon the depth. In case of such dependence, one has to investigate its impact on further analysis, namely pulse shape analysis (PSA). As for the PSA, one usually defines gates (e.g. time short vs. time long) with specific parameters. These parameters might change as a function of detector depth and also from one detector to another. In case of digital electronics, the parameters of the Jordanov method might change.

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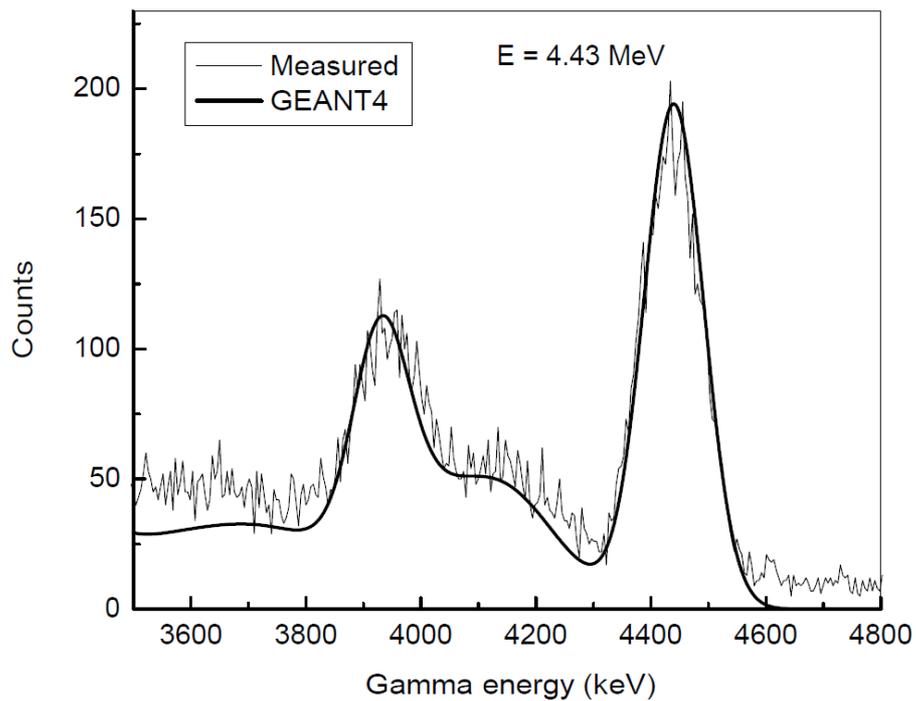


Fig. 1) Spectrum showing the photopeak and the first escape peak for 4.44 MeV gamma rays from Am-Be source measured using a large volume cylindrical (3.5 » X 6) LaBr₃:Ce detector. The solid line is the GEANT4 simulation. (*Private Communication, I. Mazumdar*)

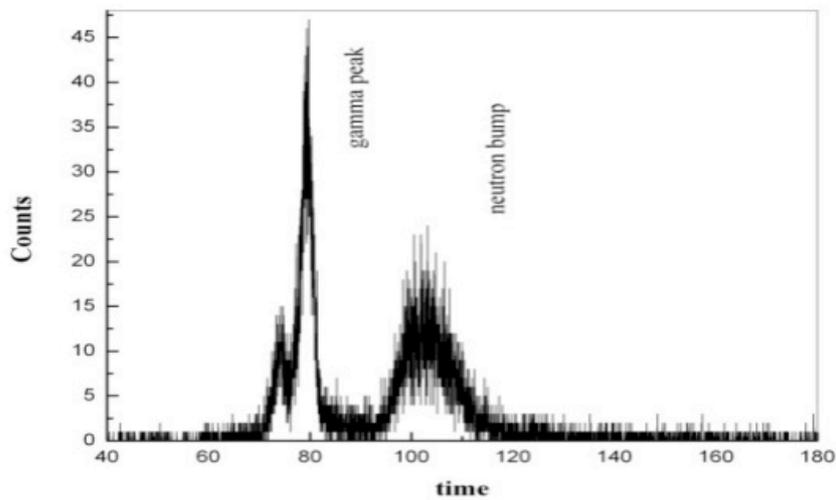


Fig. 2) A typical n- γ time spectrum measured with a neutron source and a large volume LaBr₃:Ce detector (*Priv. Comm, I. Mazumdar*).

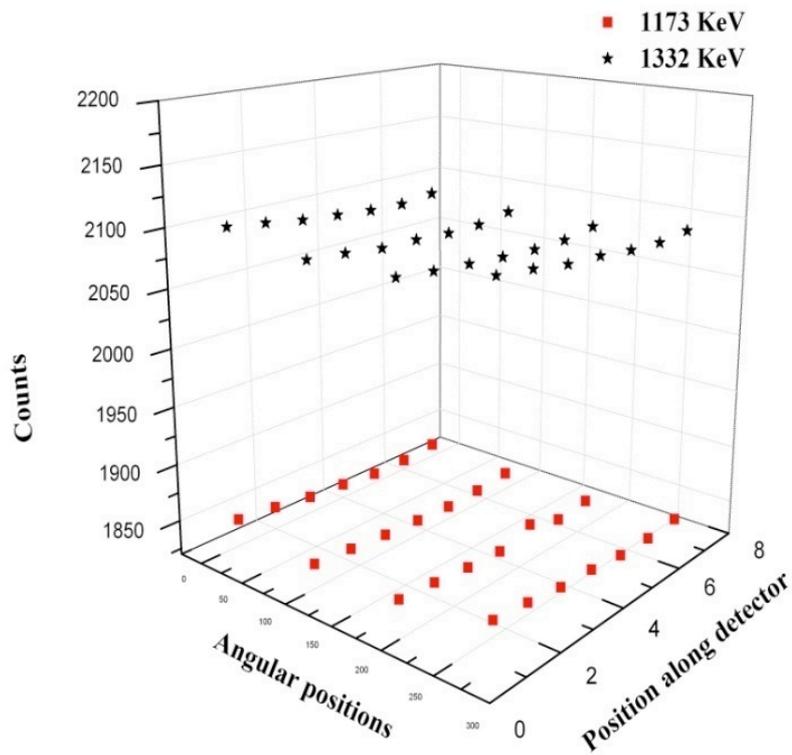


Fig.3) Checking uniformity of a large volume LaBr₃:Ce with collimated Cs and Co sources. (Priv. Comm. I.Mazumdar).

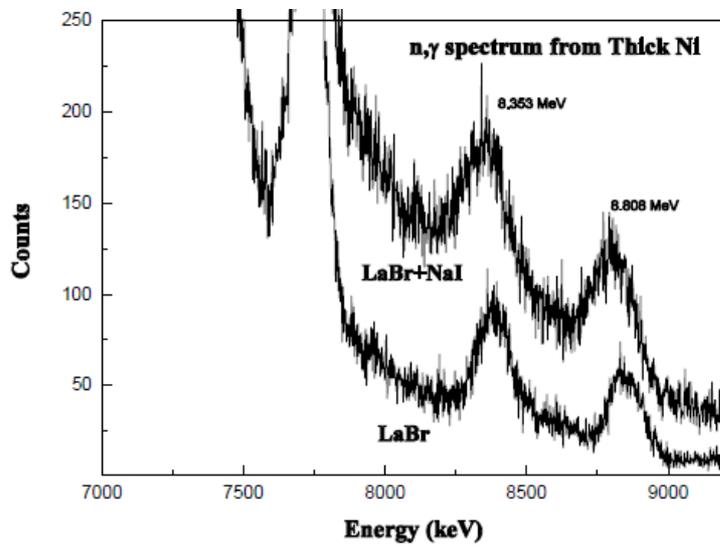


Fig.4) High energy gamma rays produced in (n,γ) reaction on Ni. and measured in a large volume LaBr detector (Priv. Comm. I. Mazumdar).

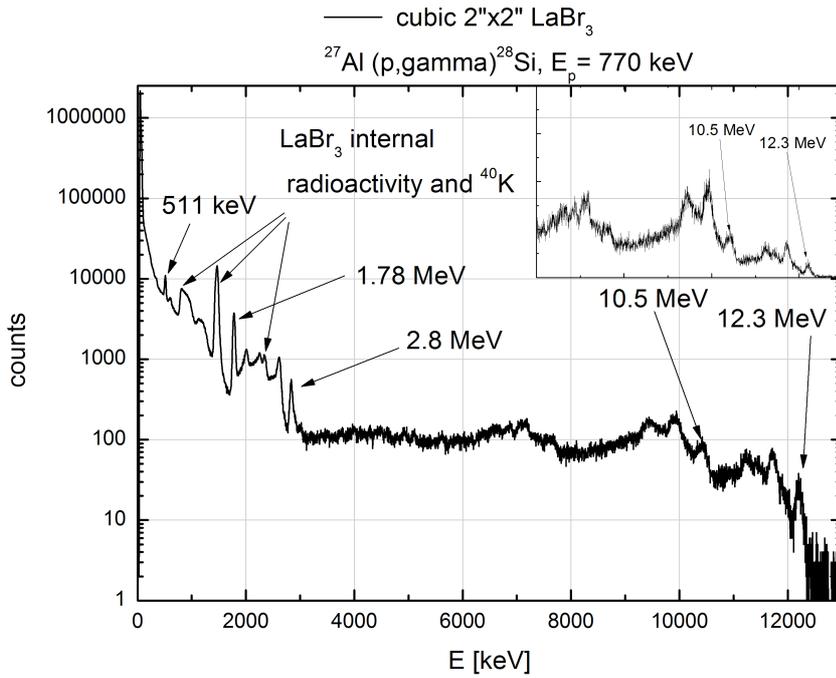


Fig.5) Spectrum recorded in a 2"x2"x2" cubic LaBr₃:Ce crystal in (p,Al) γ resonance reaction at $E_p = 770$ keV. The beam energy resolution of ± 10 keV led to the population of resonances at $E_p = 760, 767, \text{ and } 773$ keV. (Courtesy: M, Ciemala)

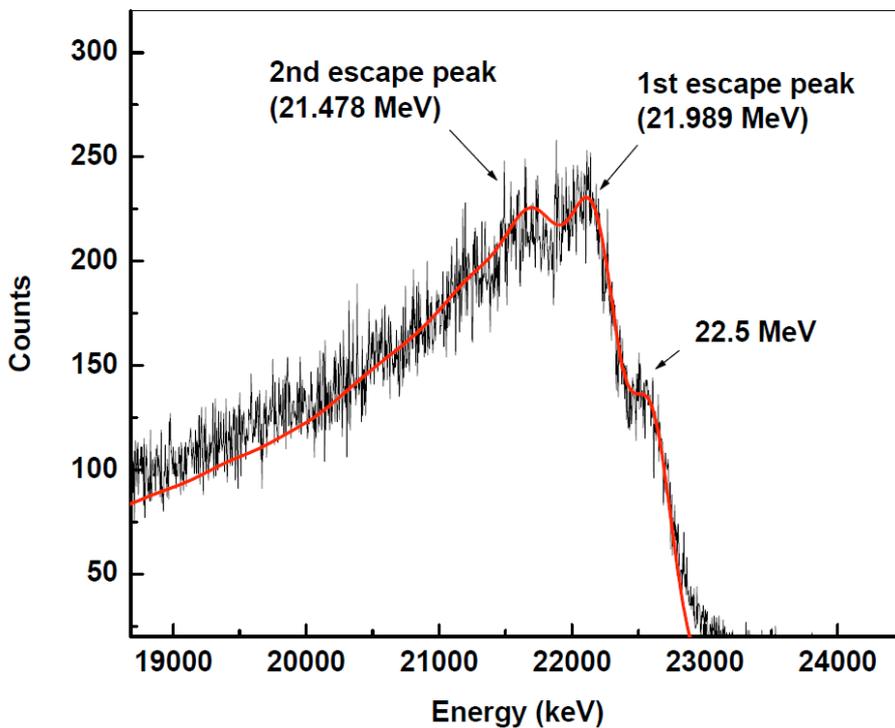


Fig. 6) The 22.5 MeV gamma ray spectrum from p+11B reaction and measured in a large volume (3.5' x 6') LaBr₃:Ce detector. (Private comm. I. Mazumdar)

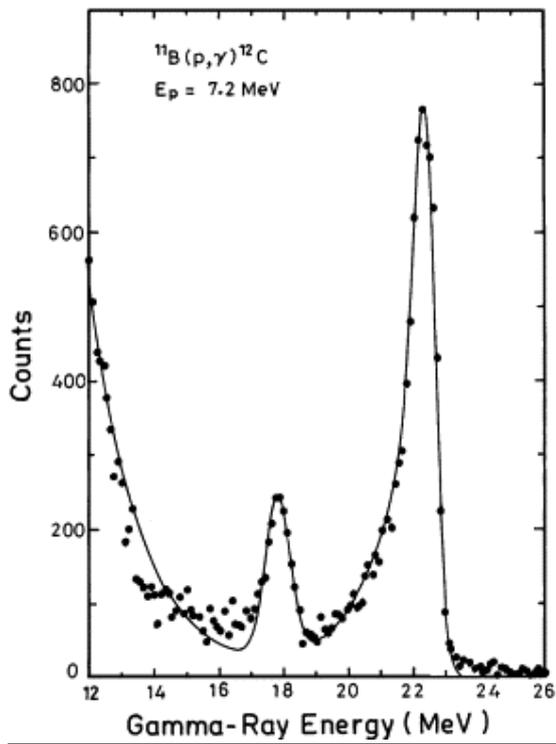


Fig. 7) Spectrum for 22.5 MeV gamma rays in a large volume NaI(Tl) detector. The solid line is a simulated reproduction of the line shape.

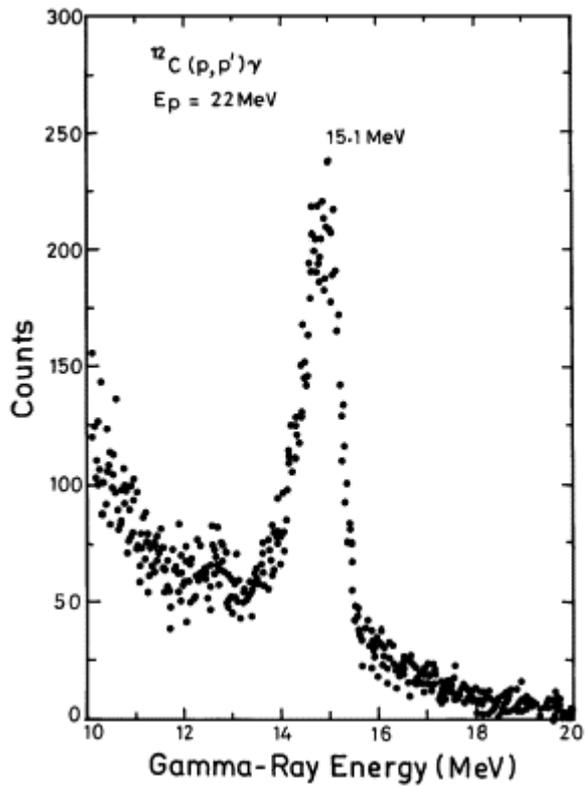


Fig.8) Spectrum for 15.1 MeV gamma rays in a large volume NaI(Tl) detector.

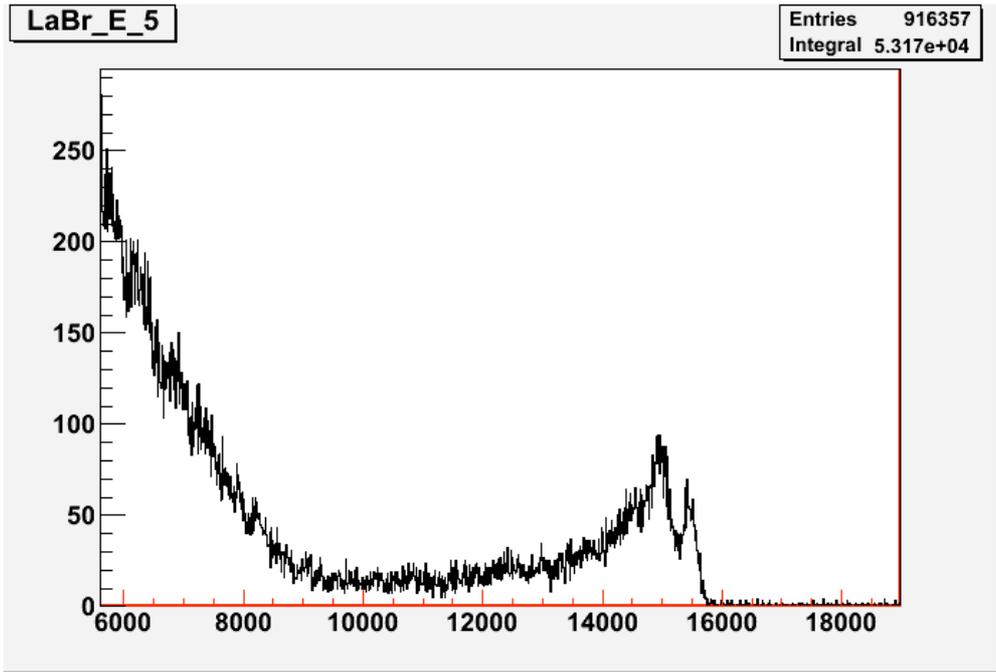


Fig.9) High energy gamma ray spectrum recorded in a large volume LaBr₃:Ce detector from ²H(¹¹B,n) γ reaction. (Courtesy: F. Camera).

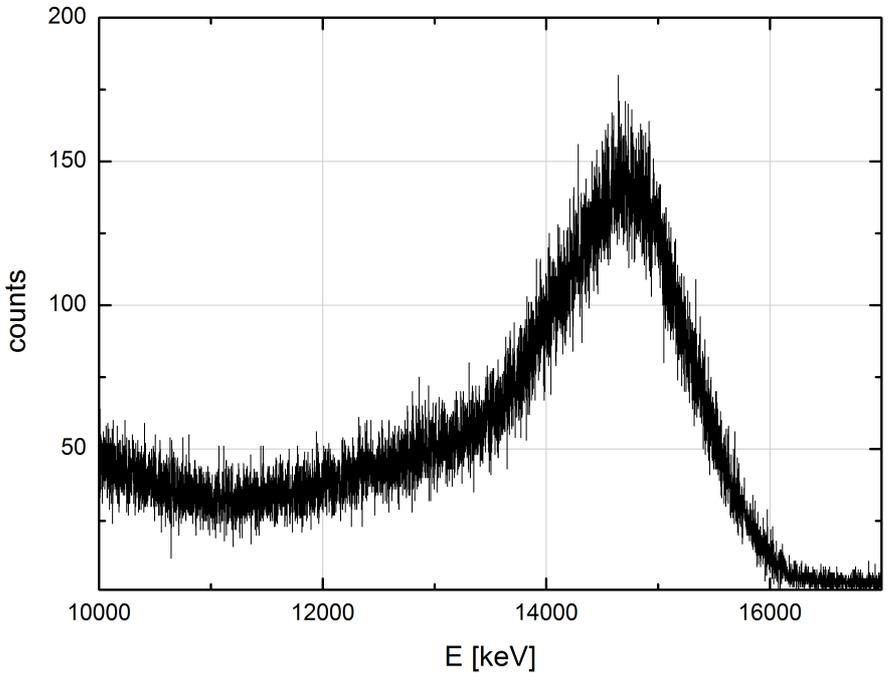


Fig. 10) High energy gamma ray spectrum from the ²H(¹¹B, n) γ reaction measured with the HECTOR array.. The much superior energy resolution of the LaBr₃:Ce detector leads to the clear separation of the photo-peak and the first escape peak in the LaBr₃:Ce spectrum (Fig. 9). (Courtesy: F. Camera)

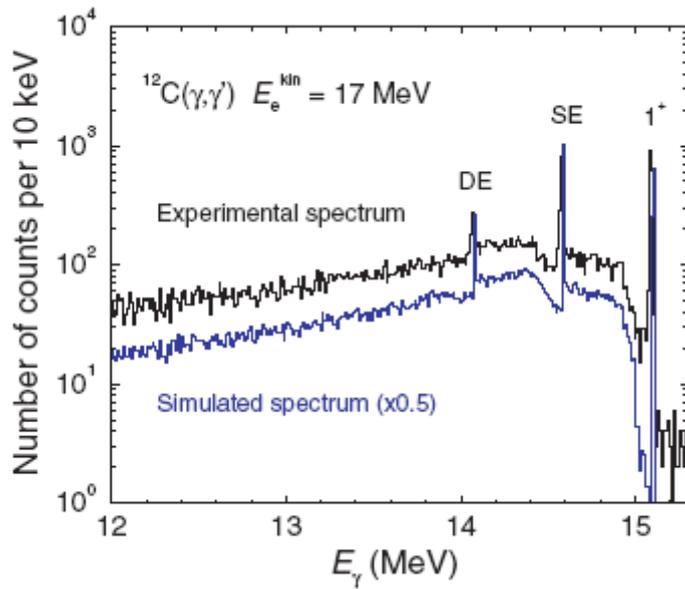


Fig.11) Gamma rays spectrum measured using (γ,γ') reaction at the ELBE facility.

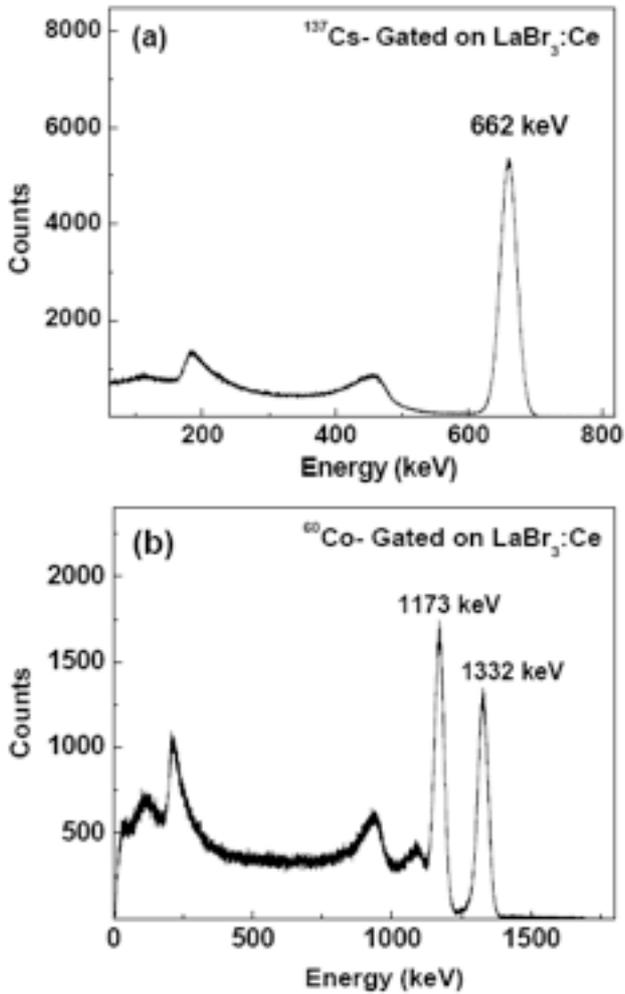


Fig.12) Spectra recorded with ^{137}Cs and ^{60}Co in a phoswich of $\text{LaBr}_3:\text{Ce}$ and $\text{NaI}(\text{Tl})$. Pulse shape discrimination allows complete segregation of energy depositions in the two sections (Ref. 13).

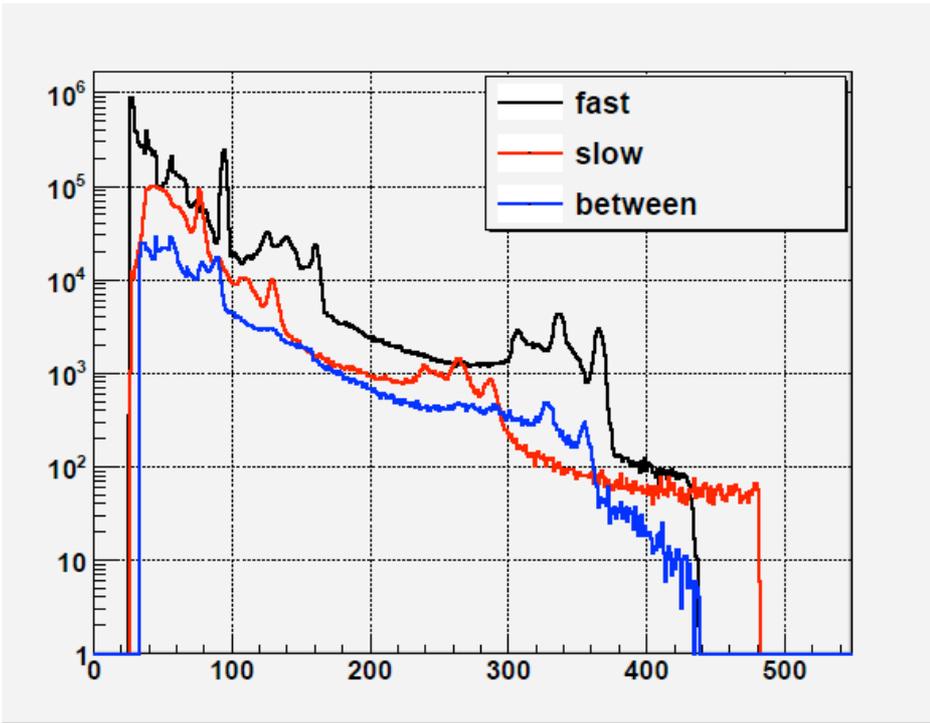
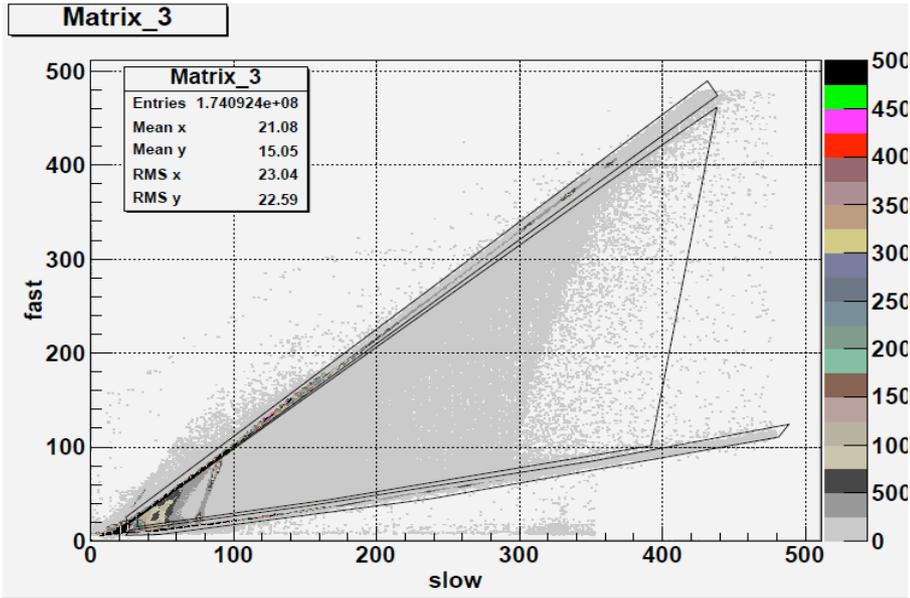


Fig. 13) Top: 2d-spectrum from the phoswich irradiated by the ^{244}Cm - ^{13}C source (6.13 MeV) measured in Krakow using the "Milano BaF board". Bottom: Projection on the 2d-spectrum. Black corresponds to cases where all energy was deposited in LaBr_3 , blue – only in NaI , red – where the deposition was both in LaBr_3 and NaI . (Courtesy of M. Zieblinski, M. Jastrzab and S. Brambilla.)

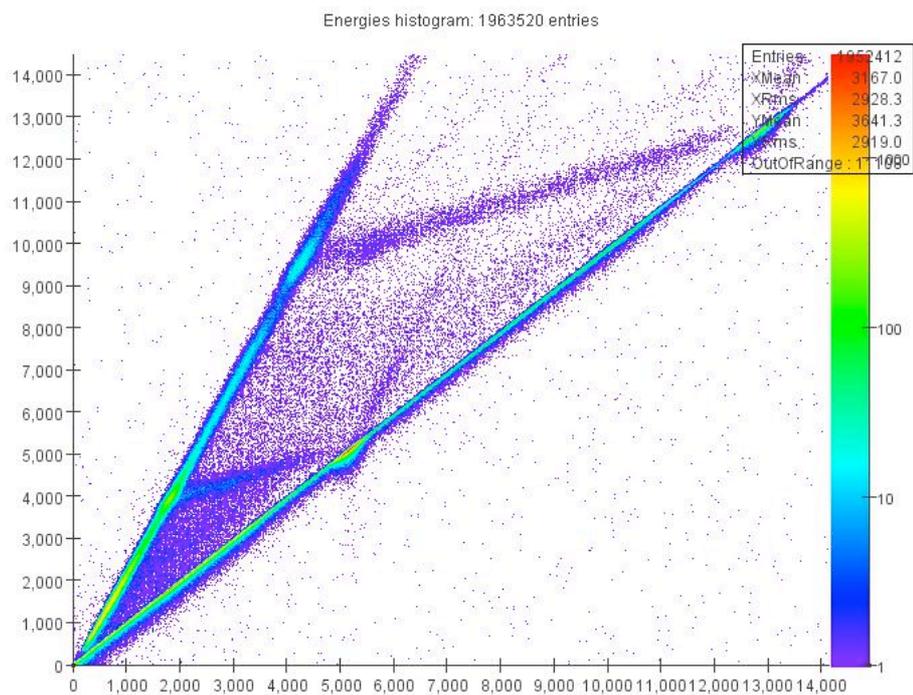


Fig. 14) 2d-spectrum (similar to that of Fig.13) from the phoswich irradiated by the ^{137}Cs source (662 keV) measured in Strasbourg using TNT digitizer. (Courtesy of M. Rousseau, Ch. Finck and O. Dorvaux.)