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Characterization of Fast Scintillator Detectors using Digital Data Acquisition System

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Abstract: ***Scintillator detectors coupled with fast photo-multiplier tubes (PMT) are used extensively in experimental γ-ray spectroscopy. Although the energy resolutions of these detectors are very poor than the standard Ge detectors, much better timing resolution has made these the detectors of choice while dealing with timing measurements. Fast scintillator detectors are used extensively to measure a wide range of lifetime of nuclear excited states using centroid difference method. Furthermore, these can be used as multiplicity filters and also as Compton suppression shields to Ge detectors. In the present work, several fast scintillator detectors, such as, $LaBr_3$(Ce), BaF_2 , BGO have been characterized by using different radioactive sources (^{152}Eu, ^{60}Co, ^{22}Na). A state-of-the-art digital signal processing based data acquisition system has been used to record the energy and timing spectra. The energy and timing resolutions of the detectors were studied in detail. The detection efficiency of $LaBr_3$(Ce) has been compared with that of the clover Ge detector.***

Keywords: Scintillator detectors, γ-ray spectroscopy, radioactive sources, data acquisition system

1. Introduction

1.1 $LaBr_3$(Ce) scintillator detectors

Recent advances in scintillator material have resulted in the development of Cerium activated Lanthanum Bromide ($LaBr_3$) detectors. $LaBr_3$ was discovered in 2001. These detectors offer improved energy resolution, fast emission and excellent temperature and linearity characteristics. Typical energy resolution at 662 keV is around 3% as compared to sodium iodide detectors (~ 7%). The improved resolution is due to a photoelectron yield that is ~160% greater than is achieved with sodium iodide. Another advantage of $LaBr_3$ is the nearly flat photo emission over a temperature range up to 70^{o}C (~1% change in light output).

Nowadays $LaBr_3$ detectors are offered with bialkali Photo Multiplier Tubes (PMT) that can be two inches in diameter and ten or more inches long. However, miniature packaging can be obtained by the use of a silicon drift detector (SDD) or a silicon photomultiplier (SiPM). These UV enhanced diodes provide excellent wavelength which matches to the 380 nano-meter (nm) emission of $LaBr_3$.

Figure 1.1: $LaBr_3$ (Ce) Scintillator.

1.2 BaF_2 detectors

Barium fluoride has the distinction of being the first inorganic crystal discovered to have a very fast component in its scintillation decay. It is the only presently known scintillator with high atomic number components that has a decay time of less than 1 ns. This combination of properties therefore makes the material attractive for scintillation detectors in which both high detection efficiency per unit volume and a fast response are required.

Inactivated BaF_2 is known as a scintillation material since the early 1970s. However, it was not until 1983 that it was shown that the scintillation light actually consists of two components: a fast component with decay time of 0.6 ns emitted in the short wavelength region of the spectrum, and a slower component with 630 ns decay time at somewhat longer wavelengths. The fast component went unobserved for many years because most photo multiplier tubes were not sensitive to this short wavelength region of the spectrum. However, if quartz end-window tubes or other light sensors are used that are sensitive in the ultraviolet, about 20% of the total scintillation yield at room temperature is measured in the fast component. It results from the creation of a hole in the outer core band of the ionic crystal, followed by the filling of this hole by an electron from the valence band. This process is characterized by very short transition times and the resulting emission is usually in the ultraviolet region of the spectrum. If the principal band gap of the crystal is larger than the energy of the UV photon, then the scintillation light can escape re-absorption and be collected by the photo multiplier tube.

1.3 BGO detectors

An alternative scintillation material, $Bi_4Ge_3O_{I2}$ (commonly abbreviated as BGO) is commercially available as crystals of reasonable sizes. A major advantage over many other scintillators is its high density (~7.13 g/cm3) and the large atomic number (83) of the bismuth component. These properties result in the largest probability per unit volume of any commonly available scintillation material for the photoelectric absorption of gamma rays. Its mechanical and chemical properties make it easy to handle and use, and detectors using BGO can be made more rugged than those employing the more fragile and hygroscopic sodium iodide (NaI). Unfortunately, the light yield from BGO is relatively low, being variously reported at 10−20% of that of NaI(T1). Furthermore, its relatively high refractive index (2.15)

makes efficient collection of the light more difficult than for scintillators with lower index values. It is therefore of primary interest when the need for high γ-ray counting efficiency outweighs considerations of energy resolution.

BGO is an example of a "pure" inorganic scintillator that does not require the presence of a trace activator element to promote the scintillation process. Instead, the luminescence is associated with an optical transition of the Bi^{3+} ion that is a major constituent of the crystal. There is a relatively large shift between the optical absorption and emission spectra of the Bi^{3+} states. Therefore, relatively little self-absorption of the scintillation light occurs, and the crystal remains transparent to its own emission over dimensions of many centimeters. The scintillation efficiency depends strongly on the purity of the crystal, and some of the variability in the light yield reported from BGO in the past can be attributed to using crystals with different residual levels of impurity. The crystals are mixture of bismuth oxide and germanium oxide at a rate of a few millimeters per hour. The boule can then be cut and polished using conventional methods. BGO remains two to three times more costly than NaI(Tl) and is currently available only in limited sizes.

1.4 Energy resolution

In many applications of radiation detectors, the aim is to measure the energydistribution of the incident radiation. A formal definition of detector energy resolution is shown in Fig.1.4.1. The diff- erential pulse height distribution for a hypothetical detector is shown under the same assumption that only radiation for a single energy is being recorded. The detail information given in Ref [1].

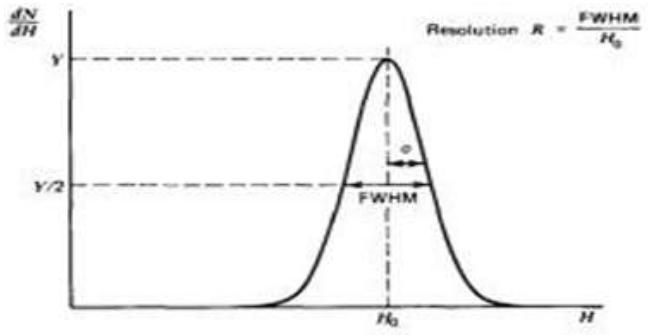

Figure 1.4.1: Definition of detector resolution. For peaks whose shape is Gaussian with standard deviation σ, the FWHM is given by 2.35σ .This figure has been taken from Ref [1].

1.5 Detection of efficiency

The absolute photo-peak efficiency of a detector is defined as the ratio of counts in the photo-peak to the number of photons emitted by the source in that counting time. For a radioactive source emitting many photons of different energy, the photo-peak efficiency η is defined as:

$$\eta E_\gamma = C.I_\gamma / N.t$$

where, C is the number of counts in the photo peak, N is the number of disintegrations per second, t is the counting time (in sec.) and I_γ is the number of photons of energy E_γ emitted per decay. The theoretical calculation of η is difficult except for detectors of ideal geometry Ref [1].

1.6 Prompt coincidence spectra and measurement of time resolution

In nuclear physics experiments, the measurements of prompt coincidences between two or more gamma rays are important. The numbers of coincidence events are also required for some specific measurements. In order to carry out such measurements, generation of time spectra is of paramount importance. In conventional electronics, the time-to-amplitude converter (TAC) device is used frequently to generate the time spectra, and, in turn, check for coincidence events Ref [1].

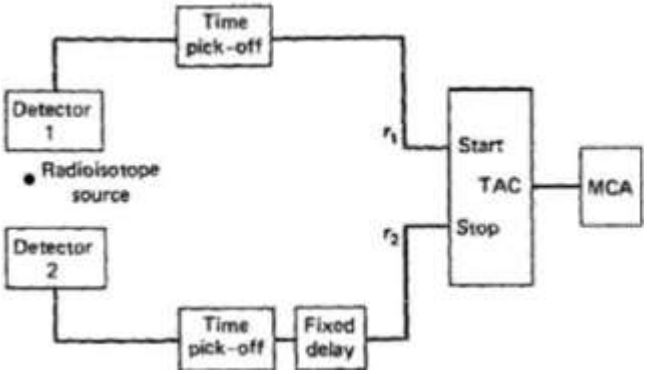

Figure 1.6.1: A simplified conventional electronic set up using TAC device to record multichannel time spectra from a radioisotope source emitting coincident radiation. This figure has been taken from Ref. [1].

A simplified system to record multichannel time spectra from a radioisotope source emitting coincident radiation is shown in Fig. 1.6.2. Two independent detectors are irradiated by a common radioisotope source that is assumed to emit two detectable quanta in true coincidence; that is, both radiations arise from the same nuclear event within the source. It is further assumed that for all true coincidences, the nuclear decay scheme is such that there is no appreciable time delay between the emissions of both radiations.

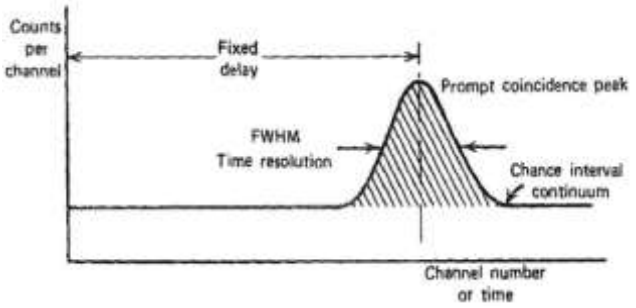

Figure 1.6.2: The multichannel time spectrum for a radioisotope source emitting some radiation in prompt coincidence. This figure has been taken from Ref. [1].

In this work, time spectra were generated directly from the time-stamped data collected using digitizers [2]. Raw pre-amplifier signals were fed to the digitizer channels, with some amount of delay in the “stop” channel. Data were recorded in user-defined window and bin-size. The time difference between the “start” and “stop” channels were calculated by subtracting the associated time-stamp in the energy signal of “start” channel from that of the energy signal of “stop” channel.

2. Experimental Setup and Data Analysis

2.1 Digital data acquisition system

A digital signal processing based data acquisition system has been developed in NPD, BARC, in collaboration with CAEN S.p.A., Italy [2]. The data acquisition system has initially been designed for an array of eight Compton-suppressed clover Ge detectors and sixteen $LaBr_3$(Ce) fast scintillator detectors. Signals from the clover Ge detectors are digitized by 14-bit 100 MHz digitizers, whereas, 500 MHz digitizers of similar resolution process the signals from fast scintillator detectors. The salient features of the aforesaid system are listed below:

- Linux based, trigger-less data acquisition.
- Up to 80 MB/sec. data transfer rate per each optical link (> 1.3 mcps/ch.).
- Digitizers of different frequencies (low and high) are operated in the same crate.
- BGO-ACS veto generation by 250 MHz 12-bit digitizer for Compton suppressed data collection.
- Online TAC (time-of-flight) spectrum generation and writing into disk.
- Fine time-stamp of the order of 2 ps is achieved using digital CFD in DPP-PSD firmware.
- Online calibration, add-back, coincidence conditions for online spectrum display.
- Raw data file chopping (w.r.t. time/size), data merging in the main Graphical User Interface (GUI).
- Event building with preferred coincidence condition.

The details of this digital data acquisition system can be found in Ref. [2]. Further details on this acquisition system will be presented in a forthcoming paper [3].

2.2 Experimental details and data analysis

The work was performed using the experimental set-up as shown in Fig. 2.2.1. The detector assembly consisted of four clover Ge detectors with BGO anti-Compton shields and three $LaBr_3$(Ce) detectors. However, in order to fulfil the purpose of the project, only $LaBr_3$(Ce) and BaF_2 fast scintillator detectors were used for energy and timing measurements. Data were collected in triggerless mode using ^{152}Eu, ^{60}Co and ^{22}Na radioactive sources. The Anode signals from the scintillator detectors were fed to the 14-bit 500 MHz digitizers. Using high voltage power supply modules in a NIM bin, -1200 V biasing voltage was applied to the $LaBr_3$ detectors, whereas, -1750 V biasing voltage was applied was applied to the BaF_2 fast scintillator detectors for their optimum performance.

Figure 2.2.1: Clover + $LaBr_3$ experimental set up at CIRUS laboratory, BARC.

2.3 Energy measurements

After proper tuning of the raw signals from the detectors using multiple parameters in the Graphical User Interface (GUI) of the digital DAQ system, data were collected using the above-mentioned radioactive sources for 30 minutes duration (for each source). The energy spectra from $LaBr_3$ detectors are shown in Figs. 2.3.1, 2.3.2, 2.3.3. In the ^{60}Co spectrum, the single escape, double escape and backscatter peaks are very much evident (Fig. 2.3.2). Due to its much better resolution (~3% at 662 keV, as quoted by the supplier), the strong γ peaks from ^{152}Eu source appear well separated from each other. The energy spectrum from ^{22}Na source is also shown in Fig. 2.3.3.

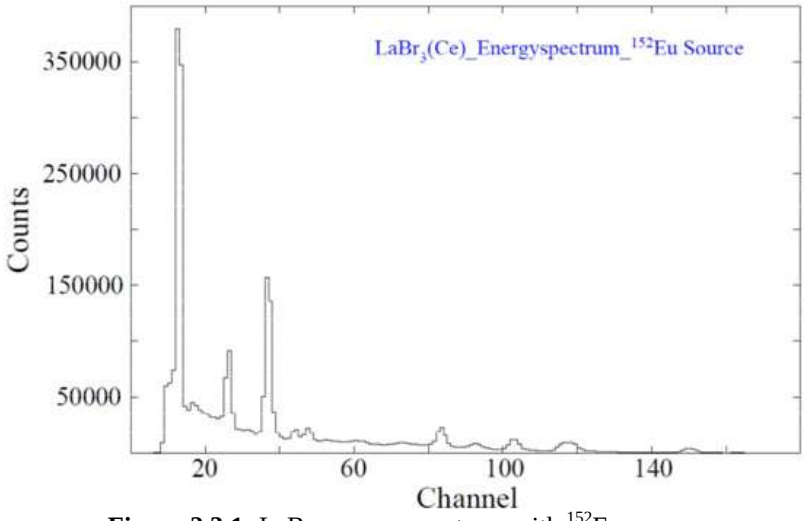

Figure 2.3.1: $LaBr_3$ energy spectrum with ^{152}Eu source.

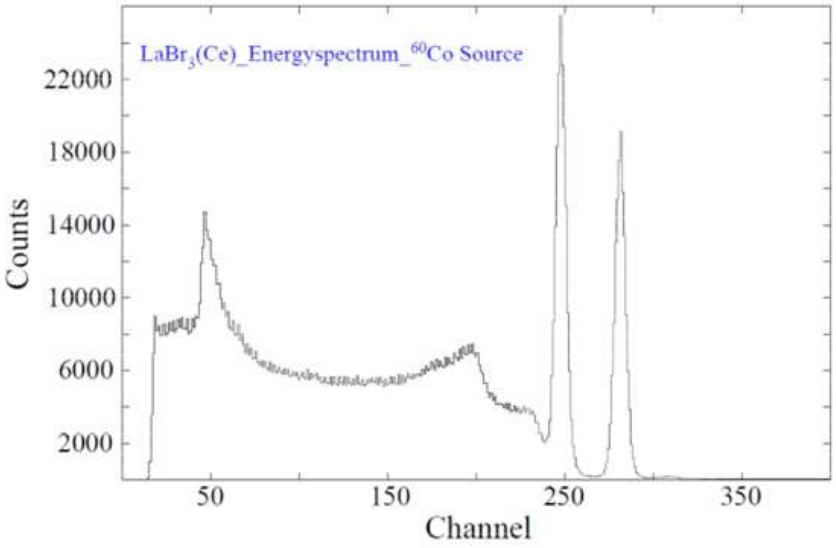

Figure 2.3.2: $LaBr_3$ energy spectrum with ^{60}Co source.

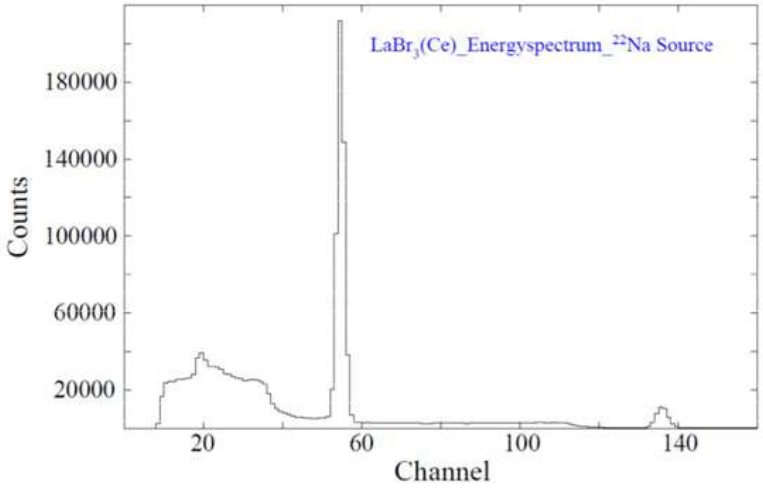

Figure 2.3.3: $LaBr_3$ energy spectrum with ^{22}Na source

The ^{60}Co spectrum was roughly calibrated (linear) on-line in the GUI while acquiring the data. However, precise calibration (quadratic) was done offline using the data points from both ^{152}Eu and ^{60}Co sources (121.783, 244.692, 344.276, 411.115, 443.976, 778.903, 867.388, 964.131, 1173.238, 1332.513 and 1408.011 keV). The standard codes in the RADWARE software package (i.e., Source and encal) [4,5] were used for this purpose. The variation of energy resolution of $LaBr_3(Ce)$ detector with energy has been depicted in Fig. 2.3.4 and Fig. 2.3.5. The variation of detection efficiency of these detectors was also deduced and plotted (Fig. 2.3.6).

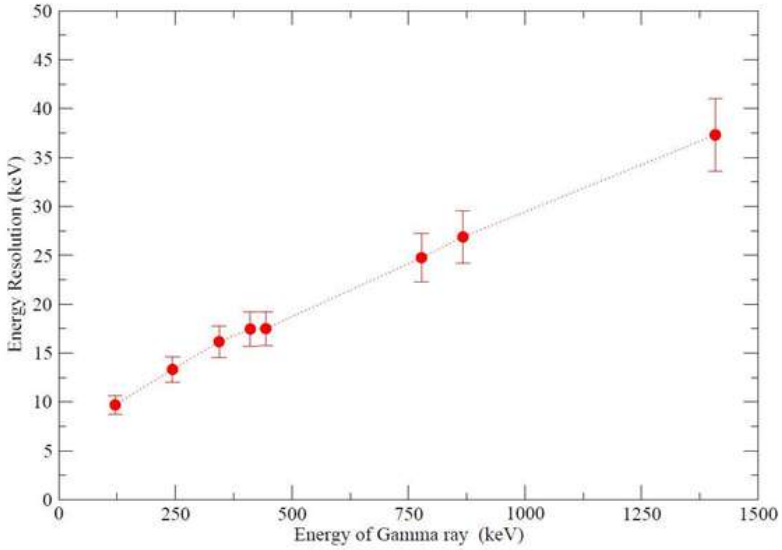

Figure 2.3.4: Variation of energy resolution (in keV) with energy.

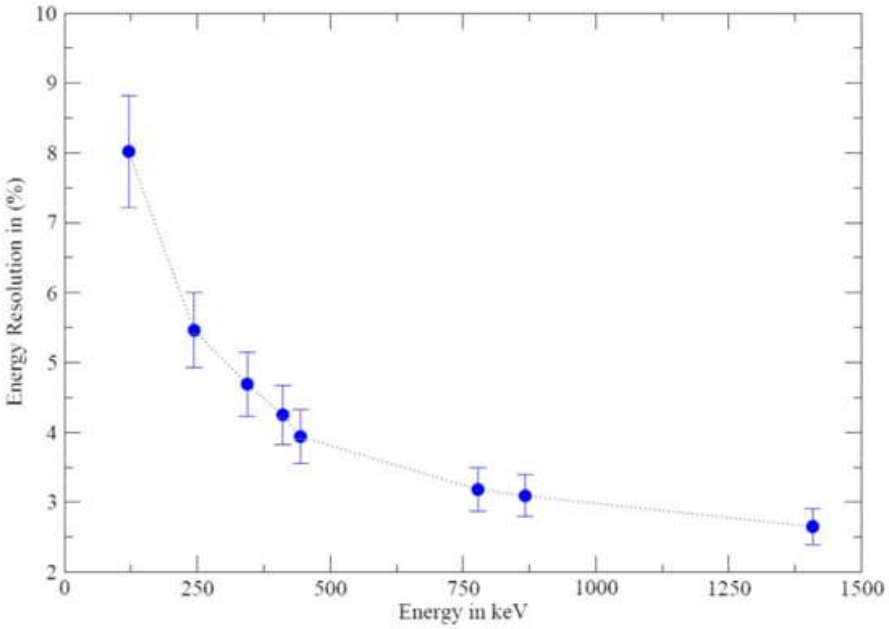

Figure 2.3.5: Variation of energy resolution (in %) with energy.

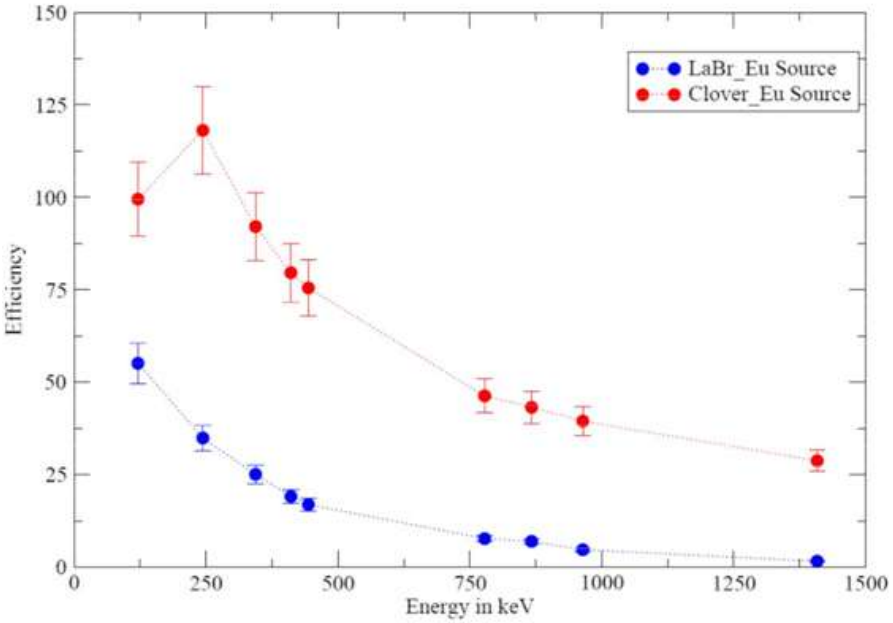

Figure 2.3.6: Comparison of detection efficiency for clover Ge detector and $LaBr_3$ fast scintillator using ^{152}Eu Source.

The energy resolution of BaF_2 detectors is very poor, and therefore, neither the ^{60}Co γ peaks nor the ^{152}Eu γ peaks were separated in its energy spectrum. As BaF_2 has a faster timing response with respect to $LaBr_3$ detectors, more attention was devoted toward studying its timing characteristics.

2.4 Time-of-flight measurements

As expected, the rise-time of the raw signal from the BaF_2 detector was much less than the one from $LaBr_3$ detectors. To measure the timing resolution between two $LaBr_3$-$LaBr_3$ coincidence events, ^{60}Co source was used and the detectors were kept in 180 deg configuration (face-to-face). One $LaBr_3$ signal was used as "start" and the other one, after applying ~30ns delay, was used as the "stop" signal. The parameters in the configuration GUI of the digital DAQ system were tuned to optimize the signal. While acquiring data online, the time-of-flight spectrum was generated in a window of 50 nano-second with a bin size of 50 pico-second. A timing resolution of around 450 pico-second was achieved between two $LaBr_3$ detectors from the data of 30 minutes duration.

In the next measurement, one of the $LaBr_3$ detectors was replaced by a BaF_2 detector.The signal from the BaF_2 detector was used as the "start" signal, and the one from the $LaBr_3$ detector, after some 15 nano-second delay was used as the "stop" signal. The time-of-flight spectrum was again generated in a window of 50 nano-second with a bin size of 50 pico-second. The best timing resolution thus achieved from a run of same pre-set time (30 minutes) was ~297 pico-second. This attests the faster timing response of the BaF_2 detector. The time-of-flight spectra as obtained for $LaBr_3$-$LaBr_3$ as well as BaF_2-$LaBr_3$ configurations are plotted in the same panel in Fig.2.4.1 for comparison.

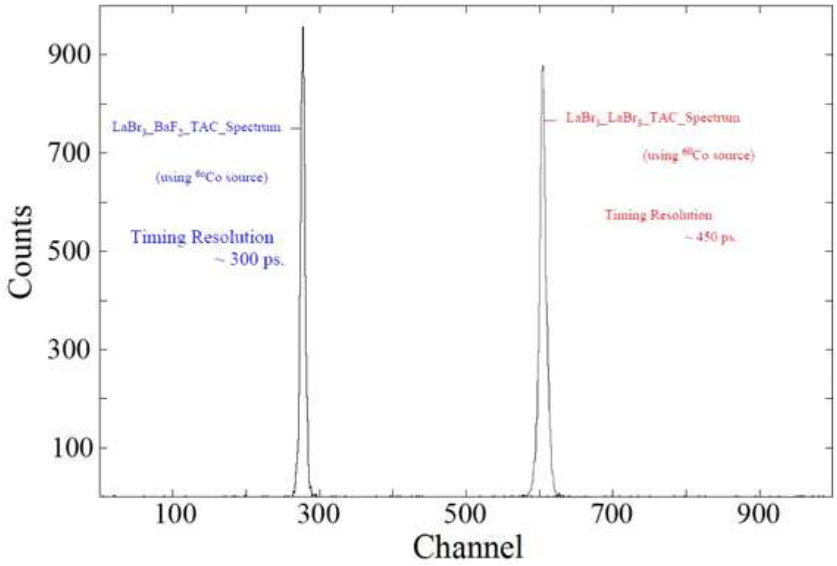

Figure 2.4.1: Time-of-flight spectra as obtained for BaF_2–$LaBr_3$ (left) and $LaBr_3$–$LaBr_3$ (right) configurations

3. Conclusion

Different fast scintillator detectors, such as $LaBr_3$(Ce), BaF_2 , BGO have been studied and detailed characterization of those were carried out using ^{152}Eu, ^{60}Co and ^{22}Na radioactive sources. A state-of-the-art digital signal processing based data acquisition system was employed in all the measurements. Variation of energy resolution and detection efficiency were deduced for the $LaBr_3$(Ce) detector and compared with standard clover Ge detectors.

Time spectra for coincidence events were studied in detail using these fast scintillator detectors. For the $LaBr_3$(Ce) − $LaBr_3$(Ce) configuration, ~450 pico-second time resolution was obtained using the ^{60}Co source. It has been observed that better time resolution (~300 ps) can be achieved if one of the $LaBr_3$(Ce) detectors is replaced by BaF_2 detector. The architecture and operation of digital data acquisition system was introduced in detail. Sufficient knowledge has been obtained to operate and evaluate the performance of similar systems in future.

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