Reduction of the effect of internal activity in LaCl₃:Ce scintillator

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ABSTRACT: Despite having excellent energy and time resolutions, the intrinsic α and β contaminations in the lanthanum halide scintillators pose severe limitations in their usage in rare-event detections, especially. In the present work, pulse shape discrimination (PSD) with a pre-defined algorithm of a commercially available fast digitizer has been utilized to separate the effect of α contamination from the spectrum. The efficacy of the method has been measured experimentally and compared with simulation. The contribution of the β activity has been eliminated by generating its shape with the help of a Monte-Carlo based simulation code. Thus the background events generated by intrinsic β and α activities have been reduced appreciably. The present study will encourage the application of these detectors in low cross-section measurement experiments.

KEYWORDS: Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Digital signal processing (DSP); Models and simulations

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1 Introduction

Commercially available La-halide detectors have been remarkably successful in the field of radiation measurement. Cerium-activated La-halide detector offers brilliant light output, excellent energy resolution, a fast response, excellent linearity [1–7] and a stable light output over a wide range of temperatures [8]. For cerium-activated LaCl$_3$ detector, the light output is ~50 photons/keV with energy resolution as low as 3.1% at 662 keV. It has fast response time with principal decay constant ~20 ns, which favours its usage in very high rate counting applications [9]. The non-linearity of the detector is below 7% from 60 to 1300 keV [10, 11]. This combination of features makes La-halide detectors useful for nuclear spectroscopy experiments [12], time of flight measurements [13] and medical imaging purposes [14]. La-halide detectors have been used for the lifetime measurements of unstable nuclei [15, 16], and even for detecting the fusion neutrons [17]. LaBr$_3$ detector was found to be the best for environmental radiation monitoring purposes due to its superior detection efficiency, high count rate handling capability with excellent spectral resolution [18]. Furthermore, due to the high Z of lanthanum (Z = 57) and high density of the crystal (for, LaCl$_3$, $\rho = 3.85$ g/cm$^3$), large volume La-halide detectors can be useful for the detection of high energy $\gamma$-rays (up to 20 MeV). However, the La-halide detector’s self-activity has been observed
to be a major issue that reduces the detector sensitivity. Thus CeBr$_3$ detectors can be considered as a close competitor to La-halides. Therefore further investigation is required to improve the performance of the La-halides. Moreover, for environmental radiation monitoring purposes the hygroscopic nature of the crystals poses another serious issue of shielding them from atmospheric exposure.

Natural lanthanum is composed of stable $^{139}$La with 99.91% abundance. The radioactive $^{138}$La with half-life $1.05 \times 10^{11}$ y contribute to the remaining 0.09% of the abundance [19]. Since the separation between the two isotopes is almost impossible, the contamination due to $^{138}$La is present in all La-halide based scintillators. $^{138}$La isotopes decay by electron capture ($e^{-}$) into $^{138}$Ba with 66.4% probability and the remaining 33.6% decay by $\beta^{-}$ — emission into $^{138}$Ce. In both cases, $^{138}$La decays into an excited state of the corresponding daughter nucleus resulting in the emission of subsequent $\gamma$-rays of equivalent energy. For the electron capture process, 1436 keV $\gamma$-ray along with 32–38 keV characteristic X-rays of Ba is emitted. In the second case, the emission of 789 keV $\gamma$-ray in coincidence with the $\beta$-continuum having endpoint energy of 255 keV is observed.

Moreover, actinium is a chemical analogue to lanthanum, i.e., they have very similar chemical properties. All the actinium isotopes are radioactive. The longest-lived actinium isotope is $^{227}$Ac, having a half-life of 21.772 y. La-halide based scintillators mostly contain actinium impurities, which contribute to the $\alpha$ contaminations due to the decay of long-lived $^{227}$Ac isotopes. The inherent radioactivity results in an intrinsic background of about 1–2 counts/cm$^3$ s [20]. As the $\alpha/\beta$ energy loss ratio is less than 1, which is typical of nearly all scintillators, the $\alpha$ peaks appear at lower energies than their actual energies when the scale is calibrated from $\gamma$-ray (or fast electron) energies [20]. The self-activity background due to $\alpha$ decay from Ac-series nuclei appears at a range of 1.5–3 MeV in the energy spectrum. The contribution of $^{227}$Ac component from impurities has been significantly reduced with the improved techniques of growing the lanthanum halides. This inevitable background can be negligible if the count rate of actual events is sufficiently larger than self-activity background events. However, it is difficult to estimate the real event rate for a low count rate experiment.

In general, for high energy $\gamma$-ray measurements, large volume La-halide detectors can be useful, but the event rate of self-activity increases with crystal volume. It has been demonstrated by Quarati et al. [21] that irrespective of their sizes, detectors show approximately the same activity of $^{138}$La per unit volume. However, the $^{227}$Ac activity, on the other hand, varies with the contamination content of the raw material depending on its geographical origin and the efficiency of the purification processes. Using cerium bromide instead of La-halide, one can obtain higher radio-purity, but CeBr$_3$ has worse energy resolution than other La-halide scintillator [19]. Therefore, initiatives taken on self-activity elimination have significant importance for the La-halide detectors to overcome the limits of their applicability in rare event detection experiments.

Several studies have been done to understand the internal activity of these detectors and find a way to eliminate them from the spectrum. Hartwell and Gehrke [22] identified the presence of $^{227}$Ac and its daughters as contamination of $\alpha$-emitting nuclides in LaCl$_3$:Ce. Milbrath et al. [23] also confirmed the presence of $^{227}$Ac as the source of $\alpha$ contamination in LaCl$_3$:Ce through coincidence measurements. Szücs et al. [24] in their paper have also pointed out the demerits of the usability of LaBr$_3$ detector in low energy nuclear astrophysics experiments within the desired energy range because of the mixing of contamination due to internal activity with the real counts.
Studies by Hoel et al. [25] and Crespi et al. [26] suggested the existence of pulse shape differences between α and γ-ray pulses. Hoel et al. [25] have also observed that for LaCl₃:Ce, the difference in pulse shapes is modest, but for LaBr₃ the difference is too small to be useful. Crespi et al. [26] by using the charge comparison method with a fast digitizer, achieved the suppression of intrinsic α background. The radioactive decays of $^{138}$La in LaBr₃:Ce and the shape of the internal β spectrum have been measured by Quarati et al. [21]. Hoel et al. [25] demonstrated the effectiveness of pulse shape discrimination (PSD) method for LaCl₃:Ce but not for LaBr₃:Ce. However, Crespi et al. [26] demonstrated that the pulses for α-particles are slightly faster than the ones generated by γ-rays, in LaBr₃:Ce, which is exactly opposite to that in LaCl₃:Ce. They proposed a simple algorithm based on this difference, which can distinguish between α-particles and γ-rays for both types of scintillators with reasonable efficiency. Recently, the shape of intrinsic alpha pulse height spectra in lanthanum halide scintillators have been studied in detail by Wolszczak and Dorenbos [27] by using a PSD factor calculated as a ratio of a raw pulse maximum amplitude ($V_p$) to integrated charge ($Q_{\text{total}}$). They used a CAEN 5730, 500 MHz fast digitizer for their work. Despite these efforts, the overall quantitative understanding of the effect of internal activity in the La-halide detector spectrum is still limited now. Lanthanum halide scintillators, namely LaCl₃:Ce and LaBr₃:Ce, show very similar trends in internal activity and, in principle, the results obtained using one of them may be directly applicable to the other. In the present work, the internal radioactivity of a LaCl₃:Ce detector has been studied.

This study aims to provide a deeper understanding of the internal α and β activities in LaCl₃ and find a way to reduce them to make the detector more effective for rare event detection experiments. For accelerator-based experiments, one can measure the natural and internal radiation very accurately in off-beam conditions without using any calibration source and placing the detector in the same position as that during the measurement. Later the background spectrum can be subtracted from the in-beam spectra. However, while measuring environmental activities or rare natural events, the subtraction method has some limitations. The rare events, the environmental background events, and the internal activities are always present together. Unlike the in-beam experiments, it is difficult, if not impossible, to acquire a spectrum containing internal radioactivity only. Only a qualitative spectrum of the internal radioactivity can be obtained by shielding the detector with thick Pb layers. The measurement has to be continued for a long time. The present method can be utilized to strengthen the experimental approach to reduce the internal background.

In this paper, we present the pulse shape discrimination (PSD) technique to eliminate the effect of internal α contamination from the spectrum in LaCl₃ detector. Unlike the methods adopted in references [26, 27], we preferred to use a PSD ratio similar to that used by Hoel et al. [25]. The PSD parameter is optimized as far as possible for better separation between α and γ-ray pulses. However, we used a digitizer similar to that in reference [27]. The sharper and narrower peaks for alphas than gammas also yield higher tail contribution for alphas for the same amount of total charge deposited. This definition of PSD was already included in the algorithm of the CAEN digitizer software. We utilized that to our benefit. In most of the earlier literature, the room-background γ-ray (2615 keV, in most cases [26]), was utilized to show the efficacy of the method. However, we have chosen a suitable long-lived laboratory radioactive source $^{207}$Bi (decay mode: EC, $\beta^+$; half-life: (11 523 ± 1) d) which emits a γ-ray at 1770 keV which is totally hidden under the internal alpha activity in single spectrum. The experimental spectrum for $^{207}$Bi (570 keV, 1064 keV,
and 1770 keV: 98%;75%;7%) has been utilized to demonstrate the efficacy of the alpha activity elimination. The impact of the PSD method on the detector efficacy to detect γ-rays is compared with Monte-Carlo based simulation results for this source. Moreover, a simulation code has been developed to eliminate β activity from the spectrum. Finally, both methods are applied simultaneously to make the spectrum free of internal activity as far as possible. The present results are indicative of the possibility of reduction of the internal background. However, for a quantitative reduction with smaller systematic error — data should be acquired for a longer time, and the simulation event number should be increased as far as computationally possible.

The paper is organized in the following way. In sections 2 and 3, the details of the experimental setup and simulations are discussed. The different techniques used for the elimination of the internal activity are discussed in section 4. In sections 5 and 6, results obtained from these methods to reduce internal activity have been analyzed and discussed. Finally, section 7 includes the summary and conclusions.

2 Experimental details

In this work, a 1” × 1” cylindrical LaCl$_3$:Ce scintillator crystal from Saint-Gobain coupled with a Philips XP2020 photo-multiplier tube (PMT) with 12 dynodes and Philips Model No. 5563 voltage divider was used. The PMT has been biased to −1800 V. Amplitude of the anode signal corresponding to the 1436 keV peak was 1.34 V. The anode signal was processed by a CAEN digitizer DT5730 (sampling rate 500 MHz) in the PSD (Pulse Shape Discriminator) mode with input range 2.0 V. The data were acquired in list mode, i.e., event by event mode, and further analyzed in off-line by LAMPS [28] data analysis software. Low activity $^{60}$Co, $^{152}$Eu, $^{133}$Ba, $^{137}$Cs, $^{241}$Am and $^{207}$Bi sources were used for energy calibration purposes. The detector is kept inside a lead shielding with thickness ∼2 cm to minimize the contribution of room background γ-radiation in the spectrum. The spectra with and without Pb shielding are shown in figure 1. The difference spectrum between unshielded and shielded spectra shows mostly the natural environmental radiation (marked in the figure) as the internal radiations are present in both spectra with almost equal intensity. As expected, the maximum suppression is observed at low energies.

3 Monte-Carlo method based simulation details

A Monte-Carlo method based GEANT4 [29] simulation has been performed to generate the detector response to its internal activity. The GEANT4 simulation platform is designed to simulate particles’ passage through matter and comes pre-configured with many standard options and examples for a user to modify. The simulations were performed using a series of GEANT4 classes like detector construction and material building, particle and physics process definition, particle tracking, event action, etc. In the detector construction class, the detector’s geometry and material information and its encasing is defined as provided by the manufacturer. The geometry consists of a small 1” × 1” cylindrical LaCl$_3$ detector surrounded by MgO reflector, and optically coupled to a Bi-alkali photocathode through a quartz PMT window. In the physics list, the necessary physics processes, such as, G4EmStandardPhysics, G4DecayPhysics, and G4RadioactiveDecayPhysics are included. The
Figure 1. (a) Normal background spectrum acquired with and without lead shielding (2 cm thick). No radiative source has been used in this setup. The room background γ-ray peaks, 1460 keV from $^{40}$K, and 2615 keV (hidden under the alpha contamination peaks) from $^{232}$Th decay series are shown. The intrinsic background components arising from the decay of $^{138}$La: β-continuum, the summing bump of 789 keV ($\beta^-$ decay) with the β continuum, 1436 keV γ-peak (electron capture) are shown. The peaks arising from α-contamination in the detector from $^{227}$Ac impurity are also indicated in the figure. (b) The difference spectrum between unshielded and shielded spectra. The peaks corresponding to natural environmental radiation are marked in the figure. The statistical error corresponding to each data point is shown in the plot.

G4EmStandardPhysics class contains the three standard electromagnetic processes like Compton scattering, photoelectric process, and pair production. The G4DecayPhysics constructor handles the decay channels for all unstable particles defined in the physics list. The same process is assigned to all unstable particles. The G4RadioactiveDecayPhysics class contains the basic features of the radioactive decay of nuclei. In the primary generator action class, the general particle source (GPS) module has been used as a particle generator to create different shapes with a specific position, angle, energy distribution, etc. In the present work, the GEANT4 toolkit version 4.10.0 has been used.

We have considered the LaCl$_3$ crystal as our volume source which emits the radioactive particles. For creating the volume source, the General Particle Source (GPS) module has been used in the simulation. The G4RadioactiveDecayPhysics class is used to define the radioactive ions ($^{138}$La). The standard input files included in GEANT4 are sourced originally from ENSDF data.
library [30]. The ions are randomly distributed within the volume source and emit the radiations isotropically. The G4RadioactiveDecayPhysics class in GEANT4 takes care of the nuclear de-excitation processes like — fluorescence, Auger electron emission, etc. The simulations were carried out for a reasonable number of events ($10^5$) to reduce the statistical uncertainty.

4 Alpha activity elimination: pulse shape discrimination (PSD)

When an energetic particle or photon is incident on a scintillator crystal, it deposits its energy in the medium. The scintillator gets excited and emits scintillation radiation. The energy loss per unit thickness ($dE/dx$) inside the scintillator material varies for different incoming particles. Hence, the luminescence rates for different particles result in pulse shape differences. Two exponentials with two-time components [31] usually characterize the time evolution of the intensity of the scintillation light. One is a fast or prompt component, and the other is a slow or delayed component. The time evolution of the number of emitted scintillation photons $N$ from a single scintillation event can be described by a linear superposition of two components given by

$$N = \frac{A}{\tau_f} e^{-\frac{t}{\tau_f}} + \frac{B}{\tau_s} e^{-\frac{t}{\tau_s}}$$

where, $\tau_f$ and $\tau_s$ are the fast and slow decay times. The majority of the scintillation intensity is contained in the prompt component. However, the long-lived or the slow component has an important implication as the fraction in it often depends on the nature of the incident particle. This dependence can be utilized to differentiate between particles of different kinds that deposit the same energy in the detector [20]. This technique is well known as pulse shape discrimination (PSD). It is widely applied to eliminate unwanted events in a mixed radiation field. The light emission intensity of a LaCl$_3$:(Ce) crystal is represented well by a two-component exponential decay with $t_f \approx 26$ ns and $t_s \approx 550$ ns at 20°C. Moreover, the ratio of $B/A$ is approximately 0.25 for $\gamma$-rays at 20°C [32]. On the other hand, that of a LaBr$_3$:(Ce) scintillator is accurately modeled with a single fast component exponential decay.

Although LaBr$_3$:Ce does not possess different components at room temperature, the capability of discriminating $\gamma$ and $\alpha$ events have been demonstrated with fast digitizers [26, 27]. The reason behind the pulse shape difference in such single-decay-component scintillators remained unclear. However, recently [33] ionization-density-dependent transport and rate equations are successfully used to quantitatively model the non-proportionality response of electrons or $\alpha$ particles explaining the measured $\gamma$ and $\alpha$ pulse-shape difference well.

4.1 The PSD method

In pulse shape discrimination with scintillators, the most frequently used technique is the charge integration method, which determines the amount of delayed light output compared to the total light output for each event to identify the corresponding ionizing radiation type. DPP-PSD firmware provided with the CAEN 5730 digitizer [34] is based on this method. The PSD parameter is then
extracted in event-by-event mode using the digitizer as,

$$PSD = \frac{(Q_l - Q_s)}{Q_l}$$

(4.2)

where, $Q_l$ and $Q_s$ are the integrated charge within the long gate and short gate, respectively, as shown in figure 2. The PSD is the ratio of charge deposited at the tail part of the pulse ($Q_l - Q_s$) to the total charge deposited in the full pulse ($Q_l$). The short window (80 ns in the present case) has been chosen such that the ratio of the tail to the total pulse would be effective for particle identification. For example, $\alpha$ and $\gamma$-rays have different interaction mechanisms with the detector material; hence they have different responses in the detectors (shown in the inset of figure 2). As we worked with a 500 MHz digitizer, the pulses are represented with a point in every 2 ns. The pulses are acquired for a window of 992 ns. The average plots till 680 ns are shown in figure 2.

For the same total charge deposited (from 80 ns to 992 ns, in the present case), average $\alpha$ pulses are narrower and sharper compared to $\gamma$-ray pulses. The $\gamma$-pulses attain the peak relatively later. We have plotted the pulses with symbols to show the precision of the digitizer explicitly. The differences in the slopes are also evident from the figure. A fitting of the rise-times with linear functions results in values of 122 (14) mV/ns and 145 (19) mV/ns for $\gamma$ and $\alpha$ pulses, respectively.

The choices of short and long gates are shown in figure 2. With this choice of gates, the PSD parameter is larger for $\alpha$’s than for $\gamma$-rays.

![Figure 2](image.png)

**Figure 2.** Average waveforms of $\alpha$ and $\gamma$-ray obtained from LaCl$_3$ detector having the same total charge deposited with integration gate ranging from 80 ns to 992 ns. The short and long gates are shown in the figure. The inset highlights the difference between an $\alpha$ and a $\gamma$ pulse.

This technique has been used to eliminate internal activity contributions due to $\alpha$ contamination from the spectrum. A two-dimensional plot of PSD vs. channel no. ($Q_l$, i.e., energy) shown in figure 3 distinguishes the $\alpha$ contamination events from the $\gamma$’s and $\beta$’s.
4.2 Testing the efficacy of the PSD method

4.2.1 The $^{207}$Bi spectra: effect of elimination of $\alpha$ contamination from the spectrum

The energy spectra using $^{207}$Bi source using a Pb-shielded detector acquired with DT5730 digitizer have been shown in figure 4. It is known that $^{207}$Bi source emits $\gamma$-rays at 570 keV, 1064 keV, and 1770 keV energies. From figure 4 (inset), the intrinsic activity of LaCl$_3$:Ce is found to be dominant in the $^{207}$Bi spectrum acquired by the shielded detector. Although 570 and 1064 keV peaks of $^{207}$Bi are seen, the 1770 keV peak is invisible. The 1770 keV peak is hidden under the $\alpha$ peaks arising from the $\alpha$ activity in the detector. Therefore, proper elimination of the effect of internal activity from the spectrum is needed.

The contamination effect due to $\alpha$ activity is eliminated from the spectrum by using pulse shape discrimination. The PSD has been calculated event-by-event from the formula mentioned above. Figure 3 shows a typical two-dimensional plot of PSD vs. channel no. (integral on the long gate). The plot shows that one can separate the contributions for the $\alpha$ events from the $\gamma$-ray events. A representative region (or a “gate”) on the two-dimensional plot has been shown in the figure. However, the $\alpha$ subtracted spectrum has been generated by plotting only those events for energies above around 1500 keV, which have PSDs corresponding to $\gamma$-ray events (PSD < 0.51, say). The spectrum thus generated is shown in figure 4. After the invoking PSD gate, the 1770 keV peak of $^{207}$Bi source is observed clearly in the $\alpha$ contamination subtracted spectrum. The cut-off PSD parameter value has been varied from 0.51 to 0.54 to see the variation in the areas of 1770 keV peaks. For a stringent cut-off (viz. PSD < 0.515), the background reduces drastically. However,
the area under the peak also reduces by 75%. The variation in the 1770 keV peak areas for PSD upper limits ranging from 0.523 to 0.540 is around 10%.

4.2.2 Simulations done to test the efficacy of the method

To check the choice of PSD cut-off parameter for generating the internal alpha activity, subtracted experimental spectrum of $^{207}$Bi, Monte-Carlo simulation has been carried out. The simulated spectrum is compared with the experimental one in figure 5, with PSD < 0.54. The $\gamma$-ray spectra were simulated with $^{207}$Bi radioactive source for the LaCl$_3$ detector. The energy dependence of the resolution has been incorporated from the fitting parameters obtained from the experimental spectra. The simulated spectra have been normalized to reproduce the peak counts of 1064 keV photo-peak observed in the experimental spectra. Under this condition, the simulated peak height at 1770 keV matches with the experimental peak within the statistical error limit. This observation clearly shows that the choice of PSD cut-off region extracts the $\gamma$-spectrum by eliminating the internal alpha activity with the expected efficacy at 1770 keV. Thus the PSD method can be utilized to regain the $\gamma$-detection capability of the La-halide detector in this energy domain by eliminating the alpha activity contaminations with increased sensitivity.

Figure 4. Raw (inset) and $\alpha$-activity subtracted spectra for $^{207}$Bi decay.
Figure 5. Comparison of the alpha background subtracted spectrum of $^{207}$Bi source with the simulated spectrum.

5 Elimination of beta activity: simulation based on Monte-Carlo method

LaCl$_3$:Ce detector has an internal $\beta$ activity that cannot be eliminated using the pulse shape discrimination as the shape of the pulses looks very similar for both $\gamma$ and $\beta$. For the elimination of the effect of internal $\beta$ activity from the $\gamma$-spectrum of LaCl$_3$:Ce, a Monte-Carlo based simulation code has been developed using the GEANT4 toolkit [29]. For the simulation of internal $\beta$ activity, a cylindrical source of same size as the detector has been used. The response function of the internal $\beta$ activities was generated using the simulation code. The detailed procedure is described below.

The number of $^{138}$La atoms ($N_0$) inside the LaCl$_3$ detector has been estimated from the following relation.

$$N_0 = \frac{N_A \cdot \rho \cdot (\pi r^2 h) \cdot (f)}{A} \quad (5.1)$$

where $N_A$ is the Avogadro number, $\rho$ is the density of the detector, $r$ is the radius, and $h$ is the height of the cylindrical detector, $f$ is the fractional abundance of $^{138}$La in mass $A$ of LaCl$_3$.

The number of $^{138}$La atoms ($N$) remaining after time $\Delta t$ can be calculated as:

$$N = N_0 \exp(-\lambda \cdot \Delta t) \quad (5.2)$$
Then the number of $^{138}\text{La}$ atoms which have decayed in this time would be:

$$N_0 - N = N_0(1 - \exp(-\lambda \cdot \Delta t)) \quad (5.3)$$

It is known that in 66.4% times $^{138}\text{La}$ decays to $^{138}\text{Ba}$ via an electron capture with the emission of $\sim 1436\text{keV}$ $\gamma$-ray. Hence in the elapsed time $\Delta t$ number of emitted $\gamma$-rays ($N_{1436}$) having an energy of $\sim 1436\text{keV}$ can be estimated as:

$$N_{1436} = 0.664 \cdot N_0(1 - \exp(-\lambda \cdot \Delta t)) \quad (5.4)$$

The simulated spectra (figure 6) have been normalized to reproduce the $N_{1436}$ counts observed in the experimental spectra to get the shape of the internal $\beta$ activity spectrum. The 1436 keV and the room background $\gamma$-ray 1460 keV are unresolved in the spectrum. Therefore, the 1460 keV room — background $\gamma$-peak contribution in $N_{1436}$ has been minimized as far as possible by using Pb shielding.

![Simulated beta activity](image)

**Figure 6.** Shape of the $\beta$ spectrum obtained from the simulation.

The $\gamma$ energy spectra of LaCl$_3$ detector for chosen energies have been generated by assuming a simplified expression of the peak shapes.

$$\sigma(E) = a + b \sqrt{E} \quad (5.5)$$
where, $\sigma(E)$ is the standard deviation of the peak shape of the $\gamma$-peak of energy $E$ in the $\gamma$-spectrum. The standard deviation is obtained from the full width at half maximum (FWHM) of a $\gamma$-peak. The value of the parameters $a$ and $b$ have been estimated by fitting the variation of FWHM of $\gamma$-peaks as a function of peak energies obtained from spectra of different radioactive sources ($^{60}\text{Co}$, $^{137}\text{Cs}$ and $^{207}\text{Bi}$). The values of $a$ and $b$ are 0.0084 (24) MeV and 0.0148 (22) MeV$^{1/2}$, respectively.

6 Results and discussions

6.1 The background spectra

Figure 1 shows the background spectrum obtained from LaCl$_3$ detector acquired with and without lead shielding. Due to the detector’s inherent radioactivity, the background spectrum is dominated by components of $^{138}\text{La}$ and $^{227}\text{Ac}$ decay. In the electron capture decay mode of $^{138}\text{La}$, a $\gamma$-ray (1436 keV) and X-ray (32 keV-K$_{\alpha}$ and 38 keV-K$_{\beta}$) from $^{138}\text{Ba}$ are emitted. The 1436 keV $\gamma$ and the 1460 keV $\gamma$ from the $^{40}\text{K}$ present in the room background cannot be resolved. The correlated $\gamma$-ray and K X-rays (32–38 keV) of $^{138}\text{Ba}$ give rise to a sum-peak at $\sim 1470$ keV [3, 35].

Following the $\beta^-$ decay, a continuum $\beta^-$ spectrum till 255 keV followed by 789 keV $\gamma$-ray from $^{138}\text{Ce}$ are emitted. The correlation between $\beta$ particles (till 255 keV) and $\gamma$-ray (789 keV) of $^{138}\text{Ce}$ generates a summed structure of $\beta$ continuum with $\gamma$-ray. The continuum structure starts at 789 keV and spreads to high energy at 1044 keV [3, 35]. The remaining $\beta$ continuum is observed at the low energy side from 0 keV to 255 keV. Between 255 keV to 750 keV, the Compton continuum from the 789 keV and 1436 keV $\gamma$-rays are observed. Above 1700 keV, the presence of $\alpha$ contaminant peaks is observed. These peaks originate from the $\alpha$’s emitted from the decay of $^{227}\text{Ac}$ contamination. The $\alpha$’s produce a broad response with several peaks from roughly 1.7–2.3 MeV$_{ee}$ (MeV electron-equivalent) [35]. Thus the background spectrum obtained from LaCl$_3$ detector is quite complicated, and background components due to natural radioactivity are mostly hidden under the intrinsic background.

6.2 Estimation of reduction factor of intrinsic background in LaCl$_3$

The detector is kept inside a 2 cm lead shielding to reduce background $\gamma$-radiation. In this way, the contributions from the room background have been reduced by a factor of $\sim 11\%$ (figure 1). However, the spectra are not free from the intrinsic background. Elimination of internal $\alpha$ and $\beta$ contamination from the spectrum is required to further reduce the background.

The pulse shape discrimination method has been adopted to eliminate $\alpha$ activity from the spectrum. Using the two-dimensional plot of PSD vs. channel no. (integral on the long gate) for background spectra, the contribution of $\alpha$ contamination is eliminated, as shown in figure 7(b). The reduction in the intrinsic alpha activity using PSD gate is $\sim 98\%$. The $\alpha$-activity contribution has been removed from the spectra by selecting events in the energy region (identified from the 2D plot) corresponding to the specific PSD values corresponding to $\gamma$ events only.

The $\alpha$ subtracted spectrum still contains the effect of $\beta$ contamination. The contribution of $\beta$ activities and the shape of the spectrum due to $\beta$ contamination alone has been simulated using GEANT4 based simulation code. In figure 6, the shape of the spectrum due to the $\beta$ contamination...
Figure 7. (a) Normal room background spectrum acquired with lead shielding compared with that after elimination of α contamination, and also with that after elimination of both α and β activities. The room background γ-ray peaks, 1460 keV from $^{40}$K, and 2615 keV from $^{232}$Th decay series are clearly seen after the elimination of the intrinsic background. (b) The effect of removal of α activity from the spectrum, (c) and (d) show the spectra generated from (c) alpha activity only and (d) the sum of alpha and normalized β activities due to internal contamination of the detector.

is shown. Finally, the total intrinsic activity, i.e., the sum of the activities due to α and β decays, is subtracted from the raw spectrum. The simulated β spectra have been normalized according to the prescription discussed in the earlier section. The reduction factor (figure 7) to estimate the suppression in the intrinsic background at different energy regions is calculated. The time normalized background events after elimination of intrinsic activities have been reduced by $\sim 48\%$ compared to a Pb-shielded detector. The reduction in the internal activity in the energy range $> 1550$ keV is $\sim 98\%$. 
7 Summary and conclusions

In the present work, intrinsic activity due to $\alpha$-decay events in the LaCl$_3$:Ce scintillator has been eliminated by the pulse shape discrimination method using a fast digitizer. The pre-defined PSD algorithm provided in the CAEN digitizer was used. The efficacy of the method has been tested experimentally and compared with simulation. The shape of the $\beta$ continuum has been simulated via a GEANT4 based simulation code. The appropriately normalized simulated spectra have been subtracted from the raw spectra for the elimination of the effect of $\beta$ activity. This work provides a method to reduce the internal activity from the spectrum. This method can be helpful in situations where the acquisition of internal activity generated experimental spectra is difficult, if not impossible. The La-halide detectors’ applicability for rare event detection experiments has been improved by reducing background events by 48% compared to a 2 cm Pb shielded detector. The discrimination method presented in this paper would be more beneficial for LaCl$_3$:Ce detectors, which have a slow part in the scintillation pulse useful for pulse shape discrimination. However, for LaBr$_3$:Ce detectors also, the applicability of this method can be tested.

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