| Title | Feasibility study on signal separation for spontaneous alpha decay in LaBr₃:Ce scintillator by signal peak-to-charge discrimination |
|-------|----------------------------------------------------------------------------------------------------------------------------------|
| Author(s) | Ogawara, R.; Ishikawa, M. |
| Citation | Review of scientific instruments, 86(8), 85108 |
| Issue Date | 2015-08 |
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| Type | article |
| File Information | Rev Sci Instrum 86(8)_085108.pdf |

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Feasibility study on signal separation for spontaneous alpha decay in LaBr₃: Ce scintillator by signal peak-to-charge discrimination

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Citation: Review of Scientific Instruments 86, 085108 (2015); doi: 10.1063/1.4928115
View online: http://dx.doi.org/10.1063/1.4928115
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Feasibility study on signal separation for spontaneous alpha decay in LaBr$_3$:Ce scintillator by signal peak-to-charge discrimination

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(Received 23 March 2015; accepted 25 July 2015; published online 11 August 2015)

A novel analysis method named peak-to-charge ratio ($V_p/Q_{total}$) discrimination, aiming at background rejection especially for alpha decay self-activity in LaBr$_3$:Ce scintillators has been developed. This method is based on a waveform analysis using the peak-to-charge ratio in the output waveform of a photomultiplier tube. The discrimination of alpha-induced events was achieved by using a threshold function based on the error propagation of the $V_p/Q_{total}$ value. The accidental rejection ratio of gamma-induced events was evaluated to be 0.17%. Furthermore, a total absorption peak spectrum processed with the $V_p/Q_{total}$ discrimination method for $^{68}$Ga 1.883 MeV gamma rays, where the energy was overlapped with background alpha events, reproduced exactly the same result as that of the background subtraction method. The difference in measured peak counts of both methods was 0.716%, and the statistical error in the $V_p/Q_{total}$ discrimination method and background subtraction was 4.81% and 8.70%, respectively. Thus a higher-accuracy measurement could be achieved using the $V_p/Q_{total}$ discrimination method. The present study demonstrates that the $V_p/Q_{total}$ discrimination method is a promising method for background rejection of the spontaneous alpha decay in LaBr$_3$:Ce scintillators. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4928115]

I. INTRODUCTION

Recent developments of inorganic scintillators have been remarkable in the field of radiation measurement. In particular, the LaBr$_3$:Ce scintillator yields excellent energy resolution (<3% at 662 keV) with intrinsic time resolution of about 107 ps. These characteristics are useful for gamma ray spectrometry, development of gamma cameras, and time of flight measurements. According to previous studies, LaBr$_3$:Ce scintillators have also been used for lifetime measurement of unstable nuclei and observation of the response to fusion neutrons. Furthermore, LaBr$_3$:Ce scintillators have large stopping power in spite of their relatively lower effective atomic number, since it is possible to make a large crystal with high density (5.3 g/cm$^3$). They are also suitable for high energy gamma ray measurements (e.g., cosmic ray, characteristic gamma ray due to nuclear reactions and environmental radiation). Additionally, fluorescence characteristics of LaBr$_3$:Ce scintillators have only a small dependency on thermal changes and have strong radiation-resistance. In recent years, CeBr$_3$ scintillators with high energy resolution (4.0% at 662 keV) and fast timing resolution of 119 ps with a self-activity much lower than the LaBr$_3$:Ce scintillator have also been developed. However, the characteristics of CeBr$_3$ scintillators are slightly inferior to LaBr$_3$:Ce scintillators at present. Yet, self-activity of LaBr$_3$:Ce crystals is considered to be a serious defect in LaBr$_3$:Ce scintillators.

The major components of this self-activity are 1436 keV gamma rays from electron capture disintegration (66.4%) of $^{138}$La nuclei with 32 keV K-X ray of Ba atom, and 789 keV gamma rays with 255 keV electron from beta decay (33.6%) of $^{138}$La nuclei. Moreover, the self-activity background due to alpha decay from Ac-series nuclei is distributed at a range of 1.5–3 MeV in the energy spectrum and a characteristic gamma ray induced from the alpha decay is also emitted almost at the same time. Much research has been carried out on particle identification of alpha-decay nuclei using coincidence measurement of alpha-decay events and its induced characteristic gamma ray. This inevitable background can be negligible if the count rate of true events is sufficiently larger than self-activity background; however, it is difficult to observe the true event when a low count rate is taken into account. In general, large volume LaBr$_3$:Ce crystals are used for high energy gamma ray measurements, but the event rate of self-activity increases with crystal volume. Therefore, research on the self-activity suppression carries a significant importance for the development of large volume LaBr$_3$:Ce crystals.

Research by Hoel et al. and Crespi et al. suggested that there exists a difference between alpha and gamma induced events in the vicinity of the peak voltage in the output waveform of a photomultiplier tube (PMT) equipped with a LaBr$_3$:Ce scintillator. However, to the best of our knowledge, almost no research has been done in the field of pulse shape discrimination (PSD) for rejected alpha-decay events. This is because the waveform difference obtained is almost imperceptible. In research by Crespi et al., self-activity rejection of alpha-decay was achieved by comparing the total integrated charge and the partial integrated charge in a suitable time domain in the vicinity of the peak voltage. In the present work, the domain of integration and threshold constant in the whole energy range have been determined discretely, and a post hoc analysis is necessary for the optimization.
II. MATERIAL AND METHOD

A. Data acquisition system and noise reduction

As shown in Figure 1, the electric signal waveforms from a PMT (R6231-100, Hamamatsu Photonics) equipped with a LaBr₃:Ce scintillator (38S382/B380, BrilLanCe™ Saint-Gobain) were measured using an oscilloscope (Wave Runner 64xi, LeCroy, 5 GS/s) without electronic devices such as a shaping amplifier. The raw waveforms were stored to an external storage device. The values of V_p and Q_total were obtained from the analysis of the measured waveforms using in-house software which has several functions such as offset correction, a moving average for waveform smoothing, a frequency analysis using Fast Fourier Transform (FFT), a digital low pass filter using FFT with inverse FFT (IFFT), and spectrum generation for all measured data. In particular, the function related to noise suppression is important for the V_p/Q_total value, since the V_p is sensitive to high-frequency noise. Therefore, the high-frequency noise was suppressed using a moving average with a time width of 2 ns, and a digital low pass filter using FFT and IFFT suppressed the noise component of >50 MHz in the entire waveform.

B. Alpha-event discrimination using V_p/Q_total

Although the background suppression method for self-activity has been discussed in previous research, it is still difficult to assess the rejection accuracy quantitatively. This is because a threshold for discriminating alpha and gamma events could not be determined theoretically as described in Section I. In the present work, the peak-to-charge ratio V_p/Q_total is expected to be constant for gamma events, and a different constant value is expected for alpha events. However, the V_p/Q_total value fluctuated according to the uncertainties of V_p and Q_total values, and a function of σ_V_p/Q_total (Equation (1)) deduced from an error propagation of V_p/Q_total was therefore used for discriminating alpha and gamma events. Since the σ_V_p/Q_total function varies according to the supplied voltage to the PMT, the parameters for the function should be obtained as a calibration. This process requires a gamma ray source. However, LaBr₃:Ce self-activity generates a gamma ray emission statistically sufficient for the calibration.

\[
\sigma_{V_p/Q_{total}} = \sqrt{\left(\frac{1}{Q_{total}} \sigma_{V_p}\right)^2 + \left(\frac{V_p}{Q_{total}^2} \sigma_{Q_{total}}\right)^2} \tag{1}
\]

C. Evaluation of alpha event rejection using V_p/Q_total discrimination method

In order to confirm the efficacy of alpha-event discrimination, a quantitative assessment was performed using an external gamma ray source. Since the energy range of background alpha-decay is distributed from 1.5 to 3 MeV (gamma equivalent), a Ge-68/Ga-68 source (CS-6-14, 12.4 kBq, Siemens Medical Solutions) which emits 1.883 MeV gamma rays from ⁶⁸Ga was used as the external gamma-ray source. The rejection accuracy of alpha-induced events was assessed by comparing the energy spectrum between the V_p/Q_total discrimination method and conventional method (background subtraction). The ⁶⁸Ga source was placed 0.6 m away from the LaBr₃:Ce scintillation detector. Waveforms of 60000 events were used for the comparison.

III. RESULT

A. Noise reduction to improve measurement accuracy

The raw waveform data at a detection energy of 511 keV and the waveform of high-frequency noise suppressed by a moving average with a time width of 2 ns and 50 MHz digital low pass filter using FFT and IFFT are shown in Figures 2(a.1)–2(a.3). Since components of instantaneous noise affect the raw waveform, the values of V_p obtained from raw data was about 4.7% larger than noise-suppressed waveform of 511 keV gamma ray, and in the case of V_p obtained from 1.883 MeV gamma ray which is emitted form ⁶⁸Ga was 0.71% larger. The signal to noise ratio in the V_p value...
B. Demonstration of the \( V_p/Q_{total} \) discrimination method using LaBr\(_3\):Ce self-activity

Figure 3(a.1) shows the energy (\( Q_{total} \) equivalent) dependence of the \( V_p/Q_{total} \) value for self-activity of the LaBr\(_3\):Ce scintillator. Two components of the \( V_p/Q_{total} \) value at the energy range of 1.5–3 MeV were observed. According to Crespi et al., the waveform of alpha-induced events contains a higher value of peak intensity than the gamma-induced events in the same detection energy. Hence, the alpha-induced events should be distributed at a higher value than the gamma-induced events. For the lower component of \( V_p/Q_{total} \), it is considered to be a gamma-induced event from environmental radiation such as \( ^{210}\text{Po} \) (2.615 MeV). On the other hand, the \( V_p/Q_{total} \) value in Fig. 3(a.1) decreases with increase in energy, although \( V_p/Q_{total} \) was expected to be a constant. The reason for the decrease seems to be due to saturation of \( V_p \) as shown in Figure 3(b.1). The linearity between \( V_p \) and \( Q_{total} \) was only kept in the low energy region. In order to correct the saturated \( V_p \), the saturation curve of \( V_p \) was assumed to be in the form of Equation (2) which consists of a linear term \( \alpha Q_{total} \) (\( \alpha = \text{const.} \)) and a saturation term \( 1 + \beta Q_{total} \) (\( \beta = \text{const.} \)). Equation (3) was deduced by assuming that the corrected peak voltage \( V_{p\text{corr}} \) is proportional to \( Q_{total} \) such as \( V_{p\text{corr}} = \alpha Q_{total} \). Note that these parameters \( \alpha \) and \( \beta \) which are necessary for the saturation correction were obtained by a fitting analysis with Equation (2) in the experimental value without alpha-induced events. The coefficient of correlation \( R^2 \) between the measurement value and Equation (2) was found to be 0.9976, which shows a strong correlation between them. Figs. 3(a.2) and 3(b.2) show that the saturation was corrected properly using Equation (3). The optimized threshold function on the \( V_p/Q_{total} \) value was configured theoretically using its standard deviation of \( \sigma V_p/Q_{total} \). As mentioned for Equation (1), \( \sigma V_p/Q_{total} \) is a function of \( Q_{total} \) in approximate inverse proportion. Threshold functions of 1 to 3 \( \sigma V_p/Q_{total} \) were obtained by the calibration using a fitting analysis with \( \sigma V_p/Q_{total} = kQ_{total}^{-1} \) (\( k = \text{const.} \), \( l = \text{const.} \)). The fitting curves adequately expressed their measured values as shown in Figure 4(a). In this analysis, since the component of alpha-induced events ranged from 1.5 to 3 MeV, only the data lower than 1.4 MeV were used. Figure 4(b) shows that for each threshold function with

\[
V_p = \frac{\alpha Q_{total}}{1 + \beta Q_{total}} \quad (\alpha = \text{const.}, \beta = \text{const.}),
\]

\[
V_{p\text{corr}} = \frac{V_p}{1 - (\beta/\alpha)V_p}.
\]

FIG. 2. (a.1) The raw waveform data measured by the data acquisition system for a detection energy of 511 keV, and the noise-suppressed waveform using (a.2) the moving average with a time width of 2 ns and (a.3) 50 MHz digital low pass filter using FFT with IFFT analysis. (b) Comparison of self-activity spectrum of LaBr\(_3\):Ce before (raw data) and after noise-suppression by digital low pass filter.

FIG. 3. (a.1) Energy (\( Q_{total} \) equivalent) dependence of the peak-to-charge ratio \( V_p/Q_{total} \) in raw data waveform. (b.1) The energy (\( Q_{total} \)) dependence of the \( V_p \) with the ideal linear function and the saturation curve used for the fitting analysis. (a.2), (b.2) Saturation correction of \( V_p \) using the Equation (3).
V_p/Q_total scatter plot in Figure 3(a.2), alpha-induced events seem to be adequately discriminated using the threshold function. Figures 5(a.1)–5(a.3) shows the energy spectrum with and without alpha event discrimination in LaBr_3:Ce self-activity using the present method. It is shown that the alpha-decay event can be discriminated effectively. On the other hand, the accidental rejection of gamma-induced events occurred by the threshold function as shown in Figures 5(b.1)–5(b.3). Accidental gamma-rejection depends on the threshold function; the probability of gamma-rejection for 1, 2, 3 σ\ V_p/Q_total was evaluated as 4.661%, 0.809%, and 0.172%, respectively, in the energy range of <1.5 MeV where alpha-induced events are not contained.

C. Assessment of alpha-discrimination accuracy

In the present experiment, the rejection accuracy of alpha-induced events was assessed using an external radiation source (68Ga 1.883 MeV). Figures 6(a) and 6(b) show the energy spectrum for the background subtraction and V_p/Q_total discrimination methods, respectively. The energy spectrum without radiation source was normalized by the integrated event counts in the energy range of >2 MeV for background subtraction. As shown in Figure 6(b), only the 68Ga 1.883 MeV gamma ray peak remained clear by using the 3 σ\ V_p/Q_total threshold function. Similarly, Figure 6(c) shows the enlarged energy spectra dedicated for 68Ga 1.883 MeV gamma rays for detailed comparison. The V_p/Q_total discrimination method accurately reproduced the result as that using the background subtraction method. In both methods, the difference in measured peak counts was 0.716%. And the difference in parameters obtained by the fitting analysis with a gauss function in the spectrum such as peak counts, mean energy, full width at half maximum (FWHM) was 1.694%, 0.021%, and 0.165%, respectively, as shown in Table I. Additionally, statistical errors in measured total peak counts for the V_p/Q_total discrimination method and subtraction method were 4.81% and 8.70%, respectively, at a range of ±3σ. A reduction in statistical error was thus observed using the former method.

IV. DISCUSSION

A. Calibration of threshold function and correction for V_p saturation

The V_p/Q_total value increases along with the supplied voltage of the PMT because the pulse width in the PMT declines with the rise in supplied voltage. Accordingly, the threshold function must be calibrated for each measurement condition especially for the supplied voltage. The actual supplied voltage must be taken into account for a successful calibration, but the V_p/Q_total difference between alpha and gamma events could be observed in the range of typical voltage (500–1000 V) for gamma-ray spectrometry using a LaBr_3:Ce scintillator. Once the calibration is done for a specific supplied voltage, the stability and reproducibility of the threshold function is confirmed with the fixed supplied voltage. Moreover, the advantage of this calibration process...
B. System dead time of the data acquisition

In an energy range of about 2.6 MeV, the contribution of alpha events from \(^{215}\)Po in the LaBr\(_3\):Ce crystal should be observed. However, the contribution was not seen in the energy spectrum in Figure 2(b). The alpha decay of the \(^{215}\)Po with shorter lifetime of 1.785 ms occurs immediately after the disintegration of the parent nuclide such as \(^{219}\)Rn. The reason for the unrecorded alpha event from \(^{215}\)Po is due to long dead time of the present data acquisition system. The acquisition system requires at least 50 ms for storing measured waveform, and this latency rises to about 200 ms with increasing a number of stored waveform to the external hard drive. The dead time for this data acquisition system is difficult to measure precisely due to low reproducibility. However, event losses for alpha and gamma are not essential in discriminating alpha event because the event loss occurred not only for alpha event from \(^{215}\)Po nuclei but also following events. For that reason, it was difficult to estimate the real measured time. We therefore used event counts for normalization to compare the subtraction method and \(V_p/Q_{total}\) discrimination methods in Section III C.

C. Detection of low-rate environmental gamma ray

As shown in Figure 7, the contribution of \(^{208}\)Tl (2.614 MeV) gamma rays was clearly detected. This means that Thorium series nuclei exist in the measurement environment. In the raw data, \(^{210}\)Bi (1.764 MeV) of Uranium series could not be identified; however, they were clearly identified using the \(V_p/Q_{total}\) discrimination method with the 3 \(\sigma_{V_p}/Q_{total}\) threshold function. On the other hand, \(^{212}\)Bi (1.620 MeV) of Thorium series nuclei could be observed in both cases of raw data and alpha rejection as shown in Fig. 7. For the subtraction method, the actual background spectrum also depends on the surrounding materials and it would therefore be quite difficult to eliminate from it the ubiquitous presence of \(^{212}\)Bi. With a background spectrum containing \(^{212}\)Bi peak, it will thus be difficult to identify \(^{212}\)Bi in the actual measurement. Therefore, the \(V_p/Q_{total}\) discrimination method can be considered a more practical approach for surveying environmental radiation.

D. The \(V_p/Q_{total}\) discrimination method extensibility

Although the \(V_p/Q_{total}\) discrimination seems to be categorized in the PSD, the use of this method is not restricted only for alpha discrimination in LaBr3 self-activity. The PSD method is applied in discriminating neutron and gamma event using a plastic scintillator. Rise time to fall time ratio is analyzed by a partial integration window in the traditional method. Recently, oscilloscope and flash analog-to-digital

### TABLE I. Total energy peak distribution of rejected alpha-decay background using the background subtraction method and \(V_p/Q_{total}\) discrimination method.

| Peak counts                     | Measurement (MeV) | Fitting (MeV) | Mean energy (MeV) | FWHM (keV) |
|---------------------------------|-------------------|---------------|-------------------|------------|
| BG subtraction                  | 139.6 \pm 28.54   | 129.9 \pm 6.34| 1885.9 \pm 0.7334 | 33.1 \pm 3.62 (1.755%) |
| \(V_p/Q_{total}\) discrimination | 138.6 \pm 19.22  | 127.7 \pm 4.46| 1885.5 \pm 0.5281 | 36.2 \pm 3.31 (1.920%) |
| Difference (%)                  | 0.716             | 1.694         | 0.021             | 0.165      |

*aThe error of measured value is a statistics error, and the error of other parameters mean a fitting error.
The energy spectrum of environmental radiation obtained by using the LaBr₃:Ce scintillator with the \( V_p/Q_{total} \) analysis (3 \( \sigma V_p/Q_{total} \) threshold function).

FIG. 7. The energy spectrum of environmental radiation obtained by using the LaBr₃:Ce scintillator with the \( V_p/Q_{total} \) analysis (3 \( \sigma V_p/Q_{total} \) threshold function).

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