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TEMPERATURE DEPENDENCE OF BGO–CsI(Tl) PHOSWICH DETECTOR PROPERTIES

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We have studied the variations of the performances, and particularly the discrimination efficiency, of a BGO–CsI(Tl) phoswich detector in the temperature range 2.5–40 ° C.

The scintillation decay time evaluation has been carried out by means of a double constant fraction discriminator and a time to amplitude converter on 1 μs shaped pulses. Good discrimination between BGO and CsI(Tl) events has been obtained over the whole temperature range, even though small efficiency variations are present because of the relative displacement of the acceptance window of the discriminator due to the decay time dependence on temperature. A criterium to minimize this effect, useful in particular for the BGO–CsI(Tl) phoswich, has been developed.

1. Introduction

Bismuth germanate (BGO) is particularly suited to high energy photon detection because of its high density and high absorption coefficient. Its typical scintillation decay time is comparable to that of NaI(Tl) and therefore it can be coupled to CsI(Tl) in a phoswich arrangement. This combination is for several reasons an attractive new device when compared with a NaI–CsI phoswich. The same photopeak efficiency is achieved with a reduced Compton background and with a significantly reduced exposure to photons incident from the sides because of the reduced thickness. High sensitivity, combined with the intrinsic ruggedness of the combination are good reasons to prefer this new detector to the NaI–CsI phoswich at energies above a few hundred keV, wherever energy resolution is not of prime interest. In particular, for low intensity source detection in a high background environment, such as in the case of γ-ray astronomy, this device seems a quite good choice.

In a previous paper, Costa et al. [1] have already described the main characteristics of a laboratory prototype of a BGO–CsI(Tl) phoswich detector having in mind possible applications to X- and γ-ray astronomy. In this paper we will examine the behaviour of this detector under temperature variation.

A temperature variation produces changes of both the scintillation light and the decay time of the crystals. This reduces the use of scintillation detectors in many applications where a thermal control cannot be easily achieved, for instance in balloon borne experiments, where a fine thermal stability is difficult and energy expensive. Therefore, an accurate knowledge of these effects is important in order to apply the right corrections.

Temperature variations are particularly important in BGO. It is known that the BGO light yield has a negative temperature gradient of 1.0–1.2%/K, while its decay time decreases at a rate of ~ 6 ns/K [2,3]. One has to expect, therefore, that the performances of a BGO–CsI(Tl) phoswich, and particularly the pulse-shape discrimination efficiency, will vary in the course of a measurement giving a nonconstant background level dependent on temperature.

We have measured the variations of the performances of a BGO–CsI(Tl) phoswich in the range (2.5–40 ° C) typical of a night/day-time balloon flight with many laboratory tests. Our approach has been

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essentially practical and therefore we have studied the behaviour of the whole system (including photomultiplier and voltage divider) and not only that of the phoswich.

In sect. 2 the electronic chain and the measurement techniques used are briefly described, in sect. 3 the resulting data are illustrated and in sect. 4 the criteria for optimum pulse shape window selection in the presence of thermal variations are discussed.

2. Measurement techniques

The phoswich detector used in our measurements was made from a cylindrical BGO crystal of 2 inches diameter and 10 mm thickness, optically coupled to a CsI(Tl) crystal of equal diameter but 20 mm thickness. Both scintillators were produced by Harshaw Chemie BV. The optical contacts between the two crystals and between the photomultiplier and the CsI(Tl) were ensured by a thin layer of stick silicon grease, which showed quite good stability with temperature. The photomultiplier tube used was a 3 inch diameter Thorn–EMI 9758 (with a bialkali cathode) in order to ensure a complete and uniform light collection. A white Teflon ribbon was employed as a light diffuser around the sides of the CsI(Tl) crystal, whereas on the front side of the BGO was placed a millipore filter layer with Al_2O_3 powder around its sides.

The measurements started several days after the phoswich assembling, when the system had reached good mechanical stability and the effects of activation of both crystals had disappeared.

The whole system (detector, photomuliplier, and voltage divider) was enclosed in a heat insulating vessel, whose internal temperature was varied by the introduction of precooled cryogenic mixtures or by means of an externally controlled electric resistor. A temperature transducer (AD 590) was placed in direct contact with the BGO crystal. All measurements were made when the system was at the thermal equilibrium. During each set of measurements, the temperature variation was never greater than 0.2° C. In some measurements a pulsed reference light signal was also sent to the photocathode of the 9758 by means of an optical fiber in order to achieve an independent control of the stability of the voltage divider and photomultiplier itself.

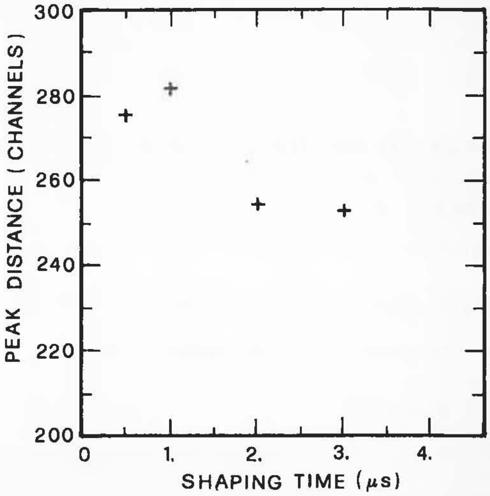

Fig. 2. The distance between the BGO and CsI peaks in the pulse shape spectrum as a function of the shaping time. The maximum distance is reached at 1 μs.

The electronic chain, shown in the block diagram of fig. 1, was the same as used in the work of Costa et al. [1], where the general performance of this new phoswich has been discussed. Pulse shape discrimination was performed by means of an Ortec 467/552 system, composed of a double constant fraction discriminator and a time to amplitude converter (TAC). This system was adjusted to give a signal proportional to the time inter-

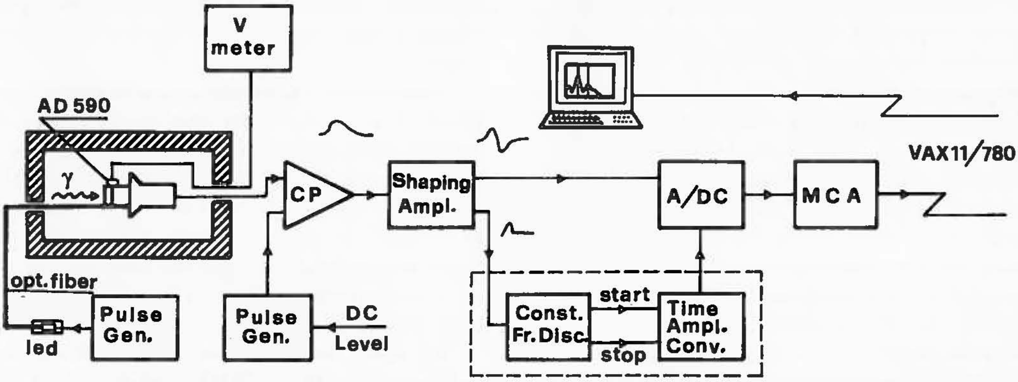

Fig. 1. The block diagram of the experimental apparatus used in our measurements. The temperature transducer and the LED with the optical fiber used to monitor the stability of the photomultiplier and voltage divider are also shown.

val between 90% and 10% of the maximum on the trailing edge of the amplifier output, and a logic signal for times within a selected window. The latter signal was used to coincide or anticoincide the A/D conversion (by a Silena 7411) of the pulse amplitudes. In all measurements the shaping time of the amplifier was set at 1 μs. This choice was a compromise between two opposing tendencies: a shaping time greater than the pulse decay time of the slower crystal secures the analysis of the entire pulse, but a much greater constant makes the pulse shape discrimination less efficient, because the distance between the decay time peaks becomes smaller (see fig. 2). We will discuss this effect in more detail in sect. 3.

An accurate calibration of the whole chain has been performed using the same procedure as described in ref. [1]. The photopeak position has been reduced to the equivalent voltage at the test input of the charge preamplifier (CP).

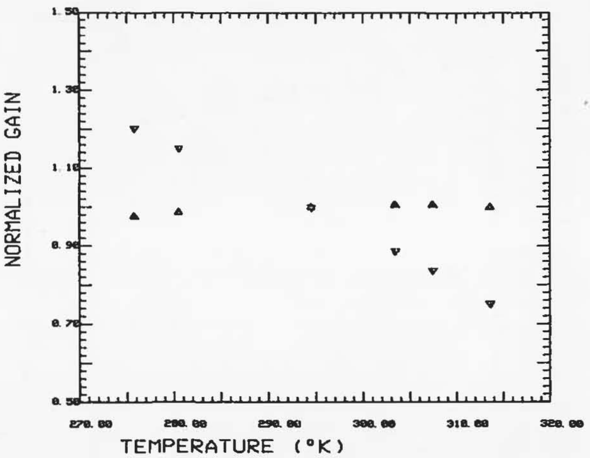

Fig. 4. The gain vs temperature relation for BGO (▼) and CsI(Tl) (▲). Both curves have been normalized to the T_0 values.

3. Results

During the measurements the behaviour of the voltage divider and of the photomultiplier were controlled by the LED (see sect. 2). This illustrated that they were stable in amplitude within 1% at each temperature, and no appreciable variations were found in the LED decay time spectra, therefore, any changes in gain or decay time would be attributed to the scintillators only.

The effects of the temperature variations on the BGO-CsI(Tl) phoswich are evident from the BGO linearity curves of fig. 3. These were produced for three different temperature values in a range of about 40 K: the central one corresponds to room temperature ($T_0 = 294.5$ K) and the two others represent the extremes of the interval spanned in our measurements: $T_1 = 275.8$ K, $T_2 = 313.6$ K. From these curves we have obtained the gain (g) at different temperatures. The gain ratio (g/g_0) vs T, where g_0 is the gain at room temperature T_0, is reported in fig. 4 for both crystals: the BGO has a

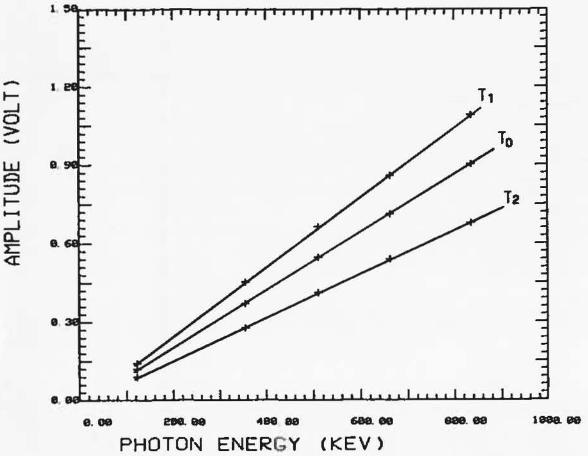

Fig. 3. The linearity curves of the BGO–CsI(Tl) phoswich detector at three different temperatures. The intermediate one ($T_0 = 294.5$ K) is the room temperature, the two others ($T_1 = 275.8$ and $T_2 = 313.6$ K) are the two extremes of the interval covered by our measurements.

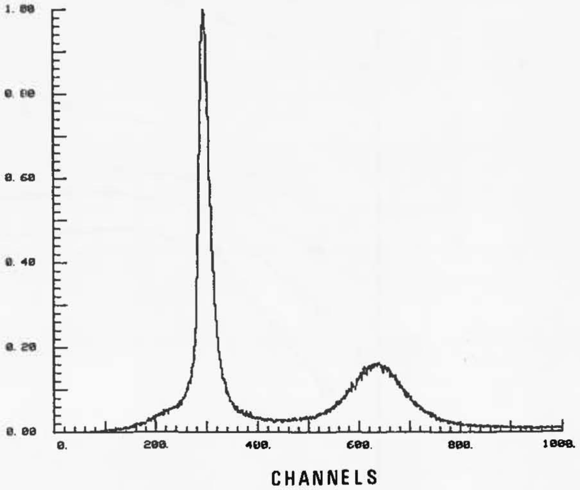

Fig. 5. A typical pulse shape spectrum of the BGO–CsI(Tl) phoswich for 662 keV photons. The two peaks correspond to pure BGO (left) and CsI(Tl) (right) events. The horizontal axis is in channel units, the ordinate is normalized to the maximum of the BGO peak.

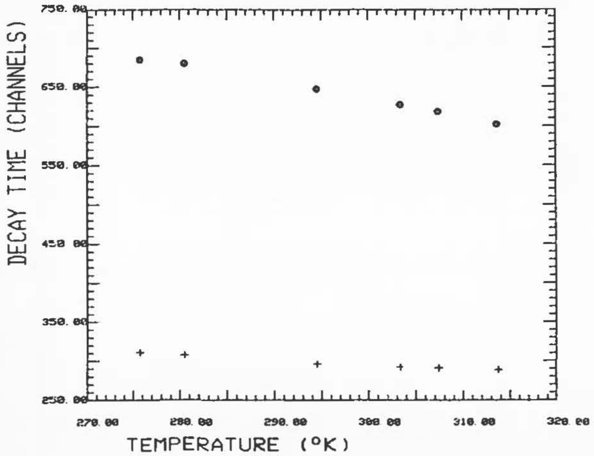

Fig. 6. The temperature dependence of the peak maxima of BGO (+) and CsI(Tl) (●) in the pulse shape spectra.

negative derivative corresponding to −1.2%/K in good agreement with other published data [4]; the CsI(Tl) is nearly independent of T, in this temperature range, consistently with the previously described behaviour of this scintillator [4].

In fig. 5 a decay time spectrum is shown: the two well resolved peaks correspond to BGO (the narrower) and CsI(Tl) events respectively.

Temperature variations produce changes in the decay time peak positions of BGO and CsI(Tl) (see fig. 6): both decrease with increasing T, but CsI(Tl) is characterized by the higher rate of change. This fact is in apparent contradiction with the reported properties of these materials [4], but it can be understood when taking into account the pulse shaping time effects. When the shaping time of the amplifier is much greater than the pulse decay time the relation between the latter and the output of the pulse shape analyzer becomes nonlinear. We checked this effect using a spectroscopic pulse generator which provides pulses with different decay times, and found that the pulse shape analysis became less sensitive to decay time variations when the decay time was decreased to about one third of the shaping time. We stress, however, that such behaviour is not present only in the Ortec system used by us, but it is typical of several other pulse shape discriminators such as, for example, the Harshaw NC-25A [5].

All measurements have performed done by setting a window on the signal amplitude including only the photopeak. In this way we were able to investigate the

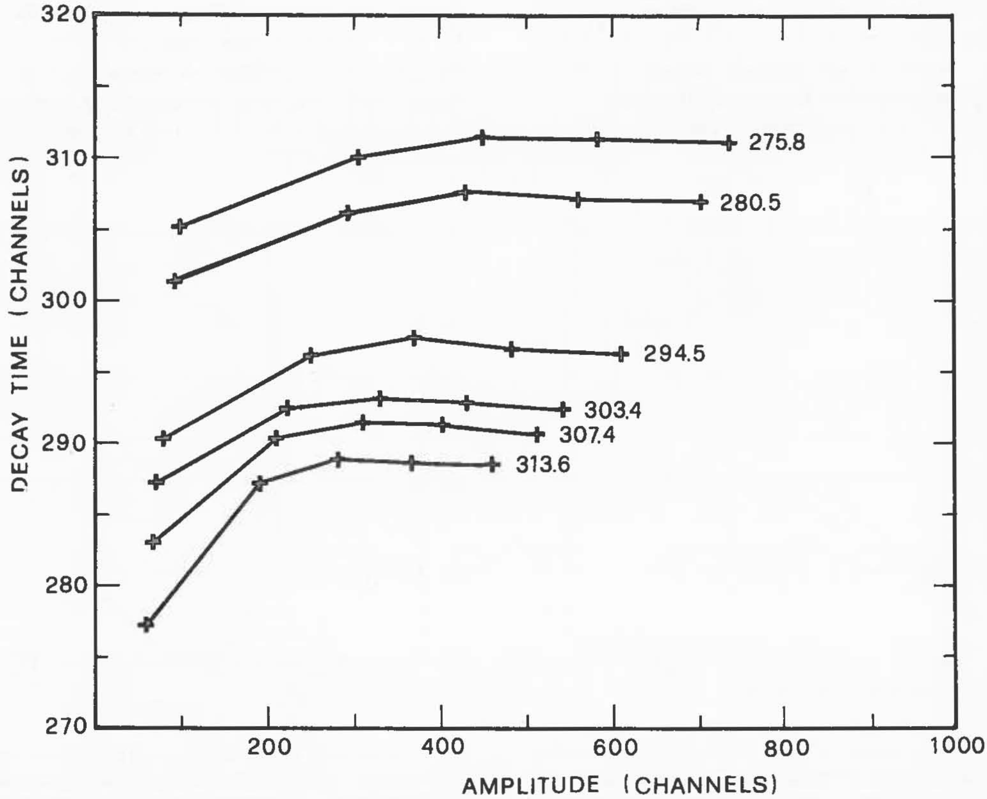

Fig. 7. The decay time–amplitude relation at various temperatures for the BGO crystal. The decay time is practically independent on the signal amplitude for photon energies greater than 300 keV. Both axes are in channel units.

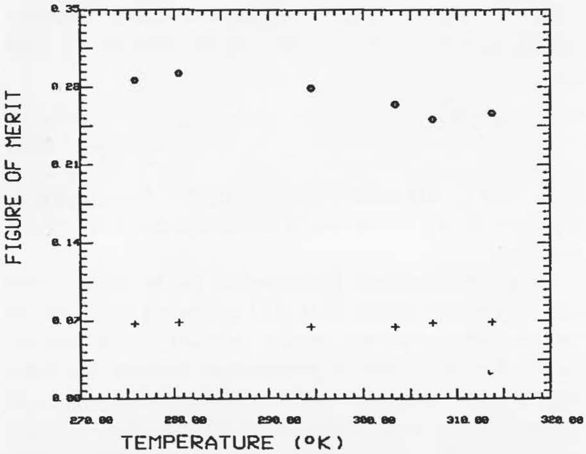

Fig. 8. The figures of merit for the two crystals of the BGO (+) – CsI(Tl) (●) phoswich as a function of the temperature for 662 keV (^{137}Cs line) photons.

time–amplitude relation at various temperatures. This is shown for the BGO in fig. 7: note that for photon energies greater than about 300 keV the positions of the peaks in the decay time spectra are nearly independent of the signal amplitude; for small amplitude signals, the residual amplitude walk gives an underestimation of the pulse duration. This effect is particularly evident in the higher temperature curves, where, despite the small amplitude variation of the signal from the ^{57}Co line (122 keV), the difference between the decay time peak of this source and that of the others is about 0.7 of the fwhm.

An estimate of the performance can be made by evaluating the figures of merit introduced by Bleeker and Overtoom [6]:

$$f_B = \delta_B / \Delta, \tag{1a}$$

$$f_C = \delta_C / \Delta, \tag{1b}$$

δ_B and δ_C being the fwhm of the BGO and CsI(Tl) peaks, respectively, and

$$\Delta = p_C - p_B \tag{2}$$

is their distance apart (p_B and p_C are the positions of the decay time peaks). The measured f values vs T for both scintillators are plotted in fig. 8 for the photon energy of 662 keV (^{137}Cs line). One sees that, across the whole temperature interval, the BGO figure of merit has the constant value of 0.067 ± 0.002; that of CsI(Tl)

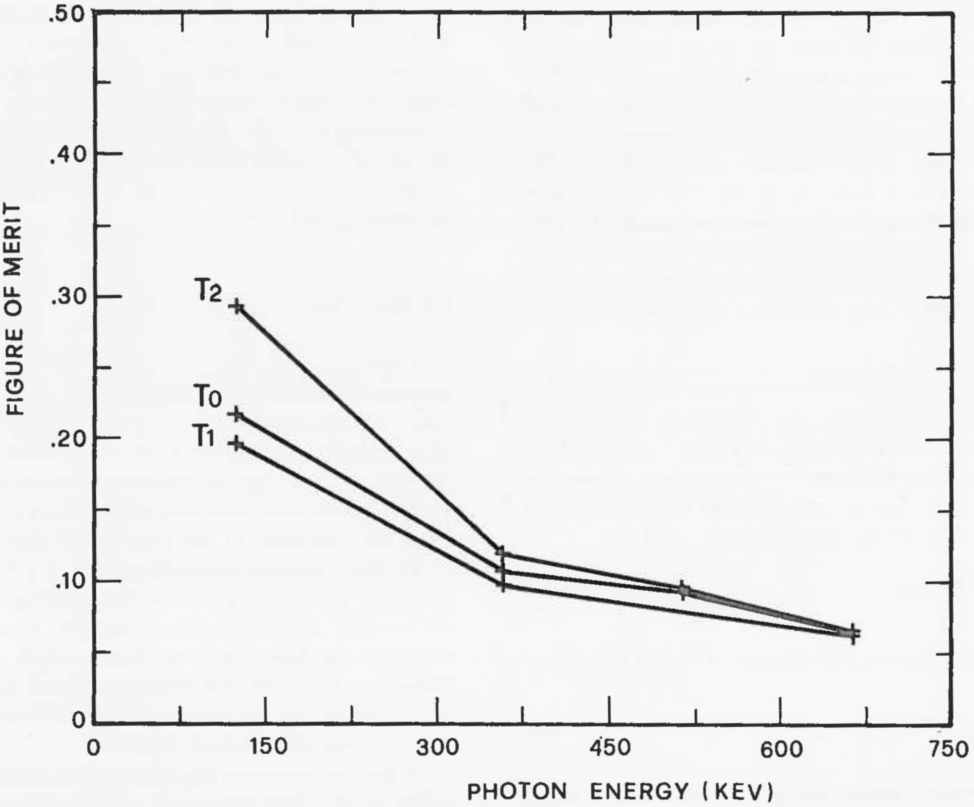

Fig. 9. The energy dependence of the BGO figure of merit at three different temperatures ($T_0 = 294.5$, $T_1 = 275.8$ and $T_2 = 313.6$ K), as a function of energy of incoming photons.

shows a slight dependence on T and tends to improve with increasing temperature. It lies, however, within the interval 0.25–0.30.

It is interesting, finally, to study the behavior of f with the energy of incoming photons. The resulting values for BGO are plotted in fig. 9 for the three temperatures T_0, T_1 and T_2. We have verified that with a very narrow amplitude window the widths of the peaks are intrinsic and are not due to the amplitude walk.

4. Time window selection and counting efficiencies

The results of the previous section can improve the strategy for performing reliable measurements in critical conditions with the BGO–CsI phoswich. The main problem affecting the reliability of a measurement are changes in: (1) the detection efficiency of the signal, and (2) the rejection efficiency of the background.

The variation in light yield with temperature and the related variation of the gain will affect both (1) and (2) as in any conventional system because the levels of the electronic thresholds will change with respect to the spectrum being measured. If the gain is continuously monitored by radioactive sources this effect can be compensated for either by on-line adjustment (for instance, by reaction on HV or on a programmable amplifier) or by corrections in the off-line analysis. The procedure is not trivial when the signal is of the order of 1% of the background, but it is well established.

The knowledge of the behavior of f with temperature can be useful in order to set the best time window upper limit in the pulse shape discrimination. Usually this limit w is fixed near the minimum between the two peaks. Normally it differs from the two peak positions by some multiple (n_B and n_C) of their respective fwhm:

$$w = n_B\delta_B + p_B = p_C - n_C\delta_C. \tag{3}$$

As shown by our results p_B, p_C, δ_B, δ_C vary with T. If one wishes to maintain unchanged the fraction of the accepted (or rejected) events, it is necessary to keep n_B and n_C constant. Let us introduce the window limits at any temperature for fixed values of n_B and n_C:

$$w_B = n_B\delta_B + p_B, \tag{4a}$$

$$w_C = p_C - n_C\delta_C, \tag{4b}$$

where at T_0, $w_B = w_C$. From eqs. (1), (2) and (4) it follows that:

$$w_C - w_B = \Delta(1 - n_B f_B - n_C f_C). \tag{5}$$

At the reference temperature T_0, n_B and n_C are bound by the following relation:

$$n_C f_{C0} = 1 - n_B f_{B0}, \tag{6}$$

where f_{C0} and f_{B0} are the figures of merit of the two scintillators at T_0. By inserting eq. (6) into eq. (5), one has:

$$w_C - w_B = \Delta[(1 - f_C/f_{C0}) + n_B f_{B0}(f_C/f_{C0} - f_B/f_{B0})]. \tag{7}$$

If f_B and f_C are both independent of T (i.e., $f_B/f_{B0} = f_C/f_{C0} = 1$), w_B turns out to be always equal to w_C, as expected.

The considerations developed so far are general and can be applied also to NaI–CsI phoswich detectors. In this respect we do not expect relevant differences between the two types of phoswiches because the main temperature variations have been observed for the CsI crystal. In the case of the BGO–CsI(Tl) phoswich our measurements indicate that f_B is independent of temperature. Then eq. (7) can be simplified to:

$$w_C - w_B = \Delta[(1 - n_B f_B)(1 - f_C/f_{C0})]. \tag{8}$$

For example, we can evaluate the window difference for one of the cases discussed in sect. 3. Taking $n_B = 4.5$, which at the reference temperature T_0 gives good discrimination, at $T_2 = 313.6$ K and with $f_C/f_{C0} = 0.9$ we find a difference between the two windows of 20 channels, a figure comparable to δ_B and to $\delta_C/7$. Moreover, we have verified that a window relation with n_B constant actually gives the same fraction of counts in the BGO photopeak at different temperatures. To verify this we have evaluated the ratio of BGO photopeak events detected in anticoincidence to those detected in coincidence with the above time window ($n_B = 4.5$) set on the BGO peak. This fraction is equal to 5% and remains constant as expected at each temperature within the investigated interval.

5. Conclusions

Phoswich detectors are suited for X- and γ-ray astronomy or field applications, where it is necessary to detect a weak signal from an intense, often anisotropic, environmental background. In such conditions, however, it is not simple to achieve a thermal stabilization of the detector and therefore temperature variations can affect the efficiency of the pulse shape discrimination.

We have checked the performance of a BGO–CsI(Tl) phoswich at several temperatures ranging from 2.5 to 40 ° C, with laboratory measurements. Apart from the effects of the light yield variations, which can be controlled by adequate HV adjustments, we have focused our attention on the discrimination efficiency and the criteria to choose the best window.

When the temperature changes, the position of both peaks in the time spectrum move, and an adjustable threshold could completely compensate for only one of the two crystals. Therefore, if the threshold is set to keep the efficiency constant some change in background rejection can be expected. As discussed in sect. 4 this can be expressed as a variation of the figure of merit. For the BGO–CsI(Tl) phoswich investigated by us the difference will always be small. The best strategy is to fix the threshold with the criterium that the systematic effects are maximized where the statistical errors are also expected to be larger. For example, if the signal is only a small fraction of the background of the order of a few percent as in many astrophysical conditions, one could set the window on the CsI peak in order to have a constant background level. When the signal to noise ratio is high, it is better to set the window on the BGO peak in order to avoid the detection of fictitious signal variations of the source.

Finally, we stress the result that a good discrimination between BGO and CsI events is obtained within the investigated temperature interval with the only limitation that the BGO signal be strong enough to give a decay time estimate independent of the amplitude. This condition is reached for γ-ray energies greater than about 300 keV, which represent the lower threshold for the optimal use condition of this device.

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