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Interior temperature monitoring of NaI(Tl) crystal in space environment by pulse width measurement

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ABSTRACT

In this paper, we develop a direct and reliable method of monitoring the interior temperature of a NaI(Tl) crystal in space environment. This method employs the temperature-dependent pulse width measured with a new pulse shape analyzer (PSA). The temperature dependence of the scintillation properties of the NaI(Tl) crystal is measured three times in the temperature range −20 to 45 °C from August to December 2008. Those measurements show that the pulse width of the NaI(Tl) crystal monotonically depends only on the temperature of the crystal. The relation between pulse width and temperature of the NaI(Tl) crystal is calibrated with a third-order polynomial. We apply this relation to monitor the interior temperature of the NaI(Tl) crystal under thermal non-equilibrium environments. We found that the crystal's interior temperature is generally quite different from that of its surrounding locations. This method is then used to improve the energy resolution of the detector in a temperature varying environment, by correcting the signal amplitude of each recorded event based on its pulse width.

1. Introduction

The hard X-ray modulation telescope (HXMT) is a Chinese high-energy astrophysics mission [1]. The satellite payload contains 18 high-energy X-ray detectors (HED), which are NaI(Tl)/CsI(Na) phoswich detectors operating between 20 and 250 keV. The surrounding temperature of the HED is expected to be from −10 to 40 °C, when the HXMT is in orbit. Within such a wide temperature range, the detector gain will vary significantly due to the temperature-dependent characteristics of NaI(Tl) crystal [2–4]; consequently this will degrade the energy resolution of the detectors significantly. It is thus crucial to monitor the interior temperature of the NaI(Tl) crystal, in order to make temperature-dependent correction to the amplitude of the signal to reflect the true energy deposition of each event.

Due to the combination of the bad thermal conductivity of NaI(Tl) crystal and the sealing because of its easy deliquescence, there is normally a non-negligible temperature gradient between the interior of the NaI(Tl) crystal and temperature sensors outside when the ambient temperature changes rapidly in a large range. In this case the commonly used temperature sensors outside cannot measure the interior temperature adequately, and thus does not allow temperature-dependent corrections to the recorded signal amplitude reliably. Therefore the strongly temperature-dependent pulse shape of its scintillation signal has been exploited to monitor the crystal's interior temperature. For example, the zero-crossing technique [5] is widely applied in pulse shape discrimination to obtain the amplitude-independent pulse time [6], which can be used to measure the crystal's interior temperature. Pausch et al. [7] found that the zero-crossing time obtained from a pulsed signal is linearly dependent on the light decay time and thus can be applied to derive the crystal's interior temperature; their methods made use of the rising edge of the pulsed signal.

Alternatively, in this work we develop a method of monitoring the interior temperature of a NaI(Tl) crystal, utilizing a new PSA [8] to measure the pulse width of its output signal, which makes use of the whole pulse including the rising and the falling edge. We find that the pulse width depends almost only on the crystal temperature, making it possible to monitor the interior temperature of the NaI(Tl) crystal reliably. In this work we first measure and calibrate the relation between the pulse width and crystal's interior temperature. We then apply this relation to trace the interior temperature of NaI(Tl) crystal under thermally non-equilibrium environment, mimicking the space environment. Finally the temperature-dependent correction to the crystal's temperature in energy measurement of gamma-rays is made by utilizing the measured pulse width of each recorded event.

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2. Experiment methods

Fig. 1 is an illustration of a HED used in our experiments. A cylindrical NaI(Tl) crystal with a 190 mm diameter and 3.5 mm thick, and a CsI(Na) crystal with a 190 mm diameter and 40 mm thick produced in Ukraine, are air-sealed in an Al-alloy housing with a 1.5 mm thick Be entrance window and a 10 mm thick quartz exit window. The NaI(Tl) crystal is used to detect the front incident X-rays, and the CsI(Na) crystal serves to shield the energetic particles coming from the opposite directions with almost a 2π solid angle and to exclude those Compton scattering events which deposit energies in both crystals. A Hamamatsu R877 PMT, coupled with the quartz window by a piece of Saint-Gobain BC-634A film, is used to collect the scintillation photons. In the backend of the HED, a direct-coupling voltage preamplifier is connected to the PMT with a shaping constant τ of 240 ns in the anode. Two heating belts of about 16 W are wrapped around the Al-alloy shell, forming an unclosed circle with two gaps. In one gap a temperature sensor T_c is adhered tightly to the Al-alloy shell; T_c is also used to feed the temperature value back to the controller for switching the power of heating belts on or off. Another temperature senor T_a is adhered to the front surface of the Be window. Both sensors are covered with a thermally insulating plastic to reduce the effect of the surrounding temperature. The third sensor T_b is inserted between the quartz window and PMT glass, and also thermally insulated from the Al-alloy shell. All three temperature sensors have a precision of 0.03 °C.

Fig. 2 shows a typical voltage pulse from the preamplifier. It has been known that a NaI(Tl) crystal has several decay components [4,9] with different decay time τ_f and intensity percent ρ_f (f=1, …, n). It is reasonable to assume that the light output of each component is almost purely exponential; the relatively short transit time in the PMT is also ignored. Therefore the recorded pulse's voltage for each event can be expressed as

$$V(t) = V_0 \sum_{f=1}^{n} \rho_f \frac{\tau}{\tau_f - \tau} (\exp(-t/\tau_f) - \exp(-t/\tau)) \quad (1)$$

where $\Sigma\rho_f$=1 and the constant V_0 involves characteristics of the NaI(Tl) crystal, the PMT, and the preamplifier for a certain energy deposition in the crystal [3]. According to Eq. (1), the pulse width W defined as the difference between t_β and t_α is almost uniquely determined by the temperature of the NaI(Tl) crystal, because the decay time τ_f and intensity percent ρ_f are only functions of the temperature in a certain NaI(Tl) crystal for a given type of incident particle. In this work we focus our study on gamma-rays only, and thus do not consider the temperature dependence due to other types of particle [11,12]. This is the basis for monitoring the crystal's interior temperature by measuring its pulse width.

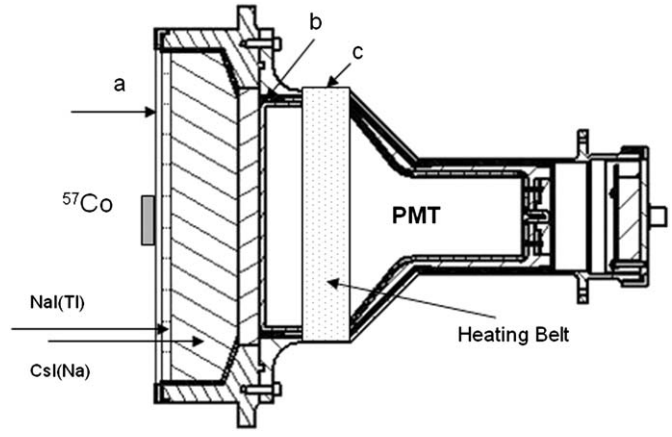

Fig. 1. Illustration of the HED used in our experiments. See text for detailed descriptions.

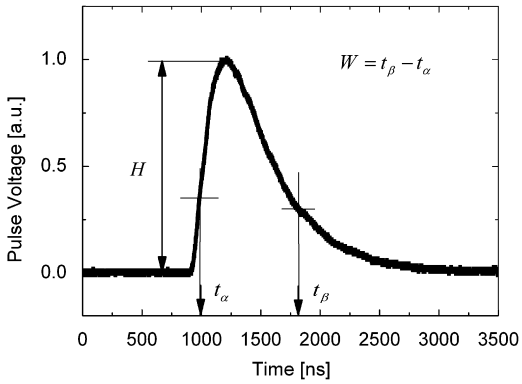

Fig. 2. Definition of the pulse width W and the pulse height H. t_α is the time when the amplitude-percentile reaches $\alpha(0\sim1)$ at the rising edge of the pulse, and t_β stands for that time when the amplitude-percentile is β $(0\sim1)$ at the falling edge.

In our experiment, the temperature dependence of the NaI(Tl) crystal is measured in the temperature range −20 to 45 °C. The scintillation detector is placed in a chamber which provides the necessary temperature and pressure environments. An un-collimated radioactive isotope ^{57}Co source of about 200 Bq is placed at the center of the entrance window of the detector. The electronic system containing the PSA is outside the chamber for convenient operation. The unipolar signal, as shown in Fig. 2, is analyzed with the PSA, in which the signal is digitized by the 10 bit AD9215 FADC with a sampling rate of 105 MSPS made by Analog Devices Inc.; the precision of the PSA is 8.33 ns. Its pulse height and percentile times t_α and t_β are extracted with the Spartan-3 FPGA from Xilinx Inc. Our experience has shown that the amplitude-percentiles α and β should be taken to be around 0.3 [8].

3. Measurement and calibration of the pulse width—temperature relation

In our experiment, the temperature dependence of the NaI(Tl) crystal is measured in the temperature range −20 to 45 °C. At each temperature, the assembly is held for more than 10 h to reach a complete thermal equilibrium, by judgment of steady pulse width spectrum of the NaI(Tl) signals. Three experiments have been done in the past four months. Two of them were carried out under a normal pressure; the third one was at a low pressure of 1 Pa.

In Fig. 3, three gray-scale graphs show the two dimensional distributions of pulse heights and pulse widths of the NaI(Tl) signals, measured in the third experiment at the low pressure of 1 Pa and at three different temperatures of 39.9, 10.8, and −11.5 °C. The black ellipse, surrounded by a dashed box, stands for the 122.1 keV gamma ray's photoelectric peak of the ^{57}Co source. The other parts of the spectra are contributed by characteristic signals of the shielding lead, escaped signals of iodine in the NaI(Tl) crystal and other background signals. From Fig. 3, we can obviously see that the measured pulse width is almost independent of pulse height (corresponding to different energy deposition) at a given temperature. The variation of the average pulse width caused by pulse height varying from 170 to 230 channels is less than 1%, which is much less than that of about 50% due to the temperature change of the crystal between −20 and 45 °C.

For further analysis, the dependence of the pulse height H_{pp} of the 122 keV photo-peak as a function of temperature is shown in Fig. 4, for all three experiments with the same HED during four months. The pulse heights H_{pp} measured in the two later