Study of Undoped CeF₃ Scintillators at Room and Liquid Nitrogen Temperature

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Abstract—In this paper properties of various undoped CeF₃ scintillators were investigated at room and liquid nitrogen (LN₂) temperature. The study was focused on measurements of radioluminescence spectra, decay time, non-proportional response on X- and γ-rays and energy resolution at different temperature environment. Surprisingly, the pure CeF₃ crystals show comparable non-proportionality curves, which are very similar to that presented by inorganic scintillators. The investigation of the phenomenon occurring in CeF₃ scintillators would be another step to get a better knowledge of the scintillators nature, which still haven’t been entirely understood.

Index Terms—gamma spectroscopy, scintillators, CeF₃, pure CeF₃, decay time, emission spectra, non-proportionality, energy resolution, intrinsic resolution, light output, liquid nitrogen, LN₂.

1. Introduction

Scintillation properties of CeF₃ crystals at room temperature were subject to a number of studies [1] - [3]. It is a dense (6.16 g/cm³) and non-hygroscopic crystal, characterized by a fast (30 ns time constant) light response and light yield of the order of few percents of that of NaI(Tl). The CeF₃ was considered as a detector material for calorimeters in high energy physics and rare nuclear decay experiments. Most of inorganic scintillators reveal a non-proportional light response, as studied for gamma-rays, an effect mostly pronounced in the low energy region below 100 keV [4]. Recent results for undoped YAP, CdWO and ZnWO indicated that this effect is temperature depended, with higher proportionality at lower temperatures, as observed at liquid nitrogen (LN₂) temperature [5] - [8]. Present studies aim at scintillation properties of undoped CeF₃ at room and LN₂ temperatures, which includes measurements of emission spectra, gamma-ray response and non-proportionality.

2. Emission spectra

Emission spectra were performed using Digikrom CM110 monochromator synchronized with Ortec 994 counter by a dedicated software, a system formerly used in [6]. Acquired data were transferred to a PC via RS232 cables. Diffracted light was recorded by Photonis XP 52128 photomultiplier. The counter was gated to record only the pulses originated from single photoelectrons. Radioluminescence spectra at room and LN₂ temperature were also performed and compared with the spectra recorded previously for other crystal by 254 nm UV light [1]. In this study, a strong (1.37 GBq) ²⁴¹Am source, emitting 59.5 keV γ-rays, was used to irradiate the scintillator. The crystal was placed inside a cryostat and mounted on a cold finger, behind the beryllium window, situated on one side of the cryostat. Measurements showed that the maximum emission is actually the same both at room and LN₂ temperature and is situated at about 310 nm. However, at room temperature additional structures at 340 and 420 nm are observed. These structures disappear after cooling down the crystal to LN₂ temperature. Even more, intensities of the light emission structures are different in comparison with that curves measured with UV light, because X-rays excite higher energy states of the crystals. The emission spectra curves are presented in Fig. 1.

3. Decay time

It was showed in [1] that scintillation decay of a CeF₃ crystal consists of decay constant of 27.2 ns. In our study, the decay time of the 7x8.5x5 mm³ CeF₃ sample has been measured. The decay curve is presented in Fig. 2. Our measurements showed that the crystal has a fast decay component of 31.9 ± 0.5 ns, which is in good agreement with that measured by Anderson [1].

4. Light output and energy resolution

In the measurements at both room and LN₂ temperatures the crystals were coated by several layers of Teflon tape. At room temperature studies the crystals were coupled by silicon grease to a Photonis XP 5212B photomultiplier.
(PMT). A signal from the PMT anode was processed by a Canberra 2005 preamplifier and sent to an Ortec 672 spectroscopy amplifier working at 1 µs shaping time. Finally, spectra were acquired by Tukan 8K Multi-Channel Analyzer [9].

![Image of decay curve](image)

Fig. 2. The decay time of the 7x8.5x5 mm$^3$ CeF$_3$ sample at RT, recorded by Tektronix TDS 3032B digital oscilloscope. The decay curve is slightly distorted due to insufficient vertical resolution of the oscilloscope.

In the case of LN$_2$ temperature the experiments were performed only for the 7x8.5x5mm sample, due to its superior light yield at RT. The crystal was mechanically coupled (no silicone grease) to a UV enhanced Large Area Avalanche Photodiode (LAAPD) with diameter 16 mm situated in a cryostat. The sample was placed in the center of the LAAPD and the remaining open area, outside the crystal, enabled direct X-ray illumination of the photodiode. In this way 5.9 keV X-rays from a $^{55}$Fe source could be recorded, used as a reference in the determination of the electron-hole pairs (e-h) generated by the scintillation light.

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Size</th>
<th>Light Output</th>
<th>Energy resolution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CeF$_3$ RT</td>
<td>7x7x9 mm$^3$</td>
<td>360±20 phe/MeV</td>
<td>17.0±0.5</td>
</tr>
<tr>
<td>CeF$_3$ RT</td>
<td>7x8.5x5 mm$^3$</td>
<td>450±20 phe/MeV</td>
<td>16.2±0.5</td>
</tr>
<tr>
<td>CeF$_3$ LN$_2$</td>
<td>7x8.5x5 mm$^3$</td>
<td>920±30 e-h/MeV</td>
<td>16.4±0.5</td>
</tr>
<tr>
<td>CeF$_3$ Crytur RT</td>
<td>10x10x5 mm$^3$</td>
<td>160±10 phe/MeV</td>
<td>21.0±0.6</td>
</tr>
</tbody>
</table>

Table 1. The undoped scintillators used in the present investigation. The light output and energy resolution are obtained from a Gaussian fit of the 661.7 keV ($^{137}$Cs) full energy peak.

The yields of photoelectrons at room temperature (RT) for all the crystals compiled in Table 1 were determined by relating the photopeak position of the 662 keV gamma line in the energy spectrum to the single photoelectron peak of the XP5212B photomultiplier. In similar way, at LN$_2$ temperature, comparison of the 662 keV peak position due to the scintillation light to that of the 5.9 keV X-rays ($^{55}$Fe) detected in the LAAPD itself, allowed determination of the number of e-h pairs produced in LAAPD. The results in Table 1 indicates the 7x8.5x5 mm crystal to be much superior compared to the other ones, why chosen for studies at LN$_2$ temperature.

5. Non-proportionality

Fig. 4 exhibits the non-proportionality values for the 7x8.5x5 mm crystal as extracted from the measurements at RT and LN$_2$ temperatures. During measurements at LN$_2$ temperature peaks in the range of energy from 122 to 1274 keV were collected. Due to low light output of the crystal, below 122 keV peaks were covered by noise generated by LAAPD, thus, analyzing of this energy range was impossible. There is one general feature for the results, which is a distinct non-proportionality in the wide energy region up to the highest gamma energy of 5.1 MeV. This is much contrary to previous observations for a large number of scintillators, showing a well pronounced light yield non-proportionality but only at energies below 100 keV. In addition, values in Fig. 4 at the two temperatures are much the same, i.e. no temperature effect is observed. In next section will be present that intrinsic resolution of CeF$_3$ is also unchanged after the crystal cooling down in comparison with that at RT.

6. Intrinsic resolution

The energy resolution of full energy peak measured with scintillator coupled to photodetector was derived with formula proposed in [10], [11]:

$$\left(\frac{dE}{E}\right)^2 = \left(\delta_{\text{int}}\right)^2 + \left(\delta_{\text{stat}}\right)^2 + \left(\delta_{\text{noise}}\right)^2$$

(1)

where $\delta_{\text{int}}$ is an intrinsic resolution of the scintillator, $\delta_{\text{stat}}$ is a statistical factor of the photodetector and $\delta_{\text{noise}}$ is a dark noise contribution. It is easy to calculate the intrinsic resolution using that formula. The $(\delta_{\text{noise}})^2$ contribution is negligible for PMT.
We estimated the intrinsic resolution of the 7x8.5x5 mm$^3$ CeF$_3$ sample at RT and LN$_2$, see Fig. 4. We observed that cooling the crystal to LN$_2$ temperature doesn’t affect the intrinsic resolution. We weren’t able to measure the peaks corresponding to lower energy at LN$_2$. It was due to the fact that the crystal has low light output and peaks were covered by the noise generated by LAAPD.

![Intrinsic resolution of the 7x8.5x5 mm$^3$ CeF$_3$ measured both at room and LN$_2$ temperature.](image)

**Fig. 4.** Intrinsic resolution of the 7x8.5x5 mm$^3$ CeF$_3$ measured both at room and LN$_2$ temperature.

### 7. Conclusion

The CeF$_3$ scintillator is a very attractive material to study due to its unusual non-proportional response on X- and $\gamma$-rays with regards to inorganic scintillator. Moreover, it was shown that the non-proportionality and intrinsic resolution does not change after crystal cooling down to liquid nitrogen temperature. This paper shows that fundamental research in the field of scintillator spectrometry each year presents a new and interesting behavior of the scintillating crystals.

### References


