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Development of techniques for characterisation of scintillation materials for cryogenic application

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HIGHLIGHTS

► Multi-photon counting technique was designed to measure response of scintillators.
► Technique is tailored to study slow scintillation processes and temperature changes.
► Latest development of the technique permitting wide application are discussed.
► Studies of scintillation characteristics of MgF_2 are presented as illustrative case.

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ABSTRACT

The multi-photon counting (MPC) technique was designed to record photon emission of scintillators and, as a very powerful method of material characterisation, is enjoying increasing popularity. The technique is especially advantageous for the analysis of slow scintillation processes and the investigation of temperature-dependent scintillator properties. The paper describes the latest development of the technique aiming to improve performance and widen the scope of applications. The results from characterising MgF_2 are presented to illustrate the capabilities of the MPC technique.

1. Introduction

The search for rare events is a most vibrant research area in astroparticle physics.[1] Finding neutrino-less double beta decay and detecting weakly interacting massive particles requires detectors capable of discriminating the weak and rare signal over the dominating background of spurious events caused by natural radioactivity and cosmic rays. This can be achieved, for example, in low-temperature detectors by the simultaneous measurement of the phonon and scintillation responses (Alessandrello et al., 1998; Meunier et al., 1999; Mikhailik and Kraus, 2006). The technique exhibits efficient event type discrimination, providing a very important tool for the identification of radioactive background. This, in combination with other advantages of cryogenic phonon detectors, such as greatly enhanced energy resolution and low threshold, elevated cryogenic phonon-scintillation detectors (CPSD) to the category of especially promising techniques for next-generation experiments searching for WIMP Dark Matter (Cebrian et al., 2004; Angloher et al., 2009; Brown et al., 2012), neutrinoless double beta decay (Pirro et al., 2006; Arnaboldi et al., 2011) and radioactive decay of very long-living isotopes (De Marcillac et al., 2003; Cozzini et al., 2004). Inorganic scintillators are a key element of CPSD and in recent years there has been a continuous increase in research activities and the development of scintillator materials capable of meeting the strict design requirements of rare event experiments (Mikhailik et al., 2006; Nagornaya et al., 2009; Kraus et al., 2009; Dubovik et al., 2010; Gironi et al., 2010; Lee et al., 2011; Alenkov et al., 2011).

Unlike most conventional applications of scintillators, rare event searches do not require sintillators with fast decay times. Therefore

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[1] http://www.aspera-eu.org/images/stories/files/Roadmap.pdf

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they have the option to use scintillators which are traditionally considered as "slow" (Mikhailik and Kraus, 2010). One of the ways to gain insight into the features of the scintillation process of a material, and to identify possible improvements, is via measurements of temperature dependence of decay times and the light yield. To address this issue we developed the multi-photon counting (MPC) technique that allows measurement of these scintillator parameters over a wide range of temperatures (Kraus et al., 2005).

Since the first publication on MPC, there have been substantial upgrades of the technique's hard- and software with the aim to improve overall performance and extend the capabilities of MPC, making it suitable for versatile studies that involve measurements of slow decay processes over a wide temperature range (Kraus et al., 2007a; Mikhailik et al., 2007a,b; Kraus et al., 2007b; Danevich et al., 2008; Verdier et al., 2009). MPC is also becoming a key component of newly emerging methods, such as the Monte Carlo refraction index matching technique (MCRIM) (Wahl et al., 2007). Given such success of the technique, and addressing the growing interest of the community in practical implementations of this development, as shown elsewhere in this paper, we present the main principles, describe the practical implementation of the method, and discuss performance characteristics of the MCP in its latest version.

2. Characterisation of scintillators at low temperatures – main issues

Characterisation of scintillation detectors has so far relied almost exclusively on the use of high-gain photomultiplying tubes (PMT) or avalanche photodiodes (APD). However it is very difficult to carry out reliable measurements of light yield using conventional techniques if the detector and scintillator under investigation are subjected to a change of temperature. In addition to the technical difficulties of operation, the response of PMTs and APDs strongly depend on temperature (Moszynski et al., 2003; Nikkel et al., 2007; Kraus and Mikhailik, 2010) and filtering out these contributions can be difficult (Piltingsrud, 1979; Valentine et al., 1993; Yang et al., 2003; Ikagawa et al., 2005; Bizarri et al., 2006). To avoid this problem it is preferable to keep the light detector at constant temperature, i.e. outside of the cryogenic apparatus. However this inevitably reduces the solid angle, causing a reduction of the light collection efficiency. In such geometry merely fast scintillators with high light yield can be studied when using a conventional method for data recording and analysis.

Additional problems associated with the necessity to cover a large range of decay time constants arise in their studies as function of temperature. The delayed coincidence single-photon counting (DC-SPC) technique has excellent timing resolution (ca. 0.5 ns) and it is commonly used for measuring the decay characteristics of traditional fast scintillators with decay time constants in the range of nano-seconds to micro-seconds (Moszynski and Bengtson, 1977). If the decay time constant of the scintillator is in the region of several micro-seconds, pulse shape analysis (PSA) can be implemented (Knoll, 1999; Zdesenko et al., 2005). One generic source of error is inherent for these measurement techniques. Measurements of the temperature dependence of the decay time constant must allow for its variation over a large range of values (from tens of μs to tens of ms). This requires a correspondingly long recording time. As it is not practically possible to fully control the rate at which ionising radiation interacts with the scintillator, there are always events recorded in which a second (or more) scintillation event will have occurred during the measurement period of the first, a so-called multiple excitation event or "pile-up". These events contribute to the total signal resulting in a roughly even time difference distribution throughout the decay time spectrum, and if not removed can cause false atty component. This issue is becoming even more important with a decrease of temperature, when the scintillation decay time increases, which in turn leads to enhancing the probability of multiple excitations. The only practical approach to overcome this problem would be to implement appropriate statistical methods of analysis allowing recognition of single and multiple events.

3. Setting-up multi-photon counting

There are two key considerations concerning the characterisation of scintillators over a wide temperature range that arise from the previous section. Firstly, the detector and scintillator should be spatially separated and secondly, to enable off-line analysis on event-by-event basis, the single photon counting mode should be used to record the scintillation events. Fortuitously these conditions can be reconciled: single photon counting requires a rate low enough to avoid pile-up of individual photoelectrons generated. In this case, the measurements imply detection of a few tens of photons distributed throughout an interval of 10–1000 μs duration of the slow scintillation processes, and that can be easily arranged by using ~100 MHz electronics. This also determines the optimum range for decay time constant that can be confidently measured by method as 10^{-6}–10^{-2} s. The lower limit is due to the pile-up of signals from the individual photoelectrons in the initial part of fast scintillation event. The upper limit is determined by the pile-up of different scintillation events and therefore it is controlled by values of measured decay time constant τ and excitation rate; as a rule of thumb the excitation rate should be $< 1/3\tau$.

The MPC method is based on recording a sequence of photoelectron pulses produced by a PMT when detecting photons from a scintillation event. Each pulse in the sequence corresponds to an individual photon impinging on the photocathode of the PMT. The output PMT signal is statistical in nature, both with regard to the time interval between photons and the total number of detected photons. The distribution of arrival times of the photons provides information on the decay characteristics of the scintillation process, while the number of photons recorded per event is proportional to the light yield of the scintillator. Thus, recording a large number of scintillation events (10^3–10^4) one can obtain the decay time characteristics and the light yield in a single measurement.

For scintillation detection we use bi-alkali 9125BQ or multi-alkali 9124A PMTs (Electron Tube Enterprise, Ruislip, UK) with a single electron pulse width of 7.5 and 5 ns, respectively. To detect a sequence of single photoelectron pulses, a data acquisition chain with a ~10 ns resolution is adequate. The charge signals of the PMT are converted into voltage pulses, using an integrating amplifier with a time constant of ~10 ns. After that, the signal is transmitted into comparatively long coaxial cables. Part of the signal is fed into a transient recorder while another is passed to the slow part of the electronics to derive the trigger.

To record the signal produced by PMT and pre-amplifier we use LeCroy CAMAC-based transient recorders TR8828D or TR8818A. The model TR8828D permits recording with a sampling interval of 5 ns; and that is useful when higher resolution is required to resolve scintillation events with a high rate of PMT pulses, i.e. while studying the scintillation processes at room temperature under conditions when the scintillator is close to the PMT (Kraus et al., 2007b; Mikhailik et al., 2007a,b; Danevich et al., 2008). The characteristic time resolution of the setup is defined by the FWHM of the individual pulses formed by the preamplifier, which accounts for ~15 ns and therefore a 5 ns sampling interval is adequate. Conversely, for the investigation of temperature dependences of the scintillation characteristics, the sampling interval can be longer (10 or 20 ns) but one needs a long record length (Mikhailik et al., 2006; Nagornaya et al., 2009; Dubovik et al., 2010; Alenkov et al.,