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Measurement of propagation time dispersion in a scintillator

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Abstract

One contribution to the time resolution of a scintillation detector is the signal time spread due to path length variations of the detected photons from a point source. In an experimental study, a rectangular scintillator was excited by means of a fast pulsed ultraviolet laser at different positions along its longitudinal axis. Timing measurements with a photomultiplier tube in a detection plane displaced from the scintillator end face showed a correlation between signal time and tube position indicating only a small distortion of photon angles during transmission. The data is in good agreement with a Monte Carlo simulation used to compute the average photon angle with respect to the detection plane and the average propagation time. Limitations on timing performance that arise from propagation time dispersion are expected for long and thin scintillators used in future particle identification systems.

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1. Introduction

There has been recent interest in the timing performance of long and thin plastic scintillation detectors with demands on the time resolution of 100 ps and below, e.g. for the future $\overline{\mathrm{P}}$ANDA experiment at FAIR [1]. An existing experiment with a challenging scintillator system is COMPASS with the installation of the 2.8 m long and 4 mm thin recoil detector under way [2]. This paper shows that the detector performance required by these experiments is close to the fundamental limit that arises from the statistical fluctuations in the process of the signal generation.

At $\overline{\mathrm{P}}$ANDA, the identification of charged particles with momenta up to several GeV/c will be performed by the detection of internally reflected Cherenkov (DIRC) light [3]. Any measurement of the time-of-propagation (TOP) in the DIRC counter needs a precise time reference and can be combined with the time-of-flight (TOF) information from long scintillator slabs in front of the radiator barrel of the DIRC. Within the almost fully hermetic $\overline{\mathrm{P}}$ANDA detector such a scintillator array needs to be as thin as physically possible. At COMPASS, it is the need for a low momentum proton detection that requires the scintillators to be very thin.

The timing properties of scintillators are usually defined in terms of a coincidence time resolution. In a typical laboratory measurement the time difference between the discriminated signals of two photomultipliers (PMTs) placed at the extremes of a sample of scintillator is measured for minimum ionising particles crossing the scintillator at its centre. For small counters of 45 cm length and 20 mm thickness a time resolution reduced for one PMT of the order of FWHM $\approx$ 150 ps has been achieved by the authors in the laboratory. For long scintillators there are several effects degrading the time resolution, namely the light attenuation and the consequences of the

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scintillator acting as a light guide with corresponding propagation time dispersion.

First photoelectron timing errors have been evaluated for slow scintillators (BGO, $\tau_{\rm decay} \approx 300\,{\rm ns}$) and larger amplitudes (number of photoelectrons $N > 30$) previously [4,5], but not for fast plastic scintillators and small amplitudes, where the achievable timing performance depends also on path length variations. The purpose of this paper is to discuss expressions for the timing error which include propagation time dispersion and to verify experimentally the correlation between signal time and average photon angle at the read-out end of a scintillator.

In Section 2, a brief resume of scintillator timing and the sources of time jitter is given. The next section of the paper deals with statistical limitations introduced by the spread of photon propagation times. Section 4 describes an experimental set-up to test the assumed correlation between average arrival time and average exit angle. The following section shows data that prove this correlation to be measurable. The results are supported by Monte Carlo simulations which are helpful to understand when the propagation time dispersion plays an important role. Conclusions are summarised in Section 6.

2. The origin of time jitter in scintillator timing

One fundamental limit on the time resolution of scintillation counters comes as a consequence of the statistical processes involved in the generation of the signal. Post and Schiff [6] have first discussed such limitations. In general, the voltage pulse of a photomultiplier, $V_{\rm PMT}$, can be expressed as a linear superposition of N single photoelectron pulses, v_i. The pulses arrive at individual times due to the time spread in the energy transfer to the optical scintillator levels, $t_{\rm dep}$, the decay time of the light emitting states, $t_{\rm emit}$, the propagation time, $t_{\rm prop}$, and the transit time, $t_{\rm TT}$, being the time difference between photo-emission at the cathode and the arrival of the subsequent electric signal at the anode. In addition, there is white Gaussian electronic noise, $w(t)$. We incorporate these processes into a general model: $V_{\rm PMT}(t) = \sum_{i=1}^{N} v_i(t - (t_{\rm dep} + t_{\rm emit} + t_{\rm prop} + t_{\rm TT})_i) + w(t)$, where N fluctuates from one pulse to another. In a semi-classical model the probability for observing N photoelectrons during a time interval T is given by a Poissonian distribution $P(\overline{N}, N)$ with $\overline{N}$ being the mean number of photoelectrons per pulse.

The following calculation is focused on the limitations arising from the contribution of the path length variation. Central to the calculation is the relation between initial axial angle, θ, and propagation time: $t = Ln/(c\cos\theta)$, for a point like source of light placed at a distance L from the end face of a scintillator with refractive index n in a medium of refractive index $n_{\rm ext}$. In any reflection, the change in the velocity vector of a particular photon takes place in the direction perpendicular to the optical boundary it crosses or is reflected. The component of this vector along the longitudinal axis remains unchanged during the propagation and therefore the propagation time only depends on the initial axial angle, distance to the PMT, and index of refraction (disregarding any scattering processes). Consequently, a detector displaced by a distance d from the end face of the scintillator would link in one linear dimension exit angle and propagation time. Assuming that firstly the exit point of the photon on the face of the scintillator and secondly the entry point of the photon inside the detector aperture is not known, and finally that exit angle and propagation angle do not differ too much, the following approximate formula is derived: $\tan\theta = \Delta x/d$, with a variation on θ given by

$$\sigma_\theta \approx \sqrt{\frac{(t_x + a_x)^2}{12\,d^2\,(1+\tan^2\theta)}} \qquad (1)$$

where the width in x-direction of the scintillator is t_x and of the detector aperture is a_x. A schematic representation of the arrangement of scintillator and detection plane is given in Fig. 1. The trajectories of two photons leaving the scintillator in the same point illustrate the geometrical situation. With a detection plane directly at the end face of the scintillator and a trigger threshold of two photoelectrons two scenarios are possible: (i) The first photon emitted takes the *longer* path and the second photon emitted takes the *shorter* path. Hence, both photons arrive close in time, and the trigger sets off close to the arrival time of the first photon. (ii) The first photon emitted takes the *shorter* path and the second photon emitted takes the *longer* path. Hence, the two earliest photons arrive with a relevant time spread and the trigger sets off at the arrival time of the second photon. The displaced detection plane resolves this propagation time contribution. With typical parameters in our experiments of $a_x = a_y = 3\,{\rm mm}$, $L = 100\,{\rm cm}$, $d = 10\,{\rm mm}$, $t_x = 32\,{\rm mm}$, and $t_y = 10\,{\rm mm}$ the variation in x is 15–20 mm for exit angles of $15-40^\circ$. These values demonstrate that ray-tracing of single photons is not possible for d of the order of 10 mm, but the correlation

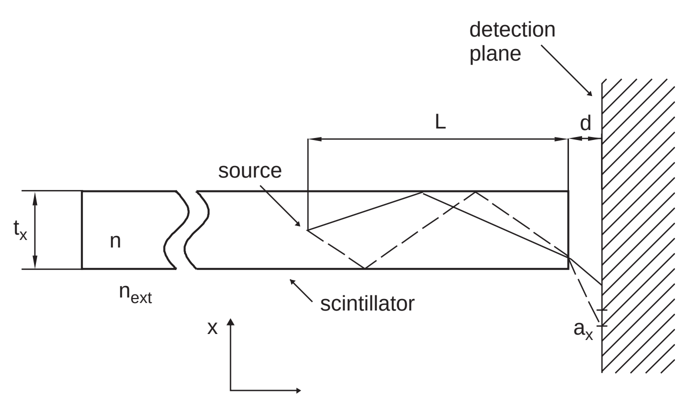

Fig. 1. Schematic representation of the arrangement of scintillator and detection plane at a distance d. The paths of two photons leaving the scintillator at the same point are shown. Typical parameters for the experiments were $a_x = a_y = 3\,{\rm mm}$, $L = 100\,{\rm cm}$, $d = 10\,{\rm mm}$, $t_x = 32\,{\rm mm}$, and $t_y = 10\,{\rm mm}$.