PAUL SCHERRER INSTITUT

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Titel	Light Collection Efficiency from Thin Plastic Scintillators	Ersetzt
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Zusammenfassung:

Fast timing with detectors based on plastic scintillators requires maximum efficiency in the collection of light from the scintillator by the photosensor. Significant light losses might occur in the scintillator itself and in the light guides. A decreasing thickness of the scintillator leads to an increasing number of reflections of photons before reaching an absorbing surface. Therefore, the scintillator quality becomes more critical for the light collection efficiency.

In this work we explore the upper limit for the efficiency of light collection (*CE*) from a thin scintillator ($10\times10\times0.2$ mm^3) via one of its 10×0.2 mm^2 faces. Results from Monte-Carlo simulations show that in an ideal case the *CE* could be as high as 45%. This estimate is supported by our measurements on test samples (*CE* $\approx$ 20%). The obtained result is important for the design of fast timing detectors for µSR-spectrometers.

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The detector system of a μSR-spectrometer consists of a muon counter (to detect incoming muons) and a positron counter (for detection of positrons from the decay of muons stopped in the sample). The μSR method [1] is based on measuring the time difference between the moment a muon enters the sample and the moment a positron from the muon's decay is registered by a detector covering a finite (typically about 10 %) solid angle. The time resolution of the detector system (muon + positron counters) is critical for the observation of muon spin precession signals in high magnetic fields: the μSR signal amplitude A decreases with increasing magnetic field H as [2]:

$$A(H) = \exp\left[-\frac{(\pi\,\Delta t\,\gamma\,H)^2}{4\,\ln 2}\right] , \tag{1}$$

where γ is the gyromagnetic ratio for the muon, and Δt is the time resolution (FWHM) of the spectrometer. According to eq. (1), in order to observe a reasonable muon spin precession signal ($A \geq 0.55$) in a magnetic field of 10 Tesla the time resolution should be better than 300 ps.

Muon detectors of μSR-spectrometers using "surface" muon beams (momentum $\sim$ 29 MeV/c) are based on $\sim 200\ \mu$m thick plastic scintillators that allow the muons to pass through the detector with minimum scattering and reach the sample. For such a thin scintillator the number of reflections for each photon before reaching one of the smaller faces (from which the light is collected) is very large and the quality of the scintillator strongly effects the light collection and, accordingly, the efficiency and timing properties of the detector.

The present investigation is aimed to study the light collection efficiency (CE) from a $10 \times 10 \times 0.2$ mm^3 plastic scintillator via one of its 10×0.2 mm^2 faces. The chosen size of the scintillator is characteristic for a future μSR-spectrometer with a 10 Tesla magnetic field: the maximum linear dimension of the sample, and accordingly of the muon detector, is defined by the characteristic bending radius of the decay positrons in the magnetic field ($\sim$ 10 mm for 30 MeV positrons in $H = 10$ T).

An estimate for the upper limit of the CE was obtained from Monte-Carlo simulations using the code described in [3]. The initial conditions for the simulations and the results are given in Figure 1. For the considered ideal case the light collection is very efficient: ≈ 45 % of photons emitted in the center of the scintillator are absorbed at one of its smaller faces in less than 200 ps.

Guided by this calculations one can estimate that a detector based on a 200 μm thick fast plastic scintillator (EJ-232, equiv. BC-422; light yield 8400 photons/MeV [4]) and a photosensor with a photon detection efficiency (PDE) of about 10% could be effectively used even for the detection of relativistic positrons (the average amplitude of the output signal could be about 10 photoelectrons).

In order to verify the rather high value predicted for the CE measurements on different scintillator samples were performed. The shape of all the samples was $10 \times 10 \times d$ mm^3 ($d \sim 200\ \mu$m), the characteristics of the samples are given in Tables 1 and 2. Figure 2 shows the setup used for the measurements. The test scintillator was mounted on the photocathode of a PMT (Hamamatsu R1828-01, cathode luminous sensitivity 101 μA/lm), denoted as C1. The second detector C2 based on a 1×1 mm^2 scintillating fiber type

BCF-10 was used to select electrons from a Sr^{90} radioactive source that pass through C1 at the center and perpendicular to its larger face. In order to select only minimum ionizing particles (MIP) a 0.3 mm thick Cu filter was placed between C1 and C2. This filter cuts electrons with energies below 0.7 MeV. The amplitude (pulse area) distributions of

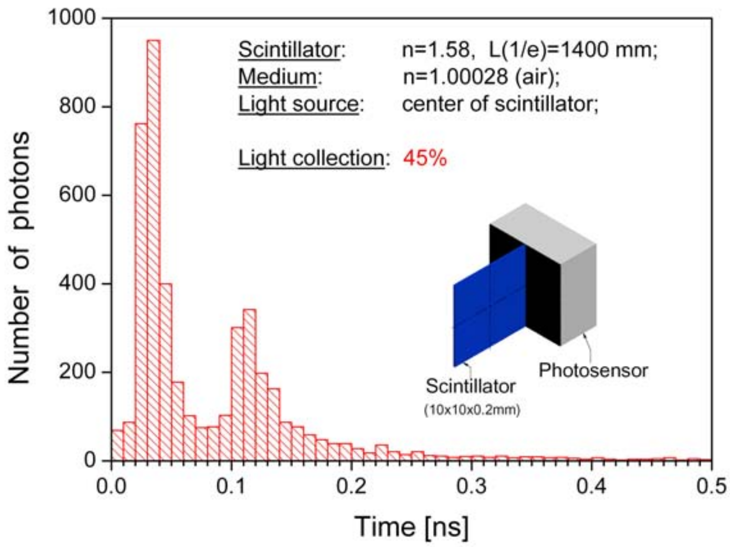

Figure 1: Result of a Monte-Carlo simulation: the time histogram for the photons collected from a $10 \times 10 \times 0.2$ mm^3 plastic scintillator (refractive index $n = 1.58$, light attenuation length $L(1/e) = 1400$ mm) via one of the 10×0.2 mm^2 faces (modelled as a photosensor absorbing all incident photons). The source of photons is at the center of the scintillator bar; all the photons are emitted at $t = 0$; the total number of photons is 10^4.

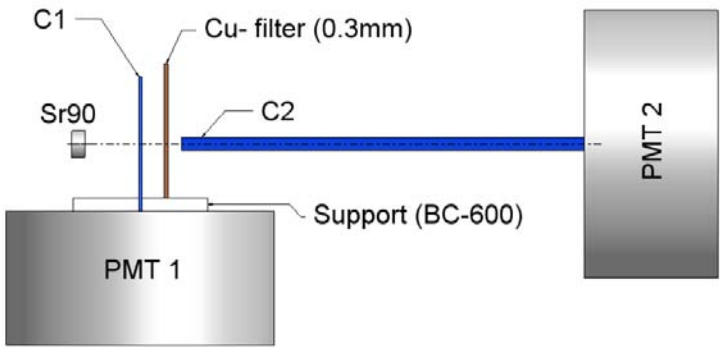

Figure 2: Setup for the measurement of the light collection efficiency. C1 denotes the scintillator under test and the detector based on it. For mounting C1 on the photocathode the scintillator is glued into a square shaped support made of BC-600 epoxy. This support is covered with mylar reflectors. The detector C2 is used to select electrons from a Sr^{90} source which pass through C1 at the center of its larger face and perpendicular to its surface. A copper filter (0.3 mm thick) between C1 and C2 cuts off electrons with energies below ~ 0.7 MeV.

the signals from C1 were analyzed using a LeCroy WavePro 960 oscilloscope, which was triggered by the signals from C2.

An example of the amplitude distribution for one of the scintillator samples is given in Figure 3. The amplitude spectrum has an asymmetric form with a longer right-hand tail which is characteristic for thin absorbers (see [5]). The most probable amplitude A_{MIP} of the distribution characterizing mean energy losses for minimum ionizing particles was obtained by fitting a Gaussian function to the spectrum as shown in the Figure. Note, that A_{MIP} is lower than the mean signal amplitude (by about $10-20\,\%$ for different samples).

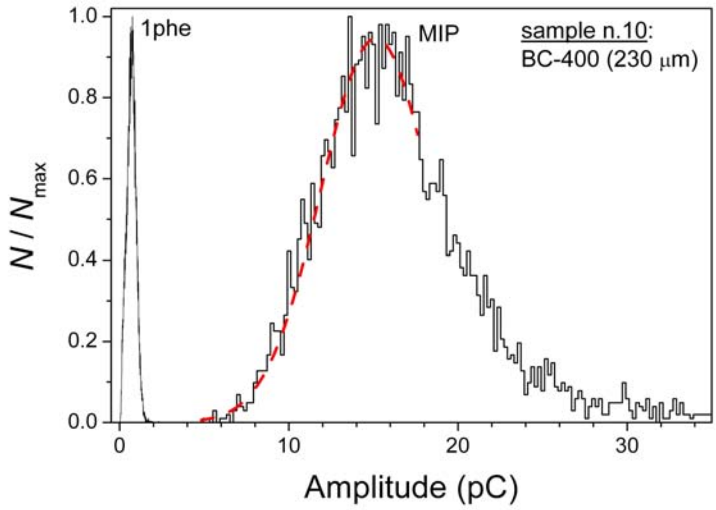

Figure 3: Amplitude distributions for one-photoelectron (1phe) PMT signals and the signals from electrons passing through a test scintillator (sample n.10, see Table 2).

The amplitude distribution of one-photoelectron (1phe) signals is also shown in Figure 3. The 1phe distributions were obtained by shining a weak continuous light on the scintillator, thus producing 1phe pulses with an intensity $\sim 5 \cdot 10^4$ s^{-1} (the intensity of 1phe pulses due to thermal generation of electrons on the photocathode was about 10^3 s^{-1}, i.e., a factor of 50 less). This ensured that the 1phe pulses and the pulses caused by scintillation light originated from photoelectrons emitted from the same photocathode area. For recording the 1phe signals the oscilloscope was operated in a self-triggering mode with a low threshold. The number of photoelectrons N_{phe} created in the PMT by a MIP passing through the test scintillator was calculated according to:
$N_{\mathrm{phe}} = A_{\mathrm{MIP}}/A_{\mathrm{1phe}} \cdot 0.2/d$,
where A_{1phe} is the mean amplitude of 1phe signals and d is the thickness of the scintillator (note that N_{phe} is scaled to 200 μm scintillator thickness). The light collection efficiency follows from:

$$CE = N_{\mathrm{phe}}/N_{\mathrm{phe}}^{\mathrm{max}} \ , \qquad N_{\mathrm{phe}}^{\mathrm{max}} = (dE/dx)_{\mathrm{MIP}} \cdot 0.02\,\rho \cdot LE \cdot QE \ ,$$

where $N_{\mathrm{phe}}^{\mathrm{max}}$ is the number of photoelectrons expected at $CE = 100\,\%$; $(dE/dx)_{\mathrm{MIP}} =$ 2 MeV/(g/cm^2) and $\rho = 1$ g/cm^3 are the stopping power of a plastic scintillator for

Scintillator	LE, ph/MeV	QE, %	$N_{\rm phe}^{\rm max}$
EJ - 204 BC - 404	10400	26	108
EJ - 230	9700	28	108
EJ - 232	8400	27	90
EJ - 212 BC - 400	10000	25	100
EJ - 232Q (0.5 %) BC - 422Q (0.5 %)	2900	27	31

Table 1: Values of the light yield of the scintillators LE and quantum efficiency QE of the PMT (averaged over the emission spectrum of the scintillators) used in this work. Data taken from [4] and [6].

Sample			Sample quality			
nn	Scint. type	d, mm	faces 10 x 10 $\rm mm^2$ & bulk	faces 10 x d $\rm mm^2$	$N_{\rm phe}$	CE, %
1	EJ - 204	0.190	$4.5^{\rm a}$	1	15.2	14
2	EJ - 230	0.200			12.3	11
3	EJ - 232	0.160			12.5	14
4	EJ - 232Q	0.180			4.4	14
5	BC - 400	0.230	$3^{\rm b}$	2.5	12.3	12
6	BC - 422	0.210			3.7	4
7	BC - 422Q	0.250			3.2	10
8	BC - 422	0.210	$3.5^{\rm c}$	4.5	9.3	10
9	BC - 422Q	0.250			4.0	13
10	BC - 400	0.230			18.9	19
11	EJ - 212	0.300			18.9	19

Table 2: Test scintillator samples, their quality estimates, and the measured values for the light collection efficiency CE. The quality of the samples was estimated visually with marks from 1 (poor) to 5 (excellent). Given are the group characteristic quality estimates: a) The samples were obtained from the supplier, cut to the specified dimensions. No microcracks are seen in the scintillator bulk but the larger faces look "wavy". Smaller faces were not polished and look rugged. b) The samples were cut from scintillator sheets using a diamond saw. Microcracks appeared due to pressing the scintillator at cutting. c) The samples were cut from scintillator sheets. The smaller faces were hand-polished. Microcracks appeared due to pressing the scintillator at polishing.

relativistic electrons and its density; LE is the light yield of the scintillator; QE is the quantum efficiency of the PMT averaged over the emission spectrum of the scintillator. The parameters LE and QE used in this calculations were obtained from the data sheets and are given in Table 1.

The results on the light collection efficiency are summarized in Table 2. The values of CE for different scintillator samples are rather widely spread, thus confirming a strong effect of scintillator quality on the light collection. For two samples (n.10 and n.11) rather high values of CE ($\approx 20\,\%$) were obtained. The samples in this group were considered to be of better quality compared to the others. For the samples (nn. $1-4$) the light collection efficiency is quite uniform but a factor of 1.5 lower than the obtained maximum. We attribute this uniformity to the identical and rather good quality of the bulk and the larger faces of these samples and to identical (extremely poor) quality of their smaller faces. Simulations show that fine polishing of the smaller faces is also very important: absorption of photons at these surfaces leads up to a factor of 4 (at full absorbtion) losses of light.

Summary

We carried out Monte-Carlo simulations and experimental tests to study the efficiency of light collection from a thin $10 \times 10 \times d$ mm^3 ($d \sim 0.2$ mm) plastic scintillator via one of its smaller $10\,\mathrm{x}\,d$ mm^2 faces. We show that for a high quality of the scintillator the light collection efficiency could be very high: the upper limit of $\approx 45\,\%$ obtained in simulations was verified by $CE \approx 20\,\%$ measured on test samples.

References

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