Measurement of absolute light yield and determination of a lower limit for the light attenuation length for YAP:Ce crystal [1]

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Abstract

In small animal PET applications YAP:Ce scintillator has given some promising results [1]. Because of its somewhat lower efficiency with respect to other PET crystals at 511 keV the depth of the crystal is a crucial parameter. Past measurements of the light attenuation length for YAP:Ce scintillator have given rather different results with values as low as 3 cm [2]. We have studied the pulse height spectra of full energy absorption events as a function of the interaction distance from the photomultiplier window for five match like $2 \times 2 \times 30$ mm^3 YAP:Ce crystals. Each crystal was covered on the four long sides and on one of the square section sides with a 5 μm reflective layer. The crystals were the middle row of a bundle of 5 by 5 such crystals.

By using a transport model for light within the crystals, for this crystal configuration, we obtained a lower limit of 6.8 ± 0.3 cm on the average 'bulk' (not including the losses from reflection) light attenuation length. This lower limit is significantly higher than the attenuation length measured by other authors.

From these measurements and calculations we have also determined the average absolute light yield for the five crystals to be 24000 ± 1400 photons/MeV.

I. INTRODUCTION

YAP:Ce scintillator is a rather versatile scintillator and easy to use because of its good physical properties [3]. A limit on the useful size of the crystals seemed to be imposed by the rather short light attenuation length of a few centimeters [2]. Within the framework of studying new materials for PET applications we have measured the decrease in pulse height of full energy absorption events at 511 keV as a function of the interaction distance from the photocathode window. This was done for the five YAP:Ce crystals in the middle row of a bundle of 5×5 match like crystals each with dimensions $2\times2\times30$ mm^3. Each crystal was separated from the adjacent ones by a 5 μm layer of reflective coating (whose properties and composition were not specified by the producer). Similar studies on other crystals have been done in the past but not for YAP:Ce scintillator [4, 5, 6].

We will define as average 'bulk' attenuation length the loss in light due only to absorption within the crystal averaged over the emission spectrum reaching the photocathode. The losses due to reflection at each surface are considered separately. We have obtained a lower limit on the average 'bulk' attenuation length, which is significantly higher than past measurements.

From these measurements we also determined the absolute light yield for our crystals. By simulating the light transport within the crystals we show that the relation between pulse-height and interaction distance from the photocathode obtained experimentally can be fitted with many pairs of reflectivity values and 'bulk' attenuation length. For each pair though the percentage of light reaching the photocathode is virtually the same. Therefore from the energy resolution (assuming that the fluctuations on the pulse-height are due to Poisson statistics of the photoelectrons) one can determine the number of photoelectrons produced at the photocathode. Knowing the percentage of light reaching the photocathode one can go back to the original number of photons produced in the scintillation.

II. APPARATUS AND METHOD

A scheme of the experimental set-up is shown in figure 1. The YAP:Ce multi-crystal is composed of 25 matchstick crystals each of dimensions $2\times2\times30$ mm^3, bundled together to form the detector of $1.0\times1.0\times3.0$ cm^3. Each crystal is separated from the adjacent one by a thin reflective layer ($\approx$ 5 μm). The multi-crystal is directly coupled to the PSPMT (Position Sensitive PhotoMultiplier Tube) photocathode (Hamamatsu R2486-06). This detector was used for preliminary studies toward Positron Emission Tomography applications [1]. The source used during these measurements was ^{22}Na. The second detector used for the $\gamma - \gamma$ coincidence is a cylinder BGO crystal, 2.5 cm diameter and 2.5 cm thick, coupled to a standard PMT. This second (BGO) detector defines the spot dimension for the photons incident onto the YAP:Ce crystal. The ^{22}Na source is placed near the position sensitive detector (8 cm from the YAP:Ce) and as far away as possible from the BGO detector (100 cm). With this configuration the spot size of coincidence events on the YAP:Ce is 2 mm. The YAP:Ce matrix is oriented so that the photons enter the long side. Furthermore it is mounted on a XYZ position system so as to vary the interaction distance in the YAP:Ce crystal from the PSPMT photocathode.

The BGO signal and the signal from the last dynode of the PSPMT are amplified and sent to two Constant Fraction

[1]This work has been partially supported by MURST 40% 1994 and 1995

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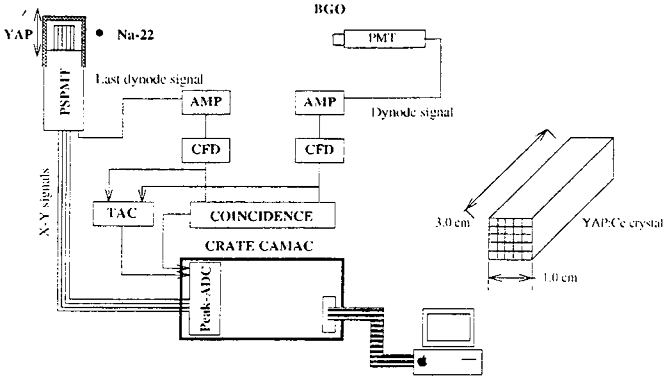

Fig. 1 Scheme of the setup and of the YAP:Ce multi-crystal. The single YAP:Ce crystals are separated from each other by a 5 μm metallic reflecting layer.

Discriminators (CFD) for fast timing. The logic outputs from the CFDs are sent to a coincidence unit whose output is used to form the gate signal for a Peak ADC (Phillips 7164). The analog (X,Y) outputs of the PSPMT are sent to the Peak ADC channels for conversion. The total energy of the YAP:Ce detector is calculated by summing the four output signals from the resistive chains. For each distance of the YAP:Ce from the photocathode we determine the peak position and energy resolution of the full absorption peak. Five different distances were chosen: 0.5 cm, 1.0 cm 1.5 cm 2.0 cm and 2.5 cm.

III. Simulation

A simple calculation for light transport in the crystal has been done to estimate the light reaching the photomultiplier photocathode as a function of the reflectivity and the average 'bulk' attenuation length of the crystal.

Similar calculations have been reported elsewhere [7, 8]. The calculation is based on a model where the crystal is isotropic, with a refractive index (n_1) of 1.95 [9]. The crystal is coupled to optical grease whose index of refraction is (n_2) 1.5 and therefore output angles greater than the limit angle (50.3°) are discarded. At the interface YAP-grease we considered that the light reflected back into the crystal due to the different refractive index, as given by the Fresnel relations, is lost. The reflection coefficient of the internal surfaces is assumed constant for all incident angles. This assumption is justified by the fact that only light with almost grazing incident angles will exit efficiently from the crystal in which case there is total internal reflection. Some small losses might be present in the internal reflections and so reflectivity values below 1.0 were also considered. Not knowing the exact nature of the reflective layers, the reflection off the back end of the crystal was assumed to be 0.85. This is the approximate value for Al covered surfaces like mirrors. In any case this parameter did not result to be critical in the light transport calculation.

In figure 2 we show an example of the expected percentage of light reaching the photocathode as a function of the distance of the scintillation point from the photomultiplier window. In this example we fixed the reflectivity at 100 % and varied the average 'bulk' attenuation length (λ) from 3 cm to 30 cm. The percentage of light varies very significantly.

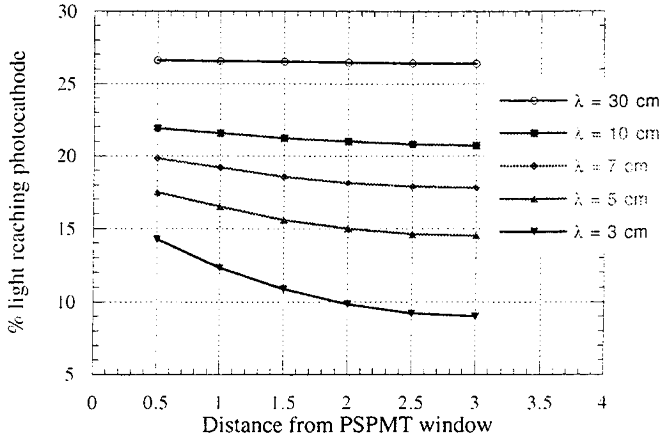

Fig. 2 Simulated percentage of light reaching the photocathode as a function the distance of scintillation point from the photomultiplier window. The reflective layers are given a reflectivity of 100 % and the 'bulk' attenuation length (λ) is varied from 3 cm to 30 cm. The dimensions of the YAP:Ce crystal are $2 \times 2 \times 30$ mm^3.

IV. Experimental Results

In figure 3 one can see the experimental image reconstructed by the PSPMT of the crystal bundle. One can nicely distinguish all five crystals. A slight shadow of events are also present in the crystals not belonging to the central row. This is due to Compton scattering of photons in the bundle. A selection of the events within a radius of $\approx$ 0.5 mm from the center of each crystal was done.

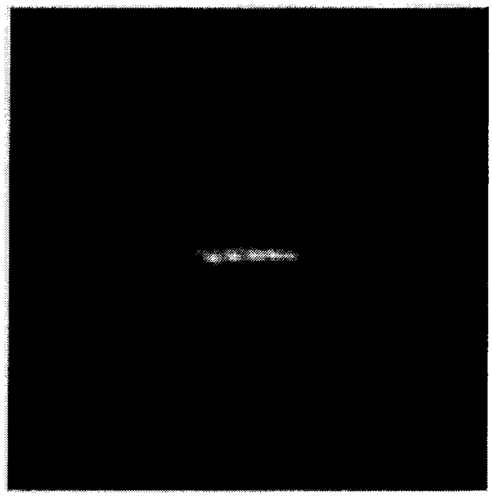

Fig. 3 Image of 511 keV photons obtained using the PSPMT for the five YAP:Ce crystals of dimensions $2 \times 2 \times 30$ mm^3. The spatial resolution is sufficient to clearly distinguish the five crystals.

In figure 4 one can compare the two spectra for 511 keV photons when interacting at 0.5 cm and 2.5 cm from the photomultiplier window. The shift in the peak position is evident. In both spectra the full energy absorption peak is well separated from the Compton edge. A typical value for the FWHM energy resolution at 511 keV is about 14.5 % which is really quite good considering the crystal geometry.

Figure 5 shows the peak position as a function of the spot distance from the photocathode for each of the five crystals considered. The errors given are the statistical ones obtained by fitting the pulse-height spectra with gaussian

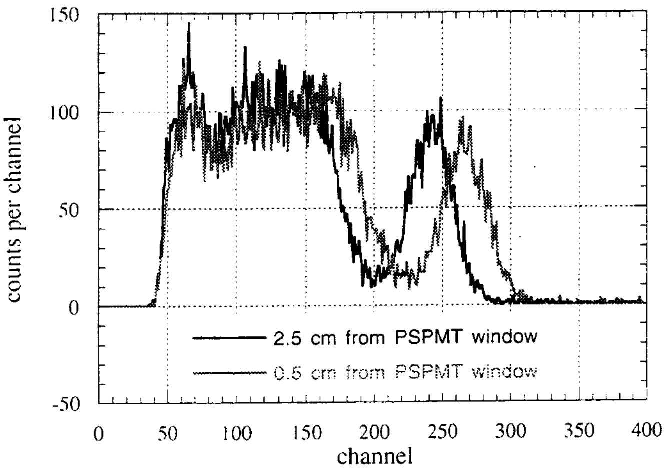

Fig. 4 Spectra obtained using the PSPMT for 511 keV photons interacting at 0.5 cm and at 2.5 cm from the photomultiplier window. The YAP:Ce crystal has dimensions $2 \times 2 \times 30$ mm^3.

curves. These errors are probably underestimated due to spot size and alignment as well as slight non uniformities of the crystals which one can reasonably expect. As can be seen for these crystals the light output decreases by about 10% between the minimum and maximum distances reported from the photocathode. Superimposed on the experimental data is also shown the best fit, using MINUIT [10], with the transport model described above in the case of a reflectivity of the lateral surfaces equal to 1.0. This is the case from which one can obtain the lower limit on the average 'bulk' attenuation length for the crystal. In table 1 we have reported the 'bulk' attenuation lengths for the five crystals. These range from a minimum of 6.5 ± 0.1 cm to a maximum of 7.1 ± 0.1 cm.

This leads us to an average lower limit for the five crystals on the 'bulk' attenuation length of the crystal of 6.8 ± 0.3 cm where the error given is the standard deviation calculated from the 5 different values reported in table 1 for the 5 crystals.

In figure 6 the fractional FWHM energy resolution is shown as a function of the spot distance from the photocathode for the same five crystals. The errors are statistical from the gaussian fit. Due to the statistics it is difficult to see any relative broadening due to the small loss in light as one moves away from the PSPMT window. From the $1/\sqrt{E}$ law one would expect an increase in the energy resolution of about 5 % which in our case is within the errors.

V. ABSOLUTE LIGHT YIELD FOR YAP:CE SCINTILLATOR

Several different values for the reflective coefficients were chosen in the model and for each value we determined the average 'bulk' light attenuation length which best fits the experimental data for each of the five crystals. Figure 7 shows the results of these fits for one of the crystals reporting on the y-axis the percentage of light arriving at the photocathode versus distance of interaction from photocathode. As can be seen it is not possible to isolate a single pair of values for the 'bulk' attenuation length and reflectivity.

It must be noticed that in figure 7 all the curves coincide within about 1 % (absolute) in the percentage of light reaching the photocathode for any one of the distances considered. This means that independently of the attenuation length and reflectivity, if one can find a pair which fits the experimental data, then one has found the number of photons reaching the photocathode within 1 % absolute. Therefore, from the energy resolution measured at 511 keV one can estimate the number of photoelectrons emitted at the photocathode as

$$N_{phe} = \left(\frac{2.3548}{R}\right)^2 \frac{\delta}{\delta - 1} \quad (1)$$

where δ =2.61 is the gain for each dynode and R is the FWHM energy resolution. The number of scintillation photons emitted at 511 keV is therefore

$$N_{photons} = \frac{N_{phe}}{qTP} \quad (2)$$

where q = 0.20 ± 0.02 is the average quantum efficiency of the photocathode over the spectrum of YAP:Ce scintillation reaching the photocathode [11], T = 0.85 ± 0.03 is the photomultiplier window transparency [11] and P = 0.195 ± 0.003 is the percentage of light reaching the photomultiplier photocathode obtained from the calculation for an interaction point at 0.5 cm from the photocathode.

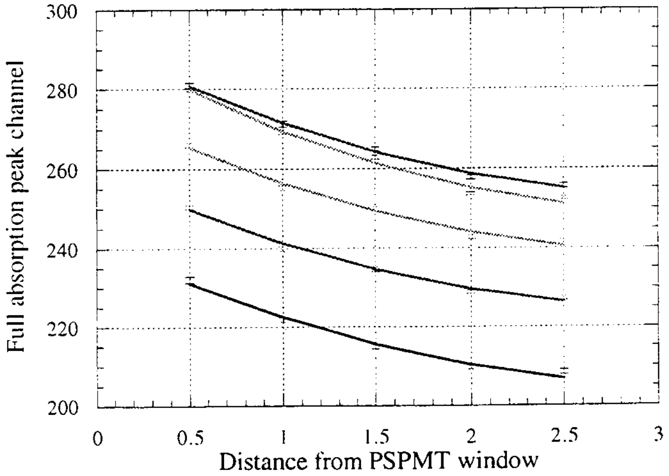

Fig. 5 Measured peak position vs interaction distance from photocathode (points) with the best fit superimposed for each of the 5 crystals (lines).

The quantum efficiency error has been evaluated from the data on our PSPMT uniformity response measured by Hamamatsu [11]. Because the relative standard deviation of our photomultiplier response is $\approx$ 10.0%, we use this value as upper limit of the relative standard deviation of quantum efficiency. On the other hand a large standard deviation is possible for other class PSPMT.

By substituting the values for each crystal we obtain the absolute light yields reported in table 1. The average light yield for the crystals is 24000 ± 1400 photons/MeV where the error is the standard deviation obtained using the yields for the five crystals. This value is significantly higher than other values available in literature [3, 2]. This is not surprising due to the fact that the quality of YAP:Ce scintillator has improved.

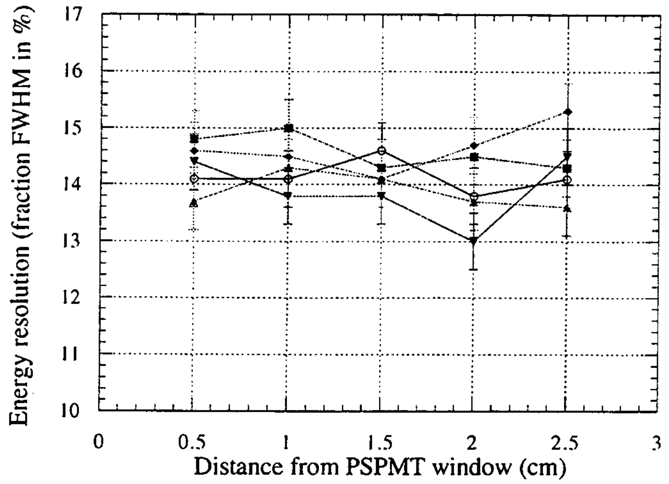

Fig. 6 Measured energy resolution vs interaction distance from photocathode for each of the five crystals.

Table 1
'Bulk' attenuation length, energy resolution and absolute light yield for the 5 crystals considered.

crystal	'bulk' attenuation length (cm)	FWHM (%) Distance = 0.5 cm	light yield (photons/MeV)
1	6.5 ± 0.1	14.1 ± 0.5	25000 ± 3100
2	7.0 ± 0.1	14.8 ± 0.5	22500 ± 3100
3	7.0 ± 0.1	14.6 ± 0.5	23100 ± 3100
4	6.6 ± 0.1	13.7 ± 0.5	26000 ± 3100
5	7.1 ± 0.1	14.4 ± 0.5	23700 ± 3100

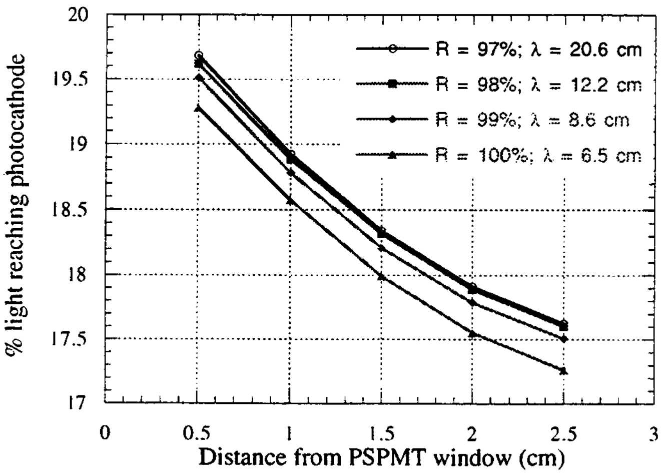

Fig. 7 Simulated percentage light output vs interaction distance from photocathode for different pairs of reflectivity of the reflective coatings and 'bulk' attenuation length which fit the data. The absolute percentage of light reaching the photocathode is almost insensitive so long as the correct decay is obtained.

VI. Conclusions

Using small $2 \times 2 \times 30$ mm^3 match like YAP:Ce crystals, produced by PRECIOSA Co. Turnov, Czech Republic, coated on the four long sides and at one end with a reflective coating we have measured the channel corresponding to the full energy absorption for 511 keV photons as a function of the interaction distance from the photocathode in the case of five samples. We found a decrease of only 10 % of the channel peak position between events scintillating at the two extremities of the crystal. Using a simple light transport model and imposing a reflectivity of 100 % we therefore determined a lower limit for the average (average over the emission spectrum of YAP:Ce in our geometry) 'bulk' attenuation length for each crystal giving an average of $\lambda = 6.8 \pm 0.3$ cm. This value is significantly higher than values found previously in literature.

We have also shown that it is possible to determine the absolute light yield for YAP:Ce scintillator from these measurements and calculations. We have found a light yield of 24000 photons/MeV with a standard deviation calculated from the 5 yields of 1400 photons/MeV. These YAP:Ce crystals have a light yield which is 60 % that of NaI(Tl) clearly higher than the value usually reported by about 40 %. This scintillator is still in evolution and these results show this quite clearly.

VII. References

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