Separation of PbWO$_4$ and BGO signals into Čerenkov and scintillation components

C. Voena, for the DREAM collaboration
Università Sapienza di Roma and INFN Sezione di Roma, Italy
E-mail: cecilia.voena@roma1.infn.it

Abstract. We present results from beam tests performed in 2007 on PbWO$_4$ and BGO crystals in the context of the DREAM project. Signals from high energy electrons and pions are analyzed and the possibility of separating the contributions from Čerenkov (C) and scintillation (S) light for individual events is investigated. Different methods exploiting the difference in timing, in the spectra and in the directionality of the two types of light have been developed to determine the contribution of the two components. In the BGO crystal, Čerenkov signals have been enhanced with the use of optical filters and the ratio C/S is measured with good precision (~20-30% for energy deposits less than 1 GeV).

1. Introduction
The Dual Readout method allows to improve the performances in hadronic calorimetry by measuring event-by-event the electromagnetic fraction of the hadronic cascades. The principle has been proved by the DREAM calorimeter [1]. The main limitation to the energy resolution of the DREAM detector is the small number of photo-electrons (8 per deposited GeV). This can be improved with the use of homogeneous detectors if Čerenkov light can be separated from scintillation light.

In this paper the results of the measurements performed on a PbWO$_4$ crystal and on a BGO (Bi$_4$Ge$_3$O$_{12}$) crystal are described. In order to separate the Čerenkov from the scintillation signals the following differences between the two components are considered:

- Differences in directionality. Scintillation light is emitted isotropically, Čerenkov light is emitted at a characteristic angle with respect to the emitting particle.
- Differences in time structure. Scintillation light is characterized by one or various time constants, Čerenkov light is prompt.
- Differences in spectral properties. Scintillation light has a characteristic spectrum for the crystal in question, Čerenkov light has a $\lambda^{-2}$ behavior.

2. Crystals and experimental setup
The measurements described in this paper were performed in the H4 beam line of the Super Proton Synchrotron at CERN. The PbWO$_4$ crystal has a length of 18 cm and a cross section of 2.2×2.2 cm$^2$ (the transverse dimensions correspond to 2.5 radiation lengths, X$_0$). The BGO crystal has a length of 24 cm and a truncated-pyramidal shape, resulting in a cross section that varied from 2.4×2.4 cm$^2$ on one side to 3.2×3.2 cm$^2$ to the opposite side. The transverse
The dimensions thus varied between 2.2 and 2.9X0. The index of refractions are 2.2 and 2.15 for the PbWO₄ and the BGO, respectively. The PbWO₄ scintillation decay time is 10 ns while the BGO decay time is 300 ns. The crystals were read out by two phototubes located on opposite ends and, to reduce the light trapping effects of the large refractive index, in most of the measurements the PMTs were coupled to the crystal by means of silicone “cookies” (n=1.403). In the case of the BGO the light generated in the crystal was filtered before reading it out with a “Yellow” (Y) filter on the small side and a “Ultraviolet” filter (UV) on the large side. The Y filter is highly transparent to the scintillation light, the UV filter is transparent for light in the 300-400 nm range while less than 0.1% of the scintillation light penetrates it (taking into account also the quantum efficiency of the PMTs). The experimental setup is shown in fig. 1.

Figure 1. Test beam setup. The scintillation counters (TC) were used to trigger the data acquisition system. The drift chambers (DC1,DC2) were used to reconstruct the impact point of the particles and to select events that entered in a small region (10x10 mm²) around the crystal center.

The crystal under study was mounted on a platform that could rotate around a vertical axis through its geometrical center. The beam was also steered through this center. The angle θ used through the paper is defined as the angle between the crystal axis and a plane perpendicular to the beam line; the sign is defined such that the crystal orientation in fig. 1 corresponds to θ = −30°. The crystal signals were acquired with an ADC and with an oscilloscope with a sampling capability of 5 GSample/s at a analog bandwidth of 2.5 GHz.

3. PbWO₄ results
Since Čerenkov light is emitted at an angle θ₈=63° by the charged relativistic particles the acceptance of this light for each PMT strongly depends on the angle θ. For the signal from PMT right, this contribution is larger for θ=27°, for which the Čerenkov light goes directly into the PMT. The corresponding angle for PMT left is θ=−27°. Figure 2 (left) shows the average time structure of the signals from 50 GeV electrons in PMT left, for θ=30° and θ=−30°. The trailing edges of the signals are very similar while the leading edge is steeper at θ=−30° and the signal is larger at this angle.
The time structure of the signals can be used to determine the relative contribution of the Čerenkov light in different ways. We describe here the most effective method that consists in the measure of the time difference between the moments at which the signals from the two PMTs cross a given threshold level, $\Delta t(L-R)$. Figure 2 (right) shows $\Delta t(L-R)$ as a function of $\theta$ for 50 GeV electrons and different threshold levels. This difference changes sign at $\theta=0^\circ$ as expected and has broad peaks at the angles where acceptance for Čerenkov light is maximal for one of the two PMTs. The performances of this method can be studied by comparing the signal event-by-event distribution with the corresponding distribution at an angle $\theta$ for which almost only scintillation light contributes, for example $\theta=0^\circ$. The separation power $\Pi$ is defined as the ratio of the difference between the mean values and the average width of the two distributions. Figure 3 (left) shows the event-by-event distributions of $\Delta t(L-R)$ for 50 GeV electrons at $\theta=0^\circ$ and $\theta=30^\circ$ from which $\Pi = 3.3$ is obtained. The separation power as a function of the energy deposit is shown in fig. 3 (right) where the energy scale is derived from Monte Carlo simulation. The expected behavior if photo-electron statistics were the only contribution is also shown for a Čerenkov photo-electron yield of $\sim 50$ photo-electrons per deposited GeV. The curve describes the general tendency of the data, but other factors are present: since these have the effect of reducing the separation power, 50 photo-electrons should be interpreted as a lower limit.

In order to investigate different stages of the electromagnetic shower, lead absorber of various thickness was installed upstream of the crystal. As the shower develops the shower particles may not be considered a collection of mips traversing the crystal in the same direction, so it is expected that the directionality of the Čerenkov light is somehow lost while its prompt nature is conserved. The results are in agreement with this expectation and the separation power tends to decrease as the lead thickness increases.

4. BGO results
As stated before, the two PMTs reading the BGO crystal were equipped with two optical filters. Figure 4 shows, for 50 GeV electrons, the average time structure of signals in the Y and UV side with the crystal oriented perpendicular to the beam ($\theta=0^\circ$).

Even if the Čerenkov light represents a very small fraction of the total light it is prominently present in the signals from the UV side.
Figure 3. Left: event-by-event distributions of the time difference between the moments the signals from PMT left and right cross a preset threshold level, for 50 GeV electrons in PbWO$_4$ for two different angles. Right: separation power for 50 GeV electrons traversing the PbWO$_4$ crystal as a function of the energy deposit i.e. the amplitude of the signal. The curve describes the expected energy dependence if photo-electron statistics were the only contribution.

Figure 4. Average time structure of signals from 50 GeV electrons measured in the BGO crystal. Left: Y side. Right: UV side. The crystal was oriented perpendicular to the beam.

The Čerenkov contribution can be measured by integrating the UV signal in a given time window $\Delta t$ after the start of the pulse. The scintillation contamination in this window is subtracted by taking the shape of the scintillation signal from the Y side and normalizing it to the tail of the UV side distribution. The level of the contamination at a given angle depends on the time window, for example at $\theta=0^\circ$ in a $\Delta t=20$ ns window 20% of the UV signal is due to scintillation light (all the Čerenkov signal is included in such a time window). The ratio $\tilde{C}/S$ averaged over many events, in a time window $\Delta t=10$ ns is shown in fig. 5 (left) as a function of $\theta$. The distribution has a peak at $\theta=30^\circ$ for which the Čerenkov contribution is maximum in the UV side. The peak is broader for electrons than for pions, probably due to the spread in direction of the particles constituting the shower in the electron signals. Around 20-30 degrees there is a fine structure with peaks for both electrons and pions: since the point-to-point fluctuations are very small this should be a systematic effect, probably related to the details of the light
collection mechanism.

In order to estimate the Čerenkov light yield 50 GeV electrons have been used. The fractional width of the Č/S event-by-event distribution is shown in fig. 5 (right) as a function of the inverse of the square root of the total UV signal (i.e. the energy deposit in the crystal). The energy scale is obtained on the basis of Monte Carlo studies. A linear fit shows that the resolution on Č/S can be described by the relation:

\[
\sigma_{\text{rms}} \frac{< C/S >}{E(\text{GeV})} = 0.220
\]

Since the ratio of the numbers of the Č and S photo-electrons in the total UV signals at \(\theta=30^\circ\) is about 0.44, and assuming that the energy dependence is due entirely to fluctuations in the total number of photo-electrons, the number of Č photo-electrons per deposited GeV is 30.

The precision on the Č/S measurement is shown in fig. 6 (left) as a function of \(\theta\), for particles that deposited 1 GeV in the crystal. A precision of 20%-30% is reached.

5. Instrumental effects

5.1. Light attenuation

The short-wavelength Čerenkov light can be attenuated on its way from the production to the light detector and this may give rise to systematic effects. The ratio Č/S is studied as a function of the impact point of the beam particles, i.e. as a function of the distance the light had to travel to the UV filter and its associated PMT, at \(\theta=0^\circ\). The measurement were also performed with the filters in the reverse position in order to eliminate effects due to the shape of the crystal. The genuine UV signal attenuation is \(\sim 10\%\) over the 24 cm length of the crystal while the ratio Č/S is fairly constant.
5.2. Reflections

Light traveling along the crystal axis experiences a (Fresnel) reflection coefficient of 13% which is reduced to 4% when the silicon cookies are installed between the crystal and the PMT, and the reflection coefficient increases with the angle of incidence to reach 100% at the critical angle. The importance of internal reflections becomes very evident when the silicon cookies are removed, as illustrated in fig. 6 (right) that shows the average time structure of the UV signal component from 50 GeV electrons traversing the BGO crystal at $\theta=0^\circ$, measured with and without cookies. The measurement without cookies reveals an oscillating pattern which is absent when the cookies are in place. The equally spaced peaks that can be observed are separated by 4 ns which corresponds to the time light travels a distance of $4 \times 30/2.15 = 55.8$ cm. The light thus travels at an average angle of $\arccos(48/55.8) = 30^\circ$, very close to the critical angle. An exponential fit to these peaks gives 6.1 ns which corresponds to an attenuation length of the crystal of $\sim 80$ cm.

5.3. Velocity of light in the crystal

The cookie-less measurement has been repeated at different impact points. By measuring the time of the first peak with respect to the trigger of the oscilloscope as a function of the distance traveled by the light (i.e. the impact point of the beam), after correcting for the true longer light path due to reflections, the velocity of light in the crystal can be obtained. The result is 13.3 cm/ns, in good agreement with the expected value, 13.9 cm/ns that can be obtained on the basis of the index of refraction of the crystal.

6. Conclusions

High-Z crystals such as PbWO$_4$ and BGO produce a significant amount of Čerenkov light in addition to scintillation light. We have investigated several methods to extract the Čerenkov contribution to the signals produced by these crystals. BGO turned out to be the more favorable because the spectra of the two lights are quite different, which made possible to produce clean signals of about equal strength with the help of optical filter. Also, the decay time is conveniently
long so that the two components can be easily distinguished on the basis of the time structure. We can measure the ratio $C/S$ in individual events with a relative accuracy of 20-30% for 1 GeV energy deposit in BGO. Although the Čerenkov fraction of the total signal is considerably larger for PbWO$_4$, the absence of the two advantages listed for BGO made it harder to extract precise Č information. Both crystals produce at least 30 photo-electrons per GeV deposited energy which is a substantial improvement with respect the DREAM calorimeter which had 8 photoelectrons per deposited GeV.

[1] N. Akchurin at al., Nucl. Instr. and Meth. A 537, 537 (2005).