

Contributions of Cherenkov light to the signals from lead tungstate crystals

N. Akchurin^a, L. Berntzon^a, A. Cardini^b, R. Ferrari^c, G. Gaudio^c, J. Hauptman^d, H. Kim^a,
L. La Rotonda^e, M. Livan^c, E. Meoni^e, H. Paar^f, A. Penzo^g, D. Pinci^h, A. Policicchio^e,
S. Popescu^{i,1}, G. Susinno^e, Y. Roh^a, W. Vandelli^c, R. Wigmans^{a,*}

^aTexas Tech University, Lubbock, TX, USA

^bDipartimento di Fisica, Università di Cagliari and INFN Sezione di Cagliari, Italy

^cDipartimento di Fisica Nucleare e Teorica, Università di Pavia and INFN Sezione di Pavia, Italy

^dIowa State University, Ames, IA, USA

^eDipartimento di Fisica, Università della Calabria and INFN Cosenza, Italy

^fUniversity of California at San Diego, La Jolla, CA, USA

^gINFN Trieste, Italy

^hDipartimento di Fisica, Università di Roma "La Sapienza" and INFN Sezione di Roma

ⁱCERN, Genève, Switzerland

Received 25 July 2007; received in revised form 13 August 2007; accepted 16 August 2007

Available online 29 August 2007

Abstract

Results are presented of detailed measurements of the signals generated by high-energy electrons and muons in lead tungstate crystals. A significant fraction of the light produced in these crystals and detected by photomultiplier tubes is the result of the Cherenkov mechanism. This is concluded from the angular dependence of the signals and from their time structure. Depending on the orientation of the crystals and on the particle type, Cherenkov light may account for up to 15% of the total signals.

© 2007 Elsevier B.V. All rights reserved.

PACS: 29.40.Ka; 29.40.Mc; 29.40.Vj

Keywords: Cherenkov light; Lead tungstate; Hadron calorimetry

1. Introduction

In recent years, there has been a growing interest in lead tungstate (PbWO₄) crystals as detectors for high-energy particles. At CERN's Large Hadron Collider, both the CMS [1] and ALICE [2] experiments are completing very large electromagnetic (em) calorimeter systems consisting of these crystals. Smaller detectors of this type are either operating or planned, for example for the PANDA [3] and HYCAL [4] experiments. Lead tungstate crystals are

attractive as detectors for em showers because of their high density, which implies a short radiation length and Molière radius, their fast signals and their relative insensitivity to the effects of radiation damage. On the downside, we mention the small light yield, less than $\frac{1}{300}$ of the light yield of the widely used NaI(Tl) and CsI(Tl) crystals [5]. Because of this small light yield, and the large effective Z value, it is reasonable to assume that a significant fraction of the light produced by PbWO₄ crystals is actually the result of Cherenkov radiation, rather than electronic de-excitation.

We have shown previously that the combined availability of Cherenkov and scintillation signals for hadronic showers makes it possible to eliminate the effects of the dominating source of fluctuations in calorimetric hadron

*Corresponding author. Fax: +1 806 742 1182.

E-mail addresses: Richard.Wigmans@ttu.edu, wigmans@ttu.edu (R. Wigmans).

¹On leave from IFIN-HH, Bucharest, Romania.

detection, and thus considerably improve hadronic calorimeter performance [6]. However, because of the small Cherenkov light yield, sampling calorimeters are less than ideal for taking full advantage of this. On the other hand, homogeneous calorimeters whose light signals could be split into scintillation and Cherenkov components hold great promise for high-quality hadron calorimetry [7].

For these reasons, we set out to measure the composition of the signals produced by PbWO₄ crystals.² In Sections 2 and 3, we describe the methods used to determine the Cherenkov component of the measured signals, and the experimental setup in which the crystals were tested. In Section 4, we discuss the experimental data that were taken and the methods used to analyze these data. In Section 5, the experimental results are presented and discussed. A summary and conclusions are presented in Section 6.

2. Methods to distinguish Cherenkov from scintillation light

If one wants to distinguish the contributions from the Cherenkov and scintillation components to the signals from crystals that generate a mixture of these, such as PbWO₄, one could use one or several of the following characteristics:

- (1) *Directionality*. The Cherenkov light is emitted at a fixed angle with respect to the momentum vector of the particle that generates it, while the scintillation light is isotropically emitted.
- (2) *Time structure*. The Cherenkov light is *prompt*, whereas scintillation processes have one or several characteristic decay times.
- (3) *The spectrum*. The Cherenkov light is emitted with a characteristic λ^{-2} spectrum, while the scintillation processes have their own characteristic spectra.
- (4) *Polarization*. Contrary to scintillation light, Cherenkov light is polarized.

In the present study, we have exploited the first two characteristics. It is a well-known fact that the light yield of PbWO₄ crystals is very temperature dependent. It changes by -2.3% per degree Celsius. This is obviously only true for the *scintillation* light. Therefore, the fraction of the light that is produced by the Cherenkov mechanism is expected to increase with temperature. Our measurements have been performed at room temperature. One should keep this in mind when translating our results to the ALICE experiment, from which the crystals we tested were borrowed. The ALICE PbWO₄ calorimeter operates at a much lower temperature (-15°C), where the relative contributions of Cherenkov light to the signals are correspondingly smaller.³

²The PbWO₄ crystals used for these studies were provided by the ALICE Collaboration, who use them for their PHOS calorimeter.

³The PbWO₄ ECAL of the CMS experiment is designed to operate at 18°C .

2.1. Directionality

Cherenkov light is emitted by charged particles traveling faster than c/n , the speed of light in the medium with refractive index n in which this process takes place. The light is emitted at a characteristic angle, θ_C , defined by $\cos\theta_C = 1/\beta n$. In the case of sufficiently relativistic particles (i.e., $\beta \sim 1$) traversing PbWO₄ crystals ($n = 2.2$), $\theta_C \sim 63^\circ$.⁴

In order to detect the contribution of Cherenkov light to the signals from a PbWO₄ crystal, we equipped both ends of the crystal with a photomultiplier tube (PMT). By varying the detector *orientation* with respect to the direction of the incoming particles, a contribution of Cherenkov light would then manifest itself as an angle-dependent asymmetry. This is illustrated in Fig. 1, which shows the setup of the initial measurements we performed with a cosmic-ray telescope to test this principle [7]. The PMT gains were equalized for the leftmost geometry, in which the crystal was oriented horizontally. By tilting the crystal through an angle (θ) such that the axis of the crystal is at the Cherenkov angle θ_C with respect to the particle direction, Cherenkov light produced by the cosmic rays traversing the trigger counters would be preferably detected in either the *L* (central geometry) or *R* (rightmost geometry) PMT. By measuring the response asymmetry $(R - L)/(R + L)$ as a function of the tilt angle θ , the contribution of Cherenkov light to the detector signals could be determined.

The initial cosmic-ray measurements indicated that the contribution of Cherenkov light was at the level of 15–20% [7]. Because of the extremely low event rates and the tiny signals (typically 20–30 MeV), we decided to perform systematic studies using particle beams. The results of these studies are the topic of the present paper.

2.2. Time structure

The scintillation process in PbWO₄ has a decay constant of ~ 10 ns, whereas the Cherenkov component of the signals is prompt. In the cosmic-ray measurements mentioned above, we also studied the time structure of the signals, using a fast oscilloscope capable of storing both pulse shapes simultaneously. These measurements qualitatively confirmed the expected differences between the signals measured in the *R* and *L* PMTs [7]. However, low statistics and very small signals limited the quality of the information that could be derived from these measurements. In the beam measurements described here, we measured the signal shapes with very fast Flash ADCs (FADC). As is shown in Fig. 2, this turned out to be a

⁴The reality may be somewhat more complicated, because of the anisotropic optical properties of lead tungstate crystals [8,9], which might affect some aspects of Cherenkov light emission [10]. However, this anisotropy is inconsequential for the principles applied and the conclusions obtained in our study.

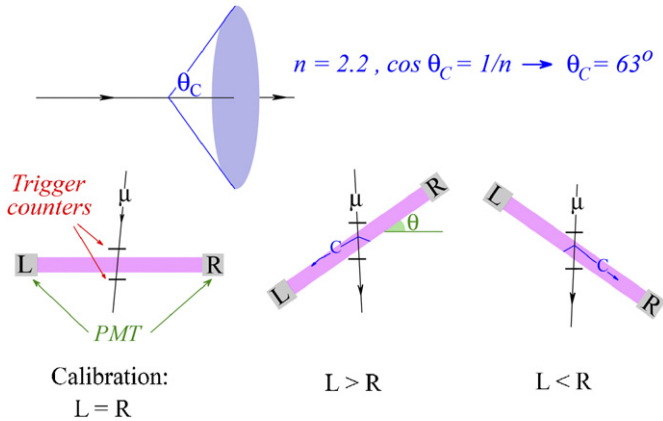


Fig. 1. Principle of the asymmetry measurement used to establish the contribution of Cherenkov light to the signals from the PbWO₄ crystals. Depending on the orientation, this directionally emitted light contributes differently to the signals from the left and right photomultiplier tubes.

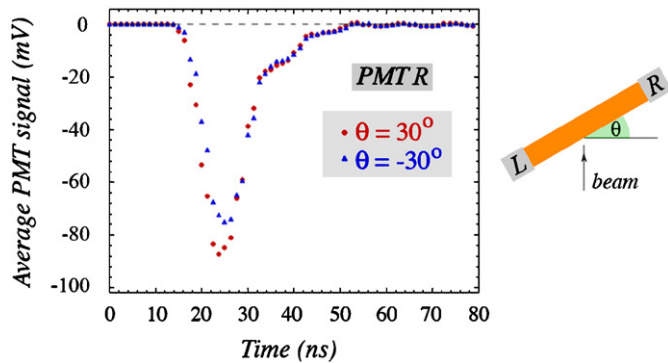


Fig. 2. Average time structure of the signals measured with the PMT reading out one end (R) of a PbWO₄ crystal traversed by 10 GeV electrons, for two different orientations of the crystal. At $\theta = 30^\circ$, Cherenkov light contributes to the signals, at $\theta = -30^\circ$, it does not.

wonderful experimental tool. In a period of a few days, detailed pulse shapes were recorded for millions of events. The figure clearly shows the additional prompt signal component that appears when the crystal is rotated from a position in which Cherenkov light does not contribute to the signals ($\theta = -30^\circ$) to a position where it does ($\theta = 30^\circ$). The trailing edge of the PMT signals is not affected by this rotation and is indeed in great detail (including the effects of reflections in the signal cables) identical for these two pulse shapes.

3. Experimental setup

3.1. Detector and beam line

The measurements described in this paper were performed in the H4 beam line of the Super Proton Synchrotron at CERN. Our detector was a PbWO₄ crystal with a length of 18 cm and a cross-section of $2.2 \times 2.2 \text{ cm}^2$.

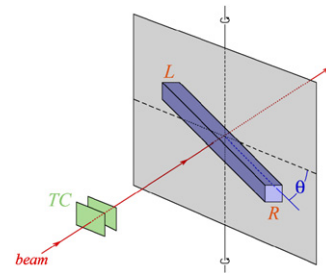


Fig. 3. Experimental setup in which the beam tests were performed.

The transverse dimension, relevant for our measurements, corresponds to 2.5 radiation lengths. The light produced by particles traversing this crystal was read out by two PMTs,⁵ located at opposite ends. In order to reduce the light trapping effects of the large refractive index of PbWO₄, the PMTs were coupled to the crystal by means of silicone “cookies” ($n = 1.403$).

This crystal was mounted on a platform that could rotate around a vertical axis. The crystal was oriented in the horizontal plane and the rotation axis went through its geometrical center. The particle beam was also steered through this center, as illustrated in Fig. 3. The angle θ , which is frequently used in the following, represents the angle between the crystal axis and a plane perpendicular to the beam line. The angle increases when the crystal is rotated such that the crystal axis L–R approaches the direction of the traveling beam particles. The crystal orientations shown in Figs. 2 and 3 correspond thus to $\theta > 0$ and $\theta < 0$, respectively.

Two small scintillation counters provided the signals that were used to trigger the data acquisition system. These trigger counters (TC) were 2.5 mm thick, and the area of overlap was $6 \times 6 \text{ cm}^2$. A coincidence between the logic signals from these counters provided the trigger.

3.2. Data acquisition

Measurement of the time structure of the crystal signals formed a very important part of the tests described here. In order to limit distortion of this structure as much as possible, we used 15 mm thick air-core cables to transport the detector signals to the counting room. Such cables were also used for the signals from the TC, and these were routed such as to minimize delays in the DAQ system.⁶

Depending on the desired type of information, the crystal signals were either sent to a charge ADC, or to the FADC. The response asymmetry measurements were based on the digitized integrated charge, the time structure was measured with the FADC,⁷ which digitized the amplitude

⁵Hamamatsu R5900U, 10-stage, bialkali photocathode, borosilicate window.

⁶We measured the signal speed to be $0.78c$ in these cables.

⁷Dr. Struck SIS3320, <http://www.struck.de/sis3320.htm>.

of the signals at a rate of 200 MHz. During a time interval of 80 ns, 16 measurements of the amplitude were thus obtained. In order to further increase this rate, and thus improve the time resolution of this measurement, we used several input channels for each signal. The crystal signals were split (passively, with correct impedance matching) into four equal parts at the counting room end. These four signals were measured separately in four different channels of the FADC module. Signals 2, 3 and 4 were delayed by 1.25, 2.50 and 3.75 ns with respect to signal 1. By using the FADC module in this way, the time structure of the signals was probed every 1.25 ns.⁸

The quality of the information obtained in this way is illustrated in Fig. 2, which shows the average time structure of the signals from 10 GeV electrons traversing the crystal for $\theta = 30^\circ$ and -30° , respectively.

The charge measurements were performed with 12-bit LeCroy 1182 ADCs. These had a sensitivity of 50 fC/count and a conversion time of 16 μ s. The ADC gate width was 100 ns, and the calorimeter signals arrived ~ 20 ns after the start of the gate.

The data acquisition system used VME electronics. A single VME crate hosted all the needed readout and control boards. The trigger logic was implemented through NIM modules and the signals were sent to a VME I/O register, which also collected the spill and the global busy information. The VME crate was linked to a Linux based computer through an SBS 620⁹ optical VME–PCI interface that allowed memory mapping of the VME resources via an open source driver.¹⁰ The computer was equipped with a 2 GHz Pentium-4 CPU, 1 GB of RAM, and was running a CERN SLC 4.3 operating system.¹¹

The data acquisition was based on a single-event polling mechanism and performed by a pair of independent programs that communicated through a first-in-first-out buffer, built on top of a 32 MB shared memory. Only exclusive accesses were allowed and concurrent requests were synchronized with semaphores. The chosen scheme optimized the CPU utilization and increased the data taking efficiency by exploiting the bunch structure of the SPS, where beam particles were provided to our experiment during a spill of 4.8 s, out of a total cycle time of 16.8 s. During the spill, the readout program collected data from the VME modules and stored them into the shared memory, with small access times. During the remainder of the SPS cycle, a recorder program dumped the events to the disk. Moreover, the buffer presence allowed low-priority monitoring programs to run (off-spill) in spy mode. With this scheme, we were able to reach a data acquisition rate as high as 2 kHz, limited by the FADC

readout time. The typical event size was ~ 1 kB. All detector signals were monitored on-line.

3.3. Calibration of the detectors

The absolute calibration of the signals generated by the crystal was not a major concern in these tests. On the other hand, it was absolutely essential that the gains of the 2 PMTs, *L* and *R*, that collected the light generated in the crystals at the two opposite ends of the crystal were equalized. We used 10 GeV electrons for that purpose. The crystal was oriented such that the beam entered the detector perpendicular to the crystal axis ($\theta = 0$), so that any Cherenkov light generated by the beam particles would be observed in the same proportion by both PMTs. The high voltages were chosen such that the average signals were about 300 ADC counts above the pedestal value. Off-line, the calibration constants were fine-tuned such as to equalize the responses of the two PMTs.

4. Experimental data

The crystals were exposed to beams of 150 GeV μ^+ and 10 GeV electrons. The angle θ between the crystal axis and the plane perpendicular to the beam line was varied from -45° to 45° , in steps of 7.5° . At each angle, 100 000 events were collected for the response asymmetry measurements, and another 100 000 for the time structure.

Since the particles traversed the detector perpendicular to the longitudinal crystal axis, the effective thickness of the crystal was only a few radiation lengths ($2.5X_0/\cos\theta$) in this setup. In order to probe the em showers at greater depth, we also performed a series of measurements in which the electrons traversed 4 cm of lead ($\sim 7X_0$) installed directly upstream of the crystal. In this way, the light generated in the crystals reflected the particle distribution just beyond the shower maximum, at a depth of $7-10X_0$. To avoid introducing too large a change in this effective depth, the latter measurements were limited to angles θ ranging from -30° to 30° . Separate measurements were performed of the response asymmetry and of the time structure. As before, 100 000 events were collected for each run.

5. Experimental results

5.1. Left–right asymmetry

We define the response asymmetry as the ratio $(R - L)/(R + L)$, where *R* and *L* represent the average signals measured in the PMTs *R* and *L* for the same events. Since these signals were equalized for $\theta = 0$, any non-zero value in this ratio is indicative for a non-isotropic component in the light generated in the crystals, i.e., Cherenkov light.

The relationship between this response asymmetry (to be called α in the following) and the relative contribution of

⁸This constituted in fact an oversampling. According to the manufacturer of the FADC unit, the effective analog bandwidth at the input stage amounted to ~ 200 MHz. Therefore, the effective time resolution was ~ 2.5 ns.

⁹<http://www.gefanuembedded.com/products/457>.

¹⁰<http://www.awa.tohoku.ac.jp/~sanshiro/kinoko-e/vmedrv/>.

¹¹<http://linux.web.cern.ch/linux/scientific4/>.

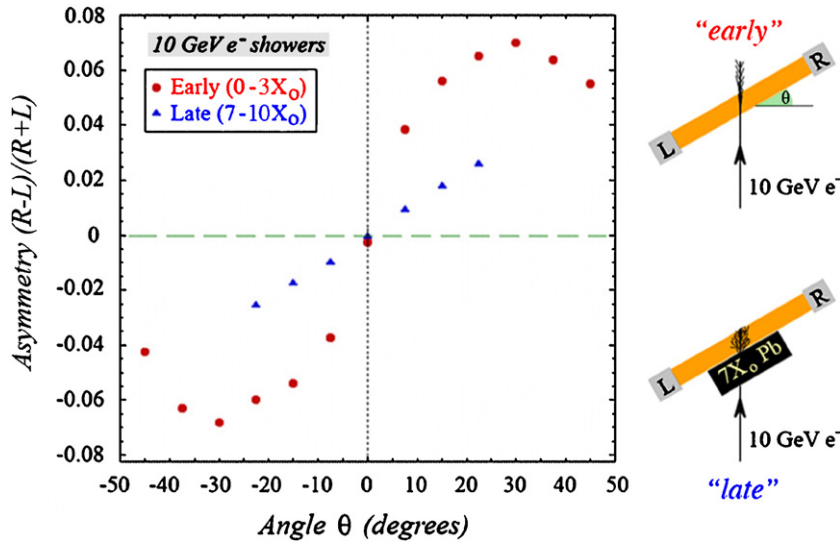


Fig. 4. Left–right response asymmetry measured for 10 GeV electrons showering in a $2.5X_0$ thick PbWO_4 crystal, as a function of the orientation of the crystal (the angle θ). Results are shown for the early and the late components of the showers. The latter measurements were obtained by placing 4 cm of lead upstream of the crystal.

Cherenkov light to the PMT signals¹² can be seen as follows. If we call the relative contributions of Cherenkov light to the R and L signals ε_R and ε_L , respectively (with ε_R and ε_L normalized to the scintillator signals in each channel), then

$$\alpha = \frac{\varepsilon_R - \varepsilon_L}{2 + \varepsilon_R + \varepsilon_L}. \quad (1)$$

This ratio reaches its maximum possible value when Cherenkov light reaches only one of the PMTs, e.g., R . In that case, $\varepsilon_L = 0$, $\alpha = \varepsilon_R/(2 + \varepsilon_R)$, and the relative contribution of Cherenkov light to the *total* signal from this PMT equals

$$f_C = \frac{\varepsilon_R}{1 + \varepsilon_R} = \frac{2\alpha}{1 + \alpha}. \quad (2)$$

This situation may occur when a single relativistic charged particle traverses the crystal. Depending on the orientation of the crystal and the index of refraction, the acceptance of the Cherenkov light emitted by that particle may in that case be limited to one PMT only. Eq. (1) shows that when the Cherenkov light produced in the crystal is shared between both PMTs, i.e., when both ε_R and ε_L are non-zero, then the measured value of the asymmetry is smaller than the maximum possible value mentioned above, and Eq. (2) underestimates the contribution of Cherenkov light to the signals. As we shall see below, this situation occurs in developing showers.

Fig. 4 shows the response asymmetry measured for 10 GeV electrons, as a function of the angle θ . This curve

exhibits exactly the characteristics expected from a contribution of Cherenkov light:

- It is symmetric around $\theta = 0$, i.e., the measured response asymmetry at an angle θ is equal to that at $-\theta$.
- The asymmetry rapidly increases when the crystal is rotated, reaches a maximum value for $\theta = \pm 30^\circ$, and declines again for larger angles. This reflects the changing acceptance of Cherenkov light, as we verified with a very simple light tracing Monte Carlo simulation.
- The maximum asymmetry is measured for an angle that is close to the expected value of $90^\circ - \theta_C = 27^\circ$, at which angle the acceptance for Cherenkov light is largest in this geometry.

The maximum asymmetry amounts to 0.07, and we conclude from this that when the crystal is oriented at $\theta = \pm 30^\circ$, $\sim 13\%$ of the signal measured in the PMT that is optimally located for detecting Cherenkov light, is indeed Cherenkov light (Eq. (2)). As the orientation of the crystal is changed, this percentage decreases, reflecting the reduced acceptance for Cherenkov light of the PMTs. At $\theta = 0$, the total acceptance for Cherenkov light in both PMTs combined reaches its minimum value.

The above arguments are, strictly speaking, only valid for particles that traverse the crystal in a direction parallel to the beam. Upon traversing the crystal, the beam electrons lose a large fraction of their energy (typically $> 80\%$) radiating bremsstrahlung photons. The relativistic electrons and positrons produced when these photons convert in the crystal travel also predominantly in the same direction. For the purpose of this experiment, the early part of the em showers probed in this measurement thus resembles a collection of particles traveling all approximately in the same direction, i.e., parallel to the beam line.

¹²It should be emphasized that this discussion concerns the PMT signals, and *not* the numbers of photons produced by the different mechanisms. For the latter, differences in production spectra and photocathode quantum efficiencies would have to be taken into account.

However, as the shower develops, so does its isotropic component. This component is primarily due to shower electrons generated in Compton scattering or through the photoelectric effect. In fully contained em showers, this component is responsible for about half of the signal [11]. It is also thanks to this component that 0° quartz-fiber calorimeters, such as the CMS Forward Calorimeter (HF), produce meaningful signals [12].

For this reason, we also wanted to measure the effect of this increased isotropy on the left/right response asymmetry. By placing 4 cm of lead directly upstream of the crystal, the electron showers developed in a lead/PbWO₄ combination. For 10 GeV electrons, the shower maximum was located at a depth of $\sim 5X_0$, (i.e., inside the lead absorber), and the crystal probed the light produced at a depth of $7-10X_0$.

Fig. 4 also shows the response asymmetry measured for this light. The asymmetry is considerably smaller than for the light produced in the early part of the shower, by about a factor of three. Yet, the characteristics of the $(R-L)/(R+L)$ curve indicate that also in this case, the asymmetry is the result of the contribution of Cherenkov light to the signals. The reduction in the net directionality of the measured light indicates the importance of the isotropic shower component.

In another paper, we describe the results of measurements we performed on (almost fully) contained em showers with a PbWO₄ calorimeter [13]. In that case, the asymmetry resulted from the integration over the full longitudinal shower profile, with the early part contributing most to the net asymmetry and the latest parts very little, if anything. We measured for such showers an overall response asymmetry of 0.044, i.e., $\sim 60\%$ of the asymmetry observed in the first $2-3X_0$ reported here.

The signals measured in these experiments were very small. According to EGS4 simulations [14], 10 GeV electrons deposited on average 320 MeV in the PbWO₄ crystal, when it was placed perpendicular to the beam line. However, this was still one order of magnitude larger than the signals recorded for the muons. Fig. 5 shows a typical signal distribution, measured in one of the PMTs for $\theta = 0$. Based on a comparison with the 10 GeV electron signals, this distribution gave a most probable energy deposit of 25 MeV.

The most probable signal value was also used for the response asymmetry measurement for these particles. However, the Landau fits did in general not reproduce the measured signal distributions very well. This is because the beam spot was larger than the transverse size of the crystal. As a result, many beam particles missed the crystal (as evidenced by the large pedestal peak in Fig. 5), whereas others traversed it close to the edge, scattering out, leading to sub-mip signals. For this reason, we also studied the left–right asymmetry using two other characteristics of the signal distribution: the average signal and the result of a Gaussian fit around the most probable value (see inset Fig. 5).

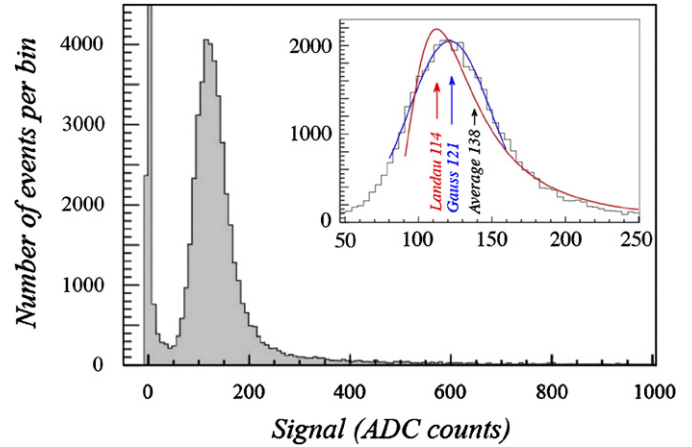


Fig. 5. Signal distribution for 150 GeV μ^+ traversing the $2.5X_0$ thick PbWO₄ crystal perpendicularly ($\theta = 0$). The inset shows the results of fits to the most probable signal region. See text for details.

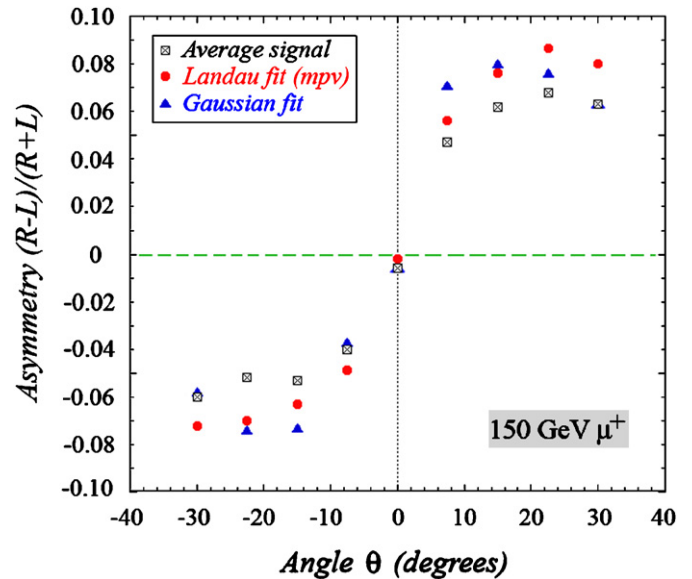


Fig. 6. Left–right response asymmetry measured for 150 GeV muons traversing a $2.5X_0$ thick PbWO₄ crystal, as a function of the orientation of the crystal (the angle θ). The asymmetry concerns the *most probable* signal value derived from a Landau fit (the circles) or a Gaussian fit (the triangles), or the average signal value (the open squares).

The angular dependence of the left–right asymmetry for muons traversing the PbWO₄ crystal is shown in Fig. 6, for all three figures-of-merit derived from the signal distributions. This curve shows the same general characteristics as the one measured for the electrons (Fig. 4). The maximum asymmetry is measured for $\theta \approx \theta_C$ (27°), in the PMT oriented in the optimal direction for detecting the Cherenkov light. The maximum asymmetry is ~ 0.08 , which translates into a 15% contribution of Cherenkov light to the total signals at that angle (Eq. (2)). It also seems that the asymmetry is somewhat smaller when the average detector signal is used instead of the most probable value. This might indicate that Cherenkov light produced in the

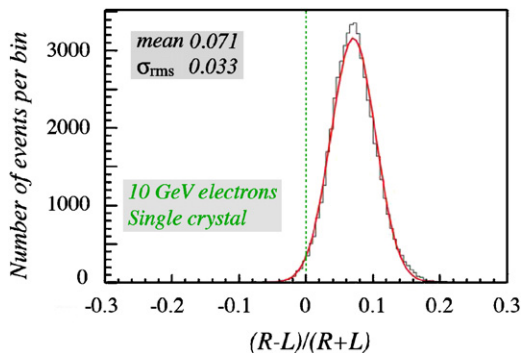


Fig. 7. Distribution of the left–right response asymmetry, measured for 10 GeV electrons traversing the crystal at $\theta = 30^\circ$, together with the results of a Gaussian fit.

radiative component of the energy lost by the muons is somewhat less directional than that produced by the ionizing component. This would be consistent with the observations of the asymmetry in em showers discussed above.

Based on the signal distributions observed in these measurements and on the assumption that the energy deposition by 10 GeV electrons is calculated correctly by GEANT4 [15], we can determine the specific energy loss of muons in PbWO_4 . The most probable energy loss is 11.6 MeV/cm, while the measured average energy lost by 150 GeV μ^+ is 13.2 MeV/cm.

We can also determine the “light yield” of the crystals and PMTs used in our studies, or rather the number of photoelectrons measured (with the PMTs chosen for these studies) per unit deposited energy. Fig. 7 shows the event-to-event distribution of the left–right asymmetry measured for 10 GeV electrons traversing the crystal at $\theta = 30^\circ$, together with the results of a Gaussian fit. At $\theta = 0^\circ$, the width of the distribution increased from 0.0334 to 0.0384. If we assume that the width is dominated by statistical fluctuations in the number of photoelectrons, then a σ of 0.0384 translates into an average number of photoelectrons of ~ 340 per PMT, or ~ 1 photoelectron per MeV deposited energy. At $\theta = 0^\circ$, the width of the $(R - L)/(R + L)$ distribution for the 150 GeV μ^+ was 0.1274, which translates into an average signal of 31 photoelectrons per PMT.

The average signal from the 10 GeV electrons increased by 47% when the crystal was rotated from 0° to 30° . This reflects the onset of the shower development, since a simple increase in path length ($\sim \cos^{-1} \theta$) would only lead to a 15% increase. The measured width of the asymmetry distribution at 30° ($\sigma = 0.0334$) corresponds to the statistical fluctuations in 448 photoelectrons/PMT, an increase of only 32% with respect to the 0° case. The fact that the decreasing width does not match the increased signal indicates that other factors (e.g., temperature effects, response nonuniformities) did contribute to the measured width and that, therefore, the estimated light yield is in fact a lower limit.

The distribution shown in Fig. 7 illustrates one other important aspect of these experimental data. All the measurement results reported in this paper concern *averages*. Both the observed left/right asymmetries, and also the angular dependence of the time structure discussed in the next subsection, concern the average characteristics of a large number of events, typically 100 000. The question arises how accurately one can determine the Cherenkov content of the signal from one particular event on the basis of these characteristics. Fig. 7 provides an answer to that question, for what concerns the left/right asymmetry. It shows that, if for a particular 10 GeV electron traversing this crystal, an asymmetry is measured of 0.080, the experimental uncertainty on this number is 0.033 (1 standard deviation). In other words, that particular signal contains $14.8 \pm 5.9\%$ Cherenkov light (Eq. (2)). Of course, this error bar is strongly determined by photoelectron statistics, especially at these low energies (~ 0.4 GeV).

We want to re-emphasize that all these results concern one particular crystal, operated at room temperature. No attempts were made to control the temperature, or to measure a temperature dependence of the observed effects.

5.2. Time structure of the signals

A second valuable tool for recognizing the contributions of Cherenkov light to the calorimeter signals is derived from the time structure of the events. This is illustrated in Fig. 8, which shows the average time structure of the 10 GeV shower signals recorded with the same PMT at different angles of incidence, namely $\theta = 30^\circ$ and -30° . The diagrams on the left-hand side of this figure concern PMT R.

Cherenkov light produced by the traversing electron and by the particles produced in the early shower component are expected to be detected by this PMT when the crystal is oriented at $\theta = 30^\circ$, while very little, if anything, will reach this PMT at $\theta = -30^\circ$. The figure shows that the trailing edges of both time structures are almost completely identical. This part of the time structure of the pulses is completely determined by the decay characteristics of the scintillation processes in the PbWO_4 crystals and should thus indeed be independent of the detector orientation.

However, there is a very significant difference in the leading edge of the pulses. The ones measured for $\theta = 30^\circ$ exhibit a steeper rise than the ones for $\theta = -30^\circ$. The top graphs show the result of subtracting the latter pulse shape from the “ 30° ” one: The pulses recorded at $\theta = 30^\circ$ contain an additional “prompt” component of the type one would expect from Cherenkov light.

The reverse situation is observed in the other PMT (L). Here, the prompt additional component is observed in the time structure of the pulses recorded when the crystal was oriented at $\theta = -30^\circ$. Also in this PMT, the time structure beyond the amplitude of the signals was found to be independent of the crystal orientation.

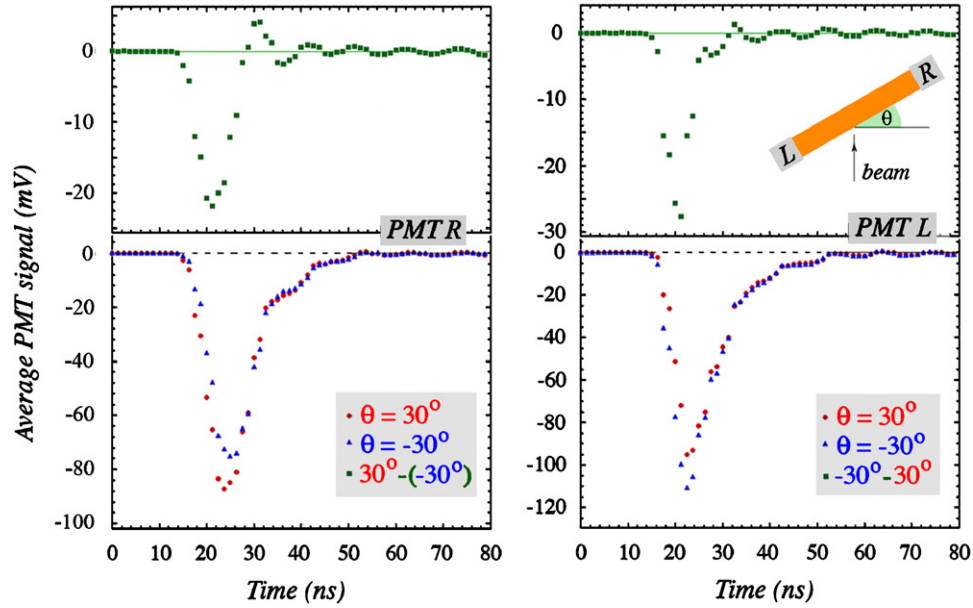


Fig. 8. Average time structures of the signals measured in the left (*L*) and right (*R*) photomultiplier tubes that detect the light produced by 10 GeV electrons in a $2.2X_0$ thick PbWO_4 crystal. The bottom plots show these signals for angles $\theta = \pm 30^\circ$, for PMTs *R* and *L*, respectively. The top plots show the difference between the two orientations, i.e., the PMTs response function to a prompt Cherenkov component in the signal.

These results confirm the prompt nature of the additional light component observed in the left/right asymmetry measurements, and provide more evidence for the Cherenkov mechanism being responsible for the observed phenomena.

The figure shows minor differences between the shapes of the prompt components observed in the two PMTs. These are most likely due to differences in the characteristics of these tubes. PMT *L*, which operated at a slightly higher high voltage, responded to a δ -function with a σ_{rms} of 2.3 ns, vs. 2.8 ns for PMT *R*. As a result, the response to the Cherenkov component had a slightly different time structure in these PMTs.

The average pulse shapes shown in Fig. 8 make it also possible to determine the contribution of Cherenkov light to the crystal signals. In the case of the 10 GeV electrons, the additional component represented $\sim 12\%$ of the total signal in PMT *R* and 13% in PMT *L*. For comparison, we recall that the left/right asymmetry measurements led us to conclude that, at the Cherenkov angle, these signals contained, on average, $\sim 13\%$ of Cherenkov light.¹³

We have also studied the angular dependence of the average pulse shape. Since the Cherenkov contribution manifests itself in the leading edge of the time structure, we have developed several methods to characterize the properties of that part of the pulse shape in a quantitative manner. Two of these methods are illustrated in Fig. 9. In the first method (Fig. 9a), we used an appropriate function to describe the time structure. It turns out that the leading

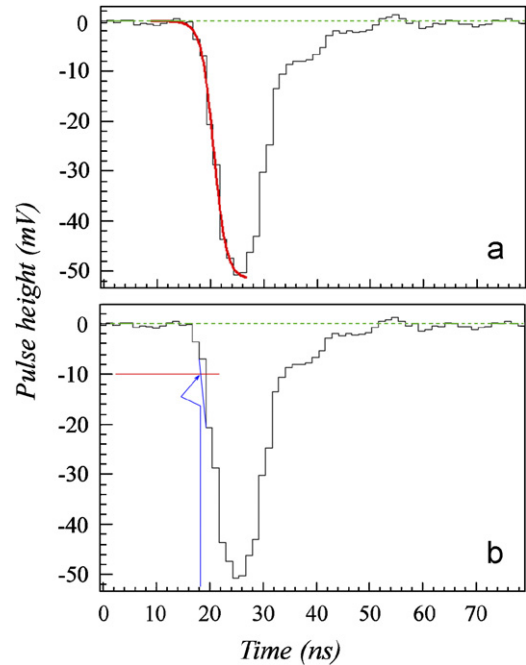


Fig. 9. The characteristics of the time structure of the signals are determined with two different methods. In method *a*, the leading edge is fitted to Eq. (3), and the fitted parameters t_L and τ_L determine the Cherenkov content of the signal. In method *b*, the time at which the pulse height exceeds a certain threshold level is used for this purpose. See text for details.

edge of the pulse shape, $V(t)$, is well described by a function of the following type:

$$V(t) = |A| \left[\frac{1}{e^{(t-t_L)/\tau_L} + 1} - 1 \right]. \quad (3)$$

¹³As before, these percentages represent the ratio of the Cherenkov component and the total signal measured at the angle at which the contribution of this component is largest.

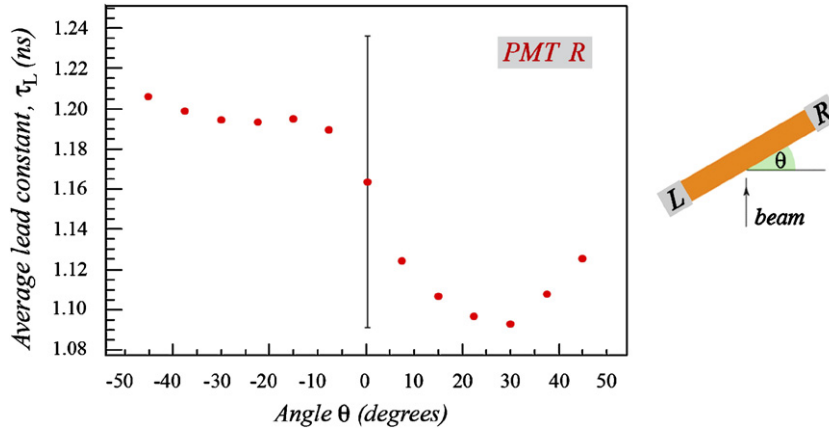


Fig. 10. Average lead constant, τ_L (see Eq. (3)), of the pulses recorded by PMT R, as a function of the orientation of the crystal, i.e., the angle θ . Data for 10 GeV electrons.

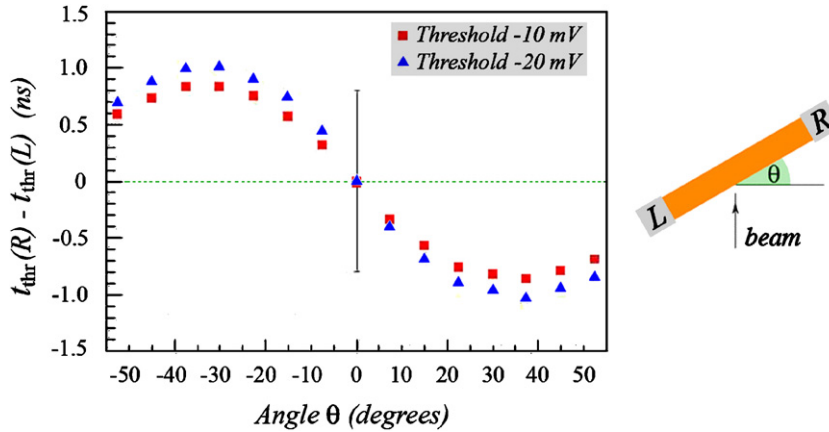


Fig. 11. Average difference between the times the two PMTs reading out the two sides of the crystal needed to reach a certain threshold level, as a function of the orientation of the crystal (i.e., the angle θ). Data for 150 GeV μ^+ , and two different threshold values.

The characteristics of the leading edge of the pulse shape are then determined by the values of the *lead time* t_L and the *lead constant* τ_L , which are independent of the amplitude A of the signal. For example, an increase in the Cherenkov content of the signal will manifest itself as a decrease in the value of τ_L , since the leading edge is becoming steeper.

In the second method (Fig. 9b), we determined the precise time at which the pulse height exceeds a certain fixed threshold level, e.g., -10 mV. An increase in the Cherenkov content of the signal will shift that point to an earlier moment.

Some results of these analyses are shown in Figs. 10 and 11. Fig. 10 shows the value of the lead constant, τ_L , measured for the 10 GeV electron signals from PMT R, as a function of the angle θ . For negative values of θ , Cherenkov light produced by the electrons was not detected by this PMT. The pulse shape is independent of θ , with a τ_L value of 1.20 ns. However, when the crystal was rotated towards values of $\theta > 0$, Cherenkov light produced by the showering particles became a significant component of the signals measured by PMT R, and the leading edge of

the pulse shape steepened (τ_L became smaller). This process continued until θ reached the Cherenkov angle ($\sim 30^\circ$), at which point τ_L reached a minimum value of ~ 1.09 ns. For larger angles, the acceptance of Cherenkov light decreased again and the leading edge became less steep, τ_L increased. The τ_L value measured for the signals from PMT L shows a similar behavior: It is constant for $\theta > 0$, decreases for $\theta < 0$, reaches a minimum value for $\theta = -30^\circ$ and increases again for larger angles.

Fig. 11 shows the results of an analysis of the threshold crossing time, for signals generated by 150 GeV μ^+ . The *difference* between the crossing times of the signals recorded by PMTs R and L is given as a function of the angle θ , for two different threshold levels. This difference is set to zero for $\theta = 0$. The figure shows that the difference is negative for $\theta > 0$. As a result of the increasing contribution of Cherenkov light to the signals from PMT R, the threshold was crossed earlier in this PMT, and therefore the plotted quantity is negative. When $\theta < 0$, Cherenkov light contributed to the signals from PMT L, and the plotted quantity is positive. As in the case of the response asymmetry, the maximum difference is observed for angles

near the Cherenkov angle, $\sim 30^\circ$. The results are qualitatively not significantly different for the two different threshold levels, but they do indicate a slightly larger effect for the higher threshold.

As in the case of the left/right asymmetry, the results shown in Figs. 10 and 11 concern the average behavior observed for large numbers of events (100 000). The error bars in these figures indicate the precision with which the parameter in question is determined for *individual* events. The size of these error bars, which for these small signals is completely dominated by photoelectron statistics, is such that the value of the lead constant (τ_L) or the threshold crossing time does not provide statistically significant information about the (size of the) contribution of Cherenkov light to the signal in question.

6. Conclusions

We have measured the contribution of Cherenkov light to the signals from electrons and muons in lead tungstate crystals. In the chosen geometry, which was optimized for detecting this component, information about this contribution was obtained from the left/right response asymmetry and from the time structure of the signals. For single particles traversing the calorimeter (muons), the maximum Cherenkov contribution to the signals was measured to be 15–20%. The measurements for electron showers indicated somewhat lower values, because of the contributions of isotropically distributed shower particles to the signals. This reduced the measured asymmetries in the response and time structure of the signals. This effect was measured to increase in importance as the shower developed. The asymmetries measured for 10 GeV electrons in the first 2–3 radiation lengths were about three times larger than those measured at a depth of $7\text{--}10X_0$, i.e., just beyond the shower maximum.

Acknowledgments

The studies reported in this paper were carried out with PbWO₄ crystals made available to us by the PHOS group of the ALICE Collaboration. We sincerely thank Drs.

Mikhail Ippolitov and Hans Muller for their help and generosity in this context. We thank CERN for making particle beams of excellent quality available. This study was carried out with financial support of the United States Department of Energy, under Contract DE-FG02-95ER40938.

References

- [1] P. Rumerio, Commissioning of the CMS electromagnetic calorimeter and operational experience, Proceedings of the XIIth International Conference on Calorimetry in High Energy Physics, Chicago, June 5–9, 2006, AIP Conference Proceedings, vol. 867, 2006, p. 301.
- [2] M. Ippolitov, Energy, timing and two-photon invariant mass resolution of a 256-channel PbWO₄ calorimeter, Proceedings of the XIth International Conference on Calorimetry in High Energy Physics, Perugia, March 29–April 2, 2004, World Scientific, Singapore, 2006, p. 103.
- [3] R. Novotny, The electromagnetic calorimeter of the future PANDA detector, Proceedings of the XIIth International Conference on Calorimetry in High Energy Physics, Chicago, June 5–9, 2006, AIP Conference Proceedings, vol. 867, 2006, p. 106.
- [4] A. Gasparian, A high-performance hybrid electromagnetic calorimeter at Jefferson lab, Proceedings of the XIth International Conference on Calorimetry in High Energy Physics, Perugia, March 29–April 2, 2004, World Scientific, Singapore, 2006, p. 109.
- [5] R.Y. Zhu, Precision crystal calorimeters in high energy physics: past, present and future, Proceedings of the XIIth International Conference on Calorimetry in High Energy Physics, Chicago, June 5–9, 2006, AIP Conference Proceedings, vol. 867, 2006, p. 61.
- [6] N. Akchurin, et al., Nucl. Instr. and Meth. A 537 (2005) 537.
- [7] R. Wigmans, Nucl. Instr. and Meth. A 572 (2007) 215.
- [8] S. Baccaro, et al., Nucl. Instr. and Meth. A 385 (1997) 209.
- [9] R. Chipaux, M. Géléoc, in: V.V. Mikhailin, M.V. Lomonosov (Eds.), Proceedings of the Fifth International Conference on Scintillators and their Applications (SCINT99), 2000, p. 629.
- [10] A. Delbart, Eur. Phys. J. D 1 (1998) 109.
- [11] R. Wigmans, Calorimetry—Energy Measurement in Particle Physics, International Series of Monographs on Physics, vol. 107, Oxford University Press, Oxford, 2000.
- [12] N. Akchurin, R. Wigmans, Rev. Sci. Instr. 74 (2003) 2955.
- [13] N. Akchurin, et al., (DREAM Collaboration), Dual-readout calorimetry with lead tungstate crystals, preprint arXiv:0707.4021 [physics.ins-det].
- [14] W.R. Nelson, H. Hirayama, D.W.O. Rogers, EGS4, SLAC Report 165, 1978, Stanford, CA, USA.
- [15] S. Agostinelli, et al., (GEANT4 Collaboration), Nucl. Instr. and Meth. A 506 (2003) 250.