Čerenkov light contribution in lead tungstate crystals

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Abstract. Results of detailed measurements of the Čerenkov light yield from lead tungstate (PbWO₄) crystals are presented. A single crystal as well as a small homogeneous calorimeter (ECAL), consisting of 19 PbWO₄ crystals, were exposed to electrons, muons and pions at the H4 beam line at CERN. It turns out that a significant fraction of the detected light is not the result of scintillation processes, but rather of the Čerenkov mechanism. This can be assessed from the analysis of both the angular dependence of the signals and their time structure. Detailed studies of the ECAL signals, corroborated by the measurements taken with the Dual-Readout calorimeter (DREAM), backing up the ECAL during beam tests, show that it is possible to estimate the independent contributions of scintillation and Čerenkov light. This information makes it possible to account for one of the dominant sources of fluctuations in hadronic showers and thus to achieve a significant improvement in hadronic calorimetry performance.

1. Introduction
The energy resolution of calorimeters is determined by fluctuations. In non-compensating calorimeters, fluctuations in the electromagnetic shower fraction ($f_{em}$) dominate the energy resolution for hadrons and jets. However the compensating option [1], while removing the detrimental effects of the $f_{em}$ fluctuations, can only be achieved in sampling calorimeters with a small sampling fraction.

We have previously shown that an alternative technique is possible: the Dual-REadout Method (DREAM) [2]. The DREAM calorimeter is a sampling detector based on the combined availability of Čerenkov and scintillation signals for hadronic showers. Since the Čerenkov light

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is mostly emitted by electromagnetic particles, the DREAM technique allows to measure $f_{em}$ event-by-event, improving the final hadronic resolution.

While the DREAM calorimeter exploits different active media to separate Čerenkov and scintillation light, the same approach can in principle be extended to an homogenous detector, in which the amounts of scintillation and Čerenkov lights are assessed thanks to their different emission properties.

In this paper, measurements of the Čerenkov light contribution in lead tungstate crystals (PbWO$_4$) are presented together with the results of a small electromagnetic calorimeter made of the same crystals.

2. Evidence of Čerenkov light in PbWO$_4$ crystals

In order to understand if the above extension of the DREAM principle is possible, we started studying the Čerenkov light yield in a PbWO$_4$ crystal$^1$ equipped with two PMTs$^2$. We exposed the crystal to particle beams, provided by the SPS at CERN, and we acquired the charge and the time structure of the signals rotating the crystal setup at different angles with respect to the beam (diagram in figure 1). Measurements of the Čerenkov light yield were done exploiting its directionality and timing properties. Čerenkov light is emitted at an angle $\cos \theta_C = 1/\beta n$ (for $n = 2.2$ and $\beta \sim 1$, $\theta_C = 63^\circ$), promptly during the passage of the particles, whereas the scintillation process features typical decay times and an isotropic emission.

![Figure 1](attachment:image1.png)

**Figure 1.** Charge asymmetry as a function of the crystal angle in respect of the beam axis.

![Figure 2](attachment:image2.png)

**Figure 2.** PMT-signal lead-constant as a function of the crystal angle in respect of the beam axis.

Figure 1 presents the charge asymmetry $(R - L)/(R + L)$ as function of the crystal angle for 10 GeV electrons. The detection of Čerenkov light by the PMTs is pointed out by the shape of the response and by the limits at about $\pm 30^\circ$, corresponding to the maximum illumination of one PMT by the Čerenkov light. From the maximum asymmetry we estimated the amount of Čerenkov light contributing to signal, corresponding to at least 13%. Showers in a latter development stage, obtained through a 7$X_0$ lead block placed in front of the crystal, present a smaller asymmetry because of their isotropic component becoming larger and then reducing the directionality of the Čerenkov light. The presence of the Čerenkov light can be also spotlighted thanks to its emission promptness. We analysed the pulse-shape samples both fitting their leading edge and through a time-over-threshold (ToT) technique. The results for the first technique are presented in figure 2: the lead constant $\tau_L$, describing the steepness of the signal leading edge, provides a measure of the Čerenkov light. Indeed $\tau_L$ is almost constant.

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1 Kindly provided by the PHOS group of the ALICE experiment.
2 Hamamatsu R5900U
when the PMT is not illuminated by the Čerenkov light (i.e. negative angles), while the signal reaches its maximum steepness, corresponding to the minimum $\tau_L$, at about $30^\circ$. The results of ToT analysis, represented by the angular dependency of left-right threshold-time difference, are analogous to those of the charge asymmetry technique.

We want to emphasize that these results are averaged on large number of events ($10^5$), since there is not sensitivity to the Čerenkov light content in a single event because of the small photoelectron statistic ($\sim 1$ p.e./MeV) of this simple setup. This is shown by the error bar in figure 2 which represents the width (RMS) of the lead constant distribution.

3. Measurements of $f_{em}$ in a homogeneous detector

We also measured the response of a small electromagnetic calorimeter (ECAL), made of 19 PbWO$_4$ crystals arranged in matrix, to electron and pion beams. The ECAL was readout with two PMTs through aluminized mylar cones and backed-up with the DREAM dual-readout module used as hadronic section (HCAL). We calibrated the ECAL with 50 GeV electrons, positioning the crystals perpendicular to the beam; then we operated it in an optimized $63^\circ$ geometry to maximize the asymmetry response.

![Figure 3](image3.png)

**Figure 3.** Charge asymmetry in ECAL as a function of the $Q/S$ ratio in HCAL.

![Figure 4](image4.png)

**Figure 4.** Lead time difference in ECAL as a function of the $Q/S$ ratio in HCAL.

In figure 3 the charge asymmetry measured in ECAL for a 50 GeV $\pi^-$ beam is plotted as a function of the $Q/S$ ratio in HCAL. Since the $Q/S$ ratio is directly related to the $f_{em}$, we can conclude that the charge asymmetry is an indicator of the em content of the showers. Moreover, as presented in figure 4, we found a similar result performing a ToT analysis on the ECAL-signal time-structure.

4. Conclusions

We measured the Čerenkov light contribution to the signals of PbWO$_4$ crystals for electrons and muons. This contribution respectively corresponds to 13% and 15-20%. Furthermore we were able to determine the electromagnetic content of hadronic showers using a small calorimeter made of lead tungstate crystals. This information was found to correlate well with explicit measurements of $f_{em}$ in a dual-readout calorimeter.

References

[1] Wigmans R 2000 *Calorimetry - Energy Measurement in Particle Physics* (Oxford: Oxford University Press)
[2] Akchurin N et al 2005 *Nucl. Instr. and Meth.* A 537 537-61