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New crystals for Dual Readout calorimetry

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Summary. — Dual Readout Calorimetry is a promising new technique for high-resolution calorimetry. It is based on simultaneous measurements, in the shower development process, of the scintillation and Cherenkov light (only produced by the electromagnetic shower component). In this way it is possible to measure, event by event, the contribution of the electromagnetic fraction, and to compensate for its fluctuations, that are the main source of degrading the hadronic energy resolution of calorimeters. In order to further improve both the electromagnetic and hadronic resolution, it is possible to reduce both the sampling fluctuations and the quantum fluctuations by using homogeneous, dense crystals. Promising results have been obtained by lead tungstate crystals ($PbWO_4$), doped with small fractions of praseodymium or molybdenum. Results from the 2008 testbeam and perspective for the coming one this year will be shown.

PACS `29.00` – Experimental methods and instrumentation for elementary-particle and nuclear physics.
PACS `29.40.Vj` – Calorimeters.
PACS `29.40.Mc` – Scintillation detectors.
PACS `29.40.Ka` – Cherenkov detectors.

1. – Introduction

The Dual Readout Method (DREAM) 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 fiber calorimeter [1], but the performances obtained were limited by different factors, such as shower containment, sampling fluctuations and quantum fluctuations. The latter two effects can be reduced by using homogeneous media, provided that an event-by-event separation of scintillation (S) and Cherenkov light (C) could be achieved.

A description of the methods that were successfully used to achieve this separation in past beam tests is given in sect. **2**. A resume of the first results obtained with crystals used in the DREAM project is given in sect. **3**. In 2008, dedicated crystals for dual readout were developed and tested in particle beams. The results are presented in sects. **4** and **5**, and projects planned for the 2009 testbeam are described in sect. **6**.

2. – Separation of Cherenkov and scintillation lights

Separation of C and S light in crystals can be achieved on the basis of the different properties of the two signals, in particular from the time structure, the emission spectrum and directionality. In fact, C light is prompt, exhibits a $1/\lambda^2$ spectrum, and is emitted at a characteristic angle ($\theta_C = \arccos(1/\beta n)$) by the relativistic (shower) particles that traverse the detector. On the other hand, S light is isotropic, and is characterized by one or several time constants and emission wavelenghts, that are characteristic of the crystal.

3. – Results of DREAM with crystals

In a recent paper [2], we have demonstrated that a significant fraction of the signals from scintillating lead tungstate ($PbWO_4$) crystals is due to Cherenkov radiation. This was concluded from measurements of the time structure of the signals and from the non-isotropic nature of the light generated by high-energy electrons traversing the crystal.

Even better results were obtained with a BGO crystal [3]. Unfortunately BGO is a much brighter scintillator than $PbWO_4$ and, therefore, C only represents a small fraction (less than 1%) of the light produced in this material by relativistic ionizing particles. However, since the spectra of the two types of light are very different, we managed to obtain an excellent separation by filtering the light. In addition, the relatively long decay time of the S component (300 ns) was helpful in separating it from the prompt C component(1).

Based on this experience, we decided to explore the possibility to combine the advantages of BGO with the intrinsically much higher C fraction of $PbWO_4$. To reach this goal, we developed a number of dedicated $PbWO_4$ crystals doped with small fractions of impurities chosen such as to achieve a shift of the scintillation spectrum to longer wavelengths, and a longer decay time [5].

The measurements described were performed in the H4 beam line of the SPS at CERN with a beam of 50 GeV electrons.

Two different types of crystals were studied in these tests: $PbWO_4$ crystals doped with Mo, and Pr(2). The aim of the test was to understand if doping the $PbWO_4$ crystal would improve its properties for dual readout calorimeters. In evaluating the results, we focused our attention on the possibility to separate the S and the C components thanks to their different characteristics in time and spectral emission. We studied also the attenuation of the light, and the number of C p.e. (Cherenkov light yield).

Figure 1 shows the radioluminescence spectra [6, 7] measured on small samples of doped and undoped $PbWO_4$. Both dopings create a shift of the scintillation wavelength, making it possible to use simple filters to separate the C from the S components. For undoped $PbWO_4$ crystals, instead, it is very hard to obtain a reasonable separation because the S peaks on the blue light, where there is also the maximum of the C spectrum.

In both cases, we adopted a readout scheme which consists of one PMT at each side of the crystal, associated with a short-pass filter that selects Cherenkov light, and long-pass filter for scintillation light(3).

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(1) This separation was harder with the $PbWO_4$ crystal with 10 ns [4] of scintillating component.

(2) We tested six crystals doped with Mo at 1% and 5%, with Pr at 0.5%, 1%, 1.5%, and an undoped crystal as reference.

(3) For C we used UG11 filter, called in the following “UV”, selects $\lambda < 400$ nm and BG3, Blue filter “B”, with a cut-off of 500 nm; for S we tested different filters. Measurements reported here used a GG495 filter, yellow “Y”, which selects $\lambda > 495$ nm.

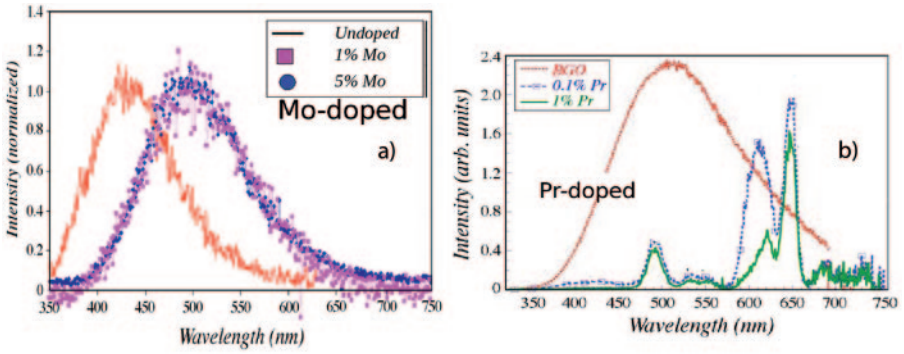

Fig. 1. – Radioluminescence emission spectra of $PbWO_4$ samples, doped with Mo (a) and Pr (b).

4. – $PbWO_4$ doped with molybdenum

As suggested by the radioluminescence measurements, essentially all light selected with the UV filter should be the result of pure C radiation, while the region above 500 nm (Y filter) is strongly dominated by S light. This is confirmed by our measurements of the time structure of the signal.

In fig. 2a the time structure of the signal passing through the UV filter (blue line), and on the Y filter (red line) are shown. These two time structures, which were measured for the same sample of events, are spectacularly different; in particular, the UV filtered signals show a very narrow peak and return to the baseline within few ns. On the other hand, signals selected with the Y filter show the typical exponential tail of scintillation. A C/S ratio as good as 5 can thus be obtained. We also measured the decay time components to be 26 and 59 ns. This time scale is ideal for our calorimetric applications, and makes it much easier to separate the C prompt peak from the S exponential decay signal than in the case of undoped crystals. Unfortunately, the Mo doping also shifts the absorption edge of the crystal to longer wavelengths, thus reducing the available window

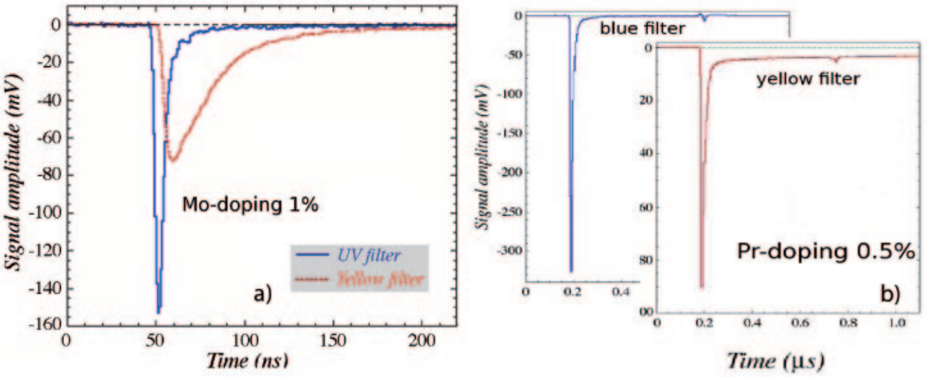

Fig. 2. – (Colour on-line) a) Average time structure of the signals from a $PbWO_4$ crystal 1% Mo-doped with filters UV (blue line) and Y (red line) (a), and 0.5% Pr-doped with filter B (b) and Y (c).

in which C light can be detected. This results in strong self-absorption of the C signal in the crystal, which is not acceptable for real calorimeters. Due to this absorpion, also the C light yield is affected; in fact we estimated it to be 8 p.e./GeV, that is similar to the value obtained in the case of the fiber DREAM calorimeter.

We have also tested the 5% Mo-doping, but the signal on the UV side is much more attenuated by the self-absorption of the crystal.

5. – $PbWO_4$ doped with praseodymium

The time spectrum of $PbWO_4$ doped with 0.5% Pr, read through the B and Y filter respectively, is shown in fig. 2b. With respect to the Mo-doping, one observes two peculiar behaviors. The first one is that, interestingly, also the yellow signal has a dominant prompt component, just like the blue signal, where we expect such a component as a result of the Cherenkov radiation. In order to investigate the nature of this signal component, we studied its angular dependence, and we observed that this prompt component is really caused by the tail of the C radiation that is transmitted by the Y filter. The second effect is that, even after few μs, the signal passing through the Y filter does not reach the baseline. This is due to the fact that the Pr-doping increases the scintillation decay time to a level not compatible for most of high-energy physics devices.

The contamination of C in the S signals could be kept at the level of a few percent by integrating the signal in a time window that is far from the prompt peak. In fact, the tail of the time signal is only due to the scintillation process. In this way it was possible to obtain a C/S ratio of 2. Self-absorption of C light, in the case of Pr-doping, does not seem to be an important problem.

6. – New ideas for the 2009 test beam

The results shown here and, in more detail, in [8] are extremely encouraging. Nonetheless, an increase of the wavelength gap between crystal absorption edge and filters cutoff is needed in order to avoid light attenuation and increase the C light yield, still maintaining a good separation in both time structure and spectral properties. To do that, we have chosen two possible candidates for the 2009 testbeam, that we are now preparing:

- Mo-doped $PbWO_4$ (0.1%, 0.2%, 0.3%): it has been shown that a lower Mo concentration allows to maintain the shift of the scintillation emission spectrum to higher λ with respect to undoped $PbWO_4$, but reduces the shift of the absorption cut-off to higher wavelength with respect to higher Mo concentrations. By combining these features with a higher QE PMT and C filters with transmission region extended through higher wavelenths, we expect to reduce the problems of self-absorption and low C light yield.

- BSO: we proved BGO to be a fairly good candidate for DREAM technique. We found BSO(4) shows even more suitable characteristics for dual readout, in particular a lower-wavelength absorption cut-off.

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(4) BSO has almost the same chemical composition as BGO, but with silicon atoms instead of germanium ones: $Bi_4Ge_3O_{12}$.

7. – Conclusion

$PbWO_4$ crystals doped with Mo or Pr have been tested and shown to represent a considerable improvement with respect to undoped ones, on the basis of the temporal and spectral differences of the light emitted in the Cherenkov and scintillation processes. However, in order to make them realistic candidates for application in practical calorimeters, further improvements would be needed. In particular, the scintillation process in the Pr-doped crystals is unacceptably slow and the self-absorption of Cherenkov light in the Mo-doped crystals is unacceptably large. Further studies to improve on these aspects are ongoing, and new results are expected from the 2009 test beam.

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