Lead-tungstate scintillator studies for a fast low-energy calorimeter

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Lead-tungstate scintillator studies for a fast low-energy calorimeter

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Abstract: Detector cells consisting of fast lead-tungstate crystals viewed by avalanche photodiodes were designed, built and bench-tested. It was found that cooling the crystals to -20°C, using two avalanche photodiodes per crystal, and using fast pulse shaping provided the light yield, low noise, and fast response needed for use in 100 MeV calorimetry at high beam rates. The achieved stochastic term coefficient is 0.8% and the time response is characterized by a single decay term of 24 ns.

Keywords: Scintillators and scintillating fibres and light guides; Calorimeters

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1 Introduction

In order to meet the need of a detector to search for the lepton-flavor violating muon-to-electron conversion process [1], we have bench-tested a small crystal calorimeter prototype. The requirements included fast response with good energy resolution at 100 MeV, a non-exorbitant cost, operation in a magnetic field of order one Tesla, and the ability to observe electrons in a pulsed-beam environment in between intense particle-flux flashes separated by under one µs.

Among crystals which could be considered, bismuth germanate (BGO) would provide sufficient light yield for our purposes, but its 300 ns decay time eliminates it for our pulsed beam application. Lead-tungstate (PbWO$_4$) is a favorable because of its short radiation length, high density, good transparency, and short decay time. However, it has the disadvantage of low light yield, two orders of magnitude below that of BGO and has therefore previously been used only in higher energy calorimetry applications [2, 3]. Table 1 summarizes the relevant properties of lead-tungstate crystals.

We have achieved sufficient photo-statistics and reasonable energy resolution by operating the calorimeter crystals at -20 C, which doubles the light yield compared to that at room temperature [3] and by collecting the scintillation light with two large area avalanche photo-diodes (APD’s) per crystal. Such APD’s are now commercially available. The APD’s allow operation of the calorimeter in high magnetic fields. The fast lead tungstate decay time of about 20 ns at -20 C is a good match to the pulsed beam application. The use of two APDs per crystal allowed us to do bench tests using cosmic rays to study light yield, noise, and energy resolution for a PbWO$_4$ crystal array. We have also used a radioactive source to study the decay characteristics of the PbWO$_4$ crystals. In this paper we report results of both of these studies. The exposure of a prototype calorimeter to a tagged photon beam would be a natural future step for the calorimeter development.

<table>
<thead>
<tr>
<th>Table 1. Lead Tungstate Properties [4].</th>
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<tr>
<td>Index of ref.</td>
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<tr>
<td>2.2</td>
</tr>
</tbody>
</table>

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2 Light yield and resolution

In addition to yielding more light, the use of two APDs per crystal allows an event-by-event comparison of measurements for the same energy deposit in a crystal thus making it possible to estimate resolution dependent parameters, even with a cosmic-ray measurement.

We have performed cosmic-ray bench tests on two sizes of PbWO$_4$ crystals of square cross-section, 30.0 $\times$ 30.0 $\times$ 150.0 mm$^3$ and 37.5 $\times$ 37.5 $\times$ 150.0 mm$^3$. The crystals were manufactured by Bogoroditsk Techno-Chemical Plant (BTCP), Russia [5]. Two 13 $\times$ 13 mm$^2$ APD’s (RMD Inc. Watertown, MA USA) were mounted on one square face of each crystal, as shown in figure 1. All other sides were wrapped in a diffuse white Tyvek DuPont reflector encased by a light tight cover. For the smaller crystals the outside of the two APD’s overhangs the crystal edge in one direction; alternating the orientation of adjacent crystals nevertheless allows close-packing.

Each APD was read out by a charge-sensitive FET-input preamplifier mounted directly behind it. The preamps were home-built with discrete components. Preampl outputs were sent to shaper amplifiers through 4 m-long twisted pair cables. Two alternate shaping times, 60 ns and 90 ns, were used. Shaper amplifier outputs were digitized by CAEN V785 multichannel ADC’s. An event record consisted of the digitized signals of all the APD’s, thus allowing the analysis of combinations of signals for each event. Typical APD bias voltages were 1600 volts giving an APD-gain of order 400. For calibration, provisions were made for injecting a charge pulse at the APD-preamp interface and for illuminating the APD with a light pulse from a fast pulsed LED. The schematic of the setup of 4 crystals for the cosmic-ray tests is shown in figure 2. Plastic scintillators Sc1 and Sc2 are each of size 10x40x100 mm$^3$, while plastic scintillator Sc3 is 10x100x200 mm$^3$. The geometry is such that a cosmic ray passing through all three plastic scintillation counters will pass through crystals in both layers. The coincidence of 3 plastic scintillator paddles triggered on a muon traversing the short dimension of the crystals to start the signal digitization. The crystals with their APD’s and preamps, together with the two smaller trigger paddles were enclosed in an insulated cold-box kept at a temperature of -22.5 C by a remote commercial chiller (Julabo model F32). The temperature was stable to within 0.05 C. The temperature distribution during a run is shown in figure 3 (a).

The pipes to and from the chiller were brazed to a copper box enclosing the crystals, APD’s
Figure 2. Schematic Diagram of Cosmic Ray Test Setup.

Figure 3. The bench test temperature distribution (a) and its fit to a Gaussian distribution. Typical cosmic-ray spectrum of APD on the large crystal (b) and its fit to a Landau distribution.

and preamps. This copper box acted as a Faraday cage for the on-board electronics as well as a heat sink for stabilizing the temperature.

The most probable values of the energy deposition from a muon traversing a square face of a
Figure 3 (b) shows the spectrum in ADC counts of the observed cosmic ray muons in one APD. The spectrum shows the typical asymmetric shape due to Landau fluctuations. We convert the ADC scale to a physical energy scale by using the ratio of the observed position (minus the pedestal) of the peaks in ADC counts and the calculated most-probable value.

The dominant contributions to the spread of the energy deposited by a muon are photoelectron statistics, electronic noise, and Landau fluctuations. The choice of using two APD’s to collect the light from each crystal provided a natural way to separate the photoelectron statistics and electronic noise from energy deposition fluctuations by taking the event-by-event difference of the two APD amplitudes $A_1 - A_2$. Given the large number of photoelectrons and good crystal uniformity in our setup, the photoelectron statistics and electronic noise contributions to resolution are largely statistically independent in each APD and thus contribute equally to the sum and difference signal. On the other hand, both APDs view the same crystal energy deposition in each event, so that event-by-event differences in energy distribution, such as those due to different path lengths from muons traversing the crystal at different angles, largely cancel. The width of the difference distribution in figure 4 thus gives an estimate of the combined photoelectron statistics and electronic noise contribution to the resolution.

Figure 4 shows the observed spectra of the event-by-event difference $A_1 - A_2$ and sum $A_1 + A_2$, for a large crystal. The asymmetric Landau fluctuations are clearly seen in the sum signal but are absent in the difference signal which is fitted well by a gaussian.

It remained to separate the photostatistics resolution, commonly called the stochastic resolution term, from the electronics noise resolution. This separation was needed since the first is energy dependent while the second is independent of energy. The electronics noise was obtained by pulsing the preamp inputs with a fixed-charge input, and measuring the width of the shaper-amplifier output ADC distributions. It was seen to be stable over a range of a factor of 15 in signal input size.

The stochastic resolution was then estimated by taking the quadrature difference between the $A_1 - A_2$ distribution and the measured electronic noise. Our neglect of other potential contributions, such as nonuniform light collection, to the observed resolution, makes the estimate of the stochastic...
Table 2. Resolution contributions by crystal for a 60 ns shaper amplifier. The errors shown are the combined statistical and systematic errors, which were comparable in size and added linearly to be conservative.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>1 (large)</th>
<th>2 (large)</th>
<th>3 (small)</th>
<th>4 (small)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{en}$ (MeV)</td>
<td>0.93±0.06</td>
<td>1.04±0.07</td>
<td>0.82±0.06</td>
<td>0.83±0.06</td>
</tr>
<tr>
<td>$\sigma_{st}$ (MeV)</td>
<td>1.51±0.08</td>
<td>1.86±0.09</td>
<td>1.21±0.06</td>
<td>1.16±0.07</td>
</tr>
<tr>
<td>NPE</td>
<td>1670±165</td>
<td>1107±109</td>
<td>1660±175</td>
<td>1820±127</td>
</tr>
<tr>
<td>NPE/MeV</td>
<td>38.±3.8</td>
<td>25.3±2.5</td>
<td>47.4±5.0</td>
<td>51.9±6.6</td>
</tr>
<tr>
<td>$\alpha$ (%)</td>
<td>0.72±0.04</td>
<td>0.89±0.04</td>
<td>0.65±0.04</td>
<td>0.62±0.04</td>
</tr>
</tbody>
</table>

Table 3. Average electronic noise resolution and stochastic term coefficient by crystal size for 60 ns shaping time. The errors shown are the combined statistical and systematic errors, which were comparable in size and added linearly to be conservative.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Large</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic noise $\sigma_{en}$ (MeV)</td>
<td>0.98±0.05</td>
<td>0.82±0.04</td>
</tr>
<tr>
<td>Stochastic term $\alpha$ (%)</td>
<td>0.81±0.03</td>
<td>0.63±0.03</td>
</tr>
</tbody>
</table>

term conservative. The conventional parametrization of the energy dependence of the stochastic resolution is given in terms of a stochastic term coefficient $\alpha$ by

$$\frac{\sigma_{st}}{E}[\%] = \frac{\alpha[\%]}{\sqrt(E)}, \quad (2.1)$$

with $E$ in GeV, while the number of photoelectrons NPE is estimated from

$$\frac{\sigma_{st}}{E} = \sqrt(F/NPE), \quad (2.2)$$

where $F$ is the excess noise factor, for which we used the approximation $F = 2.1$ from the simplified theory of APD’s [6, 7].

Combining equations (2.1) and (2.2) and solving for NPE gives NPE directly in terms of the stochastic term coefficient $\alpha$:

$$NPE = 2.1 \times 10^4 E[GeV]/[\alpha[\%]^2 \quad (2.3)$$

We tabulate our results for the 4 crystals with 60 ns shaping time in table 2. Results using a 90 ns shaping time were similar.

There is some crystal to crystal variation, with crystal 2 apparently yielding less light than the others. However, the ratio of the number of photoelectrons/MeV collected by the small and large crystals is in rough agreement with the expectation that the light collection efficiency should scale as the area of the APD’s divided by the area of the crystal face, namely $R_{predict} = (3.75/3.00)^2 = 1.56$.

We averaged the electronics noise resolution and the stochastic term coefficient of crystals of a given size and show the results in table 3 for 60 ns shaping.

Using these measurements, we can now estimate the response of a low energy PbWO$_4$ calorimeter by adding the stochastic term and the electronic noise in quadrature. We pick the
large crystal size yielding 30 photoelectrons per MeV, a 60 ns shaping time, and assume three crystals in the energy sum. We estimate the total resolution ($\sigma$) for such a calorimeter to be 3% for 100 MeV electrons.

### 3 Time profile of light emission

In the high flux and repetition rate environment for which this calorimeter is being developed, it is important that no substantial component be present with a decay-time longer than about 50 ns. Measurements were therefore performed to determine whether the crystals used had any such long decay-time components.

The crystal scintillation light emission time dependence was determined using a setup based on the one-photon method [8]. The crystal is viewed by a photomultiplier tube (PMT A) through a barrier with a hole small enough so that, for most events, only one photo-electron is observed per passage of a particle into the crystal. Since the photon detection probability is independent of its emission time, the resulting one-photon time distribution also gives the crystal light emission time distribution. The PMT-viewed crystal and a fast plastic scintillation counter were placed near a $^{60}$Co source, which promptly emits two $\sim 1$MeV photons upon decay. Events where light is detected from both the plastic scintillator and the crystal due to each being struck by a photon allow measurement of the crystal’s photon emission time as the time difference between the crystal and plastic scintillator signals.

A schematic of the time measurement setup is shown in figure 5. PMT A viewed the crystal through an aperture in a black shield set small enough to allow measurement of single photoelectron signals. A first run was done with a very small aperture size. Aperture size was then increased (to maximize event rate) to as large as possible without making a statistically significant change in charge and time distributions. The PMT A signal was sent through a discriminator with threshold set at a fraction of a photo-electron. A second photomultiplier tube (PMT B) also viewed the crystal, but through a large aperture hole. The signal from PMT B was sent to a high threshold discriminator and put in coincidence with the PMT A signal to reduce accidental background. The signals were delayed so that PMT A determined the timing of a stop pulse to a VME TDC (CAEN V775N). To confirm that signals were due to one photoelectron, an analog signal from PMT A was integrated by a VME QDC (CAEN V792).

The signal from a photomultiplier tube, PMT P, attached to the plastic scintillator was split into two signals, PMT $P_{\text{low}}$ and PMT $P_{\text{high}}$ going to low and high threshold discriminator channels used to provide good timing and lower the accidental rate respectively. A coincidence of these two pulses and the PMT A and PMT B pulses, with PMT P low delayed so that it determined the timing, was used as a TDC start pulse. This 4-fold coincidence gave a considerable reduction of the accidental background and a precise measurement of the PbWO$_4$ decay time. It was also used to provide an ADC gate during which the current from PMT A was integrated.

The TDC time distribution was analyzed for events having integrated charge consistent with a single photoelectron signal. A single fit was done to the full measured distribution. An exponential sum of the form $\Sigma [A_i/\tau_i]exp[(t - t_0)/\tau_i]$ was used to model the crystal light emission time dependence where $A_i$ are the contributions of the components with decay times $\tau_i$ and $t_0$ is the TDC value for prompt emission. Because the high threshold used corresponded to
many photoelectrons, the plastic scintillator time dependence could be modeled with a single exponential of decay time $\tau_{\text{left}}$. The difference between the crystal and scintillator time emission distributions was convoluted with a gaussian resolution function of standard deviation $\sigma$. Finally, a time independent constant accidental background fraction was used, resulting in a six-parameter (eight-parameter) fit for a one (two) exponential crystal decay time model. A 500K event sample took about 4 weeks to collect, with some dependence on the light output of individual crystals. QDC and TDC distributions were monitored to check for pedestal shifts during the run, and measurements with large shifts were rejected.

The entire setup was kept in the cooled environment described in the previous section. NIM compatible electronics was used for the logic circuits and a computer controlled VME system was used to digitize and record time and PMT A signal charge.

Time measurements were made for three crystals delivered by BTCP (labeled R1, R2, and R3) and three delivered by The Shanghai Institute of Ceramics Academia Sinica (labeled C1, C2, and C3) [9].

For all crystals measured at -20 C the distributions were fit well by a single exponential. The measurement and fit results for crystal C1 at -20 C are presented in figure 6. The abscissa in the figure is in TDC counts, with a scale of 8 counts per ns. The results of the fit are shown in the figure as TDC value for prompt emission ($t_0$), resolution (sigma) of 1.6 ns, a background (bg) of 4.0 events per bin (giving a background fraction of 3.3% of the recorded events), and a plastic scintillator decay time (left time) of 1.2 ns. The crystal time emission amplitude $A_1$ and decay constant $\tau_1$ are labeled “amp_1” and “time_1” respectively in the figure. For times near the peak, the spread of the data is less than the fit line thickness and is hidden by it.
Figure 6. Sample time distribution and fit for a crystal measured at -20 °C. The fit parameters are given in TDC counts, with 8 counts per nanosecond. Zero in the nanosecond scale is determined from $t_0$ of the fit.

Table 4. Crystal Timing Results at -20 °C and 20 °C.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>$\tau$ (ns)</th>
<th>$F_1$ (%)</th>
<th>$\tau_1$ (ns)</th>
<th>$F_2$ (%)</th>
<th>$\tau_2$ (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>22.66 ± 0.04</td>
<td>25.0 ± 0.4</td>
<td>3.57 ± 0.09</td>
<td>75.0 ± 0.4</td>
<td>14.71 ± 0.06</td>
</tr>
<tr>
<td>R2</td>
<td>21.98 ± 0.04</td>
<td>31.4 ± 0.4</td>
<td>3.80 ± 0.08</td>
<td>68.6 ± 0.4</td>
<td>15.11 ± 0.06</td>
</tr>
<tr>
<td>R3</td>
<td>22.20 ± 0.04</td>
<td>30.3 ± 0.4</td>
<td>3.18 ± 0.07</td>
<td>69.7 ± 0.4</td>
<td>13.85 ± 0.06</td>
</tr>
<tr>
<td>C1</td>
<td>24.06 ± 0.04</td>
<td>29.1 ± 0.4</td>
<td>3.90 ± 0.08</td>
<td>70.8 ± 0.4</td>
<td>15.80 ± 0.07</td>
</tr>
<tr>
<td>C2</td>
<td>23.25 ± 0.04</td>
<td>33.7 ± 0.9</td>
<td>4.42 ± 0.11</td>
<td>66.3 ± 0.9</td>
<td>12.66 ± 0.08</td>
</tr>
<tr>
<td>C3</td>
<td>26.45 ± 0.05</td>
<td>14.3 ± 0.4</td>
<td>3.38 ± 0.15</td>
<td>85.7 ± 0.4</td>
<td>14.87 ± 0.05</td>
</tr>
</tbody>
</table>

Only a single exponential decay term was used in this fit, with a returned fit value of 24 ns. Fits with additional exponential terms returned identical decay times for all crystals measured at -20 °C. The fit values presented in the second column of table 4 are therefore for a fit done with a single exponential. The fits at -20 °C mostly give agreement in time resolution and plastic scintillator decay time to about half a nanosecond, though some fits are insensitive to vanishing plastic scintillator decay time. This agreement over the course of measurements spanning over half a year gives some indication of the excellent stability of the apparatus and the fit procedure. The percentage of accidental coincidences is dependent on PMT singles rates and the crystal light yield, so some variation from crystal to crystal is expected. The value of only about 3% achieved with the quadruple coincidence provides great sensitivity to any long time decay components.

As is seen in the table, the decay times for all crystals measured lie in the range of 20 to 30 ns. There is no evidence of a long decay-time term.
Figure 7. Sample time distribution and fit for a crystal measured at 20 C. The fit parameters are given in TDC counts, with 8 counts per nanosecond. Zero in the nanosecond scale is determined from $t_0$ of the fit.

Time distributions measured at 20 C required a minimum of two exponentials when fit. Figure 7 shows the time distribution measured for crystal R1 at 20 C and the fit curve. The fitted curve reproduces the data superbly, as was the case for all measurements at 20 C. An indication of the measurement and fit stability is that the fit yielded time resolution and plastic scintillator decay time identical in all six crystal measurements to better than 0.1 ns.

Results of the fit for 20 C are presented in the last 4 columns of table 4, where the normalized fractions $F_1$ and $F_2$ are defined as $F_{1,2} = A_{1,2} / (A_1 + A_2)$. As seen in the table, for all crystals the longest decay times are up to about 16 ns. No evidence of a long decay time component is observed. Adding a third exponential to the fit typically splits the shorter component into two but does not appreciably improve the fit. When an additional longer component is found, it is at the level of a few percent and under 40 ns.

The existence of two decay times in the warm crystal measurements, in contrast to a single decay time cold, may be of interest in the study of scintillation mechanisms. However, we have not undertaken such a study in this paper.

For the measurements done at both temperatures, there is thus no evidence of any long decay-time component. A Monte Carlo simulation was used to determine the amplitude of such components to which our measurement is sensitive. A large number of 500K event samples were generated using a full set of parameters identical to what was found in the fits to the data, but adding a long decay-time term. The measurement sensitivity was determined by the amplitude of the additional term needed so that fits to the simulated data sets reliably detected the admixture.

For a small admixture of a long decay-time exponential, the simulation shows that long tails are sometimes fitted as two very close shorter tails. It is therefore difficult to set an upper limit on the possible fraction of a long decay time component from the 20 C measurements. However,
The fraction of the additional term was started at 0.5% and was increased in 0.5% steps until fits to at least 95% of the simulated 500K samples detected the admixture. The resulting fractions necessary for a 95% detection probability varied with the decay time of the extra term and are presented in table 5. Typical numbers are 1 to 2 percent. Very short times (∼50 ns) are difficult to disentangle from the ∼30 ns short time so need a larger fraction to be detected with high efficiency. Time scales longer than the range of the experiment (∼450 ns) need larger fractions because many of the events in the long tail occur at times later than what was recorded.

Finally, as an additional check to the procedure, the probability of the fit finding a tail when none is present was tested with a simulation. For 500K event samples with only a short exponential and all other parameters, including background fraction, with values similar to those obtained in the data, the simulation gives 98% probability of the fit finding no evidence for a long tail.

In summary, the one-photon measurement for these crystals shows no evidence of a long time decay component at any temperature measured. When cooled to -20 C, only one crystal decay time is observed of length about 50% greater than the longest component observed at room temperature. This decay constant is still less than 30 ns for all crystals tested, matching well the needs for a fast calorimeter.

4 Conclusions

The measurements presented in this work demonstrate that detectors consisting of fast lead-tungstate crystals cooled to -20 C and viewed by two large area avalanche photo-diodes provide sufficient light, short enough decay time and low enough noise to be used in 100 MeV calorimetry at high beam rates. Extrapolating from our measurement near 40 MeV, we estimate a resolution of about 3% at 100 MeV with a single exponential decay time of 24 ns.

Acknowledgments

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References


