Estimate of neutrons event-by-event in DREAM

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Abstract. We have measured the contribution of neutrons to hadronic showers in the DREAM module event-by-event as a means to estimate the event-by-event fluctuations in binding energy losses by hadrons as they break up nuclei of the Cu absorber. We make a preliminary assessment of the consequences for hadronic energy resolution in dual-readout calorimeters.

1. Introduction
The DREAM module was designed to measure the electromagnetic content of hadronic showers event-by-event and thereby suppress the effects of these fluctuations in order to not only improve the hadronic energy resolution, but also to achieve a Gaussian response and hadronic linearity in a calorimeter calibrated with electrons. These were achieved in the first DREAM test beam. The next largest fluctuation is the binding energy losses as hadronic particles of the shower lose energy in breaking up the nuclei of the Cu absorber medium. These energy losses are roughly proportional to the MeV neutrons liberated in nuclear break-up, and the energy carried by these neutrons is estimated to be about 20-25% of the total shower energy.

The DREAM module is described in detail in Ref. 1 and consists of 1 tonne of Cu absorber with two types of fibers embedded throughout its volume: scintillating fibers that sample the $dE/dx$ ionization energy loss of all charged particles, and two types of clear fibers (hereafter called Čerenkov fibers) that sample relativistic particles above Čerenkov threshold, $\beta \approx 1/n \approx 0.65$. These particles are predominantly $e^\pm$ from the $\gamma$-induced showers from the decays of $\pi^0 \rightarrow \gamma\gamma$ produced in the hadronic shower. The central seven channels were filled with high-purity quartz fibers and the 12 channels of the outer ring were filled with acrylic plastic fibers.

We modified the DREAM module by summing the PMT signals for the whole DREAM volume for both scintillation and Čerenkov fibers, and sending these through fast cables to a digital oscilloscope in the counting room. The central scintillating channel ($S_0$) was sent to the first input; the inner ring of six (6) scintillating channels ($S_1$) was summed in a standard linear summing unit and sent to the second oscilloscope input; the outer ring of 12 scintillating channels ($S_2$) was sent to the third oscilloscope input; and, 16 of the 19 Čerenkov channels ($C$) were summed and sent to the fourth oscilloscope input.

For an overview of this and other work by the DREAM Collaboration, see the talk by R. Wigmans, these Proceedings.

1 SCSF-81J produced by Kuraray Co., Ltd, Tokyo, Japan.
2 Polymer-clad fused silica fibers, Polymicro, Phoenix, Arizona, USA.
3 Raytela PJR-FB750, produced by Toray, Japan.
4 These LeCroy units from the CERN electronic pool were LeCroy 127EW (or, 127FL) CERN pool ID 4355.
5 The maximum number of inputs was 16, and since the total number of Čerenkov channels is 19, we chose to leave out three evenly spaced outer channels rather than chain summing units together.
Neutrons liberated from broken-up nuclei will have kinetic energies, $T$, in the MeV region, velocities of $v \sim \sqrt{2T/M_n} \sim 0.04c \sim 1$ cm/ns, and will therefore persist in the calorimeter volume for tens of nanoseconds as the neutrons elastically scatter from (mostly) Cu nuclei.

The protons in the H-C molecules of the scintillating fibers and the outer ring of Čerenkov fibers are the only free protons in or near the calorimeter. A neutron signal is generated when a neutron elastically scatters from a free proton in a scintillating fiber, $np \rightarrow np$, and the recoil proton ionizes in the scintillator generating scintillation light. This scintillation light luminosity is suppressed by Birks recombination for densely ionizing slow protons by a factor approximately $\sim (1 + k_B \cdot dE/dx)^{-1}$ for $dE/dx$ in MeV/g-cm$^{-2}$ and $k_B \approx 0.008$ g-cm$^{-2}$/MeV. In addition, the scattering from a free proton is the only effective mechanism for the slowing down of the neutrons from MeV energies to negligible energies below keV over a measurement time of $\sim 100$ ns.

2. Analysis

The neutron signal is defined as the integral under the $S(t) = S_1(t) + S_2(t)$ curve in Fig. 2, from 20 to 40 ns for each event. This is a very simple definition, but an appropriate start on this problem. The distribution of this neutron signal for 200 GeV “jets” is shown in Fig. 3.

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**Figure 1.** Geometry of the scintillation and Čerenkov channel sums sent to the digitizing oscilloscope. We label the central scintillation channel $S_0$ (sent to the first input of the fast oscilloscope), and the inner and outer rings $S_1$ and $S_2$ (sent to inputs 2 and 3). The Čerenkov sum is labeled $C$ (sent to input 4).

**Figure 2.** The average Čerenkov pulse, $C(t)$, and the average scintillation pulse, $S_1(t) + S_2(t)$, both centered at $t = 0$. The Čerenkov pulse is very narrow in time, in spite of it being a sum of 16 PMT pulses, and roughly measures the time response of an instantaneous signal. The scintillation pulse is slower due to the finite lifetime of the scintillating fluor (2-3 ns), but also shows a long-lived component with an exponential fall-off with a time constant of 20 ns. This is evidence for slow neutrons in the scintillating fibers.

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7 These are “interaction” jets generated by placing a 0.1-$\lambda_{\text{air}}$ lucite block in front of DREAM and accepting events with a charged particle multiplicity above 12 exiting the lucite.
Figure 3. (a) The distribution of the “neutron signal” integral for individual 200 GeV hadronic showers; and, (b) the normalized neutron fraction, $f_n$.

This neutron fraction is anti-correlated with the Čerenkov pulse displayed in Fig. 4, as it should be, but more interestingly the distribution of the Čerenkov signal is seen to be a superposition of the different slices of the Čerenkov distribution. Selecting on the neutron fraction, $f_n$, yields the individual nearly Gaussian distributions that make up the total Čerenkov pulse height distribution, as shown in Fig. 5. This decomposition of the total Čerenkov distribution into $f_n$-selected parts is analogous to the same Čerenkov distribution decomposed into $f_{EM}$-selected parts in Fig. 34 of the DREAM hadron paper [Ref. 1] and also shown in Figs. 1(a,b) in the talk by Wigmans in these Proceedings.

Figure 4. The anti-correlation of the neutron fraction with the Čerenkov signal. This the first and simplest test that $f_n$ is a measure of hadronic content, in this case neutrons. These two variables are as close to the raw measurements as possible.

Figure 5. The total distribution is simply the Čerenkov signal for all events. The separate components of the Čerenkov signal distribution are selected as a function of the neutron fraction, $f_n$, from which it is clear that the wide and asymmetric Čerenkov distribution is just a sum of near-Gaussian distributions for each $f_n$.

The distribution of the total Čerenkov distribution is shown in Fig. 6(a) for the same 200 GeV hadronic showers, and the rms width of this distribution is shown in the circled points of Fig. 7. This
Figure 6. (a) The total Čerenkov distribution from Fig. 5. (b) The separate Čerenkov distributions of Fig. 5, for each small $f_n$ bin, are corrected to a same mean of $f_n = 0.07$ and summed.

width is narrowed by using the $f_n$-Čerenkov correlation to center each subdistribution at $f_n = 0.07$, shown in Fig. 6(b). The reduction in the rms spread is shown as a function of hadronic shower energy in Fig. 7. The narrowing is about 25% but, maybe more importantly, the $f_n$-corrected points leave behind no sign of a constant term, as seen by the line drawn through the origin (not a fit). This does not necessarily demonstrate a quantitative improvement in the hadronic energy resolution, but does show that more information leads to a narrowing of the originally wide Čerenkov pulse height distribution. This exercise indicates that there is some useful information in the neutron measurement, $f_n$, but this might be due in part to its correlation with the EM fraction, $f_{EM}$.

Figure 7. The dependence of the rms widths divided by the means of the distributions in Fig. 6 are plotted for data samples at 100, 200 and 300 GeV beam energy.

Figure 8. A plot of the neutron fraction, $f_n$, against the electromagnetic fraction, $f_{EM}$, is approximately linear, and demonstrates the essential value of this measurement. There are two physical effects which depress the value of $f_n$: the small 1 kt volume of the DREAM module and the recombination of electrons and ions in the column of dense ionization left by a slow MeV proton, and the consequence suppression of scintillation light yield (Birks mechanism). The EM fraction is linearly related to the ratio $Q/S(C/S)$.

A stronger test is to hold $f_{EM}$ constant and look at the fluctuations in $f_n$. This is shown using Fig. 8, the nearly linear relationship between $f_{EM}$ and $f_n$. A selection of showers with $0.70 < Q/S < 0.75$
Figure 9. The dispersion left in \( f_n \) for fixed \( f_{EM} \). The difference in the total Čerenkov signal is due to the difference in the \( Q/S \) selections.

from Fig. 8 is shown plotted against \( f_n \) and the total Čerenkov signal in Fig. 9. For fixed \( f_{EM} \) the neutron fraction varies by approximately 15%, and these are the binding energy loss fluctuations on top of the EM fraction fluctuations. This is also shown for another selection in \( f_{EM} \), \( 0.40 < Q/S < 0.42 \).

The important question is how does an independent measurement of the neutron content of a hadronic shower serve to improve the overall energy resolution.\(^8\) The hadronic shower energy resolution of the DREAM module is limited by lateral leakage fluctuations in this small proof-of-principle module.\(^9\) These leakage fluctuations are estimated at about 4% rms, and therefore any analysis of an unbiased ensemble will be limited to 4% resolution in energy.

With this in mind, we plot the rms width of the Čerenkov signal divided by the mean for showers with fixed EM fraction, \( 0.40 < Q/S < 0.42 \), as a function of the neutron fraction, \( f_n \), in Fig. 10(a). This resolution statistic increases as \( f_n \) increases, as it should if the neutron content of showers contributes to the fluctuations in the total energy signal of those showers. If both the EM fraction, \( f_{EM} \), and the neutron fraction, \( f_n \), are held fixed, \( f_{EM} \approx 0.55 \) and \( 0.045 < f_n < 0.065 \), then the width of the Čerenkov signal narrows to about 4.7% as shown in Fig. 10(b). This Čerenkov signal distribution is also nicely Gaussian. For a tighter selection on \( f_n \), \( 0.050 < f_n < 0.055 \), this distribution narrows further to 4.4%, coming interestingly close to our estimate of the leakage fluctuation limit for the DREAM module.

3. Plans for neutrons in DREAM

This measurement is limited by several physical effects: lateral particle leakage, an impedance mismatch in the LeCroy summing units that results in a reflection beginning at about 48ns, low Čerenkov photoelectron statistics, and the somewhat time-incoherent sum of multiple PMT channels into a single (oscilloscope) readout channel. We were possibly lucky that it wasn’t worse: the PMT signals went into BNC cable, then into LEMO, then into the 16-input summing units, and the outputs into fast (0.78c) cable to the oscilloscope inputs in the counting room.

\(^8\) It certainly serves to improve particle identification of hadronic vs. non-hadronic showers in the calorimeter.

\(^9\) The DREAM module was presciently funded by the ADR (Advance Detector Research) program of the Dept. of Energy with a small grant to study the concept of dual-readout calorimetry. It has achieved this goal with a dozen published papers in Nucl. Instr. Meths., but it was never intended to be a high-performance calorimeter itself.
Figure 10.  (a) The rms width of the Čerenkov distribution as a function of the neutron fraction, $f_n$. (b) The Čerenkov signal distribution with an rms width of 4.7% for fixed $f_{EM} \approx 0.55$ and fixed $f_n$, 0.045 < $f_n$ < 0.065, fractions.

In the upcoming CERN beam test we expect to read out each DREAM channel independently into a fast circular buffer flash ADC[2] and repeat this neutron analysis, although we will still be limited in overall energy resolution by lateral leakage fluctuations. We will make an attempt at a crude measurement of the leakage event-by-event.

Three decades ago, hadronic calorimeters functioned as counters of penetrating energy rather than as precision devices to measure the energy of a particle or jet of particles. The understanding of the role of neutrons, specifically their role in compensation to achieve equal calorimeter response to hadronic and electromagnetic energy, was established by the SPACAL module[5] 25 years ago. In the present era of a high energy proton collider (LHC) and the prospects for an electron collider (ILC or CLIC), we now seek the ultimate energy resolution possible for hadronic energy. A estimate by Wigmans[4] is that $(13-15)/\sqrt{E}$ is the lower limit, essentially determined by unknowable fluctuations in nuclear physics. At a high energy collider, this puts hadronic calorimetry in the “one percent” league with electromagnetic calorimetry.

3.1. Acknowledgments

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