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Physics of hadron shower development and the implications for calorimetric resolution

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We present studies of the space-time development of hadronic showers using the GEANT-4 simulation framework. The dominant physics processes responsible for the energy deposited by different kinds of showering particles have been identified. We study how various particles contribute differently to the observable Scintillation and Čerenkov signal of a total-absorption dual read-out calorimeter (HHCAL). In addition we present how spallation protons and neutrons contribute differently to the signal of an HHCAL compared to sampling calorimeters with plastic scintillators as the active medium.

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1. Introduction

In this article we use a full GEANT 4 simulation[1]([1], [2]) to study the properties and performance of a homogeneous total-absorption dual readout calorimeter (HHCAL). For these studies we have developed a flexible GEANT 4 based simulation framework named *CaTS* (Calorimeter and Tracker Simulation) [3], which allows us to study various aspects of dual read-out and sampling calorimeters. In particular we want to identify the dominant physics processes and showering particles responsible for the energy deposition and how they contribute to the Scintillation and Čerenkov signal taking saturation effects (Birks suppression [4]) into account. It is demonstrated that nuclear interactions with significant amount of energy released in the form of spallation protons contribute significantly to the observed signal in such a calorimeter. The situation is quite different for sampling calorimeters with plastic scintillators as the active medium. The short interaction length of protons in the absorber causes them to deposit most of their energy in the inactive absorber, reducing the average observed energy of hadron-induced showers and introducing fluctuations beyond the normal sampling fluctuations." We also demonstrate that spallation neutrons play a very different role contributing to the signal in and HHCAL compared to sampling calorimeters with plastic scintillators.

2. The HHCAL detector concept

The HHCAL calorimeter addresses the following principal contributions to hadron energy resolution and non-linearity:

- Fluctuations in nuclear binding energy loss dominate the energy resolution resulting in a non-linear, non-Gaussian hadron response. This is mitigated using dual readout where both Čerenkov Č and scintillation S signal are read out from the same crystal and the Č/S ratio is used to correct the scintillation signal. This way one can achieve linear and Gaussian response and improved hadronic resolution (see [5]). Full GEANT 4 simulation predicts excellent energy resolution of $\approx 10\%/\sqrt{E}$ for single π^- before detectors effects are taking into account.

- Sampling fluctuations in the sharing of the shower energy between the active and passive materials in sampling calorimeters are eliminated by making the calorimeter homogeneous and totally active.

- Difference in the "sampling fractions" (i.e. ratio in the effective energy loss) between the different materials in the sampling calorimeters can be eliminated by making the calorimeters homogeneous. There is no structural boundary between the electromagnetic (ECAL) and hadronic (HCAL) sections of this calorimeter, so it does not suffer from the effects of dead material in the middle of hadronic showers. In addition there is no difference in energy response since ECAL and HCAL are composed of the same material.

[1] throughout the article we use GEANT 4 version 4.9.6.p02 and unless otherwise indicated the default physics list is FTFP_BERT.

- While leakage fluctuations due to escaping neutrinos and muons can not be avoided, tails of the hadronic shower escaping the detector can be minimized by using high density heavy metal crystals. The availability of such crystals means that full containment of hadronic showers can be achieved with a total-absorption calorimeter with a volume fitting into a present collider detector. All considered materials are dense (density ranging from 7.13 (BGO) to 8.3 g/cm^3 ($PbWO_4$))with a nuclear interaction length λ_I ranging from 21 ($PbWO_4$ and PbF_2) to 23 cm (BGO). For a complete list of crystal properties see [6].
- Fine segmentation allows (ECAL finer than HCAL) for the application of particle flow algorithms [7] to further improve energy resolution and event reconstruction.

3. Per-particle contributions to ionization and Čerenkov signal of a HHCAL calorimeter

Fig. 2 and Fig. 3 show the per-particle contributions to ionization and Čerenkov signal of a HHCAL calorimeter. One should point out that the Čerenkov signal is not only due to e^- and e^+ but the contribution of pions (incident particle or produced in nuclear reactions) is significant. Especially the leading incident π^- contributes significantly to the Čerenkov signal at low energy. In the next section we will discuss the contribution of spallation neutrons and protons in detail.

4. Implications of Spallation protons and neutrons for Calorimetry

4.1 Nuclear spallation reactions

Spallation [8] is a process in which a light projectile (e.g. meson, proton, neutron) with the kinetic energy from several hundreds of MeV to several GeV interacts with a heavy nucleus and causes the emission of a large number of hadrons (mostly neutrons) or fragments. Spallation has two stages:

- **The intra-nuclear cascade (INC):** is a fast direct stage ($\approx 10^{-22}$ s), where the incident projectile interacts with individual nucleons in the target nucleus and shares its kinetic energy with target nucleons by elastic collisions and a cascade of nucleon-nucleon collisions proceeds. At low projectile energies ($\approx 100 MeV$), all interactions occur just between nucleons and the process is called nucleon cascade. Once the incident particle energy is above the threshold energy for particle production first pions (at energies of about hundreds of MeV (see the rise of the π^+ contribution in Fig. 2)), and at higher energies ($\approx 2-10 GeV$) heavier hadrons are produced. They can also participate in the intra-nuclear cascade and interact between each other. Particles that obtain energy high enough to escape the nucleus are being emitted mainly in the direction of the incident particle. The rest of the energy is equally distributed among nucleons in the nucleus which is left in a highly excited state. The energies of pre-equilibrium particles are greater than energies of particles emitted during the equilibrium decay. In the fast intra-nuclear cascade stage, protons and neutrons are emitted in the ratio in which they are present in the target nucleus. The left Plot of Fig. 1 shows the kinetic energy of protons and neutrons created in Pb^{208}_{82} as predicted by Geant 4. For higher kinetic energies ($E_{kin} > 20 MeV$) the neutron/proton ratio is expected to be ~ 1.5 for *Pb* as indicated by the horizontal line. The positively charged protons have to overcome the Coulomb barrier to escape the nucleus. The vertical line represents the energy of the Coulomb barrier, given by the electrostatic potential energy (≈ 12 *MeV* for *Pb*) : $\frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 r}$ where r = atomic radius ($\sim$ 0.175 nm for *Pb*), e = proton charge, Z_1 = atomic number (82 for *Pb*) and $Z_2 = 1$ = proton atomic number.

- **Deexcitation:** In the equilibrium stage ($\approx 10^{-16}$ s) energy is equally distributed throughout the highly excited nucleus that is in a highly excited. The nucleus loses its energy by evaporation of neutrons or light charged fragments (e.g., d, t, α) which are emitted isotropically. When the nucleus does not have enough energy to emit neutrons (its excitation energy becomes smaller than the binding energy, typically about 8 *MeV*), it deexcites by γ-emission.

4.2 Protons

In a total-absorption calorimeter these prompt protons contribute significantly to the observed ionization signal. Fig. 2 shows that for π^- showers between 1 and 100 *GeV* the contribution from protons ranges from 23 % at 5 *GeV* to 16% at 100 *GeV*. The kinetic energy of these protons is high enough that the corresponding scintillation light is only slightly suppressed (by ≈ 10 % see Fig.2). These protons are mainly not relativistic and contribute only about 2 % to the Čerenkov signal (see Fig. 3). The situation is quite different for sampling calorimeters with plastic scintillators as the active medium. The short range of the spallation protons (≈ 1 mm) causes them to deposit their energy mainly in the inactive absorber, reducing the average observed energy of hadron-induced showers and introducing fluctuations beyond the normal sampling fluctuations.

4.3 Neutrons

In a total-absorption crystal calorimeter the spallation neutrons can participate in additional nuclear reactions if they have enough energy, they might leave the calorimeter volume undetected or they are thermalized and captured (on a microsecond timescale) and “return” all of their energy to the observed ionization signal in from of γ’s. The right plot of Fig. 1 shows the time distribution of γ’s created by the neutrons capture process for different crystal materials. Note the shallow slope in case of PbF_2 a material transparent to neutrons due to its low capture cross section. These γs from neutron capture contribute significantly to both the Scintillation and the Čerenkov signal depending on integration time and material. Assuming an integration time ($> 10\mu s$) for a 5 *GeV* π^- shower in a PbF_2 calorimeter one observes that $\approx 17\%$ of the Scintillation signal and $\approx 23\%$ of the Čerenkov signal are due to γ’s from neutron capture. We found that the magnitude of the dual readout correction depends on the timing gate but the energy resolution after the corresponding correction does not.

In a sampling calorimeter with hydrogenous active material the dynamic is far more complicated. The hydrogenous active medium serves as a very efficient moderator. Neutrons produced in the absorber are observed via the ionization signal from very soft protons produced in elastic $n-p$ reactions. These scintillation signal caused by these protons is highly suppressed. For a sampling calorimeter with repeating 4mm Pb and 1mm Scintillator planes we observed that the observable signal is suppressed by a factor of ≈ 2 compared to the deposited energy.

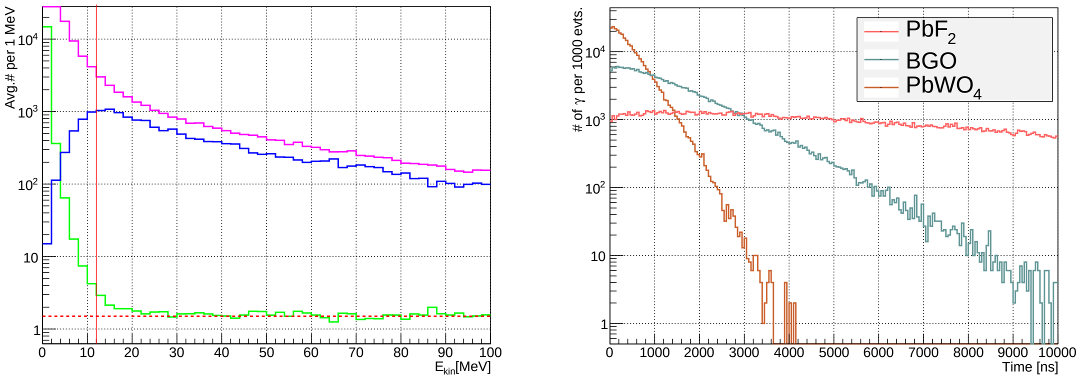

Figure 1: (*left*) Kinetic Energy of neutrons (magenta) and protons(blue) created in Pb^{208}_{82} and the ratio thereof(green) as predicted by Geant 4. The vertical line represents the energy of the Coulomb barrier ($\approx 12MeV$). The horizontal line represents the ratio in which neutrons and protons are present in the target nucleus (≈ 1.54). (*right*) Creation time distribution of γ's created by the neutrons capture process for different crystal materials.

5. Conclusions

We created a flexible, easy to use simulation framework (CaTS) which allows us to identify the dominant physics processes responsible for the energy deposited by different kinds of showering particles. We show how various particles contribute differently to the observable Scintillation and Čerenkov signal of a total-absorption dual read-out calorimeter (HHCAL). We studied how spalation protons and neutrons contribute differently to the signal of an HHCAL compared to sampling calorimeters with plastic scintillators as the active medium. Full GEANT 4 simulation supports the HHCAL concept and predicts excellent energy resolution of $\approx 10\%/\sqrt{E}$ for single π^- before detector effects are taken into account.

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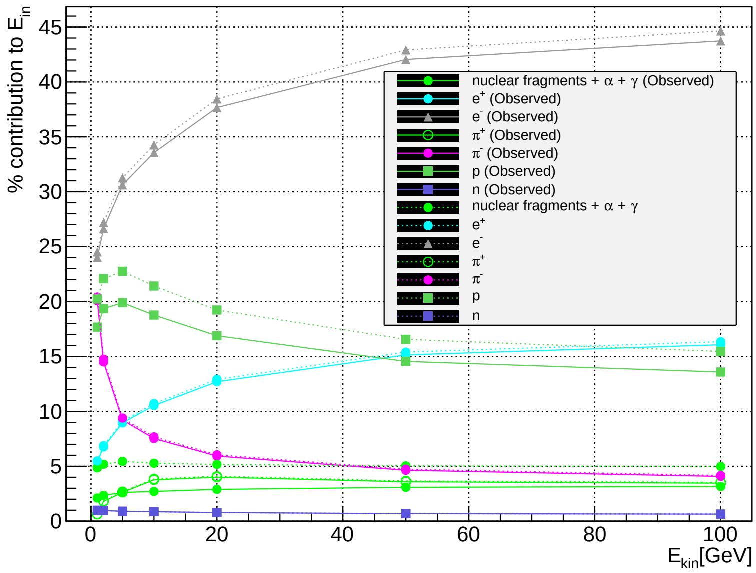

Figure 2: Comparison of the per-particle contributions to ionization (dotted line) and scintillation (continuous line, Observed) signals in a π^- shower for a PbF_2 calorimeter. Saturation effects (Birks suppression) have been taken into account to convert deposited energy to scintillation light.

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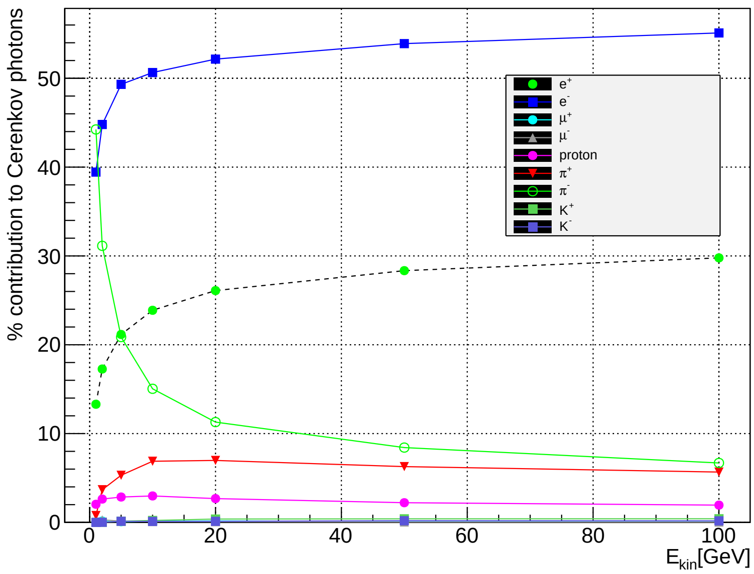

Figure 3: Per-particle contributions to the Čerenkov signal for a π^- shower in a PbF_2 calorimeter. One observes that the Čerenkov signal is not only due to e^- and e^+ but the contribution of pions (incident particle or produced in nuclear reactions) is significant. Especially the leading incident π^- contributes significantly to the Čerenkov signal at low energy.