GEANT4-Based Model of the CREAM Timing Charge Scintillation Detector


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Abstract: The Cosmic Ray Energetics And Mass (CREAM) instrument is a balloon-borne detector designed to measure the cosmic-ray spectrum in the 1-1000 TeV energy range, with good charge resolution from protons to iron (Z = 1 to 26). The CREAM instrument has had two successful flights, both from McMurdo Station, Antarctica in the 2004-2005 and 2005-2006 Antarctic summer campaigns, with a combined flight duration of approximately 70 days. The CREAM-I instrument consisted of a fast scintillation-based Timing Charge Detector (TCD), a Transition Radiation Detector and a sampling calorimeter. Here we describe a GEANT4-based model for a CREAM TCD scintillation counter, used in characterizing the charge and timing response of the counters to various incident particles. The model incorporates all counter components, including the scintillator, light guides and an approximation of the photomultiplier tube (PMT) readout. We compare the simulated output results to actual event signals.

Introduction

The CREAM TCD consists of 8 identical scintillation charge detector paddles arranged in two crossed layers at the top of the instrument. Each paddle is constructed of Saint-Gobain BC408 plastic scintillator, with twisted-strip adiabatic light guides at each end. The light guides are made from acrylic (BC802) with enhanced UV attenuation [2].

Readout of each paddle is done with two Photonis XP2020 fast PMTs. Each PMT is read out at the anode and 5 dynode taps [2]. Four dynode taps go to custom analog-to-digital peak detectors (ADCs), while the anode and one additional dynode tap each go to two time-to-digital converters (TDCs). By utilizing very fast electronics, the TCD is able to quickly acquire the signal from the primary incident particle, and then reject the contamination from any albedo particles from high-energy showers generated in the calorimeter located 1.1 m below the TCD [3].
Model Overview

A model of a CREAM TCD paddle was constructed using the GEANT4 [1] simulation package. The purpose of this model was to better understand the optical response of the paddles to both the primary cosmic rays, and to albedo particles from the calorimeter.

The complete simulation consists of a GEANT4-based model of one TCD paddle, plus optionally the tungsten calorimeter and associated carbon targets. Optical photon physics is included in a separate module which is then registered with whatever physics model is being used. Output for each event is written to an ASCII file. The output file is read in by a stand-alone C++ program which models PMT and electronics response, and outputs a ROOT [4] tree for analysis.

Detector Definition

The TCD paddle model consists of a block of plastic scintillator of dimensions 120cm × 30cm × 0.5cm, twisted adiabatic light guides, aluminum foil wrapping, a glass face for the PMTs, and small aluminum disks to approximate the PMT photocathodes. Figure 1 illustrates the paddle elements modeled.

The light guide models each consist of 28 individual pieces of BC802 acrylic. The light guide parts are assembled into a G4LogicalVolume using repeated iterations of G4AdditionSolid. The foil wrapping is constructed in a similar way.

Once all the individual parts for the paddle are assembled into logical volumes, physical instances of all the parts are placed into a G4AssemblyVolume. Then one copy of the paddle is placed where desired in the world volume. Using the G4AssemblyVolume, we could extend this model to include more than one paddle if desired, though this has not been done.

The calorimeter consists of 20 tungsten plates, plus two carbon targets. By default the calorimeter is not placed in the detector, but it can be inserted with a simple command.

The bulk material properties of BC408, BC802, glass, aluminum, tungsten, and graphite were defined manually. The optical properties (both bulk and surface) were also also defined for all materials present in the paddle using instances of the G4MaterialPropertiesTable class. The optical surface properties of each part were also set by creating a G4OpticalSurface class for each, and attaching a G4MaterialPropertiesTable to it.

One important optical property of the BC408 scintillator is the scintillation yield. This was made adjustable for debugging and prototyping reasons via a G4UImessenger class. The yield for BC408 is approximately 10,000 photons/MeV deposited energy [5][7], however the simulation runs were typically done at a value of 3000. The reasons for this were twofold: to approximate the quantum efficiency of the PMTs, and to dramatically increase the speed of the code because there were 2/3 fewer optical tracks to calculate.

Sensitive Detectors and Hits Collections

Two different types of sensitive detectors were implemented in the model. One detector was used to find the energy deposited in the TCD scintillator paddle, the other to find photon arrival times at each PMT.
In the first implementation of the detector, the scin-
tillator logical volume itself was set as a sensitive
detector. The scintillator sensitive detector then
yielded the total energy deposited in the scintilla-
tor, and the average position of the hit. The sen-
sitive detector then recorded those values into an
instance of the G4VHit hits collection class.

The PMT sensitive detector is a bit more involved
because GEANT4 does not implement a PMT
type detector. To work around this limitation, the
G4UserSteppingAction class is implemented. The
boundary status of each track is examined such that
those optical photons which reach one of the pho-
tocathodes defined in the detector definition each
count as a hit. The PMT sensitive detector is called
by the stepping action when this occurs, and then
the desired quantities are stored in the PMT hits
collection.

For each photon which arrives at a PMT we store
the following: the PMT struck (pmt ID), the arrival
time, the time it entered one of the light guides
(to study dispersion), the number of reflections it
underwent, and the total distance it traveled from
generation.

The detection efficiency of the PMT photocathodes
is defined in the detector definition. For a realistic
PMT this would be the quantum efficiency of the
PMT, and would also be dependent on the wave-
length of the incident photons. Since our PMT
wavelength response and the output of our scin-
tillator were well matched we did not include any
energy dependence in our PMT response. Furth-
ernore, the efficiency of photon detection for our
PMTs was set to 100%, because this was compen-
sated for by setting the scintillation yield to 30% as
discussed above.

**Physics Models and Signal Digitization**

This simulation can utilize any of the built-
in GEANT4 physics models to handle elec-
tromagnetic and hadronic interactions, such as
QGSP, QGSC, LHEP. Optical physics is
added separately by creating an instance of the
G4VPhysicsConstructor class to which we add
all the relevant physics for the G4OpticalPhoton
class. We then register this module with any par-
ticular physics model that is being used. The

GEANT4 optical processes included were the fol-
lowing: scintillation, Cherenkov, optical absorp-
tion, optical Rayleigh scattering and optical bound-
ary processes.

Output for each event was generated in the
G4UserEventAction class. At the end of each
event, the contents of the two hits collections, plus
some additional information about the event, are
formatted and appended to an ASCII file for later
processing. Information stored includes arrival
time of photons at each PMT and light guide, en-
ergy deposit in the scintillator, position of the pri-
mary hit, incidence angle of the primary track,
number of reflections for each photon, number
of photons absorbed (and in what volume), and
charge of the primary.

The PMT output from the GEANT4 simulation is
a list of photon arrival times. To produce realis-
tic PMT-like pulses, each photon needs to be con-
volved with the PMT single photoelectron (PE) res-
pone. The average single PE response was mea-
sured with an actual flight XP2020 PMT, read out
with a fast digital oscilloscope. An average single
PE pulse shape was determined using the averag-
ing feature of the oscilloscope.

The convolution of the simulated photon arrival
times with the measured single PE response yields
a realistic PMT response. This is illustrated in Fig.
2, which shows the average of 256 experimentally
measured atmospheric muon pulses, with the av-
erage of 1000 simulated muon pulses. An overall
10% scale factor (multiplying by 90%) was applied
to the time of the simulated PMT pulse to decrease
the width of the pulse. This was introduced to ad-
just for any systematic bias introduced from slew
rate and sampling limitations of the single PE pulse
measurement.

**Results and Conclusions**

Figure 3 shows the average simulated ADC (peak
detector plus pedestal) response for 10 GeV pro-
tons as a function of the position of the hit along
the paddle. This compares with an experimentally
measured average attenuation curve also shown in
Fig. 3, derived from the CREAM flight data.

A great feature of this sort of model is that it pro-
vides us with a tool to better understand the sources
Figure 2: The average PMT response for muons - simulated and measured.

of any non-linearities in the detector response. For example, it can decouple non-linearities from the geometric arrangement and optical properties of the detector from electronics-based effects.

We are also using this package for prototyping analysis strategies of actual data, since the simulation provides an idealized yet still reasonably realistic set of simulated events [6]. One has access to a large number of possible choices of simulated test beams, as well as extra information not measured in a real detector.

Finally this model of one TCD paddle is being used to calibrate the response of the TCD model in a full CREAM instrument Monte Carlo package. The full instrument MC will not have optical physics present, but with sufficient mapping of the single paddle response using the standalone optical model outlined in this paper, the output should be comparable in accuracy.

Acknowledgements

This work is supported by NASA, NSF, INFN, KICOS, MOST and CSBF.

References