Boronated Scintillator Detector for Use in Space with Ionization Calorimeters

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Abstract. Boronated Scintillator Detector (BSD) for use in space with ionization calorimeters was suggested. BSD improved e/h showers separation, which are initiated in the ionization calorimeter in interaction it with high energy particles. Improve the rejection is based on the hadron-induced showers tend to be accompanied by significantly more neutron activity than electromagnetic showers. The detector is composed of natural boron-loaded (5%) castable plastic scintillation plates. To collect light using wavelength-shifting (WLS) fibers. The experiment showed that the photoelectron yield is ~ 40 ph.el./MeV with using PMT EMI 9954KB. Simulation on GEANT4 was obtained neutron detection efficiency. The simulation was conducted in the assumption that neutrons have the spectrum $^{252}$Cf and fall plane-parallel on the entry surface of the detector.

1. Introduction
In many physics experiments where ionization calorimeters are employed, the requirement of an accurate energy measurement is accompanied by the requirement of very high hadron-electron rejection power. Normally the latter requirement is achieved by designing a high-granularity calorimeter with sufficient depth so that the showers can fully develop. Particle showers initiated by nuclei in the calorimeter have a profile different from an electron-induced electromagnetic cascade, and the hadron rejection power deriving from this difference can be significantly enhanced by making use of the thermal neutron activity at late times relative to the start of the shower. A feature of the use the BSD in space with ionization calorimeters is the low contribution of gamma background, which is a sum of 60% the diffusion space of gamma radiation [1] plus 40% gamma albedo from the atmosphere [2] and short time of detection neutron. It is a few hundred microseconds. Indeed hadron-induced showers tend to be accompanied by significantly more neutron activity than electromagnetic showers. In order to precisely characterize the neutron component associated with the different types of showers, a detailed Monte Carlo simulation has been performed using the FLUKA simulation package. The CALET BGO homogeneous calorimeter, consisting of a BGO tower (60×60×30 cm$^3$) with a vertical depth of approximately 30 cm has been simulated as a “test detector”. For each simulated event the produced neutrons have been propagated till they reached the outside of...
the calorimeter. Neutron yield outside the CALET calorimeter shown on figure 1 for 1 TeV interacting protons and 400 GeV electrons (1 TeV proton showers give the same calorimetric signal as 400 GeV electrons in BGO on average).

Figure 1. Neutron yield outside the CALET calorimeter for (a) 1 TeV interacting protons and (b) 400 GeV electrons [3]

The rejection factor achievable for hadronic showers can be as high as \( \sim 10^3 \) considering the neutron counting. The bulk of neutrons originate from the excitation and de-excitation of nuclei and exhibit a maximum in a several MeV energy region. Many neutrons undergo moderation before escaping and their energy is consequently degraded down to the few eV energy region. Some neutrons can also be produced promptly in the hadronic interactions along the shower core, with an energy reaching that of the primary proton. The highest energy neutrons (\( E > 10 \) MeV) arrive simultaneously with the charged component of the shower, while the low energy and more abundant component arrives into the neutron detector with a delay ranging from 10 to 1000 ns and, thus, can be easily identified. The figure for electromagnetic showers is similar but with a much reduced contribution for the prompt neutron emission [3]. Similar results were obtained for the hadronic and electromagnetic interaction with the CsI(Tl) homogeneous calorimeter (100×100×43 cm\(^3\)) which is mounted on the GAMMA-400 gamma-ray telescope [4].

2. Overview of the known the boronated scintillator detectors for use in space with ionization calorimeters

2.1. ISS-CREAM BSD

The first Boronated Scintillator Detector (BSD) is a detector sub-system for the future Cosmic Ray Energetics and Mass for the International Space Station (ISS-CREAM) mission [5]. It aims to complement the instrument’s tungsten calorimeter in identifying cosmic-ray electrons above 100 GeV. Such electrons are of significant scientific interest, but their identification is complicated by the overwhelmingly more abundant hadronic cosmic rays, hence making significant hadronic rejection power of paramount importance. Particle showers initiated by nuclei in the ISS-CREAM calorimeter have a profile different from an electron-induced electromagnetic cascade, and the hadron rejection power deriving from this difference can be significantly enhanced by making use of the thermal neutron activity at late (>400 ns) times relative to the start of the shower. Indeed hadron-induced showers tend to be accompanied by significantly more neutron activity than electromagnetic showers. The BSD endeavors to measure this late thermal neutron shower activity by detecting the boron capture of these thermal neutrons in a boron-loaded plastic scintillator, located underneath the calorimeter. BSD represents a plastic scintillation block Eljen Technologies EJ-254 with natural boron-loaded weight percentage of 5% which is made in the form of right prism with square basis the size of 60×60×3.8 cm\(^3\). Light collection of scintillations is realized by 12 items Hamamatsu R1924A (ø22 mm) photomultiplier tubes, that are situated in groups of 6 items on opposite lateral faces of the scintillation block.
Results test of the BSD in the CERN H2 beam line shown in figure 2, where shows the resulting energy deposit distributions for electrons and pions in both the ISS-CREAM BSD and the calorimeter. The BSD's ability to distinguish electrons from hadrons is immediately clear. Even for a broad range of calorimeter signal values, the BSD's electron distribution tends to cluster at lower values of BSD signal than the pion distribution. As will be seen, these differences sharpen even more when the calorimeter's signal range is limited to emulate an energy range selection of the sort that will be carried out with flight data.

**Figure 2.** BSD signals for 75 GeV, 100 GeV, 125 GeV, 150 GeV, and 175 GeV electron runs (red) and 250 GeV, 300 GeV, and 350 GeV pion runs (blue). Histograms are normalized by total number of counts [5].

**Figure 3.** $E_{\text{frac}}$ distributions for 100 GeV – 125 GeV electrons (red) and 250 GeV – 350 GeV pions (blue). Histograms are normalized by total number of counts [5].

**Figure 4.** Rejection power versus electron acceptance for 100 GeV – 125 GeV electrons and 250 GeV– 350 GeV pions [5].

For the purpose of deriving rejection power, the parameter $E_{\text{frac}}$ is defined as

$$E_{\text{frac}} = \frac{\text{(BSD Delayed Neutron Signal)}}{\text{(Calorimeter Energy Deposit)}}$$  \hspace{1cm} (1)

A plot of $E_{\text{frac}}$ in a specific range of calorimeter energy deposit is shown in figure 3, with electrons shown in red and pions shown in blue. Clearly, the majority of pions fall well outside of the range of $E_{\text{frac}}$ values for electrons, most of which lie below $E_{\text{frac}} = 0.1$. Thus, in choosing candidate electron populations for spectral studies, a higher efficiency by reducing the maximum allowable value of $E_{\text{frac}}$. Below a given value of $E_{\text{frac}}$, hadronic rejection power for the BSD was defined as

$$\text{Rej. Power} = \frac{\text{(Fraction of Electrons Accepted)}}{\text{(Fraction of Hadrons Not Rejected)}}$$ \hspace{1cm} (2)

Figure 4 shows a plot of rejection power versus electron acceptance derived by gradually raising the maximum allowable value of $E_{\text{frac}}$ in figure 3. Error bars are statistical only. Here, the rejection power using only the BSD and the total energy deposit in the calorimeter is near 140 at 50% electron acceptance, which was the BSD target design performance specification. Rejection power from other handles on electron/hadron discrimination (e.g. shower shape) will combine with the BSD’s neutron detection to create ISS-CREAM’s overall planned rejection power of at least $10^4$.

### 2.2. DAMPE BSD

The second BSD is a detector sub-system for the future DArk Matter Particle Explore (DAMPE) mission [6]. DAMPE is a powerful space telescope for high energy gamma-ray, electron and cosmic rays detection. The ionization DAMPE calorimeter consist of about 31 radiation lengths thickness, made up of 14 layers of BGO bars in a hodoscopic arrangement. The neutron detectors is added to the
bottom of the calorimeter. Finally, in order to detect delayed neutron resulting from hadron shower and to improve the electron/proton separation power a neutron detector is placed just below the calorimeter. BSD consists of 4 plastic scintillation block Saint-Gobain Corporation BC-454 with natural boron-loaded weight percentage of 5%. The dimension of each scintillator is $30 \times 30 \times 1 \text{ cm}^3$, total size of the BSD is $60 \times 60 \times 1 \text{ cm}^2$. Total rejection power at last $10^5$.

3. The design of the BSD using boron-loaded plastic scintillation plates and wavelength-shifting (WLS) fibers for collect light

3.1. Design

The third BSD is a detector sub-system for the future space projects related to the registration of high-energy particles and gamma rays, for example, GAMMA-400 [4], NEYTRONIY-100 [7]. These projects demand neutron detectors with larger area of sensitive surface not less than 1 $\text{m}^2$. As shown in figure 5, the proposed BSD with the size of $100 \times 100 \times 10 \text{ cm}^3$ contains 800 scintillation plates with the size of $25 \times 5 \times 0.5 \text{ cm}^3$, which contain natural boron with the weight concentration up to 3% (SC-331 plastic scintillator). Scintillation plates were made by casting under the pressure according to the technology developed in Institute of High Energy Physics. Each plate has 168 holes under WLS fibers with the diameter of 1 mm. WLS fibers inserted into holes of the scintillator provides light collection for one photodetector. PMT or SiPM may be used as a photodetector. Using WLS fibers allows making neutron detectors which have great light-collecting power. In order to increase neutron detection efficiency the detector additionally contains 2 layers of hydrogen-containing moderator with the total thickness of 5 cm between which scintillation plates were placed.

![Figure 5. BSD with WLS fibers, SiPMs and moderator (yellow).](image)

![Figure 6. Experimental module detector with WLS fibers (75x25x5 cm³).](image)

3.2. Experiment

To measure quantum yield experimentally, an experimental module which is shown in figure 6 with the size of $75 \times 25 \times 5 \text{ cm}^3$ was made when using PMT. The experimental module of the detector contained scintillation plates without boron wrapped into light-reflecting material Tyvek. Light collection was realized by WLS fibers Kuraray Y-11(200) with the emission peak of 476 nm. EMI 9954KB was used as PMT with the spectral sensitivity prolonged into the green area and with the quantum detection efficiency of 16% on the wavelength of 526 nm. According to the method described in the work [8], the amount of photoelectrons was measured from the energy of gamma-quanta absorbed in the detector. From the results of the measurements shown in figure 7, it follows that quantum yield is equal to 55.17 ph.el./MeV with the error of 4%. Since the light output of scintillation plates with boron is 25% lower, quantum yield of the BSD is $\sim 41$ ph.el./MeV. When using SiPM SensL ArrayC-60035-4P ($12 \times 12 \text{ mm}^2$) as a photodetector quantum yield of the BSD is $\sim 2$ times higher. Because the light output of SC-331 plastic scintillator from $^{10}\text{B} (n,\alpha)^{\text{Li}}$ reaction products was equivalent to the light output from a $\beta$-particle with an energy of about 110–130 keV, the quantum yield is $\sim 10$ ph.el. for one absorbed neutron. The obtained amount of photoelectrons is enough for signal extraction against the noise background.
3.3. Simulation

Neutron detection efficiency was obtained by the simulation on GEANT4. The simulation was conducted in the assumption that neutrons have the spectrum $^{252}$Cf and fall plane-parallel on the entry surface of the detector. The energy spectrum of the neutron fission of $^{252}$Cf is a good approximation to the spectrum of evaporated neutrons produced in the interaction of high-energy e and h with a calorimeter. Table 1 shows the estimated efficiency of neutron detection of ISS-CREAM BSD and the BSD without or with hydrogen-containing moderator.

| Table 1. Calculated neutron absorption efficiency |
|-----------------------------------------------|
| Neutron absorption efficiency                 |
| w/o moderator | with moderator |
| ISS-CREAM BSD | 4.2% | 24.7% |
| BSD          | 4.3% | 29.8% |

Including the moderator into the detector design increases neutron detection efficiency with $^{252}$Cf spectrum by 6–7 times. The graph in figure 8 shows that the increasing of natural boron (from 2.5% to 5.0%) does not much affect neutron absorption efficiency. The decay time of Y-11(200) under laser excitation is 8.5 ns. The decay time of SC-331 plastic scintillator is 2.2 ns. Thus, WLS fibers delay rise time of rise-up portion of the scintillation impulse and shifts maximum highlighting time in comparison with the scintillator without boron. Since the proposed BSD is composed of 4 scintillation blocks with the size of 100×25×5 cm$^3$ and contains 4 separate detection channels, its operating speed does not exceed 3 ns. Figure 9 shows the differential distribution of neutron absorption time (after 400 ns) with the integration time of 1 μs for 5000 neutrons that crossed ISS-CREAM BSD (red) and BSD (blue).

4. Conclusions

The described BSD has neutron detection efficiency by 7 times more than ISS-CREAM which increases rejection power. Using thin scintillation plates and wavelength-shifting fibers for light collection allows making BSD with an area of sensitive surface with the size of a few square meters and low power consumption. Thus, BSD is a high efficiency detector for use in space with ionization calorimeters.
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