

The Borexino Muon Detector and Muon Induced Backgrounds

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Abstract. The Borexino experiment, aimed at measuring the ${}^7\text{Be}$ solar neutrinos, is currently under construction at the underground National Laboratories of Gran Sasso in central Italy. The Gran Sasso underground labs are located below 1,400 m of rocks. The equivalent shielding for cosmic rays is 3,800 m of water equivalent, and the residual muon flux is $\sim 1/\text{m}^2/\text{h}$. The number of muons crossing the Borexino detector is 10,000/day, to be compared with the number of ${}^7\text{Be}$ neutrino events in the central fiducial detector of $\sim 10/\text{day}$. A muon veto sub-detector was designed with the purpose of reducing background from muons and cosmogenic nuclides below 1 event per day in the spectral region of the equivalent energy between 250 and 800 keV, where the signal from the ${}^7\text{Be}$ neutrinos is expected.

The muon veto sub-detector consists of two separate parts. Four hundred photomultiplier tubes measure the scintillation photons and the Cerenkov photons produced by muons either in the 300 tons of scintillator or in the 1000 tons of pseudocumene buffer. Two hundred photomultiplier tubes measure the Cerenkov photons produced by muons in the water shield surrounding the pseudocumene buffer. The paper presents an overview of the muon background in Borexino and an estimate of the background reduction which is expected to be produced by the muon veto. A full discussion of the experimental apparatus is provided as well.

INTRODUCTION

For decades, solar astronomers have been preoccupied with the deficit of observed solar neutrinos from the flux predicted by the Standard Solar Model (SSM). In particular, the suppression of the monoenergetic 0.86 MeV neutrinos produced during electron capture by a ${}^7\text{Be}$ nucleus is well-known [1]. The SSM is believed to be well understood, especially with recent results in helioseismology [2]. Therefore, recent hypotheses have focused on the possibility of a non-zero neutrino mass allowing oscillations between neutrino flavors [3]. Results from Super Kamiokande [4] and SNO [5] appear to demonstrate flavor oscillations explicitly, and analyses such as [6] now show that the LMA and LOW solutions are favored over the others. Unfortunately, current experiments are not capable of both energy and position resolution at sub-MeV energies. Borexino, scheduled to begin data taking in 2002, will be such a detector.

Borexino will be an unsegmented detector based on the design principle of graded shielding, as shown in Figure 1. Its innermost sphere, or "Inner Vessel," is a transparent nylon film about 100 μm thick holding 300 t of scintillator fluid. Only events generated within the innermost 100 t, the so-called "Fiducial Volume," are trusted data; the remainder of the scintillator is used as an active shielding buffer. The scintillator is a mixture of 1,2,4-trimethylbenzene (pseudocumene) with a small quantity of the fluor 2,5-diphenyloxazole (PPO). Outside this is another nylon film, the "Outer Vessel," containing an additional 1,000 t of pseudocumene as well as 5 g/L of dimethylphthalate (DMP), a quenching compound. The pseudocumene in both regions is carefully distilled and purified of ${}^{14}\text{C}$. Beyond the Outer Vessel lies a radio-pure Stainless Steel Sphere (SSS) supporting 2,448 photomultiplier tubes. Of these, 1,843 PMTs have their fields of view restricted to the volume of the Inner Vessel with light cones; the remaining 579 will be described below. This entire apparatus is contained by 2,150 t of processed radio-pure water acting as yet another buffer against external radiation. The water is within an Outer Steel Tank. More information about the Borexino design may be found in [7].

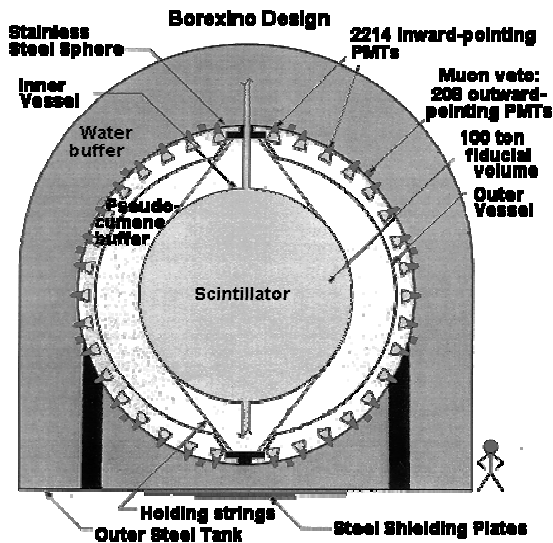


FIGURE 1. The concentric layers of shielding of the Borexino detector.

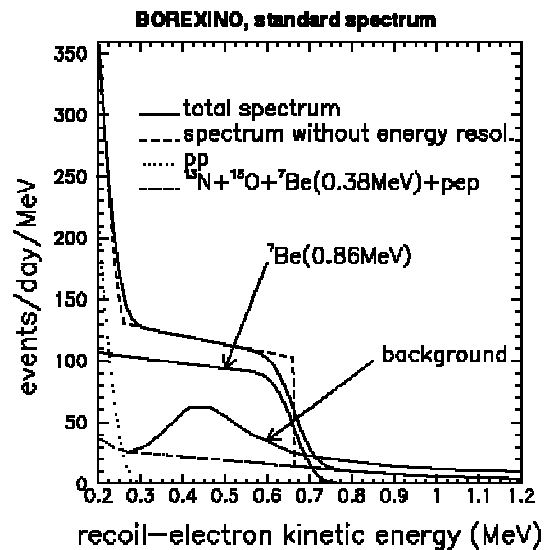


FIGURE 2. Predicted rate of neutrino events in the fiducial volume of Borexino, in the case of no neutrino flavor mixing.

Even with all of the care taken to avoid natural radioactivity, radon diffusion, and the like, Borexino is still subject to the cosmic ray background. To alleviate most of this, the experiment is in the Italian National Laboratory of Gran Sasso, 1,400 m underneath the mountain of the same name. The rock barrier, which is 3,800 m equivalent of water, eliminates all but 1.16 events/m²/h of muons [8]. This translates to about 10,000 events/day in total, still far too great a background. 5,000/day of these muons will pass within the SSS and generate hits on the internal PMTs. The rate of neutrino events in the Fiducial Volume within the desired energy range (see Figure 2) may, however, be as low as 10 events/day. It is clear that a system is needed to veto events caused within the SSS by muons, and its efficiency must be on the order of 99.98 percent.

PHYSICS OF THE MUON VETO

As detailed in the initial NSF proposal for the muon veto system [9], three distinct types of muon-related events must be vetoed. First, muons may collide with atomic nuclei in the detector, producing a shower of neutrons. Neutron capture then causes the emission of an easily recognized γ ray at 2.16 MeV, so these events are not a concern. Second, the muons themselves produce Cerenkov radiation and, within the pseudocumene buffer, scintillation light. Finally, the hadronic showers which produce neutrons may also create radioactive nuclei.

Cerenkov Radiation

The first Counting Test Facility (CTF I), a Borexino vessel prototype which took data from April 1995 to July 1997, provided data on the Cerenkov and scintillation light caused by muons. Muon events were selected by their time coincidence with events observed in two external wire chambers. For 75 percent of events in this sample, the PMT pulse heights, when reconstructed as energies, fell outside the interesting range of less than 1 MeV [10]. Two further criteria were applied to the remaining events. First, since Cerenkov radiation is produced along the entire track of the muon, it reaches the photomultiplier tubes over a broad time period. The mean delay time for arriving photons, measured from the very first PMT hit, was on average greater than 16 ns, compared to the typical 5 ns for pointlike events [10]. Second, Cerenkov radiation is directed in a cone in front of the muon. All muons arrive from above, so the pattern of photomultiplier hits resulting from Cerenkov radiation is asymmetric. With these tests, 95 percent of muon-induced events in the neutrino energy window could be recognized [10], giving an overall recognition of about 99 percent. Unfortunately, naively applying position reconstruction code to these spatially extended Cerenkov events produced no useful additional information.

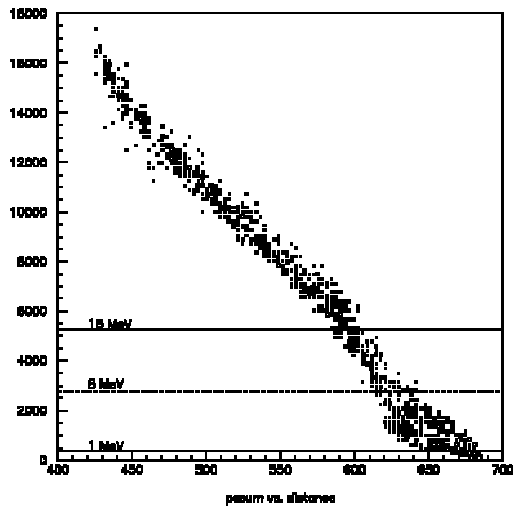


FIGURE 3. Monte Carlo simulation of the total photoelectron yield of the PMTs as a function of muon track impact parameter. The PE yields corresponding to 15 MeV, 8 MeV and 1 MeV are shown.

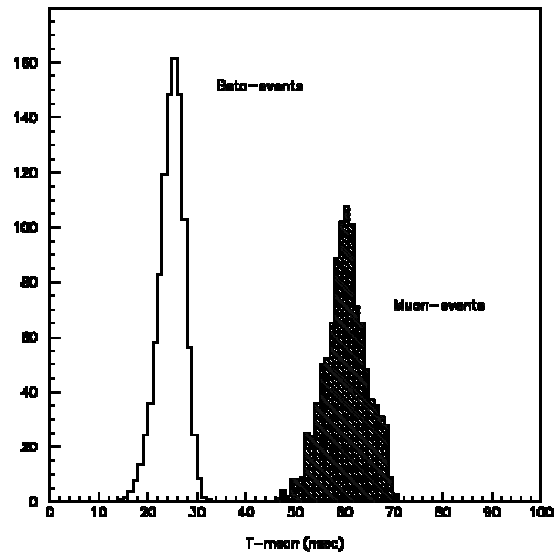


FIGURE 4. Mean time distribution of beta events and of events due to muon tracks passing through the buffer fluid in the Monte Carlo.

The Borexino detector will be substantially larger than CTF I; thus, the light yield of Cerenkov events and the time spread of PMT hits will both in general be much greater. Only tracks that barely graze the inside of the SSS are problematic. Monte Carlo simulations done at Munich show that tracks with an impact parameter greater than 6.5 m might be confused with neutrino events (see Figure 3). However, the diameter of the SSS is 13.7 m, so the proportion of such tracks is at worst ten percent. The mean delay time for photons arriving from these tracks in the simulations was 60 ns from the first PMT hit. Figure 4 shows the difference in time distribution between beta and Cerenkov events [11]. If it is conservatively assumed that the time spread can distinguish Cerenkov events with an efficiency of 95 percent, then the overall efficiency of these cuts is already 99.5 percent.

Cosmogenic Nuclides

Muons cause production of radioactive nuclides from the carbon in pseudocumene. Most resulting isotopes, though, have half-lives of 0.8 s or less. If a dead time of 3 seconds is imposed in off-line analysis after each Cerenkov event, hits from these isotopes are reduced by a factor of 15 with only 10 percent data loss. The remaining, longer-lived isotopes are listed in Table 1 [9,12]. Of these, the least problematic is ^{11}Be , for its decays usually yield energies well outside the ^7Be neutrino window. The carbon nuclides both emit positrons. These yield 1.02 MeV γ rays upon annihilation, shifting the amount of energy hitting the PMTs beyond the neutrino window. Additionally, ^{10}C events may be tagged. During production of the light isotopes of carbon, one or two neutrons are emitted. These are subject to capture by protons, producing 2.16 MeV γ rays. Any suspected neutrino event, therefore, may be checked for the presence of a recent nearby neutron capture event. Given the likelihood of convection in the scintillator, this will be more useful for ^{10}C decays than for the longer-lived ^{11}C . Ironically, ^7Be is most troublesome; its monoenergetic decay interferes directly with the ^7Be neutrino window.

TABLE 1. Long-lived Cosmogenic Nuclides in Borexino.

Isotope	$t_{1/2}$	E / MeV	Decay Path	Events/day in Fiducial Volume
^{11}Be	13.8 s	0 – 11.5	β^-	< 0.034
^{10}C	19.3 s	0 – 1.9	$\beta^+ + 0.72 \text{ MeV } \gamma$	1.95 ± 0.21
^{11}C	20.4 min	0 – 0.99	β^+	14.55 ± 1.49
^7Be	53.3 days	0.478	γ	0.34 ± 0.04

The rates at which cosmogenic nuclides will be produced in the Fiducial Volume are not well known. Some estimates have been obtained by extrapolating from an experiment at CERN [12] in which the SPS muon beam was used to calculate cross sections for $^{12}\text{C} + \mu \rightarrow$ radionuclides at muon energies of 100 and 190 GeV. From these cross sections, the estimated number of events per day due to the radionuclides listed in Table 1 was obtained. It is relieving to note that the isotope ^7Be should produce background events at the average rate of only one per three days. Overall, cosmogenic radionuclides should not produce a greater background than 0.5 events/day within the Fiducial Volume in the energy range of most interest.

MUON VETO HARDWARE

With the software-based offline methods of analysis described so far, approximately 0.5 percent of muon Cerenkov events, or 25 per day, will slip through. A physical hardware system within the detector is needed to identify these events. This system is composed of two sets of photomultiplier tubes and two layers of Tyvek, a reflective plastic. The outer set of PMTs has its own dedicated set of data acquisition electronics.

The Cerenkov events most likely to be confused with neutrino events, because they produce the least radiation, are the tracks which just graze the interior of the SSS. To distinguish these events, 371 of the 2,214 PMTs inside the SSS are not equipped with light cones; they can view the entirety of the scintillator and buffer regions. With this unrestricted view, they have a higher relative yield for muon tracks grazing the buffer than do the PMTs with light cones. Hence the ratio of the photoelectrons in the PMTs without light cones to all the photoelectrons is higher for Cerenkov events in the buffer than for neutrino events in the Fiducial Volume. The efficiency of this "fraction test" was investigated in the Munich Monte Carlo tests [11] of Figure 5. An aggressive cut might easily exclude 95 percent of Cerenkov events, abandoning only a few percent of neutrino events.

The region of the Borexino detector outside the SSS is filled with 2,150 t of ultrapure water. Besides acting as a passive radiation shield, this volume is also a Cerenkov detection system for muons. On the outside of the SSS are 208 outward-pointing PMTs and a 200 μm layer of Tyvek. A second layer of Tyvek coats the interior of the Outer Steel Tank. This white plastic has a diffuse reflectivity of 60 to 90 percent in the 300 to 500 nm spectral range of the PMTs [11]. Cerenkov radiation in the outer part of the detector is reflected several times between the two Tyvek coats, increasing the photoelectron yield and the number of PMT hits. Each muon track should generate hits on 90 to 150 of the PMTs, assuming no light obstruction [11]. Even in a worst-case light obstruction scenario, however, the number of hit PMTs is acceptable. It seems reasonable to expect that this Outer Muon Detector system can veto Cerenkov events with an efficiency of over 90 percent. Combined with the offline software cuts and fraction test, this should yield a muon-induced background of less than the desired 1 event/day.

Two scenarios are foreseen in which the Outer Muon Detector system will trigger. In the first, an event is detected by both the internal PMTs and the Outer Muon Detector PMTs. This almost certainly corresponds to a muon track. In the second, hits are generated by the outer PMTs but not inside the SSS. This is likely a muon that does not pass through the SSS. Nevertheless, neutrons produced by such an event may travel through the SSS into the buffer, there to generate PMT hits which must be correlated with the muon track. This raises the question of how the Outer Muon Detector is interfaced with the rest of the Borexino data acquisition system, described in [13].

Like the other Borexino photomultipliers, the outer PMTs are powered by a SY527 high voltage power supply manufactured by CAEN SpA, Italy. Cables from the PMTs both supply power and transmit signal, so it is necessary to feed them through nine High Voltage Decouplers (HVDs) which perform an AC decoupling of the PMT pulses. These were designed at Princeton University. The HVD required bandwidth is 1 GHz, with a cross talk reduction of 50 dB at all frequencies [14].

Decoupled PMT signals are sent on to 14 Charge-to-Time Converter boards (QTCs) designed at Princeton around a LeCroy MQT300 chip and manufactured at

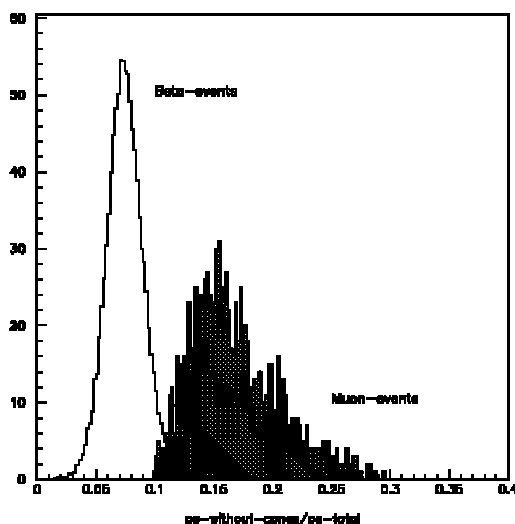


FIGURE 5. Histograms showing the results of the "fraction test" for simulated beta events and simulated muon events in the buffer region. Details are in text.

Munich [15]. Each board handles 16 PMT channels. Each channel outputs an ECL logic pulse whose duration is directly proportional to the number of photoelectrons. These pulses go to two 128-channel Time to Digital Converter boards (TDCs), model v673, made by CAEN [16]. Each QTC board also sends a logic signal encoding the number of channels fired on the board to the Muon Trigger Board (MTB) [17]. These boards are plugged into a VME bus, which is controlled by a Motorola Power PC chip running the Debian GNU/Linux operating system.

The MTB, which was designed by Princeton and the LNS laboratory at the Massachusetts Institute of Technology, sends a logical trigger signal when the number of channels fired from all QTC boards is greater than a certain programmable threshold. Once such a trigger is sent to the master Borexino Trigger Board, it responds by sending a Borexino General Trigger to the entire data acquisition system. The MTB then triggers a readout (via VME bus) of data on the TDC boards. The amount of data retained by the TDC boards is programmable; it is intended to use the maximum available storage range of 32 μ s. Custom software has been written for the Power PC which permits this data, along with a trigger ID number generated by the MTB, to be sent via network to the main computer which handles event building. Data analysis will be done off-line at a later time.

CONCLUSIONS

An overview of the expected background due to muons and muon-induced events in the Borexino neutrino detector was presented. Roughly 5,000 muons cross the detector per day and may be mistaken for neutrinos. In order to obtain the desired background of one event per day, it is necessary to veto muon events with an efficiency of 99.98 percent. Several methods were presented by which muons may be excluded in the offline analysis code. Their effectiveness, based on Monte Carlo simulations and tests from the CTF I prototype, appears to be high. Furthermore, a system of photomultipliers viewing the outside of the SSS may be used as a Cerenkov detector to veto those muon tracks which cannot be excluded offline. The logic of the electronics of this system was briefly described. The efficiency of the entire system seems more than sufficient to ensure that muon events are reduced to an acceptable background level during the operation of Borexino.

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