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2010 JINST 5 P08005

(http://iopscience.iop.org/1748-0221/5/08/P08005)

JINST
PUBLISHED BY IOP PUBLISHING FOR SISSA
RECEIVED: *July 5, 2010*
REVISED: *August 14, 2010*
ACCEPTED: *August 16, 2010*
PUBLISHED: *August 31, 2010*

Boron and thermal neutron interactions on borosilica window photomultiplier tubes

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ABSTRACT: The borosilica, a very common PMT window and envelope material, contains 5% Boron (1% ^{10}B). The high cross section for ^{10}B capturing thermal neutrons (3980 barn), is a concern for LHC experiments using borosilica window PMTs. This study investigates the rate and the size of the signals generated by thermal neutron boron interaction in borosilica window PMTs; Hamamatsu R7525-HA and R7600U-200-M4. Although virtually all of the thermal neutrons incident on the borosilicate glass are absorbed, probability of generating a PMT signal was measured to be 3×10^{-4} and 3×10^{-6} for R7525-HA and R7600U-200-M4 PMTs, respectively. For these signals the average pulse size was found to be between 20–30 photoelectrons. We also discuss that four anode PMTs allow the elimination of these events with an offline algorithm.

KEYWORDS: Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Radiation-induced secondary-electron emission; Calorimeters; Cherenkov detectors

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doi:10.1088/1748-0221/5/08/P08005

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Contents

1 Introduction

The cross section for boron capturing neutrons increases drastically with lower neutron energy, reaching to 3980 barn at thermal energy level (~ 0.025 eV). Boron and thermal neutrons interact in two possible ways;

$$^{10}B_5 + n \rightarrow ^7 Li_3 + \alpha \; (Q\ value \; = \; 2.792\ MeV,\ ground\ state) \tag{1.1}$$

$$^{10}B_5 + n \rightarrow ^7 Li_3 * + \alpha + \gamma \, (0.48\ MeV) \; (Q\ value \; = \; 2.310\ MeV,\ excited\ state). \tag{1.2}$$

When thermal neutrons interact with boron, the reaction leads to ^7Li in the excited state 94% of the time, while the remaining 6% are ground state ^7Li. In both cases, since the Q value of the reaction is very large compared to the incoming neutron energy, the kinetic energy of the products (a and Li) is almost equal to the Q value. Conservation of energy and momentum gives E_{Li} = 0.84 MeV, and E_α = 1.47 MeV, for the excited state Li reaction, and E_{Li} = 1.16 MeV, and E_α = 1.78 MeV, for the ground state Li reaction [1].

Hamamatsu R7525-HA PMTs, with borosilica windows and envelopes [2–4], are currently used in the Cherenkov calorimeters at the forward region of the Compact Muon Solenoid (CMS) experiment [5–7]. Recent upgrade R&D studies on these detectors, focus mainly on muon interactions at PMT windows, and propose to use Hamamatsu R7600U-200-M4 PMTs on readout system [8, 9]. However, while the envelopes of the Hamamatsu R7600U-200-M4 PMTs are metal, the front windows are still borosilica.

The 5% boron in the borosilica glass of these PMTs interacting with the possible thermal neutrons during the Large Hadron Collider (LHC) runs might be a substantial source of fake events. Simulation studies predict the thermal neutron flux in the PMT readout boxes, located in CMS forward region, to be $\sim 100/cm^2s$ at the LHC luminosity of 10^{34} [10].

This study investigates the boron and thermal neutron interactions on borosilica PMT windows using both Hamamatsu R7525-HA and Hamamatsu 7600-U200-M4 PMTs.

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2 Experimental setup

The University of Iowa Positron Emission Tomography (PET) center compact medical cyclotron, a cyclic accelerator, is used as the neutron source. Particles such as protons or deuterons are brought to high energies by traversing several hundred orbits within the cyclotron. During each orbit the particle receives about 90 keV of energy. When the orbits are near the maximum radius of the cyclotron particles are removed through electrostatic deflection and impinge upon small volume hollow metallic cylinders filled with a nonradioactive gas or liquid. At this point the particle energies are 17 MeV for protons and 8.5 MeV for deuterons. Nuclear reactions take place within the cylinder (also called a target) between the incoming high energy particle and the contents of the target to produce the necessary radioactivity for incorporation into the PET radiotracers.

The ^{18}F production runs, with an ^{18}O target, are used as the neutron beam in this study. If one of these high speed protons interacts with an ^{18}O nucleus (stable, 0.20% abundance), a (p,n) reaction results in the formation of the ^{18}F radioisotope with 109.74 minute half life. Specifically;

$$^{18}O_8 + p \rightarrow^{18} F_9 + n\ (14\,MeV) \tag{2.1}$$

The produced 14 MeV neutrons are emitted with a rate of $10^{10} neutrons/s$ in 4π direction. In order to thermalize these fast neutrons we built a moderator using polyethylene and paraffin, commonly used materials for this purpose [11–13]. An aluminum cylinder, with 50 cm length and 20 cm diameter, was filled with paraffin and the front window closed with polyethylene slab. A cavity at the center of the cylinder was left to hold a PMT and its base (figure 1). The stand-alone system is positioned 1 m away from the PET target. At this position, the front of the thermalizer is bombarded with $\sim 10^7$ $neutron/s$. In order to shield the PMT from gamma radiation we used a 5 cm long bismuth cylinder in front of the PMT and covered the front surface of the thermalizer with 3 mm thick lead sheet. All cables are shielded and whole system is grounded together against the electrical and RF noise. The PMT signal is carried into the control room, where it is processed using a Tektronix 5104 digital oscilloscope and a VME data acquisition system containing (i) CAEN V792 32 Channel QDC, (ii) CAEN V812 16 Channel Constant Fraction Discriminator, (iii) CAEN V976 Fan in/out and (iv) CAEN V975 8 Channel Fast Amplifier. The signal coming from the PMT is split with the fan in/out in order to create a 40 ns gate.

3 Results

A gold foil was used to determine the flux of thermal neutrons inside the moderator. A 1.36 g gold foil, with 0.254 mm thickness and 1.905 cm diameter, was taped on the front face of the PMT and bombarded with neutrons during an 80 min run at 30 μA beam. Three hours after the end of the run the gold foil was taken to the Ortec HPGe detector for gamma spectroscopy (figure 2). The gold foil was positioned on a mount, 5 cm away from the surface of the HPGe detector. During the 24 hour spectral scan the dead time of the detector was measured to be less than 0.5%. The detector efficiency corrections, which are calculated based on the previous mixed gamma source spectral scans, were applied to measure the actual number of gamma emissions at the time of the scan. Considering the 67 hours half life for gold isotopes, the decay correction was applied to calculate

Figure 1. (LEFT) The polyethylene cavity at the center of the thermalizer. (MIDDLE) Back view of the finished thermalizer, with the well to insert PMT into the cavity. (RIGHT) The thermalizer is positioned 1 m away from the target of the cyclotron machine.

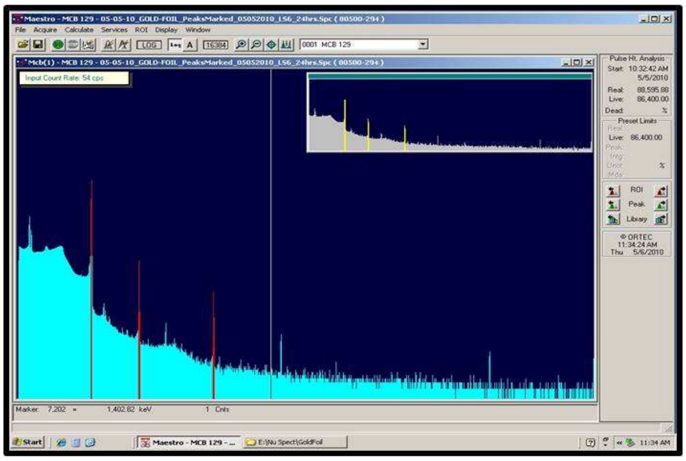

Figure 2. The screen output of the emitted gamma spectrum from gold foil, during 24 hours of HPGe detector measurements. The 411 keV photons were counted to determine the neutron flux on foil.

the activity of the foil just at the end of the beam run. The neutron flux was calculated using

$$R = m \times N_A \times \sigma \times \phi / A_r \tag{3.1}$$

Where R is the activity rate of the gold foil at the end of bombardment; After HPGe detector efficiency and decay time corrections it is measured to be 17313 Bq, m is the mass of the gold foil, N_A is the Avagadro's Number, σ is the neutron cross section of gold (98 barns), ϕ is the neutron flux density $cm^{-2}s^{-1}$, and A_r is atomic weight of gold. We measured the flux of neutrons inside the moderator to be $4.27 \pm 0.03 \times 10^4 cm^{-2}s^{-1}$ during the run.

To indentify the borosilica-neutron interactions the borosilica window PMT signals were compared to quartz window and envelope PMT (Hamamatsu R760). On scope measurements we observed occasional spikes, with ~ 1 Hz frequency and amplitudes up to three times the dark current during borosilica window PMT (Hamamatsu R7600U-200-M4 and Hamamatsu R7525-HA) runs. These spikes were not observed during quartz PMT (Hamamatsu R760) runs. The candidate neu-

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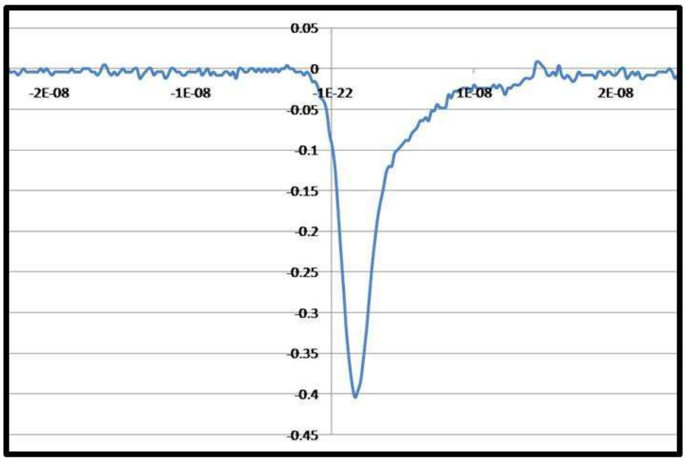

Figure 3. The scope view of an example neutron spike shows that the pulses have width between 4-5 ns with a sharp leading edge rise time and a slight tail at the fall time.

tron spikes from borosilica window PMTs have pulse width of 4-5 ns, a sharp leading edge (rise time), and a slight tail on the fall time (see figure 3).

A VME data acquisition system was used for a high statistic study of charge distributions of these spikes. Figure 4 shows pedestal subtracted distributions of 10,000,000 events from one anode of the R7600U-200-M4 PMT after $\times 10$ amplification. The PMT was set to operate at 650 V in order to yield 10^5 gain. The x-axis shows the collected charge in pC. The OR coincidence of all four anode signals was used for gate trigger. Including the $\times 10$ amplification, the average signal size above pedestal is measured to be 5 pC (around 30 photoelectron) per neutron events. After taking into account the thermal neutron flux and the number of events above pedestal, it is found that only 3×10^{-6} of the thermal neutrons hitting to the borosilica window generate signal on the PMTs.

Figure 5 shows the ADC charge distribution of 20,000,000 neutron triggers for the Hamamatsu R7525-HA PMT, operating at 1100 V, and 10^5 gain. 75% of the signals registered above one σ of pedestal region generate less than 2 pC charge, and only 0.3% are bigger than 5 pC. The number of events are much higher than that of R7600U-200-M4, one possible explanation of this can be the borosilica envelope of R7525-HA. Once the neutrons enter the moderator, during the thermalization process they fill the whole volume and can hit the PMT from any direction. Considering all surfaces of R7525-HA are borosilica, there is a very high flux of alpha particles created at the envelope of the PMT. This could be causing the high number of small signals observed during R7525-HA tests. The thermal neutron flux inside the moderator and the total number of events above pedestal suggest that 3×10^{-4} of the thermal neutrons interacting with borosilica window and envelope generate a signal at R7525 PMTs. After taking into account the $\times 10$ amplification, the average charge from the thermal neutron interactions on R7525-HA PMTs calculated to be around 20 photoelectrons. Here it should be stated that, the high number of envelope events causes the overall average to be smaller than R7600U-200-M4.

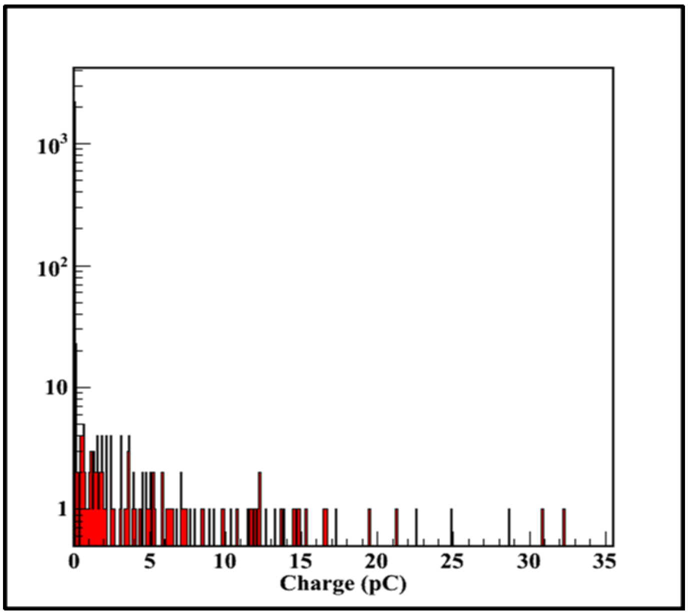

Figure 4. The pedestal subtracted ADC charge distribution of 10,000,000 triggers from Hamamatsu R7600U-200-M4 PMT. Distribution includes $\times 10$ amplification, and every bin corresponds to 0.1 pC charge.

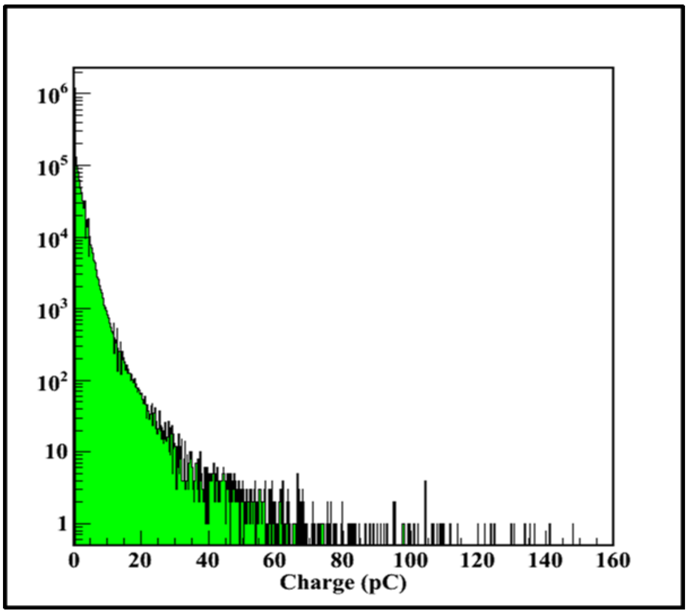

Figure 5. The pedestal subtracted ADC charge distribution of 20,000,000 triggers from Hamamatsu R7525-HA PMT. Distribution includes $\times 10$ amplification, and every bin corresponds to 0.1 pC charge.

4 Conclusion and discussion

Borosilica window PMTs are extensively used in LHC detectors. The simulations studies show that there will be a considerable flux of thermal neutrons, especially at high pseudorapidity region. To determine the extent of the possible noise that 5% boron in the PMT windows and envelopes can cause, we performed tests in the University of Iowa PET cyclotron facility. The 14 MeV neutrons were thermalized with a paraffin and polyethelene moderator. The total number of thermalized neutrons inside the moderator was measured, by using gold foil, and found to be $4.27 \pm 0.03 \times 10^4 cm^{-2} s^{-1}$. During the tests two different type of borosilica window PMTs, Hamamatsu R7600U-200-M4 and Hamamatsu R7525-HA, were used, along with a quartz window Hamamatsu R760 PMT. When the borosilica window PMTs were exposed to neutron beam, occasional spikes were observed. The scope views show that these spikes have a 4-5 ns pulse width, and a slight tail on the fall time. This characteristic pulse shape can be used to discriminate these events based on pulse shapes [9].

A high statistics run shows that only 3×10^{-4} of the thermal neutrons interacting with borosilica surface generate signal at Hamamatsu R7525-HA. The average size of these singals is 20 photoelectron. For Hamamatsu R7600U-200-M4 these numbers were calculated to be 3×10^{-6} and 30 photoelectrons. The average signal size of R7525-HA is measured to be less than R7600U-200-M4 due to the high number of events with small signal sizes are generated at the borosilica envelope. Although the window thickness of R7525-HA (1.2 mm to 6 mm) and R7600U-200-M4 (0.6 mm) are considerably different, the measured neutron signals are similar. This result hints that due to the very short range of alpha particles within glass, we are possibly detecting the interactions happening at the closest 40 μm borosilica glass slice to the photocathode.

A recent report of LHC upgrade R&D study proposes to use Hamamatsu R7600U-200-M4 PMTs on CMS Hadronic Forward calorimeter readout system [8], primarily to eliminate the abnormal events due to muon interactions on PMT window. Since the Hamamatsu R7600U-200-M4 has 4 independent anodes, the muon events can easily be tagged by a simple algorithm based on an abnormally high single anode signal [8]. Due to the short range of the alpha particle in glass the neutron events mostly show up on only one anode at a time. This makes neutron events easy to tag as the muon interactions on PMT window. Here, we tested the efficiency of the algorithm explained in reference [8] to eliminate thermal neutron interactions on borosilica window of Hamamatsu R7600U-200-M4 PMT. When the maximum signal from any anode is required to be less than 5 times the average of all anodes, the neutron events are eliminated drastically. This cut value can be optimized according the the light mixing and uniformity, as well as the signal size of the particular detector. In possible case of the real physics event and neutron event occur at the same time, one can simply reconstruct physics events from other three anode signals by multiplying their average with 4/3.

Acknowledgments

The authors would like to thank to University of Iowa Positron Emission Tomography center employees for their help during the tests, especially Dr. Richard Hichwa and Dr. Garrett Stratton.

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