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Peculiarities of the Hamamatsu R11410-20 photomultiplier tubes

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Results of a systematic study of characteristics of 34 Hamamatsu R11410-20 photomultiplier tubes to be used in the RED100 double-phase emission detector are presented. We have detected certain anomalies in noise characteristics of these PMTs. As it appeared from more close inspection, these anomalies are mainly caused by heavy light emission that was detected at least in three PMT units. The results of the photon emission intensity study as a function of the PMT cathode-to-anode bias voltage and temperature are presented.

Another distinctive feature of the devices is a large Cherenkov light yield for charged particles passing through the PMT window. The window material properties together with high quantum efficiency for VUV light (>30%) lead to generation of signals with amplitudes ~100 photoelectrons from atmospheric muons passing the horizontally placed PMT window. Such effect makes feasible the usage of a R11410-20 as a standalone particle detector.

1.Introduction

The RED100 double-phase emission detector is currently being prepared for an experiment aimed on the registration of the phenomenon of coherent neutrino scattering off xenon nuclei [1]. The emission method of particle registration is capable of detecting single ionization electrons, which could be generated in the liquid xenon volume at the point of elastic neutrino interaction with xenon nucleus: the electrons could be pulled up to the gas phase with the help of a strong electric field (up to 1 kV/cm), where an electroluminescence signal is generated. Two photodetecting arrays of 19 Hamamatsu R11410-20 PMTs each would be used in the detector. For the RED100 conditions, the electroluminescence signal generated by single ionization electron can lead to the registration of ~80 photoelectrons on the photocathodes of 19 PMTs placed in the top photodetecting array.

Since the RED100 photodetecting system must be able to detect rare events with a small amount of the released energy, it was decided to utilize Hamamatsu R11410-20 PMTs for this purpose. These devices are characterized by extremely low level of radioactive contamination ~10 mBq/PMT [2], good single photon response and high quantum efficiency for liquid xenon scintillation photons [3]. In order to check these parameters for each PMT unit to be installed to the RED100 detector, a systematic characterization procedure has been carried out, including the study of its single photon response and noise characteristics.

2.Main parameters of the R11410-20 PMTs

The first step of the testing procedure was to study the PMT single photon response by measuring LED-induced single photoelectron spectra for each PMT at different cathode-to-anode bias voltage values. All the resulting spectra could be characterized by reasonably good single photoelectron resolution with the values of peak-to-valley ratio between 1.9 and 4.0 (at optimal bias voltage). One of the best spectra obtained is shown in fig.1.

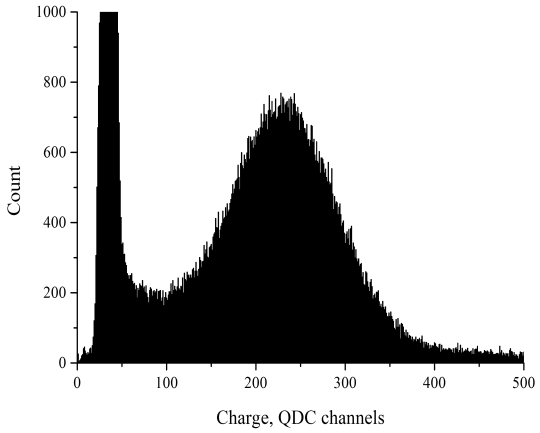

Fig.1. Example single photoelectron spectra, obtained with Hamamatsu R11410-20.

Since such spectra have been measured for each PMT under different values of the bias voltage, it became possible to measure the dark count rate dependencies on the bias voltage for all PMTs setting the discriminator threshold at the level of 1/3 of single photoelectron amplitude. The resulting distribution is shown in fig.2.

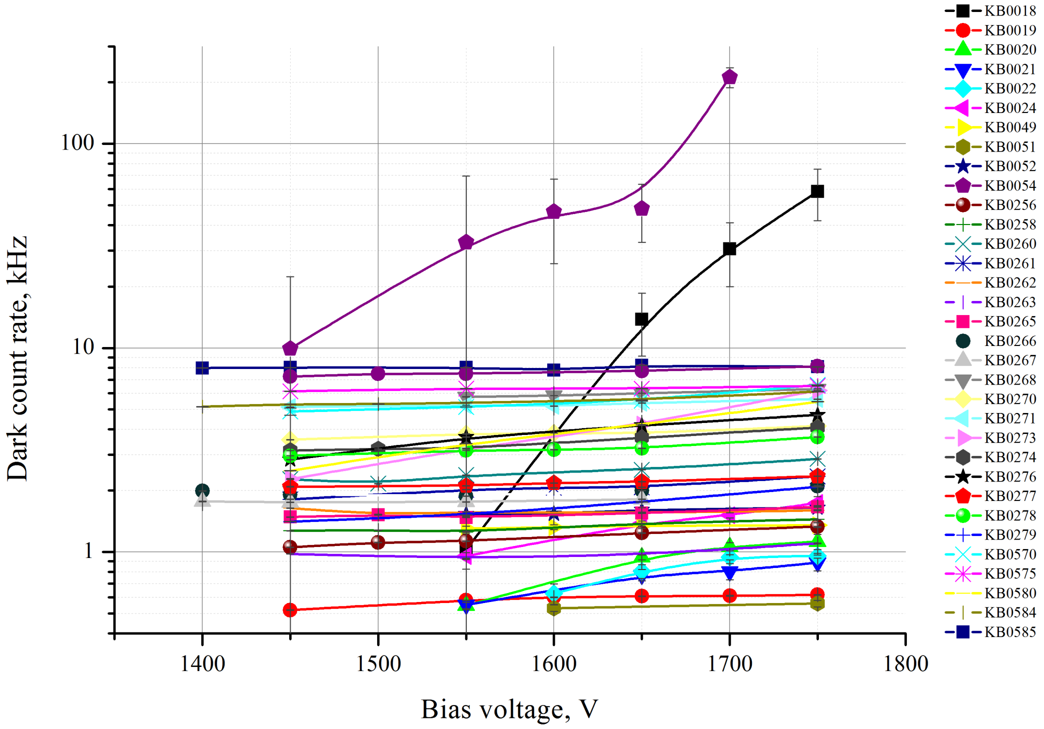

Fig.2. Room-temperature dependencies of the dark count rate on the cathode-to-anode bias voltage value for all PMTs tested.

As it could be seen from the plot, the PMTs' dark count rate values could vary from several hundred hertz to ten kilohertz for almost all the tubes. The exception is two noisy units with highly unstable rates lying in the range between 1 kHz and 200 kHz. One of these PMTs indexed KB0054 (#054) has been chosen for further study to test the assumption of possible light emission from its internal structure.

3.Checking the light-emission assumption

The experimental setup consists of two PMTs being stacked "face-to-face". In the upper position one of the noisy units (#054) was placed, while it was viewed by the PMT indexed KB0019 (#019) with the lowest measured dark count rate. During this test #019 PMT bias voltage was fixed to a constant value and #054 PMT voltage was varied between 1200 V and 1750 V with 50 V steps.

As one can see from fig.2, #054 PMT count rate is highly dependent on the value of its bias voltage. If some of #054 dark pulses are caused by photon emission of the PMT's internal structure, there should be a correlation between optically coupled #019 and #054 PMTs' count rates which could clearly be seen while #054 bias voltage is altered. At the same time, there shouldn't be any correlation of the PMT's count rate in a case of a light absorbing layer placed between the PMTs' windows.

The resultant dependencies of #019 PMT count rate on #054 PMT one while the latter PMT's bias voltage was altered are shown in fig.3 for two cases: measurements with a layer of robust optical insulation between the PMTs' windows (black square dots) and without it (red circle dots).

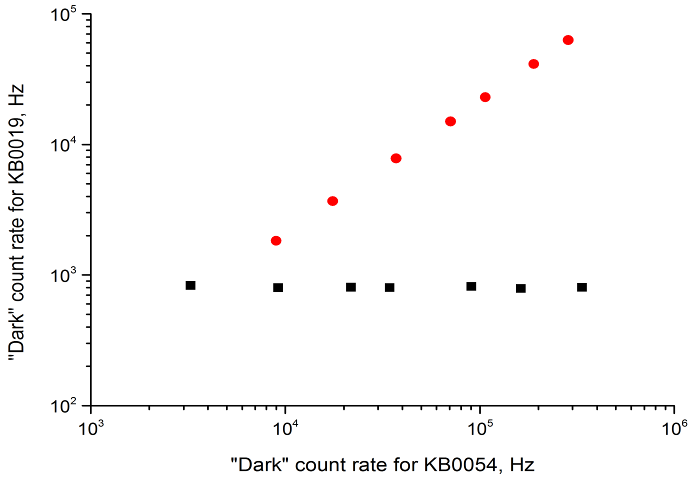

Fig.3. Dependence of the monitoring #019 PMT's dark count rate on the tested #054 PMT's with an optical contact (red circles) between the PMT windows and without it (black squares).

As one can see from fig.3, when the devices are optically coupled there is a strong correlation between the devices' count rates that is completely lost in case of introducing a layer of optical insulation between the PMT's windows.This fact suggests that major part of the #054 PMT dark counts arise from photon emission inside the PMT structure.

It is important to note, that the extra dark count pulses appear randomly and the overall dark pulses spectra both for the noisy and controlling PMT behave as typical single photoelectron spectra. So, this phenomenon could hardly be studied with the help of a coincidence method.

The measurements described above have been carried out also for the second "noisy" PMT indexed KB0018, according to the same experimental procedure and resulted in similar conclusion: photon emission evidence has also been observed for #018 PMT unit.

All the measurements described above have been carried out at room temperature. Similar measurements have been done in a thermal chamber at different temperatures down to -60 degrees Celsius, although no qualitative difference in the behavior of "noisy" PMTs at room and reduced temperatures has been observed.

Moreover, a sudden increase in the dark count rate of a PMT being cooled down were observed: #019 PMT's dark count rate increased from the value of 40 Hz at -40 degrees Celsius to 100 kHz at -45 degrees Celsius during the PMT cooldown with the cooling rate of 0.2 K/min. This phenomenon also appears to be caused by heavy light emission from the PMT internals. More precise description and results of this experiment could be found here [4].

4. On the nature of the light emission phenomenon

The possibility of light emission in such type of PMTs has already been asserted by Hamamatsu for liquid nitrogen temperatures (-196 C). As a possible explanation, the process of “electron charge up on ceramic stem” [5] was suggested. Commenting on the nature of the photon emission problem happening at higher temperatures, the manufacturer has shared with two other possible light sources in the PMT volume:

- the bremsstrahlung radiation which could occur in a PMT while the dynodes are bombarded by the signal avalanche electrons. This effect is usually negligible since such photons could be optically blocked by the internal ceramic insulation. However, in the PMTs of R11410-20 type the insulation is made of transparent quartz for radiopurity reasons;
- possible luminescent materials generation by combination of metal admixtures in the insulator’s supporting structures. For example, ruby generation from corundum and chromium admixture, which could easily be excited and then slowly emit infrared photons. Though this scenario looks unlikely, it could explain the random character of major part of the extra dark counts.

5. Cherenkov light detection in the volume of the PMT window

R11410-20 PMTs are equipped with 3.5 mm thick quartz window which is covered from the inside by bialkali photocathode with high sensitivity (maximum Q.E. is up to 40%) to blue and VUV light. At the same time, Cherenkov light yield is inversely proportional to the wavelength of the emitted photons. These two facts result in large amplitude signal’s appearance in case of a relativistic charged particle penetration through the volume of the R11410-20 PMT window.

To evaluate the performance of the Hamamatsu R11410-20 PMTs as standalone Cherenkov detectors, the atmospheric muons light yield in the volume of the PMT window has been studied for the PMT facing upwards and downwards. The PMTs head was surrounded by a scintillating “cup”, viewed by an additional XP2020 PMT selecting the events caused by real particles. The R11410-20 PMT in this experiment was optically isolated from external light.

Fig.4 shows the resulting atmospheric muons amplitude spectra measured by R11410-20 facing upwards (fig.4, left) and downwards (fig.4, right) for the events with nonzero amplitude on XP2020. As the result, atmospheric muons passing through the R11410-20 window facing upwards could result in generation of 85 ph.e. amplitude signals and a ~2.3 times smaller signals in case of the PMT facing downwards.

Such difference in the mean signal amplitude for the two PMT positions looks reasonable taking into account that the critical angle of total internal reflaction in quartz is approximately 43 degrees [6], while Cherenkov angle in quartz for relativistic particles is less then 47 degrees [7]. As an outcome, only a tiny fraction of muons travelling under zenith angles of 88-90 degrees would give totally reflacted Chernkov flashes, while flashes from major part of muons would partly be attenuated, since the outer surface of the PMT window was not covered with any reflactive material.

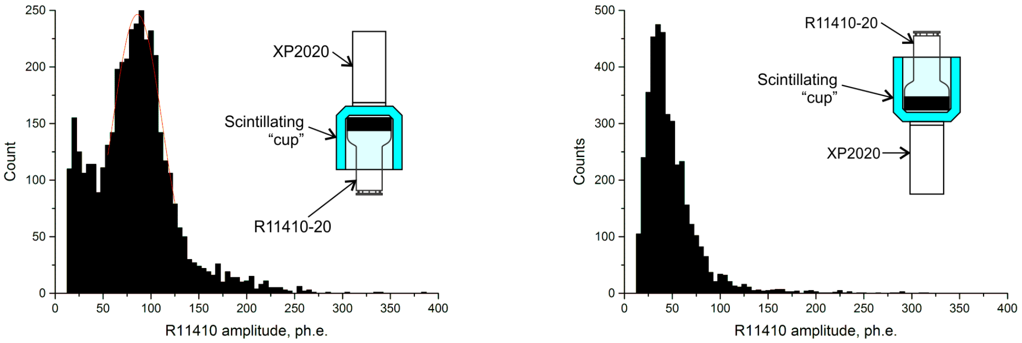

Fig.4. (Left) Amplitude spectrum of Cherenkov light signals generated by atmospheric muons passing through the Hamamatsu R11410-20 quartz window facing upwards; (right) the same spectrum, measured for the PMT facing downwards.

A Cherenkov light spectrum, generated by 511 keV gammas interaction in the PMT window's volume was also measured. However, the resulting signals amplitude is far below that of muons: only 1% of the particle hits yield in signals with amplitudes greater than 3 ph.e.

6. Summary

The Hamamatsu R11410-20 is a noteworthy type of PMTs with extraordinary good radiopurity characteristics and single photon detection capabilities. Generally, R11410-20 PMTs is a good choice for the use in a low-background double-phase emission detector, but the observed phenomenon of light emission in individual PMT units at different temperatures (which is of a great interest by itself) could become a certain obstacle for massive application of this type of PMT in low-background cryogenic detectors.

A large (up to 100 ph.e.) Cherenkov light yield in the PMT's quartz window should be taken into account when these PMTs are being used.

References

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