Development of photodetection system based on multipixel avalanche Geiger photodiodes with WLS for LXe low-background detectors.

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A multipixel avalanche Geiger photodiode with a p-terphenyl wavelength shifter in front of it has been tested in the liquid xenon to detect the 175-nm scintillation light. The global detection efficiency of the VUV photons of ~10% is obtained. A photodetection system with sensitivity to sub-keV ionization and few-mm coordinate accuracy is proposed for LXe low-background experiments.

1. Introduction

In the noble gas detectors of Dark Matter particles WIMPs of current generation, detection of scintillation and electroluminescent is performed by photomultipliers[1-4] (PMTs).

In the future Dark Matter experiments, with increasing sizes and masses of detectors and reduction of radioactive background of experimental setups down to the ultralow values of ≤ 1 event/100 kg/year a question will arise on replacement of the PMTs which are currently the most radioactive elements to the less radioactive photodetectors. Several experimental groups, which develop detectors for the Dark Matter experiments, are investigating new semiconductor devices – multipixel avalanche Geiger photodiodes MGPD (the widely used names are: SiPM, MPPC, MRS APD). These photodetectors operate in a single photon counting mode and may replace PMTs in the future because they are expected to contribute the negligibly low radioactivity (compared to the PMTs). The main obstacles now for replacement of the PMTs by them are the lack of sensitivity in the VUV region of luminescence of noble gases and the high intrinsic thermionic noise level (in compare with the noise level of the same area PMT). These photodetectors, apparently, could be used for detection of the electroluminescent signal from the very low-energy events. An elegant system comprised MPGP (SiPM) together with a wavelength shifter (WLS) (TPB; tetraphenyl-butadiene) and a thick gas electron multiplier (THGEM[5]) has been successfully tested[6] in liquid argon (LAr) for the ArDM Dark Matter experiment.

Our previous tests of these photodetectors in liquid xenon (LXe) without wavelength shifter have demonstrated the very low (less than 1%) photon detection efficiency (PDE) for the scintillation light with a wavelength[7] of 175 nm and hasn't confirmed the previous result of PDE ~ 5,5% obtained by the US group[8].

The aim of the current work is to demonstrate experimentally the possibility of the use of MPGP for detection of the LXe luminescence light together with a wavelength shifter in front of it and to estimate the global PDE of such a system.

2. Wavelength shifter

A p-terphenyl (1,4-diphenylbenzene) has been chosen as a wavelength shifter, as it has shown the high conversion efficiency[9] for the Xe emission light. Two different samples of the wavelength shifter has been tested. Since the p-terphenyl is known to be quite volatile it may seriously contaminate the gas system and the test chamber during its pumping our before filling with LXe. To avoid this, we protected the LXe from the p-terphenyl by two ways. In the first case, the vacuum deposited p-terphenyl layer was encapsulated between two windowed (sapphire) 1.33" CF flanges (see figure 1(a)). Sealing of the construction was performed in the Ar atmosphere to exclude presence of oxygen between the windows which absorbs the VUV light. In the second case, the p-terphenyl layer was coated by a 1-μm poly-para-xylylene film (see figure 1(b)). Poly-para-xylylene (Parylene N) was chosen to protect the p-terphenyl layer due to its well known properties such as very low permeability to gases, and the possibility to form a conformal optically transparent films practically free of pin-holes even for the thicknesses down to several tens of Å.

3. Experimental setup

A newly developed by CPTA LTD, Russia[10] "blue sensitive" MGPD (a vendor abbreviation is MRS APD; see more details about this device in[7]) was used for our experimental study. The size of the photodetector is 2 x 2 mm, and it contains 1584 cells. The photon detection efficiency (PDE) of this MGPD at the maximum wavelength of the p-terphenyl emission (~370 nm) is more than 15%. The details of the experimental setup are presented in figure 1. An alpha-source (^{241}Am) was used to produce a scintillation light (with a peak wavelength of ~ 175 nm). The MGPD was installed behind the wavelength shifter. A PMT Hamamatsu R7400-06 was used to detect the light reemitted by the p-terphenyl in backward direction (with respect to the direction of incident light), and thus, to provide a triggering signal. In both cases (figure 1a and b) the mechanical construction was kept the same: in the case (b) the windowed flange was replaced by the stainless steel flange having the same sizes but without optical window.

This assembly was installed in a test chamber (cryostat), filled with liquid xenon. Before filling, the xenon had undergone purification with a Mykrolis Megaline purifier.

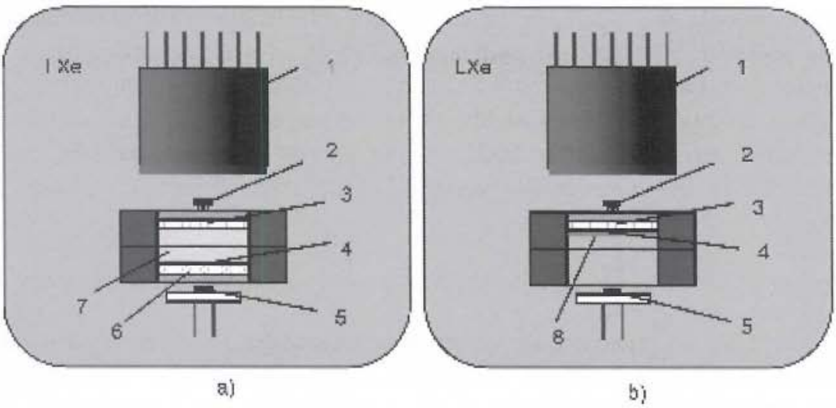

Figure 1. Scheme of measurements. a) p-terphenyl is sealed between two optical windows, b) p-terphenyl is coated by a poly-para-xylylene film. 1 – PMT Hamamatsu R7400-06, 2 – α-source ^{241}Am, 3 - optical window (sapphire), 4 – p-terphenyl, 5 – MRS APD, 6 – optical window, 7 – Ar gas between the window, 8 - poly-para-xylylene film.

Signals from the MGPD were amplified and, together with the PMT signals, arrived to the inputs of the LeCroy LT344 digital oscilloscope and were written in a computer for subsequent processing.

4. Data analysis and PDE calculation

Data analysis included event-by-event calculation of the areas of the recorded signals and plotting area distributions. The area distribution of the signals has a peak corresponded to the monoenergy of an alpha-particle. The real number of the fired cells was derived then by taking into account a correction based on a cross-talk probability obtained from the ratio of the 2-d and 1-st noise peaks. To ensure that the photodetector operated at the highest photo detection efficiency (PDE), the signals were recorded at different bias voltages. The voltage at which the number of the fired cells of the MGPD the alpha peak position reached a plateau was chosen as a working point.

The number of fired cells N_{cells} is related to the total number of photons emitted from the source N_0 as follows: $N_{cells} = f \cdot N_0 \cdot \frac{\Omega_1}{4\pi} \cdot \frac{\Omega_2}{4\pi} \cdot \eta \cdot \xi$, (1)

were f is a total attenuation coefficient of the light in the windows (including reflection from the surfaces), Ω_1 is an effective solid angle of the WLS surface with respect to the source, Ω_2 is an effective solid angle of the photodetector with respect to a wavelength shifter plane (averaged over its surface), η is an efficiency of transformation by WSL of the VUV light to the visible region, ξ is a photo detection efficiency of MGPD in the wave range of WLS emission; $N_0=E_\alpha/w$, were E_α= 5.486 MeV, is the energy of alpha particle, w = 16.3 ± 0.3 eV is a mean energy required[11] for creation of one VUV photon in LXe.

One may consider $\frac{\Omega_2}{4\pi} \cdot \eta \cdot \xi = PDE$ as a global photo detection efficiency of the whole WLS + photodetector system. It is obvious that the most efficient light collection takes place when the WLS is put immediately close to the photodetector plane in front of it. In this case Ω_2 equals 2π. To understand the real potential efficiency of the system and to compare the results of two measurements we have mathematically reduced our geometries to this ideal case when a photodetector is projected on a WLS plane and the projection of the MGPD on this plane spans an equivalent solid angle Ω_1^0 (the only part of the WLS which is within the projection area does work in this case, and $\Omega_2^0 = 1/2$):

$$\frac{\Omega_1}{4\pi} \cdot \frac{\Omega_2}{4\pi} = \mu \cdot \frac{\Omega_1^0}{4\pi} \cdot \frac{1}{2} \quad (2)$$

Finally the photo detection efficiency for the reduced case (PDE^0) will be obtained as:

$$PDE^0 = \frac{1}{2} \cdot \eta \cdot \xi = N_{cells} \cdot \frac{4\pi}{\mu \cdot f \cdot N_0 \cdot \Omega_1^0} \quad (3)$$

The results of PDE^0 calculation are shown in table 1.

Table 1. Parameters of the formula (3) and results of PDE^0 calculation for two series of measurements.

Series of measuremts	N_{cells}	μ	f	$\Omega_1^0/4\pi$	PDE^0,%
Figure 1a	24 ± 0.5	0.74	0.68	$1.35\cdot10^{-3}$	9.7 ± 1.2
Figure 1b	72 ± 1.5	0.17	0.75	$1.99\cdot10^{-2}$	8.4 ± 1.1

5. Discussion.

The result is very close to that (~10%) obtained for a blue sensitive PMT (QE ≈ 20%) with tetraphenylbutadiene (TPB) WLS coating[12] in LAr. Further increasing of the PDE^0 of the WLS + photodetector system is possible with the use of MGPD with the higher photo detection efficiency in the region of WLS emission.

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