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Characterization of the QUartz Photon Intensifying Detector (QUPID) for noble liquid detectors

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ABSTRACT

Dark matter and double beta decay experiments require extremely low radioactivity within the detector materials. For this purpose, the University of California, Los Angeles and Hamamatsu Photonics have developed the QUartz Photon Intensifying Detector (QUPID), an ultra-low background photodetector based on the Hybrid Avalanche Photo Diode (HAPD) and entirely made of ultraclean synthetic fused silica. In this work we present the basic concept of the QUPID and the testing measurements on QUPIDs from the first production line.

Screening of radioactivity at the Gator facility in the Laboratori Nazionali del Gran Sasso has shown that the QUPIDs safely fulfill the low radioactive contamination requirements for the next generation zero background experiments set by Monte Carlo simulations.

The quantum efficiency of the QUPID at room temperature is $>30\%$ at the xenon scintillation wavelength. At $-100\,^{\circ}$C, the QUPID shows a leakage current smaller than 1 nA and a global gain of 10^5. In these conditions, the photocathode and the anode show $>95\%$ linearity up to 1 μA for the cathode and 3 mA for the anode. The photocathode and collection efficiency are uniform to 80% over the entire surface. In parallel with single photon counting capabilities, the QUPIDs have a good timing response: 1.8 ± 0.1 ns rise time, 2.5 ± 0.2 ns fall time, 4.20 ± 0.05 ns (FWHM) pulse width, and 160 ± 30 ps (FWHM) transit time spread.

The QUPIDs have also been tested in a liquid xenon environment, and scintillation light from ^{57}Co and ^{210}Po radioactive sources was observed.

1. Introduction

There is overwhelming indirect evidence that dark matter (DM) accounts for $\sim25\%$ of the mass-energy of the universe. One of the most accredited theories predicts that Weakly Interacting Massive Particles (WIMPs) constitute the dark matter halos that permeate galaxies [1]. WIMPs are expected to undergo elastic collisions with noble liquid nuclei producing low energy deposits [2]. Some of the noble liquid experiments searching for WIMP interactions are XENON, ZEPLIN, LUX, DAMA/LXe and XMASS [3–8] employing liquid xenon, and WARP, DEAP/CLEAN and DARKSIDE, using liquid argon [9–11]. One promising approach for noble liquid experiments is the double phase Time Projection Chamber (TPC). Here, a WIMP deposits energy in the noble liquid creating a primary scintillation light (S1). The energy deposit also ionizes atoms, and the freed electrons are drifted to a gas phase where they undergo a secondary proportional scintillation (S2).

Natural xenon contains the isotope ^{136}Xe, which is predicted to undergo double beta decay, normally accompanied by the production of two neutrinos ($2\nu\beta\beta$). The detection of a peak in the summed energy of two electrons at 2.458 MeV would represent the unequivocal signature of neutrinoless double beta decay ($0\nu\beta\beta$), proving that the neutrino is its own antiparticle (a Majorana particle) [12,13]. Experiments using ^{136}Xe such as EXO, NEXT, and KamLAND-Zen [14–17] are underway.

Presently, the most sensitive dark matter detector using noble liquids has an effective target mass on the order of 100 kg with an expected background rate of $\sim10^{-2}$ events/kg/day/keV[2] in the region of interest [18]. Next generation detectors, with target mass

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[2] keVee and keVr are used to distinguish between electron recoil and nuclear recoil interactions. Throughout this paper, we will use keV in place of keVee.

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>1 ton, will require a background rate $<10^{-4}$ events/kg/day/keV to achieve the desired sensitivities. In order to decrease the background down to this quantity, several efforts are underway [19,20]. Of particular importance is the radioactive contamination coming from the employed photodetectors, as they are the experimental components closest to the target material. Moreover, in present experiments the majority of the background rate originates from the conventional photomultiplier tubes (PMTs).

A new photo detector, the QUartz Photon Intensifying Detector, or QUPID, has been designed as an ideal replacement for conventional PMTs[3] by the University of California, Los Angeles (UCLA) and Hamamatsu Photonics. In this work, we present the development and tests performed on a set of seven QUPIDS from an early production line. An explanation of the essential requirements that must be satisfied for dark matter and double beta decay detection, and the general QUPID concept are presented in Sections 2 and 3 respectively. In Section 4 we discuss the radioactive screening of the QUPID at the Gator screening facility at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, performed by the University of Zurich group.

In Section 5 we examine the cathode performances and those of the anode in Section 6. Section 7 is devoted to single photon counting and time response tests, while in Section 8 we show the operation of the QUPID in liquid xenon.[4] In Section 9 we present a summary of the main achievements, proving that the QUPIDS represent the most appropriate solution for the next generation of low background detectors.

2. Photodetector requirements

The photodetectors which will be employed in the next generation experiments must meet the following requirements in order to improve the performance both for reducing the background contamination and increasing sensitivity:

- *intrinsic radioactivity* significantly lower than the current generation PMTs;
- *Quantum efficiency* $>30\%$ to maximize the number of photoelectrons per deposited energy;
- high *gain* $>10^5$ so that single photoelectrons can be clearly detected above the noise;
- good *timing* performances with a pulse width <10 ns, to provide accurate time information;
- good *collection efficiency* and *uniformity* along the photodetector surface;
- a large dynamic range with superior *linearity*, for precise measurement of energy depositions in the region of interest: from a few keV for dark matter searches to several MeV for neutrinoless double beta decay.

In the following sections we describe in some detail the tests performed proving the capability for the QUPID to satisfy these requirements.

3. Concept

The QUPID is based on the Hybrid Avalanche Photodiode (HAPD). In HAPDs, photons hit the photocathode surface causing the emission of photoelectrons, which are accelerated onto an APD due to a high potential difference (several kV) applied between the photocathode and the APD. The kinetic energy of the electrons creates hundreds of electron–hole pairs within the APD. The electrons and holes are then separated and accelerated by the high bias voltage on the APD, and undergoing an avalanche effect [21–23]. On the left of Fig. 1, a drawing of the QUPID is presented, showing a simulation of the electric field equipotential lines and of the photoelectron trajectories from the photocathode onto the APD. Fig. 1 center shows the QUPID seen from the baseplate, and on the right from the hemispherical photocathode.

The QUPID is made of a cylindrical quartz tube with a hemispherical photocathode window, a baseplate, and an intermediate quartz ring. The quartz cylinder, ring, and baseplate are bonded together using indium (see Fig. 1 center and right). The outer diameter of the cylinder is 71 mm, with the hemispherical photocathode window having a radius of 37 mm. The photocathode has an effective diameter of 64 mm (for vertical incident photons). The inner part of the cylinder is coated with aluminum and the hemispherical cap is coated with a photocathode material. The baseplate on the opposite end supports a solid cylindrical quartz pillar with a 3 mm APD at the top. The APD (with 11 pF of capacitance) has been specifically developed and manufactured by Hamamatsu Photonics for use in the QUPIDS.

A negative high voltage, up to -6 kV, is applied to the photocathode through the indium sealing ring, while ground level is maintained on the baseplate and APD from the second indium ring. As in common HAPDs, the high potential difference creates an electric field which focuses the photoelectrons ejected from the photocathode onto the APD. The QUPID design has been optimized such that the photoelectron focusing is independent of the level of voltage applied to the photocathode.

4. Radioactivity

The radioactivity of the QUPIDS has been measured in the Gator screening facility, operated by the University of Zurich at LNGS. The facility consists of a high-purity, p-type coaxial germanium (HPGe) detector with a 2.2 kg sensitive mass, operated in an ultra-low background shield continuously flushed with boil-off nitrogen gas to suppress radon diffusion. With an integral background rate of 0.16 events/min in the 100–2700 keV region, Gator is one of the world's most sensitive Ge spectrometers [24]. In this work we present the results of the screening of two batches of five QUPIDS.

To determine the specific activities for the ^{238}U and ^{232}Th chains, as well as for ^{60}Co and ^{40}K, the most prominent γ-lines of the respective decays are analyzed using the efficiencies determined by a detailed Monte Carlo simulation of the detector, shield, and QUPID samples. The latest background run of Gator had been taken for a duration of two months prior to the QUPID screening. In the case in which no events were detected above the background, upper limits on the specific activities were calculated according to the method proposed in Ref. [25]. The radioactivities for each QUPID are <17.3 mBq/QUPID for ^{238}U, 0.3 ± 0.1 mBq/QUPID for ^{232}Th, 0.4 ± 0.2 mBq/QUPID for ^{40}K and <0.18 mBq/QUPID for ^{60}Co. These results[5] are reported in the first column of Table 1. The radioactivity levels of standard PMTs used in current dark matter detectors are available in Ref. [26].

[3] M. Suyama, A. Fukasawa, K. Arisaka, H. Wang, US Patent Pending, Application No. 20100102408.

[4] Although a modified version of the QUPID optimized for operating in liquid argon is in development, in this work we will concentrate on the QUPID for liquid xenon.

[5] Although ^{226}Ra belongs to the ^{238}U chain with a half-life of 1600 years, it bonds easily with other electronegative elements and can be absorbed in strong thermal and/or chemical processes, generating a break in the equilibrium of the chain. For this reason, the two parts of the chain (i.e. ^{238}U and ^{226}Ra) have been treated separately in the analysis.