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Performance and behaviour of photomultiplier tubes at cryogenic temperature

M. Prata, M.C. Prata, G.L. Raselli, M. Rossella*, C. Vignoli

Istituto Nazionale di Fisica Nucleare (INFN) Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy

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Abstract

Noble-gas liquids, such as xenon and argon, have been recently proposed as scintillators in some experiments dedicated to neutrino physics and dark matter research. These experiments need to use large-area high-sensitivity light detectors directly immersed in the liquid phase and operating at cryogenic temperature.

We carried out a detailed investigation on the use of conventional and dedicated photomultiplier tubes in collaboration with two manufacturers: Electron Tubes Ltd. and Hamamatsu Photonics K.K. Once verified the capability to withstand thermal shocks from room to cryogenic temperature, we studied the device characteristics in different temperature conditions.

Good quantum efficiencies can be achieved with multialkali photocathodes or bialkali photocathodes on platinum under-coatings. Gain losses and an increase of the dark count rate at low temperature are also observed.

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Keywords: Photomultiplier tubes; Scintillation detectors; Cryogenics

1. Introduction

Noble-gas liquids, such as xenon and argon, have been recently proposed as scintillators in some experiments dedicated to neutrino physics and dark matter research. These experiments require large-area, high-sensitivity light detectors directly immersed in the liquid phase, or placed in gas above the liquid, thus operating at cryogenic temperature.

We carried out a detailed investigation on the use of either conventional or dedicated photomultiplier tubes (PMTs) in collaboration with two manufacturers: Electron Tubes Ltd. and Hamamatsu Photonics K.K. Different photomultiplier samples were tested and characterized at the liquid nitrogen temperature (77 K). Once verified the capability of the devices to withstand thermal shocks from room to cryogenic temperature, we studied the behaviour of the following PMT parameters in different temperature conditions: quantum efficiency of different photocathode types as a function of the light intensity and wavelength (spectral response), dark count rate, multiplier-chain response and linearity.

Measurements were carried out using commercial bialkali and multialkali PMT models, in addition to two custom-made units, specifically manufactured to operate at cryogenic temperature: (1) ETL 9357FLA with 8 in. $K_2CsSb + Pt$ cathode and 12 LF CsSb dynodes; (2) Hamamatsu R5912-02MOD with 8 in. $K_2CsSb + Pt$ cathode and 14 LF CsSb dynodes.

2. The experimental set-up

The comparison of the PMT properties between room and cryogenic temperature was carried out using a stainless-steel dewar designed to house the device under test (see Fig. 1). The dewar was filled with liquid nitrogen for the measurements at 77 K. Light from an external pulsed source (a laser diode or a LED) was brought to the photocathode by means of an optical fibre.

*Corresponding author. Tel.: +39 382 987 780; fax: +39 382 423241.
E-mail address: massimo.rossella@pv.infn.it (M. Rossella).

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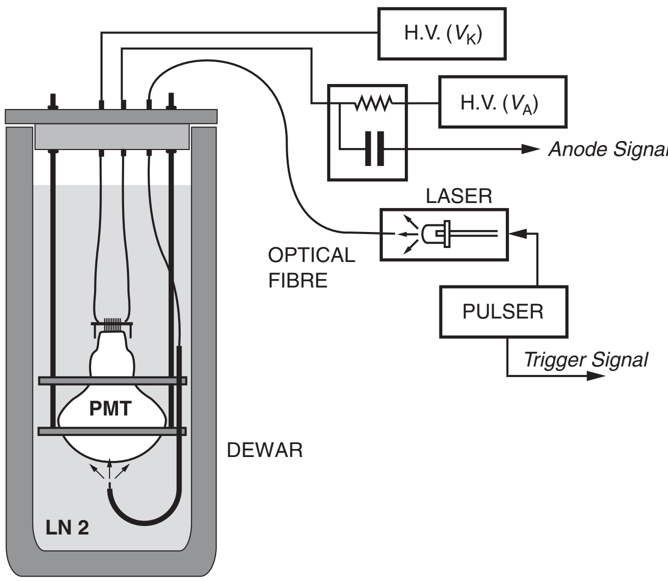

Fig. 1. Experimental set-up for the PMT characterization at cryogenic temperature.

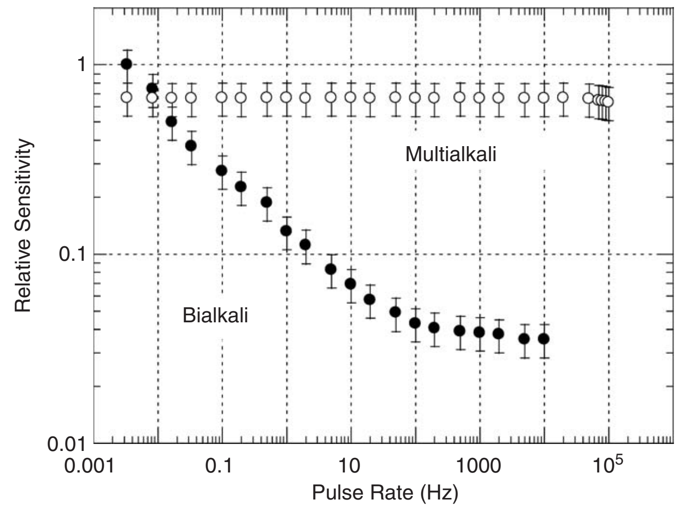

Fig. 2. Relative sensitivity vs. light pulse rate for multialkali and bialkali photocathodes using a 470 nm wavelength light source.

3. Photocathode resistivity

Because of the semiconductor nature of photosensitive material, bialkali photocathode exhibits a rapid increase of resistivity at low temperature causing poor collection efficiencies [1–4]. The relative sensitivity of different photocathode types, defined as the ratio between the cathode signals at $T = 77$ and 300 K, as a function of the light pulse rate is presented in Fig. 2. The measurements were carried out using a LED with 470 nm central emission wavelength and with pulse duration and intensity in order to get 1 pC per pulse from the cathode.

The conventional bialkali cathodes show a sensitivity reduction even at pulse rate lower than 1 Hz making this device useless at cryogenic temperature.

The resistivity increase of bialkali photocathodes can be avoided at manufacture by the use of nearly transparent platinum under-coatings. The ETL 9357FLA and Hamamatsu R5912-02MOD photomultipliers adopt standard biakali K_2CsSb cathodes deposited on Pt under-layers. These PMTs show a sensitivity reduction of about 20% from room to cryogenic temperature, independent from light pulse rate.

4. Photocathode spectral response

It is well-known that the spectral response of a photocathode depends on the operating temperature. We investigated the behaviour at cryogenic temperature of the $K_2CsSb + Pt$ and the multialkali photocathode as a function of the light wavelength.

The results, presented in Fig. 3, show that the bialkali + Pt cathode is characterized by small reduction of its sensitivity for wavelength values from 400 to 500 nm and by a continuous decrease beyond this range; the multialkali sensitivity shows an increase over 600 nm. Tests carried out with different light intensities (10 fC–10 pC per pulse) and repetition rates (1 Hz–100 kHz) brought to the same results.

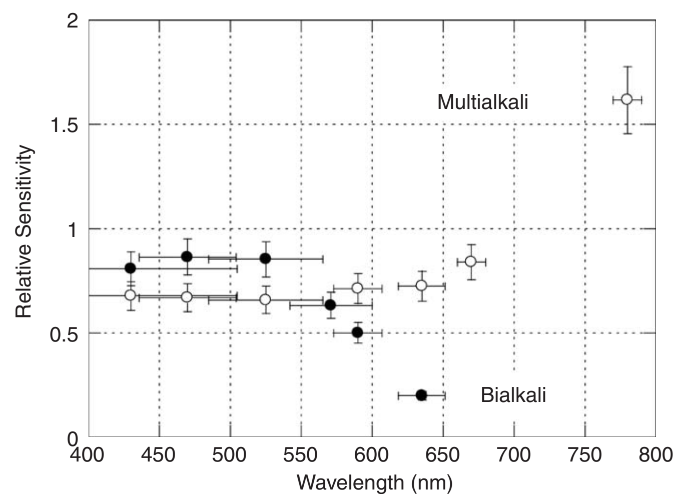

Fig. 3. Relative sensitivity of $K_2CsSb + Pt$ and multialkali photocathodes vs. light wavelength. The horizontal bars represent the wavelength spreads of the light sources.

5. Dark counts and spectrum

The output pulses coming from a PMT under test, operating in complete darkness condition, were discriminated and counted during repetitive cycles in which the discrimination threshold was adjusted in a two photoelectrons (phe) wide-range.

The resulting dark count rate spectra for ETL and Hamamatsu PMTs as a function of the discrimination