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Operating characteristics of photomultipliers at low temperature

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The operating characteristics of photomultipliers with multialkali and bialkali photocathodes at low temperatures have been investigated. The photomultipliers were cooled down with liquid nitrogen and exposed to light led by an optical fiber. A blue LED was chosen as light source to simulate the spectrum where most scintillators emit. The bialkali photomultipliers, which are most popular nowadays, showed a rapid decrease in the output response below −110°C and no response around −130°C. Multialkali photomultipliers could be operated normally with small decrease even at −190°C.

1. Introduction

Liquid noble gases such as liquid argon or liquid xenon are known as excellent scintillators. The scintillation light is usually detected by a photomultiplier. But the wavelength of the light from a liquid noble gas is too short to be observed by a photomultiplier. Therefore, the scintillation light should be converted to longer wavelengths by a wavelength shifter such as sodium salicylate. In order to collect efficiently the light one has to install the photomultipliers near the cold place or even in the liquid.

The photomultiplier was developed by Zworykin et al. in 1936 [1]. In the first stage Ag–O–Cs or Cs_2Sb were used as photo-emission material, but their quantum efficiency was very low [2]. In 1955 Sommer discovered the multialkali photocathode based on Na_2KSb:Cs [3]. It had a peak quantum efficiency of more than 30% in the blue light region. Some ten years later the bialkali photocathode was also developed by Sommer [2]. Since the bialkali photocathode has a very low dark current emission and a better sensitivity to the most scintillators, nowadays bialkali photomultipliers are most popular in particle physics. But ordinary bialkali photomultipliers might not be usable at low temperatures, because of the very high electrical resistivity. Therefore, we checked the operating characteristics of bialkali photomultipliers from room temperature to liquid nitrogen temperature, comparing them with other kinds of photocathodes. The temperature dependence of the spectral sensitivity in Cs_3Sb and Na_2KSb:Cs photomultipliers has been measured by Murray and Manning [4]. They observed that the response of commercial photomultipliers fell abruptly and disappeared at low temperature. Photomultipliers modified by backing the photocathode with a metallic layers eliminated the resistivity effect at low temperatures and responded to the light of wavelength less than 500 nm. But it is conjectured that their quantum efficiency was lowered with the metallic backing. Budde and Kelly reported that the RCA 6217 with a Ag–Bi–O–Cs photocathode showed a quite different behavior from other types at low temperatures [5]. Even if the temperature in the vicinity of the photomultiplier was kept stable for 16 h, the response still continued to decrease and could not be plotted as a function of temperature.

2. Experimental apparatus and procedure

All the photomultipliers checked in this investigation were 2-in. tubes with borosilicate glass window and supplied from Hamamatsu Photonics Co. Ltd.. They were R329 and R464 with bialkali photocathode, 1221 and R649 with multialkali and 7696 with Cs_3Sb. Photomultipliers R329 and R1221 have the same structure except for different photocathode material. The same holds for R464 and R649. The cross sectional view of the experimental setup is shown in fig. 1. Hermetically sealed feed-throughs for three thermocouples and the penetration of an optical fiber are mounted on the upper flange of a test chamber. The pressure in the chamber is monitored by a Burdon-type gauge and a piezoelectricity pressure gauge and checked with a safety relief valve of 10 psiG. After the chamber is roughly evacuated by a oil rotary pump, nitrogen gas is filled to about 1.5 kg/cm^2 through a

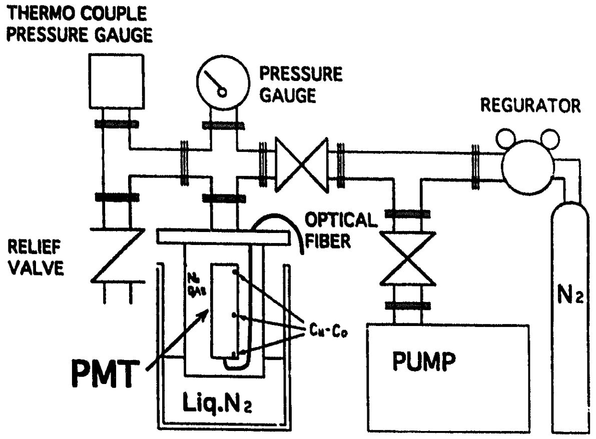

Fig. 1. The experimental setup.

pipe on the top flange. Nitrogen gas prevents the high voltage of the photomultiplier from sparking and makes cooling by liquid nitrogen easy. The chamber is hanging, and an open dewar filled with liquid nitrogen is placed below the chamber. The chamber temperature is controlled by the quantity of liquid nitrogen. The temperature is monitored by three copper– constantan thermocouple on three positions of the photomultiplier, one is on the upper part (anode), one is on the middle and the another is on the lower part (photocathode).

A silicon carbide blue LED, type P-884-1 supplied from Sanyo Electric Co. Ltd. was chosen as a light source. The peak wavelength is 470 nm, and the width of the spectrum is 70 nm FWHM. The light yield can be adjusted by applying a current according to the V–I characteristics of the LED. Since the above mentioned LED works with about 20 mA in the region of 3 to 4 V, we operate it by the output pulse from a NIM to TTL level adapter circuit. The light is led to the photomultiplier by an optical fiber with a diameter of 1 mm and illuminates a photocathode area of about 6 mm in diameter. The block diagram of data-taking system is shown in fig. 2. The output pulse from a clock generator is divided to two pulses. One generates a 3 μs TTL pulse applyed to the LED. The pulse height is arranged to 3.0 and 3.6 V by a drive resister. The other pulse is changed to a 4 μs pulse and fed into a gate input of a pulse height analyzer (PHA). The output signal of the photomultiplier is led to a preamp input of the PHA, Tracer Northern TN7200. In this measurement, the PHA works as charge sensitive ADC and sends the data to a personal computer (NEC PC9801) for storage. Practically, the luminous intensity at the photocathode is controlled by the applied voltage to the LED and the repetition rate of the pulses, The luminous intensity per pulse is about 2×10^{-11} lm and 8×10^{-11} lm for an applied voltage of 3.0 and 3.6 V, respectively. These values correspond almost to a light yield from a NaI(Tl) scintillator exposed to an Am^{241} α-source (about 1.6×10^{-11} lm/count).

3. Results and discussion

Typical distributions of the output signal are shown in fig. 3. The output from R329 (bialkali) decreases to about 1/4 at −110°C and the resolution also reduces to 1/4 as compared with those at 0°C. On the other hand the output from R1221 (multialkali) shows a small decrease and about the same resolution even at

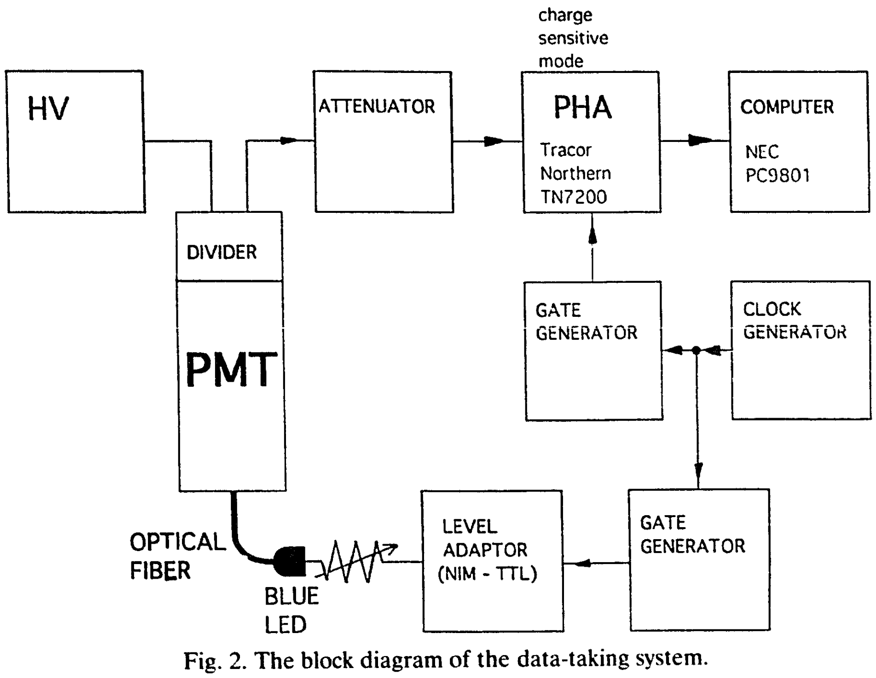

Fig. 2. The block diagram of the data-taking system.

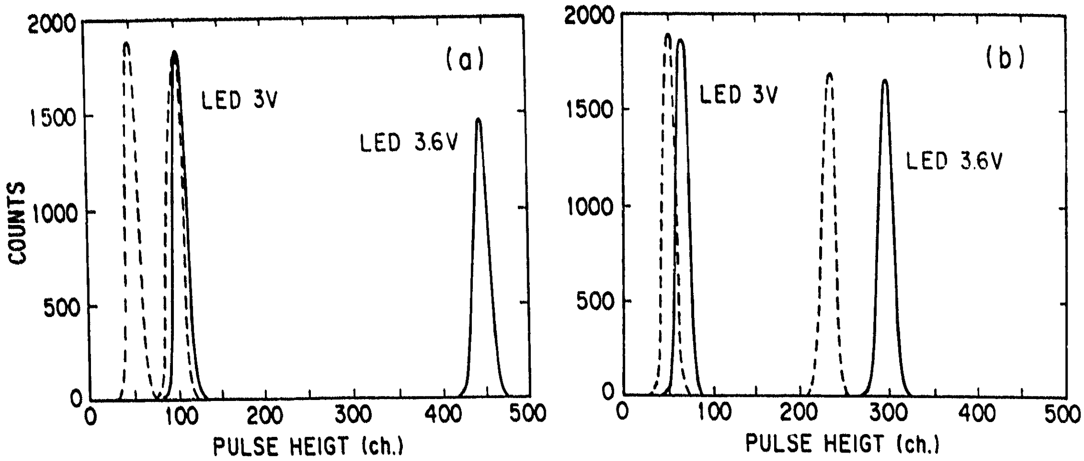

Fig. 3. Typical distributions of the output signal. (a) Signal from R239 (bialkali) at 0°C (solid line) and −110°C (dotted line). (b) Signal from R1221 (multialkali) at 0°C (solid line) and −180°C (dotted line). The LED is operated at 3 and 3.6 V.

−180°C. The temperature dependence of the output signal is shown in fig. 4 together with results for the other photomultipliers. The LED is operated by the pulse of 3.6 V at 1 kHz, and the applied high tensions to R329, R464, R1221, R649 and 7696 are 1600, 700, 1800, 700 and 900 V, respectively. It is confirmed that the output of the Cs_3Sb photomultiplier falls abruptly like Murray and Manning have reported [4]. The bialkali photomultiplier has a critical temperature at which a rapid decrease is observed and the output signal disappears completely at lower temperatures. The critical temperature depends on the high tension and the luminous intensity as shown in figs. 5 and 6. In contrast to these findings fig. 7 illustrates that the output of the multialkali photomultiplier does not depend on the luminous intensity.

The temperature dependence of the sheet resistivity of bialkali and multialkali material is quite different. In particular, at a temperature less than −50°C the ratio between them becomes larger than 1 million as shown in fig. 8 [1,6]. Although the photocathode material must be a semiconductor, the resistivity of the Cs_3Sb and of bialkali photocathodes increases to high values of 10^{11} Ω/cm^2 below −100°C. When bialkali or Sb–Cs photocathodes are cooled below the critical temperature, the charge cannot be supplied to the photocathode after the emission of photoelectrons. Since the capacitance of photocathodes is known to be of the order of 0.1 pF/cm^2, the time constant of recovery and the voltage drop can be estimated to be 0.01 s and

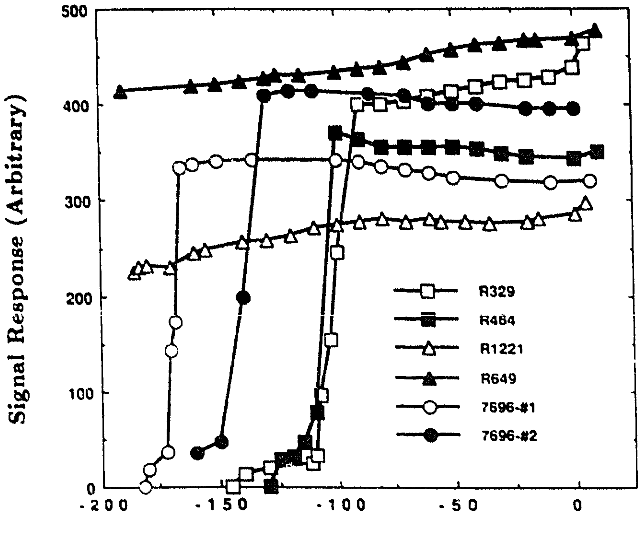

Fig. 4. The temperature dependence of the output pulse for different types of photomultipliers.

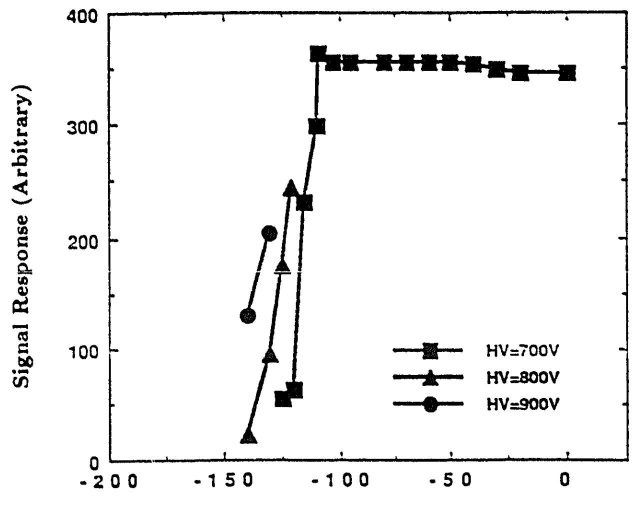

Fig. 5. The high tension dependence of the bialkali R464 photomultiplier.

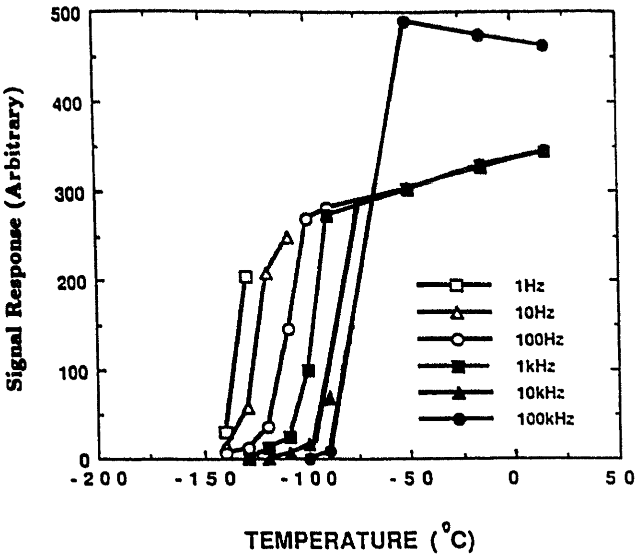

Fig. 6. The signal response versus temperature for a R329 photomultiplier. The luminous intensity dependence is seen.

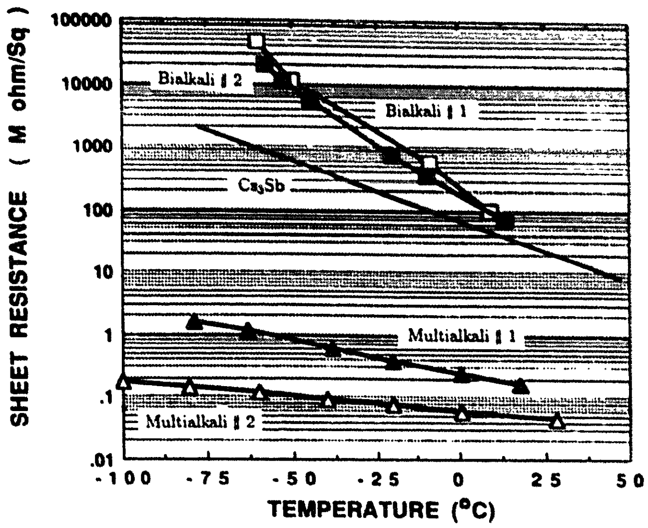

Fig. 8. The sheet resistance of different photocathodes as function of temperature.

about 0.1 V for single exposure with our luminous intensity. This estimation can explain the luminous intensity dependence of fig. 6 extrapolating the curves of the Cs_3Sb and bialkali photocathodes.

Multialkali photomultipliers work from room temperature to liquid nitrogen temperatures, while bialkali and Cs_3Sb photomultipliers can not be operated normally at temperatures less than about $-100°C$. This different behaviour is caused by the difference of the resistivity of their photocathodes. But we can not understand presently the rapid decrease in the signal response of the bialkali photomultiplier.

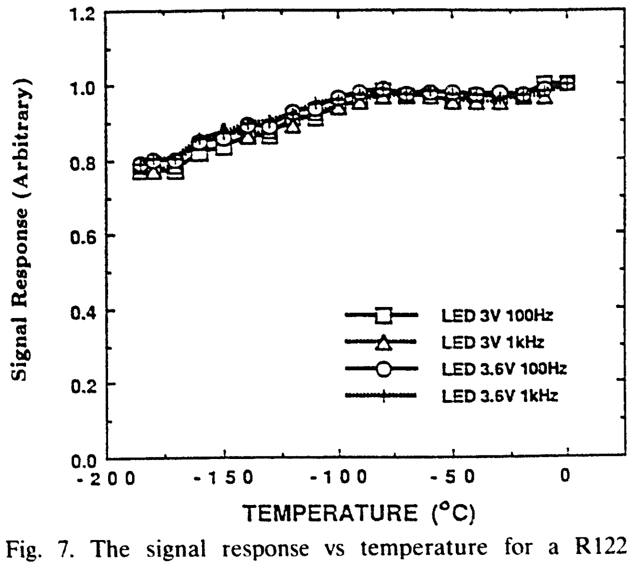

Fig. 7. The signal response vs temperature for a R1221 photomultiplier.

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