Precise Analysis of the Metal Package Photomultiplier Spectra taken in Single Photoelectron Mode.

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A deconvolution method based on a sophisticated photomultiplier response function was used to analyse the compact metal package photomultiplier spectra taken in single photoelectron mode. The spectra taken by Hamamatsu R5600 and R5900 photomultipliers have been analysed. The detailed analysis shows that the method appropriately describes the process of charge multiplication in these photomultipliers in wide range of working regimes and the deconvoluted parameters are establish with about 1% accuracy.The method can be used for a detailed photomultiplier noise analysis and for calibration purposes.

1 Introduction

In many photomultiplier (PMT) applications the faint input light signals (a few photons) should be detected (different types of scintillation and Cherenkov detectors). Except of that, analysis of the PMT pulse height spectra from the faint light sources, usually called the single photoelectron spectra, is of a great importance because can reveal many features and find relevant parameters of PMTs. The single photoelectron analysis ([1–3]) can be used for:

– calibration and monitoring of the PMT-based spectrometric channels.
– finding of the PMT noise characteristics, especially so called excess factor (see below).

In addition, study of the PMT intrinsic parameters is inevitable for a correct estimate of the basic characteristics of PMT based detectors like calorimeters (the energy to signal conversion factor, etc). In our previous work [4] we presented a method of the single photoelectron analysis based on the response functions reflecting peculiarities of the metal channel PMTs [6] and applied it on analysis of the experimental spectra taken by a Hamamatsu R5600 PMT. It was shown that the method satisfactorily describes the experimental spectra and enables to see such subtle effect as the photoproduction on first dynode.

In the present work a modification of the response function has been done with a goal to apply the method for the PMT low gain regimes. The method has been then applied for analysis of the excess factor of a Hamamatsu R5900 PMT.

2 Photomultiplier Response Function

A key point of single photoelectron analysis is a correct PMT response function which must take into account all substantial features of the photoconversion and charge multiplication processes. The PMT response function presented in this paper was built up under the same principles as the one in our previous work [4], but some modifications have been done to enable employment of the method for the low gain ($\sim 10^5$) applications. As before we assume that:

(i) Only the low charge background processes connected to the leakage current, etc. [1] are assumed for this type of PMT. The processes will lead to the finite width of pedestal and may be represented by a Gaussian function.
(ii) Incident light can create photoelectrons from the PMT photocathode, as well as from the first dynode with the occurrence probability for n photoelectrons created from the photocathode and k photoelectrons created from the first dynode given by Poison distribution.
(iii) Charge multiplication process in dynode system is governed by Poisson law.

The details concerning of the included physical processes can be found elsewhere [1,4].

The output charge spectrum is a sum of all possible convolutions corresponding to the charge multiplication processes initiated by n photoelectrons from photocathode and k ones from first dynode:

$$S_{real}(x) = \sum_{n,k=0}^{\infty} \frac{\mu_{pc}^{n}\, e^{-\mu_{pc}}}{n!} \cdot \frac{\mu_1^k\, e^{-\mu_1}}{k!} \cdot \int dx'\, S_n^{(1)}(x') \cdot S_k^{(2)}(x - x') \tag{1}$$

where μ_{pc} is the number of photoelectrons created on the photocathode and captured by the PMT dynode system, μ_1 is the number of photoelectrons created on the first dynode and captured by the following part of the dynode system and $S_n^{(1)}(x)$ ($S_k^{(2)}(x)$) is the PMT output charge when multiplication process is initiated by n photoelectrons from photocathode (k photoelectrons from first dynode).

The Poisson factors in (1), standing before the convolution of the responses $S_n^{(1)}$ and $S_k^{(2)}$, express the probability that the charge multiplication process was initiated by n photoelectrons from photocathode and k ones from first dynode. A modification of the previously presented response function was evoked by a need to employ the metal package PMTs at low gains [7]. At low gains the charge output distribution is asymmetric if the multiplication process is initiated by three or less photoelectrons. This fact is supported by simulation (see part3). Due to the above mentioned we have modified the previous PMT response function in such a way that the Gaussian approximation is used for the charge distribution at PMT output initiated by 4 or more photoelectrons and a special expansion is used in case for 3 or less photoelectrons. In the low photoelectron case the response is expressed as a sum of the responses corresponding to different numbers of electrons collected by the second dynode and weighted by the corresponding Poisson factors. Practically, the boundary for the low photoelectron case is for the present response function increased to 3 in compare with the previous one where this boundary was 2. Using this one can write:

$$S_n^{(1)}(x) = \begin{cases} \sum_{m=0}^{\infty} \frac{K_1^m \cdot e^{-K_1}}{m!} \cdot S_m^{(2)}(x) & n=1 \\ \\ \sum_{m=0}^{\infty} K_1^m e^{-2K_1} \cdot S_m^{(2)}(x) \cdot \sum_{l=0}^{n} \frac{1}{(m-l)!l!} & n=2 \\ \\ \sum_{m=0}^{\infty} K_1^m e^{-3K_1} \cdot S_m^{(2)}(x) \cdot \sum_{l=0}^{m} \frac{1}{l!} \sum_{k=0}^{m-l} \frac{1}{k!(m-l-k)!l!} & n=3 \\ \\ G\left(x,\, Q_0 + nQ_1,\, \sigma_0^2 + n\sigma_1^2\right) & n=0,\, n \geq 4 \end{cases} \tag{2}$$

where, Q_0, σ_0 are the pedestal and its width; Q_1, σ_1 are the multiplication process parameters gain, one photoelectron response standard deviation; K_1 is the secondary emission coefficient of the first dynode; $S_m^{(2)}(x)$ is the PMT response for the multiplication process started by an electron from the first dynode; $G\left(x, Q, \sigma^2\right)$ is a Gaussian distribution with the mean value of Q and dispersion σ^2: μ_{pc}- from the photocathode and μ_1- from the first dynode.

For the response when photoelectrons are created on first dynode, an expression analogous to (2) can be written. However, in this case (like before [4]) the expansion through Poisson factors is done only if the charge multiplication is initiated by one electron from the first dynode.

2.1 Limit Spectrum

For many applications it is important to consider the limit of the real spectrum (1) for high intensity light sources ($\mu_{pc} \to \infty$). As was shown in our previous works [2,4] at large values of μ_{pc} the Poisson distribution in (1) becomes Gaussian and the PMT response function goes to a limit spectrum:

$$S_{real}(x) \xrightarrow{\mu_{pc} \to \infty} S_\infty(x) = \frac{1}{\sqrt{2\pi}\sigma_\infty} \exp\left(\frac{(x - Q_0 - Q_\infty)^2}{2\sigma_\infty^2}\right) \tag{3}$$

where

$$Q_\infty = \mu_{pc} Q_1 + \mu_1 Q_2 = \mu_{pc} Q_1 \left(1 + \frac{\varepsilon}{K_1}\right) \tag{4}$$

$$\sigma_\infty = \sqrt{\sigma_0^2 + \mu_{pc}\left(\sigma_1^2 + Q_1^2\right) + \mu_1\left(\sigma_2^2 + Q_2^2\right)} \xrightarrow{\epsilon < 0.1} \sqrt{\mu_{pc}\left(\sigma_1^2 + Q_1^2\right)} \tag{5}$$

where $\epsilon = \mu_1 / \mu_{pc}$ and K_1 is the secondary emission coefficient on first dynode.

From (4) and (5) a relation between the limit spectrum parameters (Q_∞, σ_∞) and the mean number of photoelectrons (μ_{pc}, μ_1) can be found:

$$\mu_{pc} = f_{pmt} \cdot \frac{Q_\infty^2}{\sigma_\infty^2} \tag{6}$$

$$f_{pmt} = \frac{\sigma_1^2 + \epsilon\sigma_2^2 + Q_1^2\left(1+\frac{\epsilon}{K_1^2}\right)}{Q_1^2\left(1+\frac{\epsilon}{K_1}\right)^2} \quad \longrightarrow \quad 1 + \frac{\sigma_1^2}{Q_1^2} \tag{7}$$

The last relation is justified if the effect on the first dynode is small ($\epsilon < 0.1$). The factor f_{pmt} (usually called the excess factor) depends on the single photoelectron parameters of the PMT in question, and its value is different from one. In the excess factor is coded a quality of PMT. The second term in (7) is the ratio of the fluctuations caused by dynode system to those caused by photocathode. It is desirable to have the contribution of dynode system to PMT output charge fluctuations as low as possible. In an ideal case, when the charge multiplication process is supposed to obey Poisson law, the dynode system charge fluctuations can be determined theoretically. In this case for the variance σ_1^2 [4,9] we have:

$$\sigma_1^2 = Q_1^2\left(\frac{1}{k_1} + \frac{1}{k_1k_2} \ldots + \frac{1}{k_1 \cdots k_N}\right) \tag{8}$$

where k_i are the dynode secondary emission coefficients. These coefficients are determined by interdynode voltages [10] and can be inferred from the measured gain dependence on voltage [4].

It should be stressed the relations like (8) are valid only for an ideal case. In a real case the inhomogeneities of various kinds (like the dynode surface inhomogeneity, collection inefficiency, etc.) will make the value of standard deviation bigger than in the ideal case. In such a way, comparing the theoretical prediction for the ideal case (8) with the experimental one, determined by the single photoelectron analysis, one can make a conclusion about the presence of inhomogeneities in the charge multiplication process.

3 The Results of Analysis

To verify the response function we took and analysed a series of the single photoelectron spectra under different conditions. These spectra were analysed by means of the response function (1), for the eight dynode R5600 and R5900 Hamamatsu photomultipliers. The results of the tests of the new PMT response function as well as the results on the excess factor analysis are summarised bellow.

3.1 The Experimental Setup

Our analytical method based on the deconvolution of the LED spectra using the response function (1) was tested on the experimental data. The block diagram of the experimental setup is shown in Fig. 1. The fast AlGaAs LED HLMP8100 (”Hewlett Packard”) was used as a pulsed light source. The LED was driven by a pulse generator (GEN) with a short pulse width ($\approx 5\ ns$). An optical fiber was used to transmit light from the LED to the PMT. The photon flux incident on the photocathode was tuned by changing the supply voltage to the LED. The analog signal from the PMT was amplified by a preamplifier and measured by an ADC (LeCroy 2249A). The width of the gate signal was 120 ns and the generator sampling frequency was *1 kHz*. The output information from the ADC was read by means of a PC computer.

3.2 Comparison of the experimental spectra with the simulation.

For better understanding of the observed spectra and results of their analysis we compared the spectra with those obtain by simulation. Details of the simulation code were published elsewhere [8]. The simulation code was tested and the simulated spectra were compared with the experimental ones for different PMT regimes (mainly for gains $> 10^5$) and good agreement between the simulation and experiment was found ([4],[8]). Now we simulated an 8-staged PMT assuming the charge multiplication process is an ideal one, i.e. production of secondaries obeys Poisson law, no inhomogeneities are present, photoelectrons are created only on photocathode and collection efficiency of dynode system is 100%. We carried out the simulation for the gain 10^5 with the aim to find out how the form of PMT response depends on number of photoelectrons initiating it. The results are presented in Fig. 2, where the charge distributions initiated by $n = 1, 2, 3$ and 4 photoelectrons are shown. We can conclude that for the gains bellow 10^5 the "idealised" PMT response exhibits a noticeable asymmetry also in the case of 3 photoelectrons and symmetric (Gaussian) approximation of charge distribution components is appropriate only for 4 or more photoelectrons. One can expect that inhomogeneities (in a real case) will not change this fact dramatically, i.e. our choice to expand the PMT response, in cases when it is initiated by 3 or less photoelectrons, is justified. The low photoelectron cases is important for correct description of single photoelectron spectrum in the region between pedestal and one photoelectron maximum. In the simulation we assumed an 8 dynode stages PMT with the divider ratio $1:1:....1:1$ and the gain 10^5.

3.3 Analysis of the experimental spectra

The new PMT response function has been used for analysis of the spectra taken by the Hamamatsu R5600 and R5900 PMTs. An examples of the single photoelectron spectra for the R5600 phototube taken at the voltages of 700 V and 850 V are shown in Fig. 3. The spectra taken by the R5900/9D16C2 phototube at different voltages (700 V and 900 V) are shown in Fig.4. In all cases a good description of the experimental spectra by the suggested response function can be stated. In the R5600 case a significant first dynode effect is seen and properly treated by the presented method.

We applied the suggested response function on study of the R5900/9D16C02 PMT for the need of ATLAS/TILECAL collaboration. In Figs.5a is shown the dependence of the PMT gain (parameter Q_1, see part 2) on voltage. The dependence of the excess factor f_{PMT}, defined by (7), on voltage is shown in Fig.5b. It is interesting to compare the experimentally obtained values of f_{PMT} with the theoretical ones calculated using (8), where an ideal charge multiplication process is assumed. From the comparison in Tab. 1 we see that the experimental values of f_{PMT} are not far from those of the ideal process. The results of the time stability tests of the method are shown in Fig.6 where dependence of gain and excess factor are depicted for the spectra taken during an 80 hours interval. We have also investigated the systematics of the method taking the spectra at 712 V (nominal voltage) with different light source intensity ranging from 0.8 to 6.5 photoelectrons. The results are presented in Fig. 7 where the gains and noise factors are shown as a function of input light signal. From the figures we see that in the whole range the method is stable in frame of 2%. If we restrict the light input signal to the region from 1.5 to 5 photoelectrons the f_{PMT} values differ each other in less then 1%.

Table 1: Dependence of the excess factor on voltage (U) found experimentally by the single photoelectron analysis (f^{ex}_{PMT}) and calculated for the ideal process (f^{th}_{PMT}) using (8).

U [V]	600	650	700	750	800	850	900	950
f^{ex}_{PMT}	1.311 ±0.022	1.274 ±0.017	1.260 ±0.019	1.242 ±0.016	1.235 ±0.014	1.225 ±0.022	1.217 ±0.007	1.214 ±0.006
f^{th}_{PMT}	1.283	1.260	1.241	1.225	1.210	1.198	1.188	1.178

4 Conclusions

The presented results show that the proposed method for analysis of single photoelectron spectra, works well, at least for the class of the metal package photomultipliers.

The PMT response function used in this method enables to reveal very subtle effects as the photoconversion on first dynode and/or direct capture of photoelectrons by second dynode.

The method uses only the elementary physical principles and therefore can be easily adapted to other types of photomultipliers.

The method can be used as a tool for studying of PMT charge fluctuations - it enables to find out experimentally the PMT access factor needed for calculation of the energy-to-signal conversion factor (number of photoelectrons per GeV) for the PMT based calorimeters.

The method can be used as a calibration and monitoring tool for studying stability in time of a photomultiplier using the gain (parameter Q_1).

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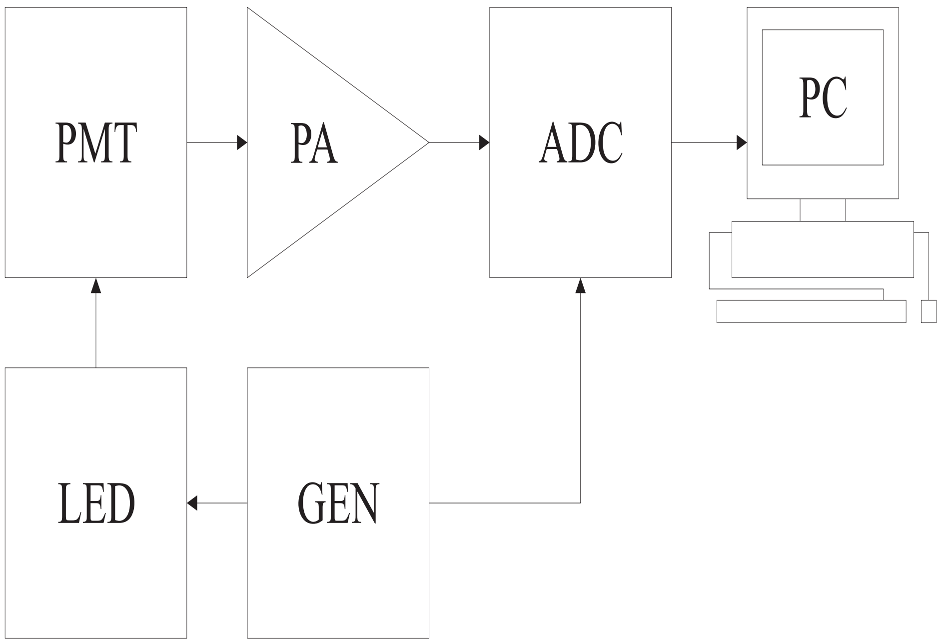

Fig. 1. Block scheme of the experimental setup for the measurement of single photoelectron spectra.

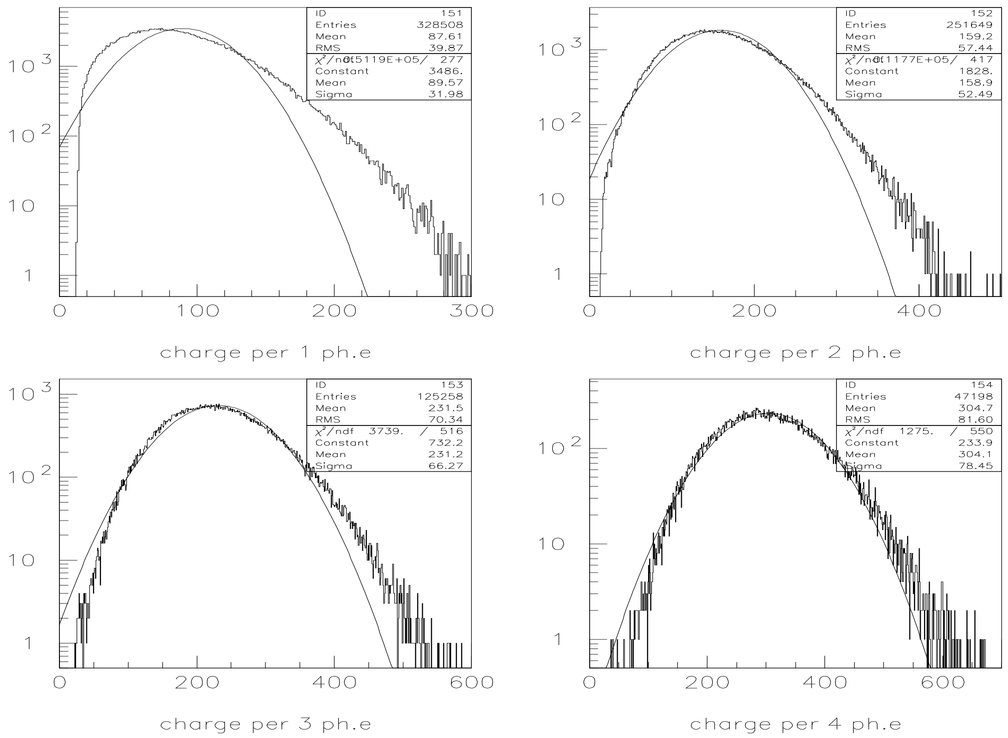

Fig. 2. The simulated PMT response initiated by different number of photoelectrons $n = 1, 2, 3$ and 4, at the gain of 10^5 .

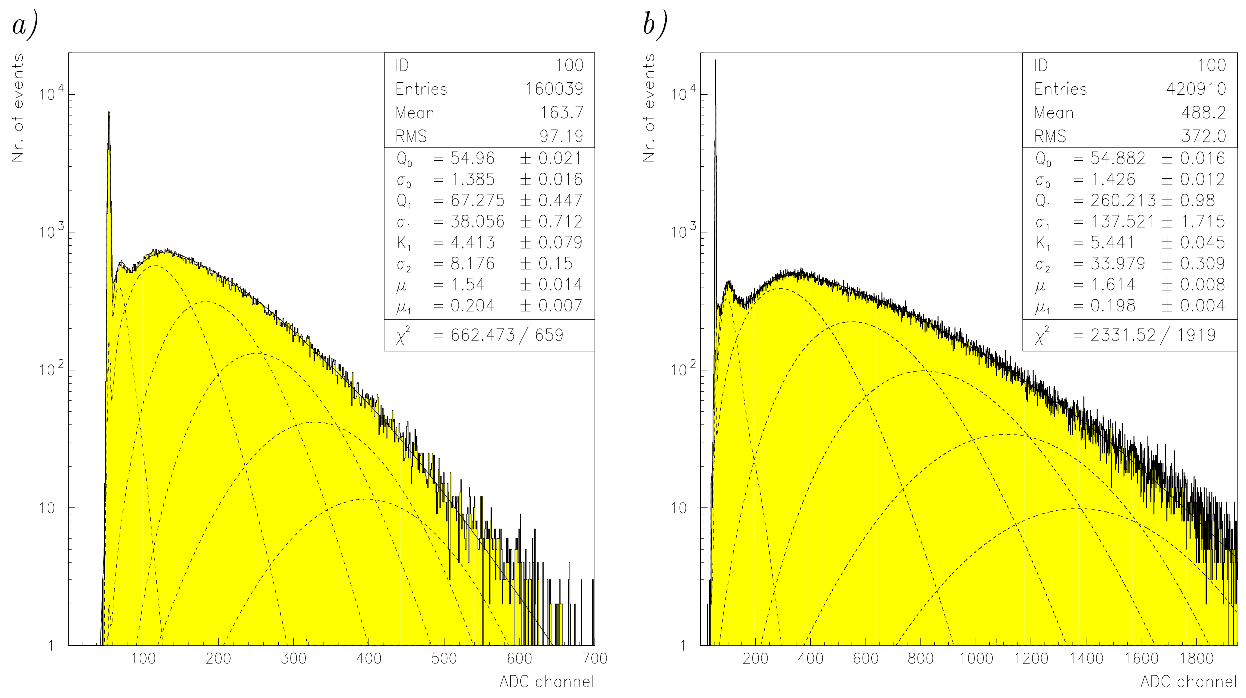

Fig. 3. The analysed LED spectrum taken at 700 V (a) and 850 V (b) by the R5600 phototube.

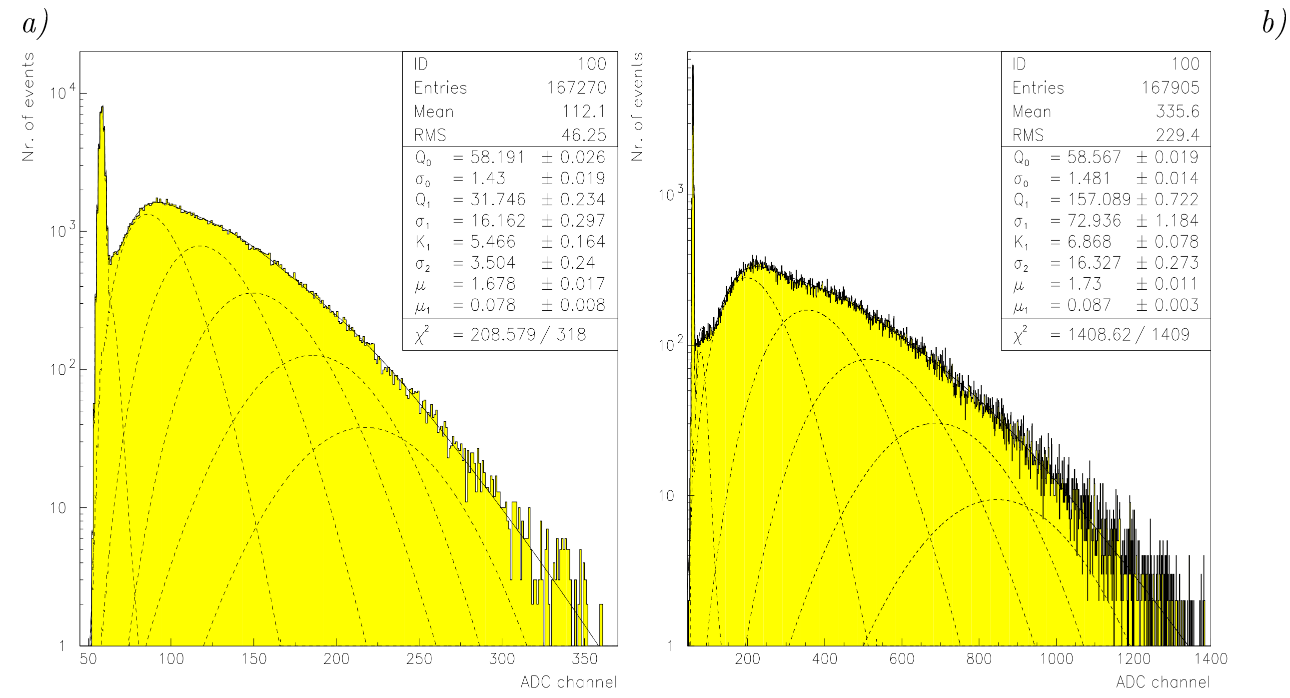

Fig. 4. The deconvoluted LED spectrum taken at 700 V (a) and 900 V (b) by the Hamamatsu R5900/9D16C2 photomultiplier.

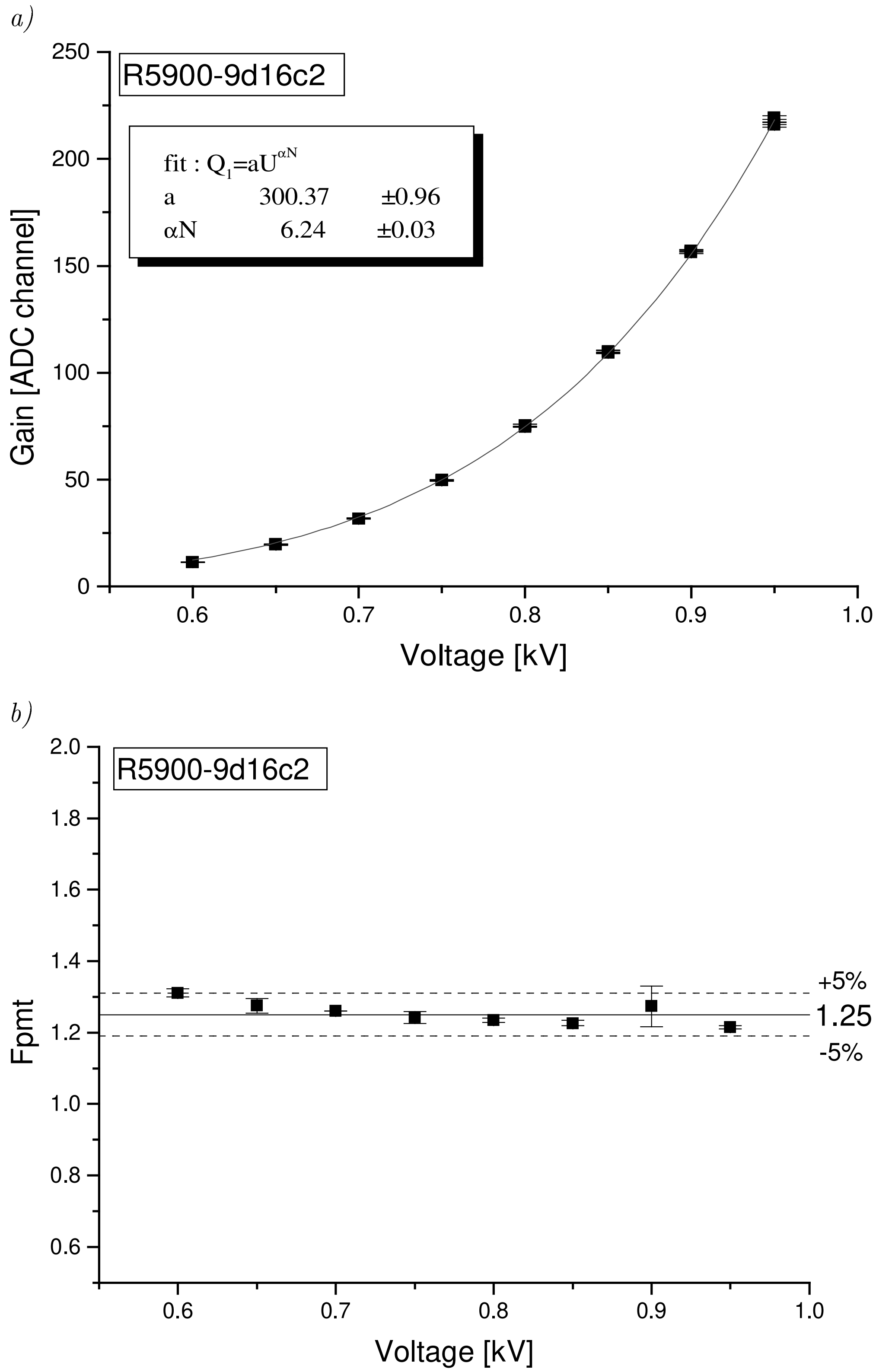

Fig. 5. The PMT R5900/9d16c2 characteristics: *a)* dependence of the PMT gain (Q_1) on voltage (kV), *b)* dependence of the excess factor on voltage.

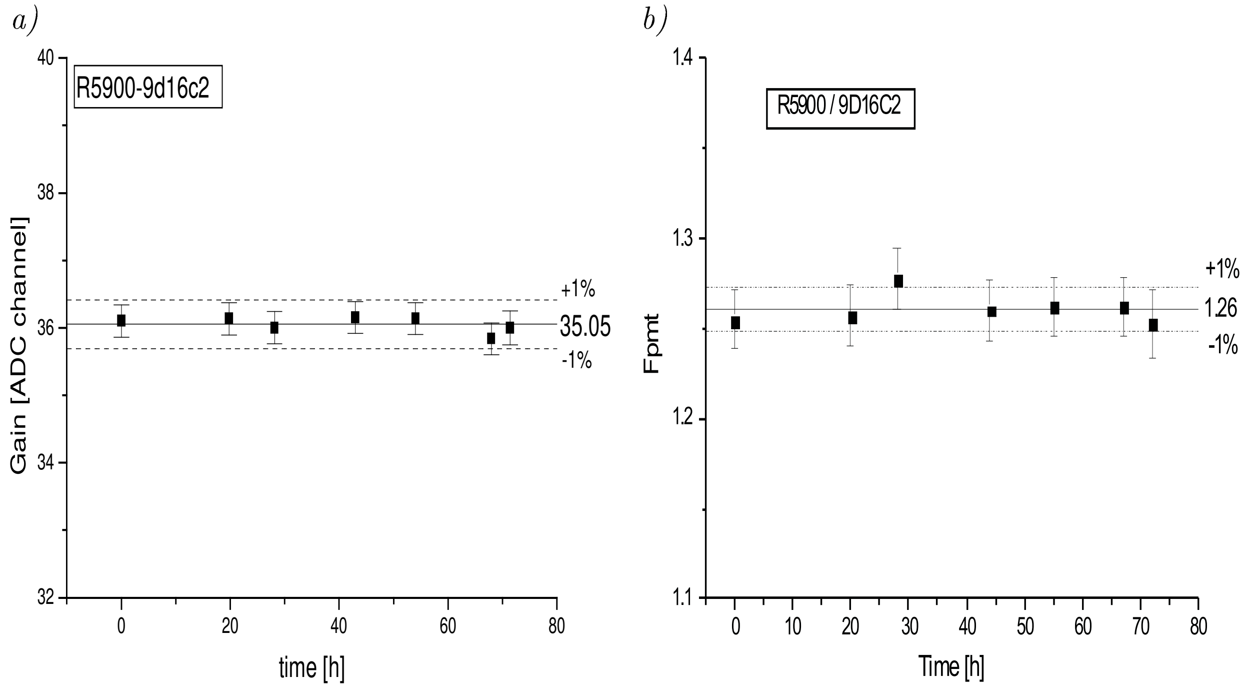

Fig. 6. The time stability of the PMT R5900/9d16c2 : *a)* the PMT gain (Q_1) vs time [hours], *b)* the excess factor vs time (hours); the used light source intensity applied was ≈ 2 photoelectrons.

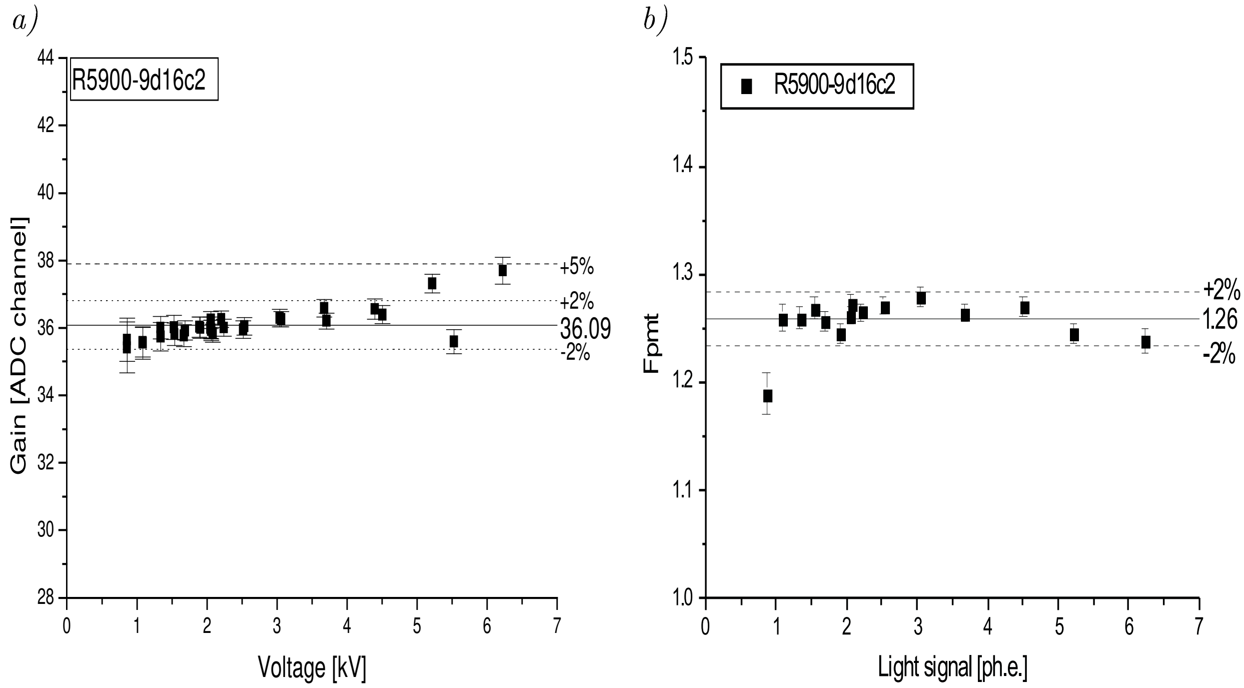

Fig. 7. Stability of retrieving of deconvoluted parameters: *a)* dependence of the PMT gain (Q_1) on light source amplitude, *b)* dependence of the excess factor on light source amplitude.