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FURTHER RESULTS ON PHOTOELECTRON COUNTING WITH SMALL DIAMETER SCINTILLATING FIBRES*

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Abstract

We measured the number of photoelectrons released from the photocathode of a newly available hybrid photomultiplier tube (HPMT) by photons from scintillating fibres. About 1600 individual 60 μm diameter fibres are contained in fused square bundles of 2.5 mm edges. The number of photoelectrons per mm fibre path changes from 10.6 at zero to 1 at 2 m bundle length. The potential difference between the HPMT photocathode and its electron detecting silicon diode amounted to 13 kV.

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1. INTRODUCTION

Photoelectron counting characterizes in an objective way the quality and the performance of scintillating fibres. To establish well defined conditions, the signals must originate from minimum ionizing particles, which traverse a known pathlength within the fibre material at a well defined distance from the photon detecting cathode.

Until recently, most of the photoelectron counting procedures were based on photomultipliers, where the Quantacon^{#1} resolved up to three photoelectron peaks [1]. Since 1992 an electrostatically focused hybrid photomultiplier tube (HPMT)^{#2} is commercially available, which contains a silicon diode bombarded with electrons from a light detecting photocathode. Each photoelectron hitting the diode creates some 275 electron-hole pairs per keV electron energy. With 13 kV potential difference, this results in 3575 electron-hole pairs per electron released from the photocathode. This number is by more than two orders of magnitude higher than the electron multiplication at the first dynode of a photomultiplier. This reflects on the statistical fluctuations and increases the number of resolved photoelectron peaks to about fifteen [2].

Therefore, we applied a HPD (HPMT) to count the photoelectrons from newly produced fibre bundles^{#3}. Their light emission was stimulated by minimum ionizing electrons from a Sr-90 source at different distances from the photocathode of the HPD.

2. EXPERIMENTAL ARRANGEMENT

Light attenuations and photoelectron yields were measured on fused fibre bundles [3] of 2 m length each and with square cross-section of 2.5 mm edges. Each of these bundles contains about 1600 fibres with individual diameters of 60 μm . These individual fibres are of hexagonal shape and share their cladding accordingly with their adjacent neighbours. The cladding material used, was fluorinated polymethacrylate of 1.42 refractive index, surrounding the polystyrene (PS) fibre cores of 1.58 refractive index, which contained 0.5 weight % of PMP^{#4} scintillator.

#1 8850, Burle Electron Tubes, Lancaster, PA, USA

#2 BV Delft Electronische Producten (DEP), NL-9300 AB Roden, The Netherlands

The name of this device has been recently changed by the manufacturer into: HPD (Hybrid Photo Diode).

#3 Kuraray Co.Ltd, Tokyo, Japan

#4 1-phenyl-3-mesityl-2-pyrazoline

The arrangement for measuring light attenuations is shown in fig. 1. The excited and transmitted light was detected with a photomultiplier^{#5}, which was coupled to the fibre bundle end via a 120 mm long and 40 mm diameter plexiglas light guide, in order to establish uniform light distribution across the 46 mm diameter multialkali-photocathode. The scintillating light was excited with β^- particles from a Sr-90 source (400 MBq). The source holder was driven by a computer controlled step-motor along the fibre bundle (fig.1). This motor was programmed for stops every 25 mm or 50 mm. The fibre bundle was fixed in the groove of a bench and at every stop, a 10 mm hole in this bench allowed for free passage of the β^- -particles, to avoid backscattering to the bundle.

To count photoelectrons, we employed β^- -particles from a 37 MBq Sr-90 source. This source is located in plexiglas [1] to avoid any noticeable bremsstrahlung contribution. The electrons were collimated through two slits of 1 mm and 0.6 mm width and 2.5 mm and 8 mm length and crossed transversely the fibre bundle, which was stretched along a groove in an aluminium bench. The beta source underneath and the coincidence detectors above this bench were positioned by a common support, which could be slid along the fibre bundle into the wanted positions. The coincidence arrangement consists of two photomultipliers^{#1} viewing via clear fibre light guides a common piece (5 mm $\times$ 10 mm) of plastic scintillator. The scintillating light reaching one end of the fibre bundle was directly detected with a HPD, this time with a reduced photocathode area (1:13) as compared to the specimen used in the preceding paper [2]. The signals of its silicon diode were gated with the coincidence pulses, as displayed in fig. 2, and counted with a multichannel analyser^{#2}.

3. MEASUREMENTS AND RESULTS

All measurements were performed in two steps for each fibre bundle. First we measured the light attenuation with our automatic arrangement, which provides 44 attenuation stops. At each of these stops, 50 dc-anode current values from the photomultiplier were recorded and averaged by a Keithley^{#3} 1 s sampling nanoamperemeter.

In a second step we counted the electrons released by the photons of the excited fibre bundle from the photocathode of the HPD. The layout of the coincidence detectors

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^{#5} 9203 B, EMI Electronics Ltd, Hayes, England

^{#1} R 1635, Hamamatsu Photonics, Toyooka-village, Japan

^{#2} Silena Multichannel Analyser (mod. 7423 VHS), SILENA, Cernusco, Italy

^{#3} Model 485, Keithley Instrument Inc, Cleveland, OH, USA

[1] was designed to count only photoelectrons arising from the passage of minimum ionizing β^- -particles through the fibre bundle. Such particles span a kinetic energy range between approximately 0.8 MeV and 2.8 MeV [4]. We therefore inserted in front of the plastic scintillator an inert plastic filter of 1 mm thickness, corresponding to 0.2 MeV energy loss and absorbing all β^- -particles leaving the bundle with less than 0.34 MeV kinetic energy. With 0.6 MeV threshold settings for the coincidence signals of the 3 mm thick plastic scintillator, we selected from the continuous Y-90 β^- -spectrum only β^- -particles leaving the fibre bundles with more than 0.8 MeV kinetic energy.

Typical photoelectron spectra are displayed in fig. 3 for different source positions, i.e. for several measured average numbers of photoelectrons $\langle n \rangle_{\text{meas}}$, where

$$\langle n \rangle_{\text{meas}} = \frac{\sum_m q_m N_m}{\sum_m N_m} \quad (1)$$

q_m being the channel number in photoelectron units (see fig. 3), and N_m the number of counts per channel.

These measurements took between 36 and 96 hours per source position, depending on its distance from the HPD. Therefore, we measured each fibre bundle at eight different source positions only and determined from each measurement the quotient between the dc-anode current from the light attenuation and the average number of photoelectrons. Table 1 shows an example. The quotient remains fairly constant and we can use our quasi-continuous attenuation curves, displayed in fig. 4, to normalize their ordinate coordinates to the number of photoelectrons per millimetre (hit densities). We measured light attenuations and hit densities of four bundles and averaged the results, which are listed in table 2.

The composition of the distributions of photoelectron peaks has been analysed in a recent paper [2], but the HPD specimen used this time produced much less dark counts due to its reduced photocathode area. All results displayed in figs 3 and 4 as well as in tables 1 and 2 have been obtained without plexiglas light guides between the fibre bundles and the HPD photocathode.

4. DISCUSSION

The number m of photoelectrons generated from an average number $\langle n \rangle$ by the photocathode follows a Poisson distribution :

$$P_m(\langle n \rangle) = \frac{\langle n \rangle^m}{m!} e^{-\langle n \rangle} \quad (2)$$

However, the measured photoelectron spectra in fig. 3 show discrete gaussian peaks on top of a continuum, which cannot be explained by the overlaps of photoelectron peaks. In our recent paper [2], we have demonstrated that this continuum is mostly caused by backscattering of accelerated photoelectrons from the surface of the HPD-diode, and to a smaller fraction by dark counts from the photocathode. The new HPD specimen used for the measurements reported in the present paper, did emit almost no dark counts. Therefore, we are only left with the backscattering contribution which leads to reduced variances of the photoelectron peaks. They decreased from around 1.7 keV [2] to 1.2 keV for the spectra measured at different source distances and remain constant for all peaks. For 13 keV electrons, the backscattered fraction we measure, amounts to 18 % (which agrees with [5]), depositing an average of ~ 0.4 of their 13 keV energy within the sensitive diode volume. As the effect of backscattering is to decrease the average number of electron-hole pairs generated by a photoelectron, $\langle n \rangle_{\text{meas}}$ from rel. (1) will be smaller than $\langle n \rangle$ from rel. (2), that is : $\langle n \rangle_{\text{meas}} \approx \langle n \rangle (1 - \alpha/2)$, with $\alpha = 0.18$ being the backscattering coefficient.

The spectra in fig. 3 show that their continuum part increases with respect to their gaussian discrete part as the β -source approaches the detector, that is with an increasing average number of generated photoelectrons. To provide a simple estimation of this percentage, we proceed as follows.

The number b of backscattered electrons follows again a Poisson distribution :

$$P_b(\langle n \rangle) = \frac{(\alpha \langle n \rangle)^b}{b!} e^{-\alpha \langle n \rangle} \quad \#1 \quad (3)$$

#1 The probability for b photoelectrons to be backscattered out of m photoelectrons hitting the silicon diode is: $\alpha^b (1 - \alpha)^{m-b} C_m^b$ with $C_m^b = \frac{m!}{b!(m-b)!}$ meaning the commutation between b and m . The total probability to have a number b of backscattered electrons with an average number of generated photoelectrons $\langle n \rangle$ is then :

$P_b(\langle n \rangle) = \sum_{m \geq b} \frac{\langle n \rangle^m}{m!} e^{-\langle n \rangle} \alpha^b (1 - \alpha)^{m-b} C_m^b = \frac{e^{-\langle n \rangle} (\alpha \langle n \rangle)^b}{b!} \sum_{m \geq b} \frac{\langle n \rangle^{m-b}}{(m-b)!} (1 - \alpha)^{m-b}$ which finally leads to relation (3).

with $P_b(\langle n \rangle)$ being the probability of having b backscattered photoelectrons. In particular, $P_0(\langle n \rangle)$ is the probability of no backscattering: for $\langle n \rangle = 1$ we obtain 0.84 non backscattered electrons. For $\langle n \rangle = 10.4$ (corresponding to $\langle n \rangle_{\text{meas}} = 9.5$), this number decreases to 0.15 with 1.9 photoelectrons backscattered.

The distribution $P_b(10.4)$ is listed as an insert in fig. 3d, and the probability of no backscattering $P_0(\langle n \rangle)$ is shown in table 3 for different source distances. Also tabulated is the ratio $(S_1 - S_2) / S_1$, where S_1 is the total area and S_2 the backscattered area of the measured spectra. These normalized peak areas agree fairly well with the estimated probabilities for non backscattered electrons $P_0(\langle n \rangle)$. From $\langle n \rangle = 18$ onward (at a distance of 10 cm) the photoelectron peak structure practically disappears since it is completely masked by the backscatter continuum.

In comparison with earlier photoelectron counting results (table 2 in reference [1]) table 2 of this paper shows higher hit densities. This improvement is mainly due to better photoelectron collection efficiency of the HPD as compared to that of first Quantacon dynode. The same effect was also observed recently by another group [6]. Since an HPD like photon-detector will be applied in future for small diameter fibre arrangements, the results presented in this paper describe the expected performance in a more realistic way.

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FIGURE CAPTIONS

- Fig. 1 Experimental device to measure the light attenuations of scintillating fibre bundles.
- Fig. 2 Bloc diagramme of the electronic components for photoelectron counting.
- Fig. 3 Photoelectron distributions measured with the 8000 channel SILENA analyser at six different β -source distances from the HPD-photocathode. The average numbers $\langle n \rangle_{\text{meas}}$ of counted photoelectrons are indicated. The insert of fig. 3e lists the probabilities P_b for the number b of backscattered electrons for $\langle n \rangle_{\text{meas}} = 9.5$.
- Fig. 4 Light attenuations averaged over four fibre bundles and normalized according to table 1 to number of photoelectrons [mm^{-1}]. The indicated open circles represent the evaluated $\langle n \rangle_{\text{meas}}$ - values.

Table 1 : Ratio of anode currents measured with the attenuation arrangement (fig. 1) to the number of photoelectrons measured with the HPD (fig. 2). The average value was taken to normalize the attenuation values to the number of photoelectrons (table 2 and fig. 5).

Position [mm]	anode current [nA]	Number of photoelectrons [p.e.]	Ratio nA / p.e.
95	443	18.44	24.02
245	335	13.60	24.63
495	230	9.54	24.11
795	166	6.74	24.63
995	136	5.59	24.33
1295	103	4.33	23.79
1595	82	3.31	24.77
1895	66	2.75	24.00

average : 24.28

Table 2 : Hit densities [photoelectrons·mm⁻¹] for 4 bundles of same dimensions : square cross-section with 2.5 mm edges containing 1600 individual fibres of 60 µm diameter.

Position [mm]	Bundle n°1	Bundle n°2	Bundle n°3	Bundle n°4	Average
0	10.94	10.38	10.67	10.38	10.59
50	8.41	8.34	8.27	8.40	8.36
100	7.03	7.15	7.06	7.18	7.11
200	5.56	5.72	5.65	6.05	5.75
300	4.71	4.8	4.71	5.09	4.83
400	4.11	4.12	4.11	4.32	4.17
600	3.20	3.27	3.24	3.34	3.26
800	2.58	2.69	2.68	2.72	2.67
1000	2.14	2.18	2.19	2.24	2.19
1200	1.77	1.77	1.81	1.88	1.81
1400	1.47	1.48	1.53	1.57	1.51
1600	1.25	1.24	1.28	1.32	1.27
1800	1.08	1.09	1.10	1.15	1.11
2000	1.01	0.97	0.94	1.04	0.99

Table 3 : Comparison between the probability $P_0(<n>)$ of non backscattered photoelectrons and the area of photoelectrons peaks (S_1-S_2) normalized with the total counting area S_1 . S_2 means the backscattered area below the peaks.

The $<n>$ values are estimated from $<n> \approx \frac{<n>_{\text{meas}}}{(1-\alpha/2)}$.

Position [mm]	$<n>$	$P_0(<n>)$	$(S_1-S_2) / S_1$
95	20.3	0.03	0.04
245	14.9	0.07	0.06
495	10.5	0.15	0.13
795	7.4	0.26	0.29
995	6.1	0.33	0.31
1295	4.8	0.42	0.41
1595	3.6	0.52	0.53
1895	3.0	0.58	0.62

Fig. 1

Fig. 2

Fig. 3

Number of photoelectrons

Fig. 3 (cont.)

Fig. 4