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**YIELD OF PHOTOELECTRONS PRODUCED IN TMAE
AND SOLID TMPD BY BaF₂ SCINTILLATION LIGHT**

Tom Francke
CERN, Geneva, Switzerland

Martin Suffert
Centre de Recherches Nucléaires, Strasbourg, France

ABSTRACT

The yield of photoelectrons produced in gaseous TMAE and solid TMPD by BaF₂ scintillation light and detected by multiwire proportional chambers operated at low pressure has been studied. The scintillation light was generated by collimated 511 keV gamma-rays from a ²²Na source. Using a new technique for analysing low-pressure MWPC spectra, it is shown that TMAE gives a spectrum corresponding to 9.6 ± 0.5 photoelectrons while the quantum efficiency of solid TMPD is only 2% of that of TMAE. Adding TMP to lower the threshold of photoelectron emission, it is possible to double the efficiency of TMPD.

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1. INTRODUCTION

Ultraviolet (UV)-sensitive multiwire proportional chambers (MWPCs) are becoming important parts of modern detector systems in particle and nuclear physics, not only because they provide nearly the only technique for large-area applications but also, because in applications of smaller size, their good time- and position-resolution, and their large amplification factor, make it possible to detect and localize single photoelectrons. In an UV-sensitive MWPC, the UV photons emitted from a scintillator or from a radiator as Cherenkov light are converted by a photosensitive material into photoelectrons which are drifted towards a MWPC where they are amplified and collected. The photocathode should have low-energy ionization threshold and high efficiency. The two photosensitive materials most frequently used are the complex organic ring molecules of trimethylamine (TEA) and tetrakis(dimethylamine)ethylene (TMAE) [1], used in gaseous form. Using a solid photocathode the photoconversion would take place in a very thin and well-defined layer which would suppress the time- and position-jitter as well as giving a faster system because of shorter drift-time.

Here a comparison between TMAE and solid tetramethyl-paraphenylendiamine (TMPD) in the region around 220 nm is presented, and tests have been done to increase the efficiency of TMPD by using tetramethylpentane (TMP) to lower the threshold for photoelectron emission of the TMPD [2]. A new analysis technique of spectra from low-pressure MWPCs is also presented, where no information from the single-photoelectron spectrum has to be provided.

2. EXPERIMENTAL SET-UP

2.1 The gas system

The low-pressure wire chamber (pressures between 2 and 10 hPa) is mounted inside a 10 ℓ aluminium vacuum chamber (Fig. 1). Great care has been taken to render the system as gastight as possible, and by using Gyrolock joints and Viton O-ring seals a vacuum down to 10^{-6} hPa can be obtained using a small turbomolecular pump. This is very important when using TMAE in closed systems for a long period of time since it is easily destroyed by oxygen. In order not to damage the rotary pump, the TMAE is recovered in a double cold-trap (-30°C) and an active charcoal filter, and the system is secured by electrovalves that automatically close if there is a power failure and remain closed when the power is switched on again. To measure the pressure a DIAVAC manometer is used to get absolute values down to 1 hPa, a Pirani manometer in the range $10\text{--}10^{-2}$ hPa and a Penning gauge down to 10^{-7} hPa.

2.2 The active system

The active system consists of a 50 mm thick BaF_2 crystal with a diameter of 50 mm, which emits scintillation light when irradiated with 511 keV gamma-rays from a collimated ^{22}Na source (Fig. 2). Since BaF_2 has a fast component around 220 nm with a decay-time of 600 ps, it is very useful as a reference light source in the region 170-240 nm (Fig. 3) [2,3,4,5]. TMAE has a threshold for emission of photoelectrons at 220 nm, and will not be affected by the slow component of BaF_2 centred around 310 nm. According to recent measurements by Peskov et al. [2], solid TMPD also has a threshold around 220 nm, and it is assumed that the TMPD is not affected by the slow component either, in order to be able to compare it with TMAE. The scintillation photons enter the box through a 6 mm thick quartz window and are converted into photoelectrons by the photosensitive material under test. These photoelectrons are then drifted towards the MWPC, where they are amplified and collected. To obtain a homogeneous drift field when using TMAE, a stainless-steel mesh with 80% transmission is placed directly under the quartz window. When testing solid TMPD as a photocathode, an aluminium plate is placed under the MWPC onto which the TMPD is deposited. Both plate and grid are connected to ground, the strength of the drift field being regulated by the cathode voltage.

2.3 The wire chamber

The multiwire proportional chamber (MWPC) consists of an anode wire plane between two cathode planes with an anode-to-cathode gap spacing of 3 mm. The anode is composed of 12 μm diameter gold-plated tungsten wires with 1 mm spacing between them. The cathode wires are perpendicular to the anode wires, are made of 50 μm diameter gold-plated tungsten, and are spaced 1 mm apart.

2.4 The trigger

The collimator is an 11 cm thick lead block in which the ^{22}Na source is placed. The two collimated 511 keV gamma-rays are emitted through a 10 mm diameter hole drilled through the lead block; one gamma-ray goes into the BaF_2 crystal used as a reference light source and the other enters the NaI(Tl) crystal connected to a photomultiplier (PM) tube used to generate a trigger signal. By means of a single-channel analyser centred on the 511 keV peak no other signals originating from Compton scattering in the crystal, cosmic rays, or noise, are accepted as trigger signals. Owing to asymmetry in the collimator and because the gamma-ray entering the box has to pass through a 2 mm thick stainless-steel cover, some gamma-rays are absorbed giving false triggers. The signals from the Compton-scattered gamma-rays in the BaF_2 crystal are later subtracted in the analysis.

2.5 The electronics

Only the anode plane is read out and the charge is converted by a 142PC Ortec preamplifier. The output pulse is later shaped and amplified again 20-50 times by a 571 Ortec amplifier with 1 μs shaping-time, and fed into two separate multi-channel analysers. The trigger signal opens a 3 μs gate for the shaped signal to allow for some time-jitter.

Both cathodes are connected to the same high voltage, normally + 150 V when using TMAE and + 250 V when testing TMPD. The amplification field is regulated by the anode voltage, and normally the highest possible voltage is used that gives a stable operation even during long runs, to maximize the signal-to-noise ratio. To be able to perform long unsupervised runs the anode HV automatically switches off if there is a discharge.

3. FILLING PROCEDURE

3.1 TMAE

When using TMAE the evacuated box is saturated with TMAE vapour (0.32 hPa at room temperature) before filling with ethane up to the desired pressure, normally 4 hPa. The ethane is bubbled through the TMAE, which gives a small improvement compared to filling the box directly with ethane.

3.2 TMPD

The TMPD is dissolved in pure ethanol (99.8%) in an argon atmosphere to prevent oxidation. The solution is then injected onto the aluminium plate, with a flush of ethane through the box to prevent oxidation. By pumping carefully the alcohol evaporates and a thin layer of solid TMPD is left. A 1 μm layer is enough to get the full effect. By making it thicker, problems might arise to get a uniform drift field since TMPD itself is an insulator. Later the box is filled with ethane to the desired pressure.

3.3 TMP

When using TMP to increase the efficiency of TMPD by lowering the threshold for photoelectron emission, TMP vapour is introduced into the box instead of ethane. Owing to the high vapour pressure of TMP (30 hPa at 25 °C) no extra filling with ethane is necessary.

4. RESULTS

4.1 TMAE + ethane

A typical pulse-height spectrum obtained with TMAE is shown in Fig. 4. The average number of photoelectrons is $\langle n \rangle = 9.6 \pm 0.5$ (see appendix). $\langle n \rangle$ depends on the specific BaF₂ crystal used, but is quite stable from one filling to another.

4.2 TMPD + ethane

We assume that solid TMPD is not sensitive to the slow component of BaF₂ centred around 310 nm. The quantum efficiency of solid TMPD should be of the order of $10^{-3}\%$ at 310 nm [6]. Using a very thin layer of TMPD ($\sim 1 \mu\text{m}$) and filling the chamber with 4 hPa of ethane as amplification gas gives an efficiency of 16%, corresponding to 0.2 photoelectrons. This is 50 times less than that of TMAE (here the efficiency is defined as the ratio between the number of counts in the spectrum and the total number of gamma-rays interacting in the BaF₂ crystal). The pure aluminium plate gives an efficiency of only 3%, so most of the photoelectrons clearly originate from the TMPD and not from the photoeffect in the aluminium plate.

4.3 TMPD + TMP

Pure TMP vapour was added to lower the threshold of photoelectron emission of solid TMPD, and to be used as the amplification gas instead of ethane. The best result was obtained by first saturating the chamber with TMP (30 hPa) and then pumping down to 4 hPa, which was the pressure where the highest efficiency was reached. This method gave an efficiency of 28%, corresponding to 0.3 photoelectrons, which is 1.5 times higher than that of pure TMPD + ethane. If the chamber was filled with TMP vapour up to 4 hPa an efficiency of 11%, corresponding to 0.1 photoelectrons, was measured.

5. DISCUSSION

TMAE is an efficient photocathode in the far UV region ($\lambda < 220 \text{ nm}$), but has some major disadvantages: the low vapour pressure gives a long conversion length; it is easily destroyed by oxygen and therefore requires very gastight systems, and it is only sensitive in the far UV region requiring the use of windows and amplification gases which are transparent far below 220 nm.

TMPD has the major advantage of being a solid at room temperature, which makes it very interesting as a photocathode. It is easy to handle, but irritates the skin, and is not so easily poisoned by air as, for example, TMAE. The efficiency, however, is very low in the region around 220 nm (180–240 nm), only 2% of that of TMAE, which limits its usefulness to applications with a fairly large amount of light. Adding TMP to try to lower the threshold for photoelectron emission of the TMPD layer it is possible to double the efficiency of TMPD.

Because of the increasing number of applications for UV-sensitive MWPCs, e.g. Ring-Imaging Cherenkov (RICH) counters, BaF₂ calorimeters, positron cameras, etc., it is important to find new photosensitive materials with lower ionization thresholds and higher efficiency than those known today, and research is going on in this field [2]. Solid photocathodes are especially interesting because they are easy to handle. Since the photoelectrons are emitted from a very thin and well-defined layer, it is possible to make a very compact counter with less time- and position-jitter than when using gaseous photocathodes, as well as giving a faster system because of shorter and well-defined drift-times. With a solid photocathode well separated from the amplification region in the MWPC, the risk of feedback from secondary photons created in the avalanches is reduced, which might increase the resolution and shorten the local dead-time.

6. CONCLUSION

The results obtained in this study confirm that TMAE is still the best photosensitive material to be used as the photocathode in UV-sensitive MWPCs when the number of photons is low, but interesting results have been obtained by Charpak et al. using ethyl ferrocene [4]. Since the efficiency of solid TMPD is only 2% of that of TMAE in the region around 220 nm, it can only be used in applications where the number of photons to detect is fairly large. Adding TMP to lower the threshold for photoelectron emission of the TMPD layer, it is possible to approximately double the efficiency of TMPD.

Spectra from photosensitive low-pressure MWPCs, corresponding to a small number of photoelectrons, are difficult to analyse because of strong correlation between the parameters in the theoretical spectrum. By taking advantage of the fact that the spectrum only consists of one single broad peak, we have developed an algorithm which makes it possible to fit a theoretical spectrum to the measured one, without any need for further information from the single-photoelectron spectrum.

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APPENDIX: FITTING LOW-PRESSURE MWPC SPECTRA

A1. INTRODUCTION TO THE STATISTICS OF A PHOTOSENSITIVE LOW-PRESSURE MWPC SYSTEM

Two factors limit the energy resolution of a MWPC used to detect a small number of photoelectrons; firstly, the fluctuations in the number of primary photoelectrons; secondly, the fluctuations in the number of secondary electrons produced in the avalanche around the anode wire of the MWPC.

One model for the statistical process of electron multiplication in proportional counters, working with strong electric fields, was independently proposed by Byrne [7] and by Lanciart and Morucci [8], and later further developed by Alkazov [9]. For large gas amplification it was proposed to use a special case of the geometrical distribution, normally called the Polya distribution, describing the size of a single-photoelectron avalanche:

$$f_z(z) = [m^m/\Gamma(m)] z^{m-1} e^{-mz} . \quad (\text{A.1})$$

Here $z = N/\langle N \rangle$ (where N is the number of electrons in the avalanche) and m is a parameter of the Polya distribution (the 'Polya parameter' that was shown [8] to be of the order of 1.5 for the chamber used by Cullan et al. [10]).

This distribution is found to be valid also for low-pressure MWPCs, where each wire acts as a nearly independent counter [11]. Fitting a single-photoelectron spectrum, obtained by illuminating a TMAE + ethane filled low-pressure MWPC with an UV lamp (Fig. 5), shows the good agreement between the measured spectrum and the theoretical distribution. This has also been tested earlier [12].

Since the size of the avalanche is quite small ($\ll 1/10$ mm) each photoelectron drifting towards the chamber can be treated independently. The measured spectrum is the weighted sum of the single-photoelectron spectra, provided that additional line broadening from technical shortcomings and from electronic noise can be neglected. The weights are given by the statistical distribution of the number of primary photoelectrons.

A2. DISTRIBUTION FUNCTION OF A SPECTRUM

Using the characteristic function of the Polya distribution it is possible to get the distribution function of a spectrum originating from k primary photoelectrons:

$$f_k(z) = [m^{mk}/\Gamma(mk)] z^{mk-1} e^{-mz} . \quad (\text{A.2})$$

The distribution of the number of primary photoelectrons is binomial, but can be approximated by a Poisson distribution since the efficiency of the system is low, when the distribution function of a measured spectrum $S(z)$ becomes

$$S(z) = P(z) + \sum_{k=1}^{\infty} f_k(z) (\langle n \rangle^k / k!) e^{-\langle n \rangle} , \quad (\text{A.3})$$

where $\langle n \rangle$ is the mean number of photoelectrons and P the distribution function of the pedestal.

A3. FITTING PROCEDURE

When fitting a spectrum from a MWPC corresponding to a small number of photoelectrons, a Gaussian approximation is not applicable. Each photoelectron peak is broadened by the Polya statistics and there will be no individual photoelectron peaks as in the case of, for example, a good PM tube.

Furthermore, the mean number of photoelectrons, $\langle n \rangle$, and the parameter of the Polya distribution, m , are strongly correlated, so some special effort has to be included in the fitting algorithm. Here a technique of doing this is described, in the region between three and twenty photoelectrons, which has been shown to be efficient without having to provide any information about the Polya parameter or the gain deduced from the single-photoelectron spectrum. For more than twenty photoelectrons a Gaussian approximation is adequate, and for spectra with fewer than three photoelectrons the efficiency can eventually be used.

A4. THE ALGORITHM

Figure 5 shows a typical reference spectrum using the scintillation light from a BaF₂ crystal produced by collimated 511 keV gamma-rays from a ²²Na source. The full-energy peak is produced by subtracting the Compton contribution measured independently to be 27%.

The mathematical approximation used here, as described above, is:

$$S(z) = P(z) + A \sum_{k=1}^{\infty} f_k(z/G) (\langle n \rangle^k / k!) e^{-\langle n \rangle} , \quad (\text{A.4})$$

where the gain, G , is the scale factor between the channel number of the multichannel analyser and the number of photoelectrons. A is a normalization factor.

Normally neither the gain, G , nor the Polya parameter, m , is known, so they have to be fitted together with the mean number of photoelectrons, $\langle n \rangle$, and A . Since the Polya parameter and the mean number of photoelectrons are strongly correlated, the usual least-squares-fit does not normally work. Generally, m is extracted from the single-photoelectron spectrum, but by using some special information about the spectrum, such as that it only consists of one peak, there is a way of getting around this problem.

The peak position, $t_{\text{peak}} = z_{\text{peak}}/G$, can be calculated from the expression:

$$d/dz \left(\sum_{k=1}^{\infty} f_k(z) (\langle n \rangle^k / k!) e^{-\langle n \rangle} \right) \Big|_{z=t_{\text{peak}}} = 0 . \quad (\text{A.5})$$

For $\langle n \rangle > 3$ this can be approximated by

$$t_{\text{peak}} = c_1 \langle n \rangle + F_1(m) , \quad \langle n \rangle > 3, \quad 1.2 < m < 3 , \quad (\text{A.6})$$

where c_1 is a constant and F_1 is a function of m alone.

To a good approximation ($< 2\%$), ($\langle n \rangle > 3, 1.2 < m < 3$)

$$\begin{aligned} c_1 &= 1.00 \\ F_1 &= 0.092 m^3 - 0.723 m^2 + 2.05 m - 2.98 . \end{aligned} \quad (\text{A.7})$$

In the same way the right half maximum position, $t_{\text{HM2}} = z_{\text{HM2}}/G$ (see Fig. 6), can be calculated from the expression:

$$\sum_{k=1}^{\infty} f_k(t_{\text{HM2}}) (\langle n \rangle^k / k!) e^{-\langle n \rangle} = 1/2 \sum_{k=1}^{\infty} f_k(t_{\text{peak}}) (\langle n \rangle^k / k!) e^{-\langle n \rangle} , \quad (\text{A.8})$$

and for $\langle n \rangle > 3$ this can be approximated to

$$t_{\text{HM2}} = c_2 \langle n \rangle + F_2(m) , \quad \langle n \rangle > 3, \quad 1.2 < m < 3 . \quad (\text{A.9})$$

To a good approximation ($< 10\%$), ($\langle n \rangle > 3$, $1.2 < m < 3$)

$$\begin{aligned} c_2 &= 1.20 , \\ F_2(m) &= -0.080 m^3 + 0.66 m^2 - 1.9 m + 4.2 . \end{aligned} \quad (\text{A.10})$$

To eliminate the unknown gain, G , the ratio between the right half maximum position and the peak position is used, which can be approximated from the measured spectrum. This results in an expression such as:

$$\frac{c_2 \langle n \rangle + F_2(m)}{c_1 \langle n \rangle + F_1(m)} = \frac{z_{HM2}}{z_{peak}} = r , \quad (\text{A.11})$$

and from this the mean number of photoelectrons can be expressed as a function of the Polya parameter alone:

$$\langle n \rangle = \frac{rF_1(m) - F_2(m)}{c_1 - rc_2} . \quad (\text{A.12})$$

By using the peak and the right half maximum position instead of the two FWHM positions the errors from an initially broad pedestal are reduced.

In expression (A.4), $\langle n \rangle$ is replaced by expression (A.12), and this results in a theoretical spectrum as a function of m , G , and A , to be fitted to the measured one. From this fitted m , the number of photoelectrons can easily be calculated from expression (A.12).

By fitting spectra taken with the same set-up, but different TMAE concentrations (owing to different temperatures and filling procedures), it is found that the chamber used has a Polya parameter around 1.5. The smaller this parameter is the more suitable is the chamber for the detection of a small number of photoelectrons. By this method no external information from the single-photoelectron spectrum has to be provided for the fitting procedure. This method has thus eliminated the risk of changes in the gain and in the TMAE concentration between the measurements of the single-photoelectron spectrum and the spectrum to be analysed.

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Figure captions

- Fig. 1** The gas system for testing TMAE together with ethane, and TMPD together with ethane or TMP.
- Fig. 2** Schematics of the active system.
- Fig. 3** BaF₂ fast emission spectrum (1) [4], quantum efficiency of TMAE (2) [5], quantum efficiency of solid TMPD (x) and solid TMPD + TMP (*) [5], as a function of wavelength.
- Fig. 4** A typical reference spectrum using TMAE to convert the scintillation light from a BaF₂ crystal. Only 22% of the triggers are true triggers. False triggers arise from gamma-rays being absorbed in the collimator or the stainless-steel cover, or not giving light in the BaF₂ crystal because the efficiency of the crystal used is only 85%.
- Fig. 5** Single-photoelectron spectrum with light from a UV lamp converted by TMAE into photoelectrons, and a fit of the Polya distribution to the measured spectrum. Error bars for three data points are given.
- Fig. 6** The reference TMAE spectrum after 27% reduction of Compton-scattered photons in the crystal, and a fitted theoretical spectrum using the algorithm described. The tail of the spectrum is due to 1.27 MeV gamma-rays from the ²²Na source that enter the BaF₂ crystal together with the 511 keV gamma-ray for some events.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

27 % COMPTON-REDUCED TMAE SPECTRUM

Fig. 6