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On the efficient operation of a CsI-coated GEM photon detector

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Abstract

We report on the efficient operation of a CsI-coated GEM photon detector. We describe its operation mode and the dependence of the single electron detection efficiency on the electric fields. Conditions for obtaining full efficiency of photoelectron extraction and their focusing into the GEM apertures, in 1 atm CH_4, are presented. The quantum efficiency of the CsI-coated GEM is 35% at 150 nm. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Gaseous photomultipliers (GPMTs), coupling a solid photocathode to a gas avalanche electron multiplier, have several advantages compared to vacuum operated devices. They can be produced with large area, provide good position and time resolutions and can operate in strong magnetic fields. Their basic properties and some recent progress in this field are reviewed in Ref. [1].

Multiwire Proportional Chambers (MWPC) coupled to CsI-photocathodes are already successfully employed in particle physics experiments; they efficiently localize single UV photons in large (square meters) Ring Imaging Cherenkov (RICH) detector systems [2]. GPMTs sensitive over the visible spectral range are currently being investigated [3]. Nevertheless, gas avalanche photomultipliers generally suffer from avalanche-induced photon and ion feedback; these limit the gain, the localization accuracy and often the lifetime of the devices.

A solution to these drawbacks is offered by the Gas Electron Multiplier (GEM) [4]. It was shown [5] that by incorporating a GEM in a CsI-equiped GPMT, the photon feedback is drastically reduced, due to the photon shadowing provided by the GEM. Recently, simulations [6] and measurements [7] showed that conditions exist to efficiently detect all photoelectrons emitted from a semi-transparent photocathode into a GEM.

Coupling a CsI photocathode to a cascade of multiple GEM elements, multiplication factors exceeding 10^5 were reached in noble gas mixtures [8]. It was demonstrated that such multi-GEM

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photomultipliers have stable operation with further reduced photon and ion feedback effects.

It was already proposed in one of the first papers on GEM to coat one of the GEM faces with a photocathode and to multiply and detect the photoelectrons by focusing them into the GEM apertures [9]. This allows for the use of thick reflective photocathodes, which are easier to produce and have higher quantum efficiency values compared to semitransparent photocathodes. Furthermore, in this geometry the GEM completely conceals the photocathode from avalanche-induced photons created within its apertures and in the following multiplying elements, thus we expect that the photon feedback is totally eliminated. Some attempts made in this direction resulted in very low photoelectron yield values [10]. The successful operation of such a photocathode-coated GEM requires efficient focusing of the photoelectrons into the GEM apertures, not reported as yet.

We report here on the first successful operation of a CsI-coated GEM photon detector, describe the operation principles and performance of the device and compare them to that of a standard gas avalanche reflective photodetector.

2. Experimental setup

The principle of the detector and the evaluation method are shown in Fig. 1. A CsI-coated GEM is mounted between two MWPC multipliers. UV-photons from a Hg(Ar) lamp induce single photoelectrons on the CsI photocathode. According to the applied electric fields the detector can be operated in two different modes:

- Reflective mode: The CsI coated face of the GEM acts simply as a reflective photocathode, with the uncoated face kept at the same potential. Electrons emitted from the CsI are extracted towards the mesh M2 and multiplied and detected at the MWPC_R. The properties of such a detector are well known and the rate of counts in this mode is used as normalization.
- Transmissive mode: In this mode of operation a potential difference V_{GEM} is applied between the two GEM sides. Depending on the value of V_{GEM}, a fraction of the photoelectrons released from the photocathode is focused into the GEM apertures. They are multiplied under the field across the GEM holes and the resulting avalanche electrons drift towards the MWPC_T, where they are further multiplied and detected.

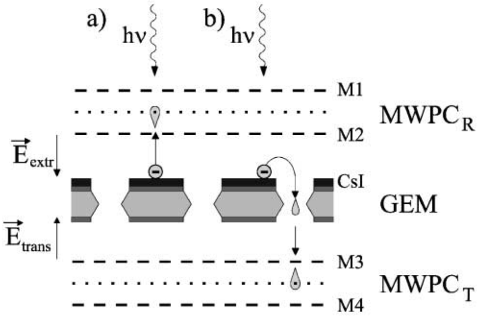

Fig. 1. The experimental setup allowing for two modes of operation of the photodetector: (a) reflective and (b) transmissive mode.

The advantage of this experimental approach is the possibility for a direct evaluation of the efficiency to extract electrons from the photocathode, transfer them into the GEM apertures, and further towards the following multiplying element. This is achieved by comparing the pulse counting rates in the reflective and transmissive modes, under carefully monitored gain conditions (see below). Further discussion of the advantages of the pulse counting approach, as compared to current recording approach, is found in Ref. [7].

The detectors employed here have a sensitive area of 30 × 30 mm^2. All meshes are made of 50 μm diameter crossed stainless-steel wires, 500 μm apart (81% optical transparency). The MWPC anode wires are 10 μm in diameter and 1 mm apart. The distances between the various electrodes are all 1.6 mm, except between the uncoated GEM side and M3 where it is 2.6 mm. We used a 50 μm thick standard GEM[1], having a hexagonal hole pattern and a double-conical hole profile. The holes have a diameter of 70 μm in the copper and 55 μm in the center of the Kapton, with a pitch of

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[1] The GEM is manufactured by CERN printed circuit services.

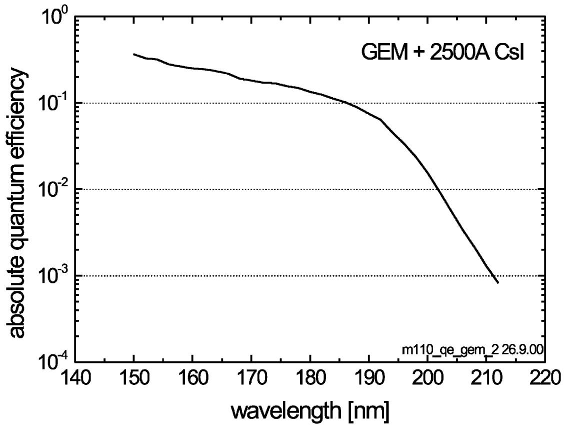

Fig. 2. The absolute quantum efficiency measured in vacuum of a 2500 Å thick CsI photocathode deposited on one GEM face. The coated fraction of the surface is 77%.

140 μm, and they constitute 23% of the GEM area. To guarantee a stable, inert substrate for the CsI, the copper cladding of the GEM was plated with a thin Ni/Au layer.

One side of the GEM was covered with a 2500 *Å* thick layer of CsI, evaporated at a rate of 10–20 *Å*/s and its absolute quantum efficiency (QE) was measured in vacuum (10^{-5} Torr) with a calibrated UV-monochromator system (Fig. 2). The QE is in agreement with previously published data of good quality CsI photocathodes [11], considering the 23% loss of active area due to the holes.

The exposure time of the photocathode to air during assembly was about 10 min, which should hardly affect its QE [11].

The detector was placed in a vacuum vessel, evacuated to 10^{-5} Torr prior to its operation under atmospheric gas flow. Some measurements were done under vacuum.

3. Methodology

Although the pulse counting method is the best approach for assessing single charge transfer efficiency, in conditions without gas amplification photocurrent measurements are also useful and provide unambiguous evaluation of the charge transfer process. Under gas amplification one cannot separate transfer efficiency and gas gain. In such conditions the pulse-counting method is the only accurate and unambiguous way of measuring the charge transfer properties of the detector [7].

In pulse-counting operation, the charge signals from the MWPCs, in the reflective and transmissive modes, were recorded with a multi-channel analyzer. The spectra have exponential shape as shown in Fig. 3.

To compare the counting rates in the two operating modes, the overall gain was held constant (at approximately 10^5) by adjusting the MWPC voltages, keeping the slopes of the single electron spectra equal. Only the middle part of each spectrum was integrated (see Fig. 3) to provide the counting rate, in order to minimize possible errors due to electronic noise contribution at the lower end of the spectrum or to feedback effects. The photon feedback is clearly appearing as an enhanced tail of the exponential distribution

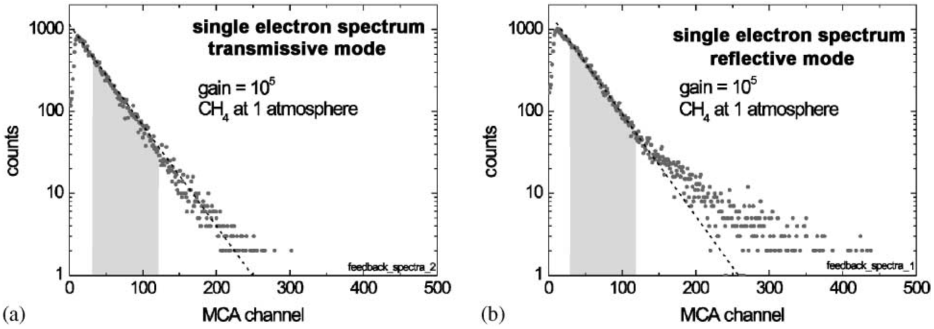

Fig. 3. Single electron pulse-height spectrum measured in (a) transmissive mode ($V_{GEM} = 510$ V, $E_{extr} = 0$, $E_{trans} = 10$ V/cm Torr) and (b) reflective mode ($E_{extr} = 5$ V/cm Torr) in CH_4 at atmospheric pressure.

in the reflective mode. The absence of excess pulses in the tail of the transmissive mode spectrum, taken under the same total gain, clearly indicates the effective photon feedback screening of this mode. A more detailed description of the measurement methodology can be found elsewhere [7].

4. Results

4.1. Measurements in vacuum

As the first step, the extraction efficiency from the photocathode was measured by photocurrent recording in both modes in vacuum (10^{-5} Torr). This provides an understanding of the photoelectron transfer processes through the various electrodes and the influence of the various electric fields without interference from electron diffusion and amplification in the gas. The detector was illuminated with high intensity UV-photon flux and the photocurrents were measured on the relevant electrodes.

In the reflective mode both GEM sides and the mesh M3 were interconnected and biased by negative voltage. Electrons released from the CsI were collected on mesh M2. Fig. 4 shows the influence of the extraction field on the current measured on M2 with a grounded pico-amperemeter in the reflective mode. After a sharp rise the current reaches a plateau and then rises only very slowly with the field. The rise, already previously observed in CsI photocathodes [12], could be due to some polarization effects at the photocathode surface, that could lead to moderate increase in QE with the field.

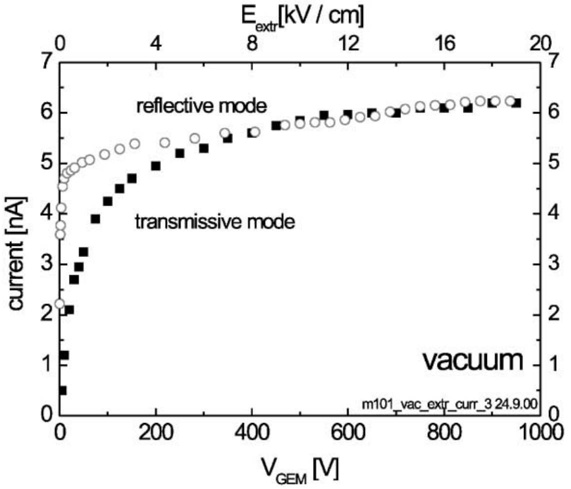

Fig. 4. Photocurrents measured on mesh M2 (circles) as a function of the extraction field E_{extr} and on the uncoated GEM face (squares) as a function of V_{GEM} in vacuum (10^{-5} Torr).

In transmissive mode, the GEM voltage, V_{GEM}, is the most important parameter. Photoelectrons will follow the field lines from the photocathode surface into the holes. The higher the GEM voltage, the stronger is the field at the coated surface and the focusing into the holes, thus the higher is the electron detection efficiency. In order to have a complete account of the electron flow, the mesh M3 and the uncoated lower GEM face were interconnected; the photocurrent on them was measured as a function of V_{GEM} (Fig. 4) with a grounded pico-amperemeter. The coated, upper GEM electrode and the mesh M2 were kept at the same potential V_{GEM}. It can be seen that around 350 V a plateau starts and the photocurrent further rises moderately, identically to the reflective mode. This indicates full extraction of the photoelectrons through the GEM holes in vacuum.

4.2. Measurements in gas

The measurements in vacuum show that in order to operate the detector efficiently in transmissive mode, high GEM voltages, above 500 V, have to be applied. This requirement is not always compatible with stable operation in gas. In addition, since the photoelectrons are emitted into the gas, one has to consider its properties regarding electron backscattering [13]. We chose methane at atmospheric pressure, a gas known to sustain high operation potentials and having practically no electron backscattering because of its high cross section for inelastic collisions with electrons. The latter makes photoelectron extraction from a photocathode in methane practically as efficient as in vacuum, at relatively low electric fields [13].

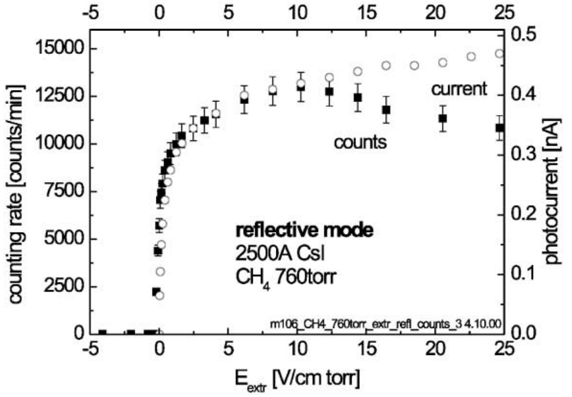

Fig. 5. Variation of the photocurrent (circles) and counting rate (squares), versus the extraction field. The CsI-coated GEM detector is operated in the reflective mode.

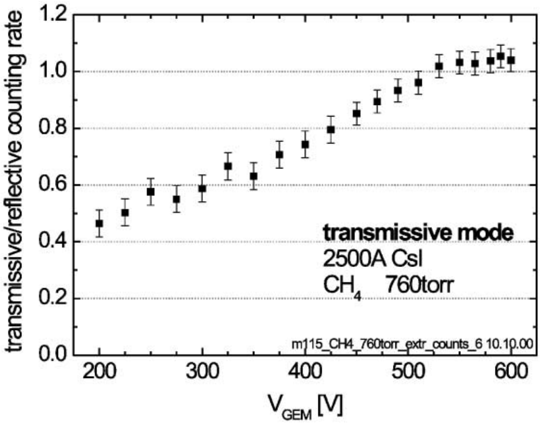

Fig. 6. Detection efficiency of photoelectrons extracted through the GEM holes, derived from the ratio of counting rates in transmissive and reflective modes. Full efficiency is reached at GEM voltages above 525 V. The mesh M2 was kept at the same potential as the coated GEM face. The transfer field E$_{\mathrm{trans}}$ was 5 V/cm Torr.

In Fig. 5 the photocurrent measured in reflective mode is plotted versus the extraction field E$_{\mathrm{extr}}$. The same behavior as in vacuum can be observed: a sharp rise followed by a moderately slanted plateau. The counting rate curve as a function of E$_{\mathrm{extr}}$ in reflective mode is also included in Fig. 5. Up to $\approx$ 10 V/cm Torr the two curves have the same shape but for higher fields the counting rate decreases. This is due to the fact that in the photocurrent measurement the electrons are collected on the mesh M2, whereas in the pulse-counting mode the electrons are transmitted through M2 and are multiplied on the multiwire anode wires. For a fixed voltage on the multiwire anodes the transmission efficiency of M2 drops with increasing field E$_{\mathrm{extr}}$, resulting in a counting rate decrease [7].

Assuming that the *counting rate* curve can be corrected for this loss of counts according to the *current* curve, we extrapolated the counting rate in reflective mode at 25 V/cm Torr and used this value for normalization.

In transmissive mode, photoelectrons emitted from the CsI photocathode have to be extracted and transferred through the GEM holes. Again, as in vacuum, the GEM voltage is the most important parameter for this process. Electrons entering the GEM holes undergo the first gas multiplication step and then drift towards the following multiwire element MWPC$_T$. Of course, a fraction of the electrons leaving the GEM holes is always collected on the lower GEM side instead of being transferred to the MWPC$_T$ anode. The influence of the GEM gain and the electric field E$_{\mathrm{trans}}$ on the charge transfer towards the following element was studied in detail in Refs. [7,14] and is well understood. No discrepancy between the results described there and the present CsI-coated GEM were observed. In all measurements presented here the value of E$_{\mathrm{trans}}$ was chosen high enough to guarantee that even at low gains at least one electron is transferred towards MWPC$_T$, assuring no loss of pulses.

Fig. 6 shows the counting rate in transmissive mode, normalized to the extrapolated plateau value of the counting rate in reflective mode, as function of the GEM voltage V$_{\mathrm{GEM}}$.The slower rise in counting rate, compared to the current rise in the vacuum measurement (Fig. 4) is probably due to electron losses on the GEM lower face, GEM insulator substrate and electron backscattering. The measurement was limited by a maximum GEM voltage of 600 V that could be safely applied prior to discharges occurring within the GEM.

At a GEM voltage of 525 V a plateau in the counting rate is reached, at a value identical to that

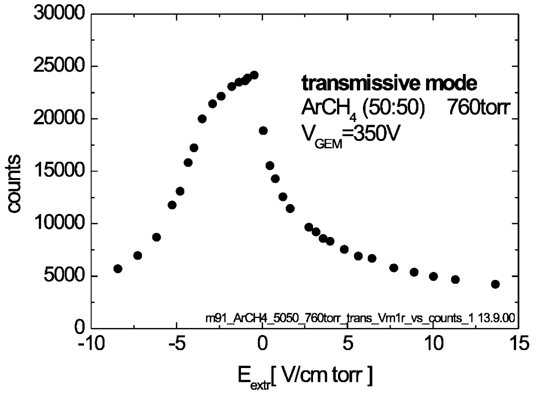

Fig. 7. Influence of the extraction field E_{extr} on the counting rate in transmissive mode.

estimated for the counting rate plateau in reflective mode. This clearly indicates that all electrons released from the photocathode are transfered through the GEM and are efficiently detected at the multiwire element.

This efficient detection of photoelectrons requires both efficient photoelectron extraction from the photocathode and their efficient transmission through the GEM holes. Both processes are not only influenced by the GEM voltage, V_{GEM}, but also by the extraction field E_{extr} (Fig. 7). A positive E_{extr} adds to the GEM field on the photocathode surface and helps to extract the photoelectrons. But, depending on its strength, a fraction of the photoelectrons is deflected towards the mesh M2 and thus leads to reduced counting rate in transmissive mode. On the other hand, a negative E_{extr} reduces the field strength on the surface and thus the probability of electron extraction.

According to Fig. 7, the optimum is at E_{extr} equals zero or slightly negative. Namely M2 should be kept at about the same potential as the CsI-coated GEM side.

5. Summary

We demonstrated that conditions can be found for providing stable and efficient operation of a CsI-coated GEM photodetector. The main advantages of this detector are the elimination of photon feedback and high photon detection efficiency. We measured high absolute QE of the CsI-coated GEM, of 35% at 150 nm, superior to the values reachable with window-deposited semitransparent photocathodes; the optimal deposition of the latter is very difficult over large area. We have demonstrated that high photoelectron detection efficiency is reached with high V_{GEM}; namely the field at the photocathode has to be high to ensure full focusing of the photoelectrons into the GEM holes. Unfortunately with standard GEM geometry this implies high GEM gain, and therefore could result in some unstable operation. Optimization of the GEM electrode geometry for photocathode-coated GEM operation mode and further investigation of ion and photon feedback effects are currently under way at our laboratory.

The CsI-coated GEM detectors pave ways towards conceiving high-efficiency gas photomultipliers, using multi-GEM structures. The results achieved in this work open a possibility for designing photon detectors for visible-light, including photocathodes deposited on top of GEM-like elements made of clean materials such as glass or ceramics. Possible electron multipliers are gas-filled MCP plates, that offer high gain in a two-stage operation mode [15]. Similar to the coated GEM, reflective photocathodes can be deposited on metallic meshes [16] preceding other types of gas avalanche electron multipliers. CsI deposited on top the micro-mesh cathode of a MICRO-MEGAS detector is one example [17], however, the absolute QE value is low due to the very high optical transparency of the mesh.

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