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Field-dependent photoelectron extraction from CsI in different gases

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Abstract

We present the results of our latest investigations, made in the laboratory and in a RICH detector, of the dependence of the UV quantum efficiency (QE) of CsI on the gas and the electric field. We confirm that in charge collection mode the QE in a gas is generally lower than in vacuum due to electron backscattering; in charge multiplication mode the QE increases with the field and reaches the vacuum value at high gas gains. The lowest photoemission under low electric field at the photocathode surface was observed in He-based gas mixtures; in Ar–hydrocarbon mixtures it approaches that of pure hydrocarbons. In CH₄ and in CH₄/i-C₄H₁₀ the QE value is practically independent of the field and is close to that in vacuum. The implications of CsI-based UV-detectors, particularly to fast RICH devices, are discussed.

1. Introduction

Recent investigations suggest that UV-photon imaging detectors based on CsI solid photoconverters coupled to gaseous electron multipliers, could be adequate for the Ring Imaging Cherenkov (RICH) technique [1–4]. The quantum efficiency (QE) of the CsI photocathode is one of the major parameters in this technique. It was recently demonstrated that the electron extraction probability from CsI is strongly dependent on the gas and on the electric field [5,6].

Already 40 years ago it was recognized that once escaped from the photocathode the photoelectrons diffuse back, even in the presence of an electric field, due to elastic collisions with the gas molecules [7]. In particular, it was observed that the backscattering contribution is large for monoatomic, noble gases and can be very small for some molecular gases such as CH₄ or CO₂ [8–12].

The results mentioned in the literature were obtained in a charge collection mode, and only recently photoelectron extraction efficiency under gas multiplication has been investigated in some hydrocarbon gases: CH₄, C₂H₆ and i-C₄H₁₀, in the pressure range 20–60 Torr [5]. It was demonstrated that the QE of CsI as a function of the electric field is rather constant in the charge collection

mode, and has a value depending on the nature of the gas. In the gas multiplication mode it enhances in coherence with the gas multiplication commencement. It was clearly observed that the QE in all gases studied approaches the QE value in vacuum, under high gas multiplication. In CH₄, the QE is rather constant and reaches 97% of the vacuum value at low fields, in the collection mode. This behaviour is explained by a reduction of the elastic backscattering due to dominating inelastic processes, i.e. ionization and excitation, in the multiplication region. Indeed, the electron direction of motion is only slightly perturbed by inelastic collisions, in contrast to the randomization of the velocity vector in elastic collisions. It was predicted that any gas, including noble gas mixtures, should obey such a universal behaviour [5].

In the present work, the combined effects of electric field, gas and pressure on photoelectron extraction from CsI are further investigated at higher pressures and in a variety of gas mixtures: CH₄, CH₄/i-C₄H₁₀, He/CH₄, He/i-C₄H₁₀, Ar/CH₄ and Ar/i-C₄H₁₀, in the pressure range 200–800 Torr. Present laboratory measurements were compared to photoelectron counting measurements in a RICH detector.

2. Experimental setup and procedure

The systematic measurements of the dependence of the CsI quantum efficiency on the electric field and on the gas

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and pressure were carried out in the laboratory, both with a single photon counting and in a DC current technique. The results in some mixtures were compared with those measured in a CsI-based wire chamber, in a RICH experiment.

The experimental setup was similar to that described elsewhere [5], replacing the two-stage gas amplification device by a three-stage one. The latter provided more stable operation at higher pressures. The experimental device consists of a two-stage parallel-plate chamber coupled to a multiwire proportional element. The CsI photocathode acts as a source of photoelectrons and a cathode of the first parallel-plate amplification element. The flux of UV-photons from a pulsed H₂ lamp in air was reduced to a single photon level. The average wavelength of photons hitting the photocathode is estimated to be about 190 nm. The measured value was the number of photoelectrons per UV-light pulse, which is proportional to the QE value. The procedure of the determination of this number is described in Ref. [5].

The measurements in the DC current mode were made with a photocathode coupled to a single mesh electrode. The pulsed lamp was replaced by an intense continuous flux lamp, either that of Hg(Ar) or D₂, with a selected wavelength of 185 nm. A picoammeter was connected to the photocathode. For each gas mixture the UV-induced photocurrent was measured first in gas and then in vacuum at the same absolute electric field values. The DC current technique was used to estimate the gas gain as well.

Other details of the apparatus and of the measurement procedure are presented in Ref. [5].

The QE of large area photocathodes (30 × 30 cm²) was evaluated using a RICH detector in a proximity focusing geometry as discussed in detail in Refs. [3,4]. The photo-sensitive CsI layer was deposited on the cathode of a wire chamber, segmented into pads, providing a 2-dimensional localization of the photoelectrons. The QE of the photocathode is obtained using the Frank–Tamm formula, on the basis of the number of counted photoelectrons per Cherenkov ring, taking into account the experimental conditions [4].

3. Results

3.1. Laboratory measurements

Fig. 1 shows the relative QE and the gas gain for He/CH₄ (95/5) and He/i-C₄H₁₀ (95/5) at 800 Torr, as a function of the reduced electric field, E/p , at the photocathode surface. At low fields in the charge collection mode, the QE increases and reaches a plateau at $E/p = 2$ V/cm·Torr, in accordance with the data in Ref. [11] for the same gas mixture. When the gas multiplication starts, approximately at $E/p = 5$ V/cm·Torr, the QE increases again and reaches a second plateau, at a gain value

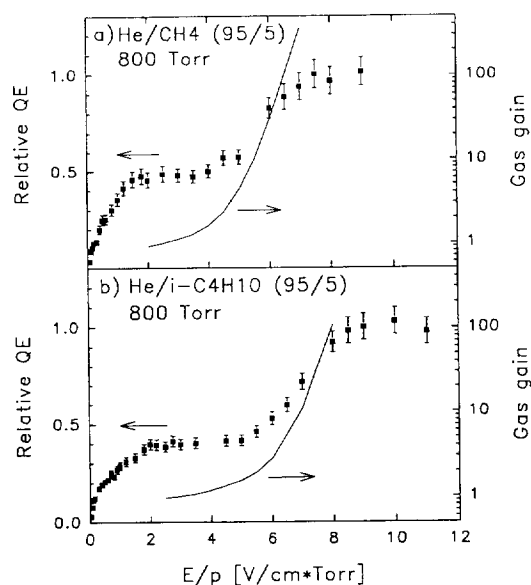


Fig. 1. The relative quantum efficiency of CsI, measured with the photon counting technique at about 190 nm, and the gas gain, as a function of the reduced electric field in He/CH₄ (95/5) and He/i-C₄H₁₀ (95/5). The QE data points are normalized to the last three points averaged.

of the order of 100. The QE data points are normalized to the value at this second plateau, obtained by averaging over the three last points. As one can see from the figure, the ratio between the QE values at the two plateaux is 50% in He/CH₄ and 40% in He/i-C₄H₁₀.

Fig. 2 shows, for the same gas mixtures and pressure, the ratio of the photocurrent in gas to that in vacuum. The value of this ratio in the middle of the charge collection plateau, around $E/p = 2.5$ V/cm·Torr, amounts to about 45% for both mixtures. This is very close to the ratio of the QE in the charge collection mode to that in the multiplication, obtained with the photon counting technique (see

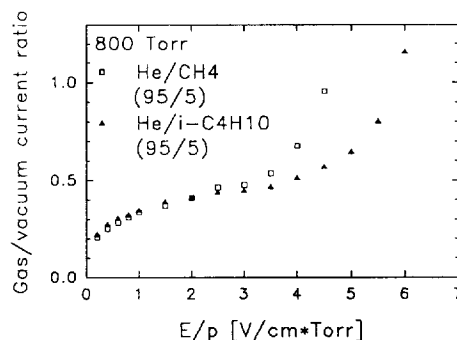


Fig. 2. The ratio of the photocurrent from CsI, at 185 nm, in He/CH₄ (95/5) and He/i-C₄H₁₀ (95/5) to the photocurrent in vacuum (measured at the same absolute electric field values), as a function of the reduced electric field in gas.

above, Fig. 1). This fact, established now for a noble gas-based mixture, supports our statement [5], that the QE value in gas in multiplication mode approaches the QE value in vacuum.

The Ar-based gas mixtures were studied with the DC current technique only. Fig. 3 shows the ratio of the photocurrent in gas to that in vacuum, measured in Ar, Ar/CH₄ (80/20), Ar/CH₄ (50/50) and Ar/i-C₄H₁₀ (80/20) at 770 Torr. The photocurrent in pure Ar at the end of the charge collection plateau is about 40% of that in vacuum. It is in accordance with the literature [8,10,12] and by a factor of 2–3 larger compared to that observed in pure He [9,12]. The lower backscattering in Ar-based mixtures results in photocurrents in the charge collection mode reaching 70–80% and 90% of the vacuum value in Ar/i-C₄H₁₀ (80/20) and Ar/CH₄ (50/50), respectively. This is very close to the respective QE values in i-C₄H₁₀ [5] and CH₄ (see below).

It is interesting that in Ar/i-C₄H₁₀ the gas multiplication starts earlier than in Ar/CH₄, in contrast to He-based mixtures (see Fig. 2). This observation can be explained by the Penning effect [13]: the ionization potential of i-C₄H₁₀ is lower than the excitation levels of Ar, leading to an additional channel for the avalanche development.

Fig. 4 shows the relative QE and the gas gain in CH₄ as a function of the reduced electric field, measured at 200, 400 and 800 Torr. The measurements at 800 Torr are limited to the low E/p values because of the chamber instability at higher fields.

Fig. 5 shows the relative QE and the gas gain in CH₄/i-C₄H₁₀ (95/5) at 200 and 400 Torr. This mixture is favorable for application in photon imaging detectors due to its better quenching properties as compared to pure CH₄. The rather flat relative QE graph indicates that this mixture preserves the advantage of CH₄.

All the data points in Figs. 4 and 5 are normalised to the QE value, averaged over the points measured at E/p values

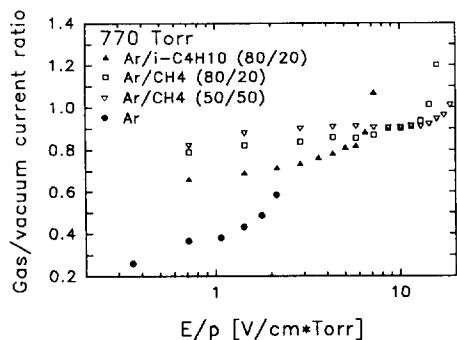


Fig. 3. The ratio of the photocurrent from CsI, at 185 nm, in Ar, Ar/CH₄ (80/20), Ar/CH₄ (50/50) and Ar/i-C₄H₁₀ (80/20) at 770 Torr to the photocurrent in vacuum (measured at the same absolute electric field values), as a function of the reduced electric field in gas.

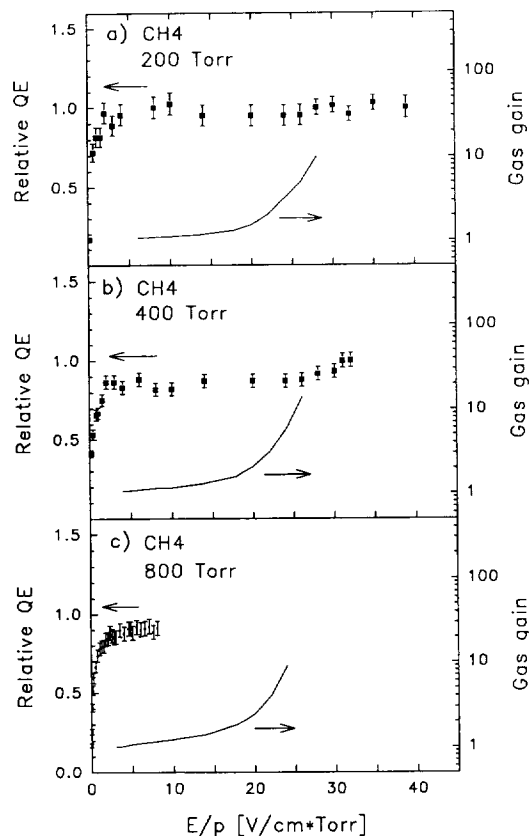


Fig. 4. The relative quantum efficiency of CsI, measured with the photon counting technique at about 190 nm, and the gas gain, as a function of the reduced electric field in CH₄ at 200, 400 and 800 Torr. For 200 and 400 Torr the QE data points are normalized to the points at $E/p \geq 30$ V/cm · Torr, averaged.

higher than 30 V/cm · Torr (under gas gain of the order of 100). The normalization for 800 Torr CH₄ is somewhat arbitrary, using the data from the photocurrent ratio measurements.

Comparing the results at 200 and 400 Torr one can deduce a very small dependence of the QE on the electric field, in pure methane. The dependence on pressure is small as well. The results obtained with CH₄/i-C₄H₁₀ mixtures indicate that the presence of isobutane, even in small percentage, decreases the QE in the collection plateau, but to a very small extent.

Fig. 6 shows the ratio of the photocurrent (in DC technique) in gas to that in vacuum for CH₄ at 200 and 800 Torr and CH₄/i-C₄H₁₀ at 800 Torr. The results are in good agreement with those obtained with the photon counting technique. The dependence of the QE on the gas pressure is more evident compared to Figs. 4 and 5. The photocurrent ratio in the middle of the charge collection plateau has a value of about 90% in 800 Torr CH₄ and about 87% in 800 Torr CH₄/i-C₄H₁₀; in 200 Torr CH₄ this

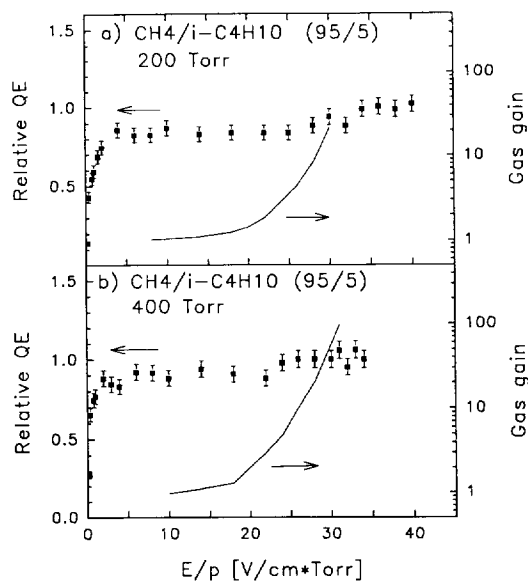


Fig. 5. The relative quantum efficiency of CsI, measured with the photon counting technique at about 190 nm, and the gas gain, as a function of the reduced electric field in $\text{CH}_4/i\text{-C}_4\text{H}_{10}$ (95/5) at 200 and 400 Torr. The QE data points are normalized to the points at $E/p \geq 30 \text{ V/cm} \cdot \text{Torr}$, averaged.

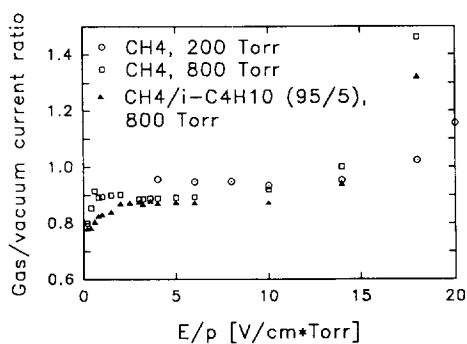


Fig. 6. The ratio of the photocurrent from CsI, at 185 nm, in CH_4 at 200 and 800 Torr and in $\text{CH}_4/i\text{-C}_4\text{H}_{10}$ at 800 Torr to the photocurrent in vacuum (measured at the same absolute electric field values), as a function of the reduced electric field in gas.

Table 1

The ratio (R_{pe}) of the number of photoelectrons measured in the gas mixture to that in CH_4 , at 1 atm, obtained in the RICH detector and the ratio (R_l) of the photocurrent at 185 nm measured in the gas mixture to that in CH_4 , obtained in the laboratory

Gas mixture	E/p [V/cm · Torr]	R_{pe} (RICH)	R_l (Lab.)
Ar/ $i\text{-C}_4\text{H}_{10}$ (80/20)	3.0–3.1	0.73–0.76	0.81
Ar/ CH_4 (80/20)	3.1	0.78	0.93
Ar/ CH_4 (50/50)	3.7–3.8	0.88–0.94	1.0
Ar/ $\text{CH}_4/i\text{-C}_4\text{H}_{10}$ (86/7/7)	2.7–2.8	0.82–0.86	–
He/ $i\text{-C}_4\text{H}_{10}$ (80/20)	2.5	0.55	–
He/ $i\text{-C}_4\text{H}_{10}$ (95/5)	2.5	–	0.49
He/ CH_4 (95/5)	2.5	–	0.51

ratio is higher, about 95%, in coherence with the results obtained at 60 Torr CH_4 [5].

3.2. Measurements with RICH

The QE of the photocathode was first measured in pure CH_4 . A potential was applied to the wire chamber, resulting in a E/p value of around $4 \text{ V/cm} \cdot \text{Torr}$ at the CsI surface. Laboratory measurements (Fig. 6) indicate that at such fields the QE value of the photocathode in CH_4 is about 90% of the maximum nominal vacuum value. Then the detector, with the same photocathode, was circulated with different noble gas-based mixtures. The mean numbers of photoelectrons per ring were compared to that obtained with CH_4 .

The detection of the Cherenkov photons was affected by particle- and photoelectron avalanche-induced secondary photon effects. In case of CH_4 , that background contribution was 5–7% of the Cherenkov photon yield. In Ar/ CH_4 (50/50 and 80/20) and He/ $i\text{-C}_4\text{H}_{10}$ (80/20) the background increased to a 20–30% level, making the counting of the Cherenkov photons more difficult. On the contrary, in Ar/ $i\text{-C}_4\text{H}_{10}$ (80/20) that level was found to be similar to that in CH_4 . The data shown below are corrected for these secondary effects.

Compared to CH_4 , a decrease of the QE was observed in these mixtures, as seen in Table 1. Table 1 shows the ratio of the number of photoelectrons measured in the gas mixture to that in CH_4 , at 1 atm, in the RICH detector. For comparison, also shown in the table is the recalculated data obtained in the laboratory: the ratio of the photocurrent at 185 nm in the gas mixture to that in CH_4 , at the reduced field values similar to that applied at the CsI surface in the wire chamber of the RICH detector. Comparing these two sets of measurements one can see a reasonable agreement between the data.

4. Summary and conclusions

We further investigated the electric field effects on the quantum efficiency (QE) of CsI in hydrocarbon- and noble

gas-based mixtures, at pressures reaching 1 atm. We confirm that the photoelectron extraction from solid photocathodes into gas media has a universal behaviour as a function of field. In a charge collection mode, the QE is lower than that in vacuum and is independent of the field. In a charge multiplication mode, the QE increases with the field and reaches the vacuum value at high gas gains. The most pronounced behaviour, leading to a very large difference in the QE between the collection and multiplication modes, was observed in He-based gas mixtures, while losses in QE observed in Ar-hydrocarbon mixtures approach that in pure hydrocarbons. In pure CH₄ and in some CH₄-hydrocarbon gas mixtures the QE is practically independent of the field and is close to that in vacuum even at low fields and at atmospheric pressure.

These results are explained by the difference in extraction efficiency of photoelectrons from CsI, which depends on the elastic backscattering probability from different gas molecules. At high gas gain elastic backscattering is taken over by inelastic collisions, resulting in a QE value equal to that in vacuum, independently of the gas nature. A more quantitative analysis of the results obtained will be possible after the next step of the present study, when the process of electron transport in gas mixtures will be simulated. Preliminary results of this computer simulation confirm the trends in the experimental results. The consequences of this study are of great relevance to the design of CsI-based wire chambers for UV-photon imaging in RICH. They open the possibility of reducing the amount of flammable gas in very large systems, as proposed for example for the ALICE/LHC experiment. However, it necessitates further studies.

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