USE OF TMAE IN A MULTISTEP PROPORTIONAL CHAMBER
FOR CHERENKOV RING IMAGING AND OTHER APPLICATIONS

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ABSTRACT

We tested a multistep proportional chamber of $20 \times 20 \text{ cm}^2$ active area, conceived to localize single vacuum ultraviolet photons. The detector has a capability of imaging large multiplicities of Cherenkov rings with a high density of detected photoelectrons, and uses tetrakis(dimethylamine)ethylene, with a threshold of 5.4 eV, as the photo-ionizing vapour. Time slicing in a conversion gap reduces the multiplicity at a given instant of time by a large factor, and permits the use of simple methods of localization. Separation of the amplifying gaps solves the problems of photon feedback encountered, at high gains, with single-step detectors. We also discuss an application of this chamber for the detection of superheavy monopoles if they have a speed in the range of the electron drift velocity.

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1. INTRODUCTION

Efficiency and localization properties of gas proportional chambers in the detection of ultraviolet (UV) photons have recently been extensively studied in view of their use for Cherenkov Ring Imaging, a technique that permits identification of fast charged particles in a wide range of velocities [1,2]. A new device, the multistep proportional chamber, operated with a photosensitive gas filling, allows the attainment of the large amplification factors (10^6 or more) necessary in order to conveniently detect and localize single electrons released in the gas by photoelectric effect [3]. Efficiency and localization properties of the device, when operated with triethylamine (TEA, $E_i = 7.5$ eV) as the photosensitive vapour, have been extensively studied [4,5].

Because of its good time and space resolutions (50 ns and 350 μm , respectively), the detector is particularly suitable for use in high-flux, very high momentum set-ups; two large-area multistep proportional chambers are indeed mounted on a 16 m long helium radiator in the first operational ring-imaging particle identifier, installed in Experiment E605 at Fermilab. Results of the test runs have been reported and are up to expectations [6,7].

Use of TEA is very convenient because of its high vapour pressure (55 Torr at 20 °C) that allows both high proportional gains and good time resolutions to be obtained. It implies, however, the use of calcium or magnesium fluoride windows and particular care concerning the purity of the radiating medium in order to avoid absorption losses. The choice of radiators is indeed restricted to pure noble gases and fluoride crystals. The use in the detector of an induced-charge cathode read-out method for localization limits, moreover, the maximum number of simultaneous photons in a ring that can be unambiguously detected to around 5.

A vapour having much lower ionization potential, tetrakis(dimethylamine)-ethylene (TMAE, $E_i = 5.4$ eV) was introduced several years ago [8] and has been adopted since in the time-projection chamber (TPC) design for Cherenkov Ring Imaging [9,10]. Opening up the possibility of using a large variety of radiators

and a fused silica window, photon detectors using TMAE are very attractive for large-area, intermediate momentum particle identifiers. The TPC approach is favoured by the very low vapour pressure of TMAE (0.5×10^{-5} Torr at 20 °C), which implies a rather thick detection layer, of about 4 to 5 cm. This leads, however, to serious background problems when charged particles are also allowed to traverse the detector. The long drift-times due to the lateral motion towards the detecting wires can also be a nuisance for high-rate experiments.

Moreover, severe problems of photon feedback have been met, because of the long path of photons emitted in the avalanches, limiting the maximum practical gain to 10^5 or less (with obvious electronics implications) and requiring a particular design of the anode structure to limit spurious points [10].

We present, in what follows, preliminary results obtained using a multistep proportional chamber, redesigned in order to allow operation with TMAE; they suggest that photon feedback can be completely suppressed by the double-gain structure, and that by recording both timing and amplitude information the intrinsic limitation of the bi-dimensional cathode read-out method in handling many simultaneous points as in a ring image can by and large be overcome.

2. THE MULTISTEP PROPORTIONAL CHAMBER USING TMAE

The original multistep proportional chamber design, conceived for the use of a high concentration of photosensitive vapour, had to be modified for operation with TMAE because of the much larger absorption length for photons, around 30 mm at room temperature. We have correspondingly increased the thickness of the conversion region to 50 mm, and, to reduce photon feedback (see below), also the thickness of the transfer region to the same value (see fig. 1). The thin-gap preamplifying structure and the multiwire proportional chamber (MWPC) were left unmodified; a field cage with graded potentials all around the edges was added to guarantee a uniform field in the thick regions. A drift field is created in the conversion region, applying a suitable potential between the upper mesh (in contact with the window) and the first mesh of the preamplifying gap; similarly a transfer field is created between the preamplifying gap and the MWPC end structure.

The operation of the multistep proportional chamber is briefly described as follows. A charge released in the upper gas layer is caused to drift into a region of very high field, the preamplification space, where avalanche multiplication occurs. This region is realized using two well-stretched meshes, 4 mm apart, with a particular profile on the frame side to avoid edge breakdown (see ref. 4). A fraction of the total electron charge produced in the avalanche, typically 10-20%, is injected into the transfer region and proceeds towards the second element of amplification, a conventional thin-gap MWPC with bi-dimensional cathode read-out.

Separating the overall multiplication process into two steps, as described in the early works on the subject, allows combined gains to be reached far in excess of the ones that could be reached in each element separately. This is partly due to the fact that photons emitted in the last avalanche have a very small probability of getting all the way through into the conversion region with the consequence of suppressing secondary effects that lead to a discharge. While using TEA (or indeed any photosensitive vapour in high concentration) the most relevant outcome of the mechanism is that it allows large gains; in TMAE one expects the suppression of the so-called "satellites" or spurious electron signals observed in Cherenkov Ring Imagers around the main event [9,10].

As gas filling for the detector we have tried various combinations of argon and helium with methane, ethane and isobutane, always saturated with TMAE at 20 °C. The highest gains and best localization properties have been obtained with He-C₄H₁₀-TMAE, a convenient gas mixture because of its low drift velocity (saturated around 2 cm/μs, see below) and low specific ionization for charged particles.

3. EXPERIMENTAL SET-UP

The multistep proportional chamber used for the present work had the structure shown in fig. 1 and an active area of 200 × 200 mm². In the MWPC section, the two cathode planes, perpendicular to each other, are made of copper-beryllium wires, of 100 μm diameter, 1 mm apart; the anode wire plane is realized with 20 μm gold-plated tungsten wires, 2 mm apart, mounted at 45° with respect to the cathodes.

All anode wires and pairs of cathode wires were equipped with individual charge amplifiers for timing and pulse-height recording.

All other electrodes in the structure are realized with a good-quality crossed-wire stainless-steel mesh having 0.5 mm pitch. The preamplifying grids, stretched originally over a 5 mm thick frame, are pushed inwards by a suitably shaped frame to reduce the gap to 4 mm, except along the edges, so as to avoid edge sparking [4].

The gas volume is delimited on one side by the UV transparent window (a mosaic of four CaF_2 crystals mounted as described in ref. 4), and on the other by two foils of 50 μm thick Mylar-Aclar, 5 mm apart; the filling gas is made to flow between the two foils before evacuation, thus preventing the pollution of the inside volume from the outside atmosphere by diffusion through the thin window.

Gain and localization properties of the detector were studied, irradiating the chamber from the thin window side with X-ray sources, or through the CaF_2 window with a photon source. This source, described in more detail in ref. 4, consists of a layer of gas between two grids traversed by α particles emitted by an internal radioactive source. Photons are emitted, with a spectrum characteristic of the gas filling, either by direct primary scintillation or by secondary scintillation of the drifting ionization electrons if the electric field is increased. A charge amplifier on one mesh is used to detect the ionization, thus allowing precise timing of the decay for triggering purposes. Using Xe as the gas filling scintillation occurs around 7.5 eV, appropriate for detection with TMAE.

For part of the measurements we have also used a pulsed N_2 gas laser beam, entering the detector through the window and inclined at about 45° . Ionization is produced in this case not directly (the laser emits at 337 nm, or 3.7 eV) but by multiple excitations; varying the beam intensity, we could cover a very wide range of specific ionization, from 10^6 down to a few electrons per centimetre.

Each anode wire and pairs of adjacent cathode wires were equipped with charge amplifiers having sensitivities of 200 and 600 mV/pC, respectively. Optimized to perform localization by the centre-of-gravity method, these amplifiers were relatively slow and not optimal for getting timing information. Pulse height and time could be recorded on each channel using a linear splitter on the amplifier output, with a set of CAMAC-based multiple analog-to-digital (ADC) and (after discrimination) time-to-digital (TDC) modules. The gating and timing signals were provided by the discriminated charge signal on the UV xenon source or, when using the N₂ laser, by a photodiode pick-up on the main beam.

As gas filling we tested several combinations of argon or helium with methane or isobutane; the mixture was bubbled through a small volume of TMAE at room temperature. To avoid the problems connected with the chemical activity of TMAE (it combines with oxygen producing oily pollutants) the complete gas system, down to the chamber input, could be evacuated and purged with a pure noble gas. To estimate the TMAE concentration in the mixture, we assumed a saturated vapour pressure at room temperature. During about a month of continuous operation we had no problems with the TMAE manipulation system, except for a slight opacity on the outer Mylar layer probably due to the described chemical reaction with oxygen molecules diffusing through the thin outer window.

Figure 2 shows measured values of drift velocity as a function of field in several gas mixtures containing TMAE; they were realized with the method outlined in section 5. It appears that addition of TMAE does not sensibly modify the drift velocity curves, at least for the mixtures we have investigated.

4. EXPERIMENTAL RESULTS OBTAINED WITH X-RAY AND UV SOURCES

Gain curves were measured, irradiating the drift volume in the chamber with a 5.9 keV X-ray source and recording the pulse-height spectra on the anode plane. For most of the measurements we kept the drift and transfer fields at constant values, about 800 V/cm. In the transfer region this is somewhat at the lower end of the useful range and implies a small transfer efficiency (around 15%); use

of larger fields, however, would imply reaching excessive potentials on the upper grid (because of the peculiar composite window mounting, the maximum safe potential that can be applied to this electrode is around 10 kV).

A typical gain curve obtained for a He-CH₄-TMAE mixture is shown in fig. 3. The MWPC potential is set so as to obtain a gain of about 3.5×10^3 in this element, and increasing the difference of potential between the 4 mm apart preamplifying grids the overall gain is increased to its maximum safe value of about 7×10^5 . In fig. 4, obtained in a He-C₄H₁₀-TMAE mixture, two curves are shown for different initial settings of the MWPC gain; the maximum overall gain that can be reached is about the same. Notice the deviation from a pure exponential behaviour at the highest gains, probably due to space-charge effects.

Although definitely smaller than the gains observed when using TEA in a similar structure, the quoted multiplication factor above 5×10^5 exceeds by an order of magnitude what could be obtained using the MWPC alone in the same gas mixture. The repartition of gains between the two elements implies that a photon emitted in the last avalanche and reconverted within the MWPC or transfer regions should not be detected. Photons emitted in the first avalanche are, of course, much reduced in number due to the moderate gain, about 10^3 , of the preamplification region (as clear from figs. 2 and 3 and taking into account the quoted transfer efficiency).

We have used the timing UV source, described in section 3, to study the detection efficiency for single photons of the chamber. Mounted on the CaF₂ window side and suitably collimated, the source was operated in the primary scintillation mode (i.e. with a very small collection potential). Evidence of single-photoelectron operation is obtained both from the value of the recorded efficiency (around 20%) and by simple oscilloscope observation of detected pulses: because of the long absorption length (30 mm), pulses due to several individual photoelectrons are generally well separated in time, see figs. 5a and b. The procedure was then as follows: starting with a source intensity such as to produce on one wire the signal structure shown in fig. 5, the source collimation was further increased so

as to have single pulses within the drift-time in about 20% of the events. This guarantees that multiple photoelectron pulses within the time window are very unlikely.

In such conditions the drift-time spectrum of detected pulses was recorded, the time zero being provided by the charge signal on the UV source. Although detection of this slow signal is not free from time jitter, operating the source without the secondary scintillation enhancement guarantees at least that all photons are emitted by primary scintillation within a very short time. Figure 6a shows an example of a recorded time spectrum; the long lines correspond, of course, to conversions close to the CaF_2 window, and the shape of the spectrum provides the absorption mean free path of ~ 30 mm compatible with the known TMAE cross-section for room-temperature operation. Notice the sharp transitions on both sides of the spectrum, the first evidence that timing is rather well preserved despite the multiple avalanching process.

The time spectrum in fig. 6a has been recorded on a single anode wire, facing the collimated source; to obtain information on satellites or background counts, we have recorded for the same amount of time the spectrum on a wire 16 mm apart (fig. 6b). The residual counts observed do not have the time structure one would expect in the case of photon-induced background, and are indeed compatible with a purely accidental distribution (events were accumulated over several minutes, with a single-electron sensitivity). In other words, we have seen no evidence of secondary, photon-induced background signals, as anticipated because of the double gain structure of the detector.

Pulse-height spectra for single photoelectrons are not as good in TMAE as they were for the TEA operation, where much higher gains could be obtained. An example is shown in fig. 7; a peaked structure begins to appear (counts in the lower channels are due to amplifier noise), but the distribution remains essentially exponential.

The picture in fig. 8 shows a single-electron event as recorded on the pulse-height measuring system: each bin in the picture represents a 2 mm wide electrode,

and the three distributions correspond respectively to the anode and the two cathode planes. Because of the long absorption length for photons in the drift volume and of the angular divergency of the source, we could not measure the localization accuracy in the MWPC plane; everything indicates, however, that it should not be very far from what was measured in the TEA operation (350-400 μm standard deviation, see ref. 4). Charge is shared between two adjacent anode wires (2 mm apart) in most of the events, giving an idea of the spatial extension of the preamplified charge and allowing interpolation.

5. EXPERIMENTAL RESULTS OBTAINED WITH THE N_2 LASER BEAM

In order to study the timing properties of the detector we have used as source of ionization a pulsed N_2 laser having very high energy density and small-beam cross-section and divergency^{*)}. This kind of laser is currently used in the high-energy physics community for calibration purposes since it allows the creation, by multiple excitation processes, of ion pair trails with densities comparable with those produced by fast charged particles in gas along a line with sub-millimetre cross-section.

In our detector laser-induced ionization densities were dramatically enhanced by a factor of 10^4 or so, when adding TMAE. We could indeed detect charge signals and measure drift velocities operating the chamber at unity gain. The estimated charge density as produced by the 200 μJ , 0.5 mm^2 section, pulsed beam was about 10^6 pairs per centimetre. Moreover, strong light emission at green wavelengths was observed along the beam in the chamber (N_2 lasers emit in the blue, at 337 nm). This can be due either to some process of multiple excitation and subsequent decay, or to direct fluorescence (TMAE is known to have a strong absorption in the blue and re-emission around 500 nm [11]).

The beam could be attenuated using neutral density filters down to the point of obtaining single electrons at an average distance exceeding the wire spacing (a condition verified with the procedure described in the previous section).

^{*)} MOPA-400, produced by Multilasers S.A. (Geneva).

We have recorded the drift-time of the detected charge on a number of adjacent anode wires and fitted a straight line through the points to obtain information on timing accuracy. An example is shown in fig. 9, as recorded for a large ionization density on a group of 8 adjacent anode wires; the abscissa is the wire position (in 2 mm steps) and the ordinate the computed vertical coordinate. The localization accuracy at these large charge densities (about $10 \times$ minimum ionizing) is about 50 μm for an average drift over 7 cm. The slope of the correlation (given the angle of crossing of the beam), of course, provides the drift velocity: the curves in fig. 2 were indeed measured in this way.

Reducing the beam intensity so as to be close to the single electron per wire condition, the method provides the time dispersion corresponding to the detection of one electron (figs. 10a and b). Several physical sources contribute to the dispersion, such as the diffusion of electrons before and after preamplification, the statistical fluctuations in the size and shape of the preamplified avalanche, the electronics slewing due to the large dynamic range of the pulses. However, in our set-up, the largest contribution is purely geometrical, owing to the angle of crossing (45°) and the 2 mm anode wire spacing: charges are created along 2 mm vertically. Not surprisingly, the resulting time localization accuracy for one electron is rather modest in our set-up, having a FWHM of 250 ns or 4 mm (fig. 11). This is to be considered an upper limit, the real intrinsic dispersion due to all physical effects being probably about 2 mm FWHM. The geometrical dispersion can be avoided, of course, setting the laser beam along a line parallel to the anode plane, a condition that could not be realized in our set-up.

6. APPLICATIONS TO CHERENKOV RING IMAGING

We have shown that the multistep proportional chamber, in the modified version described, operates satisfactorily in various gas mixtures containing TMAE and allows the detection and localization of single photoelectrons produced by quanta of energy above the photoionization threshold of 5.4 eV. Using isobutane in the gas filling, photons are absorbed above ~ 7.3 eV, which roughly corresponds to a

UV grade quartz window cut-off. The spectral range of sensitivity can be extended, of course, by using methane or ethane with a fluoride window.

The possibility of recording both the pulse height and the drift-time of detected pulses offers two advantages. Firstly, roughly knowing the conversion depth one can correct the parallax error intrinsic in the detection of photons non-perpendicular to the window surface; our results indicate that a depth accuracy of the order of 2 mm can be achieved with the corresponding angular accuracy. Moreover, one can largely overcome the major drawback of the centre-of-gravity localization method, i.e. its inability to handle events with too many simultaneous photons. For a typical cathode-induced profile of 4 mm FWHM, and with Cherenkov rings of 60 mm radius, the reconstruction algorithm quickly becomes inefficient for events consisting of more than 5-6 points, because of the overlaps and ambiguities. The time spread of pulses in the TMAE detector essentially allows the recording of pulse height in many independent time slices. With charge amplifiers having 100 ns shaping constants, and using the low-drift-velocity He-C₄H₁₀-TMAE mixture (2 cm/ μ s) one can subdivide the conversion volume into about 20 time slices, thus correspondingly increasing the multiphoton handling capability of the device. This point requires, of course, further studies with a complete detector.

As far as the electronics is concerned, a system of charged coupled devices or of flash ADCs, such as the ones developed for time projection or imaging chambers, with 40-50 ns sampling rates would be adequate.

7. THE MULTISTEP PROPORTIONAL CHAMBER AS A DETECTOR OF MONOPOLES

The detector we have described has excellent single-electron imaging capability and low intrinsic noise as shown, for example, in figs. 8 and 9. In a search for exotic particles having an ionization power far below that of minimum ionizing particles, the addition of a thicker drift volume would increase the likelihood of recognizing an anomalous energy loss. For slow, superheavy monopoles an additional factor makes a drift detector quite attractive, namely the fact that their expected velocity at the earth surface is about the same as the drift velocity of electrons

in gases. A monopole traversing the detector at that speed would generate a very peculiar charge signal, very short or corresponding to twice the maximum drift-time depending on the direction of motion. A pair of multistep proportional chambers mounted back to back, or a single central MWPC with preamplification and drift on both sides, would produce a unique electronics signature for a slow monopole candidate, easily recognizable at the trigger level.

There remains the question of estimating the ionization power of slow monopoles. Recent calculations by Drell et al. [12] have shed light on the matter. According to those authors, monopoles having masses of the order of 10^{16} GeV, as predicted in some supersymmetry models, are expected to increase substantially their ionization above a threshold velocity of about 10^{-4} ; this threshold can be even lower, 3×10^{-5} or so, in heavy noble gases. Since this value corresponds to the velocity of a free falling monopole on the earth surface, the described detector seems ideal.

Using a drift volume 50 cm thick, even one electron released (and detected) every 25 mm would provide a recognizable track, at 1% minimum ionizing. In addition, one can adjust the electrons' velocity to be about 10^6 cm/s or 3×10^{-5} . The observation of an aligned trail of electrons at very low density, having an arrival time distribution corresponding to a very anomalous drift velocity, would provide a unique signature for a slow moving particle. There exists nowadays sufficient experience in the field of gaseous detectors to make a project with a sensitive area of $\sim 1000 \text{ m}^2$, which is not too unrealistic -- at least from the technical point of view.

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Figure captions

- Fig. 1 : The multistep proportional chamber adapted for the use of TMAE. Both the conversion and the transfer spaces have been increased in thickness to 50 mm, to cope with the photon absorption length. Charges produced in the upper gas layer (e.g. by photoelectric effect from a UV photon source mounted above the CaF_2 window) drift towards the central thin-gap parallel-plate preamplifying structure. A fraction of the electrons in the avalanche enter the transfer region and reach the lower MWPC, where further amplification occurs. Localization is realized recording both pulse-height distribution and time on anode and cathode wires in the MWPC.
- Fig. 2 : Electron drift velocity plotted against field for several gas mixtures containing TMAE at saturated vapour pressure (20 °C). Mixtures with helium are attractive because of the low saturated velocity, improving the vertical separation for a given accuracy in the drift-time measurement, and because of the low ionization density produced by ionizing tracks.
- Fig. 3 : Amplification curve in the multistep proportional chamber as a function of the potential difference between the preamplification grids (4 mm apart), for a fixed gain in the MWPC (3×10^3). Gas filling $\text{He-CH}_4\text{-TMAE}$, in the percentages 80-10-5 $\times 10^{-4}$.
- Fig. 4 : Amplification curves in the multistep proportional chamber, as a function of the preamplification voltage, for two values of gain in the MWPC (3.5×10^3 and 1.5×10^4). About the same maximum gain is reached before discharge ($\sim 7 \times 10^5$). Gas filling $\text{He-C}_4\text{H}_{10}\text{-TMAE}$, in the percentages 88-12-5 $\times 10^{-4}$.

- Fig. 5 : Multiphoton events detected on a wire of the MWPC; photoelectrons are produced in the conversion volume by a collimated UV source, described in the text. Because of the long (30 mm) absorption length, photoelectrons are well separated in time at low source intensities; a single photoelectron condition can easily be reached by collimation.
- Fig. 6 : a) Time spectrum of single detected photoelectrons recorded on an anode wire (time zero provided by the source). Longer times correspond to the photons converted close to the entrance window; the cut-off at the shortest time corresponds to the preamplification region.
b) Time spectrum recorded during the same time on a wire 16 mm from the one facing the source. The absence of time-correlated feedback photoelectrons is clear.
- Fig. 7 : Single photoelectron pulse-height spectrum at high gain (5×10^5). The shape is still close to an exponential, as against the peaked structure observed using TEA at higher gains (the peak in the lower channels is due to the noise of the amplifiers).
- Fig. 8 : Charge profile recorded for one photoelectron event on the MWPC; each bin represents an anode wire or a cathode strip, all 2 mm apart. The clusters correspond to the anode and the two cathode planes, from left to right. In most of the events two adjacent anode wires detect the avalanche, because of the dispersion produced in the preamplification, thus allowing interpolation. On cathodes, the FWHM of the induced signal is about 4 mm.
- Fig. 9 : Recorded drift-time on eight adjacent anode wires, 2 mm apart, for an ionization track produced in the conversion region by a N_2 laser at 45° .

Fig. 10 : a) and b). Drift-time recorded for two events on a set of eight adjacent anode wires, operating the laser beam at very low intensity so as to reach a single photoelectron per wire condition. The dispersion of the recorded time around the straight-line fit is due to both physical and geometrical factors.

Fig. 11 : Distribution of the measured drift-time for single electrons, around the average track position (see fig. 10). The distribution has 100 ns FWHM, or 4 mm; most of the width is due to geometry (laser beam at 45° with respect to the anode wire plane). Gas filling: He-C₄H₁₀-TMAE.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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b)

Fig. 5

a)

b)

Fig. 6

Fig. 7

Fig. 8

Fig. 9

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b)

Fig. 10

Fig. 11