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Study of Columnar Recombination in Xe+trimethylamine Mixtures using a Micromegas-TPC

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Electron-ion recombination is experimentally studied in Xe+trimethylamine (Xe+TMA) mixtures, motivated by its potential use for directional dark matter searches. A Time Projection Chamber (TPC) of 2.41 volume with a novel configuration formed by two symmetric drift regions is used to measure the charge collected from α-particles and γ-rays emitted in coincidence by an ^{241}Am source, by means of two microbulk-Micromegas readouts. Xe+TMA gas mixtures are used with TMA concentrations lower than 2%. The pressure was varied from 3 to 8 bar and the reduced drift field within 10-400 V/cm/bar. The charge collected from α-particles and γ-rays exhibit recombination as the drift field decreases, being stronger for α-particles. A significant part of the observed effect can be plausibly explained by columnar recombination, due to the dependency observed with the track angle (relative to the drift field direction).

The results presented support a suggestion that has been recently put forward on how to obtain a directional signal for nuclear recoils induced by Dark Matter interactions with xenon. If finally demonstrated for nuclear recoils, this technique can be easily scaled to higher mass detectors like high pressure Xe TPCs.

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1. Introduction

High pressure xenon gas TPCs (HPXe TPCs) offer excellent properties as a detection medium for neutrinoless double beta decay ($0\nu\beta\beta$) and dark matter, due to their excellent energy resolution and the topological capabilities inherent to the gas phase [1, 2]. The Earth's rotational motion with respect to the galactic rest frame generates variations in the mean direction of incidence of WIMPs at the Earth's surface, that in the laboratory frame translates to a day-night modulation of the nuclear recoil direction. This signal is more robust than the annual modulation, since there is no known background that can mask it. A new concept based on columnar recombination in a HPXe TPC could provide the direction of the nuclear recoil on an event-by-event analysis, relying on the dependence of the charge collection with the electric field orientation prior to drifting the track ionization produced by WIMP interaction [3, 4]. In particular, the addition of Penning molecular additives (e.g. TMA) may improve the directional sensitivity because excitations of Xe translate to ionizations of TMA [5], and the diffusion is reduced [6].

In this work, we present a systematic study varying pressure and drift field of the electron-ion recombination for α-particles and γ-rays, focusing on the dependence on the track orientation relative to the drift field angle for α-particles. The main characteristics of the setup and the measurements are presented in section 2, followed by the results in section 3. Finally, in section 4 the conclusions and outlook are drawn.

2. Experimental setup and procedure

2.1 Overview

A 2.4 l TPC, hereafter NEXT-0-MM, was connected to a high purity gas system as described in [5, 6]. The gas system enabled operation with very low levels of outgassing, down to 10^5 mbar l/s, recirculation of the gas at high pressure to filter out impurities, and gas recovery and storage by means of cryopumping. A modification of the TPC drift structure was performed, while the experimental procedure to work with Xe+TMA mixtures follows the one explained in [5, 6].

2.2 Drift field configuration

The drift field configuration consists of two symmetric regions of 3 cm, formed by three circular copper plates together with a field cage defined by five copper rings and six 33 MΩ resistors. The entire structure is supported by means of three PEEK pillars. A schematic representation is shown in Fig. 1. The middle plate constitutes the common cathode for both regions, and a negative high voltage (HV) is applied to it. At its center, the plate was thinned by 1 mm over a 2 cm diameter circle, in order to gently place an ^{241}Am source with the radioactive deposit turned upwards, so as to form a coplanar surface. In addition, a centered through-hole of 2 mm in diameter was drilled, allowing the coincident 59.5 keV γ-rays from the Np daughter to reach the lower drift region. The top and the bottom copper plates are the corresponding anodes for the α and γ drift regions. In each plate a microbulk-Micromegas readout of 35 mm in diameter is housed. The mesh of each Micromegas is connected to the corresponding anode which in turn is grounded to the vessel, and the back-electrode of the Micromegas is fed to a positive HV to allow for amplification. It must be noted that the Micromegas used in the experiment have identical geometrical parameters, which are

50-90-40 μm that respectively correspond to gap-pitch-hole diameter. Prior to the measurements presented in this work, the Micromegas readouts were characterized in Ar+2%C_4H_{10} at 1 bar. The study showed that the Micromegas had similar gain and energy resolution: maximum gains above 10^4 and energy resolution below 7%(FWHM) at 22.1 keV were obtained.

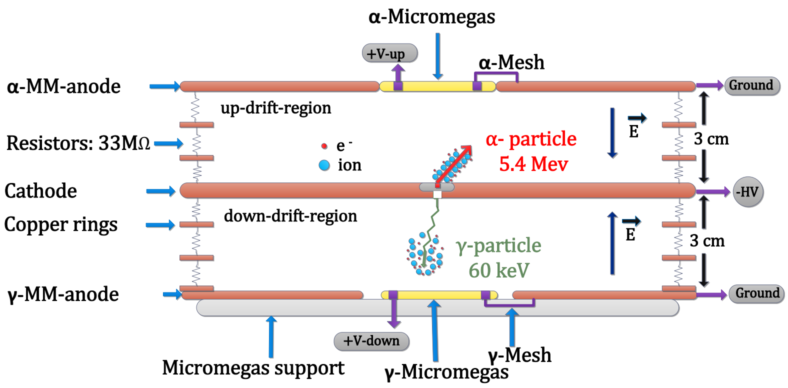

Figure 1: Schematic representation of the drift field configuration used to study the electron-ion recombination. The microbulk-Micromegas readouts and the voltage configuration are also shown.

This setup allows a coincident measurement of α's and γ's (59.5 keV γ branching ratio=36%), and the measurement of electron lifetime (τ_e) to determine the level of attachment. Each signal from the Micromegas back-electrode is fed to a CANBERRA preamplifier (model 2004) and then to an oscilloscope (model TDS5054B). Measurements were performed for pressures between 3 and 6 bar at low reduced drift field (E_d/P<100 V/cm/bar), typically, before the recombination study started.

On the other hand, signals from the two Micromegas could be read independently, providing i) the relative recombination for α-particles and γ-rays and ii) the dependence of the recombination on the track angle, by analyzing the dependence of the pulse-height (charge) on its rise-time (track angle). The output of the α-signal was fed into an ORTEC preamplifier (142C) and then to an oscilloscope (TDS5054B) for pulse digitization. Meanwhile the γ-signal was fed into a CANBERRA preamplifier+amplifier electronic chain, model 2004 and 2022, respectively. The amplified signal was connected to a multichannel analyzer (AMTEK MCA 8000A) and then to a computer where the pulse-height distribution was stored.

2.3 Measurements

Initially, it was planned to work with a 98%Xe+2%TMA mixture, because this mixture implies a TMA concentration near that optimizes Penning transfer [6]. However, given that the TMA vapor pressure is strongly dependent on temperature at ambient conditions (b.p. 3-7°) the chamber refilling from recovery bottle showed some variability. For some of the measurements, this resulted in working TMA concentrations of 1.2% and 1.5%TMA. A systematic concentration scan is currently envisaged. It should be noted that once the mixture is formed, the TMA concentration can be known with a high accuracy, by measuring with an Omnistar mass spectrometer previously calibrated [5]). Before starting the data acquisition, the gas system and the chamber were pumped until values of vacuum and outgassing rate below 5×10^{-6} mbar and 5×10^{-5} mbar l/s, respectively. Afterwards, the gas was introduced from the recovery bottle to the chamber, filling it up to the desired pressure (3-8 bar). The gas was then recirculated through a SAES filter until the end of the measurements, allowing for a complete homogenization of the mixture.

3. Results

3.1 Electron lifetime

The lifetime (τ_e) of electron clouds generated by the γ interaction was measured using the coincidence mode. For this purpose the pulse-height of the γ-pulses as a function of the drift time was studied. The drift time of electrons was determined as the temporal difference between the γ-signal and α-signal. The t_0 of each event was taken to be the point at which the maximum pulse-height for α-particles was obtained, and such a point is independent of the track angle (see Fig. 2-left). In the absence of attachment, the γ pulse-height distribution should be independent of the drift time, showing an exponential behaviour otherwise. Plotting the logarithm of the pulse-height against the drift time, we can determine the electron lifetime as the inverse slope (-t/τ_e). For illustration, Fig. 2-right shows the dependency of the logarithm of the pulse-height on the drift time for $P=6$ bar and $E_d/P=30$ V/cm/bar, from which the estimated slope is compatible with zero, providing a lower limit of $\tau_e>2$ ms (90% C.L). Measurements for $E_d/P<60$ V/cm/bar at lower pressures were performed, and similar results were found, any dendence of the charge on the drift time.

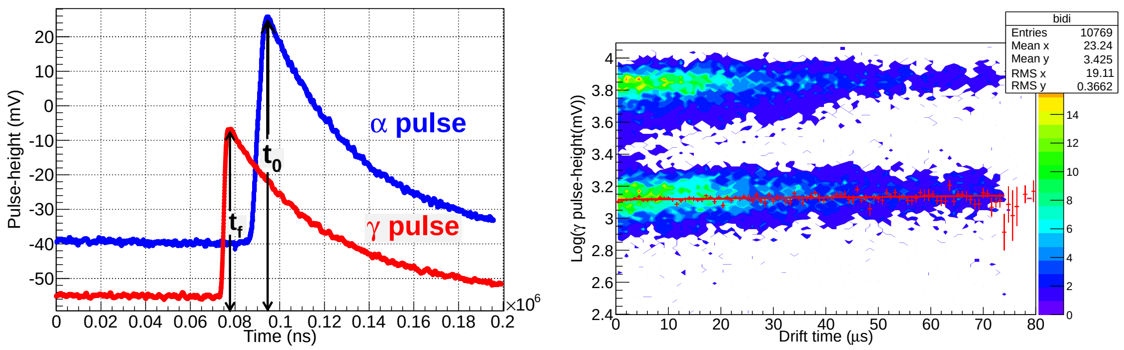

Figure 2: Left: Acquisition in coincidence of α-particle and γ-ray signals. Right: Logarithm of the pulse-height vs the drift time for electrons generated by the γ interaction in the lower drift region, acquired at 6 bar with $E_d/P=30$ V/cm/bar. The two bands in the contour plot correspond to the Xe K_α escape peak (29 keV, 3.1) and the photo-peak (59.5 keV, 3.8). The mean values and error bars for Xe K_α escape peak events are shown together with a linear fit having slope compatible with zero.

3.2 Dependence of recombination on the drift field

The relative recombination of α-particles and γ-rays has been studied with this setup by measuring the pulse-height distribution for both interactions. With this aim, the peak position at 29 keV from the γ-ray spectrum and the α-peak were determined and divided by the maximum value obtained for each drift field configuration. This ratio represents the fraction of charge that survives recombination.

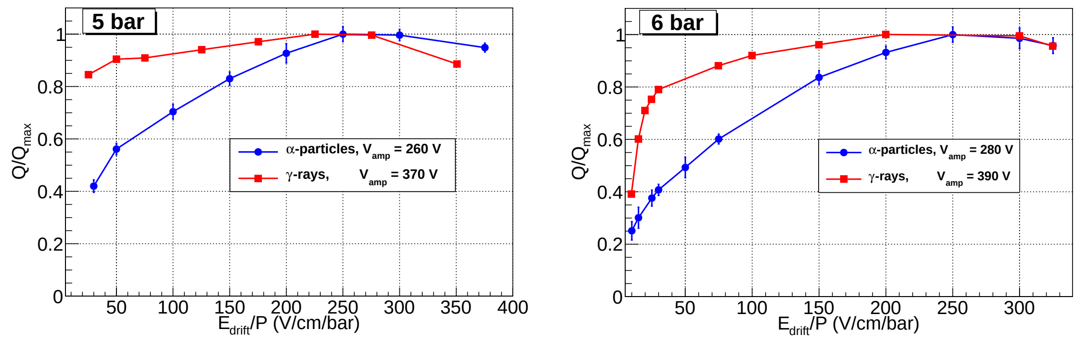

Figure 3: Fraction of charge collected for α-particles and γ-rays with E_d/P at 5 bar (left) and 6 bar (right).

Fig. 3 shows the Q/Q_{max} ratio for γ-rays and α-particles as a function of E_d/P at 5 (left) and 6 bar (right). In both cases, the values of the relative charge for γ-rays remain above those for α-particles. It is also seen that at a given E_d/P, Q/Q_{max} ratios are lower at 6 bar. These results imply that the recombination is stronger at higher pressures and for α-particles, as expected from ionization density considerations. As will be shown in the next section, the last conclusion is partially explained by the fact that α-particles would suffer more columnar recombination.

3.3 Recombination dependence on the track angle for α-particles

Pulses acquired for α-particles were analyzed offline using a pulse shape analysis (PSA); in this way, the pulse-height and the rise-time were obtained. The pulse-height is transformed to charge by multiplying by the appropriate calibration factor. The rise-time transformation to cosine of the track angle relative to the electric field ($\cos(\varphi)$) is done considering that the rise-time (t_r) is the temporal projection of the α-track over the drift field direction, thus:

$$\cos(\varphi) = \frac{\sqrt{t_r^2 - t_{r,min}^2}}{\sqrt{t_{r,max}^2 - t_{r,min}^2}} \tag{3.1}$$

where $t_{r,max}$ and $t_{r,min}$ are the maximum and minimum values of the rise-time distribution; $t_{r,min}$ is subtracted in quadrature to take into account the diffusion of electrons. In order to validate this transformation, the drift velocity (v_d) and longitudinal diffusion coefficient (divided by $\sqrt{P}$), D_L^*, were determined and compared with previous experimental results as well as with Magboltz calculations. The drift velocity is obtained as $v_d = k_1 L_P / \sqrt{t_{r,max}^2 - t_{r,min}^2}$, $k_1 = 0.8$ being a constant related with the definition of rise-time (from 0.1 to 0.9 of the pulse-height); $L_P = L_1/P$ is the track length, where L_1 is the track length at 1 bar in pure xenon, whose value is 2.2 cm according to Geant4 simulations.

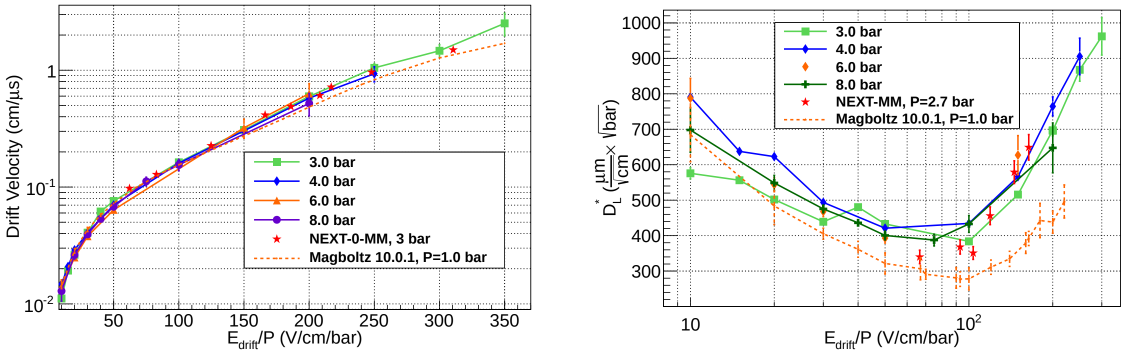

Figure 4: Drift velocity (left) and longitudinal diffusion coefficient (divided by $\sqrt{P}$), D_L^*, (right) as a function of E_d/P, for pressures between 3 and 8 bar in a mixture of 2.2%TMA together with Magboltz calculations [7] and previous experimental results taken with the same mixture [2, 6].

The longitudinal diffusion coefficient D_L^* is given by:

$$D_L^* = k_2 \frac{\sqrt{P}}{\sqrt{d}} t_r v_d, \ k_2 = 0.36 \tag{3.2}$$

where $d = 3$ cm is the drift distance and k_2 is a factor related to the convolution with the electronic response function. In Fig. 4, v_d (left) and D_L^* (right) are plotted as a function of E_d/P, for pressures between 3 and 8 bar in a mixture of 2.2%TMA. In both plots, at a given value of E_d/P, the experimental values in this work are self-consisted, and compatible with previous experimental measurements acquired with different setups [6, 2]. The behaviour with pressure is expected considering that these electronic properties are to first order dependent on the E_d/P ratio only. In addition, Magboltz calculations are also presented [7]; the results appear to be compatible with experimental measurements in the case of the v_d, and to follow a common trend with deviations up to 50% for D_L^*. These results validate our PSA and the transformation between rise-time and $\cos(\varphi)$.

The percentage of charge collected as a function of the track angle at different E_d/P is shown in Fig. 5 at 4 bar (left) and 8 bar (right). Qualitatively the dependence of the charge collected on φ shows a behaviour compatible with columnar recombination [8, 9]: namely, charge collected from parallel tracks is lower than for perpendicular ones, and the effect is increased for low diffusion. A figure of merit, defined as Q_0/Q_{90}, can be used to quantify the dependence of columnar recombination on the track angle for all pressures and E_d/P values. The Q_0 and Q_{90} values are the mean values of the pulse-height distributions formed from events with track angles between 0°-25°and 85°-90°, respectively. These ranges were selected since the $\cos(\varphi)$ distributions are uniform, and therefore similar statistics for both distributions can be obtained.

The quantity Q_0/Q_{90} plotted against E_d/P is shown in Fig. 6. The systematic variation with pressure in a mixture of 2.2%TMA is depicted in Fig. 6-left, while the variation with the TMA concentration is given in Fig. 6-right. From these observations it seems that the columnar effect on the track angle at very low drift fields may not be important, increasing with drift field up to

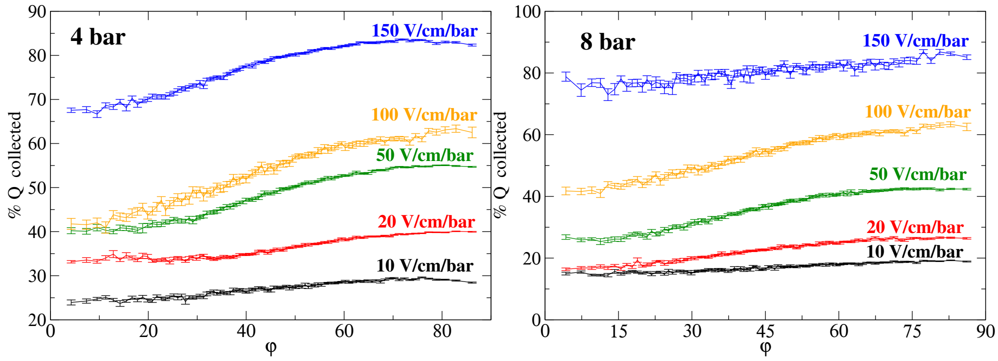

Figure 5: Dependence of the percentage of charge collected on the track angle (φ) at 4 bar (left) and 8 bar (right). This is a profile plot obtained from the scatter-plot of the charge vs track angle, in which the percentage of charge is obtained as the ratio of the mean charge for each angle bin to the maximum charge for each drift field.

its maximum strength at about 40-50 V/cm/bar, from where the dependence on the angle becomes increasingly smaller.

The overall drop of Q_0/Q_{90} with the increase of pressure and TMA concentration points to the importance of the accelerated electron thermalization and the reduced diffusion in these conditions, which helps maintain the initial track geometry in the reconstructed ionization footprint. A more thorough modeling is currently in progress.

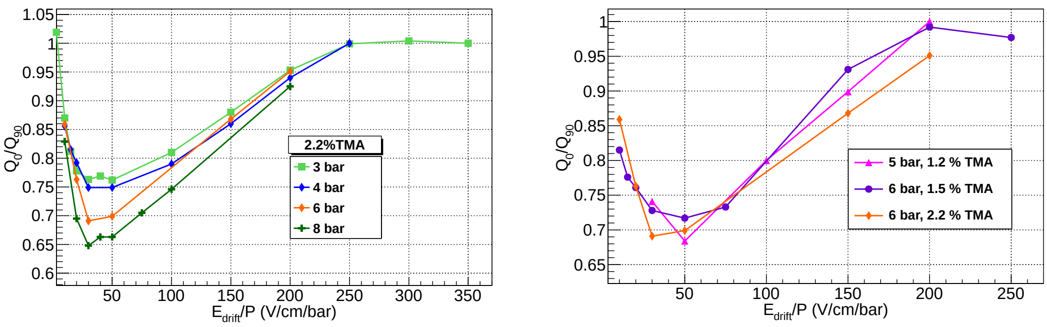

Figure 6: Ratio between charge collected for tracks parallel and perpendicular to the electric field (Q_0/Q_{90}) as a function of the reduced field (E_d/P). Left: Results for different pressures (3 to 8 bar) in a mixture of Xe+2.2%TMA, Right: Results for different Xe+TMA admixtures (1.2-2.2%TMA).

4. Conclusions and outlook

We have studied the recombination of charge stemming from α-particles and γ-rays interactions in high pressure Xe+TMA mixtures using a double drift configuration in a Micromegas-TPC. The electron-ion recombination increases with the pressure and is stronger for α-particles, as expected. The columnar effect on the track angle was observed, which is reflected in a decrease of the collected charge for small angles relative to the electric field. The definition of a figure of merit as Q_0/Q_{90}, representing the charge relation between tracks with small and large track angles, permitted evaluation of the dependence of the effect with E_d/P, pressure and TMA concentration. The columnar recombination increases with the reduced drift field, reaching a maximum around 40 V/cm/bar, and becoming increasingly smaller thereafter. At a given value of E_d/P, the Q_0/Q_{90} ratio shows that the columnar recombination increases with pressure and TMA concentration. The measurement of drift velocity and longitudinal diffusion coefficient add further support to this analysis: results are compatible with previous experimental measurements and show a reasonable agreement with Magboltz, still showing up to 50% deviations in case of the diffusion coefficient. This work represents a first step toward assessing the idea of using Xe+TMA admixtures as medium gas for directional dark matter searches on virtue of the columnar recombination effect.

We currently plan to model columnar recombination for α-particles as well for nuclear recoils. Apart from this, possible charge loses in the amplification region are being studied and it will be detailed in future work. To this end measurements at different working gains will be performed.

5. Acknowledgments

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