Characterization of the drift chamber's gas mixture in MEG II experiment

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Summary. — The gas mixture of the drift chamber in the MEG II experiment has shown very stable conditions at high rate with a lower than expected ageing rate. These features make the mixture worth to be studied not only for the MEG II collaboration but also for future experiments operating at high rate. We are going to show the results of the characterization of gas mixtures with compositions based on the MEG II mixture, focusing on the electron drift properties. To obtain these measurements, we developed an optimal setup involving a Time Projection Chamber illuminated by a UV laser. In parallel with this study we also developed a dedicated setup for the measurement of the ageing rate of these gas mixtures.

1. – Introduction

The MEG II experiment, located at the Paul Scherrer Institute in Switzerland, is the upgrade of the MEG experiment and it searches for the charged lepton flavour violating decay $\mu^+ \to e^+\gamma$. This decay is highly suppressed in the Standard Model, with an expected branching ratio far below experimental sensitivity, making any observed signal clear evidence of physics beyond the Standard Model. By combining initial MEG II data with MEG results, the collaboration has set the most stringent upper limit to date: $BR(\mu^+ \to e^+\gamma) < 3.1 \times 10^{-13}$ at 90% C.L.[1]. The Rome group is responsible for operating the drift chamber, filled with a helium-isobutane (90:10) gas mixture, with (1÷2)% isopropyl alcohol and 0.5% oxygen. These additives reduce the ageing rate and ensure stable operation under the high beam rate of $(3 \div 5) \cdot 10^7$ μ/s, although they also affect electron drift properties, introducing attachment effects that impact on signal collection.

This study aims to optimize an experimental setup for characterizing similar gas mixtures, addressing the limited existing literature on the topic. We present measurements of drift velocity and attachment coefficient using a dedicated compact time projection

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chamber (TPC) illuminated by a pulsed UV laser. The results of this study allow a deeper understanding of the MEG II drift chamber and support future high-rate experiments.

2. – Experimental Setup and Procedure

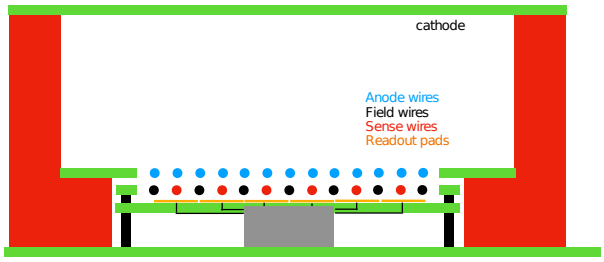


Fig. 1.: Schematic representation of our TPC.

To measure the drift velocity (Section **3**˙1) and the attachment coefficient (Section **3**˙2), we designed and assembled a complex setup that features a gas system specifically conceived to guarantee a highly stable and precise gas mixture composition. The main component of the setup is a TPC, whose scheme is shown in Figure 1, with a uniform drift region, particularly suited for studying electron drift properties. A Q-switched UV laser([1]) (wavelength: 355 nm; beam diameter: 1 mm; divergence: 0.226 mrad; pulse width: 4 ns; energy delivered: $<$100 μJ) ionizes the gas mixture along a narrow line, ensuring consistent intensity and rate. The ionizations signal is collected by the readout pads, amplified by the MEG II front-end boards[2] and readout by a WaveDream digitizer at 700 MSPS[2]. As shown in Figure 2, a mirror mounted on a micrometric translation stage allows precise adjustments of the laser beam's position relative to the TPC. This allows measurements at different drift distances while maintaining a constant gas composition and electric field, enabling accurate determination of drift velocity and attachment coefficient, as detailed in Section **3**. We conducted measurements on a helium-isobutane (90:10) mixture with 1.3% isopropyl alcohol, varying the oxygen concentration ($<$ 0.01%, 0.19%, 0.34%, 0.49%) and the drift field (700 V/cm, 1000 V/cm, 1250 V/cm, 1500 V/cm).

3. – Simulations and Results

Before assembling the TPC, we simulated the internal electric field using ANSYS Maxwell 3D([2]), a finite element analysis software, and `Garfield++`([3]), a specific tool for the simulation of gaseous detectors. These simulations were necessary to validate the assumption of electric field homogeneity within the drift region and to ensure that the field strength remained below the safety threshold of 20 kV/cm for helium-based mixtures[3]. The simulations confirmed the feasibility of our design, allowing us to proceed confidently with the TPC assembly based on the tested configuration.

([1]) https://www.gophotonics.com/products/lasers/elforlight-ltd/29-23-fqs-100-1-y-355
([2]) https://www.ansys.com/products/electronics/ansys-maxwell
([3]) https://garfield.web.cern.ch/garfield/

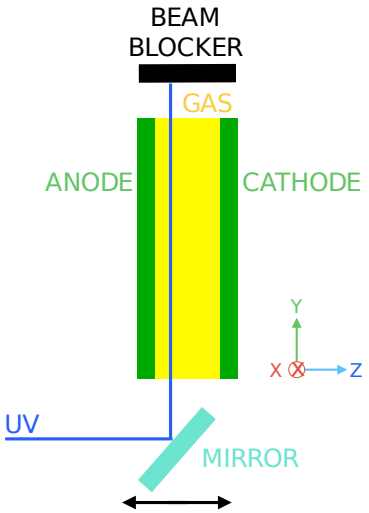


Fig. 2.: Schematic detail of the optical path. A mirror is mounted on a micrometric translation stage to regulate the laser beam's position with respect to the TPC.

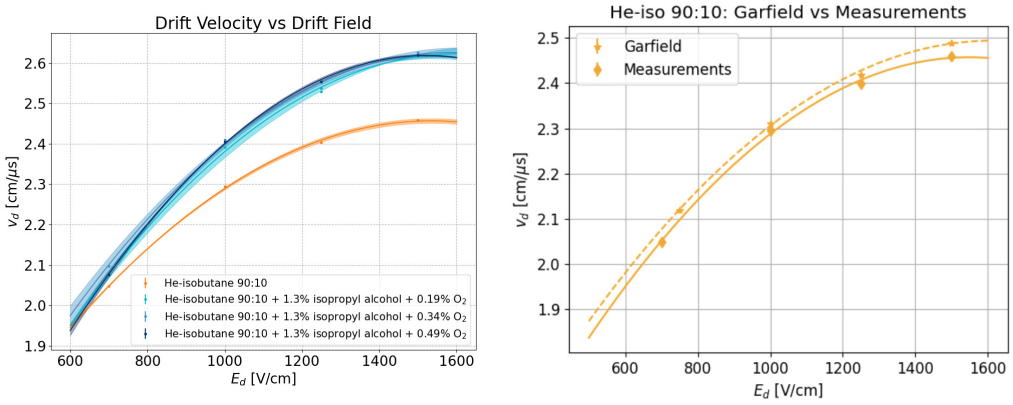
3˙1. *Drift Velocity*. – The drift velocity, v_d, is the average velocity at which ionization electrons travel toward the anode under the influence of an electric field. A trigger system synchronizes the laser pulse emission with data acquisition, setting a time reference. The drift time, t, then, can be measured as the moment when the signal reaches 20% of its total amplitude and it represents the travel time of ionization electrons from the laser ionization point, z, to the TPC readout. By adjusting z with the micrometric stage, we determine the drift velocity using the relation $z = v_d t + q$, where q accounts for any time or position offsets.

For each gas mixture composition, we studied the dependence of the drift velocity on the drift field, as shown in Figure 3a. This plot shows the uncertainty bands on the best-fit curves which are obtained from the combination of the statistical and systematic uncertainties of the data. We then compared our results with the `Garfield++` simulation. Isopropyl alcohol is known to be a complex molecule that is not easily handled by simulations. For this reason, we compared only the pure gas mixture curves (*i.e.* without the additives) obtained from measurements and simulations as a consistency check, and we found good agreement, as shown in Figure 3b.

3˙2. *Attachment Coefficient*. – The attachment coefficient, η, represents the probability per unit length that an ionization electron is captured by an electronegative element (such as oxygen) while drifting toward the anode under the influence of an electric field. By measuring the charge, C, collected on the TPC readout and knowing the laser ionization position z, the attachment coefficient can be determined using the relation $C = C_0 e^{-\eta z}$, where C_0 takes into account any offset.

For each gas mixture composition, we studied the dependence of the attachment coefficient on the drift field. The results are presented in Figure 4 and, similar to before, the uncertainty bands on the best-fit curves are obtained from the combination of the statistical and systematic uncertainties of the data.

The unreliability of `Garfield++` in correctly simulating the attachment coefficient is



(a) (b)

Fig. 3.: (a) Measured drift velocity as a function of the drift field. (b) Comparison between measured and simulated drift velocity as a function of the drift field for the pure gas mixture. Data are fitted with quadratic functions.

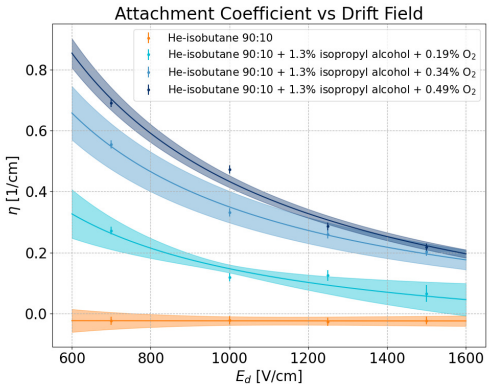


Fig. 4.: Attachment coefficient as a function of the drift field: fitted with an hyperbole.

a well-known issue currently being investigated by the MEG II collaboration.

4. – Conclusions and Future Activities

With our setup we successfully measured electron drift properties in gas mixtures like the one used in MEG II. As mentioned, this gas mixture has shown an ageing rate lower than expected on the electrode materials of the MEG II drift chamber. Therefore, a natural follow-up to this study include the direct measurement of the ageing rate. The core idea is to use a sample of the MEG II drift chamber's wires to reproduce a drift cell. As shown in Figure 5, the central region is illuminated by an X-ray source and a scintillator monitors the actual rate of the source. The measurement will be performed by monitoring the gain of the wires collecting the signal of the ionizations induced by

the radiations. The setup has been optimized in order to increase the radiation rates by a factor of ten with respect to the MEG II conditions.

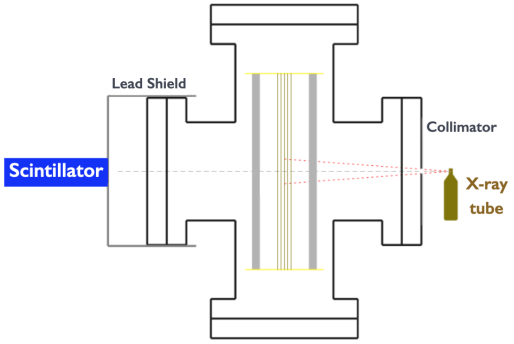


Fig. 5.: Schematic representation of the ageing rate measurements apparatus: an X-ray source illuminates the central region of a sample of the MEG II drift chamber's wires. A scintillator is used to monitor the actual rate of the source while.

The final results of this study provide a significant contribution to the MEG II experiment, advancing the understanding of its detector. Furthermore, they are in the interest of future experiments operating at high rate, which could benefit from gas mixtures with similar properties.

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[4] Cavoto G. et al, *Operating the GridPix detector with helium-isobutane gas mixtures for a high-precision, low-mass Time Projection Chamber*, *J. Instrum.*, **18** (2023) P10035