Dual-Polarity Ion Drift Chamber: Experimental results with Xe-SF_6 mixtures

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May 26, 2022

Coimbra, XeSAT 2022

Outline

The interest in negative ions as charge carriers

In large volume gas detectors, the **mobility of ions** directly affects the **attainable rate capability**, **spatial resolution**, and **pulse shape formation** [1–3]

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Positive ions may have unwanted effects as their production rate creates space charge effects that distort the electric field [4]

Negative ions are seen as an obstacle, capturing the drifting electrons leading to a reduction in the detector's signal amplitude [5]

Recently, **electronegative gases** (e.g. SF_6) have been used to improve the spatial resolution by exploiting the ions' reduced diffusion when compared with electrons [6, 7]

Diffusion coefficient (*D*), in m^2/s [8]:

$$D = \frac{2}{3\sqrt{\pi}} \frac{1}{p \cdot \sigma_0} \sqrt{\frac{(kT)^3}{m}}$$

k - Boltzmann's constant
T - temperature
p - pressure
m - charge's mass
$\boldsymbol{\sigma}_0$ - collision cross-section charge-molecule

Ions have a 10^2-10^3 times smaller diffusion when compared to electrons $\Rightarrow$ better spatial resolution

Using negative ions as charge carriers in gaseous detectors

Negative ions can also bring a new feature of great interest for rare-event searches:

- By measuring the **drift time difference** of the different anions (minority charge carriers) from the initial interaction position (at t_0) to the charge collection anode, it is possible to determine the position of the original event (z-coordinate)
- For applications where t_0 is unknown, **only through the use of minority charge carriers is it possible to perform a fully 3-D reconstruction of the ionisation track**

$\Downarrow$

This improves the experiment's event fiducialisation and background discrimination capabilities

$\Downarrow$

This interest stimulated the development of the **Dual-Polarity Ion Drift Chamber (DP-IDC)**, a detector that measures both positive and negative ion mobilities in different mixtures and different conditions

$\Downarrow$

Recently published paper **NIM A 1029 (2022) 166416** and another is on its way...

Ion mobility dynamics

(this is way ~~more real~~ easier than DM physics...)

- **When the ions reach an equilibrium** under a **weak uniform electric field E**, they will drift at an **average constant velocity v_d** and **their mobility K** is given by:

$$v_d = K \cdot E \tag{1}$$

- K is typically[a] normalized to the **gas number density N**, and to the **Loschmidt constant N_0**, and is expressed in terms of the **reduced mobility K_0** by:

$$K_0 = K \cdot \frac{N}{N_0} = \frac{v_d}{E} \cdot \frac{N}{N_0} \tag{2}$$

- **K_0 remains constant as a function of the E/N if $E/N \lesssim 60$ Td** [9], and often compared with the **Langevin polarization limit and Blanc's law**:

$$K_{pol} = 13.88 \cdot \left(\frac{1}{\alpha\mu}\right)^{1/2} \quad \text{and} \quad \frac{1}{K} = \sum_{i}^{N_{mix}} \frac{f_i}{K_i} \tag{3}$$

where α is the neutral polarizability (in Å^3) of the neutral atom/molecule, μ is the ion-neutral reduced mass, K_i is the mobility of an ion in the gas i and f_i is the fraction of the gas i in the mixture with N_{mix} components

[a] Valid if you are a theoretical physicist. If you are an experimental physicist, you are likely to reduce to pressure!

Outline

Working principle

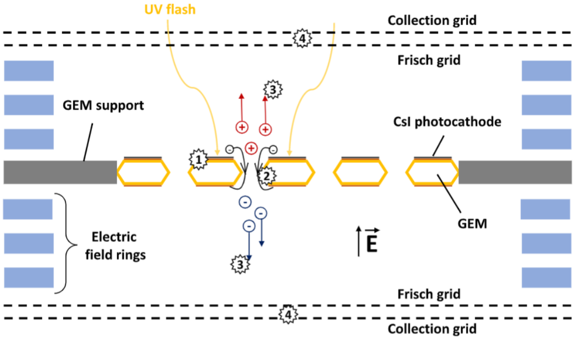

Figure 1: Working principle of the DP-IDC [10].

① Photons from a Xe UV lamp hit a CsI photocathode on top of a GEM, **releasing photoelectrons**

② The **electrons are guided to the GEM holes** due to an $\vec{E}$ where they are accelerated and generate **positive ions** by electron impact ionisation or **negative ions** by "immediate" attachment

③ The ions drift towards the **top/bottom double-grid depending on their polarity**

④ The ions induce a signal in the **Collection grid** after the **Frisch grid** which is converted to voltage and fed to a digital oscilloscope (128 pulses average)

Ion drift chamber description

- Xenon UV lamp
- 50 μm thick GEM + 300 nm thick film of CsI
- **Mirror-like drift region below/above the GEM**
- **Drift distance**: 5.0 cm
- Field rings to ensure a uniform electric field
- Double-grid for the ion collection after the drift:
  - The **first grid** acts as a **Frisch grid**
  - The **second grid collects the ion induction signal** (grounded and separated from the first using a 50 μm Kapton spacer)
- The vessel is pumped down to a pressure of $\sim 1 \cdot 10^{-6}$ Torr before each filling cycle
- The pressure is monitored in each data taking cycle

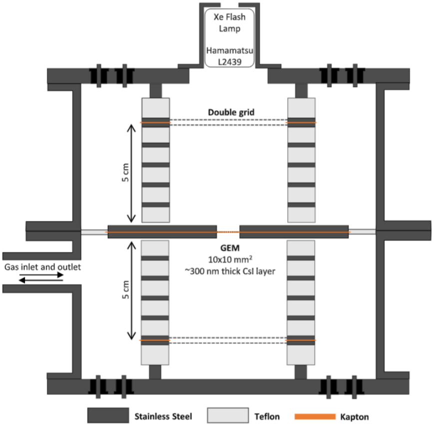

Figure 2: Schematic of the DP-IDC [10].

Data analysis

- The time-of-arrival spectra are fitted to **Gaussian curves** using a Python script
- The **ion's reduced mobility is calculated from the centroid of each peak** (the discharge of the UV flash lamp is used as a t_0 time trigger)

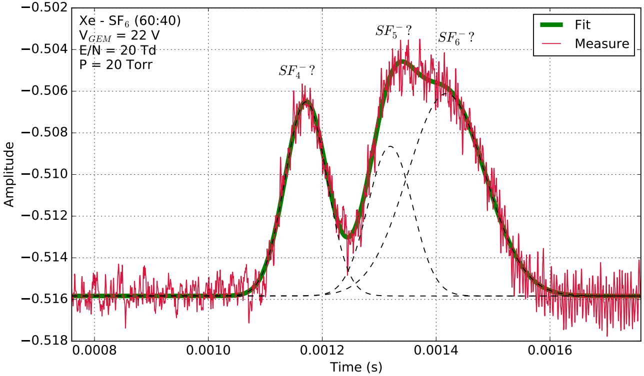

Figure 3: Example of a time-of-arrival spectrum for a mixture of Xe-SF_6 (60:40). The dashed lines represent the Gaussian fittings to the visible peaks.

Accurate drift distance

The ions are produced inside the GEM holes (50 μm long), so their initial position is well known

$\swarrow$ $\searrow$

For **positive ions**, they can only be generated for a sufficiently high electron energy (tens of eV), **granted only inside the GEM hole**

For **negative ions**, it depends on the electron attachment mean-free-path $\lambda = (\sigma N)^{-1}$ (σ is the cross-section for electron attachment)

$\downarrow$

E.g., for the SF_6^-, at tens of Torr and a few Td, $\sigma \sim 10^{-18}$ m^2 for an electron energy of 0.1 eV, $\Rightarrow \lambda \sim 1.5$ μm

Since the GEM holes are 50 μm long, **the initial negative ion is produced within these holes** which gives an **accurate measurement of the ion's drift distance** ($\sim \mu$m can be considered negligible when compared with the total drift distance of 5.0 cm)

Outline

Using SF_6 as a electronegative gas

Negative ion drift and its advantages have been successfully tested with CS_2, O_2 and SF_6 [11, 12]

↙ ↓ ↘

SF_6 is a non-toxic, non-flammable and easily accessible gas [13], but it is a green-house gas [14]

CS_2 is highly toxic [15]

O_2 has known limitations as a filling gas

↓ ↘ ↙

The **INITIUM** project is adding SF_6 to He-CF_4 mixture (NITPC to detect low-mass WIMPs)

These gases are being considered by the **DRIFT** collaboration (low-pressure NITPC designed to detect WIMPs)

⇓

- ☛ Several efforts are being carried out to reduce the release of SF_6
- ☛ We intend to **establish ion mobilities in new gas mixtures to find optimal configurations of operation for larger experiments**, while taking into account this concern

Ion species in SF_6

Table 1: Collisional processes that originate the SF_6 ion species [10].

Reaction	Process	Energy
$e^- + SF_6 \rightarrow SF_6^{-\star}$	Electron attachment	< 1 eV
$SF_6^{-\star} \rightarrow SF_6 + e^-$	Autodetachment	(Metastable: $> 1\ \mu s$)
$SF_6^{-\star} + SF_6 \rightarrow SF_6^- + SF_6$	Collisional stabilisation	
$e^- + SF_6 \rightarrow SF_5^- + F$	Dissociative electron attachment	0 - 2 eV
$e^- + SF_6 \rightarrow SF_4^- + 2F$	Dissociative electron attachment	3 - 8 eV
$e^- + SF_6 \rightarrow F^- + SF_5$	Dissociative electron attachment	1 - 14 eV
$e^- + SF_6 \rightarrow F_2^- + SF_4$	Dissociative electron attachment	1 - 14 eV
$SF_{5/6}^- + SF_6 \rightarrow SF_{5/6} + SF_6 + e^-$	Collisional detachment	> 90 eV
$SF_6^- + SF_6 \rightarrow SF_6 + SF_6^-$	Charge transfer	
$SF_6^- + SF_6 \rightarrow SF_5^- + F + SF_6$	Dissociative charge transfer	> 1 eV

- **SF_6^-** is formed from electron attachment from **electrons with < 1 eV**
- **SF_n^- ions** $(n = 5, 4, 3, 2)$ **require higher electron energies** to be formed
- **F^- and F_2^-** are also within the possible ion species

Ion mobilities in Xe - SF_6 mixtures

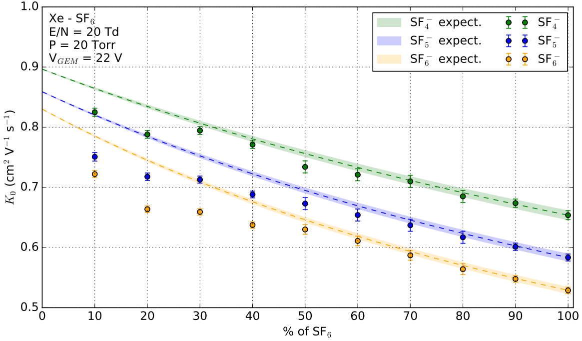

Figure 4: Reduced mobility values for a mixture of Xe-SF_6, with $E/N = 20$ Td, $P = 20$ Torr, and $V_{GEM} = 22$ V.

- As expected, K_0 is independent of the E/N (other fields were used: 10, 15 and 25 Td)
- **In accordance with the expected values** for a fraction of $SF_6 > 50\%$, but **starts deviating after that**
- For fractions of $SF_6 < 10\%$, **it had Penning mixture-like behaviour**, as it started sparking

Penning mixture

Mixture of a **noble gas** and **another compound at low concentration**, in which the **latter has an ionisation potential lower than or equal to the excitation potential of the noble gas**, thus being possible to transfer energy stored in excited metastable state of the noble gas to ionisation state of the other.

Outline

Conclusions and future work

Conclusions:

- This new detector is **capable of precisely and accurately measuring the mobilities of positive** (results in [10]) and **negative ions**
- With some degree of confidence, the reduced mobilities of SF_4^-, SF_5^- and SF_6^-, in a mixture of Xe-SF_6, were determined
- The results are a step forward to/in using negative ions as charge carriers

Future work:

- **Test other noble gases**, as well as **assess other possibilities for the electronegative molecules**
- **Upgrade the current prototype** in order to go to **higher pressures**
- Study the limitation of the Xe lamp signal in measuring positive ion mobilities (not addressed here)
- Design and construct a new prototype to infer the **efficiency of electron attachment to the electronegative molecules**, study the **optimal conditions for the electron detachment**, assess if **amplification** (charge/light) **is suppressed**...

and also...

Pray (a lot) that FCT (Portugal's main funding agency for research) approves and funds our project 🙏🙏🙏🙏

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Thank you for your attention!

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Backup

Ion drift chamber description

- The GEM is interlocked within a 125 μm thick Kapton foil that **isolates** two 2 mm thick stainless steel discs of the same size
- **The discs bias the GEM electrodes** by direct contact via teflon screws, and **ensure the uniformity of the electric field** through the whole drift region
- The whole piece is held in place by a larger Teflon support mounted in the central part of the chamber and which comprises holes to improve the gas flow within the chamber

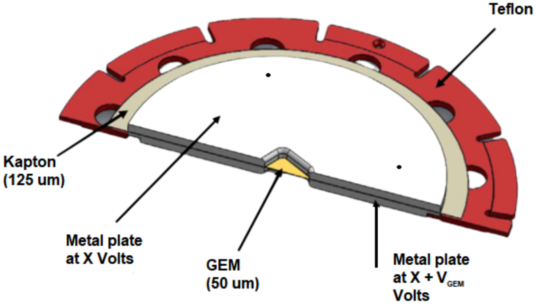

Figure 5: Design of the structure that holds the GEM [10].

Electrical system

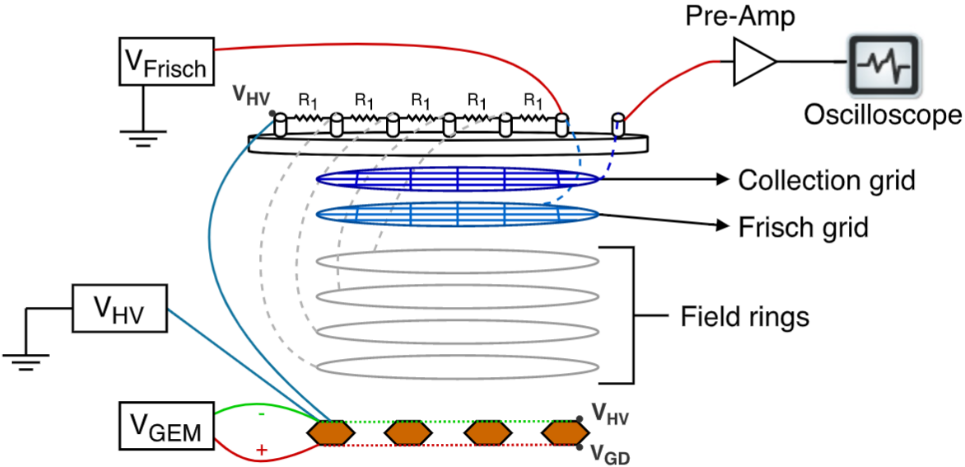

Figure 6: Detector's electrical system when operating for positive ions detection (upper part). $R_1 = 22\ \mathrm{M}\Omega$ and $V_{GD} = V_{HV} + V_{GEM}$ [10].

Cross sections for SF_6 ions species formation

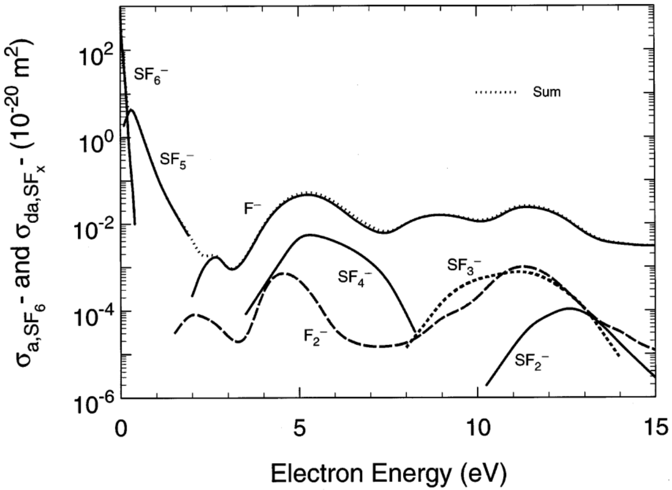

Figure 7: Cross sections for the formation of SF_6^- by electron attachment (σ_{a,SF_6^-}) and the remaining species by electron dissociative attachment (σ_{da,SF_x^-}) [16].