Negative Ion Drift and Diffusion in a TPC near 1 Bar

C. J. Martoff, R. Ayad, M. Katz-Hyman

Department of Physics, Temple University, Philadelphia, PA 19122, USA

G. Bonvicini, A. Schreiner

Department of Physics & Astronomy, Wayne State University Detroit, MI 48202, USA

Abstract

Drift velocity and longitudinal diffusion measurements are reported for a Negative Ion TPC (NITPC) operating with Helium + CS$_2$ gas mixtures at total pressures from 160 to 700 torr. Longitudinal diffusion at the thermal-limit was observed for drift fields up to at least 700 V/cm in all gas mixtures tested. The results are of particular interest in connection with mechanical simplification of Dark Matter searches such as DRIFT, and for high energy physics experiments in which a low-Z, low density, gaseous tracking detector with no appreciable Lorentz drift is needed for operation in very high magnetic fields.

1 Introduction

A TPC which drifts negative ions (in this paper, CS$_2^-$) rather than electrons, was invented to reduce diffusion in three dimensions to its thermal (lower) limit without applying a magnetic field[1,2,3]. This provides the highest 3-D space-point resolution attainable for long drifts, without the power requirements and expense of a magnet.

Such characteristics are particularly important for the development of the DRIFT series of direction-sensitive gaseous detectors searching for WIMP dark matter [4]. Three coordinates of good resolution on the recoil track are essential for DRIFT, in order to measure the length and direction of tracks from low-energy atom recoils produced by elastic scattering of massive WIMPs. The standard solution of a TPC with magnetic field along the drift direction would give good resolution in just two (transverse) coordinates. Furthermore the
necessary large magnet is impractical for underground experiments due to cost and electric power requirements.

Unlike the light electrons, negatively charged molecular ions are much more efficiently thermally coupled to the bulk of the gas than drifting electrons would be. In appropriate gas mixtures, the negative ion drift mobility is near constant, and the rms 3-D diffusion follows the “low field” limiting behavior:

\[ \sigma_D = \sqrt{\frac{4eL}{eE}} \]  

often up to reduced drift fields \( E/P \) of several tens of \( \text{V/cm-torr} \) [5].

Of course there are details to be reckoned with; the ions must form before the primary ionization electrons drift far from their point of origin, or the resolution will be spoiled from the beginning. Also the negative ions must relinquish their extra electron and produce a Townsend avalanche in the endcap gain region. Both of these requirements have been shown to be amply met by \( \text{CS}_2 \) at 40 torr and by mixtures of \( \text{CS}_2 \) with small amounts of noble gases at 40 torr total pressure[5].

The DRIFT I experiment[4] (active mass 0.16 kg) operates with a pure \( \text{CS}_2 \) fill at 40 torr, which is near-optimal pressure for a direction-sensitive WIMP search with the DRIFT I spatial resolution[6].

To achieve the much higher target masses planned for the DRIFT II (5 kg) and DRIFT III stages, higher target gas pressure and hence higher resolution are required. However, the low recoil atom energy places an absolute upper limit on the target gas density of less than 1 mg/cm\(^3\). For pure fills of the medium-mass target gases that are most interesting as WIMP targets, this would require running well below atmospheric pressure. The vacuum vessel and support then become a major element of cost and complexity, as they are in DRIFT I.

It is therefore of great interest to see whether a 1-bar gas mixture could be found which would not shorten the recoil tracks below any hope of directional detection, but would still give all the benefits of negative ion drift. In a previous paper, we reported on operation of GEM micropattern gain elements in negative ion drift mixtures near 1 bar[8]. Raising the total pressure using a Helium buffer gas is a natural solution to consider, since equal pressures of Helium and \( \text{CS}_2 \) have densities in the ratio of approximately \( 4/76 = 0.05 \). This report is to show that indeed mixtures of this kind do work well as TPC gases. The 0.9 bar limit in the present work was imposed by the apparatus and is not a limit of the technique itself. Such mixtures can therefore be considered for next-generation DRIFT detectors.
Operation at 1 Bar also permits entirely new applications for NITPC. For example, a NITPC using a helium mixture has been proposed for use as a main tracking detector in the NLC [2]. The low drift speed of negative ions (only tens to hundreds of meters per second) allows arbitrary orientation of the drift direction relative to the momentum-measuring magnetic field, without producing any significant $E \times B$ effects. The slow pulse repetition rate and low duty factor of NLC-like machines greatly mitigates the negative effects of the slow ion drift.

When combined with the very small diffusion broadening obtainable, the slow negative ion drift velocity also brings phenomenal z-resolution (along with good transverse resolution). With sufficient gas gain and amplifier sensitivity, single electrons or clusters could be detected individually as in the TEC scheme, giving a number of statistical advantages for particle measurement [7].

2 Experimental Methods

The tests were carried out with a small test TPC in a stainless steel bell jar with a simple gas manifold. A sketch of the test TPC is shown in Figure 2. The drift volume was rectangular, 50 x 60 mm transversely and 80 mm long in the drift (z) direction. The field cage was made of bare 500 micron diameter wires spaced 5 mm apart in z, stretched around nylon supports at the four corners. The drift-cathode was a solder-coated PCB with an Sn photocathode attached to it with conducting epoxy.

Charge was liberated from the photocathode by pulsed UV illumination from an EG&G Flash-Pak [9]. The Flash-Pak’s short-wavelength limit in air is ~230 nm. The standard internal capacitors of the Flash-Pak were augmented with additional HV capacitors to give a stored energy of about 0.2 Joule per pulse. The Flash-Pak was triggered by an external pulser, from which a time-zero signal was also derived. This system was a very convenient and cost-effective solution for generating variable-amplitude pulses of charge (photoelectrons) in the TPC, which were sharply defined in time and space. It was found to be essential to scrape the photocathode clean each time the detector was exposed to air between gas fills.

UV light entered the bell jar through collimating apertures and a quartz window, passed through a hole in the endcap cathode of the test-TPC, and struck the Sn photocathode. The endcap structure was an 8-wire MWPC. One cathode of this MWPC (the “grid”) terminated the drift-field region. This grid was a transparent electrode made by epoxying a stainless steel mesh under tension, to a solder-coated PCB which had a 50 x 50 mm window milled out of it. The mesh [10] pitch was nearly 40 cm$^{-1}$ and the geometrical transparency
Fig. 1. Schematic cross-sectional view of Mini-TPC. A: Sn photocathode, B: Drift cathode PCB, C: Field cage voltage divider chain, D: Field cage, E Grid support PCB, F: Grid mesh, G: Endcap MWPC anode wires, H: MWPC cathode PCB, I: UV admittance aperture, \( V_D \): Drift voltage, \( V_M \): MWPC gain voltage

was 81%. The anode plane of 8 Au-plated W wires 15 \( \mu \)m in diameter, at a pitch of 6 mm and with 50 g tension, was placed 6 mm behind the grid. The anode wires were attached to a PCB anode frame using cyano-acrylate adhesive and soldered to contacts on the PCB. The MWPC structure ended with a second cathode (the “MWPC cathode”), which was simply a solder-coated PCB.

Negative “drift voltage” up to -10 kV was applied to the drift cathode; the grid and MWPC cathode were grounded, and positive high voltage was applied to the MWPC anodes. This setup has the obvious advantage that drift and gain voltages can easily be adjusted independently.

Anode wires were read out individually through 1 nF high-voltage decoupling capacitors and amplified (and inverted) by Amptek A225 amplifiers[11]. The resulting positive signals were re-inverted by home-made common-emitter amplifiers, and then sent to the data acquisition system.

The gas system was based on a simple soft-soldered copper-tube manifold with attachments for introduction of various gases and of organic vapor (\( \text{CS}_2 \)) from a small liquid reservoir. Base pressure with the rotary pump used was
about 50 milli-torr. Negative ion drift chambers are very insensitive to contamination with anything less electronegative than CS₂ (for example, air). It has been found that extraordinary precautions with gas purity are unnecessary. Gas mixtures were prepared by admitting the minor component into the chamber first, followed by the major component. Pressures were monitored with a mechanical gauge which is insensitive to the nature of the gas being measured.

Longitudinal diffusion was measured using the Amptek outputs and a digital oscilloscope. The NITPC output pulse width and its delay relative to the FlaskPak trigger signal were measured as a function of drift field, at constant MWPC voltage and constant FlaskPak amplitude. The delay time was converted into drift speed using the known geometry. The amplifier shaping time was subtracted in quadrature from the measured width. The result was then converted from pulse width in time to pulse width in distance by multiplying with the drift speed measured at that drift field. Space charge effects were shown to be absent by checking the results at high and low FlaskPak amplitude.

3 Results and Discussion

Results for the four gas mixtures studied are shown in Table 3. To obtain the tabulated diffusion “temperatures”, the curves of FWHM diffusion width of the anode signals vs. $1/\sqrt{E_D}$ were fitted to straight lines. The slopes were set equal to the expected value for the FWHM of one coordinate in a 3-D diffusion problem, obtained from Equation 1:

$$FWHM = \frac{2.35}{\sqrt{3}} \sqrt{\frac{6kT L}{eE_D}}$$

and the corresponding temperature computed.

The deviations of the tabulated temperatures from the actual room temperature of 293 K probably reflect the limitations of the simple diffusion model used, rather than any real physics. Ohnuki et al[5] using different detectors and methods, also found diffusion temperatures differing significantly from room temperature. Typical data is shown in Figures 3 and 4 for the case 200 torr CS₂ plus 500 torr He. A line fitted to the diffusion curve has a y intercept of -.01 rather than zero, and slope 1.30 rather than 1.49 expected from Equation 2.

For the lower total-pressure mixtures, the He acts essentially as a buffer gas, hardly changing the drift properties. The drift mobility in the 700 torr mixture
| CS$_2$ (torr) | He (torr) | ion mobility $\frac{\text{cm/s}}{\text{V/cm-torrCS}_2}$ | diffusion “temperature” |
|--------------|-----------|--------------------------------|------------------------|
| 40           | 0         | 0.22                          | 258 K                  |
| 40           | 120       | 0.18                          | 281 K                  |
| 40           | 160       | 0.17                          | 281 K                  |
| 200          | 500       | 0.0071                        | 229 K                  |

Fig. 2. Longitudinal diffusion results summary

Fig. 3. Typical Drift Velocity Data. Measured drift velocity as function of drift field for 500 torr He + 200 torr CS$_2$.

however is significantly lower than would be expected if it were dependent on the partial pressure of CS$_2$ alone. The drift velocity itself drops by nearly a factor of six compared to the lower total-pressure mixtures.

4 Conclusion

Mixtures of CS$_2$ with a helium buffer gas were found to have thermal-limit diffusion up to drift fields of over 12 V/cm-torr. These mixtures also allow stable operation of a Negative Ion TPC near 1 Bar total pressure. This opens the way to numerous applications of the NITPC technique.
Fig. 4. Typical Longitudinal Diffusion Data. Longitudinal diffusion for 80 mm drift, measured as described in the text, for 500 torr He + 200 torr CS$_2$.

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