ELSEVIER

Nuclear Instruments and Methods in Physics Research A 440 (2000) 355–359

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

Suppressing drift chamber diffusion without magnetic field

C.J. Martoff[a,*], D.P. Snowden-Ifft[b], T. Ohnuki[b], N. Spooner[c], M. Lehner[c]

[a]Department of Physics, Temple University, 1900 N. 13-th St., Philadelphia, PA 19122-6082, USA
[b]Department of Physics, Occidental College, Los Angeles, CA, USA
[c]Department of Physics, University of Sheffield, Sheffield, UK

Received 2 April 1999; received in revised form 26 July 1999; accepted 24 August 1999

Abstract

The spatial resolution in drift chamber detectors for ionizing radiation is limited by diffusion of the primary electrons. A strong magnetic field along the drift direction is often applied (Fancher et al., Nucl. Instr. and Meth. A 161 (1979) 383) because it suppresses the transverse diffusion, improving the resolution but at considerable increase in cost and complexity. Here we show that transverse track diffusion can be strongly suppressed without any magnetic field. This is achieved by using a gas additive which reversibly captures primary ionization electrons, forming negative ions. The ions drift with thermal energies even at very high drift fields and low pressures ($E/P = 28.5$ V/cm torr), and the diffusion decreases with increasing drift field. Upon arrival at the avalanche region of the chamber the negative ions are efficiently stripped and ordinary avalanche gain is obtained. Using this technique, r.m.s. transverse diffusion less than 200 μm has been achieved over a 15 cm drift path at 40 torr with zero magnetic field. The method can provide high spatial resolution in detectors with long drift distances and zero magnetic field. Negative ion drift chambers would be particularly useful at low pressures and in situations such as space-based or underground experiments where detector size scaleability is important and cost, space, or power constraints preclude the use of a magnetic field. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 29.40.Cs; 29.40.Gx; 51.50. + v

Keywords: Drift chamber; Diffusion; Resolution; Negative ion; Dark matter

1. Introduction

Drift chambers and time projection chambers are the workhorse detectors of ionizing radiation in particle physics and astrophysics. In these detectors, ionization electrons which drift a distance L from a particle track to the anode gas amplification regions are spread out by diffusion with an r.m.s. spatial width given by an equation of the form [1]

$$\sigma = \sqrt{\frac{4}{3}\varepsilon L/Ee} \sim 5\,\mathrm{mm} \times \sqrt{\frac{(1\,\mathrm{kV/cm})}{E_\mathrm{d}}} \times \sqrt{L_\mathrm{d}/1\,\mathrm{m}} \tag{1}$$

where E_d is the drift field, ε is the electron characteristic energy ($\frac{3}{2}k_\mathrm{b}T$ at low drift fields), and zero

---

*Corresponding author. Tel.: 215-204-3180; fax: 215-204-5652.

E-mail address: cmartoff@nimbus.temple.edu (C.J. Martoff)

0168-9002/00/$ - see front matter © 2000 Elsevier Science B.V. All rights reserved.
PII: S0168-9002(99)00955-9

applied magnetic field is assumed. This equation shows that to reduce diffusion the drift field must be as high as possible and ε as low as possible. However, in practical cases suppression of the diffusion is limited by the rapid rise in ε which occurs for reduced drift fields E/P exceeding 0.1 V/cm Torr or less (depending on the gas), and eventually (for E/P in the range of tens to hundreds of V/cm Torr) by the onset of breakdown due to avalanche multiplication in the drift region.[1]

To obtain better resolution in zero magnetic field and high drift fields, it is necessary to limit the energy gained by the drifting charge, keeping it in thermal equilibrium with the gas. Certain molecular gases (e.g. CO_2) achieve this to a degree due to their large inelastic scattering cross sections for low-energy electrons. However, we realized that a dramatic improvement could be had if the negative species being drifted could be made much heavier than electrons, therefore exchanging energy more efficiently in collisions with the gas and eliminating the influence of Ramsauer–Townsend transparency and other effects. The only candidate species seemed to be negative ions, usually considered anathema to efficient chamber operation because the common ones (oxygen) do not produce avalanches upon arrival at the anodes. An intensive search of the older literature turned up references to studies of negative ion-induced avalanches (delayed by the low ion mobility) as a nuisance in early gas detectors [3,4]. One group [5] reported using a little-known proportional counter technique in which negative ions were intentionally formed and avalanches observed in proportional chambers for ^{14}C dating. No references to studies of drift chamber characteristics with negative ions were found. However, we expected that the large ion mass and the strong quenching action of an electronegative gas should allow very high drift fields to be applied without elevating the *ion* characteristic energy ε and without initiating chamber instability due to breakdown in the drift region. Thus, we hoped to achieve diffusion corresponding to the thermal limit of Eq. (1) up to very high drift fields. These expectations have been fully verified. The present data obtained with a diffusion test-chamber show greatly reduced diffusion in zero applied magnetic field, and efficient detection of single photoelectrons with high avalanche gain.

2. Results and discussion

The apparatus used (Fig. 1) was adapted from previous diffusion studies of drifting electrons [6]. It consisted of an evacuable acrylic chamber with an ionization source region ending in a collimating aperture. The aperture leads to a cylindrical drift region, and a single-wire proportional counter following the drift region. Photoelectrons were produced by exposing a cleaned Mg surface to UV light from a Xe flashlamp through a fused silica window. An electric field equal to that in the drift region was maintained between the plate carrying the Mg surface, and the collimator plate 2 cm away. This field accelerated negatively charged species toward the collimator plate, where they were admitted to the drift region through the 300 μm collimator aperture.

The cylindrical drift region was 15 cm long and 10 cm in diameter. It contained an axial electric field with homogeneity insured by a 7.5 mm pitch copper-on-kapton field cage, connected across the drift potential by a voltage divider ladder. In operation the proportional counter shell was grounded, the photoelectron source region top plate was run at $-$ HV, and the proportional wire was run at $+$ HV. Typical operating voltages were -2 to -8 and $+0.6$ to $+1.5$ kV, respectively.

Negatively charged species entered the proportional counter from the drift region through a 300 μm wide, 10 cm long slit oriented parallel to the proportional wire and perpendicular to the drift field. The entire proportional counter (slit, shell, and wire) could be accurately and reproducibly moved back and forth perpendicular to the drift field and to the long axis of the slit, by means of a linear motion feedthrough with micrometer drive.

Measurements were made while running the system in a continuous gas flow with throughput of 1–10 cc/min, using either one or two high-purity

---

[1] In chambers with applied magnetic fields the situation is different and a somewhat elevated ε is actually desirable [2].

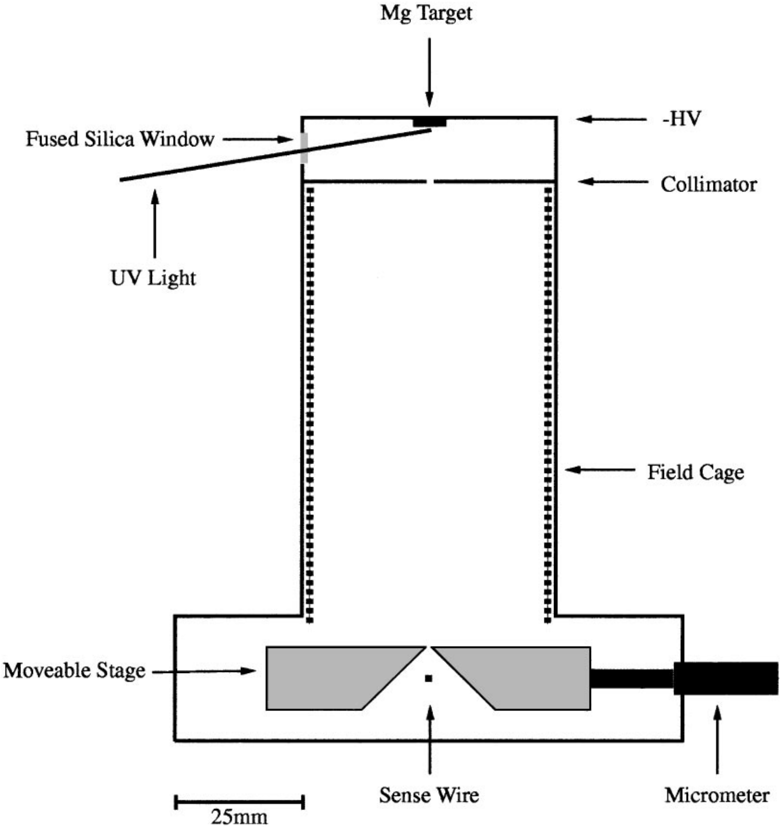

Fig. 1. Schematic diagram of the apparatus used in the present work.

argon tanks[2] with two-stage tank regulators and manual needle valves to regulate the gas flow. The inlet gas stream from one tank could be bubbled through HPLC-grade CS_2[3] contained in a glass Dreschler flask.

Drift velocity measurements were made by measuring the drift time with a Time to Amplitude Converter (TAC) started by a signal from a photodiode viewing the light pulse and stopped by the proportional counter anode wire signal, AC coupled directly through 220 pF to the 1 kΩ input of an ORTEC 450 shaping amplifier and thence to a discriminator. Gas gains of $1\text{–}2 \times 10^4$ were obtained.

For transverse diffusion measurement, the fraction of light flashes accompanied by an anode wire signal was counted, as the proportional counter was successively moved across the diffusion peak. The anode signals were required to lie within a time window 150 μs wide (much wider than the TAC peak) and centered on the ungated TAC peak. The diffusion test setup produces long drift times (typically several msec) and low probability for produced negative ions to be transmitted through the two narrow apertures, so the time gating was found necessary to reduce the accidental coincidence rate. The light intensity was adjusted to give less than 0.05 anode signals per light pulse on average, so that single-ion diffusion was measured. A correction was applied in the analysis to account for the effect of unequal electric fields in the drift region and the proportional counter.

---

[2] Air Products.

[3] Aldrich.

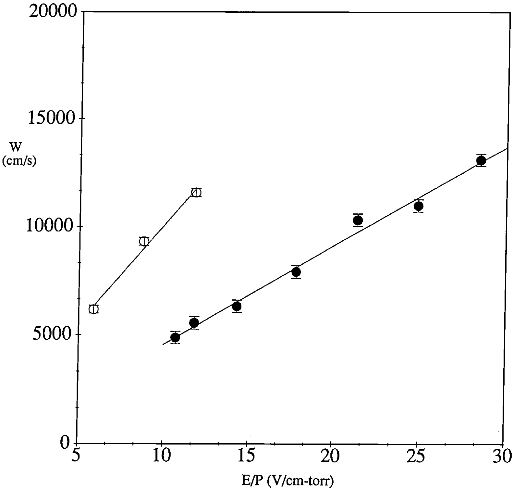

Fig. 2. Drift velocity as a function of reduced field E/P in V/cm torr, for 17 cm drift in argon/CH_4/CS_2 9:1:14.5 at 40 torr (open circles) and for xenon/CS_2 10:14.5 at 16.5 and 40 torr (closed circles). The straight line fits give mobilities of 915 ± 38 and 456 ± 8 V cm torr/s, respectively.

The results of the drift velocity measurements are summarized graphically in Fig. 2 for an argon gas mixture (Ar/CH_4/CS_2 9:1:14.5) and for a xenon mixture (Xe/CS_2 10:14.5). The strength of the reduced field which could be applied was limited by surface breakdowns across the field cage and the HV feedthroughs, not by the onset of instability in the chamber.

According to elementary diffusion theory, the drift speed can be written as [1]

$$W = \frac{eE/Pk_b T}{\sigma\sqrt{2m\varepsilon}} \tag{2}$$

where m and σ are the mass and scattering cross section of the drifting species, $k_b T$ is the absolute temperature in energy units, P is the absolute pressure, and the other symbols have the same meaning as in Eq. (1). The drift velocities in both gas mixtures were found to be linearly proportional to E/P, in agreement with Eq. (2). Thus the characteristic energy ε (or at least the indicated combination of ε and σ) in the present experiments must indeed be remaining fairly constant as the reduced field increases to more than 25 V/cm Torr.

Table 1
R.m.s. diffusion of negative ions measured in noble gas mixtures with CS_2. Drift length was 15 cm. The diffusion values reported are corrected for the finite sizes of apertures and for electric field mismatch between drift and proportional counter regions

Gas	Pressure (Torr)	E (kV/m)	Transverse diffusion (mm r.m.s.)
Ar mix	40	47.0	$0.12\ ^{+0.05}_{-0.1}$
Ar mix	40	35.3	$0.21\ ^{+0.02}_{-0.1}$
Ar mix	40	23.5	0.38 ± 0.02
Xe mix	40	47.0	$0.13\ ^{+0.05}_{-0.1}$
Xe mix	16.5	23.5	0.33 ± 0.03

At moderately high reduced fields the ions drift at about 100 m/s, compared to about 10^4 m/s for electrons in typical atmospheric pressure drift chamber conditions. The observed mobility is in the range of literature values available for negative ions near STP [7]. This slow drift speed, combined with the typical separations between primary ionization clusters in gases, will allow a negative ion drift chamber to function as a time expansion chamber [8] in which individual ionization clusters can be observed. This has been shown to give the maximum available dE/dx information from each track.

The transverse diffusion results are given in Table 1. At 23.5 kV/m, the diffusion is thermal and in agreement with Eq. (1). The trend with increasing drift field appears to fall even more rapidly than predicted by Eq. (1). This is not too surprising, since the derivation uses the assumption that the direction of the drifting species is completely randomized at each collision. This assumption may be far from satisfied for these heavy negative ions at high drift fields.

The actual measured values of the r.m.s. diffusion are extremely small. As noted above, *electrons* drifting in any real gas at even the lower E/P values studied here would have an agitation energy ε far above the thermal limit and hence much larger diffusion (see e.g. data of Ref. [6]). For example, the value of ε in pure CO_2, a gas known for low ε at high fields, already reaches 2 eV at 12 V/cm torr [9]. This would have lead to diffusion of 2.7 mm r.m.s. in the present setup, similar to the values reported [6] for electrons in low pressure P-10.

Irreversible charge losses at low pressure and high drift fields were checked for using a separate apparatus. This consisted of a multiwire drift chamber with a 10 cm drift distance between the drift cathode and the gain region. A collimated ^{55}Fe source was used to produce events at varying distances from the gain region by directing the pencil beam from the moveable source perpendicular to the drift field. The average integrated pulse height per event differed by less than 5% when the drift distance was varied from 1 to 10 cm.

The potential value of using a large gas detector at low pressure was recognized, and feasibility demonstrated in Ref. [10]. However, the best resolution achieved was several mm, and the use of a 0.4 T superconducting magnet made it difficult to envision operation underground or significant size scale-up. With the negative ion drift technique, the potential of large gas detectors for dark matter searches may at last be fully realized. Consider a 1 m^3 TPC detector using negative ion drift. At 40 Torr, this volume would contain two moles of gas. Scaling the present diffusion results from 15 cm drift to 1 m and increasing the drift field modestly, to 65 kV/m, one could expect to achieve track widths due to diffusion of 1 mm FWHM without a magnetic field. This would allow very powerful background rejection in low-rate experiments requiring particle identification at low energies, such as WIMP-Dark Matter searches [11,12]. The direction of very short tracks could also be determined, allowing the detection of the sidereal-rate diurnal directional modulation [13] which exists in standard galaxy/halo models. Detection of such a modulation would definitively prove the extraterrestrial origin of any WIMP Dark Matter signal, and is the object of intensive work by our groups.

Acknowledgements

This work was supported by the National Science Foundation, the Research Corporation, the UK Particle Physics and Astrophysics Research Council, and by Temple University, the University of Sheffield, and Occidental College. Correspondence should be addressed to C.J. Martoff.

References

[1] D. Fancher et al., Nucl. Instr. and Meth. A 161 (1979) 383.
[2] L. Rolandi, W. Blum, Particle Detection with Drift Chambers, Springer, Berlin, Germany, 1994.
[3] D.H. Wilkinson, Ionization Chambers and Counters, Cambridge at the University Press Cambridge, UK, 1950, p. 43ff, 153ff.
[4] S.A. Korff, Electron and Nuclear Counters, D. Van Nostrand Co., New York, 1955, p. 120ff, 192ff.
[5] H.R. Crane, Rev. Sci. Instrum. 32 (1961) 953.
[6] M.J. Lehner, K.N. Buckland, G.E. Masek, Astropart. Phys. 8 (1997) 43.
[7] E.W. McDaniel, H.R. Crane, Rev. Sci. Instrum. 28 (1957) 684.
[8] A.H. Walenta, IEEE Trans. Nuc. Sci. NS-26 (1978) 73.
[9] R.W. Warren, J.H. Parker Jr., Phys. Rev. 128 (1962) 2661.
[10] K. Buckland, M.J. Lehner, G.E. Masek, M. Mojaver, Phys. Rev. Lett. 73 (1994) 1067.
[11] K. Buckland, M.J. Lehner, G.E. Masek, IEEE Trans. Nuc. Sci. 44 (1997) 6.
[12] C.J. Martoff, D.S. Ifft, T. Ohnuki, M. Lehner, The DRIFT concept – sensitive WIMP dark matter search with a gas detector, Presented at Second International Workshop on the Identification of Dark Matter, available on request.
[13] D.N. Spergel, Phys. Rev. D 37 (1988) 1353.