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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Understanding the impact of additives with large inelastic cross sections on drift chamber performance

E. Fortunato, U. Becker*, R. Dinner

Massachusetts Institute of Technology, Laboratory of Nuclear Science, Cambridge, MA 02139, USA

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Abstract

We present measurements and explain a model of how gases with large cross sections for inelastic interactions with electrons significantly affect drift velocity in gaseous detectors. Empirical data confirm the model's predictions and agree with transport calculations. This understanding may allow chamber designers to choose additives that optimize detectors' performance. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Drift chamber performance; Nitrogen addition

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1. Introduction

The relationship between drift parameters and cross sections for interactions between electrons and gas molecules is described by Magboltz, a simulation of electron transport [1]. However, a verification and deeper understanding of this relationship for gases such as nitrogen, which have significant cross sections for inelastic scattering, is still needed. Even modest (and inevitable) nitrogen (N_2) contamination can have a surprisingly large effect on electron drift velocity [2], hence this understanding is essential to a more guided approach to new gas mixtures for use in modern particle detectors. In detector systems with recycled gas, the major impact of air contamination is the build up of nitrogen because the oxygen is absorbed by purifiers. Chamber designers, concerned about the introduction of nitrogen [3,4], can actually improve performance by choosing mixtures containing a small percentage of nitrogen!

2. Apparatus and measurement procedure

Our experimental setup [5] determines drift velocities and deflection angles at variable electric and magnetic fields. The voltage difference between the cathode plate and the anode mesh creates a driving electric field, E, up to 2.0 kV/cm (Fig. 1). The entire chamber is situated in the M.I.T. cyclotron magnet which provides a uniform magnetic field, B, perpendicular to E. A 337 nm N_2 laser beam provides ionization along tracks precisely known from the positioning of a mirror by a micrometer. Electrons drift under the influence of the electric and

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* Corresponding author. E-mail: becker@vx13j0.cern.ch/becker@mitlns.mit.edu

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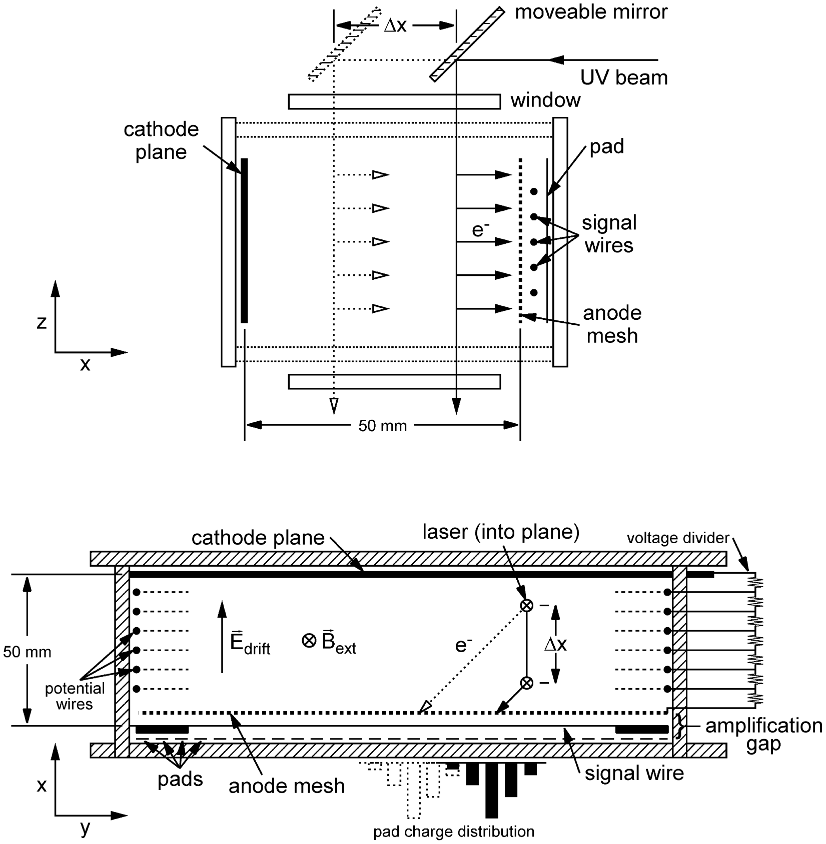

Fig. 1. Schematic diagram of test chamber used in drift velocity and Lorentz angle measurement. The side view (z–x) shows the UV laser beam displacement while the top view shows the center of gravity measurement of the magnetic deflection.

magnetic fields to the amplification gap, where signal wires measure arrival times, and induction pads measure deflection.

Differential measurements between the positions allow high accuracy. Knowing Δx and measuring Δt determines $v_{||} = \Delta x/\Delta t$, the component of velocity parallel to E. Drift time is averaged over 100 laser shots at each of the electric and magnetic field settings for at least two positions of the laser beam.

Because all observations reported are valid for modest (less than 0.5 T) magnetic fields, we choose to make comparisons for $B = 0.2$ T as a non-trivial case. For full data please refer to our online database at http://cyclotron.mit.edu/drift/.

3. A simple view of electron transport in argon

Gas cross sections are taken from the literature [1,6]. Argon's cross section shows a pronounced minimum at approximately 0.23 eV for interactions with electrons (Fig. 2). This quantum mechanical effect derived by Ramsauer [7] explains the primary drift features of argon-based gas mixtures. At lower electric fields ($E \approx 0.4$ kV/cm) the Boltzmann distribution of electron energies centers around the minimum in argon's cross section. The smaller cross section allows longer mean free paths, causing larger $v_{||}$. As the drift field increases, the distribution of energies of the drifting electrons will shift to higher energies where argon's cross section is large. The larger cross section decreases the average drift

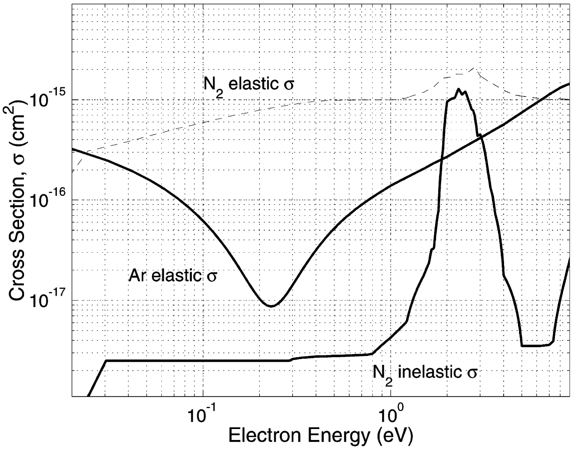

Fig. 2. Energy-dependent cross sections for elastic and inelastic interactions between electrons and gas molecules. Note the “Ramsauer” minimum in argon’s elastic cross section at 0.23 eV and the peak in nitrogen’s inelastic cross section near 2 eV.

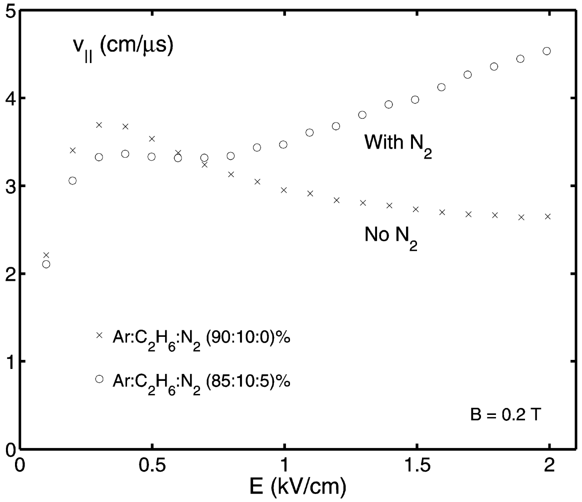

Fig. 3. Addition of 5% nitrogen to an argon-based mixture drastically changes drift velocity.

velocity despite the stronger driving E field. For gases like argon, interactions between the electrons and the gas atoms are almost entirely elastic. Thus electrons at high energies (corresponding to a large cross section) are likely to collide many times and drift more slowly as a result (see Ar : C_2H_6 in Fig. 3 as an example).

Note that the electron cross sections of all noble gases, other than neon, exhibit a Ramsauer minimum, as do reasonably spherical molecules such as methane and isobutane. Therefore, similar considerations apply noting that the minimum occurs at different electron energies.

4. Nitrogen addition

We present a set of drift velocity measurements for a gas mixture with and, for comparison, without nitrogen (Fig. 3). The addition of a few percent of nitrogen gas to the argon-based mixture produces two prominent effects. The first is the relative depression of the drift velocity at low electric fields, 0.2–0.5 kV/cm. This decrease is a consequence of nitrogen’s large elastic cross section for electrons with low energies, i.e. less than 1 eV (Fig. 2). The second feature, an almost linear rise in the drift velocity at high electric fields ($E > 0.8$ kV/cm), results from inelastic interactions between electrons and nitrogen molecules. Nitrogen’s cumulative inelastic cross section (Fig. 2) is insignificant over the lower range of energies but peaks near 2 eV. As electrons attain this high energy, they face an increasing argon cross section, but inelastic interactions with nitrogen molecules return them to the energy of argon’s minimum. The electrons retain long mean free paths as the driving electric field increases, resulting in increasing average drift velocity. The use of nitrogen to improve chamber performance was noted by the Atlas collaboration [8].

We confirmed these qualitative expectations using Magboltz [1]. The program takes gas molecules’ cross sections for electron interactions, and the electric and the magnetic fields, and then numerically solves the Boltzmann transport equation to determine $v_{||}$. The simulation was run both with the complete nitrogen cross section and with a cross section artificially altered to have no inelastic component (Fig. 4). These calculations confirm that it is the peak in nitrogen’s inelastic cross section that causes the increase in drift velocity at higher electric fields.

5. Verification with other gases

We tested our understanding of the effects of large inelastic cross sections in two additional

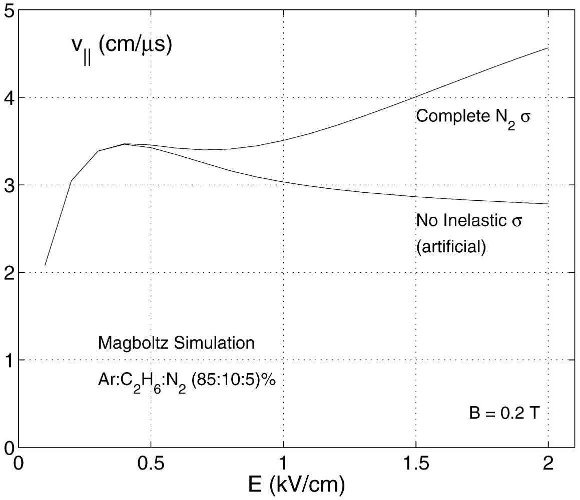

Fig. 4. Simulations of drift velocity for an addition of normal nitrogen and nitrogen without inelastic interactions reveal the causes of nitrogen's effects.

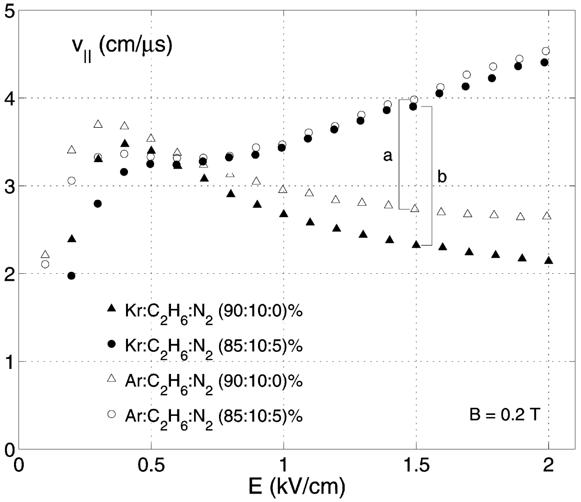

Fig. 6. Addition of nitrogen has a greater effect on drift velocity in a krypton-based mixture (b) than the equivalent argon-based mixture (a).

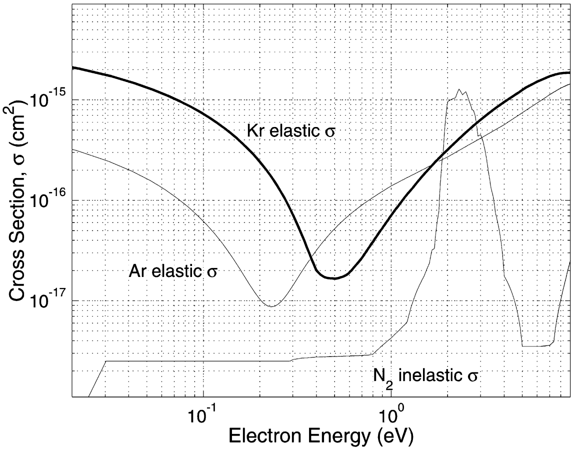

Fig. 5. Comparing the Ramsauer minima of krypton and argon relative to the peak in nitrogen's inelastic cross section.

ways. First, this model predicts that the magnitude of nitrogen's effect on the drift properties of a mixture depends on the difference in the energies at which nitrogen's inelastic peak and the other gases' Ramsauer minima occur. For example, krypton's minimum (0.49 eV) occurs at a higher energy than argon's (0.23 eV) (Fig. 5). Due to the proximity of krypton's minimum to nitrogen's peak, electrons whose energies are reduced ("cooled") by inelastic interactions with nitrogen are more likely to fall within krypton's minimum. Our measurements (Fig. 6) confirm that the relative increase in the drift velocity at high electric fields due to nitrogen additions is larger in krypton-based mixtures than in equivalent argon-based mixtures. The model also correctly predicts a similar disparity between mixtures containing methane and ethane, which have minima at 0.23 and 0.13 eV, respectively.

Second, we compared the effect of another additive, carbon dioxide (CO_2), to that of nitrogen. Carbon dioxide has a large inelastic cross section (Fig. 7) for electron energies greater than 0.08 eV. This cross section also has a peak at 3.5 eV, approximately at the same energy as the N_2 peak. As expected, the addition of 5% of CO_2 (Fig. 8) increases $v_{||}$ at medium and high E fields (0.4–2 kV/cm). Unlike in nitrogen mixtures, however, the velocity levels off over this range.

We analyzed this effect with simulations, artificially setting carbon dioxide's inelastic cross section to zero at energies below 2.5 eV and then above 2.5 eV. Keeping only the high-energy cross section (case a), carbon dioxide's effect is similar to that of nitrogen: continually increasing $v_{||}$ at higher electric fields. Keeping only the low-energy cross section (case b), we see the highest elevation of drift

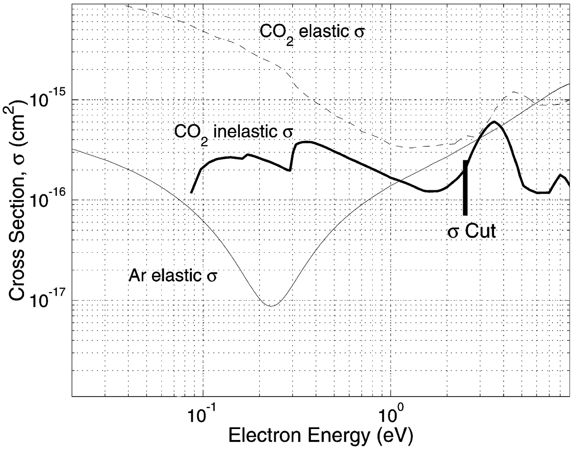

Fig. 7. Carbon dioxide's inelastic cross section, divided into low- and high-energy regions for purposes of analysis.

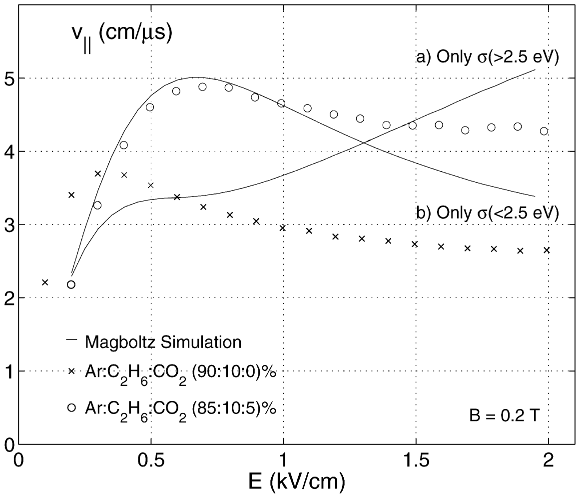

Fig. 8. Comparing measured drift velocities with a normal carbon dioxide additive to simulated velocities using carbon dioxide with low- or high-energy inelastic cross sections removed.

velocities at medium E fields (0.5–0.8 kV/cm). These effects stem from CO$_2$ cooling electrons toward the argon minimum.

As an example, Fig. 9 shows a measurement for various magnetic fields containing both N$_2$ and CO$_2$ which yields further confirmation of the above understanding. However, the combination of N$_2$ and CO$_2$ shows marked attachment of electrons which will be studied in the future. Also, additions of H$_2$O and NH$_3$ [9] will be of interest.

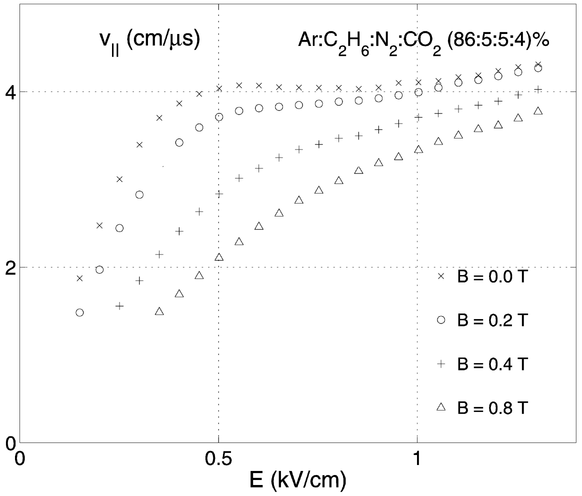

Fig. 9. Drift velocity with the addition of both N$_2$ and CO$_2$ for various magnetic fields.

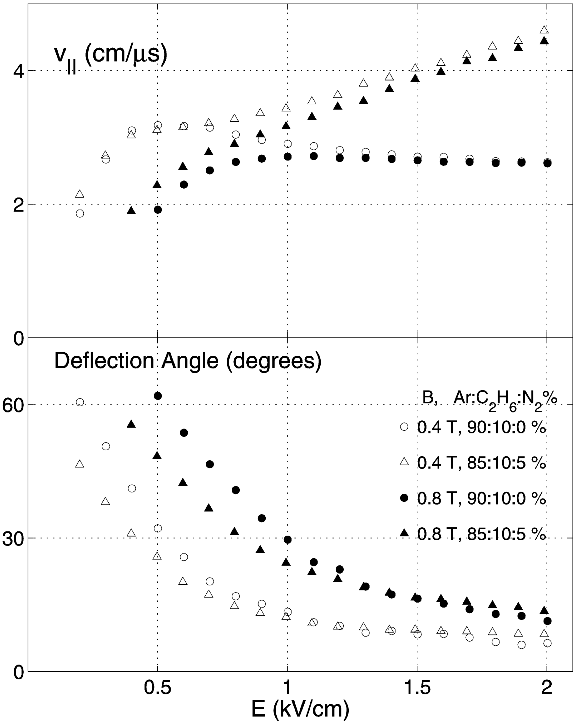

Fig. 10. Drift velocities and deflection angles at $B = 0.4$ and 0.8 T for mixtures with and, for comparison, without N$_2$. Note that the N$_2$ mixture improves (lowers) deflection at lower E, and still offers an advantage at higher E considering the larger $v_{||}$.

6. Influence on the deflection angle

Nitrogen, in addition to affecting drift velocity, can also improve the deflection angle, an important parameter of chamber performance. As shown in Fig. 10, the addition of nitrogen to an $Ar:C_2H_6$ mixture decreases deflection angles at lower E fields (< 1.2 kV/cm). Moreover, that N_2 does not significantly affect the deflection at high electric fields is surprising considering that the increased drift velocity should increase the deflection force $\propto \mathbf{v} \times \mathbf{B}$.

7. Summary

We have studied in detail how additives with known inelastic cross sections will influence drift features. Because today's gas mixtures must have low hydrocarbon content, the detailed effects of non-flammable admixtures have become important for large drift detectors. The application for new devices [10] will be interesting.

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