A Systematic Study of Electron Drift for Gaseous Chamber Design

E. Fortunato, U. Becker, R. Dinner, J. Kirchner, K. Rosera, Y. Uchida
Massachusetts Institute of Technology

Abstract

We present a consistent set of measurements of electron drift velocities and Lorentz deflection angles in all noble gases with methane and ethane as quenchers in magnetic fields up to 0.8 Tesla. These and many other results are available in a searchable database on World Wide Web at `http://cyclotron.mit.edu/drift/` to allow for guided design and optimization of future detectors. A simple model is used to form an empirical parameterization of the results. This compact form unifies the drift characteristics of a gas mixture over a range of electric (0 – 1.5 kV/cm) and magnetic (0-0.8 Tesla) fields. A more detailed model is presented which explains the surprisingly large effect of even modest (and inevitable) nitrogen contamination on electron drift velocity. Additional measurements and simulations confirm the validity of the model's predictions and show possible applications.

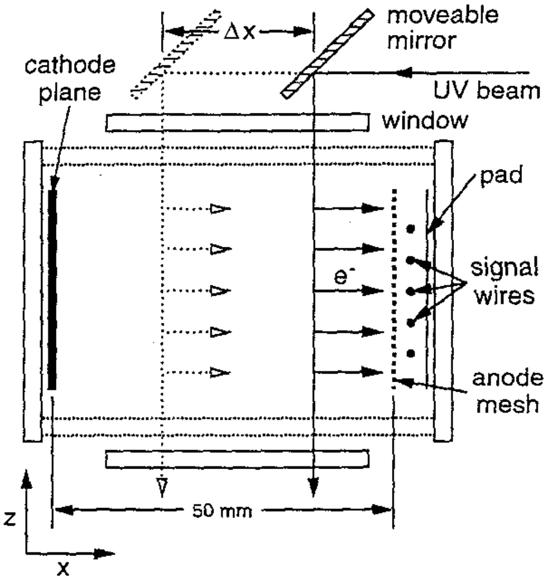
I. INTRODUCTION

A systematic knowledge of electron drift properties in various gas mixtures over a range of electric and magnetic fields is essential for the design of future particle detectors. Though measurements, calculations and interpretations of the drift velocities of electrons through many gas mixtures are available in the literature ([1],[2],[3],[4],[5]), no systematic study allowing precise interpolation of features has been done. To allow accurate comparison and detailed understanding of principle features, the project obtained a consistent set of measurements of drift velocities and Lorentz deflection angles for all noble gases with methane and then ethane as quenchers in magnetic fields up to 0.8 Tesla. Empirical fits of the data provide a more compact form to communicate the results and give physical insight.

While the relationship between the drift parameters and the electron-gas interaction cross section has been modeled for normal gases such as argon and methane, a deeper understanding of gases such as nitrogen (N_2), which have significant *inelastic* cross sections, is still needed. Chamber designers, concerned about the introduction of nitrogen, ([6],[7]) can actually improve performance by choosing mixtures containing a small percentage of nitrogen!

II. APPARATUS AND PROCEDURE

The experimental setup has been described in [8] and a schematic is shown in Figure 1. A voltage difference between the cathode plate and the anode mesh creates a variable driving electric field of 0 to 2.0 kV/cm. A 337 nm N_2 laser beam provides ionization along tracks precisely known from positioning of a mirror by a micrometer. Electrons drift under the influence of the electric and magnetic fields to the



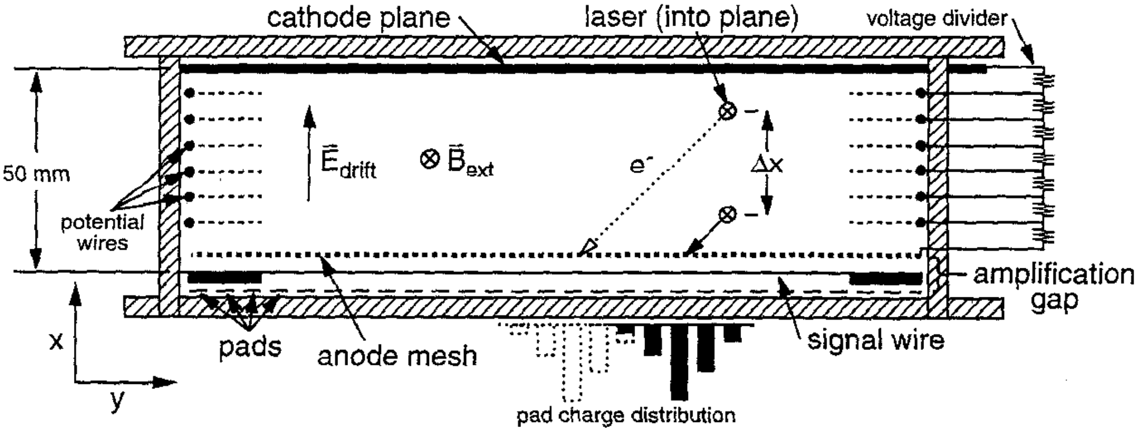


Figure 1. Chamber diagram, xz projection (top) and xy projection (bottom).

0-7803-5021-9/99/$10.00 © 1999 IEEE.

amplification gap, where signal wires measure arrival times and induction pads behind the wires measure deflection. Differential measurements between the positions allow high accuracy. Knowing Δx and measuring Δt determines $v_{\parallel} = \Delta x/\Delta t$, the velocity component parallel to **E**. The entire chamber is situated in the MIT cyclotron magnet which provides a uniform magnetic field (**B**) perpendicular to the **E** field and the wires.

Noble gases were mixed with 10 to 50% of quenching hydrocarbons, here methane and ethane. Drift times and charge distributions' "centers of gravity" for 100 laser shots were averaged for at least two position settings of the laser beam. Twenty four electric fields settings, four magnetic field settings for each of the 25 gas mixtures with two quenchers result in a total of 2*(24*4*25*2)=9,600 measurements.

III. Drift Velocities and Deflection Angles

For this reason, only some examples will be discussed here, while a complete set of results can be obtained at `http://cyclotron.mit.edu/drift/`.

Helium and xenon are slow gases relative to neon and argon. Figure 2 demonstrates that the drift velocity generally increases with methane content, which is not surprising since methane itself is a "fast" gas at low **E**. Similar to argon's cross section, methane also has a "Ramsauer" minimum at about 0.2 eV that allows for fast drifting at corresponding **E**. For increasing B fields, the drift velocity component along the **E** field is seen to diminish in all gases.

*One might expect the rms deflection, α, to grow proportionally to the magnetic force (qvx**B**), relative to the electric force (q**E**), i.e.:*

$$\tan\alpha = (v \times B)/E \qquad (1)$$

At large **E** fields, the 1/**E** dependence is found, but at low values, the situation is not so as simple, because the velocity is often changing quickly.

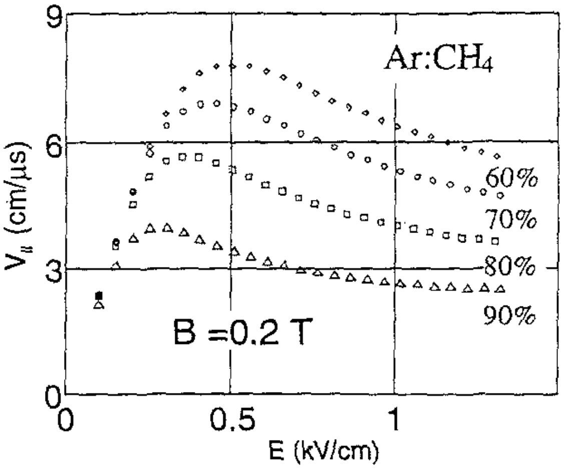


Figure 2. Argon-based mixtures with varied percentages of methane quencher.

Comparing methane and ethane additons, we generally see lower drift velocities for ethane. In addition, ethane typically produces lower α than methane, even if the velocities are roughly equal. For example, this can be seen in the comparison of Kr:CH$_4$ and Kr:C$_2$H$_6$, both at 90%:10%, at **E** = 0.4 kV/cm, as shown in Figure 3. Gases with large deflection produce less accurate coordinate reconstruction.

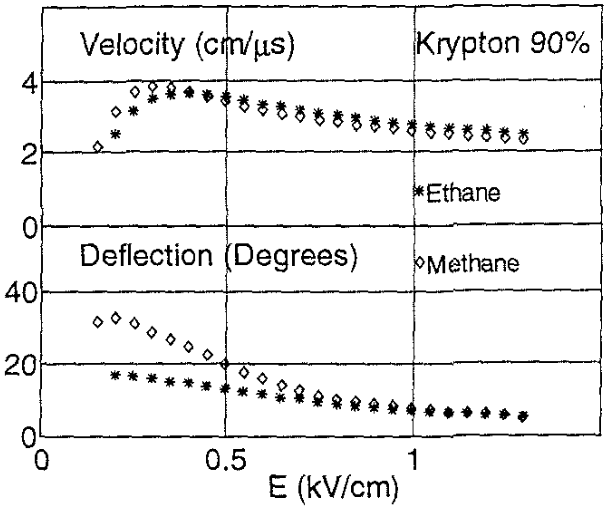


Figure 3. Krypton mixture comparing the deflection angle with for methane and ethane additives.

More precise values for these, as well as other mixtures, are best obtained from the database on the WWW. Because all measurements are made with the same apparatus, relative errors are accurate to one-percent.

III. Empirical Description

Empirical descriptions of the data, motivated by a simple physical model, allow compact communication of the results. The number of parameters is adjusted in order to obtain a χ^2 per degree of freedom less than 1.5. For the drift velocity parallel to the electric field the formula used is:

$$v_{\parallel} = u_1\left(1 - e^{-E'/E_1}\right) + u_2 E' e^{-((E'-\varepsilon_2)E_2)} + wE' \qquad (2)$$

where **E′** is the adjusted electric field, **E**-ε. The first term describes drift through a gas of constant cross section. The second term accounts for the increase in drift velocity due to the Ramsauer minimum in the electron-gas interaction cross section. The last term is a simple linear correction. The angle formula, following the discussion above, assumes simple Lorentz motion with correction terms.

$$\sin(\alpha) = \frac{v_{\parallel}B}{E} + p_1 + p_2 E + p_3 E^2 \qquad (3)$$

Gases with nearly constant cross section (such as helium) are adequately described by the first term alone. Gases with pronounced Ramsauer minima, such as argon, require the second term to account for the peak in the drift velocity (Table 1. And Figure 4). Because these simple empirical fits do not model rapid changes in $v_{\parallel}$ at low **E**, their validity is strictly limited to the range indicated by the solid line.

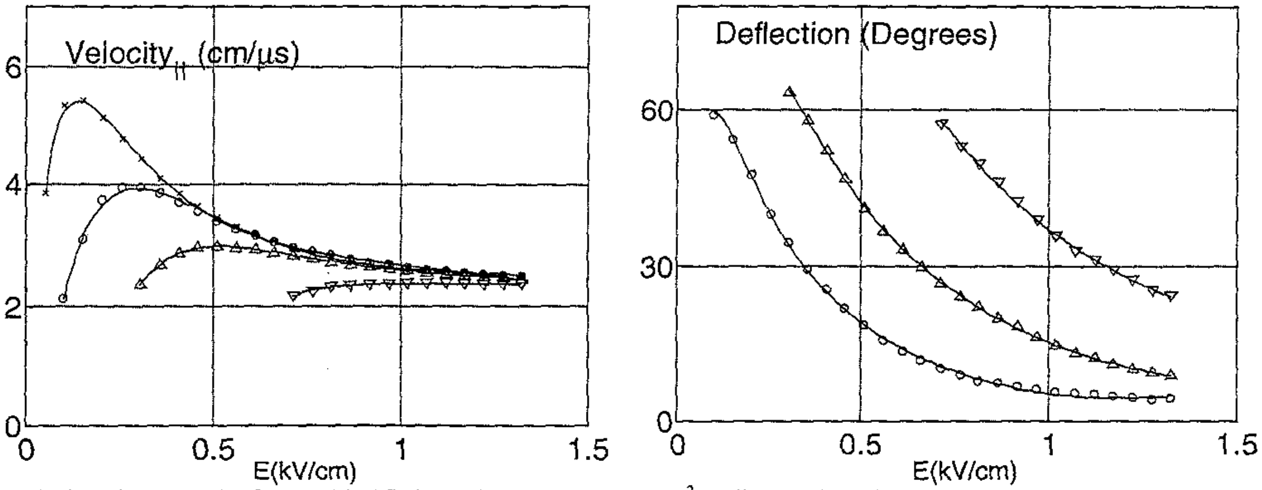


Figure 4. Graphical example of an empirical fit for Ar:CH_4. Parameters and χ^2/dof listed in the table above.

Table 1.
Example of the fitted parameters and χ^2/dof for Ar:CH_4 (90:10%) mixture.

B(T)	U_1	E_1	U_2	E_2	W	ε	ε_2	χ^2/dof	P_1	P_2	P_3	χ^2/dof
0.0	3.3	0.024	78	8.1	-0.66	0.015	0.058	0.95	0	0	0	-
0.2	2.5	0.18	34	5.7	0	0.043	0	1.36	0.53	-0.87	0.38	0.7
0.4	2.4	0.28	19	4.8	0	0.16	0	0.13	0.88	-1.1	0.36	0.15
0.8	2.4	0.078	0	0	0	0.52	0	0.1	1.3	-1.3	0.34	0.33

Further data reduction is possible with the realization that low B fields primarily change the electrons' direction rather than their velocity. Hence, plotting $v=v_{\parallel}\cos\alpha$ versus the 'effective' field component, $E^*\cos\alpha$, result in curves independent of B. These 'universal' curves describe the behavior of a given mixture very well, as we noticed in [9]. For example, argon mixtures with ethane are very predictable, while argon with methane shows deviations at 0.8 T (Figure 5).

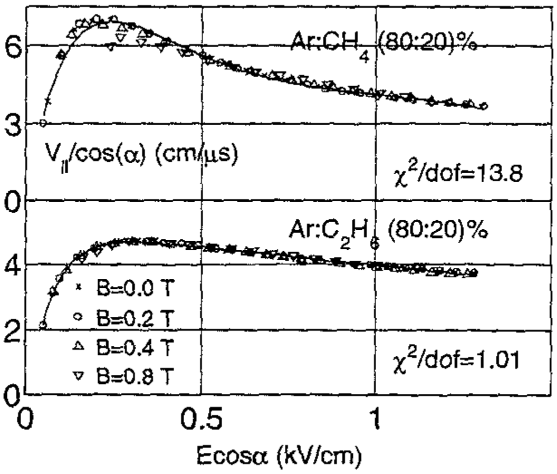


Figure 5. Comparison of 'universal' empirical fits for argon-based mixtures.

IV. EFFECTS OF ADDITIVES WITH INELASTIC CROSS SECTIONS

The Ramsauer minimum in argon's almost purely elastic cross section (Figure 6) explains the drift features of argon-based gas mixtures. At low energies the drift velocity is large due to the small interaction cross section, σ. At higher energies σ increases, reducing the mean free path and causing a reduction in $v_{\parallel}$ (as already shown in Figure 3).

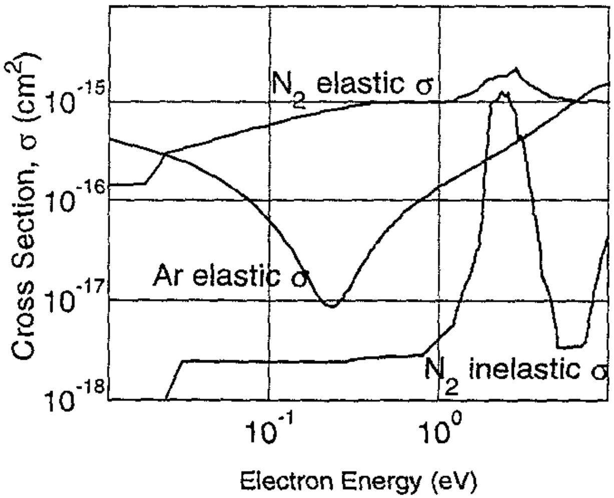


Figure 6. Electron interaction cross sections for argon and nitrogen.

The addition of a small percentage of nitrogen gas to argon-based mixtures produces two significant effects, each explained by a different feature of N_2's cross section (Figure 6). The depression of the drift velocity at low electric fields (Figure 7) is explained by nitrogen's large elastic cross section, while the peak in nitrogen's inelastic cross section explains the almost linear rise in the drift velocity at higher electric fields. Nitrogen's inelastic cross section is insignificant over the lower range of energies but spikes at energies near 2 eV. As electrons gain energy, they face larger cross sections. When they interact inelastically with the nitrogen atoms, however, their energy is reduced, shifting them back into the argon minimum. This reduced cross section allows longer mean free paths, which combine with larger driving electric fields to increase drift velocity.

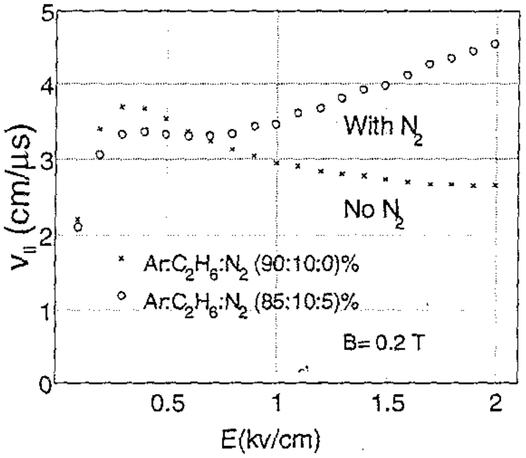


Figure 7. Effect of small N_2 additions on drift velocity.

Magboltz [5], a 3-D Monte Carlo simulation that numerically solves the Boltzmann transport equation, was used to confirm these qualitative expectations. By simulating the drift velocity for a fictitious mixture containing a nitrogen component whose inelastic cross section had been artificially removed, it showed that the linear rise in the drift velocity at higher electric fields is a direct result of the inelastic component (Figure 8).

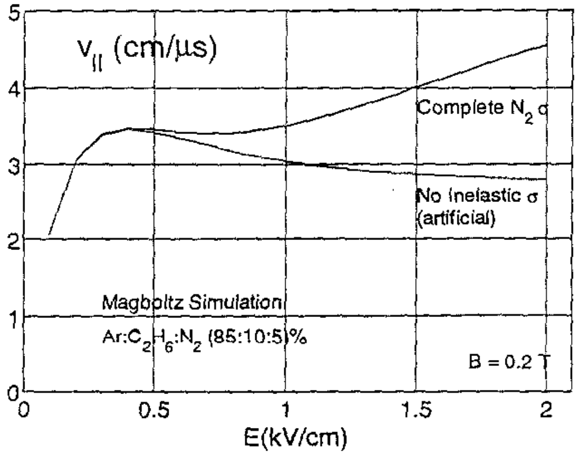


Figure 8. Simulations confirm the effect of N_2's inelastic component.

As a further test of this model, nitrogen's effect on other gas mixtures was measured. These measurements were compared to confirm the prediction 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) (Figure 9). Therefore, the electrons whose energies are reduced ("cooled") by inelastic interactions with nitrogen are more likely to fall within krypton's minimum. Measurements (Figure 10) 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.

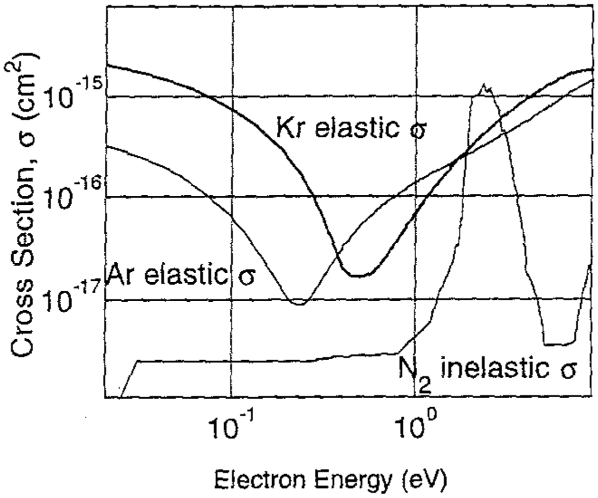


Figure 9. Electron interaction cross sections for argon and nitrogen.

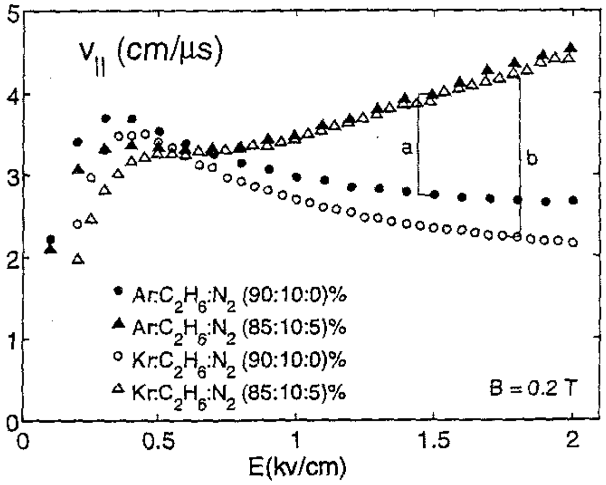


Figure 7. Effect of small N_2 additions on drift velocity.

In addition to affecting drift velocity, nitrogen can also improve the deflection angle, another important parameter of chamber performance. The addition of nitrogen to an Ar:C_2H_6 mixture decreases angles at lower **E** fields (<1.2 kV/cm) (Figure 11). Moreover, that N_2 does not significantly affect the deflection at high electric fields is surprising considering that increased drift velocity should increase the deflection force (~ v×**B**).

Gases that include N_2 additives may provide higher performance for future detectors both through better drift characteristics and due to less variation from air impurities.

V. ACKNOWLEDGMENTS

We wish to thank Cary Lapoint and Xiaofeng Zhang for help on this project. We thank the Laboratory for Nuclear Science for support, and M. Grossman for technical assistance. The work was supported under DOE contract #DE-FC02-94 ER 40818.

VI. REFERENCES

[1] F. Sauli and A. Peisert, Drift and Diffusion in Gases, CERN Internal Report, 84-08, 1994.

[2] J. Fehlmann, G. Viertel, Compilation of Data for Drift Chamber Operation, ETH, Zurich, 1983.

[3] J. Va'vra *et al*, *NIM*, A324:113, 1993.

[4] A. Sharma, http://www.slac.stanford.edu/pubs/icfa/, ICFA Instrumentation Bulletin Article, vol. 16, 1998.

[5] S.F. Biagi, Magboltz v2.2, March 1990.

[6] U. Becker *et al*, "The effect of N_2 Contamination on Drift Chambers in Magnetic Fields," *NIM*, A351:583, 1994.

[7] U. Becker *et al*, "Effect of N_2 Contamination on Drift Chambers in Magnetic Fields," *NIM*, A361:401, 1995.

[8] U. Becker *et al*, "Calibration Setup of Drift Chamber Gases," *NIM*, A306:194, 1991.

[9] Y.H. Chang *et al*, "Drift Velocities and Magnetic Deflection in CF_4 Based Gases," *NIM*, A339:524, 1994.

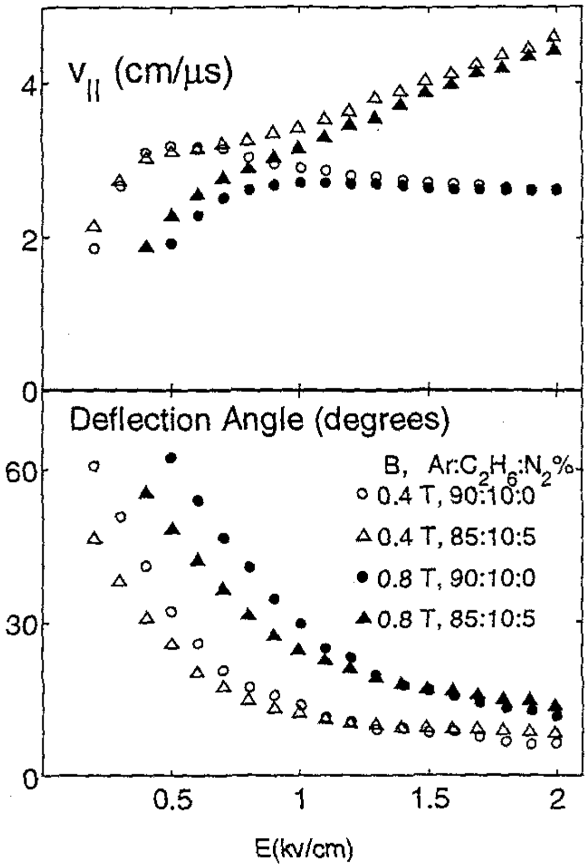


Figure 11. Deflection angles are reduced by N_2 additions for an $Ar:C_2H_6$ mixture.