Properties of some gas mixtures used in tracking detectors

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Abstract

This report summarizes some useful data on the transport characteristics of gas mixtures which are required for detection of charged particles in gas detectors. The requirements for high luminosity tracking are stringent and different at low and high momenta, representing a compromise between a fast gas mixture, small diffusion properties and having a small Lorentz angle, but high primary ionization. With the advent of a host of computing programs available the transport parameters are rather well estimated and corroborated by experiment. Mixtures of some noble gases with popular quenchers are considered, with some emphasis on low mass gases. Pure noble gases for example argon and xenon are also presented with single photon detection and medical imaging applications in view respectively.

1 INTRODUCTION

Particle physics experiments rely heavily on the detection of charged and neutral radiation with gaseous electronics. A suitable gas mixture enclosed within electrodes with an electric field between them permits the detection of charged particles. When ionizing radiation passes through such a system, free charge is liberated in the form of electrons and ions moving under the action of the electric field to the respective electrodes. In high fields, the electrons can be amplified creating a detectable charge signal. The study of the drift and amplification of electrons in a uniform (or non-uniform) electric fields has been a fascinating subject of intensive research over the past century. Pioneering work has been done by Townsend and his collaborators which has been well summarized in [1-17]; exhaustive reviews on the progress of the theory and experiments can be found in these references.

For tracking at the high luminosity hadron collider like LHC, an operational gas mixture has the following requisites: It has to be fast, so that an event can be unambiguously associated to its bunch crossing which leads to a compromise between having a high drift velocity and large primary ionization statistics. The drift velocity would ideally be saturated or have a small variation with modifications in electric and magnetic fields. The mixture needs to be well quenched with no

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secondary effects like photon feedback and field emission giving a stable gas gain well separated from the noise of the electronics. Fast ion mobility for quick clearance of positive ions to inhibit space charge effects also helps in having small EXB effects.

Experiments at the upcoming high luminosity B-f and t-charm factories require a low mass gas mixture and a lot of work has been done in this direction. For low mass gas mixtures, used for detection of low momentum particles by minimizing multiple scattering, it is known that ethane, Isobutane and dimethyl ether (DME) are good quenchers with helium [25-30] , which help increasing also the number of primary and total ion pairs per cm for a given density.

Clearly financial constraints also need to be addressed in large gas systems, and a non-flammable, eco-friendly gas mixture is often a pre-requisite for safety.

2 STATISTICS OF ELECTRON-ION PAIRS PRODUCTION IN A GAS

When an ionizing particle passes through a gas the free electrons and ions are produced in amounts that depend on the atomic number, density and ionization potential of the gas, and on the energy and charge of the incident particle. The number of primary electron pairs per cm is called N_p. The created electrons may have sufficient energy to ionize further and create secondary electron-ion pairs. The overall outcome of the two processes is called total ionization, the total number of electron-ion pairs per cm is denoted by N_t. N_p and N_t depend on incident particle charge and velocity, and are characteristic of a given gas or gas mixture. They affect the localization accuracy and in particular for thin gas gaps in chambers the accuracy is largely affected by the average distance between primary ionization clusters. These numbers have been measured and computed for a variety of gases [11, 18-24]. Table 1 lists some values for N_p and N_t, along with other general properties. Here E_x and E_i are the excitation and ionization energy, respectively, w_i is the average energy required to produce one electron-ion pair in the gas, $(dE/dx)_{mip}$ is the most probable energy loss by a minimum ionizing particle. All numbers are for normal temperature and pressure (NTP).

For gas mixtures a weighted average for N_p and N_t may be computed. Equal being the gas density, the number of primaries is larger for gases whose molecules comprise light elements. The numbers given are for minimum ionizing particles; for lower energy particles the larger ionization density helps improving accuracy.

Table 1: Physical Properties of gases at 20°C and 760 Torr

Gas	Z	A	Density 10^{-3} (g/cm^3)	E_x (eV)	E_i (eV)	w_i (eV)	$[dE/dx]_{mip}$ (keV cm^{-1})	n_p (cm^{-1}) N.T.P	n_t (cm^{-1}) N.T.P.	Radiation Length (m)
He	2	2	0.178	19.8	24.5	41	0.32	4.2	8	745
Ar	18	39.9	1.782	11.6	15.7	26	2.44	23	94	110
Ne	10	20.2	0.90	16.67	21.56	36.3	1.56	12	43	345
Xe	54	131.3	5.86	8.4	12.1	22	6.76	44	307	15
CF_4	42	88	3.93	12.5	15.9	54	7	51	100	92.4
DME	26	46	2.2	6.4	10.0	23.9	3.9	55	160	222
CO_2	22	44	1.98	5.2	13.7	33	3.01	35.5	91	183
CH_4	10	16	0.71	9.8	15.2	28	1.48	25	53	646
C_2H_6	18	30	1.34	8.7	11.7	27	1.15	41	111	340
i-C_4H_{10}	34	58	2.59	6.5	10.6	23	5.93	84	195	169

3 ELECTRON TRANSPORT PROPERTIES

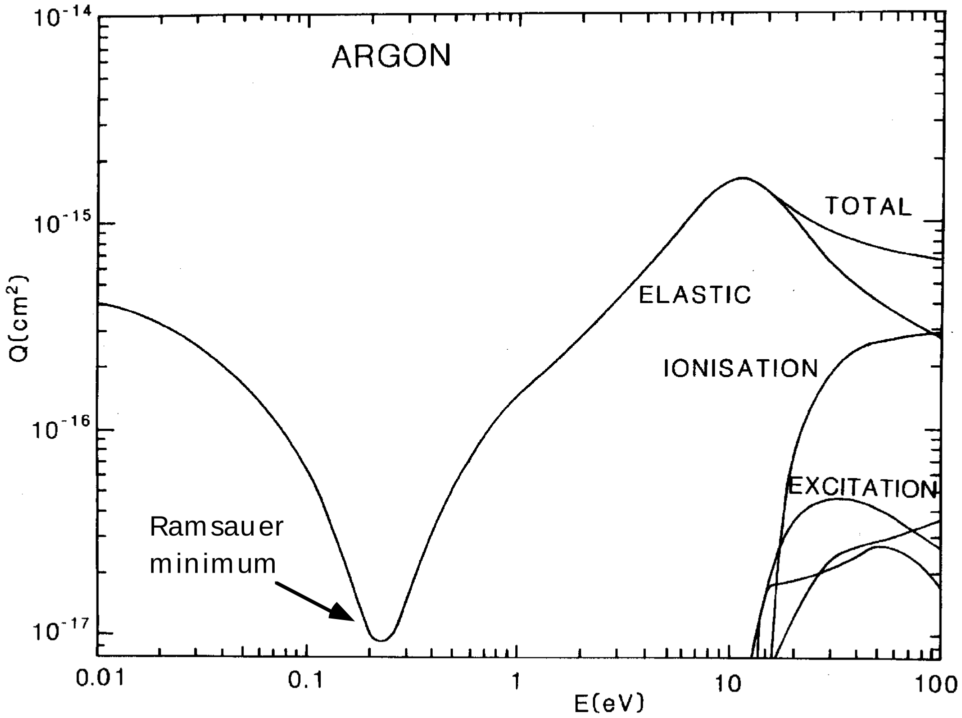

Fig. 1 Cross sections for electron collisions in Argon

Rigorous treatment of the theory of electron transport has been extensively summarized in the various references quoted [31-33]; here it is very simply reminded without mathematical detail. In the absence of electric field the free electrons in a gas will move randomly, experiencing collisions with the gas molecules with a Maxwell energy distribution, having an average thermal energy of 3/2 kT (0.04 eV at STP); when an electric field is applied, in addition to their random thermal velocity v, the electrons begin to drift in the field direction with a mean velocity v_d, the average distance covered by the drifting electron swarm per unit time. The energy distribution, Maxwellian in the absence of an electric field becomes a complicated distribution once the electrons start moving in an electric field and thus acquiring energy. This energy distribution is even more complicated in the presence of a non-uniform field, for example resulting from particular detector geometries and/or the presence of magnetic fields requisite for charged particle tracking. When the electrons move in an electric field they may still attain a steady distribution if the energy gained per mean free path is small compared with the electron energy. The momentum transfer per collision is not a constant, especially in excitation and ionization collisions between electrons and atoms, causing a larger energy loss. electrons with energies near the Ramsauer minimum in argon (see fig.1) for example (0.23 eV) have long mean free paths and as a consequence, can gain more energy before experiencing a collision with the surrounding gas. This is taken into account in computing the energy distribution function and has consequences on the gas parameters. The drift velocity is also dependent on pressure, temperature and can be modified by the presence of pollutants like water or oxygen (as will be demonstrated in section 5); electronegative pollutants deplete the gas of electrons.

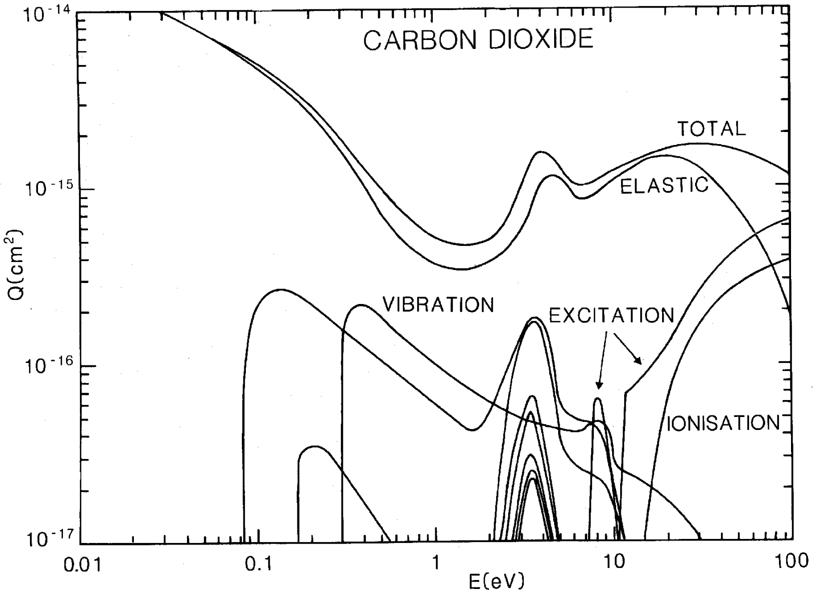

Fig. 2 Electron collisions cross sections for carbon-dioxide

Differently from noble gases, poly-atomic molecular and organic gases have many other modes of dissipating energy, namely molecular vibrations and rotations. The probabilities of these mechanical excitations can be as important as those of electronic excitations. The actual mechanism of such interactions is complex and the molecule can be in a final state very different from the ground state of the molecule. The cross-sections of carbon dioxide can be taken as an example, see fig. 2. It is seen that these collisions are produced at relatively small energies (0.1 to 1 eV) compared to excitation and ionization collisions. The vibrational and rotational excitation cross sections result in the mean fractional energy loss being large and the mean electron energy being low. The mean or 'characteristic electron energy' represents the average 'temperature' of the drifting electrons: a gas may be called warm or cold depending upon the average electron energies being above the mean energy limit, in the electric field range considered.

As the electrons are drifting in the electric field they also disperse symmetrically, thus giving rise to volume diffusion, transverse and longitudinal to the direction of motion. In cold gases like carbon-dioxide for example, the diffusion is small, while drift velocity is low and unsaturated for values of electric fields usual in gas detectors; this implies a non linear space time relation. Warm gases like argon for instance, have a higher diffusion; when mixed with polyatomic/organic gases having vibrational thresholds between 0.1 and 0.5 eV, diffusion is reduced in most cases, while the drift velocity is increased.

Clearly due to the deflection effect exerted by a magnetic field perpendicular to the electric field and the motion of the electron, the electron moves in a helical trajectory resulting in a lowered drift velocity and transverse dispersion. Thus the arrival time of electrons in a proportional counter for example changes and the spread in the drift time increases. The angle which the drifting electron swarm makes with the electric field is defined as the Lorentz angle of the particular gas or gas mixture under consideration. This depends on both the electric field and the magnetic field. It is normally large at small electric fields but falls to smaller values for larger electric fields and is approximately linear with increasing magnetic field. It has been observed that gases with low electron energies have a small Lorentz angle. In case of a small mis-alignment between the electric and magnetic fields, the resulting drift velocity and transverse diffusion will distort the space time relation at the ends of the drift space in both TPC end-cap multiwire chambers or drift chambers in a magnetic field. Therefore these effects have to be carefully studied and minimized.

The Boltzmann transport equation expresses the conservation of the number of electrons from the classical Liouvilles theorem for collisions in the absence of amplification, which may be solved numerically knowing the electron distribution function at a point of phase space as a function of time. To solve this equation, this function is expanded in Legendre polynomials, and the terms after the first two contribute to less than 1% and are neglected giving a set of two coupled differential equations which may be solved exactly.

All calculations presented here are carried out with the MAGBOLTZ computer program for transport parameters developed by S. Biagi [34]. The program was initially developed as a multiterm Boltzmann expansion allowing the extraction of the absolute cross sections for electron scattering from the experimental data on drift velocity and transverse diffusion. Data from inelastic scattering cross sections are also used. Calculations are carried through to third order Legendre polynomial expansion of the electron distribution function; neglecting higher orders leads to some discrepancy of a few percent in the predicted and measured values of diffusion, especially transverse. These cross sections are then used to compute and predict the transport parameters in various gases and gas mixtures[1]. Fig. 3 shows the cross sections DME as an example.

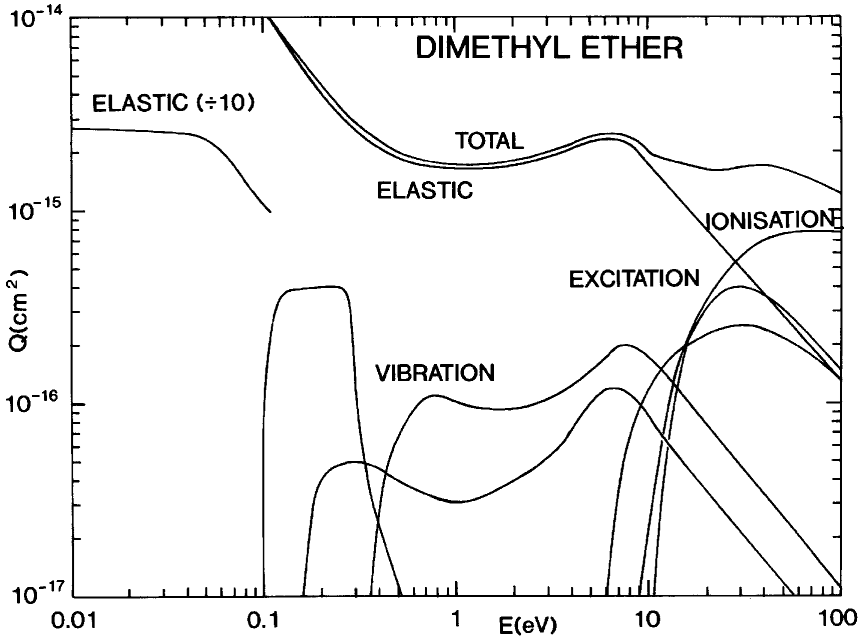

Fig. 3 Electron collision cross sections for dimethylether (DME)

The electron transport overview has been organized as follows: Noble gases Helium, Neon, Argon, and Xenon are mixed with the popular quenchers namely Methane, Ethane, Isobutane, DME, and Carbon-dioxide[2] . Each dataset has been presented in two ranges of the electric field: from 0 to 5000 V/cm on a linear scale, and from 5 to 50000 V/cm on a logarithmic scale. In the first set of transport parameters the magnetic field is zero. Transport parameters for values of B field 0.5, 1, 2 3, and 4 Tesla have been computed and presented. Wherever possible, measurements from literature are included. All the plots show the mixtures (noble gas + quencher) varying from pure noble gas to pure quencher in steps of 10 % and the scales of each plot in

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[1] Different from those which were used as input to the cross sections.

[2] available at http://wwwcn.cern.ch/writeup/garfield/examples/gas/trans2000.html and is being updated regularly.

different gas mixtures have been kept the same to ease comparison. The ambient conditions have been taken to be 20° C and 760 Torr. In this paper some examples are shown.

3.1 Drift, Diffusion and Lorentz angles

Fig. 4 show the transport parameters of helium-ethane taken from Ref.[28].The agreement for drift velocity with the computations is rather good while that for diffusion is about 2%.

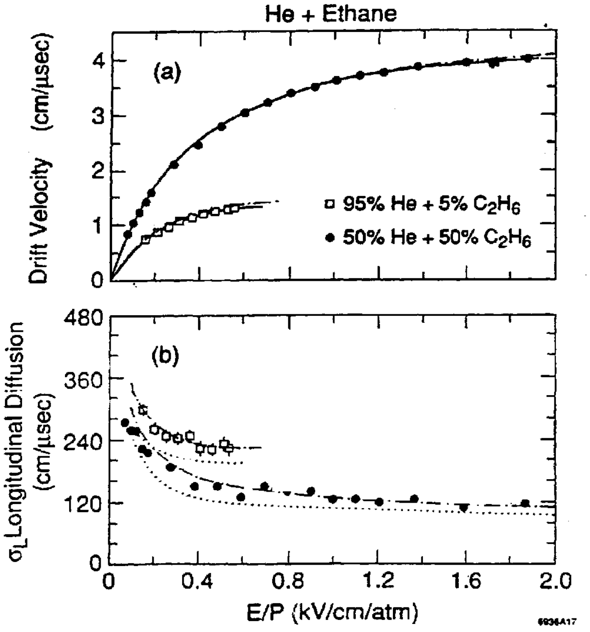

Fig. 4 Measurements and calculation of drift and diffusion for helium-ethane mixtures [28].

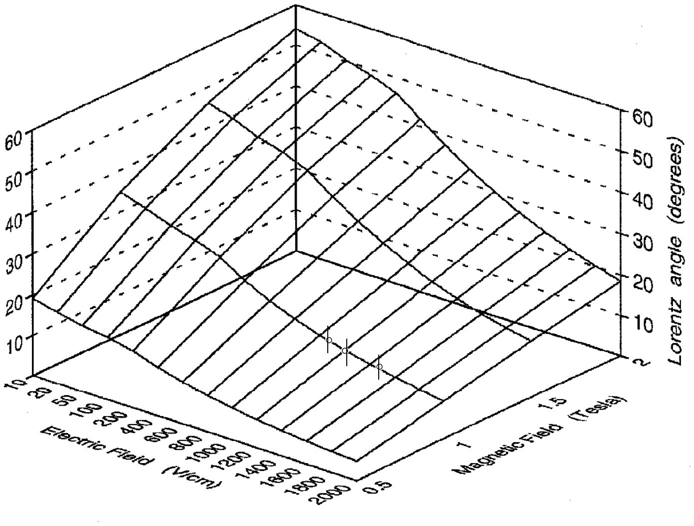

Fig. 5 Lorentz angles for helium-isobutane (90-10) as a function of electric and magnetic field. The points are taken from [35].

Computations of Lorentz angles for a (90-10) helium-isobutane mixture as a function of electric and magnetic field is shown in fig. 5, measurements shown from [35] agree within 2%; also for a 70-30 gas proportion and the results were consistent with the computations [36]. The diffusion characteristics for Ne-CO2 mixtures are shown in fig. 6 taken from [30]. As expected the results agree within a few percent.

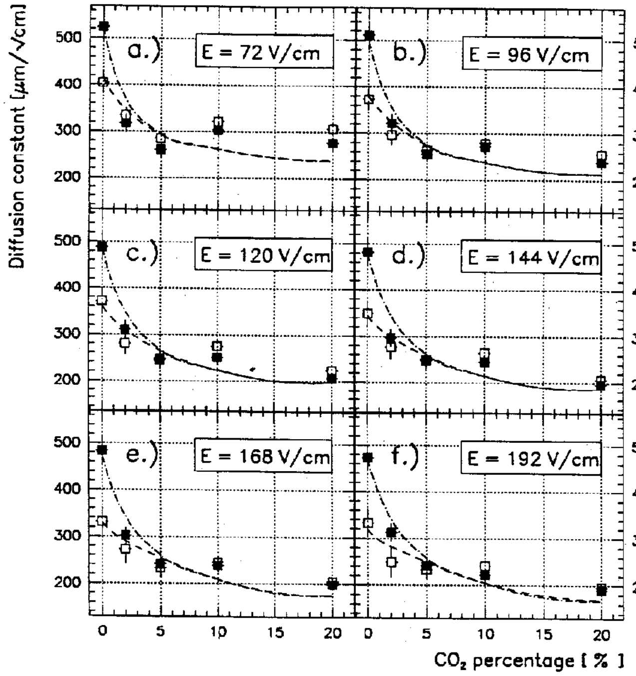

Fig. 6 Measurements (points) and calculations of the longitudinal diffusion constant as a function of the quencher percentage for several values of electric fields for Ne-CO_2 mixtures.

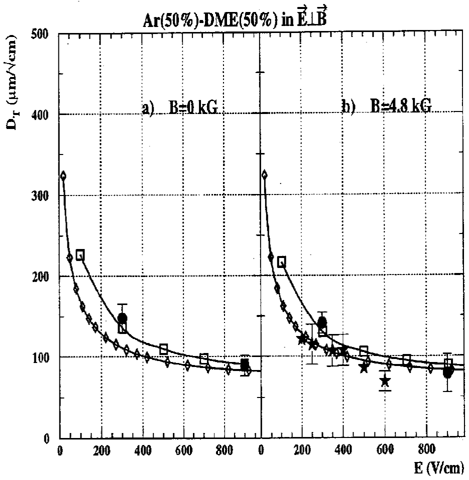

Fig. 7 Measurements and computations of transverse diffusion in Ar-DME (50-50) mixture with and without the presence of a crossed magnetic field. The agreement is within 5 %.

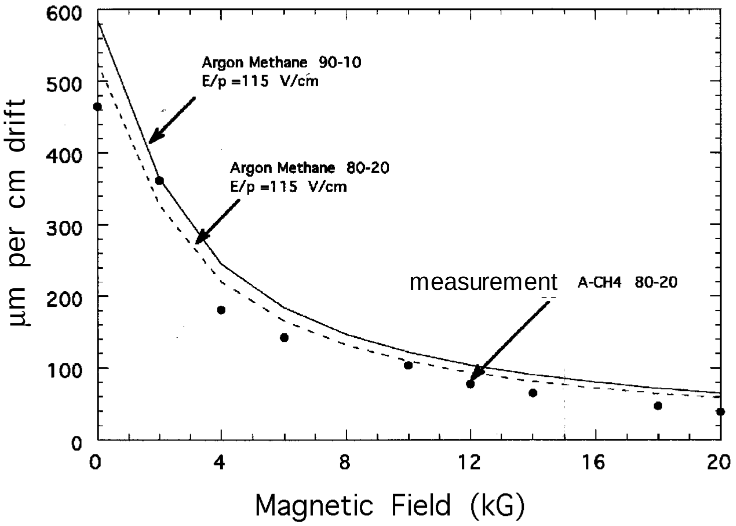

Fig. 8 Measurements [22] and calculations of transverse diffusion in Ar-CH_4 mixtures as a function of magnetic field.

There has been a lot of progress [37] in the field of single photon detection using different kinds of alkali-antimonide photocathodes, the problem being the damage in the presence of usual quencher gases thus necessitating a noble gas usually argon as the operational gas. The operation of a proportional gas detector in a pure noble gas has been the subject of many investigations [38]. Fig. 9 shows the drift velocity for pure argon taken from [39] where the curve (computation) is in very good agreement with the calculations.

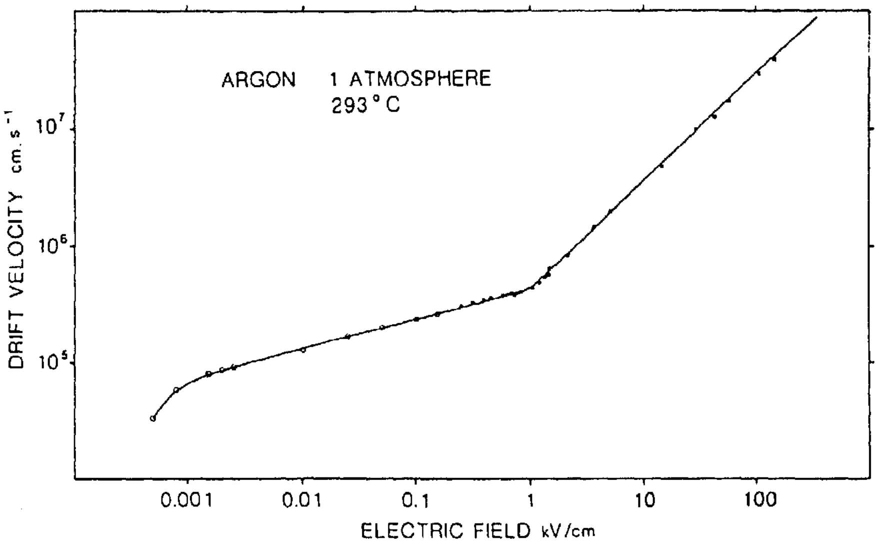

Fig. 9 Drift velocity in pure argon as a function of electric field [39].

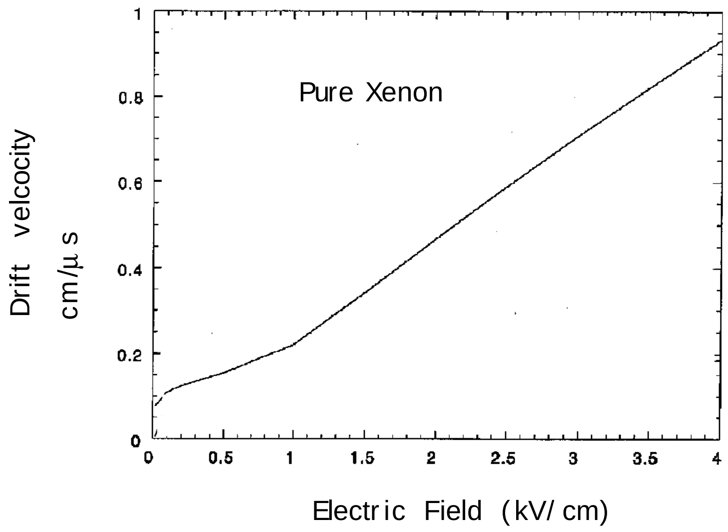

Fig. 10 Drift velocity as a function of electric field and pressure for Pure Xenon.

For the purposes of medical imaging, the gas choice is mainly determined by the spatial resolution, CO_2 is generally added to improve the diffusion characteristics. Fig. 10 shows the drift velocity for pure Xenon and fig. 11 some transport parameters for Xe-CO_2 mixtures at STP.

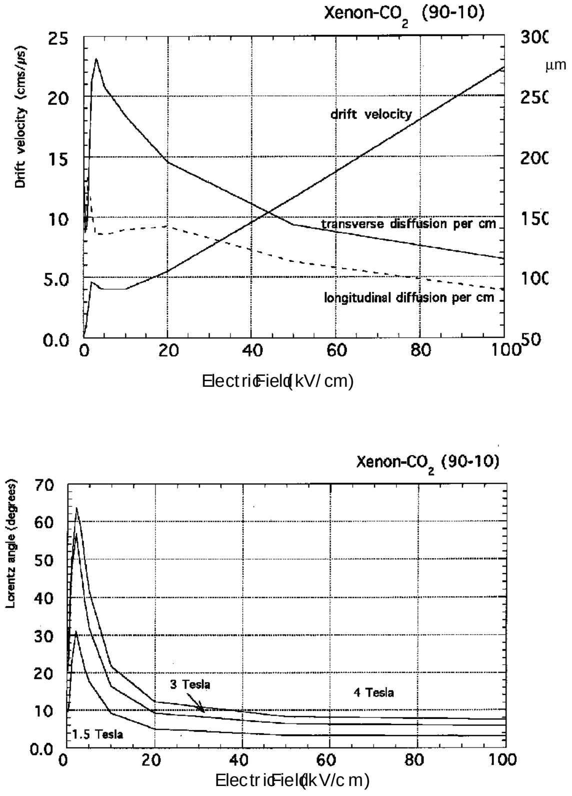

Fig. 11 Some transport parameters of Xe-CO_2 (90-10)

Fig. 12 shows the transport parameters for pure DME, used in cases where high accuracy is obtained by exploiting the very low diffusion characteristics and small Lorentz angles of this gas; the measurements are taken from [40]. DME was introduced as a better photon

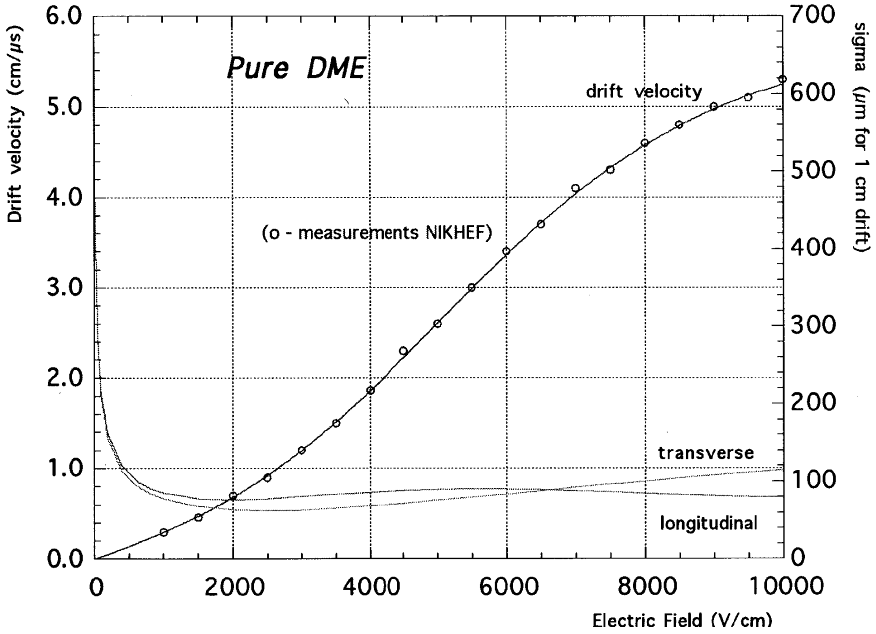

Fig. 12 Transport parameters for pure DME, measurements are taken from [40].

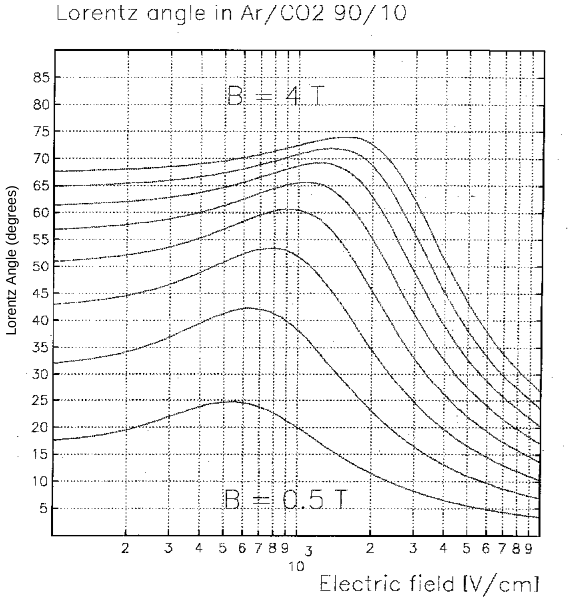

Fig. 13 Lorentz Angles in Ar-CO2 (90-10) from B=0.5 T to 4T.

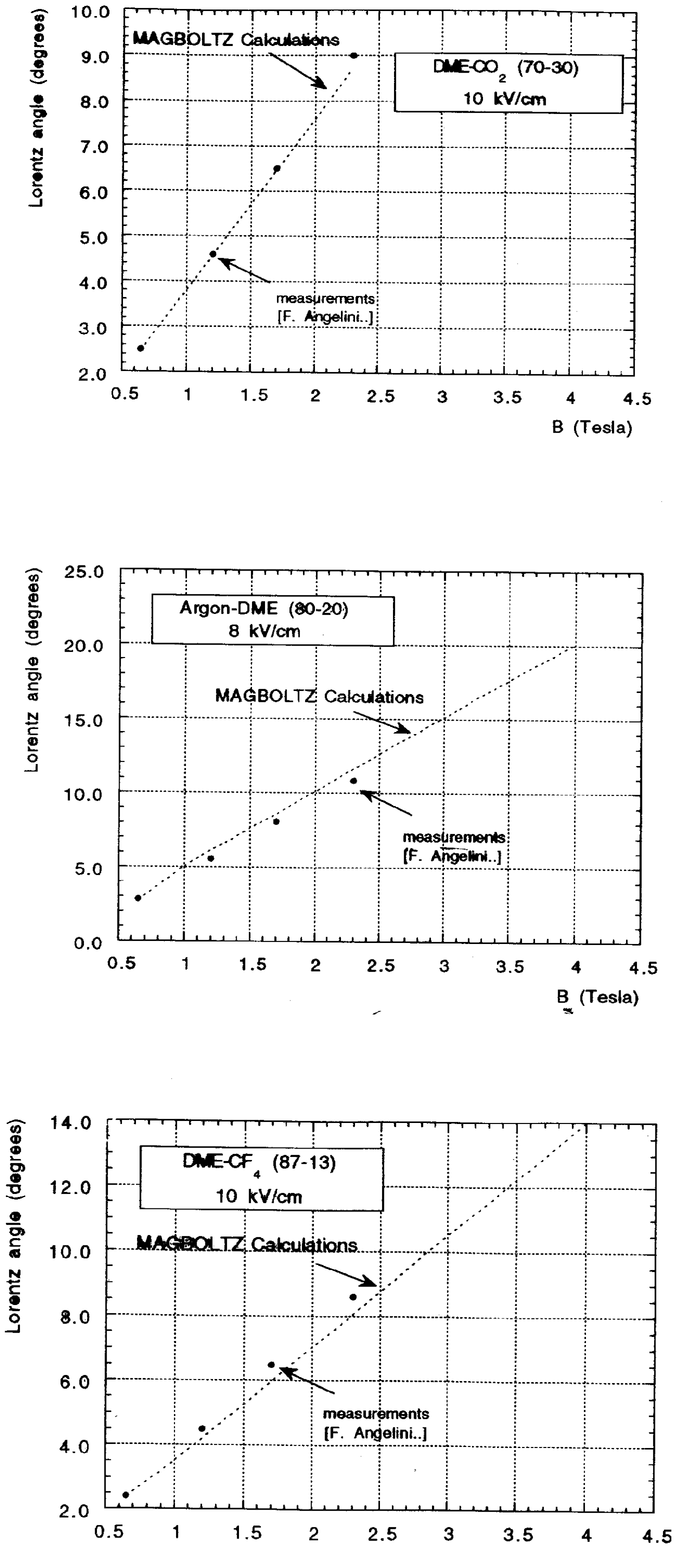

Fig. 13 Measurements of Lorentz angle for DME based mixtures

quencher than isobutane, with an absorption edge of ~ 195 nm it allows for stable operation with convenient gas multplication factors. Consequently high gains and high rates are possible without rate induced sparking. Pure DME does not polymerize due to its oxygen-carbon molecular bond, but contaminated DME with freons polymerizes, suggesting high demands on purity and careful choice of materials. Though it is a very cool gas, when mixed with noble gases like neon and argon, the drift velocity increases rapidly. Strangely one of the fastest gas mixture is made with DME and CO_2 both cool gases. Those for a non-flammable gas mixture of Ar-CO2 (90-10) are shown in fig. 13 for a magnetic field ranging from 0.5 to 4 Tesla. Some examples of the calculations and measurements [41] of Lorentz angles for DME and Argon mixtures are shown in fig. 14.

3.2 Townsend Coefficient

Recently some efforts have been devoted to the measurements of the Townsend coefficient, the mean number of ionizing collisions per unit drift length, in several gas mixtures. Measurements on argon based mixtures may be found in [42], while xenon mixtures in [43]. Some measurements of the Townsend coefficient for Helium ethane mixtures are shown in fig. 15, which were done using the experimental setup described in [42]. Comparisons of computations and the experimental data for Townsend Coefficient is exemplified in fig. 16 for argon-DME mixtures, and in fig. 16 for a DME-CO_2 mixture.

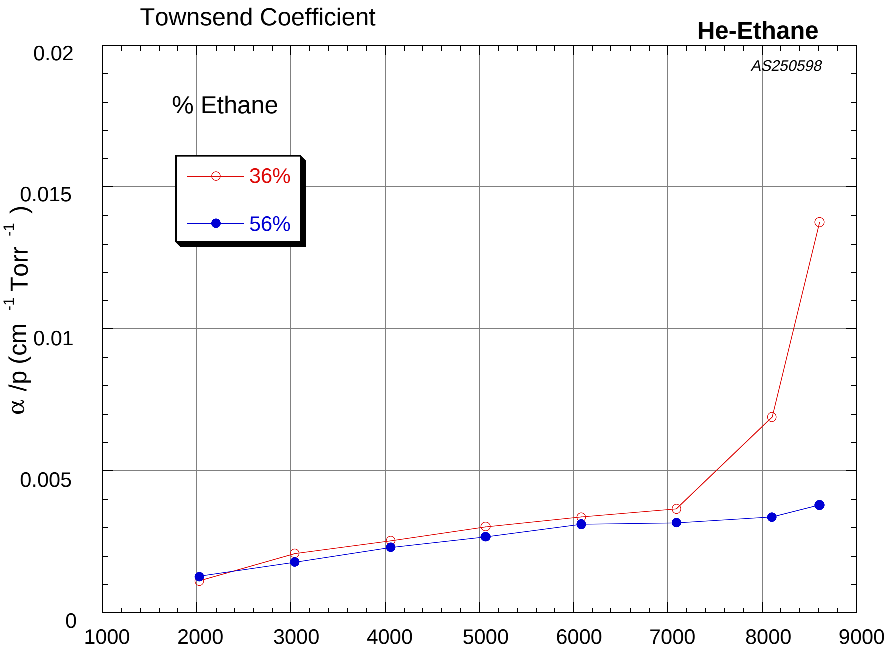

Fig. 15 Measurement of Townsend Coefficient in helium-ethane mixtures.

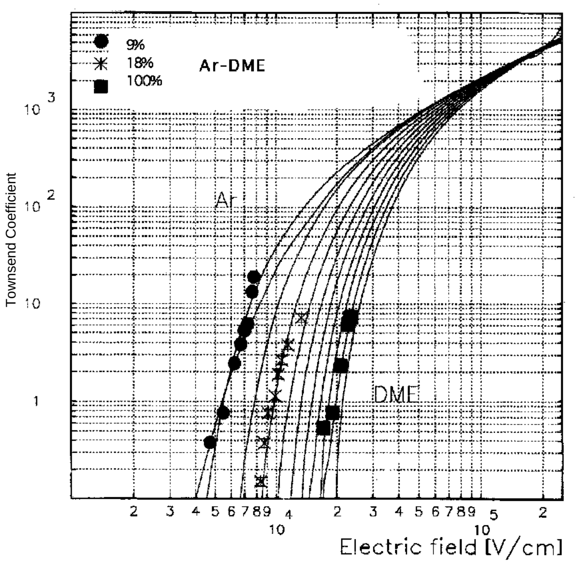

Fig. 16 Computation of Townsend coefficients and measurements from [42].

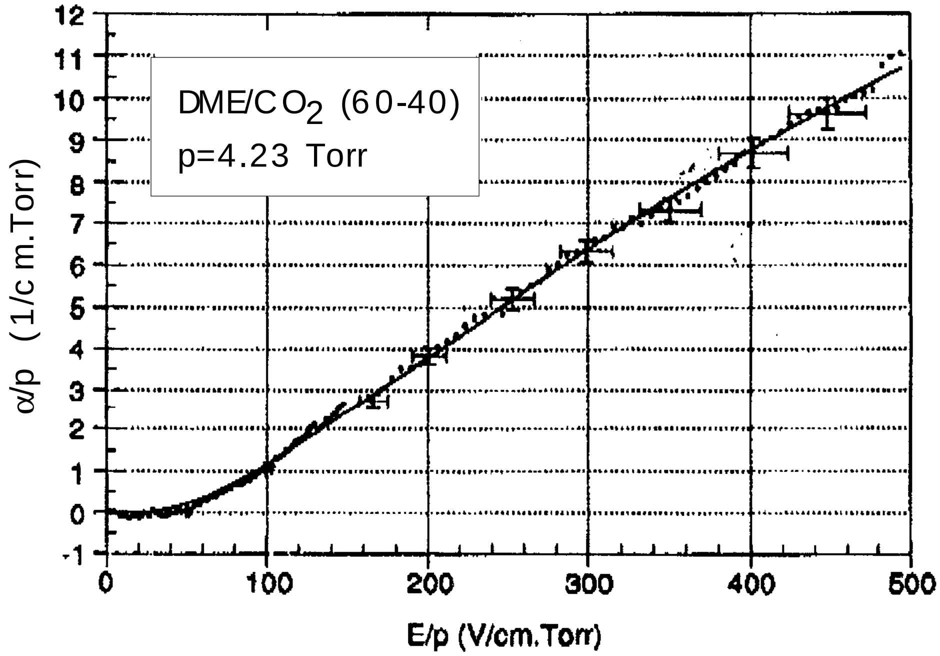

Fig. 17 Calculations and measurements [40] of the Townsend Coefficient for DME/CO_2 (60-40)

4 ION TRANSPORT PROPERTIES

The ion mobility is defined as the ratio of drift velocity (v_i) of the ions and the reduced electric field (E/p), in the absence of magnetic field, where E and p are the electric field and pressure respectively; it is almost constant up to rather high fields being specific to a particular ion moving in a specific gas. Details may be found in refs. [15,17,24].

Table 2 shows the ion-mobility at atmospheric pressure of some commonly encountered gas molecular ions. In case of two numbers for mobility, the first one comes from the reference on the left, the second from the one on the right.

Gas	Ion	Mobility [cm^2/V.sec]	Reference
Ar	Ar^+	1.00	
Ar	$Methylal^+$	1.51	
iC_4H_{10}	$Methylal^+$	0.55	[38]
Methylal	$Methylal^+$	0.26	[38]
iC_4H_{410}	$iC_4H_{10}^+$	0.614	
Ar	CH_4^+	1.87	[4]
CH_4	CH_4^+	2.26	[38]
Ar	CO_2^+	1.72	
CO_2	CO_2^+	1.09	[38]
C_2H_6	$C_2H_6^+$	1.23,1.24	[38]
CF_4	$C_2H_6^+$	1.04	[2,4]
C_3H_8	$C_3H_8^+$	0.793	[2]
CF_4	CH_4^+	1.06,1.07	[2]
DME	DME^+	0.56	[2,4]
CF_4	$C_2H_6^+$	1.04	[3]
CF_4	$C_3H_8^+$	1.04,1.05	[2]
CF_4	$iC_4H_{10}^+$	1.00	[2]
Ar	CH_4^+	2.07,1.87	[2,4]
Ar	$C_2H_6^+$	2.06,2.08	[2,4]
Ar	$C_3H_8^+$	2.08,2.07	[2,4]
Ar	$iC_4H_{10}^+$	2.15,1.56	[2,4]

5 DEPENDENCE OF THE TRANSPORT PARAMETERS ON POLLUTANTS

The presence of pollutants in the operating gas mixture affects the gas detector operation as well. There are two effects: one is the modification of transport parameters and the second is electron loss by capture due to electro-negative pollutants.

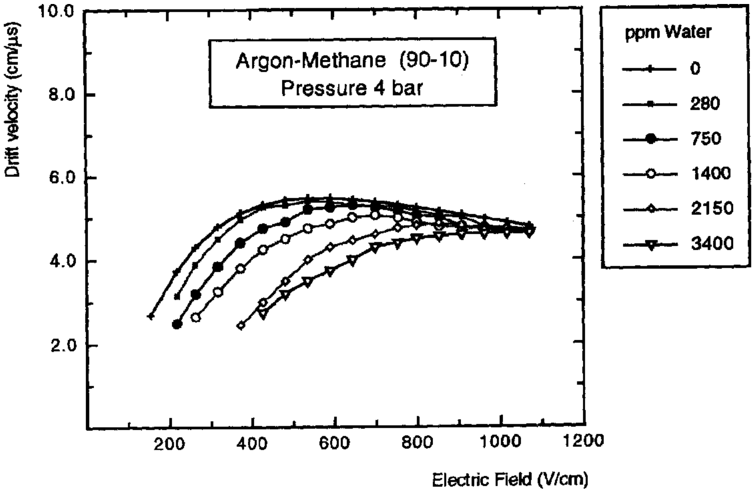

Fig. 18 Effect of the addition of water on the drift velocity in Ar-CH_4 as a function of electric field.

In the case of addition of water, the static electric dipole moment of the water molecule increases the inelastic scattering cross-section for low energy electrons, thus reducing dramatically the drift velocity.

Fig. 18 shows measurements of drift velocity [44] exemplifying the effect of addition of water to an argon-methane (90-10) mixture; at ~ 100 V/cm. Adding 1000 ppm of water changes the drift velocity by 20 %, while at higher fields the change is negligible. The change is more at higher fields for a noble gas richer mixture. An electron capture (attachment) phenomenon has also a non-negligible electron detachment probability, and the transport parameters may also be sensitive to this electron slowing down mechanism. Incidentally the first paper by Biagi [31] where the computation program was introduced exemplified the very good agreement between this data and the calculations.

The electron attachment coefficient $C_{en,M}$, may be defined as: $A = P_M.P_{en}.C_{en,M}$
where A is the attachment rate, P_M and P_{en} are the partial pressures of the gas, and that of the electronegative impurity. The units of $C_{en,M}$ are usually [$bar^{-2}.\mu s^{-1}$], thus if the total drift length in a large detector is measured say in 50 µs, an attachment coefficient of 500 represents a loss of 10 % in gain per ppm of electronegative pollutant. The gain loss per ppm of oxygen, as a function of attachment coefficient of several gas mixtures has been estimated from several measurements [45,46]. The mean capture length is l estimated and is shown in table, p being the fraction of oxygen in the mixture. For p=0.01 we have for Xenon a lp of 0.8 cm, while for warm gases this number is quite small. For cold gases however, it is difficult to drift to large distances without electron capture, as seen from the attachment coefficients; this may impose serious requirements on the purity of the gas.

Table 3

Gas Mixture	Electric Field [V/cm]	lp[cm]
Ar-CH_4 (90-10)	150	5.1 10^{-2}
Ar-CH_4 (90-10)	250	3.4 10^{-2}
Ar-CH_4 (80-20)	100	1.6 10^{-2}
Ar-CH_4 (80-20)	200	2.9 10^{-2}
Ar-CO_2 (80-20)		9.3 10^{-2}
Xe-CH_4 (90-10)	~ 500	7.8 10^{-2}

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