Ionization Detectors

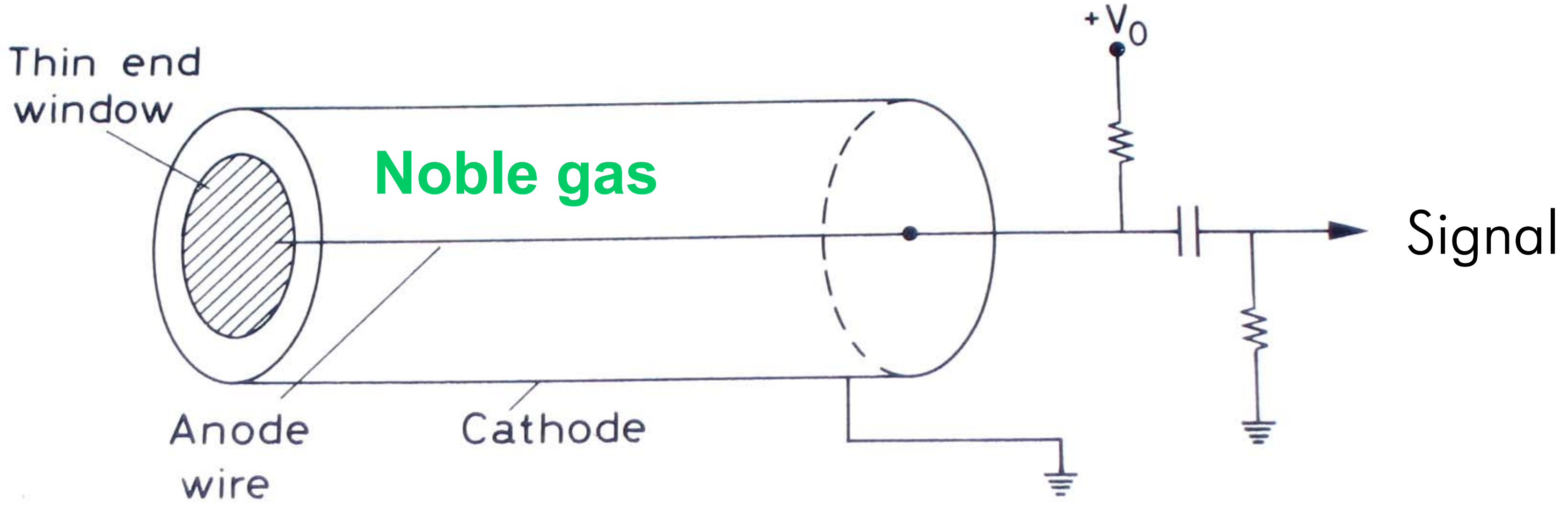
Mostly Gaseous Detectors

Introduction

- Ionization detectors were the first electrical devices developed for radiation detection
- During the first half of the century: 3 basic types of detectors
    - Ionization chamber
    - Proportional counter
    - Geiger-Müller Counter
- Still used in the lab as radiation counters, but not really used in nuclear or particle physics experiment anymore
- In the 60’s: multi-wire proportional chambers → application in particle physics (localizing particle trajectories to less than 1 mm, remember last lecture on semiconductors: CCD etc.)
- Later developments/ improvements for particle physics: drift chamber and time projection chamber
- Liquid ionization detectors

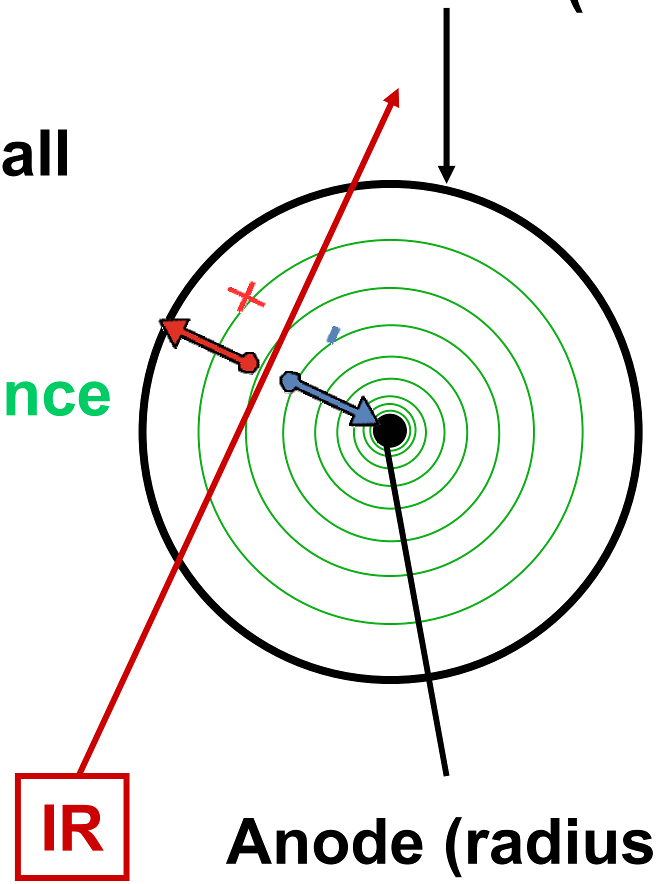
Gaseous Ionization Detectors

- Great mobility of electrons and Ions in gas → gas obvious medium to measure ionizing radiation
- Ionization in Gas has been studied thoroughly over the years, gas mixtures have been optimized for efficiency, devices have been optimized for fastness and resolution
- Basic construction of a simple gas detector (ion. chamber, prop. counter, GM-counter)



Basic Concepts of a Gaseous Detector

Positive HV +V_0 relative to the wall applied



Cathode (radius b)

***r*: radial distance from axis**

IR

Anode (radius a)

$$\boxed{E = \frac{1}{r}\frac{V_0}{\ln(b/a)}}$$

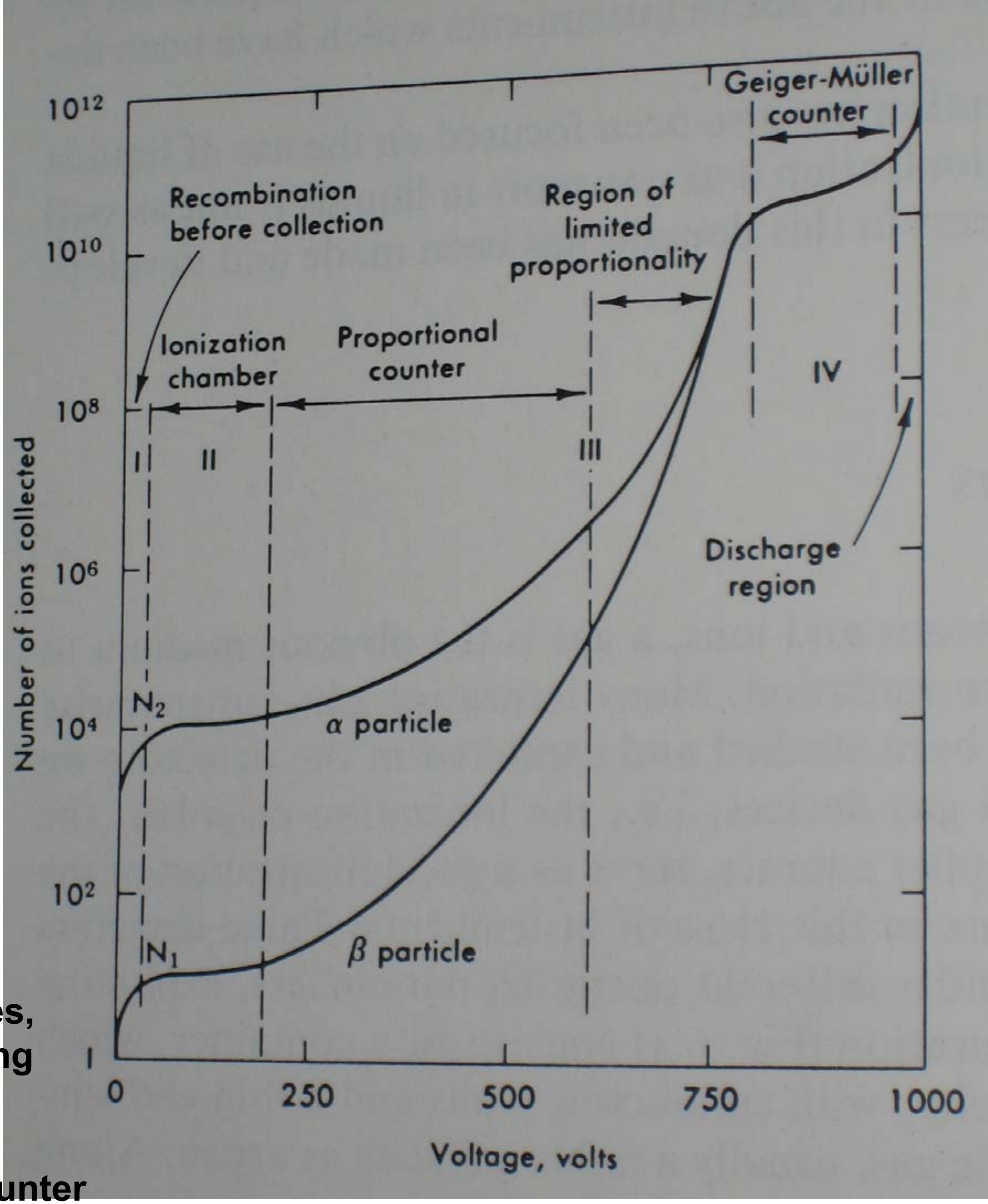
The measured current depends on the field intensity

Basic Concepts

Figure: Number of Ions collected versus applied voltage

Regions:

- **I) Recombination before collection**
- **II) All created pairs are collected**
- **Up to III) Ionization avalanche or cascade develops very quickly and almost entirely within a few radii of the wire,**
  - **$N^{eipairs}_{aval} \sim N^{e}_{prim}$**
  - **Amplification factor ~ 10^6**
- **Above III) space charge created distorts E field, proportionality begins to be lost**
- **IV) Chain reaction of many avalanches, caused by photons from deexciting molecules, saturation, discharge stopped by quenching gas**
  - **→ GM counter aka breakdown counter**



Ionization and Transport Phenomena in Gases

Ionization Mechanism

- Two types of energy loss of a charged particle in matter:
  - (1) excitation: $X + p \rightarrow X^* + p$
    $\sigma \approx 10^{-17}$cm^2, exact resonant energy required
  - (2) ionization: $X + p \rightarrow X^+ + p + e^-$
    $\sigma \approx 10^{-16}$cm^2, no exact energy requirement, however higher energy threshold
- Primary ionization: (2), secondary ionization: sufficiently large energy is transferred to the electron (delta-rays), such that it creates electron-ion pairs itself

Ionization and Transport Phenomena in Gases

Ionization Mechanism

- Penning effect: metastable states excited in process (1), do not decay immediately but collide with a second atom, e.g.: $Ne^* + Ar \rightarrow Ne + Ar^+ + e$
- Another possibility: $He^+ + He \rightarrow He_2^+$

Ionization and Transport Phenomena in Gases

Mean Number of Electron-Ion Pairs

- Ionization is of statistical nature: What is the *average* number of ion-electron pairs from all mechanism created for a given energy loss?
- For gases: of the order of 1 ion-electron pair per 30 eV, so for example for 3 eV particle an average of 3000/30=100 ion-electron pairs is created (see x-rays in the upcoming experiment)
- This average value does not depend very strongly on particle type and only weakly on the gas type.

Electron and Ion Creation:

energy dissipation per e/ion pair produced: W
first ionization potential: I

Bethe-Bloch

gas	I [eV]	W [eV] (for electrons)
Ar	15.7	26.4
He	24.5	41.3
H_2	15.6	36.5
N_2	15.5	34.8
O_2	12.5	30.8
Air		33.8
Ch_4	14.5	27.3

The Fano Factor

- Energy resolution: $R=(FWHM)/E=\Delta E/E$
- Poisson or Poisson-like statistics: resolution improves with higher energy, deposited energy E, average ionization energy w, then $J=E/w$ average number of Ionizations
- Two cases:
  (1) radiation energy not fully absorbed → poisson → $\sigma^2=J$, resolution $R=2.35*\sqrt{J}/J=2.35*\sqrt{(w/E)}$
  (2) Radiation energy fully absorbed → naïve assumption of poisson not applicable (total energy deposited is a fixed, constant number, total number of ionizations is thus constrained by the total energy, ionization events are not all independent) → resolution of such detectors is much smaller: $\sigma^2=FJ$, F: Fano Factor.

  F=1 (Poisson): Scintillator,

  F<1: semiconductors and gases

Fano factors for various gas mixtures are given in table 6.2 of your textbook

Recombination and Electron Attachment

- No electrical field → Recombination:

$X^+ + e^- \rightarrow X + hv$ or molecular ions:

$X^+ + Y^- \rightarrow XY + hv$

- Rate of recombination: $dn = b\, n^- n^+ dt$,

b: constant depending on gas type,

n^-, n^+: ion concentration

- If $n^- = n^+ = n$, integration: $n = n_0/(1 + bn_0 t)$, n_0 intial concentration at $t=0$
- Electron attachment: capture of free electrons by electronegative atoms: $X + e^- \rightarrow X^- + hv$ (atoms which have an almost full outer electron shell, energy released is known as electron affinity.), examples of electronegative gases are O_2, H_2O, CO_2 etc. → they will decrease detector efficiency

Transport of Electrons and Ions in Gases

Diffusion

- Assume absence of electric field, at thermal energies mean velocities of electrons and ions produced by passing radiation are given by:

$$v = \sqrt{\frac{8kT}{\pi m}}$$

, k: Boltzmann, T: temperature,

m: particle mass

- At room temp.: electrons: ~ 10^6cm/s, ions ~ 10^4cm/s
- From kinetic theory: distribution of charges after diffusing for a time t is gaussian, if N_0 total number of charges, x distance from point of creation, D the diffusion coefficient, then it can be expressed as

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} \exp(-\frac{x^2}{4Dt}) \rightarrow \textbf{Rms spread in x:} \quad \sigma_x = \sqrt{2Dt}$$

Transport of Electrons and Ions in Gases

Diffusion

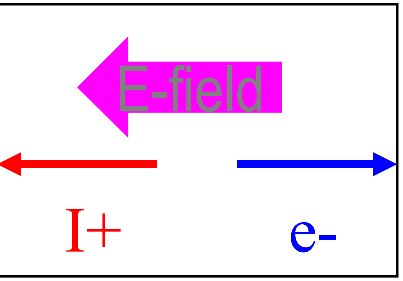
- Diffusion coefficient derived from kinetic theory: D=1/3 v λ, λ mean free path of electron or ion in gas
- For classical ideal gas at temperature T and pressure p:

$$\lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma_0 p}$$

σ_0: total cross-section for a collision with a gas molecule

Transport of Electrons and Ions in Gases

Drift and Mobility



In the presence of an electric field the electrons and ions will be accelerated along the field lines towards the anode and the cathode respectively

The acceleration will be interrupted by collisions

Maximum average velocity or
DRIFT VELOCITY *u*

Compare to thermal velocity:
Ions remain thermal up to very high fields

Reduced electric field

$u \sim E/p$

For ideal gases:

☼ ***$D/\mu = kT/e$***

Mobility
$\mu = u/E$

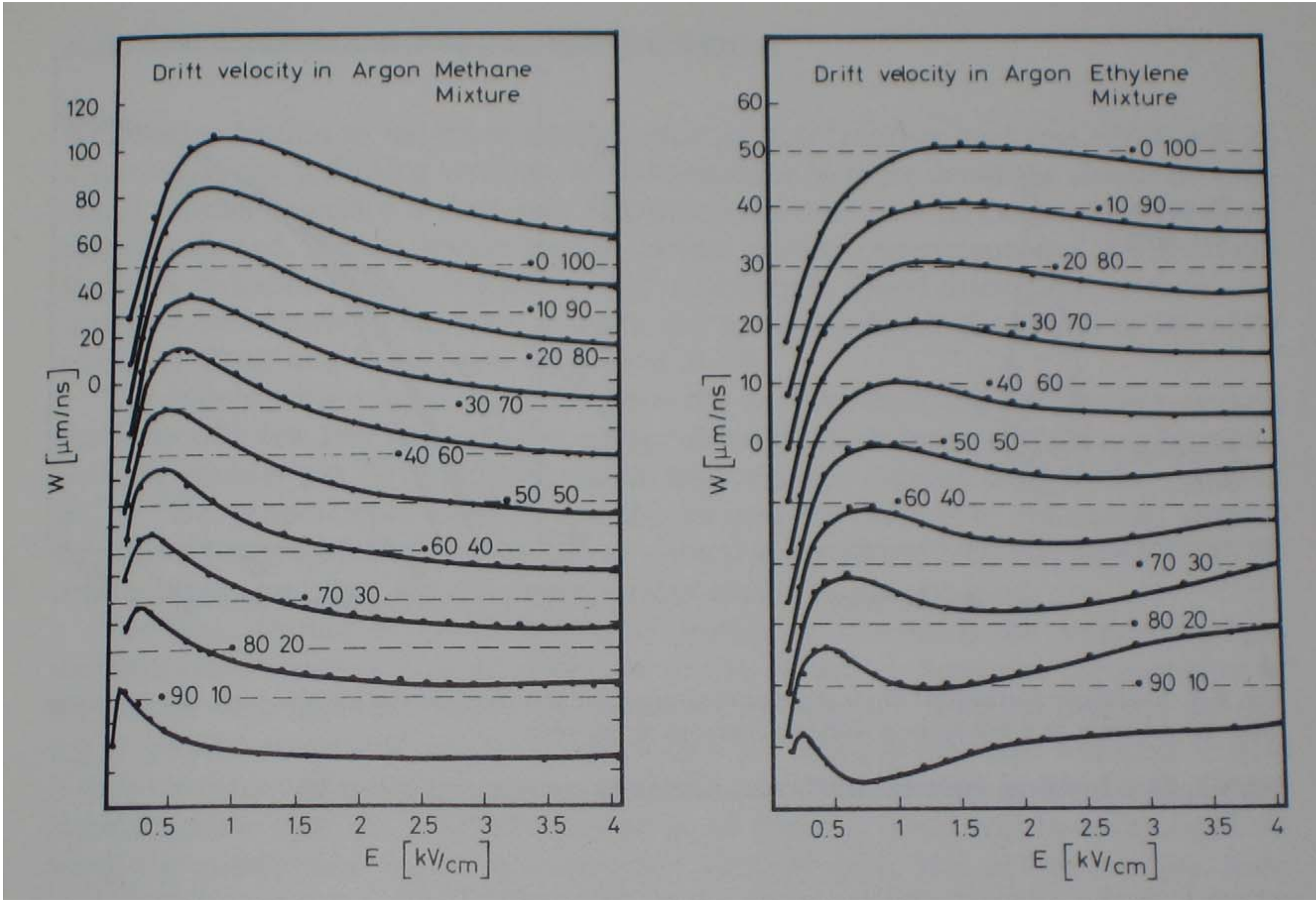
GAS	ION	μ^+ (cm^2 V^{-1} s^{-1}) @STP
Ar	Ar^+	1.51
CH_4	CH_4^+	2.26
Ar-CH_4 80-20	CH_4^+	1.61

Transport of Electrons and Ions in Gases

Drift and Mobility

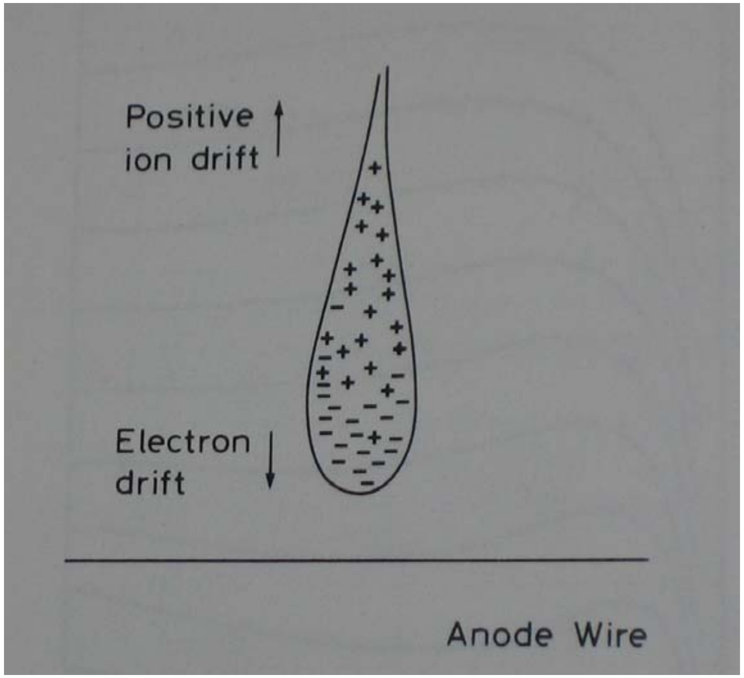
- But for electrons?
- Great mobility
- The gain in velocity of the electrons may also affect the diffusion rate if the electrons exceed thermal energies, kT in ☼ will be replaced by the mean energy of the electron → diffusion D will be increased accordingly causing a wider spread of the electron cloud
- **Important consequence when building drift chambers (measuring the position of a particle track)**

Drift Velocities of Electrons in Various Gas Mixtures as a Function of E Field



Avalanche Multiplication

- Multiplication in gas detectors occurs when the primary ionization electrons gain sufficient energy from the accelerating E field to also ionize gas molecules → secondary electrons → tertiary ionization etc. → avalanche
- Because of the greater mobility of electrons: avalanche has the from of a liquid drop:

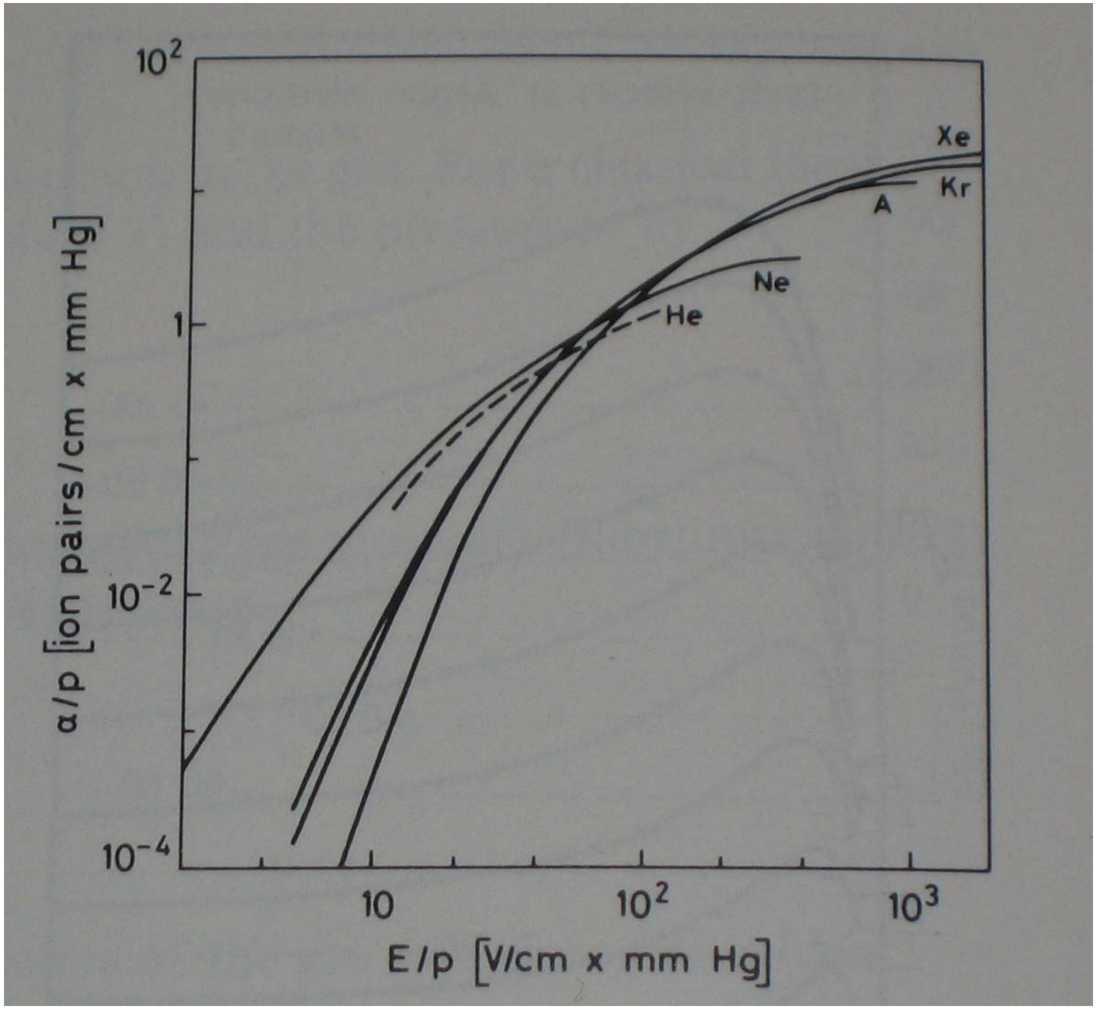


Probability of Ionization per unit path length:

$\alpha=1/\lambda$

aka as first *Townsend coefficient*

Townsend Coefficient



Avalanche Multiplication

n: number of electrons

dx: path

→ $dn = n\,\alpha\,dx$ → new electrons created in dx

Integration → total number of electrons created
in path x: $n = n_0 \exp(\alpha x)$,
n_0: original number of electrons

→ Multiplication factor: $M = n/n_0 = \exp(\alpha x)$

More general, e.g. in case of a cylindrical electrical field:

$$M = \exp\left[\int_{r_1}^{r_2} \alpha(x)\, x\, dx\right]$$

physically: $M < 108$ or $\alpha x < 20$, $\alpha x > 20$ → breakdown

Multiplication factor is also called *gas gain*

Rose & Korff:

$$\boxed{\frac{\alpha}{p} = A \exp\left(\frac{-Bp}{E}\right)}$$

A,B: constants depending on gas