Gas Detectors
Working Principles and Overview

R. Venditti

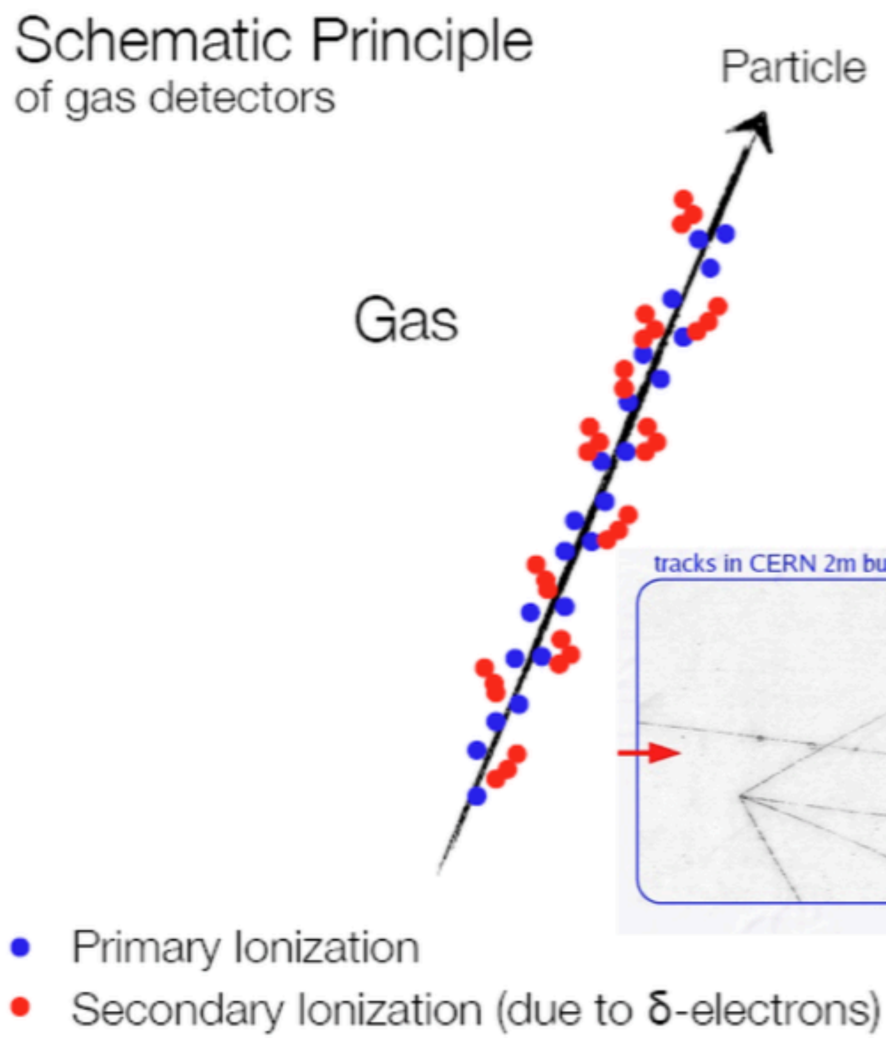
INFN-BARI, PoliBa

Lectures for PhD course, 2018

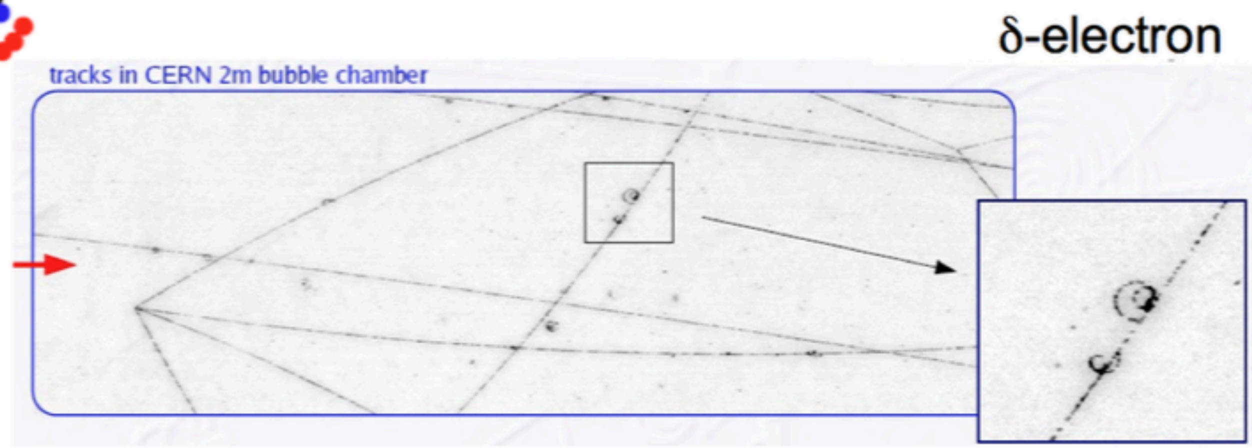
Material taken from:

- F. Sauli: "Gaseous Radiation Detectors: Fundamentals and Applications", Cambridge University Press July 2014, ISBN: 9781107337701 , https://doi.org/10.1017/CBO9781107337701
- **RD51 Open Lectures, CERN**
  - **https://indico.cern.ch/event/676702/timetable/**
    - Electron transport, mean gain (Rob Veenhof)
    - Avalanche fluctuations (Rob Veenhof)
    - Principal mechanisms for signal generation in Micro Pattern Gaseous Detectors (W. Riegler)
- W. Leo, "**Techniques for Nuclear and Particle Physics Experiments: A How-to Approach", Springer-Verlag,** ISBN-13: 978-3540572800 , ISBN-10: 3540572805
- PDG: The Review of Particle Physics - http://pdg.lbl.gov/

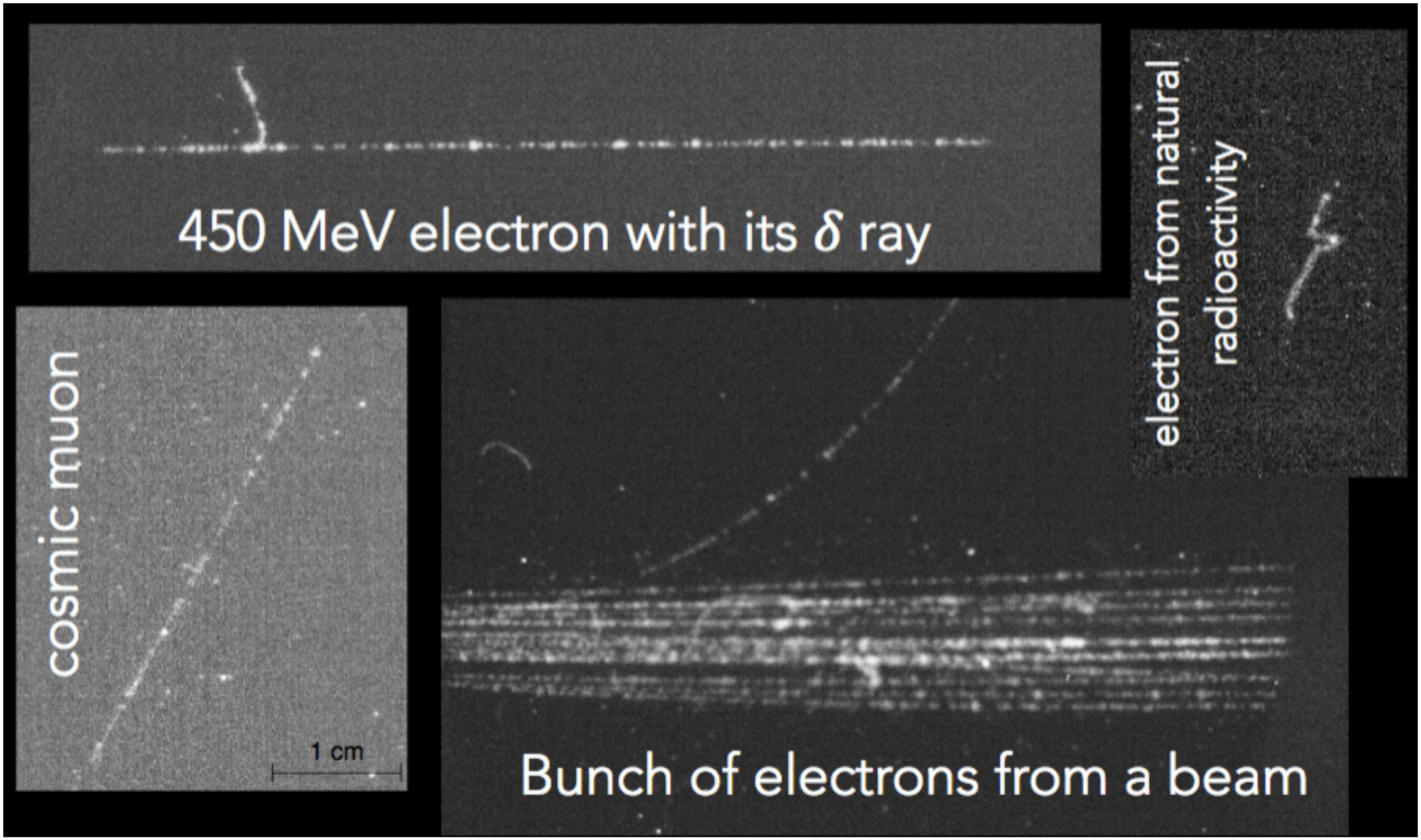
Gas detectors – the basics



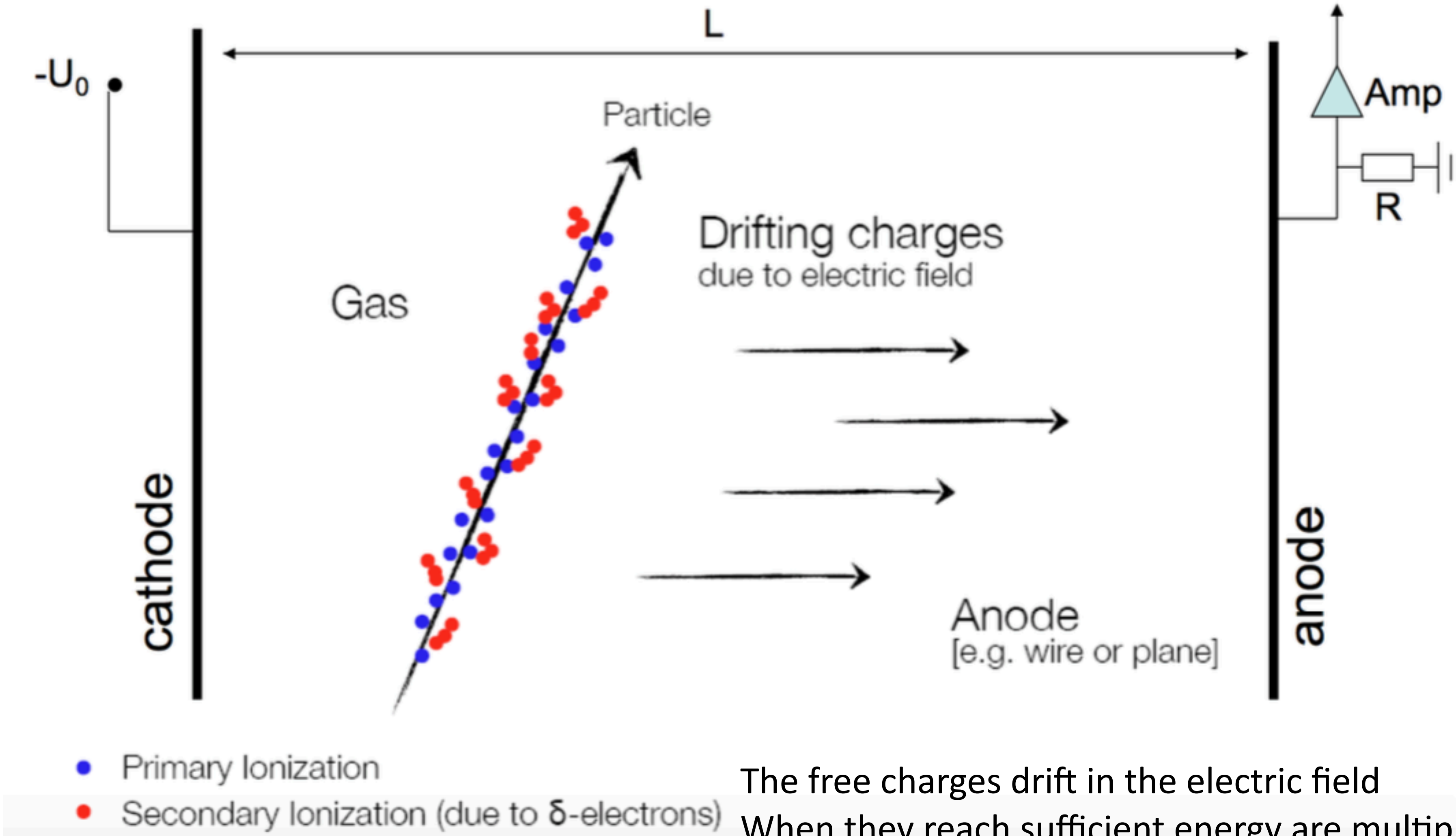
A charged particle pass through a gas volume and ionizes gas atoms/molecules



Particle tracks in triple-GEM detector



Gas detectors – the basics



The free charges drift in the electric field
When they reach sufficient energy are multiplied
The movement of the charges induces a signal on the electrodes
The signal is recorded and processed

Operation mode

Modes of operation, depending on the strength of the electric field i.e. to the voltage applied to the electrodes

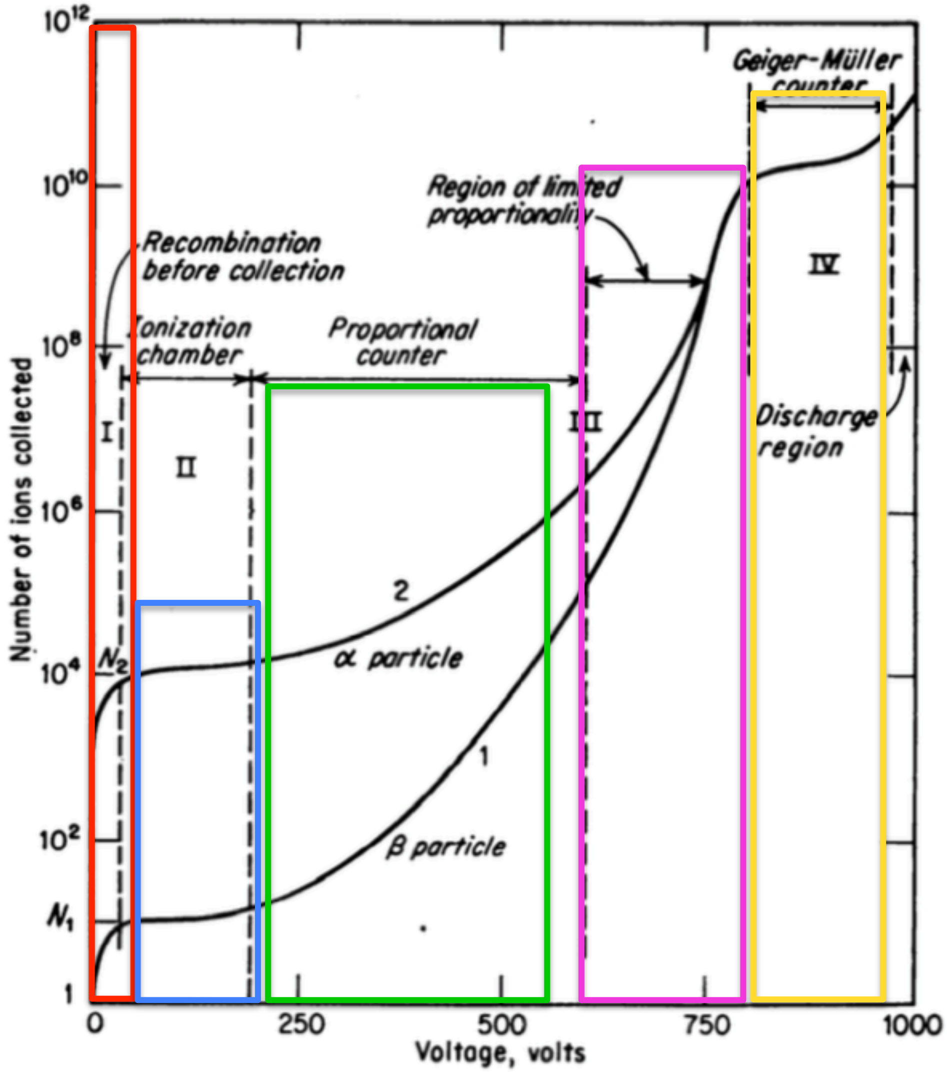


FIG. 2–2. Pulse-height versus applied-voltage curves to illustrate ionization, proportional, and Geiger-Müller regions of operation.

At 0 V the electron-ion pairs recombine

The collected charged is proportional to the energy loss of the incoming particle

The number of electron-ion pairs is flat wrt to the Electric field → working region of the ioniziation chambers

The electric field is so high that the electrons produced by the ionizing radiation gain sufficient energy to ionize nearby atoms (secondary ionization) → this can ionize other atmos →An avalanche is created by the charge multiplication

The spatial charge of the avalanche distorts the electric field → the proportionality wrt the incident radiation is lost.

Several discharge can occur in the gas (further than the one triggered by the incident radiation) because of photons emitted by de-exciting atoms that can extract electrons by the electrodes. A quenching gas can be added to drain these phenomena, so the output current has always the same amplitude.

IONIZATION

Summary of radiation-matter interactions

- Absolute basic principles: Particle must INTERACT with the material of the detector
- It has to transfer energy / momentum in some way
- Knowing the interaction of the particle with the detector material in detail allows us to deduce extended, precise and quantitative information about the particle properties
- **Particle detection happens via the energy the particle deposits in the material it traverses**
  - **Charged particles:**
    - Ionization
    - Excitation
    - Bremsstrahlung
    - Cherenkov radiation
    - Transition radiation
  - Photons
    - Photo-electric effect
    - Compton effect
    - Pair production
  - Neutrinos
    - weak interaction
  - Hadrons
    - EM + strong interaction

Relevant for gas detectors

Charged particle interaction

- **Charged particle: ze, with mass M**
  - **“heavy” particle: $Mc^2 \gg m{c_e}^2$ (electrons are discussed later)**
- 2 electromagnetic processes:
  - 1) **elastic scattering from nuclei:**

    atom + X → atom* + X excitation

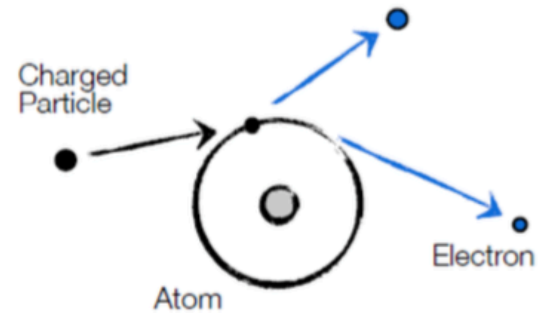
    ↳ atom + γ de-excitation
  - 2) **inelastic collisions with the atomic electrons of the material:**

    atom + X → $atom^+ + e^- + X$ ionization

- Energy of the incoming particle (ze,M) should be high enough to “resolve” the inside of the atom
- Interaction is dominated by elastic collisions with electrons:
  - Classical derivation by N. Bohr (1913)
  - Quantum mechanical derivation by H. Bethe (1930) and F. Bloch (1933)

Ionization

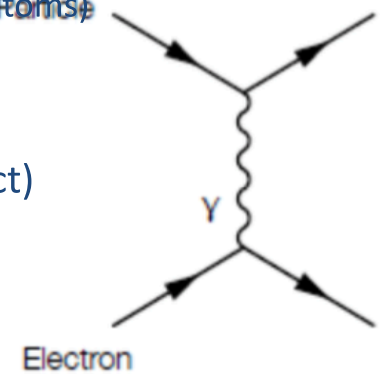
p=charged particle,
A gas atom of kind A
B gas atom of kind B



- **Primary ionization:**
  - $p + A \rightarrow p + A^{+} + e^{-}$
- **Secondary ionization:**
  - $e^{-}A \rightarrow e^{-}A^{+}e^{-}, e^{-}A^{++}e^{-}e^{-}$ (collisions of ionization electrons with atoms)
  - $pA \rightarrow pA^{*}, e^{-}A \rightarrow e^{-}A^{*}$

    $\rightarrow A^{*}B \rightarrow A+B^{+}+e^{-}$ (Penning Effect)

collision of the excited (meta-stable, optical) state with a second species, B,
of atoms or molecules that is present in the gas.
Occurs if the excitation energy of A* is above the ionization potential of B



Can be treated statistically (large number of gas molecules even inside small volumes)

$$n_T = \frac{L \times \frac{dE}{dx}}{W_i}$$

Ionization energy: Mean energy loss per unit lenght
W_i=Average energy to create e-ion pair
n_p=Average # of primary e-ion pairs [per cm]
nT =Average # of e-ion pairs [per cm] =n_p+n_s

Total number of e-ion pairs

In absence of recombination or secondary processes

Energy loss of the incoming particle
Depends on the material via Z (atomic number).
Scale with the incoming particle charge and mass.

nT =Average # of e-ion pairs [per cm] $=n_p+n_s$

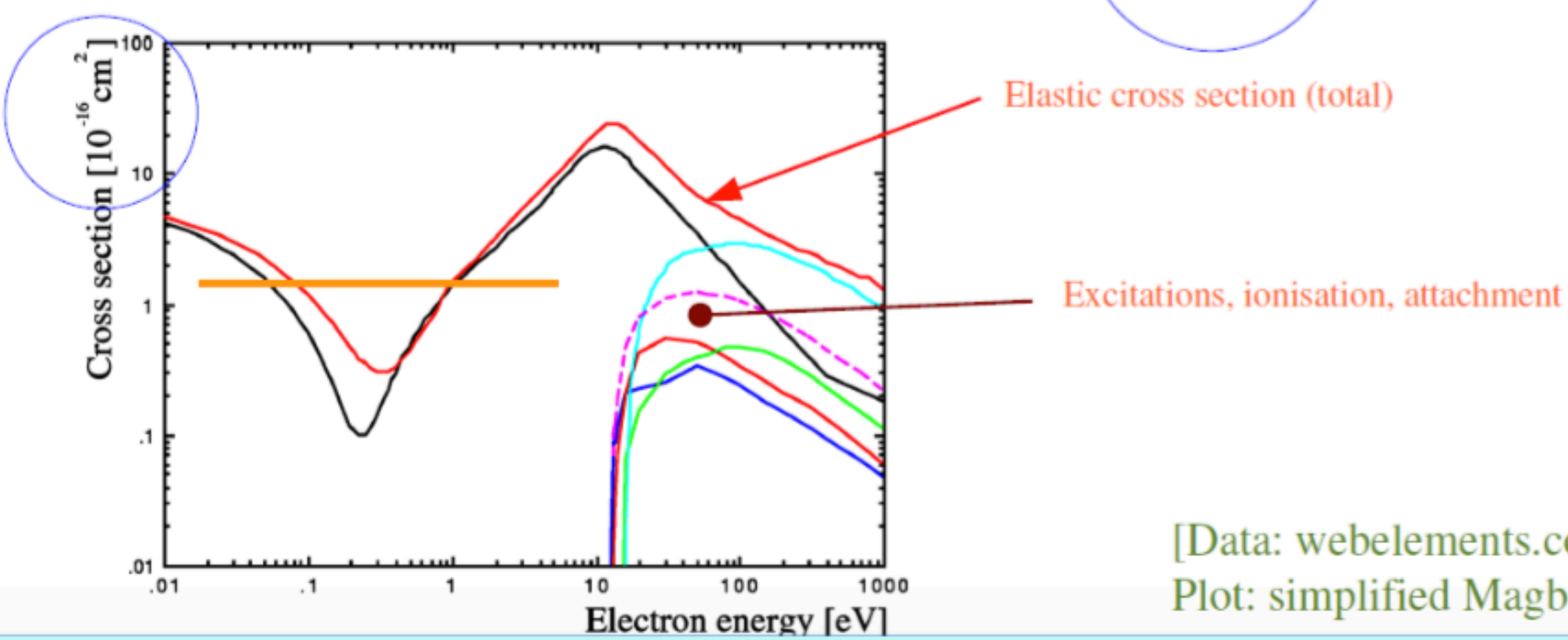
$$n_T = \frac{L \times \frac{dE}{dx}}{W_i}$$

Average energy to create e-ion pair
Depends only on the gas

Cross section of argon

Remember the unit:
1 Mb = 10^{-18} cm²
100 Mb = 10^{-16} cm²

- Cross section in a hard-sphere model:
  - Radius: ~70 pm
  - Surface: $\sigma = \pi(70\ 10^{-10}\,\text{cm})^2 \approx 1.5\ 10^{-16}\,\text{cm}^2 = 150\,\text{Mb}$



[Data: webelements.com
Plot: simplified Magboltz]

Energy Loss – the Bohr Approximation

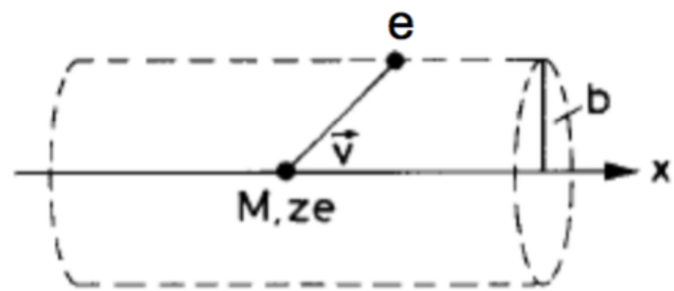
- Particle with charge ze moves with velocity β=v/c through a medium with electron density n
- Electrons in the atom are considered free and initially at rest
- Energy transfer from a particle to a single electron, transverse distance b = $\Delta E(b) = \frac{\Delta p^2}{2m_e}$

$$\Delta p_\perp = \int F_\perp dt = \int F_\perp \frac{dt}{dx} dx = \int F_\perp \frac{dx}{v}$$

because of symmetry

$\Delta p_\parallel$: averages to zero

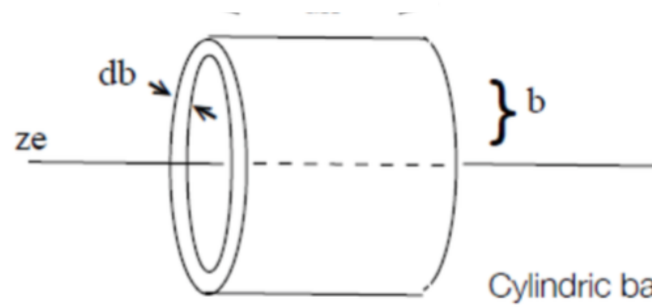
$$= \int_{-\infty}^{\infty} \frac{ze^2}{(x^2+b^2)} \cdot \frac{b}{\sqrt{x^2+b^2}} \cdot \frac{1}{v}\, dx = \frac{ze^2 b}{v}\left[\frac{x}{b^2\sqrt{x^2+b^2}}\right]_{-\infty}^{\infty} = \frac{2ze^2}{bv}$$



- To integrate over electrons present in the medium, consider a cylindrical barrel with Ne electrons: Ne = n (2πb) db dx

$$-dE(b) = \frac{\Delta p^2}{2m_e} \cdot 2\pi n b\, db\, dx = \frac{4z^2e^4}{2b^2v^2m_e} \cdot 2\pi n b\, db\, dx = \frac{4\pi\, n\, z^2 e^4}{m_e v^2}\frac{db}{b}dx$$

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e c^2 \beta^2}\, n \cdot \ln \frac{m_e c^2 \beta^2 \gamma^2}{2\pi\hbar\langle\nu_e\rangle}$$



Cylindric barrel with N_e electrons

Ionization Losses. Bethe Formula

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad [\cdot \rho]$$

density

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV g^{-1} cm^2

$T_{max} = 2 m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma\, m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

z : Charge of incident particle
M : Mass of incident particle

Z : Charge number of medium
A : Atomic mass of medium

I : Mean excitation energy of medium
δ : Density correction [transv. extension of electric field]

$N_A = 6.022 \cdot 10^{23}$
[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm
[Classical electron radius]

$m_e = 511$ keV
[Electron mass]

$\beta = v/c$
[Velocity]

$\gamma = (1-\beta^2)^{-2}$
[Lorentz factor]

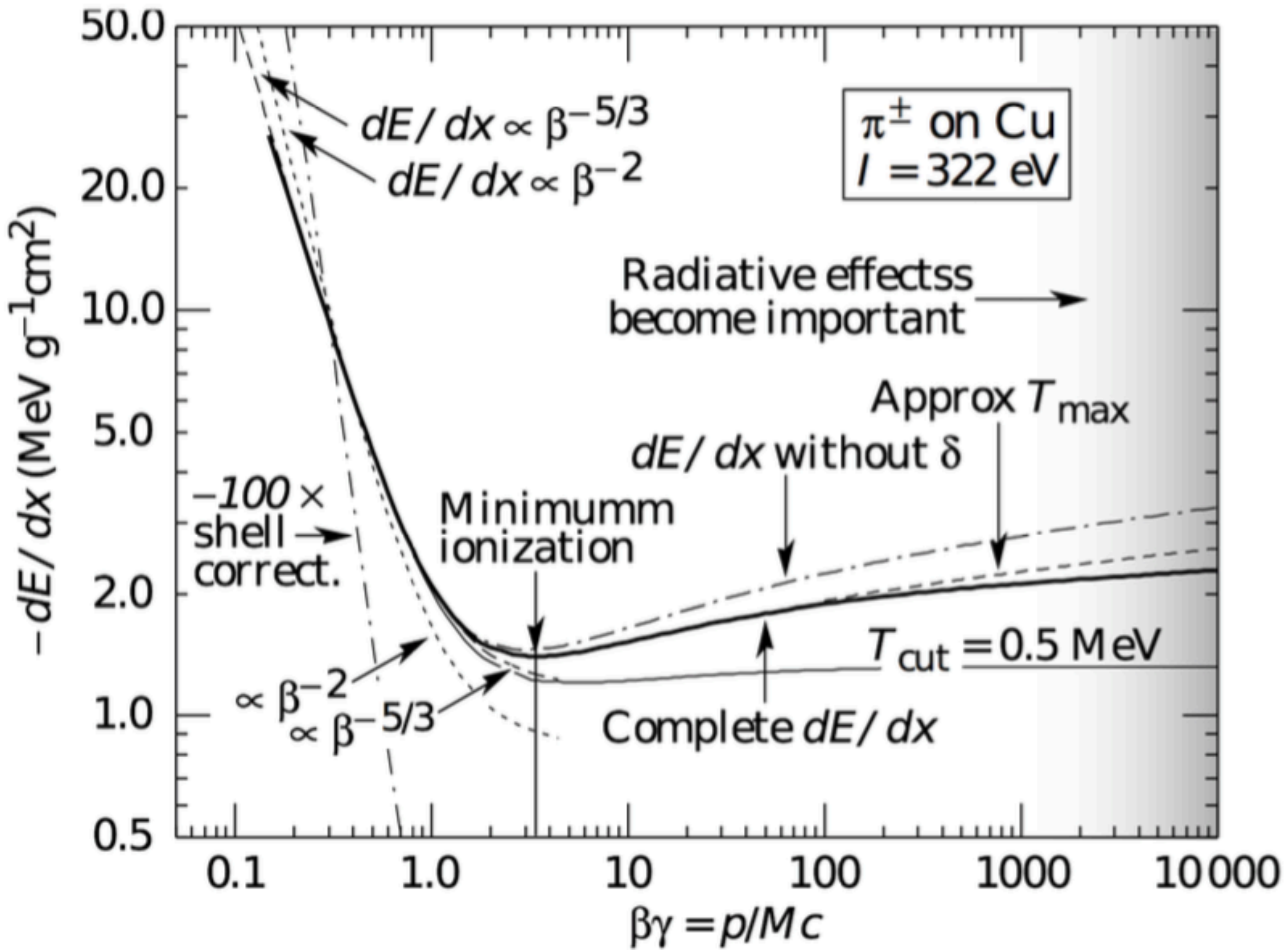
Validity:

$.05 < \beta\gamma < 500$
$M > m_\mu$

Energy Loss for Pions in Copper

Notice: normalized to the material density

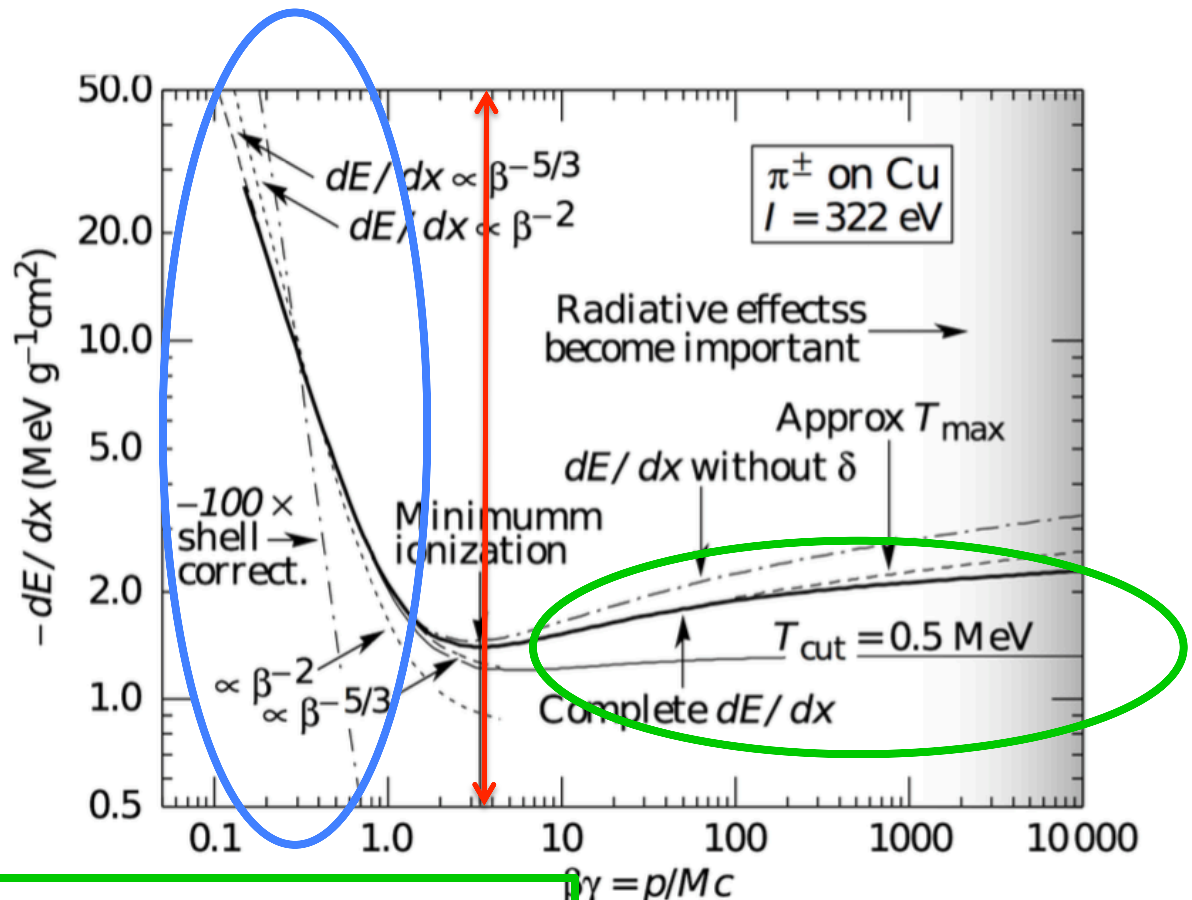
Units:
MeV g-1 cm2



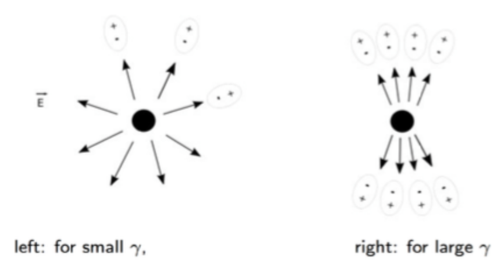
What to take in mind

Small βγ (slow particles)
quick fall of dE/dx as β^{-2}
(Bohr classical approximation)
Precisely it is $\beta^{-5/3}$: slower particles experience the electric field for a longer time → stronger energy loss!

Minimum ionization:
MIP = minimum ionizing particles for βγ ≈ 3-4
dE/dx ~ 1-2 MeV g^{-1} cm^2 @min
Density of copper: ρ=9.94 g/cm2
→ **MIP looses ~ 13 MeV/cm**

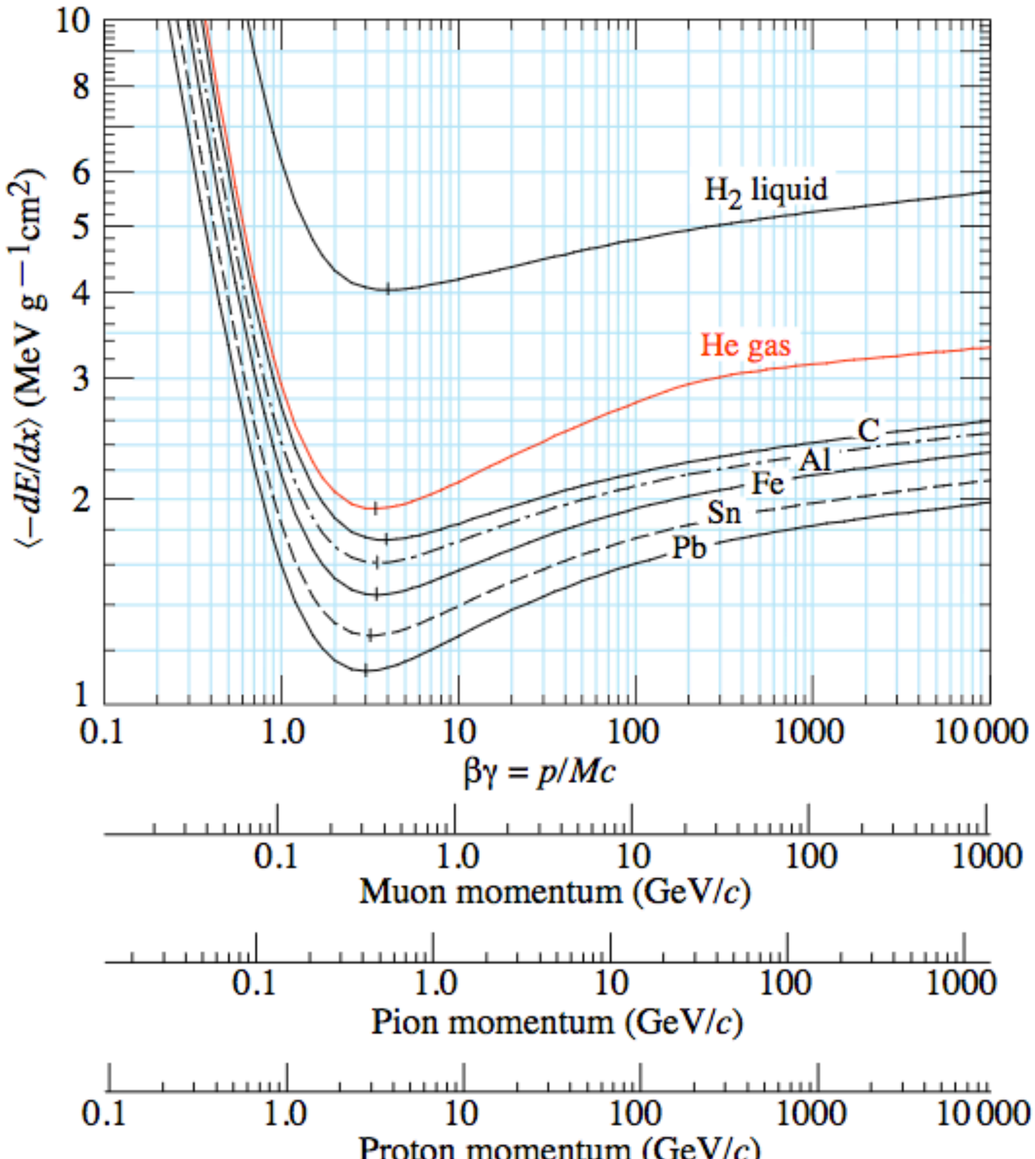


Large βγ
Relativistic rise ~ ln $\beta^2\gamma^2$
The transverse electric field increases due to Lorentz transformation



The rise is limited by the polarisation of the media which depends on the electron density. The relativistic rise is thus most suppressed for high density media. Gases, with low electron density, have a large relativistic rise.

Scale effect



dE/dx depends on βγ = p/(Mc)

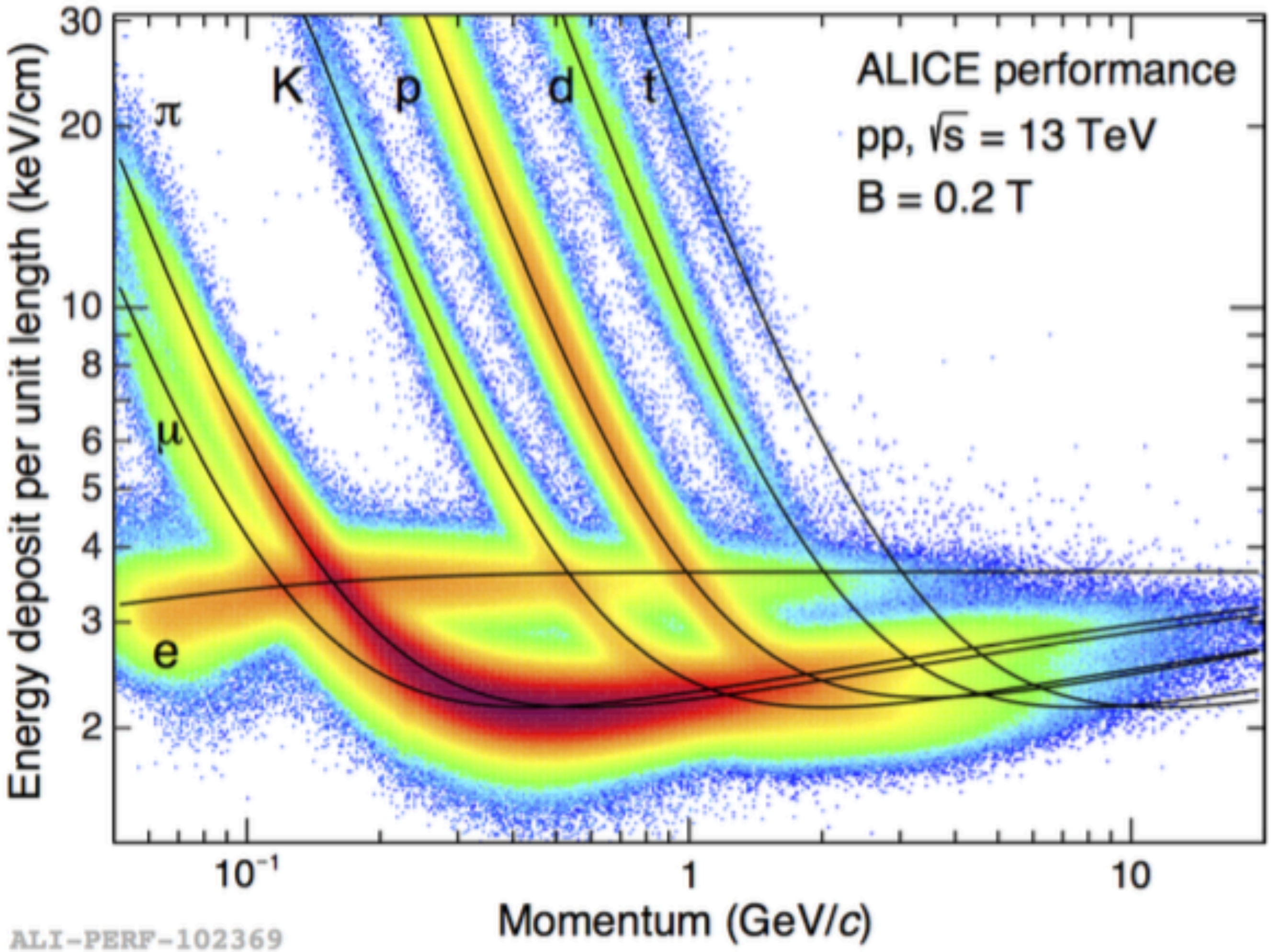
•Dependence on the particle velocity is the same for different detector materials and particle masses

• at a given p, dE/dx is different for particles with different mass M

•Different detector materials
dE/dx≈Z/A

dE/dx usage for PID

ALICE Time Projection Chamber



Wi , Mean energy to create a e-ion pair

- It strongly depends on the material and is given by two contributions:
- **Excitation of gas molecules** is a resonant phenomenon that requires a given amount of energy:
  - cross-section ~ 10^{-17} cm^2
- **Ionization (creation of electron – ion pair)** happens if the energy loss of the incident particle is above a given threshold.
  - No exact amount is required above the threshold: cross-section ~ 10^{-16} cm^2
- The mean energy required for the creation of an electron-ion pair in a real gas is a given by a combination of the excitation and ionization energy

Let's go through the parameters…

Wi = mean energy to create a e-ion pair

($E_i = I_o$)

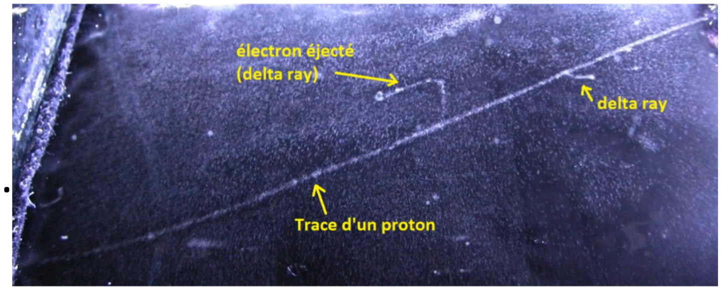
Unit charge @ minimum

Gas	ρ (g/cm^3) (STP)	I_0 (eV)	W_i (eV)	dE/dx (MeVg^{-1}cm^2)	n_p (cm^{-1})	n_t (cm^{-1})
H_2	$8.38 \cdot 10^{-5}$	15.4	37	4.03	5.2	9.2
He	$1.66 \cdot 10^{-4}$	24.6	41	1.94	5.9	7.8
N_2	$1.17 \cdot 10^{-3}$	15.5	35	1.68	(10)	56
Ne	$8.39 \cdot 10^{-4}$	21.6	36	1.68	12	39
Ar	$1.66 \cdot 10^{-3}$	15.8	26	1.47	29.4	94
Kr	$3.49 \cdot 10^{-3}$	14.0	24	1.32	(22)	192
Xe	$5.49 \cdot 10^{-3}$	12.1	22	1.23	44	307
CO_2	$1.86 \cdot 10^{-3}$	13.7	33	1.62	(34)	91
CH_4	$6.70 \cdot 10^{-4}$	13.1	28	2.21	16	53
C_4H_{10}	$2.42 \cdot 10^{-3}$	10.8	23	1.86	(46)	195

Difference among materials due to density, Z

Difference among materials due to electronic structure

Delta electrons

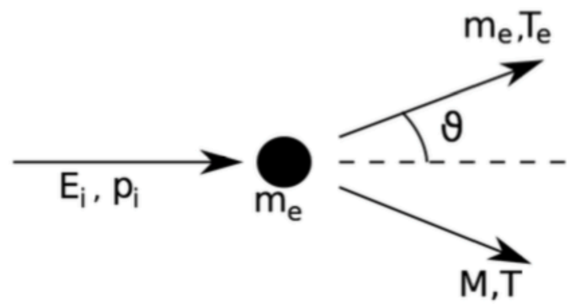


- Electrons liberated by ionization can have large energies.
- Above a certain threshold they are called **δ electrons**.

$$T_e = 2m_e \frac{\vec{p}_i^2 \cos^2\theta}{(E_i + m_e)^2 - \vec{p}_i^2 \cos^2\theta}$$

$$\Rightarrow \quad T_e^{max} = \frac{2m_e \vec{p}_i^2}{(E_i + m_e)^2 - \vec{p}_i^2}$$

$$\cong \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\frac{m_e \gamma}{M} + \left(\frac{m_e}{M}\right)^2} \quad \text{for} |\vec{p}_i| \gg M, m_e$$



- **Massive highly relativistic particle can transfer practically all its energy to a single electron**!
- Delta electrons produced by ionization with
  - High energy, Low probability → this will affect the shape of the energy loss distribution
- Probability distribution for energy transfer to a single electron:

$$\frac{d^2 W}{dx\, dE} = 2m_e c^2 \pi r_e^2 \frac{z^2}{\beta^2} \cdot \frac{Z}{A} N_A \cdot \rho \cdot \frac{1}{E^2}$$

- Unpleasant: often this electron is not detected as part of the ionisation trail,broadening of track and of energy loss distribution.
  - Limitation to the measurement of the incoming particle

Range of particles stopped in medium

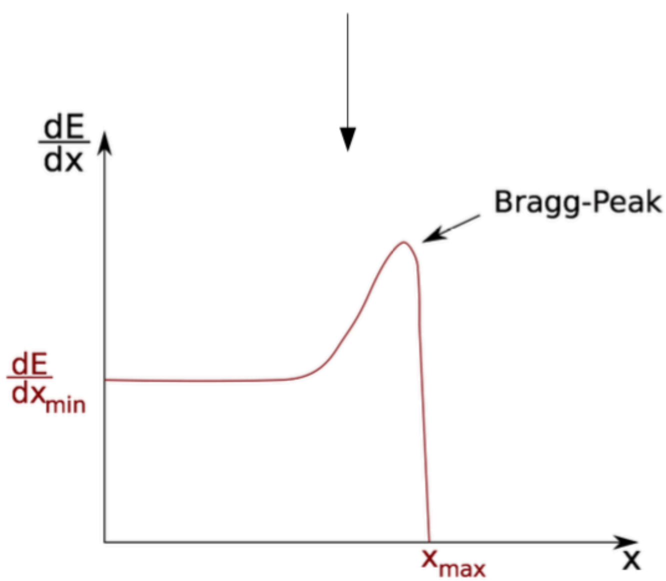
- Integrate over energy loss from initial energy E to 0, to calculate the range:

$$R = \int_E^0 \frac{\mathrm{d}E}{\mathrm{d}E/\mathrm{d}x}$$

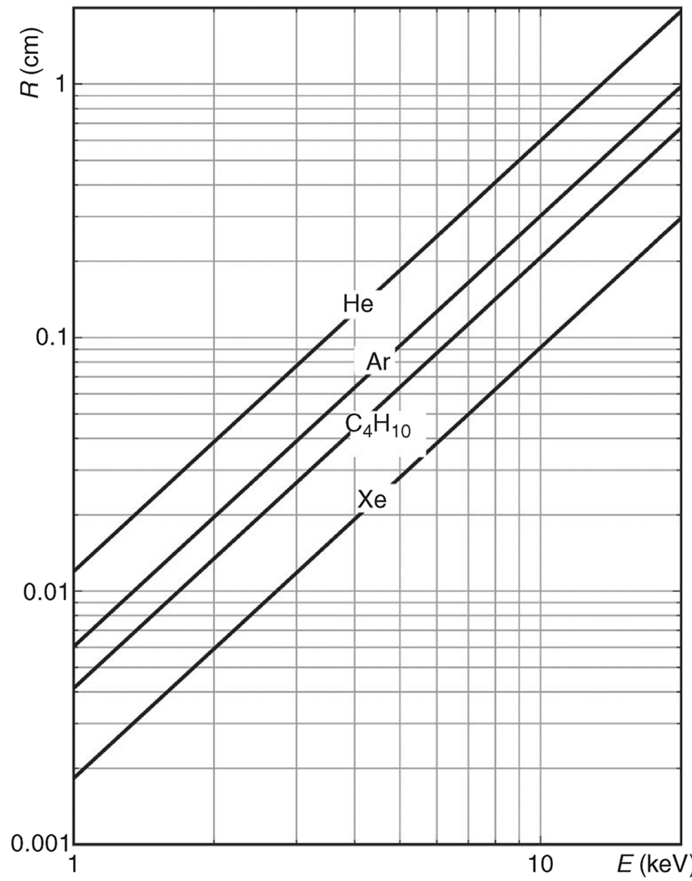
- R=10*E^(1.7) slow electrons in light material

for $\beta\gamma \simeq 3.5$ $\quad \langle \frac{\mathrm{d}E}{\mathrm{d}x} \rangle \simeq \frac{\mathrm{d}E}{\mathrm{d}x}_{\mathrm{min}}$

for $\beta\gamma \lesssim 3.5$ steep rise $\quad \langle \frac{\mathrm{d}E}{\mathrm{d}x} \rangle \gg \frac{\mathrm{d}E}{\mathrm{d}x}_{\mathrm{min}}$



Energy loss curve vs depth showing Bragg peak



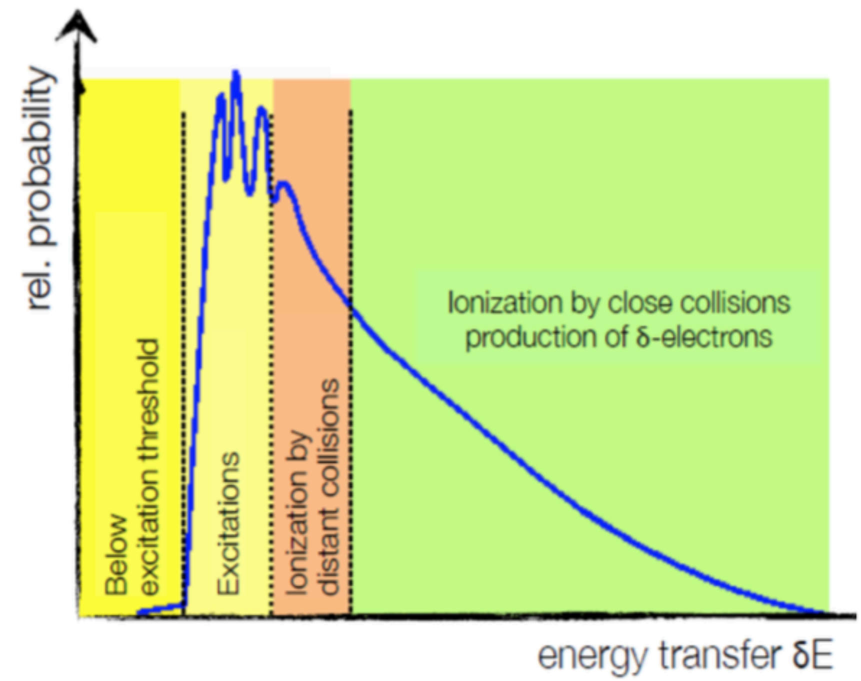
Electron range in gas as a function of their energy

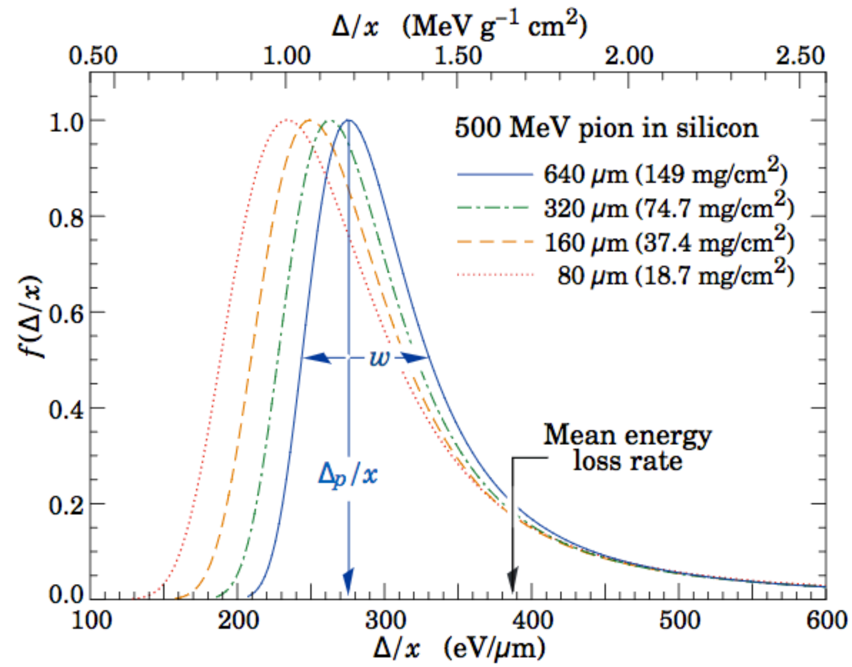
dE/dx fluctuations

- The Bethe-Bloch formula describes the MEAN energy loss. The energy loss is measured in a detector of finite thickness Δx with
  - N = number of collisions
  - δE = energy loss in a single collision

$$\Delta E = \sum_{n=1}^{N} \delta E_n$$

- The single energy loss is a statistical process, δE is distributed statistically → energy loss "straggling" (strong fluctuations, complex problem)
- For thin absorbers: Landau distribution
  - Naively, it comes from a gaussian distribution of energy loss in single collisions plus tail towards high losses due to the δ electrons
  - Energy loss distribution normalized to thickness x. For increasing x:
    - Most probable value Δp/x shifts to larger values
    - Relative width shrinks
    - Asymmetry of distribution decreases





Ionization yield

- **Ionisation electrons deposited in Argon by a minimum ionising particle:**
  - *dE/dx/I = 2.5keV/16 = 156 e-ion pairs/cm*
  - Simulation SW: Heed = 41 e-/cm
  - Simulation SW: Degrad = 50 e-/cm

- **Apparently, ionising takes more than the binding energy:**
  - not all energy is used ?
  - some energy goes into excitations (Work function) ?
  - or there may be errors in the d*E*/d*x* tables ? ☺

- **W > ionization potential I since:**
  - Some energy is also spent for the ionization of inner shells with stronger binding energy
  - Excitation of the gas atoms/molecules that may not lead to ionization
  - De-exciting atoms can emit photons that can be re-absorbed by the medium and converted into electrons

Ionization statistics

- **The creation of electron-ion pairs can be predicted using Poisson statistics: in general two incoming particles with the same energy will never creates the same numbers of pairs.**
- The encounters with the gas atoms are purely random and are characterized by a mean free flight path λ between ionizing encounters given by the ionization cross-section per electron σ_I and the density N of electrons

$$\lambda = 1/(N\sigma_I).$$

mean distance between ionization events with cross section σ and electron density N in material

- The production of e-ion pairs follows a Poisson distribution:
  - with **<n> = L/λ = mean number of ionization events per unit lenght**

$$P(n, \langle n \rangle) = \frac{\langle n \rangle^n \exp(-\langle n \rangle)}{n!}$$

- The probability of having NO ionization: $\mathbf{P(0,\langle n \rangle)=e^{-\langle n \rangle}=e^{-L/\lambda}}$
- **Detector efficiency eff =** $\mathbf{1-P(0,\langle n \rangle) = 1-e^{-L/\lambda}}$

Measuring the (in)efficiency of gas detectors (i.e. the probability of having no signals, so 0 ionizing events), <u>we can determine the value of λ, and therefore σ_I</u>

Typical values:

	λ (cm)
He	0.25
air	0.053
Xe	0.023

$\rightarrow \sigma_I = 10^{-22}$ cm^2 or 100 b

Photon interactions

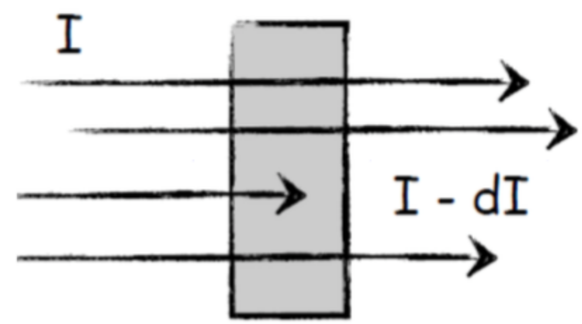
- Characteristic of photons: <u>can be removed from incoming beam of intensity </u>“I”, with one single interaction:
- **dI = - I μ dx**
  μ (E, Z, ρ): absorption coefficient
- **Lambert-Beer law of attenuation**:

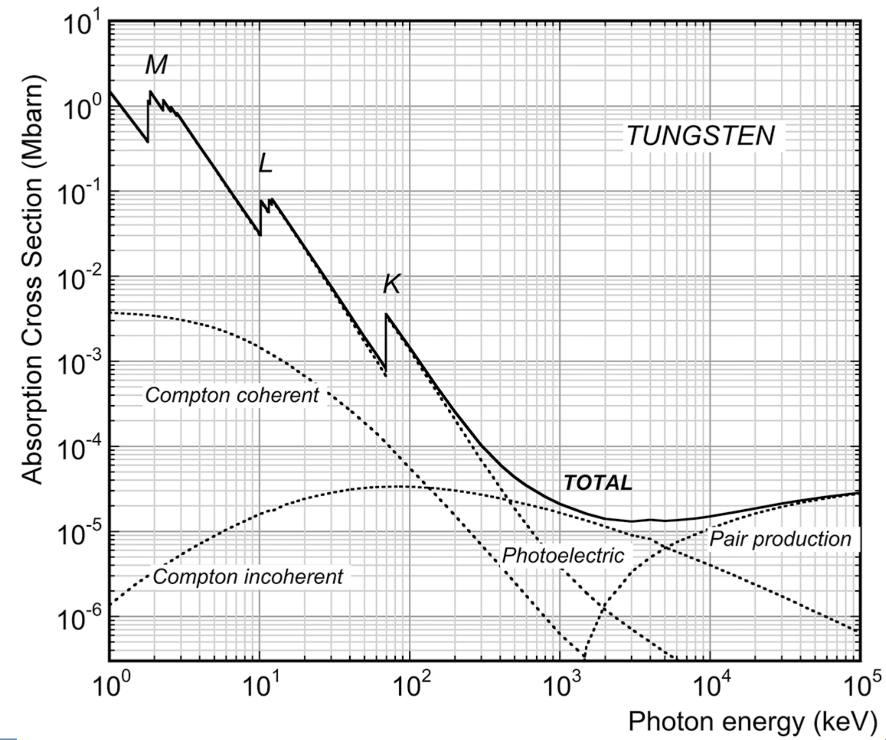
  I(x)=I0 exp(-μx)

- Mean free path of photons in matter:

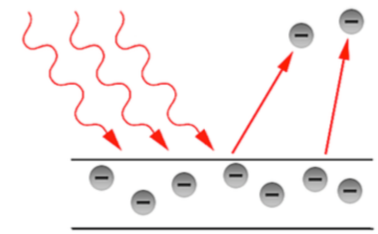
  $$\lambda = 1/N^*\sigma_{absorption} = 1/\mu$$

  $\mu = N^*\sigma_{absorption}$
- The most important processes of interaction of photons with matter are:
  - Photoelectric effect
    - most important for gas detectors
  - Compton scattering:
  - Pair creation

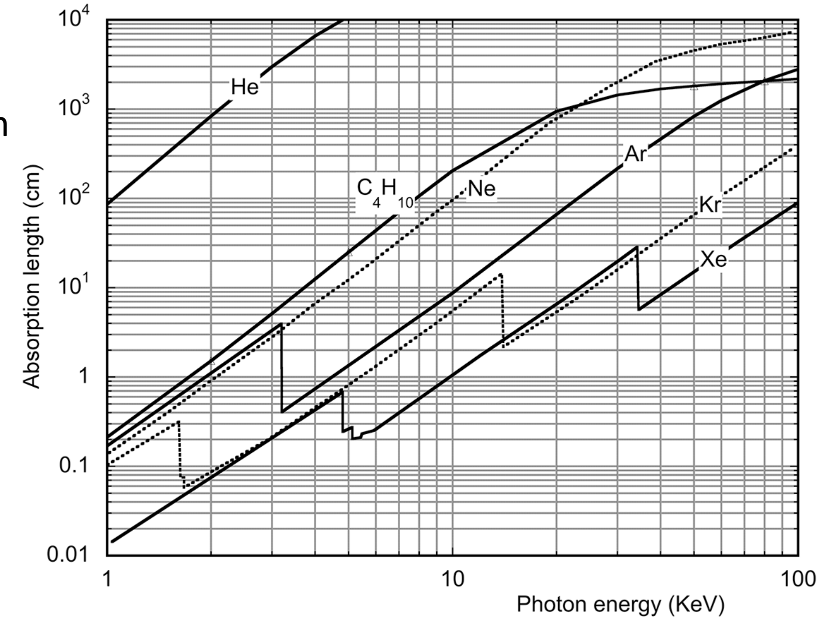




Photoelectric effect

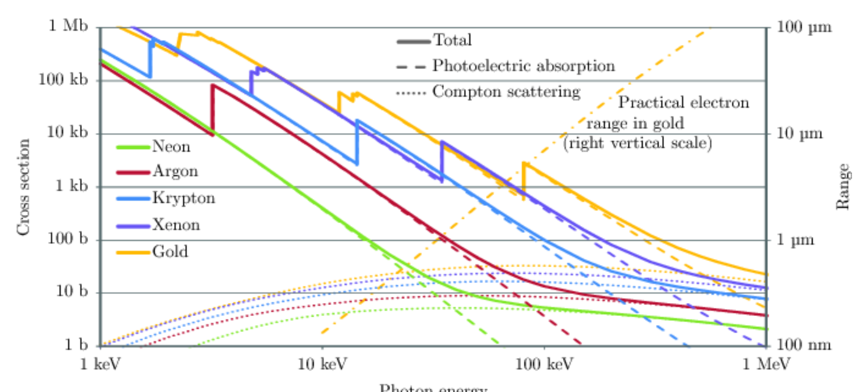


- γ + atom → atom$^+$ + e$^-$
- **$E_e = h\nu - E_b$**
- Where:
  - **$h\nu = E_\gamma$ = photon energy,**
  - **E_b = binding energy of the electron** (K, L, M absorption edges)
- Binding energy depends strongly on Z → the cross section will depend strongly on Z (dependence goes with Z^5)



- The photo-absorption leaves the gas atom in excited state→it can return to the ground state with two competing mechanism
  1. Auger effect: atom^{**+}→ atom^{*+} + e$^-$
  - It is an internal re-arrangement of the electrons in the atom, with the **emission of an electron with energy close to E_b**
  - Auger electrons deposit their energy locally due to their very small energy (<10 keV)
  2. Fluorescence: atom^{**+} → atom^{*+} + γ
  - Fluorescence photons (X-rays) must interact via the photoelectric effect → much longer range
  - The relative fluorescence yield increases with Z

w_K = P(fluor.) / [P(fluor.) + P(Auger)]



De-excitation after photo-electric absorption

- Fluorescence de-excitation in Argon~5%
- $E_{fluorescence}=E_{\gamma}$-Eb. The fluorescence photon can be
  - locally reconverted into an electron or
  - Flee the detection volume and be absorbed by the electrodes→escape peak around the energy E_{γ}-Eb
- 95% de-excitation with Auger electron emission, with energy closer the one of the k-shell

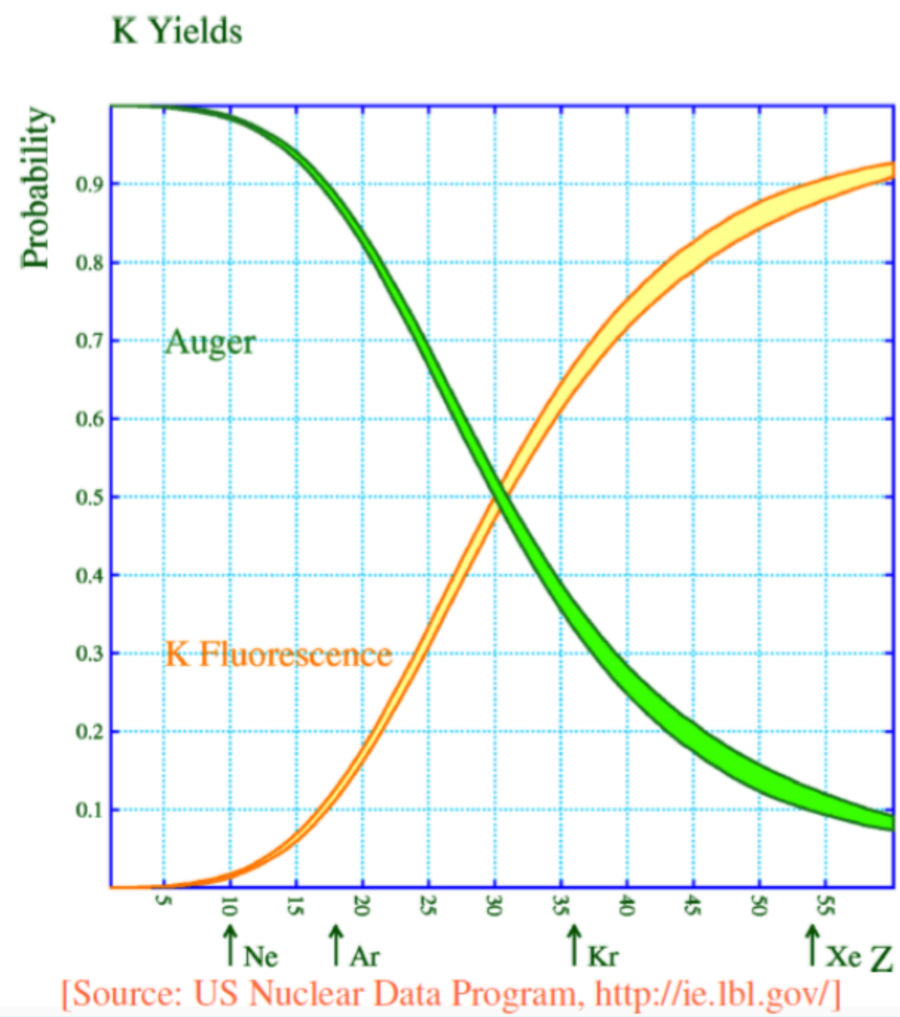


Photo-ionization statistics

- The number N of electron ion pairs released in a gas by converted X-ray can be estimated via

  $$N = E_x / W_I$$

- Where Wi is a phenomenological quantity
- While for charged particle the statistical fluctuation in the number of produced electrons is dominated by the high-tail energy loss in the Landau distribution, for X ray a constraint is imposed by the maximum energy loss that cannot exceed the one of the incoming photon
- This modify the fluctuation from the simple form $\sqrt{N}$ → the result is a reduction of energy fluctuation $\sqrt{FN}$, where F is the Fano factor F<1

Gas	W_I (eV)	F (theory)	F (exp.)
Ne	36.2	0.17	
Ar	26.2	0.17	
Xe	21.5		≤ 0.17
Ne+0.5% Ar	25.3	0.05	
Ar+0.5% C_2H_2	20.3	0.075	0.09
Ar+0.8% CH_4	26.0	0.17	0.19

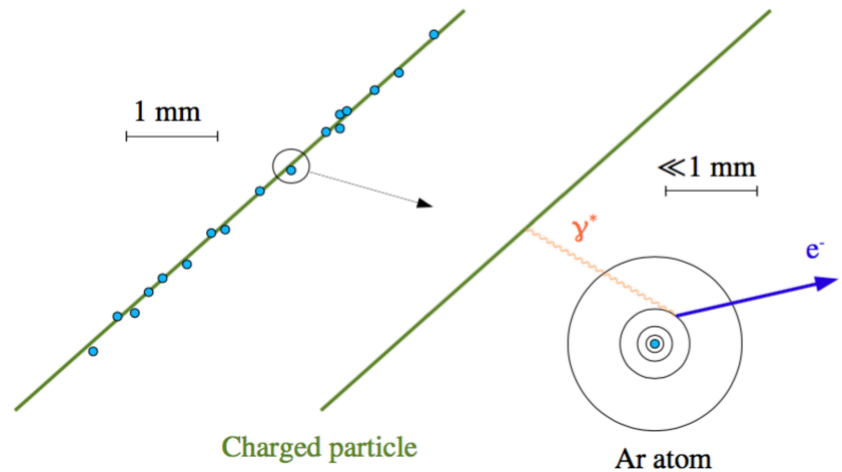
PAI Model

To simulate the true signal it is necessary to use a much more detailed model that gives the distribution of the individual ionisations along the track and their energies.

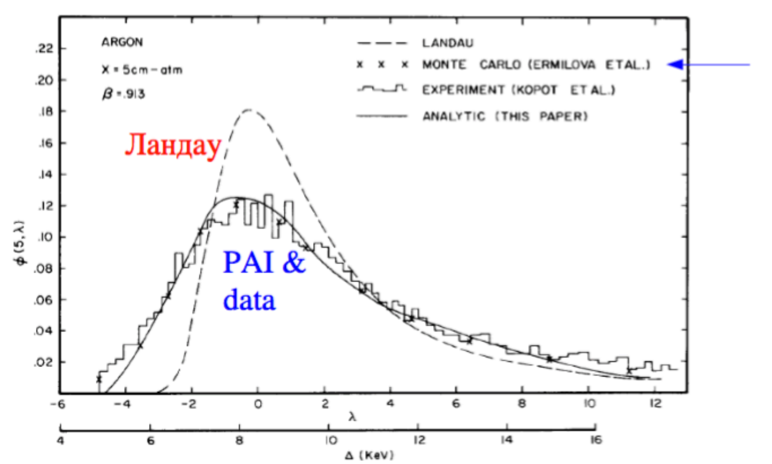
- The photo absorption ionisation (PAI) model was developed using a semi-classical approach, that starts with the Maxwell equations for a charged particle traversing a medium with dielectric constant . In this way the energy loss is expressed as

$$\frac{dE}{dx} = \frac{e\vec{E}\cdot\vec{\beta}}{\beta}$$

- Where **β** is the velocity vector of the charged particle and **E** the electric field created by the particle itself evaluated at the point of the particle.
- Making a Fourier transform of the electric field the energy loss can be described as a continuous energy loss in different frequency region
- The energy continous energy loss is then reinterpreted as a number of discrete collisions with energy transfer ω, in the implementation of the simulation software



► 2 GeV protons on an (only !) 5 cm thick Ar gas layer:



[Diagram: Richard Talman, NIM A **159** (1979) 189-211]

Basic formulae of the PAI model

- Key ingredient: photo-absorption cross section σγ(*E*)

$$\frac{\beta^2\pi}{\alpha}\frac{d\sigma}{dE}=\frac{\sigma_\gamma(E)}{E}\log\left(\frac{1}{\sqrt{(1-\beta^2\epsilon_1)^2+\beta^4\epsilon_2^2}}\right)+$$

Relativistic rise

Cross section to transfer energy E

$$\frac{1}{N\hbar c}\left(\beta^2-\frac{\epsilon_1}{|\epsilon|^2}\right)\theta+$$

Cherenkov radiation.

$$\frac{\sigma_\gamma(E)}{E}\log\left(\frac{2m_e c^2\beta^2}{E}\right)+$$

Resonance region

$$\frac{1}{E^2}\int_0^E \sigma_\gamma(E_1)\,dE_1$$

Rutherford scattering

With:

$$\epsilon_2(E)=\frac{N_e\hbar c}{EZ}\sigma_\gamma(E)$$

$$\epsilon_1(E)=1+\frac{2}{\pi}\mathrm{P}\int_0^\infty\frac{x\,\epsilon_2(x)}{x^2-E^2}\,dx$$

The dielectric constant of the medium is related to the photoabsorption cross section

responsible for the Cherenkov radiation.

$$\theta=\arg(1-\epsilon_1\beta^2+i\epsilon_2\beta^2)=\frac{\pi}{2}-\arctan\frac{1-\epsilon_1\beta^2}{\epsilon_2\beta^2}$$

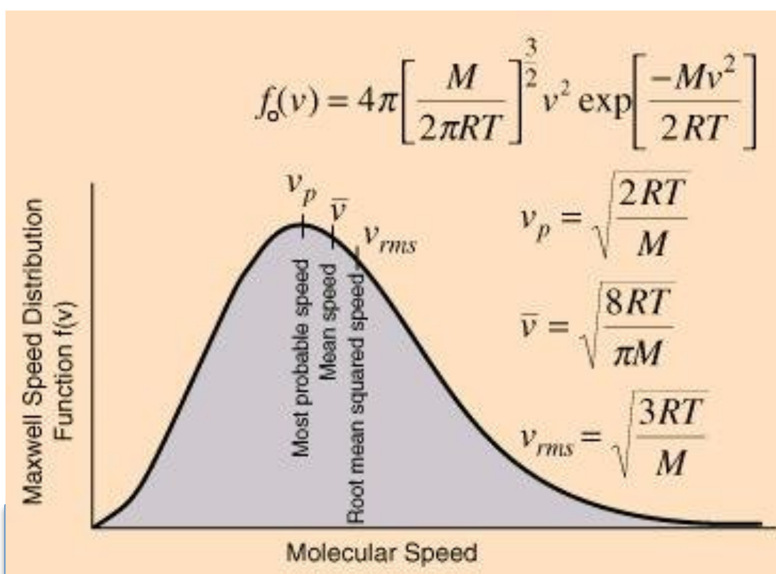
CHARGE TRANSPORT

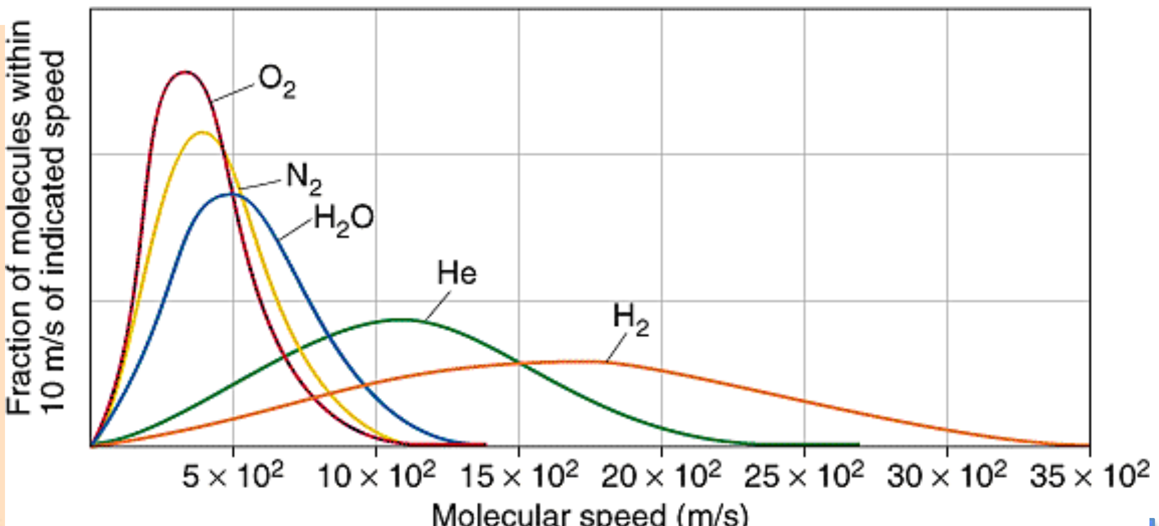
Transport of electrons and ions in the gas: Diffusion

- In absence of an applied electric field: electron-ion pairs diffused freely starting from the point of their creation, next to the incoming radiation trajectory
    - Electrons and ions behave like neutral molecules and their behaviour is described by the kinetic theory
- They collides with other atoms/molecules in the medium until they reach the thermal equilibrium with the gas.
- At thermal energies the mean velocity of electron/ions is given by the Maxwell distributon

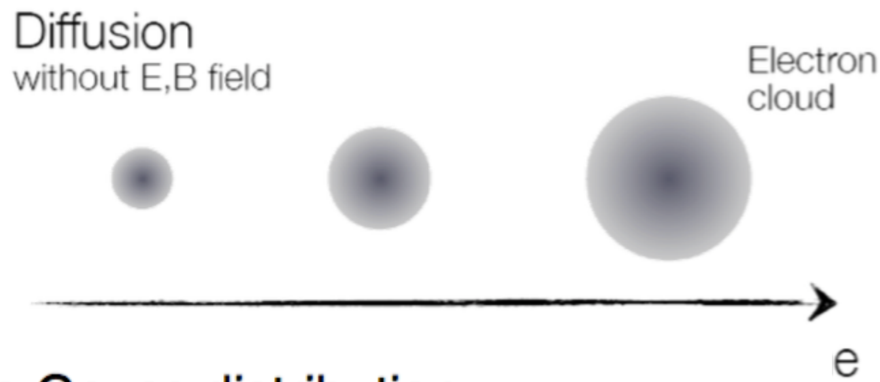
v=sqrt(8kT/πm) m=electron/ion mass, T=gas temperature

- The velocity of the ions is smaller than the one for the electrons
    - **v_{ion}~10^4cm/s, v_{e-}~10^6cm/s**





Transport of electrons and ions in the gas: Diffusion



The charge carrier distribution follows a Gauss distribution:

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$$

N … number of free charged carriers
x … distance from point of creation
t … time after creation
D … diffusion coefficient

The width (rms - root mean square) of the distribution is (linear diffusion):

$$\sigma_x = \sqrt{2Dt}$$

and for volume diffusion (spherical dispersion):

$$\sigma_{vol} = \sqrt{3} \cdot \sigma_x = \sqrt{6Dt}$$

Diffusion Coefficient

D: diffusion coefficient: $D = \frac{1}{3} v \lambda$

Mean free path of electrons/ions in gas: $\lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma_0 P}$

Mean velocity according to the Maxwell distribution: $v = \sqrt{\frac{8kT}{\pi m}}$

m=mass of particle (note difference e / ion!)

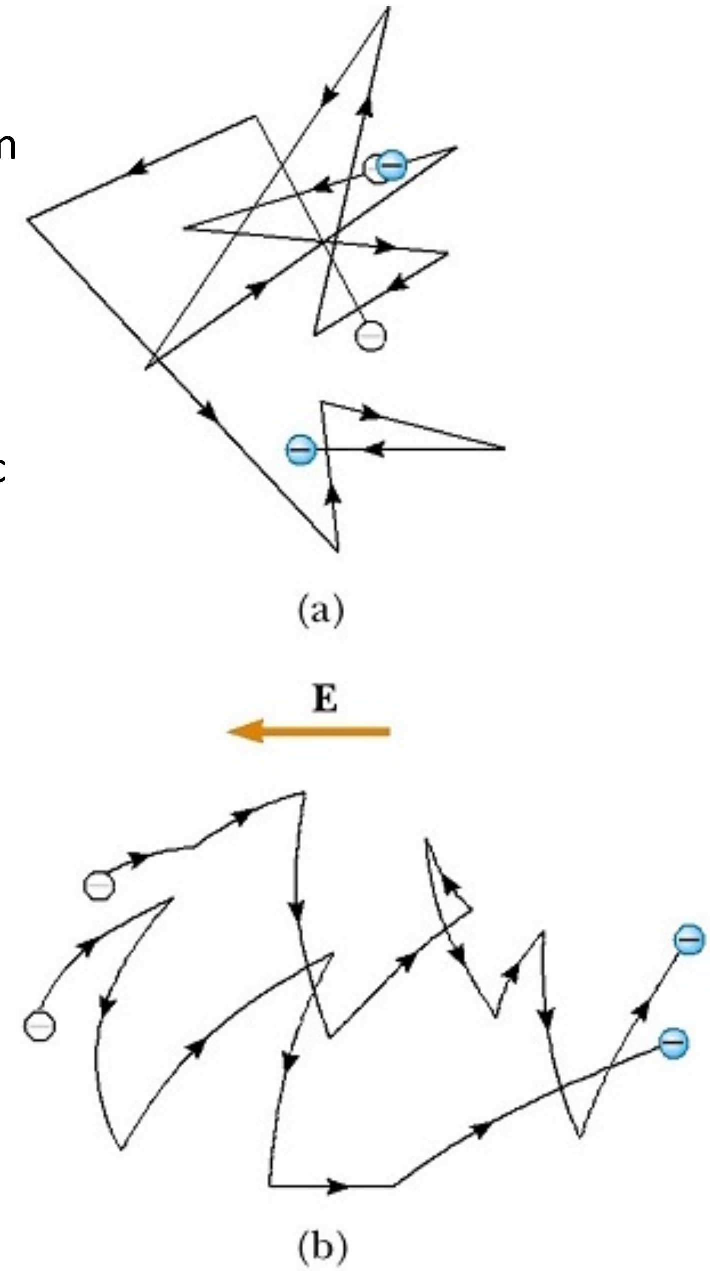
Therefore:

$$D = \frac{1}{3} v \lambda = \frac{2}{3\sqrt{\pi}} \frac{1}{\sigma_0 P} \sqrt{\frac{(kT)^3}{m}}$$

Diffusion depends on the **gas pressure P and temperature T** !!!

Drift in Electric Field

- When the electric field is applied, the e-ion pairs driftin along the electric field lines, is superimposed to the caothic thermal motion
- Acceleration is interrupted by collision with gas atoms
- This limits the drift velocity → mean drift velocity v_D!
- The drift velocity is proportional to the applied electric field



$$v_D = \mu E$$

μ=Mobility= D*q/kT

$$\vec{v}_D = \frac{q}{m} \cdot \tau(\vec{E}, \sigma) \cdot \vec{E} \cdot \frac{p_0}{p} = \mu \cdot \vec{E} \cdot \frac{p_0}{p}$$

q, m … charge and mass
E … electric field
τ … mean time between collisions
p … gas pressure, p_0 … standard pressure
μ … mobility, $\mu = \tau \cdot q/m$,

Ion Drift

- The ion drift velocity is linear with the electric field → **vD=µE**
- Ions diffuses in a space x over a time t following the gaussian law
- The spread aloing the x coordinate is given by

$$\sigma_x = \sqrt{\frac{2KT \times x}{eE}}$$

- It depends just on the electric field!! (not on pressure or gas type)
- The mobility of an ion in a different gas follow a simple dependance on the mass ratio

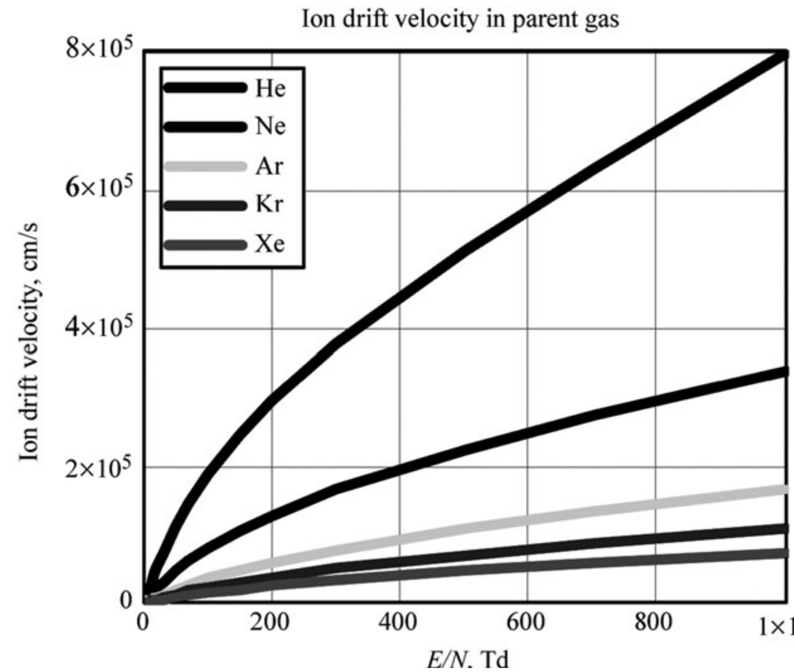
$$\mu_I = \sqrt{1 + \frac{M_M}{M_I}}$$

i=migration ions
M= support gas

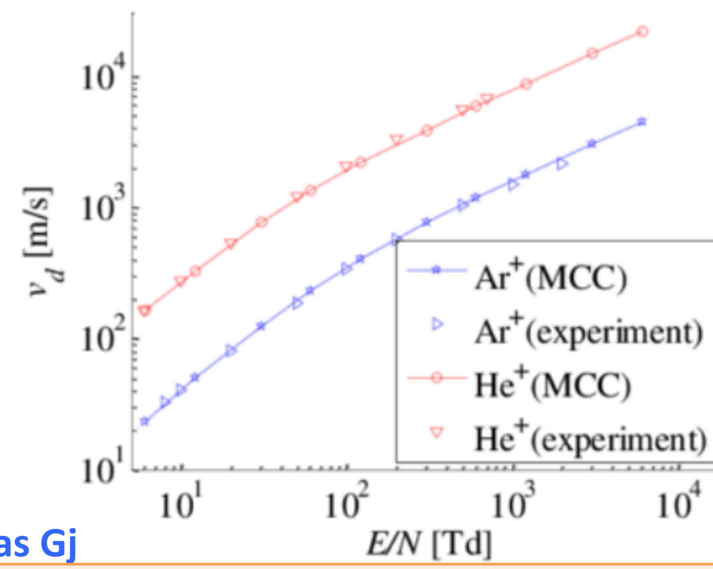
- In a mixture of gases G1,G2,… the mobility µi of the ion Gi+ is given by

$$\frac{1}{\mu_i} = \Sigma_j \frac{p_j}{\mu_{ij}}$$

pj volume concentration of gas j
µij=mobility of the ion Gi+ in the gas Gj



On the accuracy of the BGK model for ion drift in own gas



10.1088/1361-6595/26/2/024002.

If several types of ions are present the ones with bigger ionisation potentials will steal electrons from atoms with lower ionization potentials after 10^2-10^3 collisions.

Electron Drift: the theory

- The mobility of the electrons is not constant
- Because of their low mass, electrons can substantially increase their energy between collisions with gas molecules

$$v_D = ke\mathbf{E}\tau/m$$

τ= mean collision time
k=constant, k=0.75-1

- But τ depends on the gas and E, so this expression in practice is not very useful
- During the drift in the E and as a result of the colliding with the gas molecules, electrons diffuse→ the initially localized charge becomes a cloud
- The diffusion is described by

$$\sigma_x = \sqrt{\frac{2\epsilon_k x}{eE}}$$

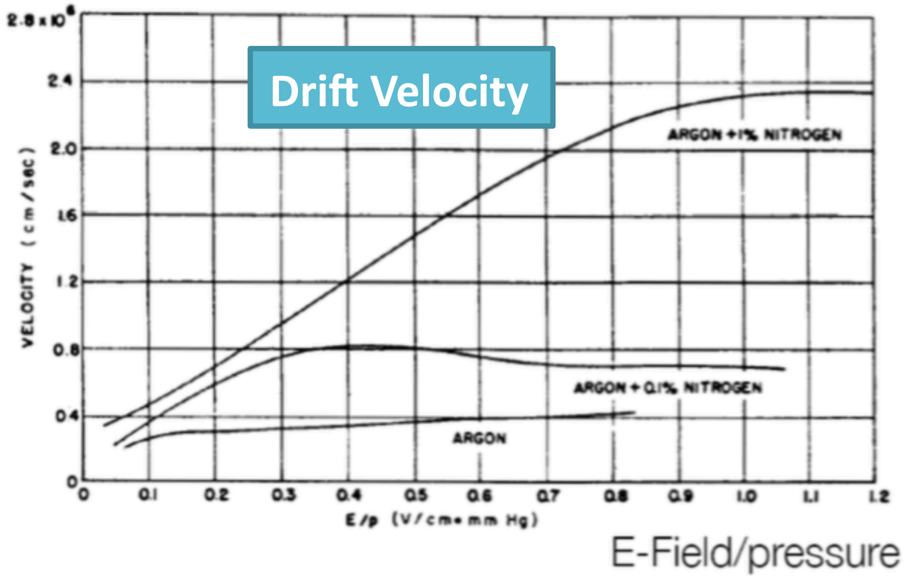
ε_k : characteristic energy
It reduces to KT @ thermal equilibrium
Average heating of the electron swarm by the electric field

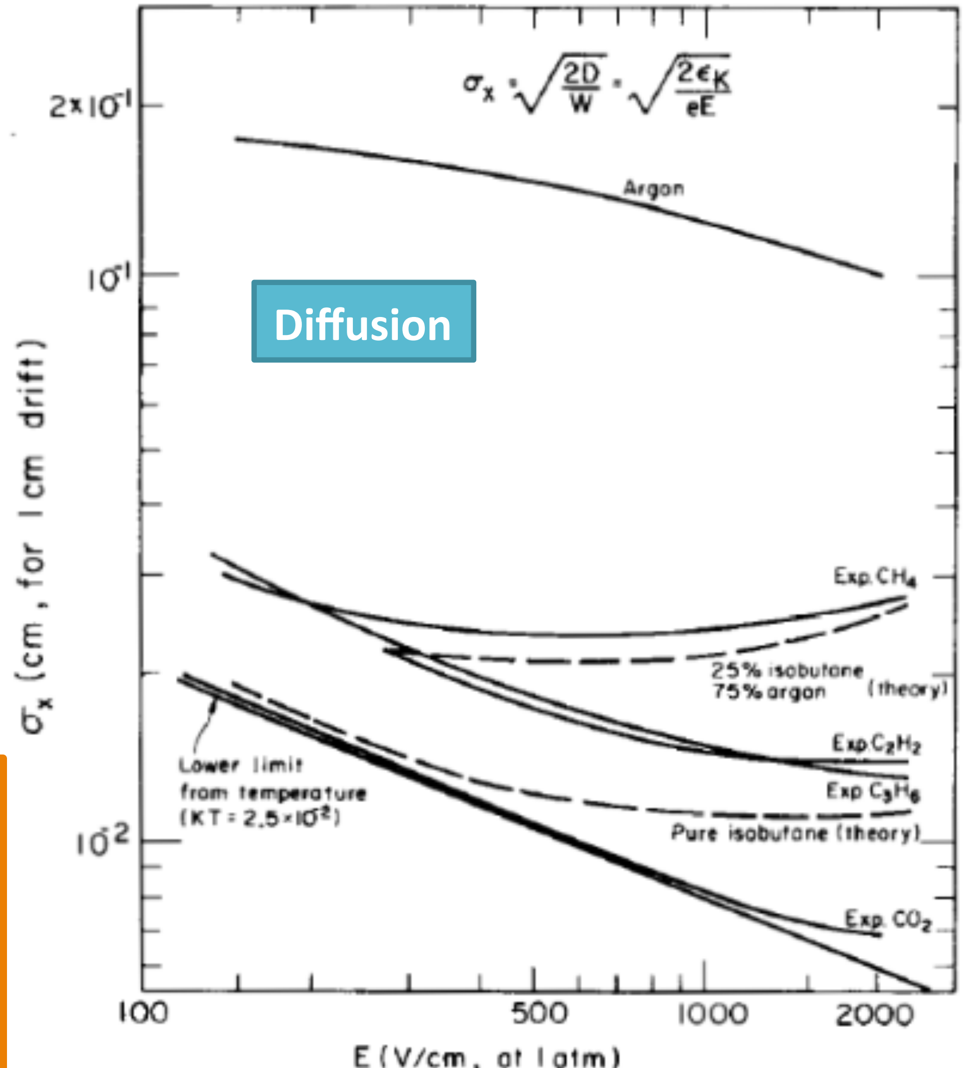
- σ_x can be written explicitly as a function of the reduced electric field E/P →

$$\sigma_x = \sqrt{\frac{2\epsilon_k}{e}} \cdot \sqrt{\frac{P}{E}} \cdot \sqrt{\frac{x}{P}}$$

Drift velocity of electrons

Use gas mixture to obtain constant v_D
Important for applications using drift time to get spatial information





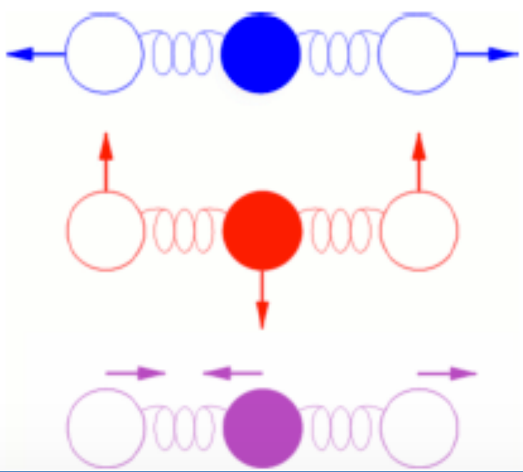
- Electron velocity increase linearly with the electric field. For some value of the applied electric field it reaches a plateau
- It depends on the gas composition→the injection of a polyatomic gas increase the drift velocity

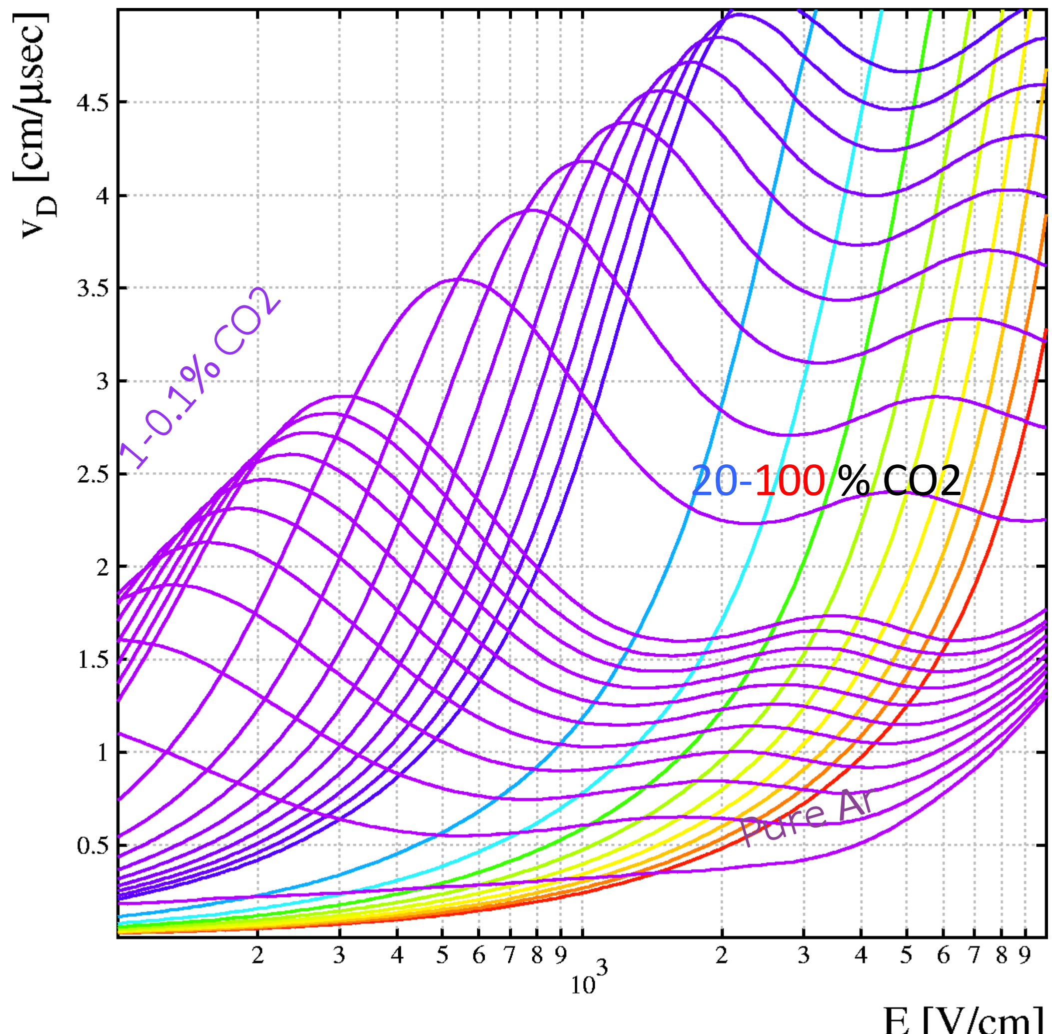
The E-field reduces the longitudinal diffusion

Electrons drift velocity adding C02

The addition of even very small fraction of one gas to another, which modify the average energy, can change the drift properties. The effect is particularly strong in noble gases

- CO2 makes the gas faster,
- Drift velocities calculated by Magboltz for Ar/CO2 at 3 bar.
- CO2 is linear:
  O – C – O
- Vibration modes are numbered V(ijk)
  - **i: symmetric,**
  - **j: bending,**
  - **k: anti-symmetric**



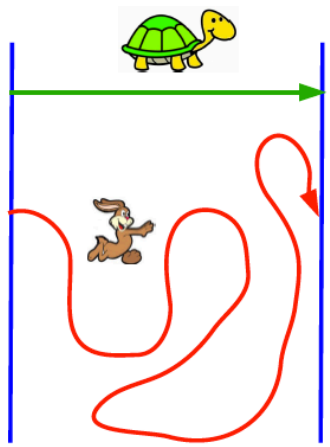


Why?

- Drift velocity v_D: distance effectively travelled ÷ time needed.
- Compare rabbit and turtle:

$$v_D = \bar{v}$$

$$v_D \ll \bar{v}$$

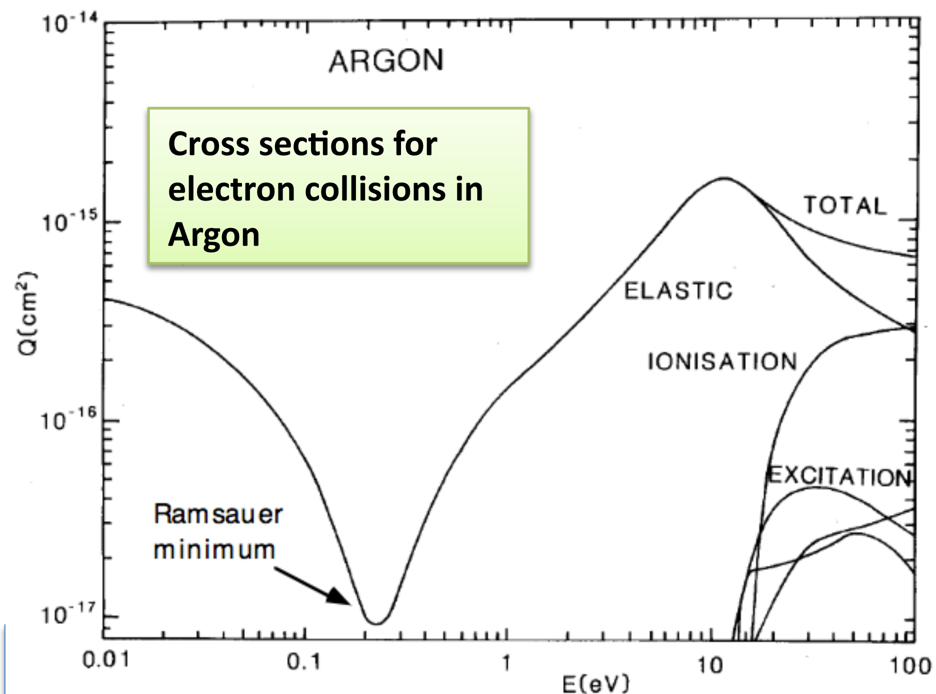


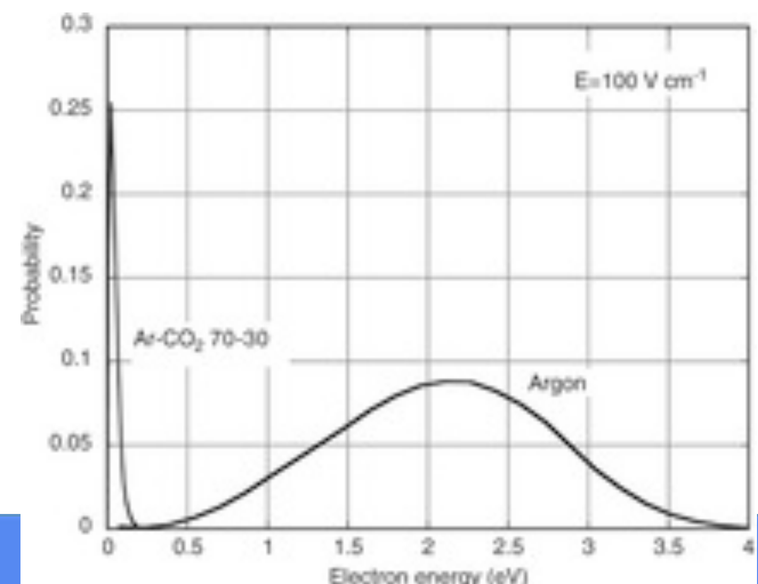
We want the electrons produced by ionization to be collected quickly after the creation.

The collisions of electrons with gas atoms slow down the electron motion

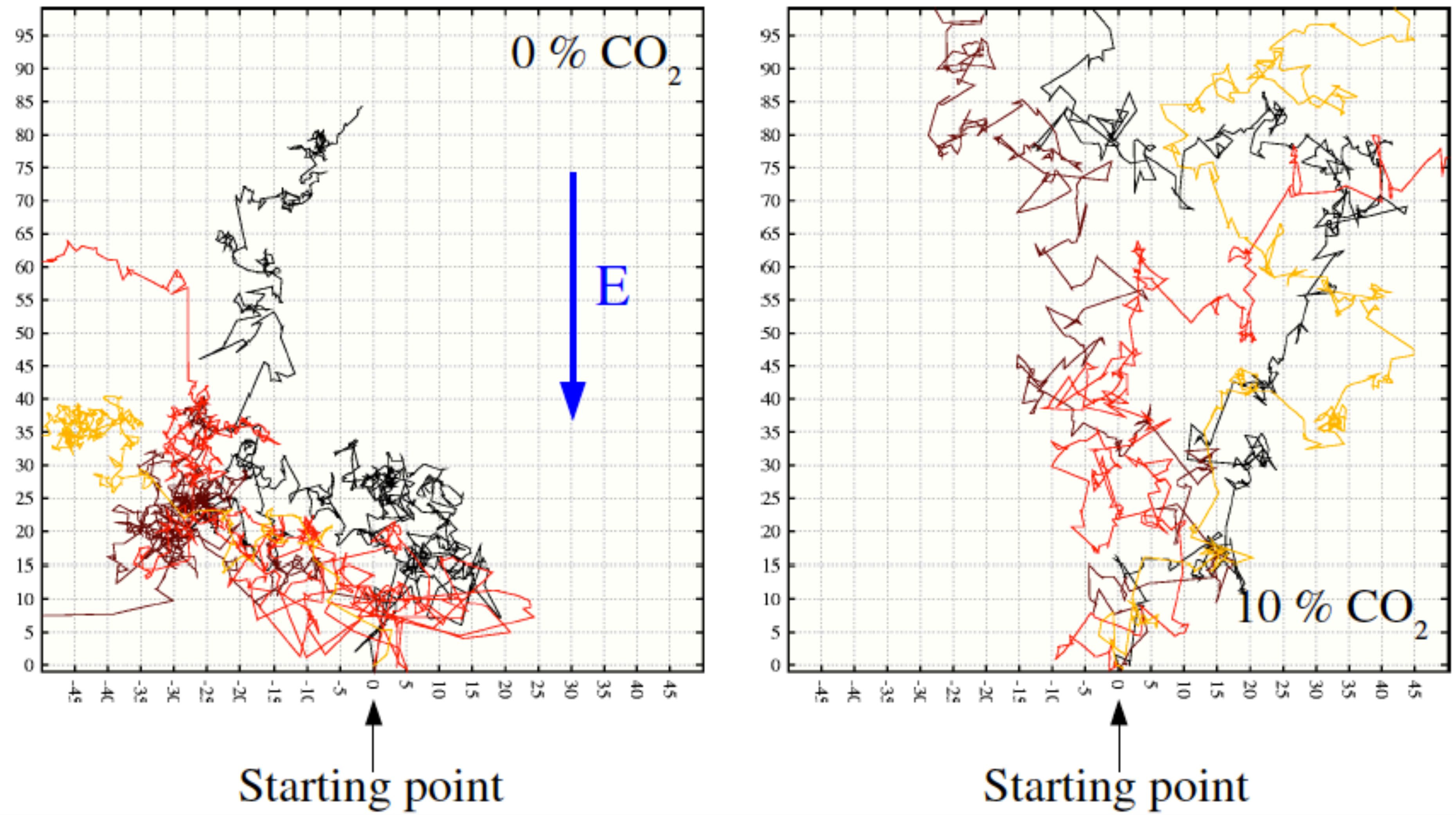
One wants to <u>decrease the collision probability</u> → exploit the Ramsauer minimum of noble gases

How to reach the Ramsauer mimimum?
→By Adding CO2 to let the electron energy reach the thermal value

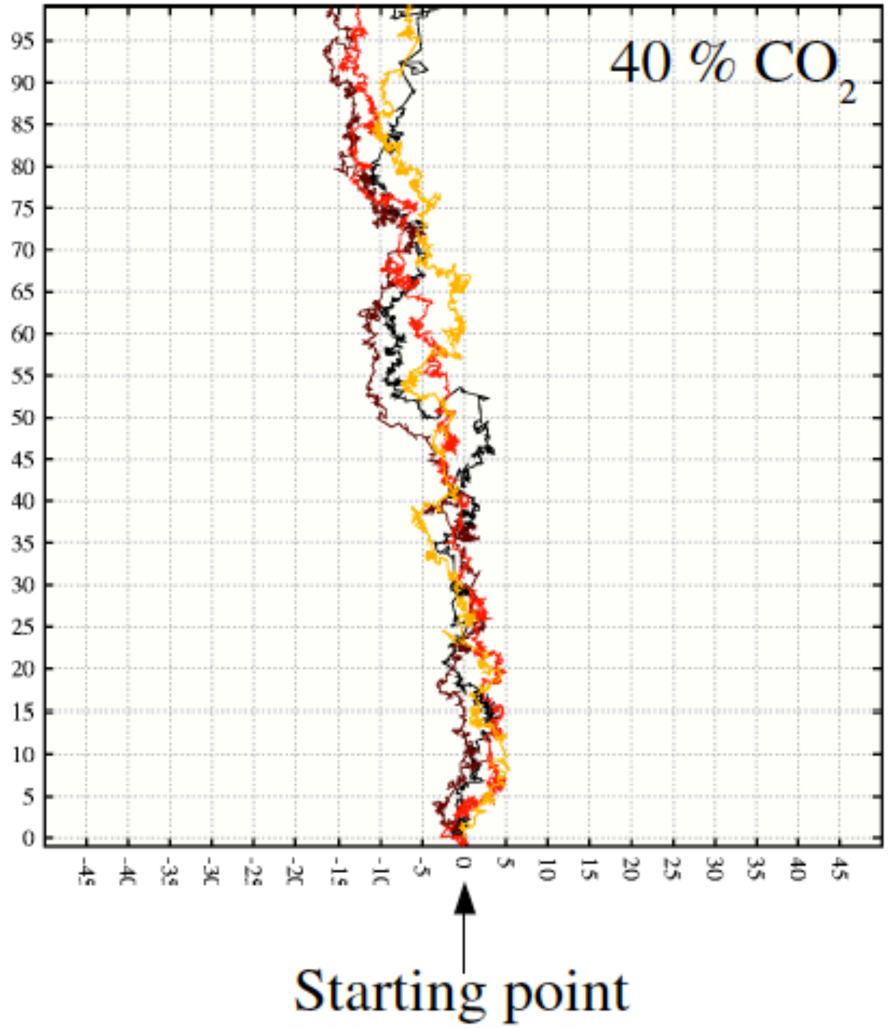


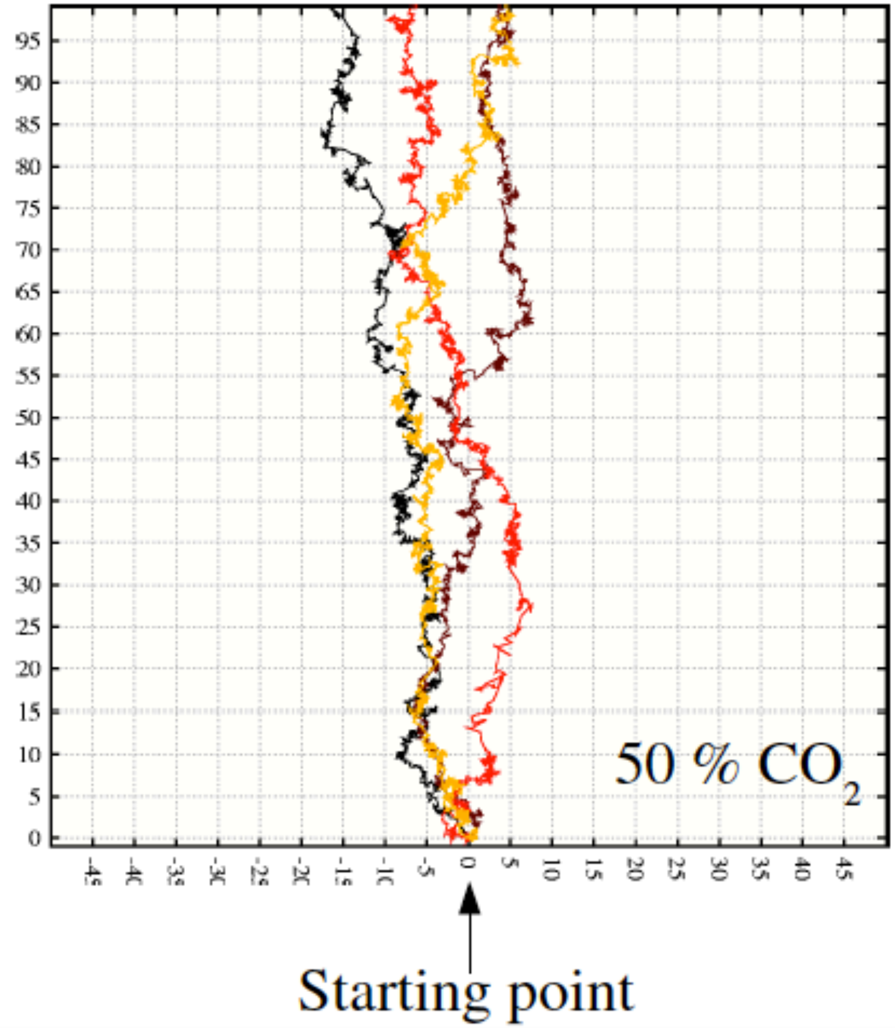


Electrons in Ar/CO2 at E=1 kV/cm



Electrons in Ar/CO2 at E=1 kV/cm

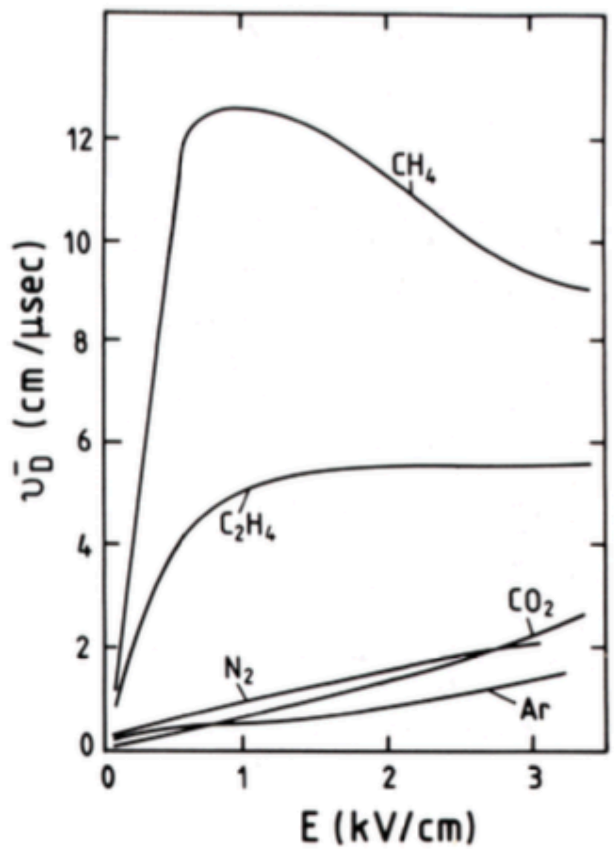




Drift in Electric Field

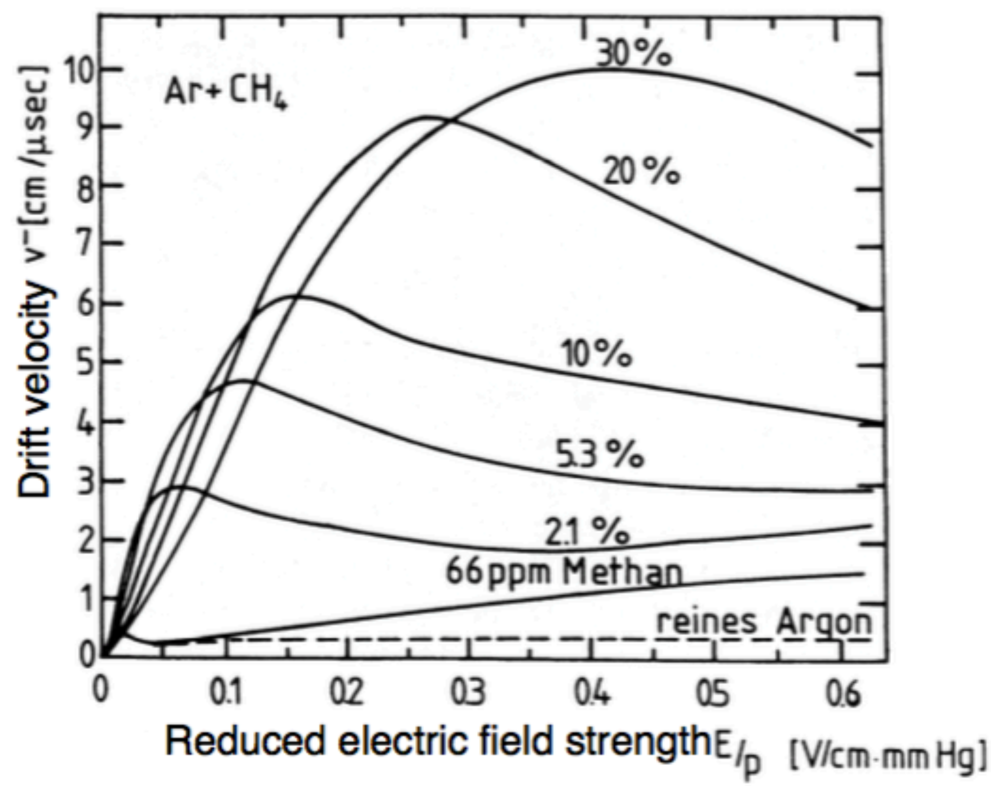
$v_D = \mu E$

Drift velocity of electrons for different gases (STP):



K. Kleinknecht, *Detektoren für Teilchenstrahlung*, B.G. Teubner, 1992

Drift velocity of electrons for various Argon Methan gas mixtures:



C. Grupen, *Teilchendetektoren*, B.I. Wissenschaftsverlag, 1993

Electron motion in B-fields

Langevin equation

instantaneous velocity v

stochastic, time dependent term Q due to **collisions with the gas atoms** (stopping force)

$$m\frac{d\vec{v}}{dt} = e\vec{E} + e(\vec{v}\times\vec{B}) + \vec{Q}(t)$$

- Assume:
  - collision time τ
  - E and B constant between collisions
- The drift velocity will adjust itself in such a way that the stopping force cancels the force due to EM fields → resulting acceleration will be 0.
  - Q(t) = mA(t)
  - take Δt ≫ τ (average) → Q(t) is a friction term = − m*($\mathbf{v_D}$/τ) (Stokes type)
- Thus →

$$0 = q(\vec{E} + \vec{v}_D \times \vec{B}) - m\frac{v_D}{\tau}$$

Solution →

Diffusion and Drift Influence of an external magnetic field

Magnetic fields modify the flight path of the charge carriers. In addition to the drift direction following the electric field lines, the Lorentz force forces the charge carriers between two collisions onto circular or spiral trajectories.

The mean drift velocity v_D becomes:

$$\vec{v}_D = \frac{\mu}{1+\omega^2\tau^2} \cdot \left(\vec{E} + \frac{\vec{E} \times \vec{B}}{B}\omega\tau + \frac{(\vec{E}\cdot\vec{B})\cdot\vec{B}}{B^2}\omega^2\tau^2 \right)$$

E … external electric field

μ … mobility of charge carriers, $\mu = \tau \cdot q/m$

q, m … charge, mass of charge carriers

B … external magnetic field

ω … cyclotron frequency, $\omega = B \cdot q/m$

τ … mean time between collisions

Special case that electric and magnetic field are perpendicular:

The effect of the B-field is a net reduction of the magnitude of drift velocity

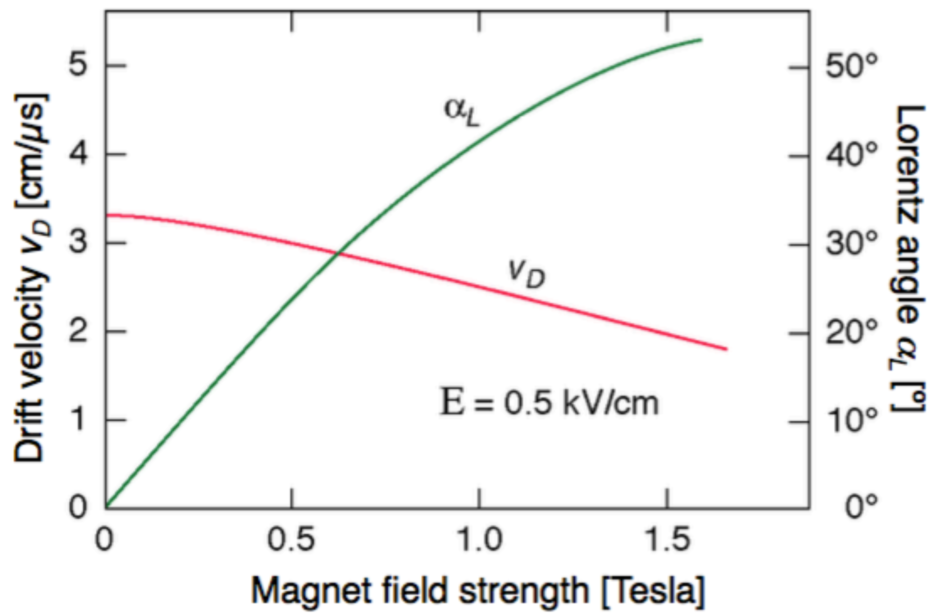
$$v_D = |\vec{v}_D| = \frac{\mu E}{\sqrt{1+\omega^2\tau^2}} \quad \text{for } \vec{E} \perp \vec{B}$$

Lorentz angle

- The most important effect of the B-filed is the **change in the direction of the eletron trajectory.**
- The Lorentz angle is the angle between the direction of the **electric field** and the drift direction of **electrons** under the influence of the **magnetic field.**
- In the case of perpendicular electric and magnetic fields, the Lorentz angle is:

$$\tan \alpha_L = \omega\tau = v_D \frac{B}{E}$$

v_D and α_L in a gas mixture of Argon (67.2%), Isobutane (30.3%) und Methylal (2.5%) for perpendicular E and B fields:



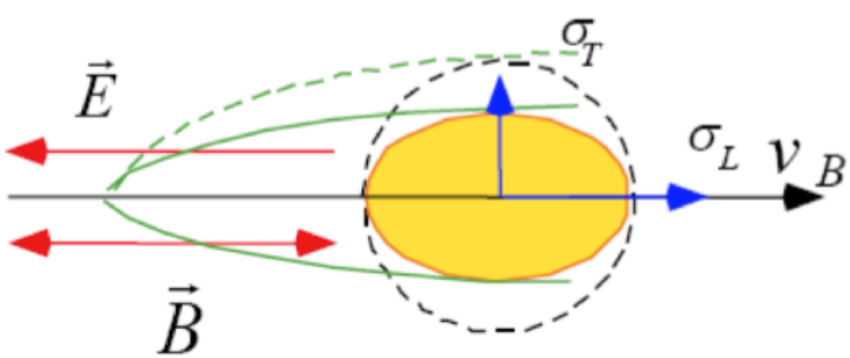
Original from C. Grupen, *Teilchendetektoren*, B.I. Wissenschaftsverlag, 1993

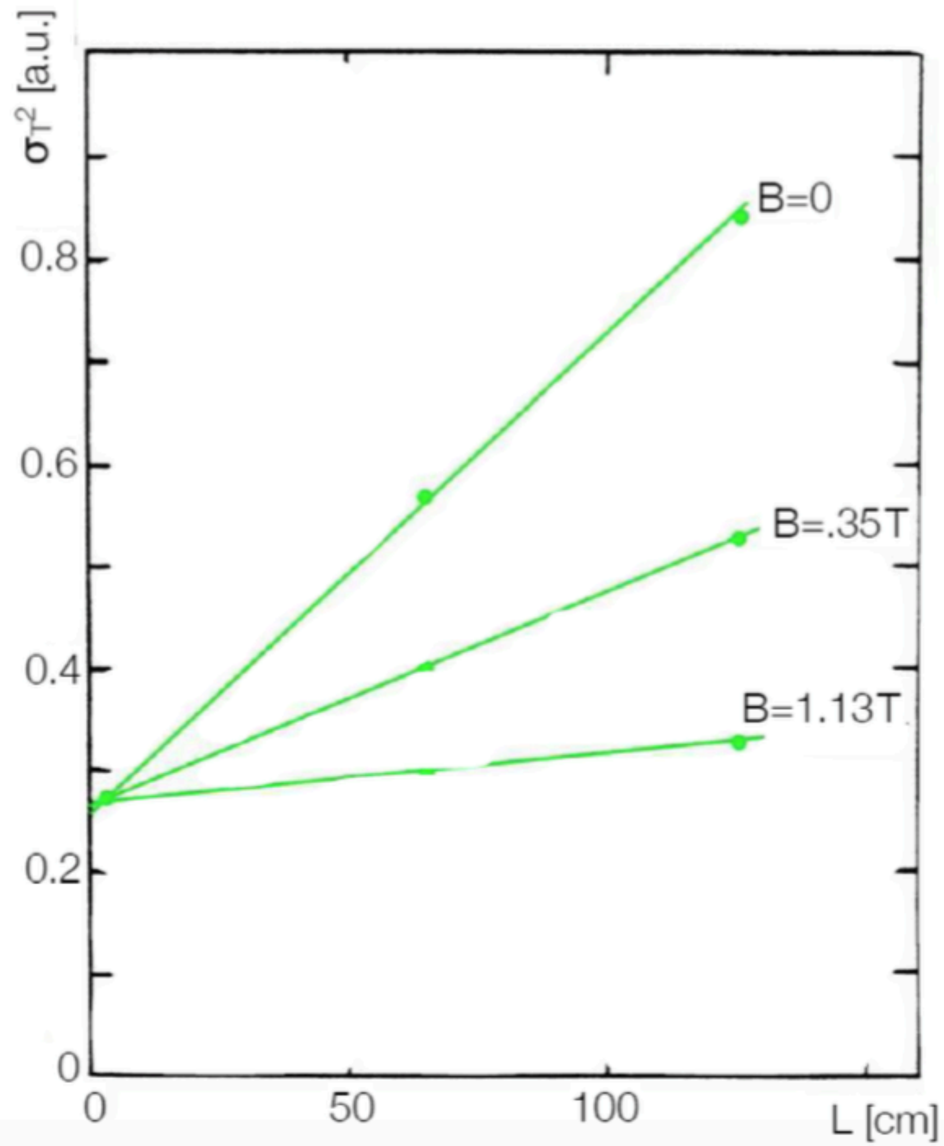
Diffusion in B field

- Different effects on longitudinal and transverse diffusion.
- Magnetic fields will **decrease diffusion perpendicular to field direction** by "curling down" thermal velocities : For B along z we have :

$$D_Z = D \quad ; D_X = D_Y = \frac{D}{1+\omega^2\tau^2}$$

- In practice we would like to decrease diffusion perpendicular to E → this results in choice of B parallel to E for drift detectors, whenever possible





Electron Loss

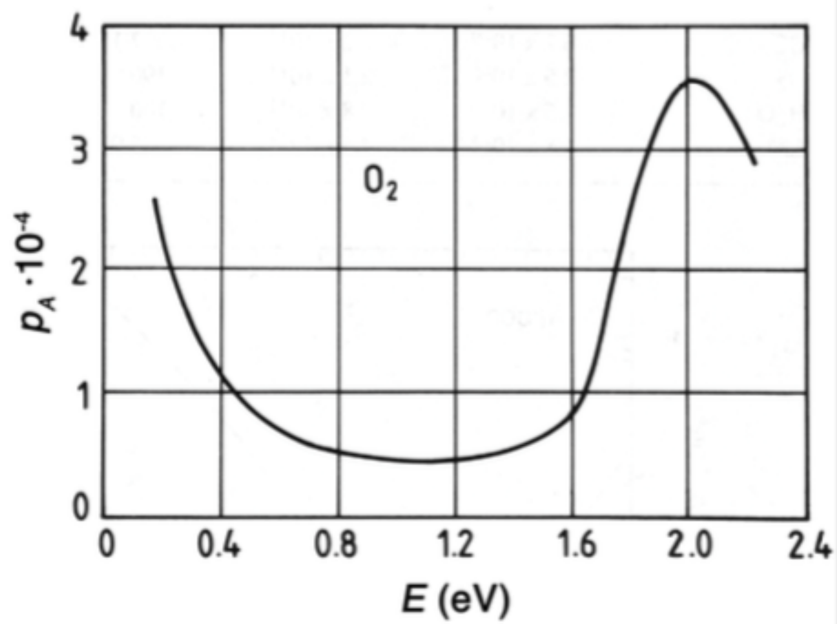
Electrons (but also ions) can be neutralized before detected via:

- **Recombination** of ions and electrons Depends on number of charge carriers and recombination coefficient.
  - Generally not too significant

- **Electron Attachment**
  - Electrons with energies in the eV range may become attached to gas atoms. The probability for electron attachment is called the **attachment coefficient**.
  - This effect is negligible for noble gases, N2, H2 and CH4.
  - Needs to be considered for **electronegative gases** such as O_2, Cl_2, NH_3 und H_2O.
  - **Already small impurities (per mill) of electronegative gases cause strong deterioration of the detector performance! →Leaking detectors!**
  - electro-negative gas molecules (O2, Freon, ...) bind electrons: $e^- + M \rightarrow M^-$

    or $e^- + XY \rightarrow X + Y^-$

Attachment coefficient of Oxygen for electrons as function of the energy (Minimum at 1 eV → Ramsauer effect):



K. Kleinknecht, *Detektoren für Teilchenstrahlung*, B.G. Teubner, 1992