Chapter VIII:
Detectors based in ionization in gases

Content

- General principles of a gas detector
- Transport of charges in a gas
- Ionization chamber
- Proportional counter
- Geiger counter

General principles

- A charged particle passes through a gas → creates both excited and ionized molecules along its path
- When a neutral molecule is ionized → the resulting positive ion and free electron are called an ion pair
- The number N_i of ion pairs is

$$N_i = \frac{E_{abs}}{W}$$

- Without collection mechanism → they diffuse uniformly → they suffer multiple collisions with the gas molecules → they lose their energy → they come quickly into thermal equilibrium → they recombine

General principles (2)

- With an electric field between two electrodes → + and - charges are accelerated along field lines towards electrodes
- This acceleration is interrupted by collisions with the gas molecules → electrons and ions completely change direction → the average drift velocity of the charge in the direction of the field backs to zero
- After the collision → the charge is again accelerated in the direction of the electric field
- At the microscopic scale the movement is quite chaotic, but at the macroscopic level, the charges drift with constant velocity in the direction of the electric field → a diffusion component is superimposed on the uniform drift velocity
- It results a signal that must be measured

Example

Consider W ≈ 30 eV

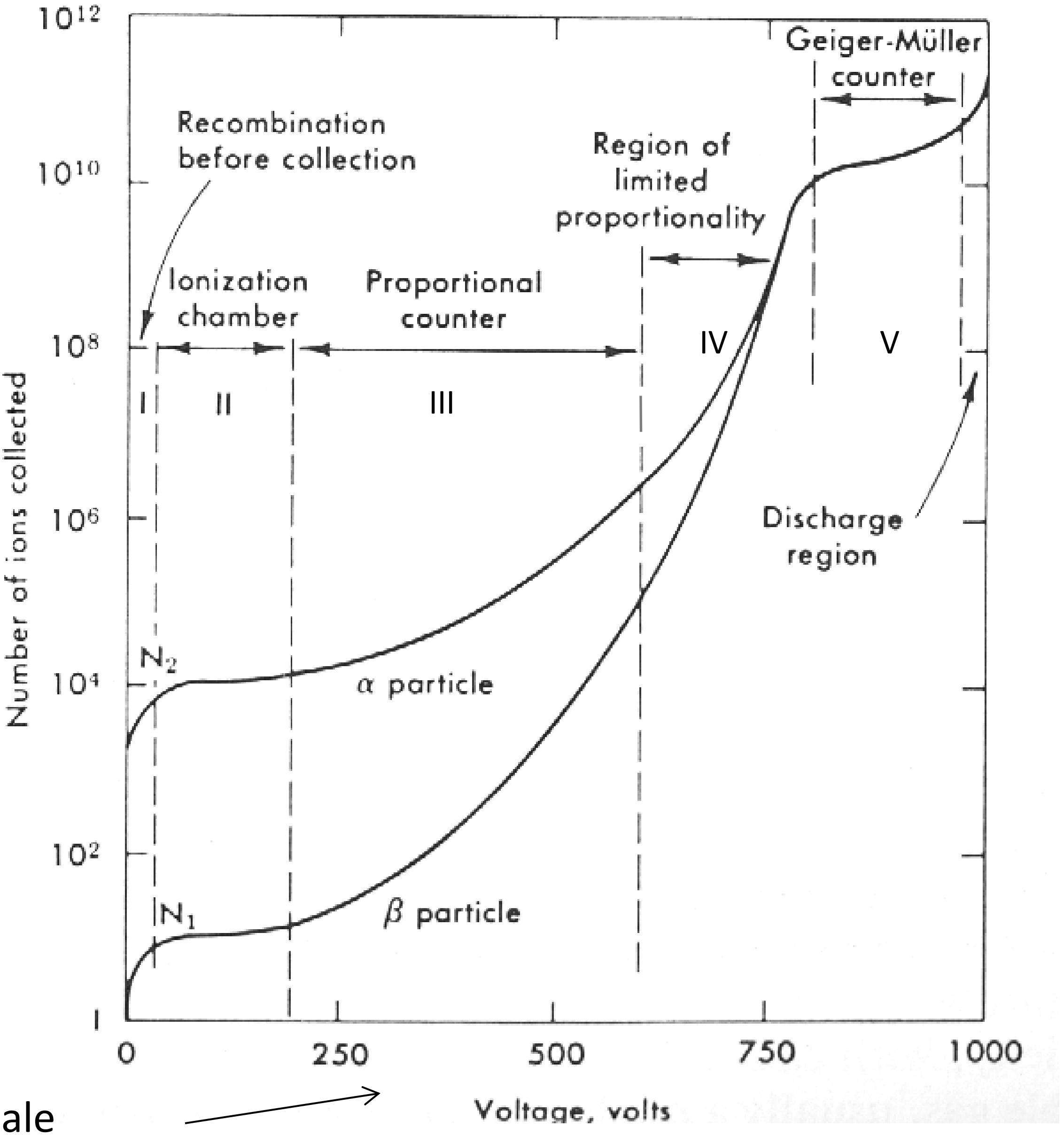
→ 1 MeV particle creates about 30 000 ions pairs

→ it corresponds to a collected charge of 5 10^{-15} C

→ for a detector with a standard capacitance of 30 pF

→ the amplitude of the signal is about 0.15 mV

Dependence on the field intensity



Arbitrary voltage scale

Region I

- At zero voltage, no charge collected due to the recombination

- As voltage ↗ the recombination forces are overcome and the current ↗ ↔ More and more of electron-ion pairs are collected before they can recombine

- Not used in practical applications

Region II

- At some voltage → all created charges are collected → further voltage increase has no effect
- A detector working in this region collects the ionization produced directly by the passing radiation ↔ it is called an **ionization chamber**
- The signal current is very small → ionization chambers are generally used for gamma ray exposure or as monitoring instruments for large fluxes of irradiation
- They are usually used in current mode

Region III

- If voltage ↗ current again ↗ ↔ the electric field is strong enough to accelerate freed electrons to an energy where they are also capable to ionize gas molecules → these electrons ionized in these secondary step then accelerate to produce still more ionizations and so on → cascade or avalanche
- The number of pairs in the avalanche is directly proportional to the number of primary electrons → amplification of the current (the multiplication factor depends on the voltage)
- Detectors in this region are known as **proportional counters**

Vocabulary remark

- Attention to terms « primary » and « secondary »
- Primary ionization is ionization produced by the incident particle and by all secondary particles set in motion
- Secondary ionization is ionization produced by secondary particles due to the supplementary energy supplied by the electric field

Region IV

- As voltage ↗ again → ionizations created during the cascade so large that space charge distorts the electric field at the anode → proportionality is lost

- Region of limited proportionality → no detectors are working within this region

Region V

- As voltage ↗ again → energy becomes so large that discharge occurs in gas
- This discharge is maintained by ultraviolet radiations emitted by deexciting molecules
- These radiations create further ionizations → the output current becomes completely saturated (always the same amplitude regardless of the energy of the initial event)
- Detectors working in this region are **Geiger-Müller counters** (or simply **Geiger counters**)
- This region IV is characterized by a plateau over which the count rate varies little

Beyond region V

- If voltage ↗ more → continuous breakdown occurs with or without external radiation

- This region is avoided to prevent damage to the counter

Caution

It does not exist a «general» detector that can work for all voltage regions ↔ each type of gas detector has its own characteristics, geometry, type of gas,…

General properties of charge transport in gas

- Diffusion

- Charge modification

- Electron and ion transport

Diffusion in a gas at equilibrium (1)

- Neutral atoms or molecules of a gas are in constant thermal motion
- Distribution of velocities is the Maxwell-Boltzmann distribution:

$$f(\vec{v})d\vec{v} = \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-mv^2/2kT\right)d\vec{v}$$

k = 1.38 10^{-23} JK^{-1} , Boltzmann's constant, T, the temperature (K), m: mass of the gas particle

➡ The Mean velocity: $\langle v \rangle = \sqrt{\frac{8kT}{\pi m}}$

Diffusion in a gas at equilibrium (2)

- e^- have small mass → diffusion is thus more pronounced → at room temperature: $\langle v_{e-} \rangle \approx 10^5$ m/s

- For Ar ions for instance velocity is about 370 m/s → generally factor 100 - 1000 of difference

Cross section and mean free path (1)

- In an ideal gas of one molecules species → determination of the probability per time unit (τ^{-1}) for a gas molecule to have one collision with another molecule (by assuming a constant cross section of collision σ_0) →

  $$\tau^{-1} = \langle v_r \rangle \sigma_0 N$$

  with N, the density of particles and $\langle v_r \rangle$, the relative velocity between 2 particles

- Between 2 particles A and B →

  $$\overrightarrow{v}_r = \overrightarrow{v}_A - \overrightarrow{v}_B \Rightarrow \langle v_r^2 \rangle = \langle v_A^2 + v_B^2 - 2\overrightarrow{v}_A \overrightarrow{v}_B \rangle$$

  and as the directions of the velocities are arbitrary → the scalar product is zero and $\langle v_r \rangle = \sqrt{2} \langle v \rangle$

Cross section and mean free path (2)

- For normal conditions of temperature and pressure (NTP) i.e. $T = 273.15$ K and $p = 101325$ Pa → $N = N_L = 2.687 \times 10^{25}$ m^{-3} (number of Loschmidt → $N_L = N_A/V^*$ with $V^* = 22.41$ m^{3}mol^{-1}, the molar volume of an ideal gas)
- The time τ is the mean time interval between 2 collisions for a molecule in a gas at thermodynamic equilibrium
- If the equilibrium is momentarily disturbed → it recovered after the relaxation time which depends on τ (the exchanges of energy and momentum during these collisions allow the equipartition of the total energy and the return at the thermal equilibrium)

Cross section and mean free path (3)

- It is possible to calculate the mean free path λ → mean distance between 2 collisions for a molecule in the gas →

$$\lambda = \langle v \rangle \tau = \frac{1}{\sqrt{2}\sigma_0 N}$$

- λ depends on the density (and thus on pressure) via *N*
- Example → molecule = rigid sphere with radius *d* → $\sigma_0 = \pi d^2$ → for Ar: *d*(Ar) = 3.7×10^{-10} m → σ_0(Ar) = 4.3×10^{-19} m^2 and $\langle v_{Ar} \rangle$ = 370 m/s → τ(Ar) = 1.65×10^{-10} s and λ(Ar) = 6.12×10^{-8} m ≈ 165 *d*(Ar) → at atomic scale collisions are relatively not very frequent

Remarks on previous relations

- If pressure ↘ → free path ↗ (for p ≈ 1 Pa → λ ≈ 1cm) → the collisions of a molecule with the walls are as frequent as collisions with the other molecules
- For an extremely weak pressure → the collisions with the walls dominate → ultra-high-vacuum and previous relations have no more sense
- If the pressure is very high → it is necessary to take into account the interactions between more than 2 molecules at once
- At atmospheric pressure → the collisions with the walls and between more than 2 molecules can be ignored

Diffusion without electric field (1)

- Without electric field → electrons and ions created in the gas interact with molecules of the gas → they give energy up → they are finally thermalized with a kinetic energy ≈ $kT \approx 0.025$ eV
- A charge distribution N_0 initially localized at the origin diffuse due to collisions with gas molecules as a Gaussian distribution
- At 3D →

$$dN(\overrightarrow{r}) = \frac{N_0}{(4\pi Dt)^{3/2}} \exp\left(-\frac{r^2}{4Dt}\right) d\overrightarrow{r}$$

with D (unit: m^2s^{-1}), the diffusion coefficient depending on the charge, on the gas, on T,…

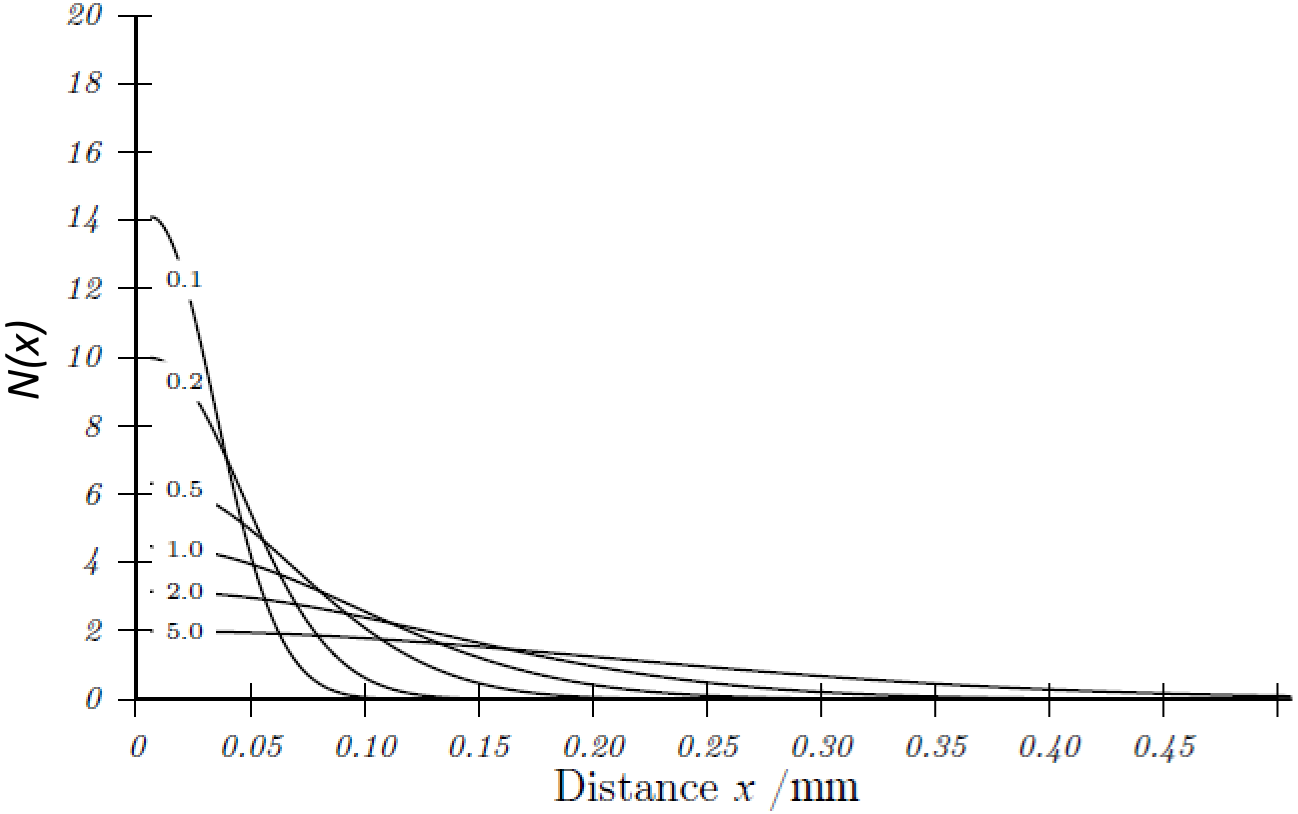
Diffusion without electric field (2)

- At 1D →

$$dN(x) = \frac{N_0}{(4\pi Dt)^{1/2}} \exp\left(-\frac{x^2}{4Dt}\right) dx$$

- This distribution is characterized by a variance $\sigma^2 = 2Dt$ → ↗ for t ↗

Diffusion without electric field (3)



N(x) for Ar^+ characterized by *D* = 4 mm^2s^{-1} for ≠ values of *t* (in ms)

Transport of particles

- If an electric field is applied → ions and electrons move to cathode and anode, respectively

- This drift motion is superimposed to the thermal motion

- The ions and electrons undergo collisions with molecules of the gas → it is necessary to separate the case of electrons having a small mass and the case of ions having a mass comparable to the mass of the molecules

Transport of electrons (1)

- Collision electron - molecule → large ≠ of mass → diffusion of the electron in all directions in a quasi-isotropic way → it loses the memory of its initial direction
- Calculation of the drift velocity u of the electrons in an electric field E → we consider an interaction in which the electron receives a velocity $\overrightarrow{v}_0$ → just before the next collision (time interval t_c between 2 collisions) its instantaneous velocity is:

$$\overrightarrow{v} = \overrightarrow{v}_0 - \frac{eE}{m} t_c$$

- As the diffusion is isotropic → the mean value of $\overrightarrow{v}_0$ is zero and the amplitude of the drift velocity $u = \langle v \rangle$ is

$$u = \frac{eE}{m} \tau$$

Transport of electrons (2)

- On average the energy provided by the electric field is compensated by the energy lost during collisions (in excitation or recoil energy form) → stationary state is reached
- Along a drift distance *x* → the electron has $x/(u\tau)$ collisions → at each collision it loses a fraction γ of the energy ϵ given by the field
- We have the energy balance →

$$\frac{x}{u\tau}\gamma\epsilon = eEx$$

Transport of electrons (3)

- By considering that the instantaneous velocity of the electrons is quite larger than the velocity of the atoms of the gas →

$$\epsilon = \frac{1}{2}mv^2 \quad \text{and} \quad \frac{1}{\tau} = N\sigma_0 v$$

- We eliminate τ and ϵ from the equations →

$$uv = \frac{eE}{mN\sigma_0} \quad \text{and} \quad \frac{1}{2}mv^2 = \frac{eEu}{N\sigma_0\gamma v}$$

- We get the expressions of u^2 and v^2 →

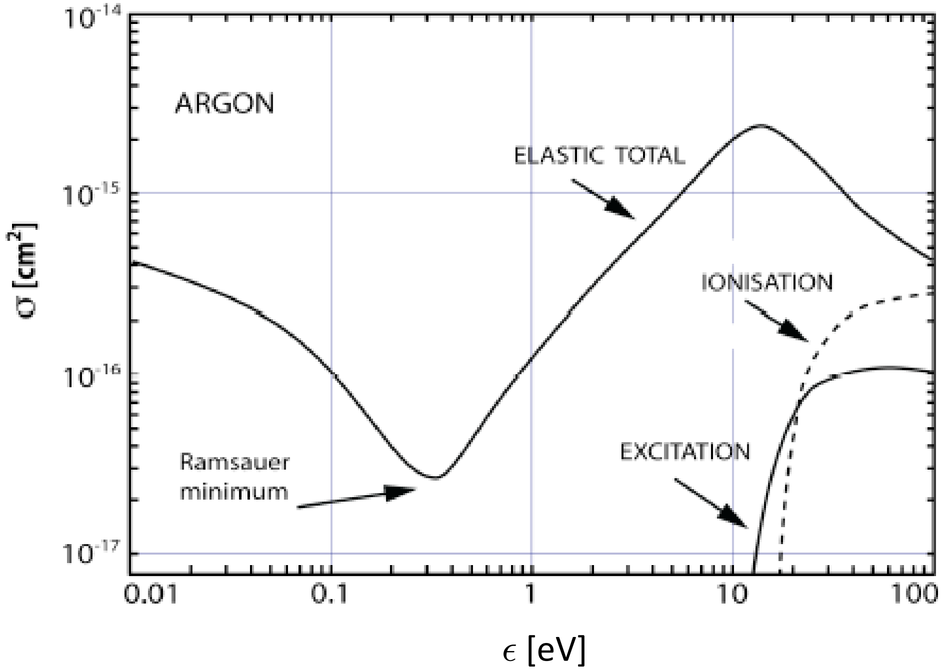
$$u^2 = \frac{eE}{mN\sigma_0}\sqrt{\frac{\gamma}{2}} \quad \text{and} \quad v^2 = \frac{eE}{mN\sigma_0}\sqrt{\frac{2}{\gamma}}$$

Transport of electrons (4)

- We notice that the drift velocity is a function depending on the ratio E/N i.e. a function of the ratio E/p (called reduced electric field) when temperature is fixed

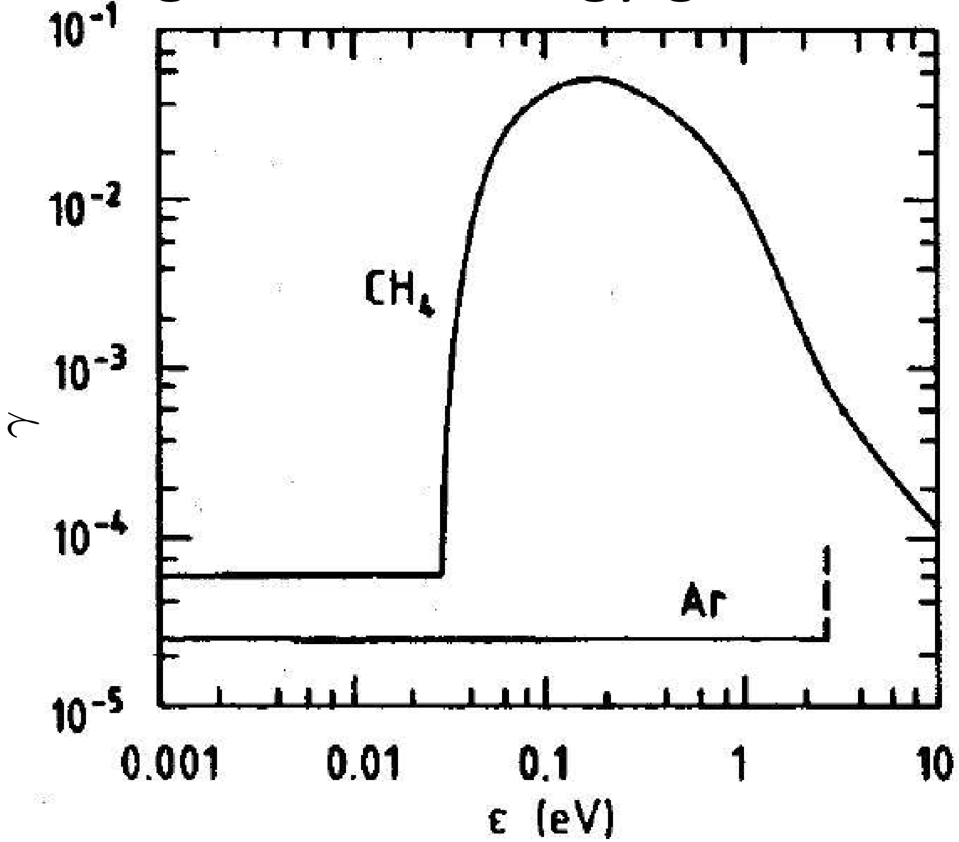
- The 2 quantities σ_0 and γ depend on ϵ and thus on E

Ramsauer-Townsend effect



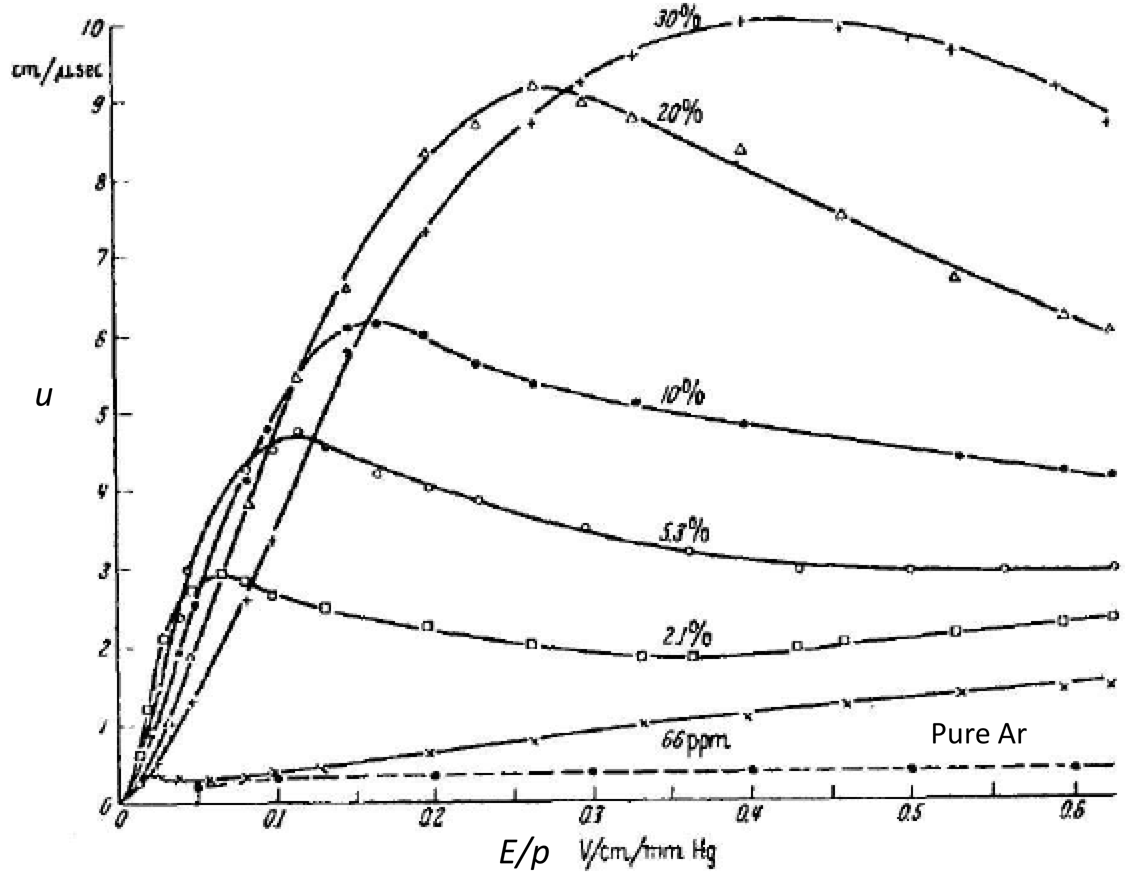
- For energies < the excitation energy→ interaction of the e^- with the nucleus → small energy losses
- Classical theory → σ_0 ↘ for ϵ ↗
- Observation of a minimum and afterwards σ_0 ↗ for ϵ ↗
- Quantum mechanics → the atom is considered as a potential well

Percentage of the energy given in 1 collision



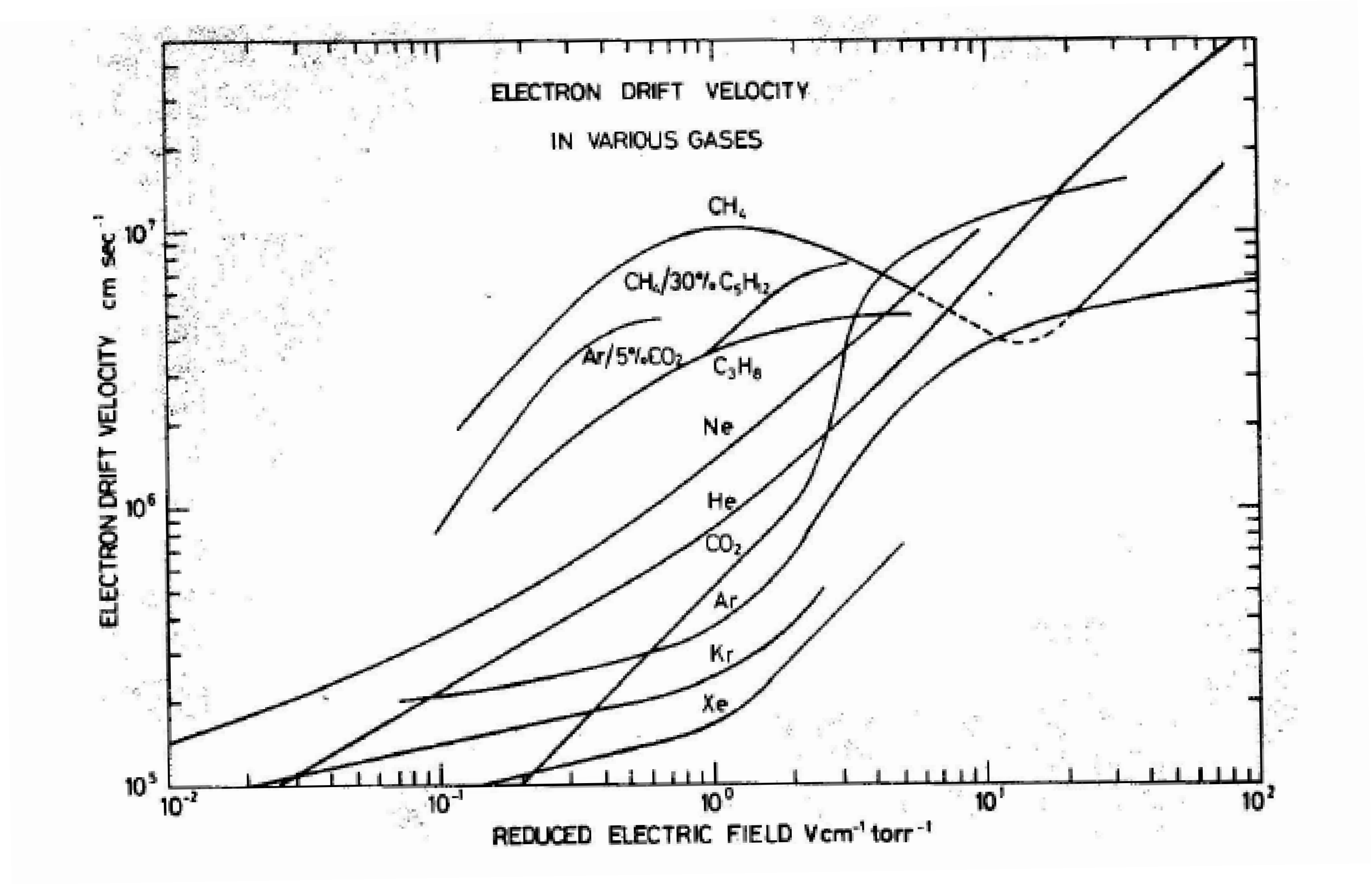
- For small E → small γ (≈ 10^{-4}) → small drift velocity
- From an energy equal to the minimal excitation energy (*I*) → fast increase of the energy losses
- As *I* varies a lot from one gas to another → *u* depends a lot on the exact composition of the gas mixture

Examples of drift velocities for ≠ gas mixtures



Argon with added CH_4

Typical drift velocities for e$^-$ in gases



Typical drift velocity ≈ 10^4 m/s → comparable to the mean velocity of electrons at thermodynamic equilibrium ≈ 10^5 m/s

Transport of ions (1)

- An ion (with mass M_i) can lose more and more energy after each collision with a molecule (with mass M_m)
- An ion is not isotropically scattered → it partially remember its trajectory before the collision → the calculation of the drift velocity is more complicated than for electrons
- « It is possible to show that » →

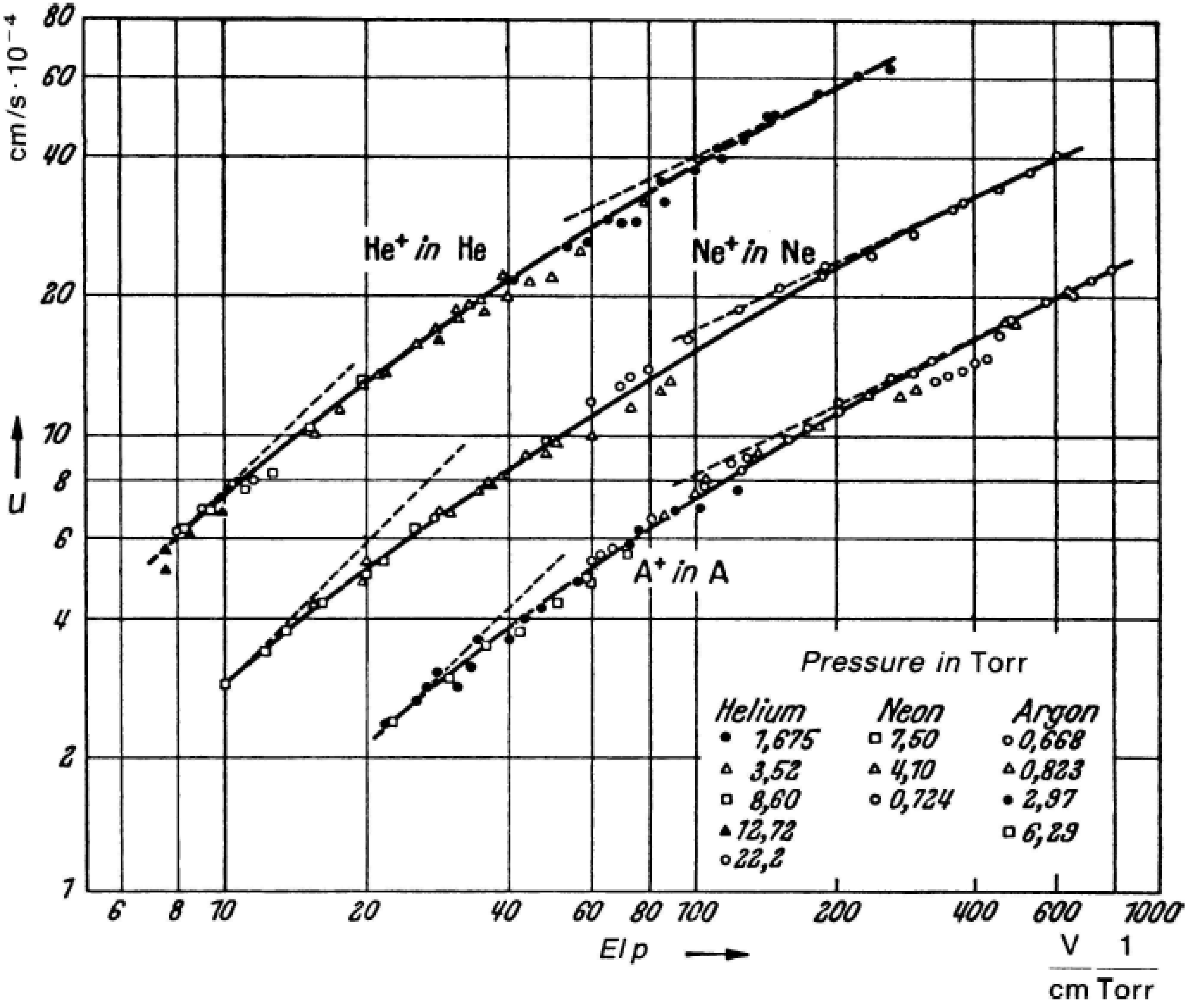
$$\begin{cases} u = \left(\dfrac{1}{3 M_{im} k T} \right)^{1/2} \dfrac{eE}{N \sigma_0} & \text{for small E} \\ u = \left(\dfrac{M_i}{M_m} \dfrac{eE}{M_{im} N \sigma_0} \right)^{1/2} & \text{for large E} \end{cases}$$

with the reduced mass $M_{im} = M_i M_m / (M_i + M_m)$

Transport of ions (2)

- We notice again that the drift velocity is a function of *E/N* or equivalently of *E/p* → $u \propto E/P$ for small *E* and $u \propto (E/P)^{1/2}$ for large *E*
- Typically → $u \approx$ 1-10 m/s
- We have thus $u_{ion} \ll u_{élec}$
- And also u_{ion} < mean velocity of the electrons at thermodynamic equilibrium

Transport of ions (3)



Mobility (1)

- The notion of mobility μ of the ions is often introduced →

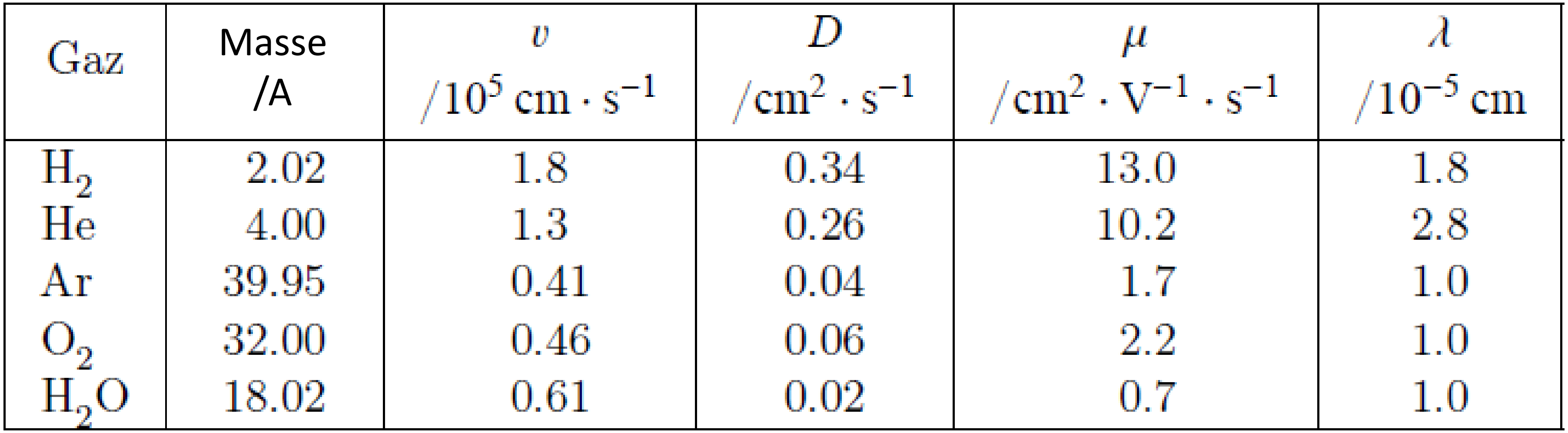
$$u = \mu E$$

- At weak fields → μ is independent on *E* (because *u* $\propto$ *E/P*) and $\mu \propto$ *P* → at *P* constant → μ is constant
- At large fields → the mobility depends on the electric field
- The mobility is bound to the diffusion coefficient by the formula of Einstein →

$$D/\mu = kT/e$$

- Typical value for μ → ≈ 10^{-4} $m^2/(Vs)$

Mobility (2)

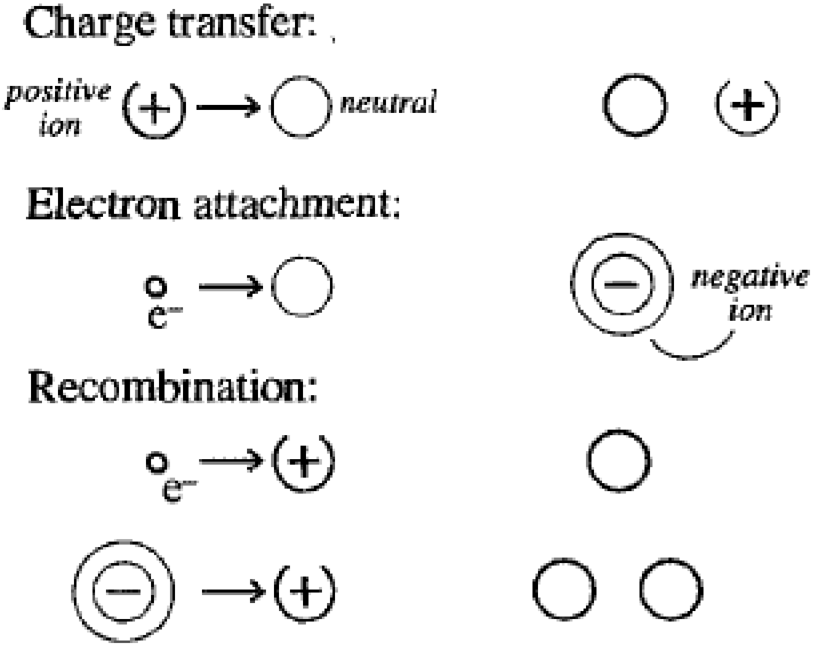


Gaz	Masse /A	v $/10^5\ \mathrm{cm \cdot s^{-1}}$	D $/\mathrm{cm^2 \cdot s^{-1}}$	μ $/\mathrm{cm^2 \cdot V^{-1} \cdot s^{-1}}$	λ $/10^{-5}\ \mathrm{cm}$
H_2	2.02	1.8	0.34	13.0	1.8
He	4.00	1.3	0.26	10.2	2.8
Ar	39.95	0.41	0.04	1.7	1.0
O_2	32.00	0.46	0.06	2.2	1.0
H_2O	18.02	0.61	0.02	0.7	1.0

Mass, thermal velocity, diffusion coefficient, mobility and mean free path for ≠ gases

Modification of the charge inside the gas

- Ions and electrons undergo collisions which lead to the neutralization of the ion (recombination) and to the capture of the electron by a neutral molecule (attachment)
- The ion can also exchange its charge with a neutral atom (charge transfer) → roles inversion



Recombination

Definition of a recombination collision rate *R* ($m^{-3}s^{-1}$) and of a recombination coefficient α (m^3s^{-1}) such as:

$$R = -\frac{dn^+}{dt} = -\frac{dn^-}{dt} = \alpha n^+ n^-$$

with n^+ and n^-, the volume densities of charge

Types of recombination

- Columnar (or initial) recombination: ion pairs are formed into a column along the track of the ionizing particle → density of pairs is high along the track until pairs diffuse → columnar recombination is most severe for densely ionizing particles (as α) compared to electrons that deposit their energy over a much longer track → independent on the irradiation rate

- Volume recombination: due to encounters between ions and/or electrons after they left the location of the track → since ions slowly drift to electrodes → ions and/or electrons from independent tracks can recombine → increases with irradiation rate

Attachment

- An e^- created during an ionization can be fixed (attached) by a neutral atom of the gas → negative ion
- This phenomenon strongly depends on the type of gas
- Attachment occurs for electronegative gases (halogen compounds, O_2 – and thus air)
- On the contrary attachment is weak for of nitrogen, hydrogen, hydrocarbon gases and noble gases

Ionization chamber

- Ionization chamber is the simplest gas detector → collection of all charges created by direct ionization
- Constituted by 2 electrodes (anode and cathode) with an applied difference of potential U_0 → condenser
- The ionizing particle crosses space between the 2 electrodes and produces ion–electron pairs in the gas
- Charges move due to the electric field present between the electrodes → electron migrate to the anode and ion to the cathode
- Negative charges are finally collected by the anode and positive charges by the cathode
- Attention → drift velocity of electrons is 10^3 - 10^4 times larger than the drift velocity of ions

Operation of ionization chamber (1)

- Most of the time → ionization chamber Is used in current mode
- The measured currents are usually extremely weak (≈ 10^{-12} A) → without precautions, the leakage current can be largely more important than the ionization current
- Perfectly adapted as monitor (instantaneous measurements of dose rate) for the detection of X- and γ- rays with high rate (due to efficiency generally < 10% - see attenuation coefficients of photons)
- With a thin entrance window → possibility of detection of α and β particles → in this case efficiency can reach 100% (see particles ranges)
- In some conditions → neutrons detection

Operation of ionization chamber (2)

- An ionization chamber is a well-suited device to measure **gamma ray exposure** (symbol: X) of γ or X-rays
- *X* (unit: Ckg^{-1}) → quotient of *dQ* by *dm* with *dQ* the absolute value of the charge of all ions (of one sign) produced in *air* when all e^- and e^+ liberated or created by X-rays or γ in a volume *dV* of air (with mass *dm*) are stopped in air →

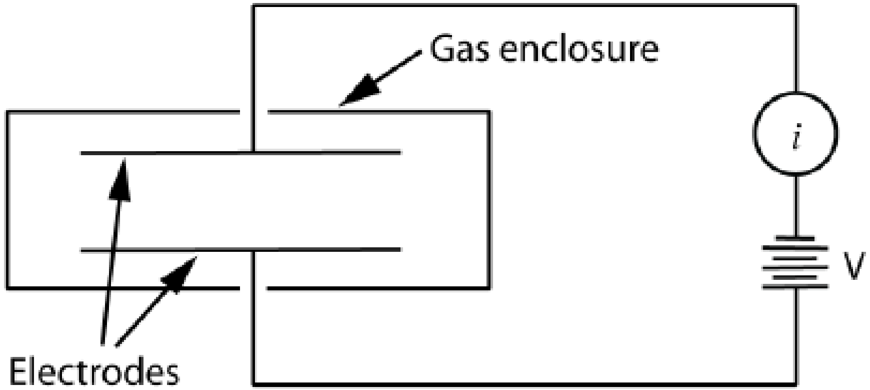
$$X = \frac{dQ}{dm}$$

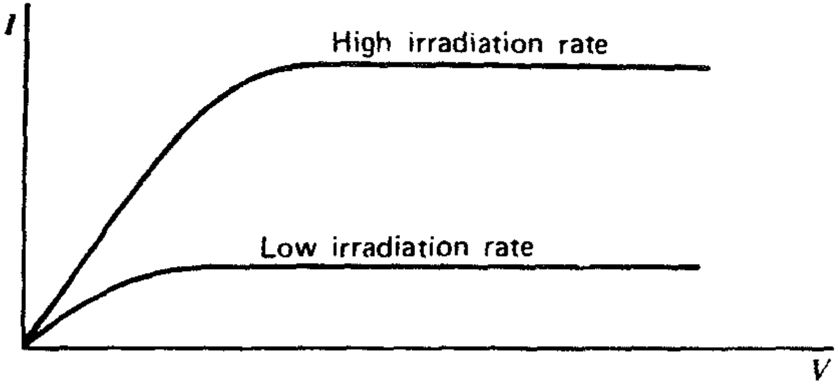
- Exposure → the measure of the ionization produced in <u>air</u> by <u>X-rays</u> or <u>gamma rays</u>

Operation of ionization chamber (3)

- It is possible to collect negative charges as free electron or as negative ions
- Consequently → virtually all types of gases can be used in an ionization chamber, including gases characterized by a high electron attachment (as oxygen)

Scheme of an ionization chamber in current mode





Ionization chamber and electrodes are unavoidably made of some suitable solid material → to limit perturbation, the electrodes are made in aluminium and the detector walls in plastic (the more equivalent materials)

Geometrical configurations of an ionization chamber (1)

- The ionization chambers exist in ≠ geometrical configurations → ≠ distributions of the electric field *E* and ≠ values of the capacitance *C* of the detector
- These configurations can be summarized in 3 simple cases → plane and parallel electrodes, cylindrical coaxial electrodes or spherical concentric electrodes
  1. Plane electrodes of area *S* separated by a distance *d* → between the electrodes the field is uniform and perpendicular to the electrodes (with ϵ the permittivity of the gas) →

$$E = \frac{U_0}{d} \quad \text{and} \quad C = \epsilon \frac{S}{d}$$

Geometrical configurations of an ionization chamber (2)

2. Cylindrical electrodes of length *L* with the cathode (radius *b*) as external electrode and the anode (radius *a* < *b*) as internal electrode → the electric field is non-uniform → *E* is radial and only depends on the distance *r* to the axis of the detector →

$$E(r) = \frac{U_0}{r \ln(b/a)} \qquad C = \epsilon \frac{2\pi L}{\ln(b/a)}$$

$$E(r) = \frac{C/L}{2\pi\epsilon} \frac{U_0}{r} \qquad V(r) = U_0 \left(1 - \frac{\ln(r/a)}{\ln(b/a)}\right)$$

3. Spherical electrodes ques with the cathode (radius *b*) as external electrode and the anode (radius *a* < *b*) as internal electrode the electric field is non-uniform → *E* is radial and only depends on the distance *r* to the center of the detector →

$$E(r) = U_0 \frac{ab}{r^2(b-a)} \qquad C = \epsilon \frac{4\pi ab}{b-a}$$

$$E(r) = \frac{C}{4\pi\epsilon} \frac{U_0}{r^2} \qquad V(r) = U_0 \left(1 - \frac{1 - a/r}{1 - a/b}\right)$$

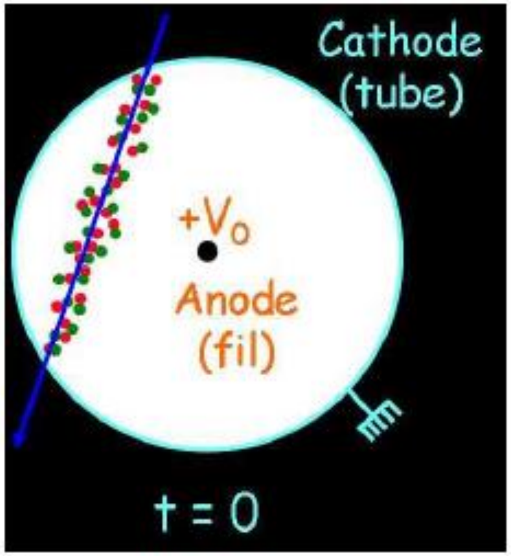
Charges collection (1)

1. The initial particle creates in a time < 10^{-7} s N_i ion-electron pairs (most of them have a kinetic energy < 10 eV)
2. The electrons and ions have collisions with the atoms of the gas inside the chamber (diffusion + recombination, attachment, charge transfer)
3. The ions and electrons are accelerated along a direction parallel to the electric field
4. At each collision → they tend to lose memory of the acceleration acquired before the collision (completely for the e^-, partially for the ions) → the path followed by the charge is thus a succession of collisions and accelerations

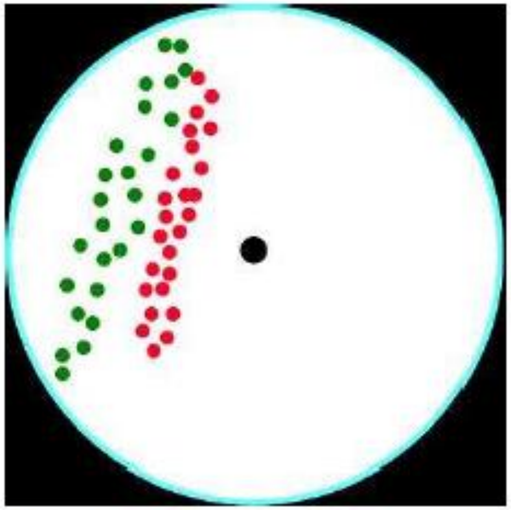
Charges collection (2)

5. The movement of charges is thus a combination of 2 processes: diffusion (due to collisions with atoms) and drift (due to electric field)
6. Due to the difference of mass → the drift velocity u_+ of the ions is much weaker than the drift velocity u_- of the electrons (an e^- crosses the detector in ≈ 1 μs and an ion in 1-10 ms)
7. During the drift → the charge and the potential of the condenser (constituted by the 2 electrodes) change up to complete collection of the charges
8. Remark → the signal appears immediately the electrons and the ions moves to the electrodes (before the collection of the charges) → it is induced by the positive et negative charges present inside the electrodes → little influence in current mode

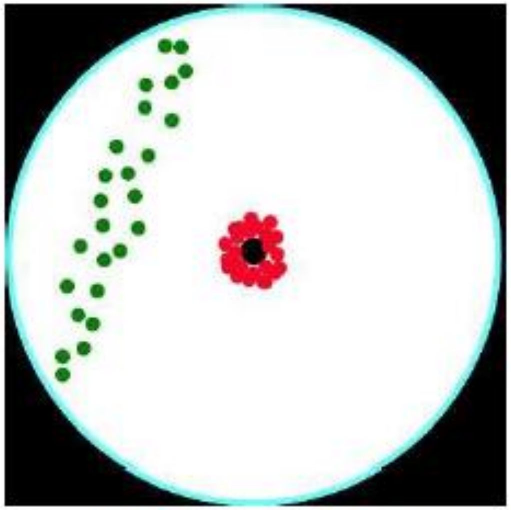
Charges collection: Illustration



(a) Paires ion–électron produites le long de la trajectoire de la particule inci-



(b) Les ions migrent plus lentement que les électrons.



(c) Tous les électrons sont arrivés à l'anode, les ions migrent encore.

Attention → for a non-electronegative gas → no attachment

Example of ionization chamber in current mode (1)

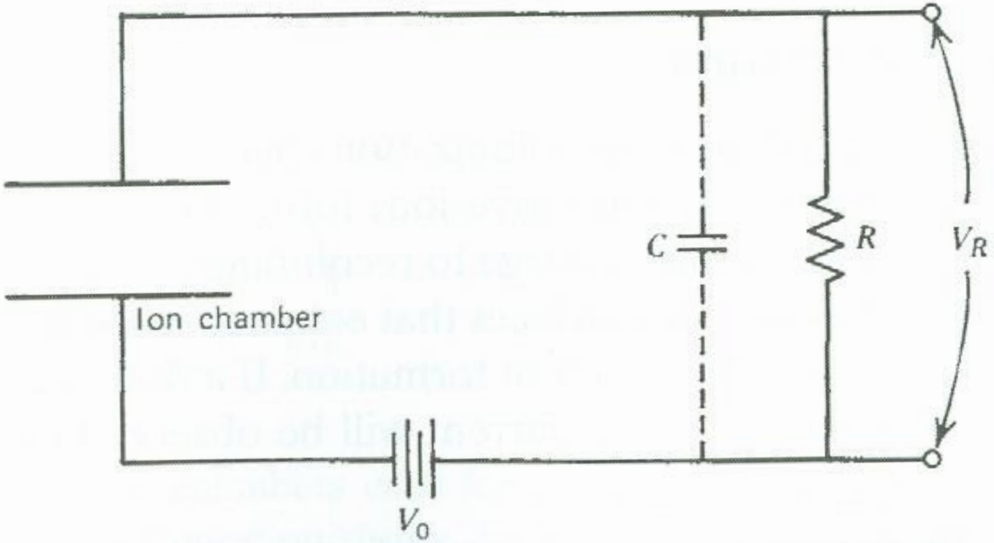
Ionization Chamber "Cutie Pie" manufactured by Nuclear Chicago

Example of ionization chamber in current mode (2)

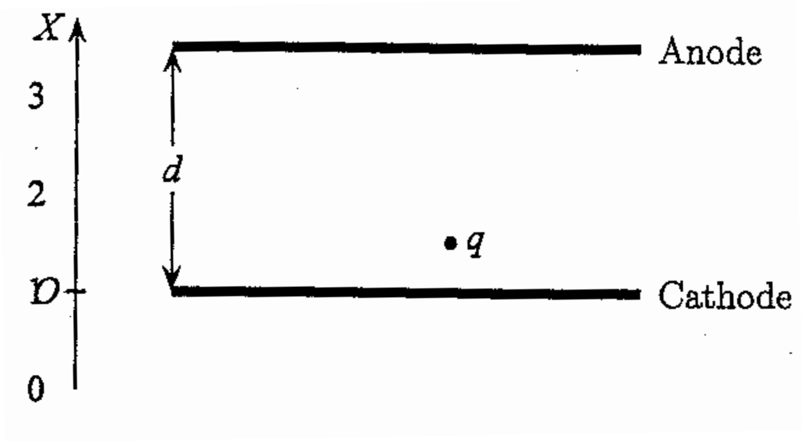
Ionization Chamber Model 451B manufactured by Fluke Biomedical

Pulse mode operation for an ionization chamber

Pulse mode ionization chambers are used to some extent in radiation spectroscopy (although they have largely been replaced by semiconductor diode detectors) and in some specialized applications as large-area alpha spectrometers or for neutron detection.



Pulse development in an ionization chamber (1)



- Let us consider a detector consisting of two parallel plates separated by distance d and enclosing a gas with low electron attachment coefficient → e^- is free → for a gas containing O_2 → a important part of the signal is due to O_2^- ions → signal shape ≠ of following treatment
- These two plates form a capacitor with a capacitance C
- A potential difference V_0 between the plates causes a constant and ⊥ electric field between them

Pulse development in an ionization chamber (2)

- One e^--ion pair is formed → electron and positive ion will drift towards the anode and cathode, respectively
- When an ion pair is created, each charge induces an image charge of same absolute value on the electrode → the signal thus appears from the pair formation and not only when charges are really collected by the electrodes
- e^- travels much faster than the positive ion → reaches the anode in a short time called T_-
- The movement of the positive ion is much slower → the positive ion lasts much longer: T_+
- The current pulse consists of two parts, one fast part from the e^- movement and one slow part from the movement of the positive ions.

Shockley-Ramo theorem

- To calculate the charge and the current development → use of the Shockley-Ramo theorem
- We assume there are *n* electrodes in the detector and we want to know the current i_k ($k = 1, 2, \ldots, n$) injected in one of these electrodes by the motion of a charge *q* somewhere between the electrodes.
- The current injected in this electrode is

$$i_k = \frac{dQ_k}{dt} = q\vec{u_q}\vec{E_k}$$

Q_k is the induced charge on the electrode k, $\vec{u_q} = u_q\vec{1_q}$ is the velocity of the charge q and $\vec{E_k}$ is the electric field at the point occupied by charge q when the electrode k is at 1 V potential and all other electrodes are set at zero potential

Pulse development in an ionization chamber (3)

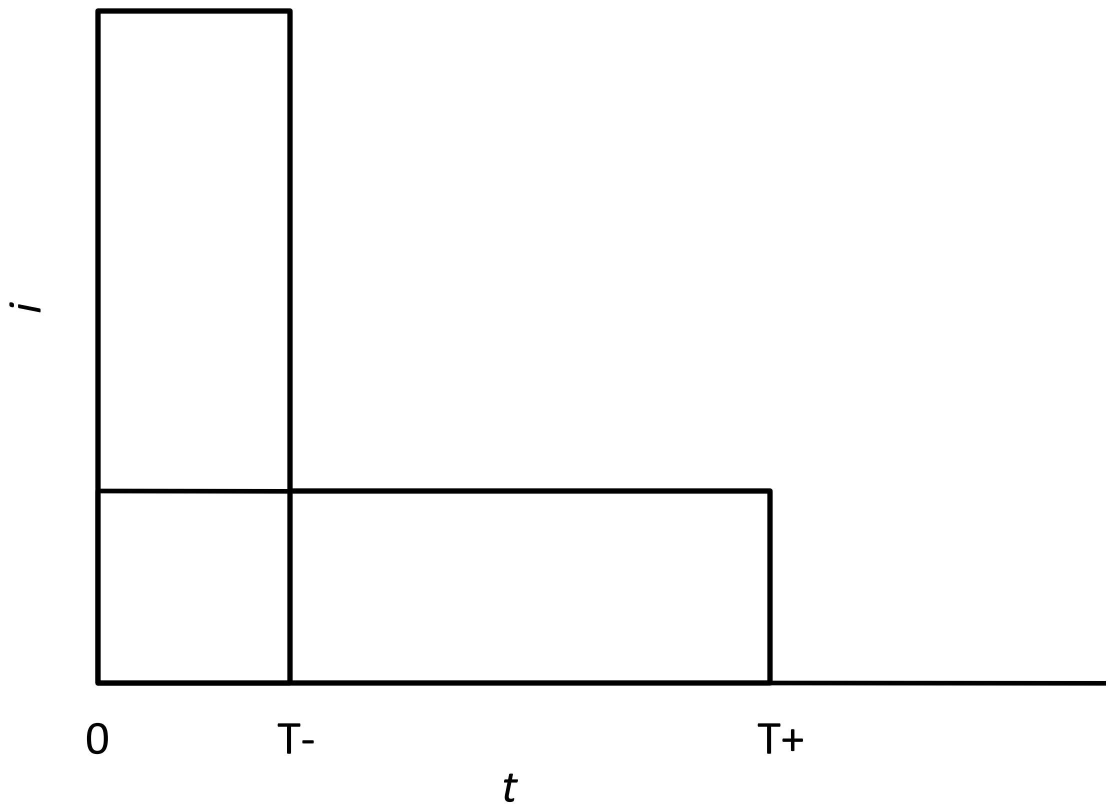
- We can now obtain current $i_a = i_- + i_+$ at the anode for an electron moving with velocity v_- to the anode and an ion moving with velocity v_+ to the cathode

$$i_- = -e\vec{u}_-\vec{E}_a = e\frac{u_-}{d}$$

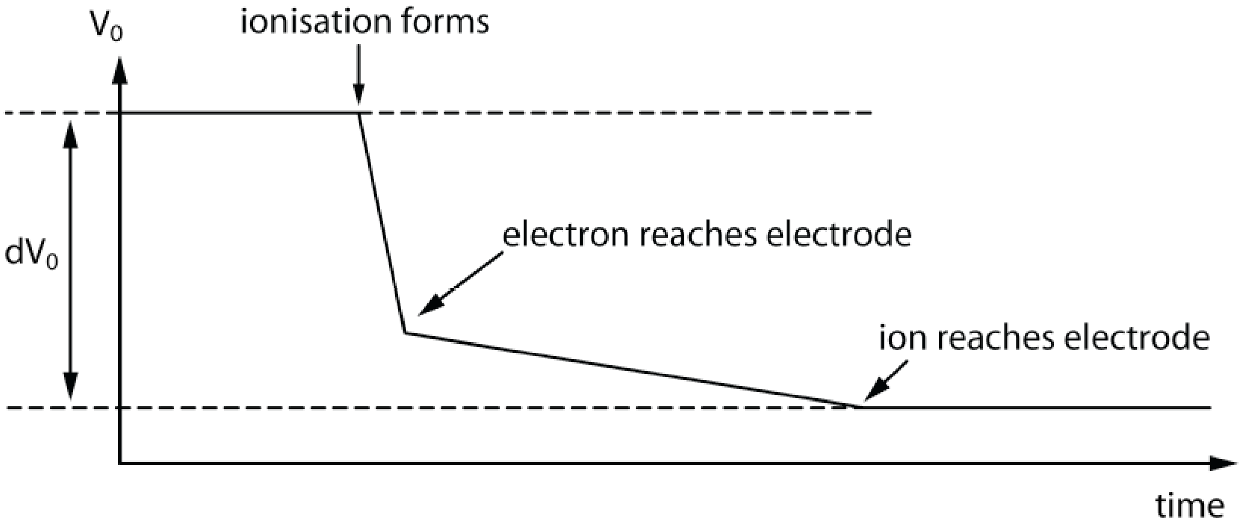
$$i_+ = e\vec{u}_+\vec{E}_a = e\frac{u_+}{d}$$

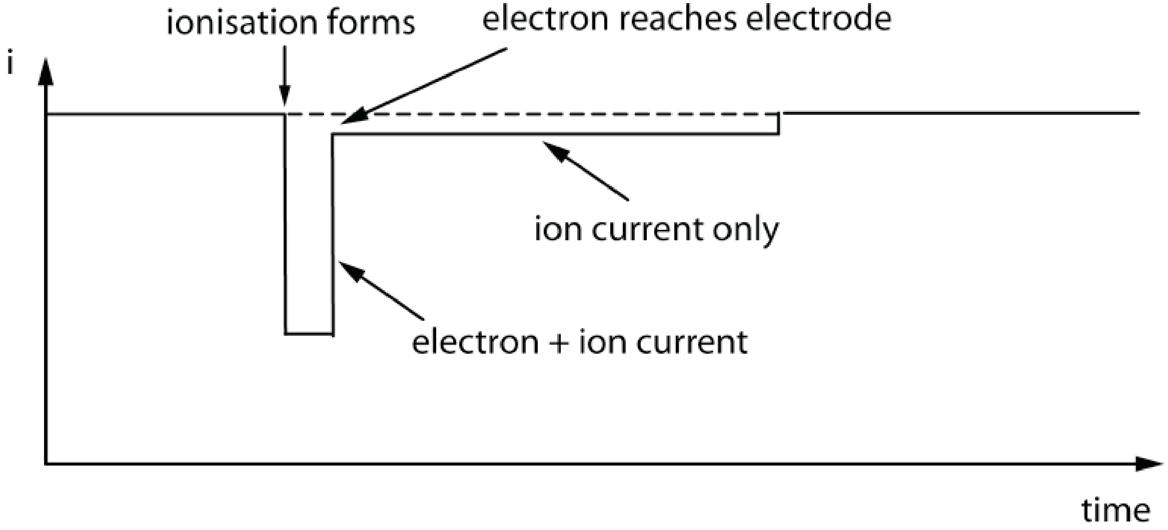
- If the pair is created at point $x = x_0$ at time $t = 0$, it appears a current i_+ that cancels out at time $T_+ = x_0/u_+$ when the ion is collected by the cathode and also a current i_- that cancels out at time $T_- = (d-x_0)/u_-$ when electron is collected by the anode
- We have $T_+ \gg T_-$ due the large drift velocity of electron compared to ion

Current pulse in an ionization chamber



Current – voltage responses

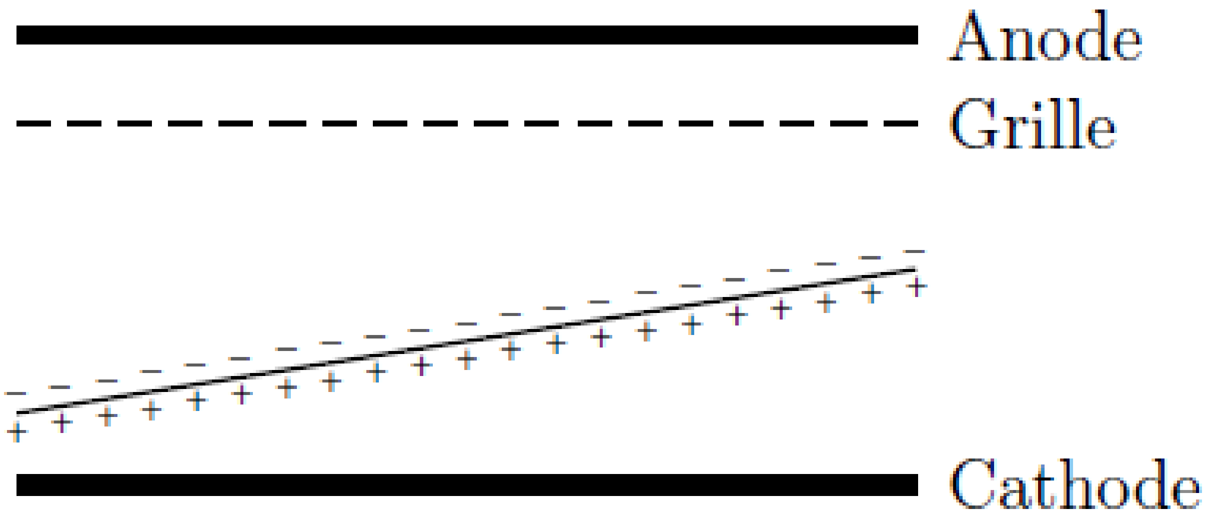




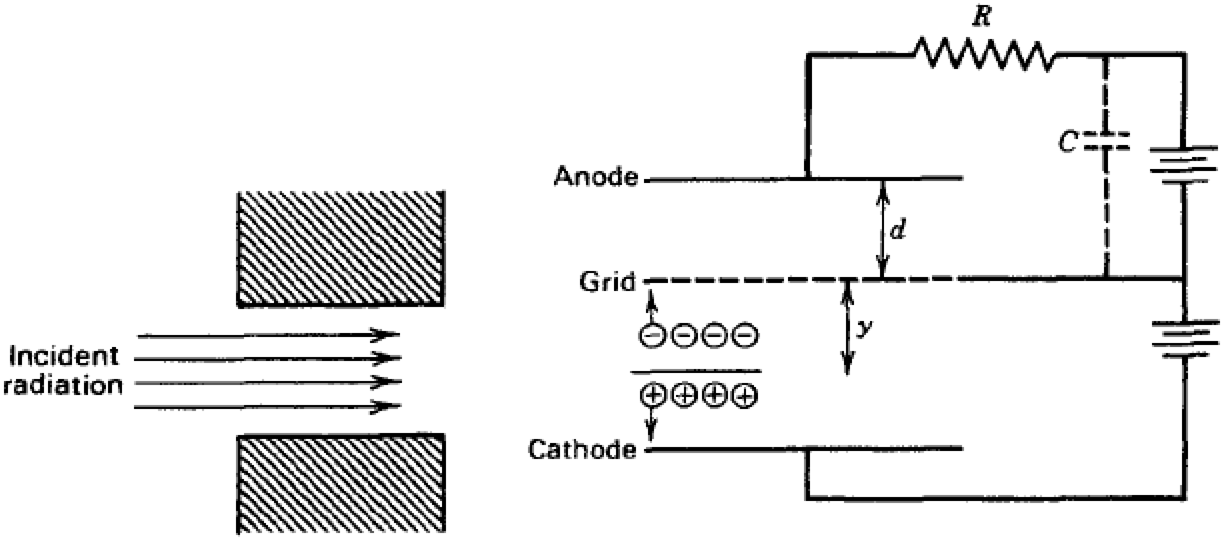
Frisch chamber

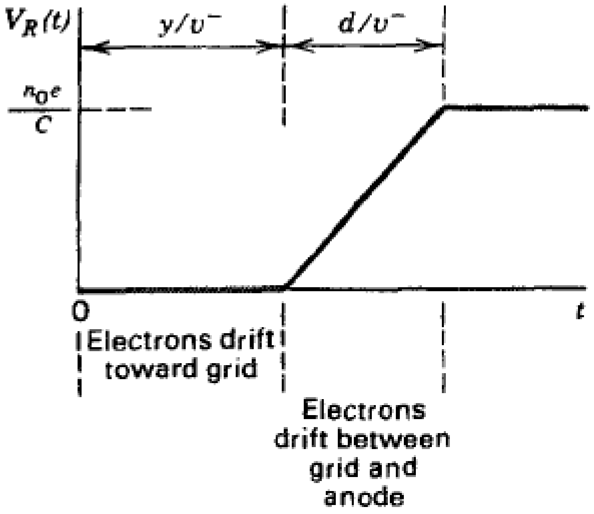
- To suppress the influence of positive ions on the anode → solution of Frisch → addition of a grid between anode and cathode
- This grid is maintained at an intermediate potential (between 0 and U_0)
- It acts as an electrostatic screen → the anode is only influenced by charges between the anode and the grid
- All the radiations interactions are confined to the volume between the cathode and the grid → as long as the electrons and the ions are in this volume → the anode charge does not change
- The ions drift to the cathode and never influence the anode and the electrons drift to the grid → once they pass trough the grid they produce a signal voltage at the anode
- There is no influence of the ions because they only move in volume between the cathode and the grid
- The width of the pulse is thus only determined by the time collection of the electrons (and by the time constant of the electronic circuit)

Scheme of a Frisch chamber



Pulse shape for a Frisch chamber





Energy resolution for an ionization chamber

- For an ionization chamber → Fano factor is about 0.15
- Example → α particle with *E*= 5.5 MeV completely stopped in a gas for which *W* = 30 eV →

$$N_i = \frac{E_{abs}}{W} = \frac{5.5 \times 10^6}{30} = 1.83 \times 10^5 \text{pairs}$$

- We have the resolution *R* →

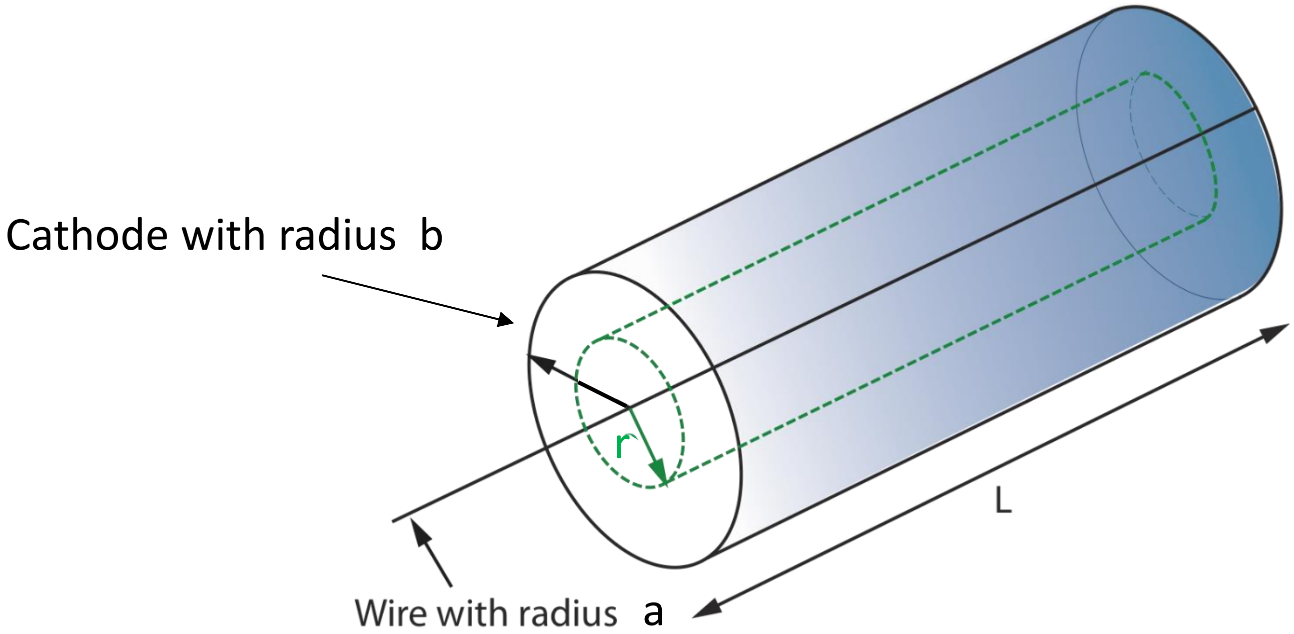
$$R = 2.35\sqrt{\frac{F}{N_i}} = 0.213\%$$

- Corresponding to a width of *R* $\times$ 5500 keV = 11.7 keV

Proportional counter

- Electrical signal produced by one charged is often too small to be observable
- In a proportional counter → charge amplification **in** the gas (electron multiplication process) → larger electrical signal
- Proportional counters are almost always used in pulse mode
- Proportional counters can be used (with thin entrance window) for detection and spectrometry of α particles and for electrons detection
- Two important applications of proportional counters are the detection and spectroscopy of low X-ray radiations (< 100 keV → thin entrance window) and the neutron detection (see « Neutrons detection »)

Choice of geometry: Cylinder



From Maxwell equations over an imaginary cylindrical volume V of radius r and surface S (in green) with q the charge density inside V:

$$\int \vec{E}d\vec{S} = \frac{1}{\epsilon_0}\int q dV$$

Electric field and potential in the cylinder

- E over the plugs at both ends points radially outwards from the center → no contribution to the surface integral →

$$E(r)2\pi r L = Q \Rightarrow E(r) = \frac{Q}{2\pi\epsilon_0 r L}$$

- The electric field in the cylinder: $E = -\frac{dV}{dr}$

- Integrating along a radial line between a and b:

$$V(b) - V(a) = \int_a^b E(r)dr$$

Electric field and potential in the cylinder (2)

- The outer cylinder is at ground potential, *V(b) = 0* and the central wire is connected to the external applied voltage such as $V(a) = V_0$:

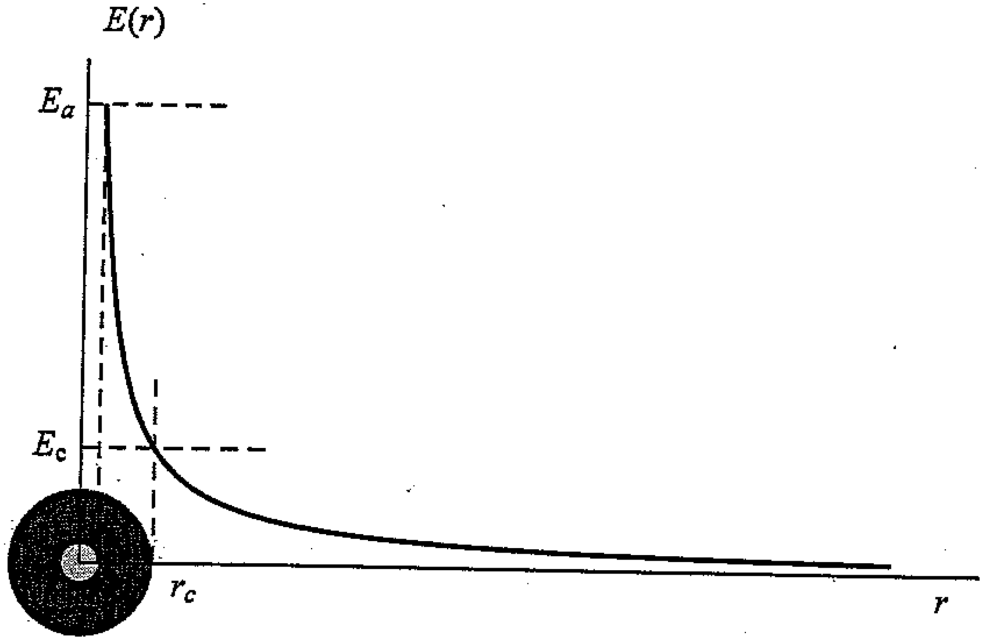
$$V_0 = \int_a^b E(r)dr = \frac{Q}{2\pi\epsilon_0 L}\ln\left(\frac{b}{a}\right)$$

- Eliminating *Q*:

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

- Large values of the E in the intermediate vicinity of the anode wire for small r → this region is the multiplication region (with radius r_c the critical radius) with an electric field larger than E_c (critical electric field for which electron multiplication is possible)

Behaviour of the electric field in a proportional counter



For a=80μm, b=1 cm and a V_0=2000 V, E close to the central wire is ≈5 10^7 V/m → sufficient for electron multiplication (typically in a gas at normal pressure $E_c \approx 10^6$ V/m) → only valid for electrons multiplication → for ions a quite more important field is necessary because of their mass ($a = qE/M$)

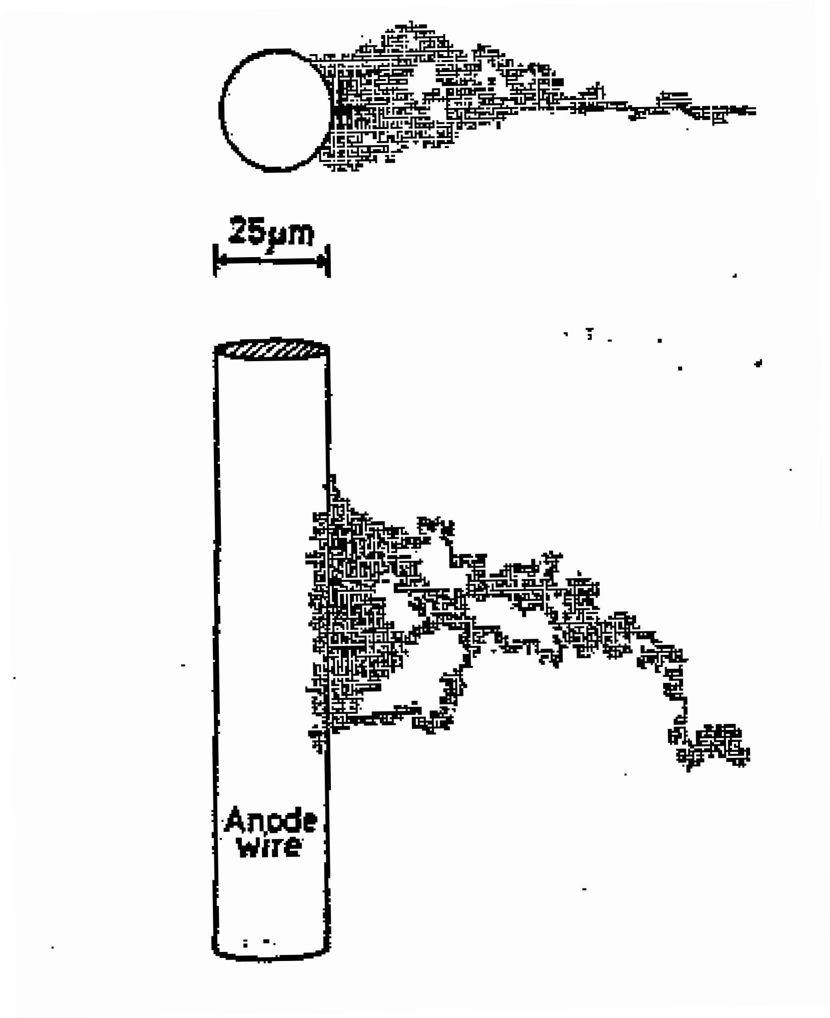
Principle of the multiplication (1)

- A particle produces a number of electron-ion pairs in the gas
- Due to E, e^- and ions move towards the anode and cathode
- Close to the anode E ↗ → in the multiplication region (few μm) → charge multiplication
- The e^- have enough energy to ionize other atoms → additional free e^- → number of e^- increases exponentially (number of ions also)
- The secondary ionizations **exclusively** occur in the multiplication region in a same way for all primary electrons ↔ r_c is very small (the volume within r_c is less than 0.2 % of the total volume) → this region is never crossed over by the initial particle → the gain of the counter is independent of the position of the charged particle trajectory

Principle of the multiplication (2)

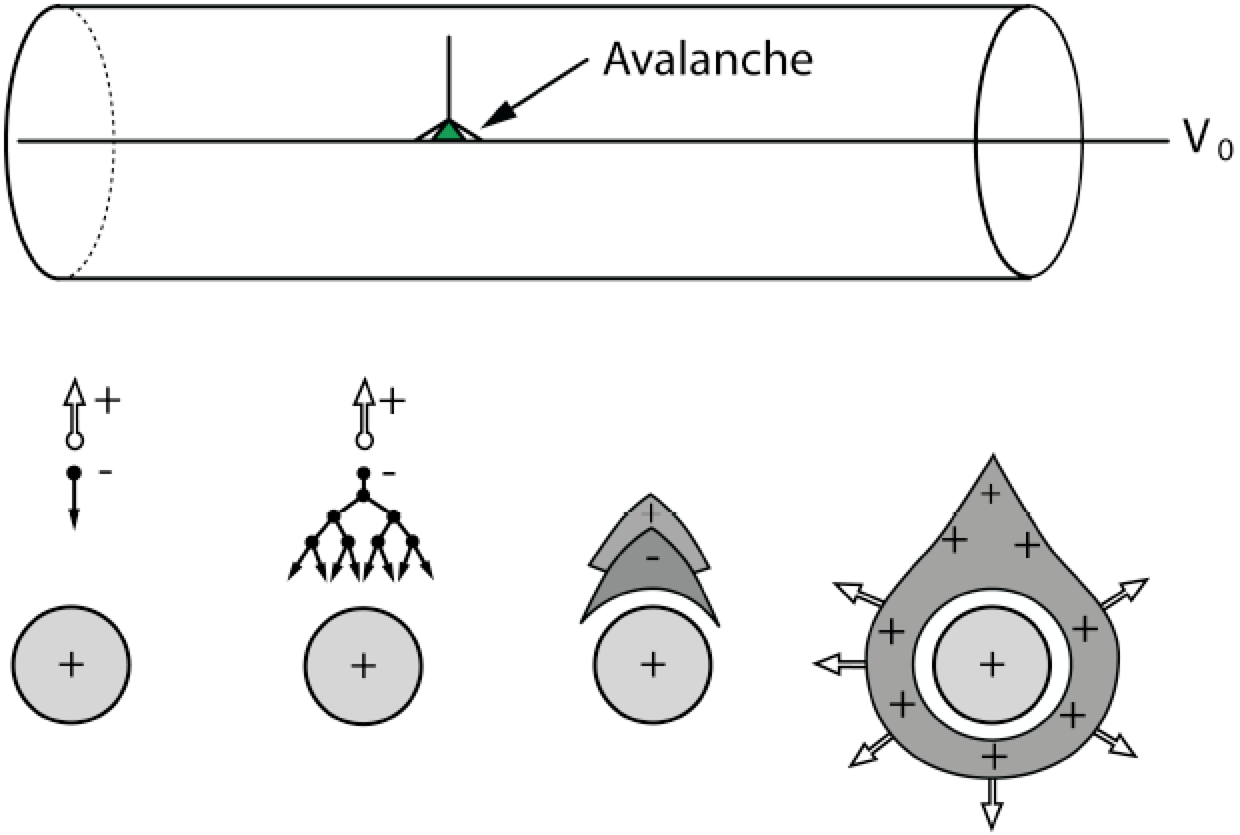
- An equal number of e^- and positive ions are formed
- The e^- move much faster than the positive ions→ e^- reach the anode in ≈1 ns and leave the positive ions behind
- The ions move slowly towards the cathode
- No charge multiplication for ions because it needs much larger E (due to its mass)
- The ions need several 100 μs to reach the cathode

Representation of the avalanche



Monte Carlo Simulation

Scheme of the avalanche



Due to diffusion → the e^- « surround » the wire during avalanche

Charges collection (1)

- Almost all charges created inside the counter have as origin the multiplication region regardless of the position of appearance of the initial pair
- The time necessary to fully collect the signal can be divided into 2 parts → the drift time t_r (time needed by the free e^- to reach the multiplication region) and the multiplication time t_m (time between the begin of the avalanche and the complete collection)
- The contribution to the signal during $t_r \ll$ than the contribution during t_m → the drift time (≈ 1 μs → depends on the position of creation of the initial pair) only introduce a delay before the measurement of the pulse

Charges collection (2)

- The quasi-totality of the ions and e^- are created close to the anode → the measured signal is mainly due to the drift of the ions instead of the motion of the e^-
- Initially → the ions are subject to an intense electric field → rapid motion (without multiplication!) → pulse with fast rising slope
- Afterwards → ↘ of the field (radius of the tube ↗) → ↘ of the velocity → the pulse ↗ very slowly → not observed in practice because of the finite time constant of the electronic circuit connected to the detector

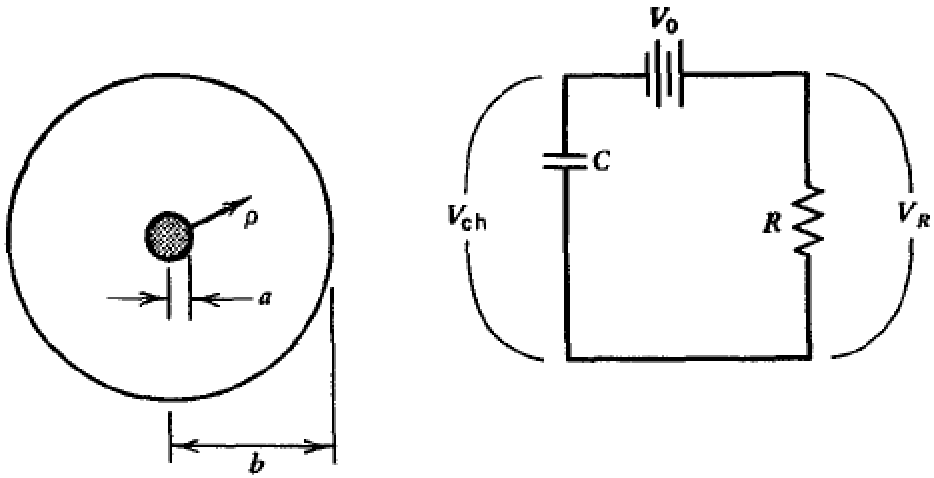
Simplified analysis of the charges collection (1)

- We consider a cylindrical capacitor (with internal and external radii a and b, respectively) charged via a potential difference U_0 → capacitor with capacitance C
- The absorbed energy $d\varepsilon$ due to the motion of a positive charge Q along the distance dr →

$$\frac{d\varepsilon}{dr} = QE(r) = Q\frac{U_0}{r\ln(b/a)}$$

- We suppose that n_0 e^- and ions are created in the avalanche at a distance ρ from the anode surface (and thus $Q = en_0$)
- We suppose that U_{ch} and U_R are the voltages (after collection of the charge) at the terminals of the chamber and of the resistance of the measurement circuit

Simplified analysis of the charges collection (2)



- The absorbed energy during the motion of the positive ions towards the cathode →

$$\begin{aligned}\varepsilon^+ &= \int_{a+\rho}^{b} \frac{d\varepsilon}{dr} dr = \frac{QU_0}{\ln{(b/a)}} \int_{a+\rho}^{b} \frac{dr}{r} \\ &= \frac{QU_0}{\ln{(b/a)}} \ln \frac{b}{a+\rho}\end{aligned}$$

Simplified analysis of the charges collection (3)

- Same calculation for the e$^-$ →

$$\begin{aligned}\varepsilon^- &= -\frac{QU_0}{\ln(b/a)}\int_{a+\rho}^{a}\frac{dr}{r}\\ &= \frac{QU_0}{\ln(b/a)}\ln\frac{a+\rho}{a}\end{aligned}$$

- The total energy absorbed after complete collection of the 2 types of charges →

$$\begin{aligned}\Delta\varepsilon &= \varepsilon^+ + \varepsilon^- = \frac{QU_0}{\ln(b/a)}\ln\left(\frac{b}{a+\rho}\frac{a+\rho}{a}\right)\\ &= QU_0\end{aligned}$$

Simplified analysis of the charges collection (4)

- By energy conservation → the energy remaining inside the condenser = the initial energy -$\Delta\varepsilon$ →

$$\frac{CU_{ch}^2}{2} = \frac{CU_0^2}{2} - \Delta\varepsilon$$

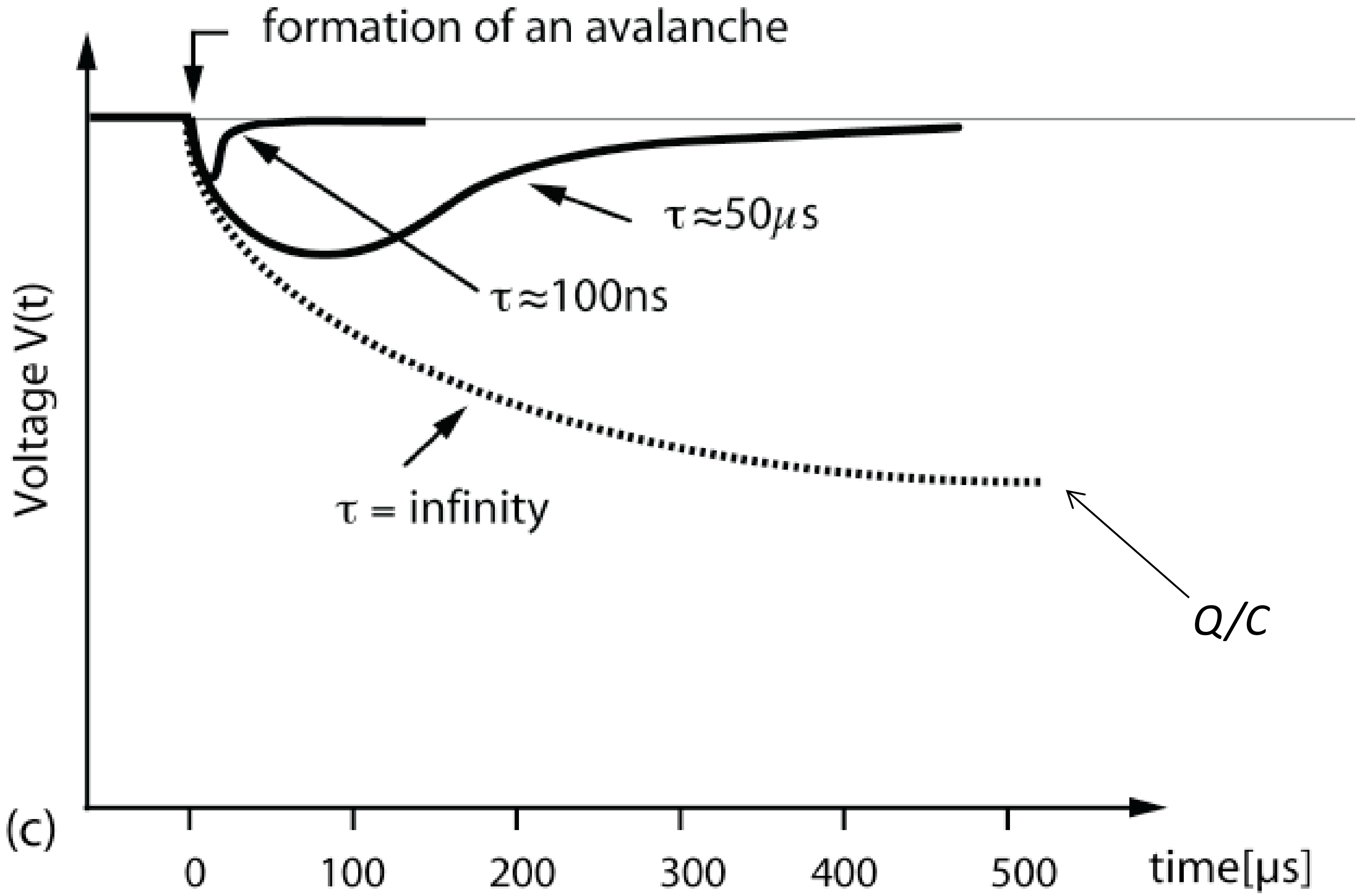
$$\frac{C}{2}(U_{ch} - U_0)(U_{ch} + U_0) = -\Delta\varepsilon$$

- By assuming $\Delta\varepsilon$ small → $U_{ch} + U_0 = 2U_0$ and $U_R = U_0 - U_{ch}$ →

$$U_R = \frac{\Delta\varepsilon}{CU_0} = \frac{QU_0}{CU_0} = \frac{Q}{C}$$

- U_R is the maximal measured amplitude → only if *RC* is large by comparison to collection time of the ions → in practice this condition is never observed → the maximum depends on *RC*

Shape of the pulse



Signal of the ion ↔ signal of the electron

- The ratio of the energies absorbed during the motion of the negative electrons and of the positive ions (or equivalently the ratio of the maximal amplitudes of the signals due to the e^- and to the ions)→

$$\frac{\varepsilon^-}{\varepsilon^+} = \frac{\ln\left[(a+\rho)/a\right]}{\ln\left[b/(a+\rho)\right]}$$

- For $a = 25\ \mu$m, $b = 1$ cm and $\rho = 3\ \mu$m →

$$\frac{\varepsilon^-}{\varepsilon^+} = 0.019$$

- For this example → less than 2% of the signal results from the drift of e^- → this e^-contribution can be neglected

Multiplication time for the ions (1)

- The drift velocity of the ion is given by →

$$u^{+}(r) = \mu E(r) = \mu \frac{U_0}{\ln(b/a)} \frac{1}{r}$$

- The position of the ions is obtained with →

$$\int_a^{r(t)} \frac{dr'}{u^{+}(r')} = \int_0^t dt' \Rightarrow r(t) = \left(2\mu \frac{U_0}{\ln(b/a)} t + a^2 \right)^{1/2}$$

- The multiplication time t_m is given by $r(t) = b$ →

$$t_m = \frac{(b^2 - a^2)\ln(b/a)}{2\mu U_0}$$

Multiplication time for the ions (2)

- This time can be very long → several hundred of μs
- However a large part of the signal grows during the first part of the ions drift
- The energy absorbed during the motion of the ions as a function of the time is:

$$\varepsilon^+(t) = \frac{QU_0}{\ln(b/a)} \int_a^{r(t)} \frac{dr'}{r'} = \frac{QU_0}{\ln(b/a)} \ln \frac{r(t)}{a}$$

- By using the expressions of *r(t)* and $U_R(t) = \varepsilon^+(t)/CU_0$ →

$$U_R(t) = \frac{Q}{C \ln(b/a)} \ln \left(\frac{2\mu U_0}{a^2 \ln(b/a)} t + 1 \right)^{1/2}$$

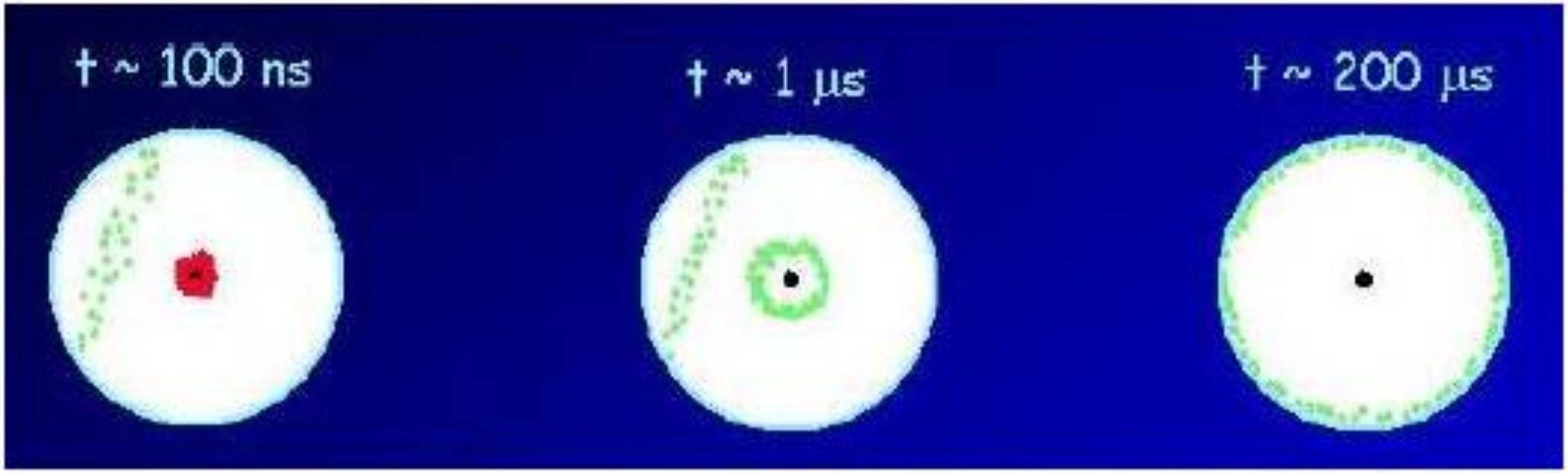
Multiplication time for the ions (3)

- The pulse thus reaches the half of its maximal amplitude for a time →

$$t_{1/2} = \frac{a}{a+b} t_m$$

- With previous data → $t_{1/2}/t_m$ = 0.25% → fast increase of the pulse and then slower increase
- During signal shaping→ the slow part does not contribute any more to the signal amplitude
- Attention → the drift time t_r introduces a temporal dispersion → deterioration of the resolution

Charges collection: Illustration



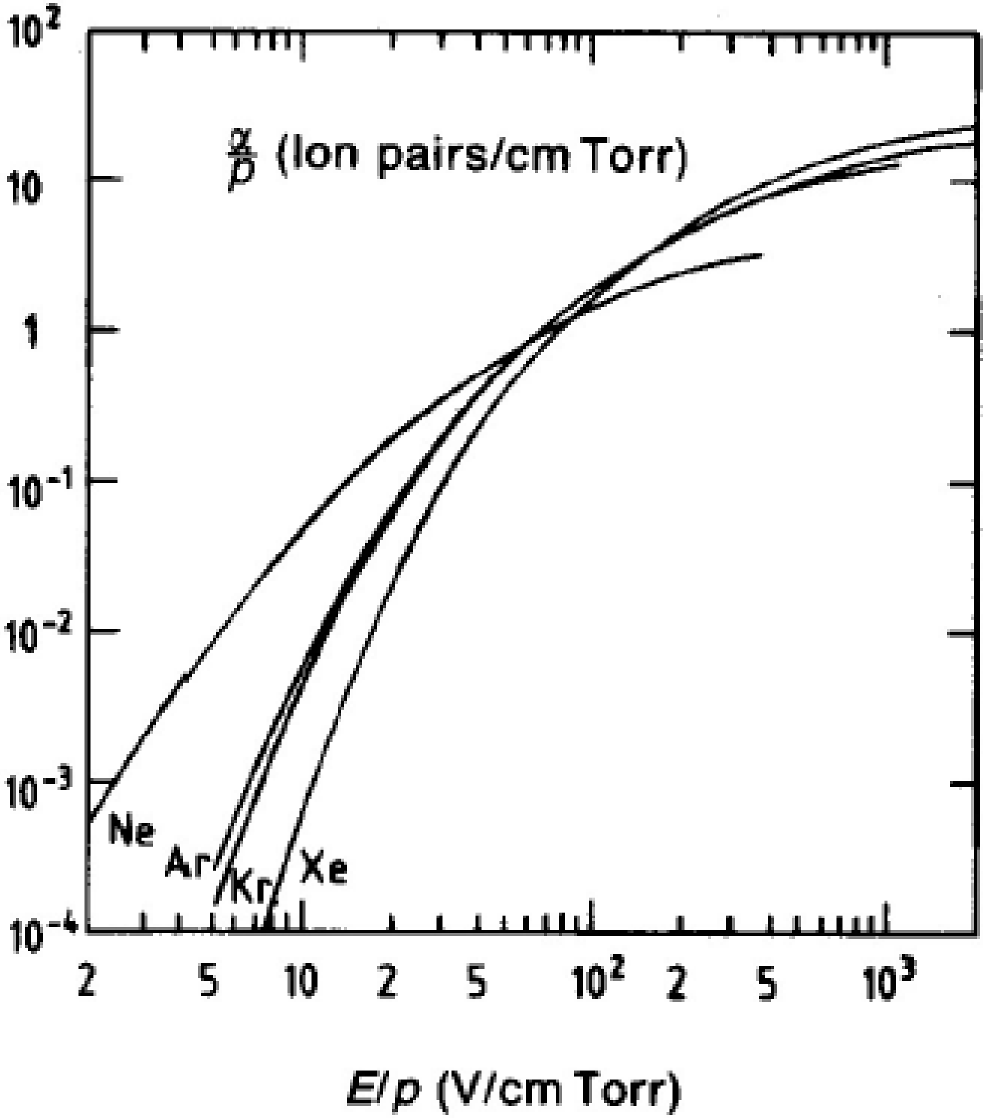
Equation of Townsend

- The probability for an e^- to create an additional e^- along a distance *dx* is αdx (α is the first coefficient of Townsend)
- The multiplication process is governed by the equation of Townsend → relative variation of the electrons number *n(x)* per unit of travelled path →

$$\frac{dn}{n} = \alpha dx \quad \text{with} \quad \alpha = 0 \quad \text{for} \quad E < E_c$$

- α depends on the excitation and ionization cross sections of the e^- in the gas (and thus on the gas), on the electric field (and thus on *x*) because it determines the energy acquired by the electrons and on the gas density ρ (and thus on pressure *p*)

First coefficient of Townsend



1 Torr = 1 mmHg

Mathematical expression of the multiplication coefficient (1)

- For $E > E_c$ → the number of e^- increases exponentially with the travelled path →

$$n(x) = n(0)\exp\left(\alpha x\right) \quad \text{for} \quad E > E_c$$

- We define the multiplication coefficient of the counter (also called gain of the counter) with $M = n(x)/n(0)$ →

$$\text{for} \quad a < x < r_c \Rightarrow \ln M = \int_a^{r_c} \alpha(x)dx = \int_{E_a}^{E_c} \frac{\alpha(E)}{(dE/dx)}dE$$

- It does not exist fundamental expression for $\alpha(E)$ → but for E not too high → $\alpha(E) = \beta E$

Mathematical expression of the multiplication coefficient (2)

- By integration →

$$\ln M = \beta \frac{U_0}{\ln(b/a)} \ln \frac{E(a)}{E_c} = \beta \frac{U_0}{\ln(b/a)} \ln \frac{r_c}{a}$$
$$= \beta \frac{U_0}{\ln(b/a)} \ln \frac{U_0}{E_c a \ln(b/a)}$$

- *M* can be calculated in another way → the potential difference between the anode (*r = a)* and the critical radius (*r* = r_c) is →

$$V(a) - V(r_c) = \frac{U_0}{\ln(b/a)} \ln \frac{r_c}{a}$$

Mathematical expression of the multiplication coefficient (3)

- If $e\Delta V$ is the mean energy necessary to create an supplementary electron → the number Z of electrons productions is →

$$Z = \frac{V(a) - V(r_c)}{\Delta V}$$

- And the gain is →

$$M = 2^Z \Rightarrow \ln M = \ln 2 Z = \frac{\ln 2}{\Delta V} \frac{U_0}{\ln(b/a)} \ln \frac{r_c}{a}$$

- Assuming that $E_c \propto \rho$ → $E_c(\rho) = E_c(\rho_0)\rho/\rho_0$ (with ρ_0 the gas density for normal conditions of pressure and temperature → $T = 0°$ and $p = 1$ atm) → we obtain the expression of Diethorn for M

Expression of Diethorn

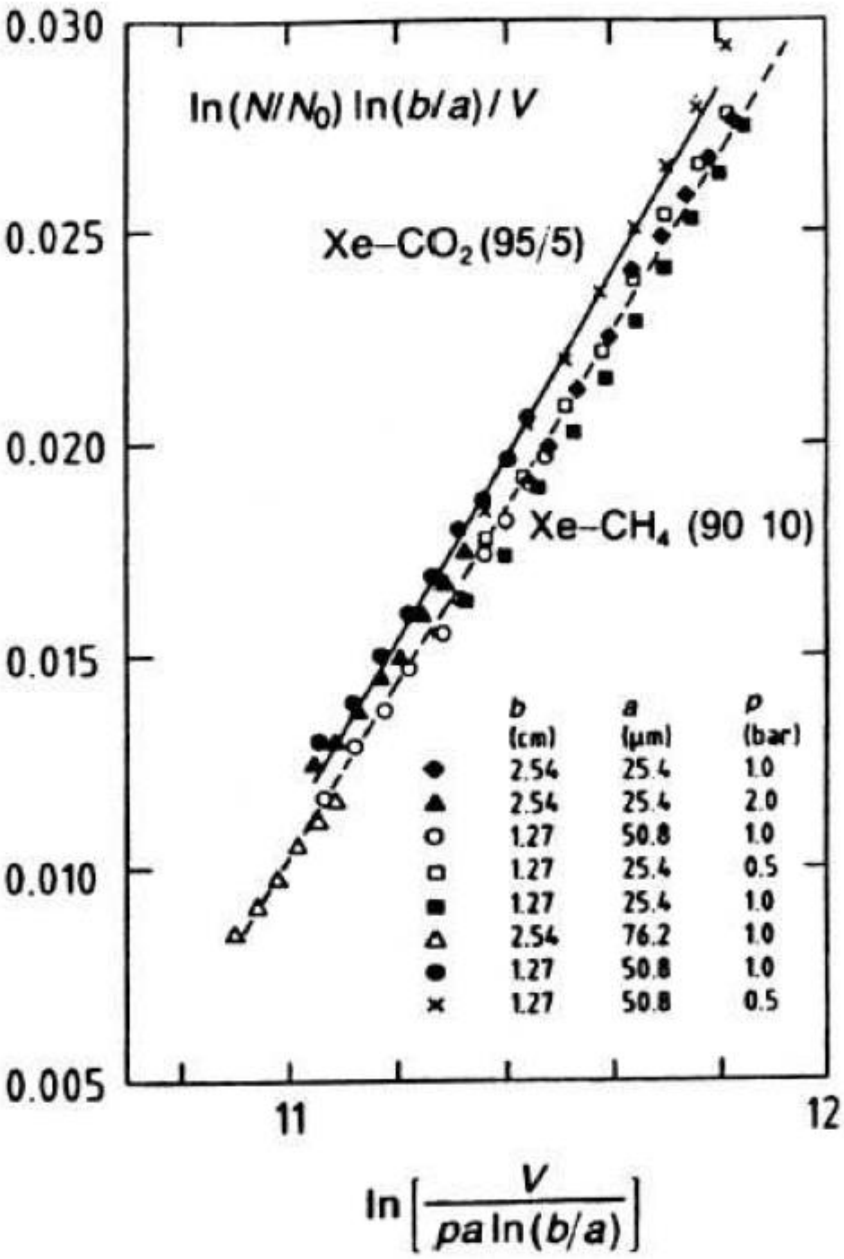
$$\ln M = \frac{\ln 2}{\Delta V} \frac{U_0}{\ln b/a} \ln \frac{\rho_0 U_0}{\rho E_c(\rho_0) a \ln b/a}$$

- Parameters ΔV and $E_c(\rho_0)$ are obtained by comparison with experimental data
- Without knowing them we deduce →

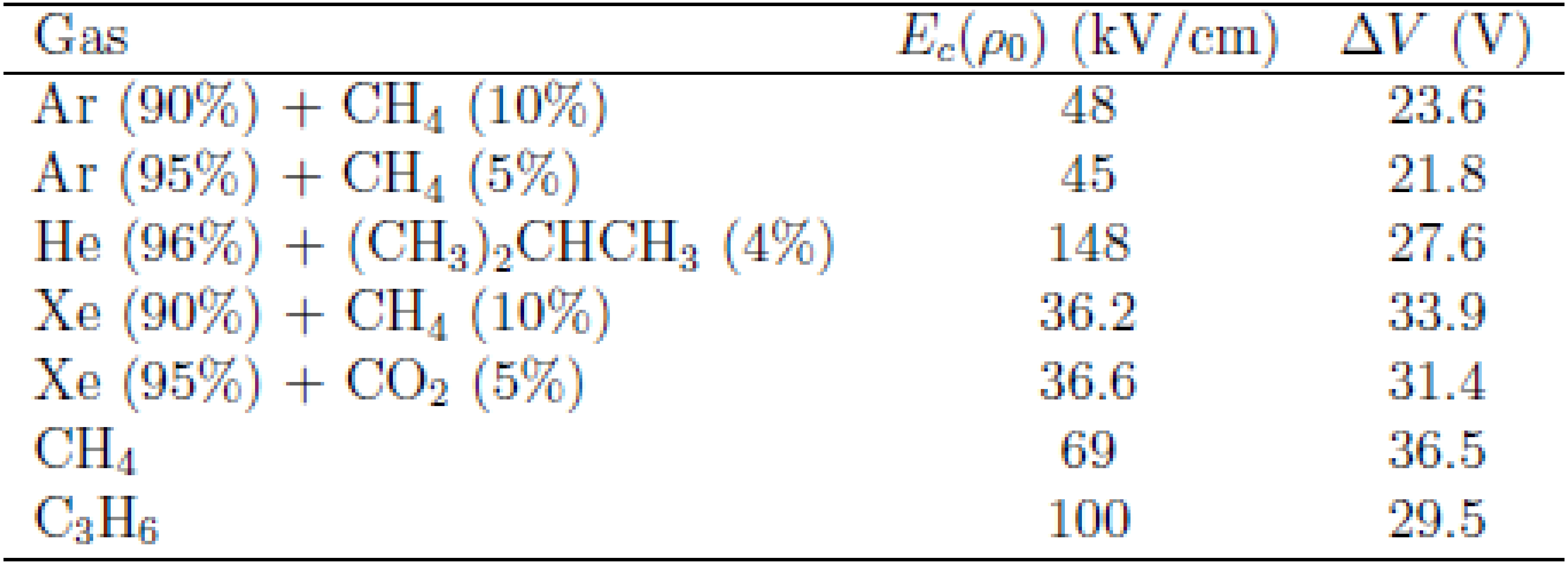
$$\frac{\ln b/a}{U_0} \ln M \propto \ln \frac{\rho_0 U_0}{\rho E_c(\rho_0) a \ln b/a}$$

→ graphs of Diethorn

Graphs of Diethorn

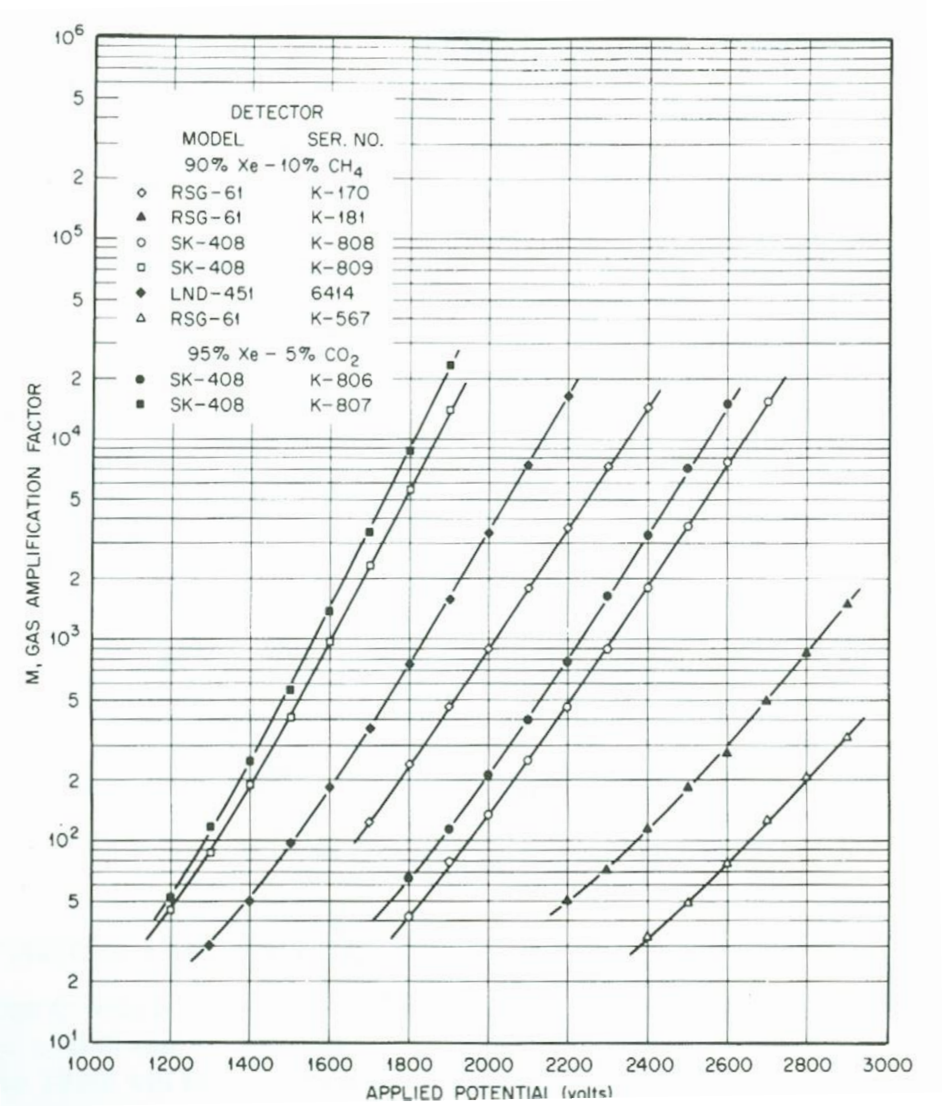


Parameters of Diethorn



Gas	$E_c(\rho_0)$ (kV/cm)	ΔV (V)
Ar (90%) + CH_4 (10%)	48	23.6
Ar (95%) + CH_4 (5%)	45	21.8
He (96%) + $(CH_3)_2CHCH_3$ (4%)	148	27.6
Xe (90%) + CH_4 (10%)	36.2	33.9
Xe (95%) + CO_2 (5%)	36.6	31.4
CH_4	69	36.5
C_3H_6	100	29.5

Gas multiplication factor for different gas mixtures



M typically varies between 10^2 and 10^4

Choice of fill gas (1)

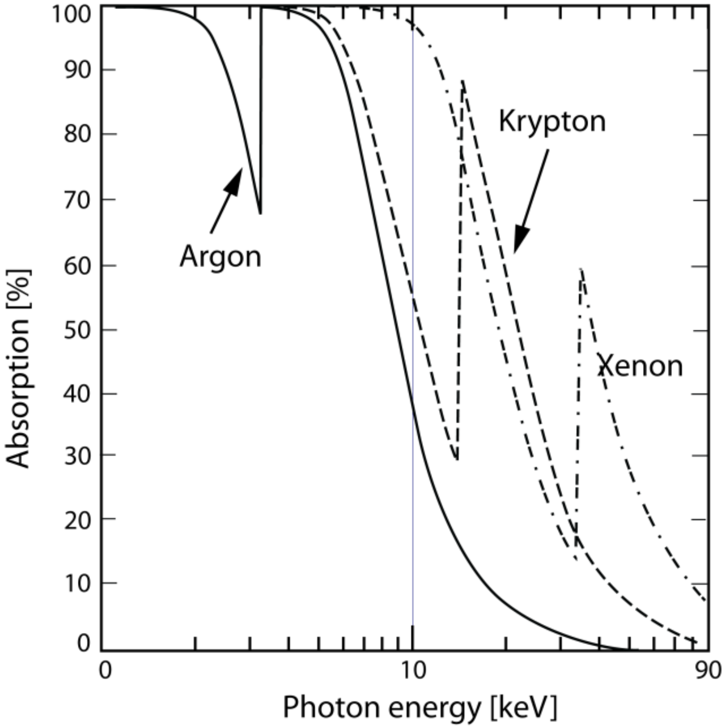
- Gas should **not** contain any electronegative component (except particular cases) ↔ electronegative molecule tends to form negative ions → no charge multiplication for generally used *E*
- Since oxygen is electronegative → **no** air
- Noble gas is a good choice: not electronegative, easily purified and single atoms → no rotation or vibration states that can absorb electron energy → avalanche occurs at a lower voltage than in other gases
- Argon is the least expensive → very frequent use

Choice of fill gas (2)

- However → a pure noble gas shows problems →
  1. Beside ionizations → excitations → deexcitation by photons emission(most of the time UV) → even though the gas is « almost » transparent to UV → possibility of UV absorption and e^- emission → avalanche repeat
  2. The recombination e^-/ion also induces UV → same phenomenon
  3. The mean excitation energy of noble gases is high (ex: 11.6 eV for Ar) → deexcitation photon with higher energy than the ionization threshold of all metals which can compose the walls (ex: I(Cu) = 7.7 eV) → UV can extract an e^- from the cathode → avalanche repeat
  4. The Ar^+ arriving at the cathode cancel each other out by extraction of an e^- from the cathode → the dissipated energy can cause the extraction of an additional e^- from the cathode → additional avalanche (weak probability, almost negligible)
- Solution: addition (typically 10%) of a « quenching » gas → polyatomic gas: isobutane (C_4H_{10}), methane (CH_4),… which have many degrees of freedom of rotation and vibration to disperse energy →
  1. Absorption of UV photons
  2. Charge transfer $Ar^+ + \text{gas} \rightarrow Ar + \text{gas}^+$

Choice of fill gas (3)

- For X-ray detection, Ar is not the more suitable gas ↔ interaction probability of X-rays in argon drops to a very low value above 20 keV → too large size of the detector
- With Kr or Xe, sizeable detection efficiencies up to 100 keV can be obtained



Absorption of X-rays in 5 cm of gas for at atmospheric pressure

Effect of space charges

- If the number of created ions id too high (for a too important electric field for instance) → their space charge can disturb the electric field
- In a first time → ↘ of the resolution
- In a second time → loss of proportionality → no use of a proportional counter for too high applied voltages

Detector resolution (1)

- We consider the charge *Q* collected by the proportional counter (in the absence of non-linear effects), N_i the number of e$^-$/ion pairs and *M* the multiplication factor such as (without recombination) →

$$\langle Q \rangle = e \langle N_i \rangle \langle M \rangle$$

- Assuming that N_i et *M* are independent → the variance on *Q* is given by →

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \left(\frac{\sigma_{N_i}}{N_i}\right)^2 + \left(\frac{\sigma_M}{M}\right)^2$$

Detector resolution (2)

- Generally the variance on the multiplication factor *A* for *only one electron* initially created is considered →

$$M = \frac{1}{N_i}\sum_{i=1}^{N_i} A_i \equiv \bar{A}$$

- The avalanches for each electron being independent →

$$\sigma_M^2 = \left(\frac{1}{N_i}\right)^2 \sum_{i=1}^{N_i} \sigma_A^2 = \frac{1}{N_i}\sigma_A^2$$

- The variance on *Q* becomes →

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \left(\frac{\sigma_{N_i}}{N_i}\right)^2 + \frac{1}{N_i}\left(\frac{\sigma_A}{\bar{A}}\right)^2$$

Detector resolution (3)

a. Variations on N_i → introduction of the Fano factor F →

$$\begin{aligned} \sigma^2_{N_i} &= F N_i \\ \left(\frac{\sigma_{N_i}}{N_i}\right)^2 &= \frac{F}{N_i} \end{aligned}$$

as a function of the gas mixture → $0.05 < F < 0.20$

b. Variations on A → ≠ models have been considered →

- Distribution of Furry →

$$P(A) = \frac{(1 - 1/\bar{A})^{A-1}}{\bar{A}}$$

- Distribution of Furry for large values of Ā →

$$P(A) = \frac{e^{-A/\bar{A}}}{\bar{A}}$$

Detector resolution (4)

and in this case →

$$\left(\frac{\sigma_A}{\bar{A}}\right)^2 = 1$$

however → experimentally values are different from 1 → problem

- Distribution of Polya →

$$P(A) = \left[\frac{A(1+\theta)}{\bar{A}}\right]^{\theta} \exp\left[\frac{-A(1+\theta)}{\bar{A}}\right]$$

where θ is a parameter such as $0 < \theta < 1$

and in this case →

$$\left(\frac{\sigma_A}{\bar{A}}\right)^2 = \frac{1}{\bar{A}} + b \simeq b$$

for large values of Ā (we consider $b = 1/(1+\theta)$ such $0.4 < b < 0.7$)

Detector resolution (5)

c. Variations on Q →

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \frac{F}{N_i} + \frac{b}{N_i}$$

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \frac{1}{N_i}(F + b)$$

and the fluctuation on the avalanche is dominating

This equation can be written considering $N_i = E/W$ →

$$\frac{\sigma_Q}{Q} = \left[\frac{W(F + b)}{E}\right]^{1/2}$$

Examples of resolution

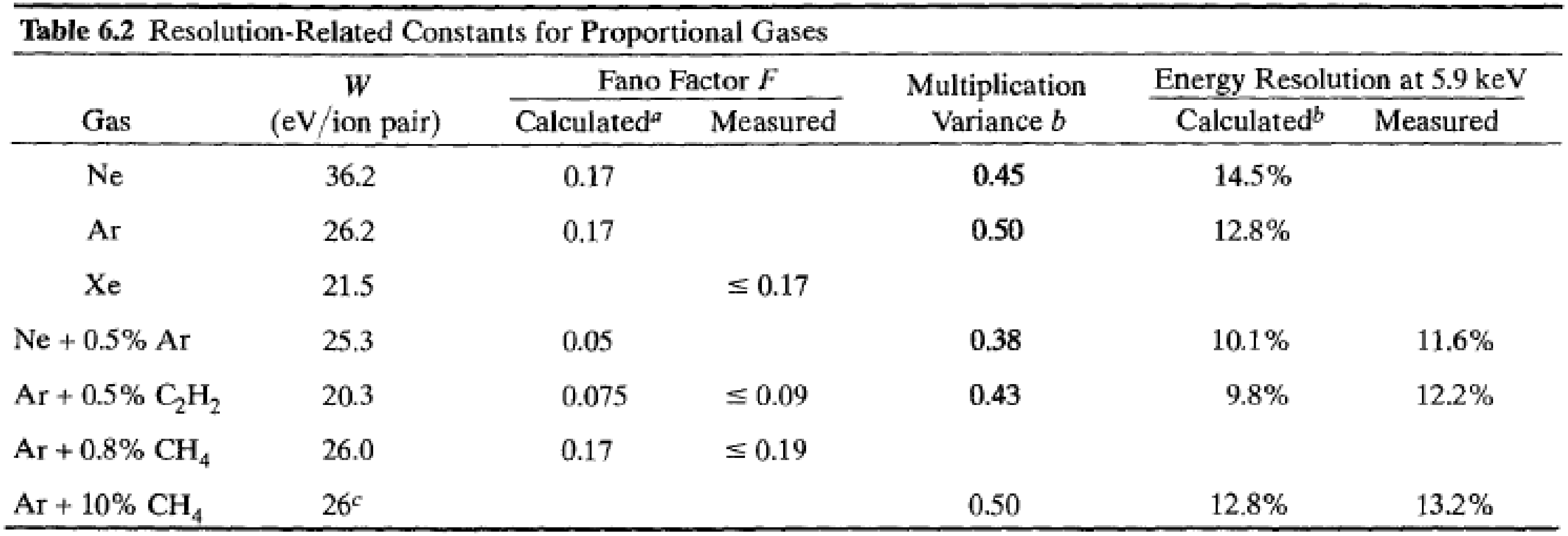
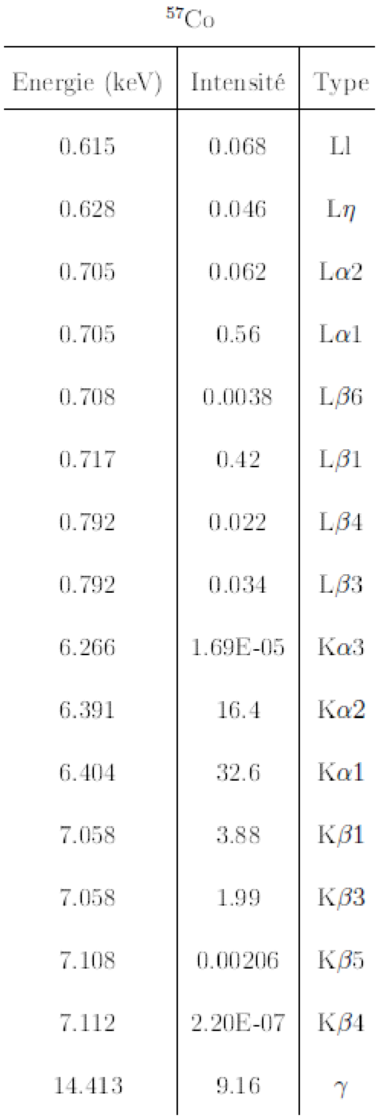


Table 6.2 Resolution-Related Constants for Proportional Gases

	W	Fano Factor F		Multiplication	Energy Resolution at 5.9 keV	
Gas	(eV/ion pair)	Calculated[a]	Measured	Variance b	Calculated[b]	Measured
Ne	36.2	0.17		0.45	14.5%	
Ar	26.2	0.17		0.50	12.8%	
Xe	21.5		≤ 0.17			
Ne + 0.5% Ar	25.3	0.05		0.38	10.1%	11.6%
Ar + 0.5% C_2H_2	20.3	0.075	≤ 0.09	0.43	9.8%	12.2%
Ar + 0.8% CH_4	26.0	0.17	≤ 0.19			
Ar + 10% CH_4	26[c]			0.50	12.8%	13.2%

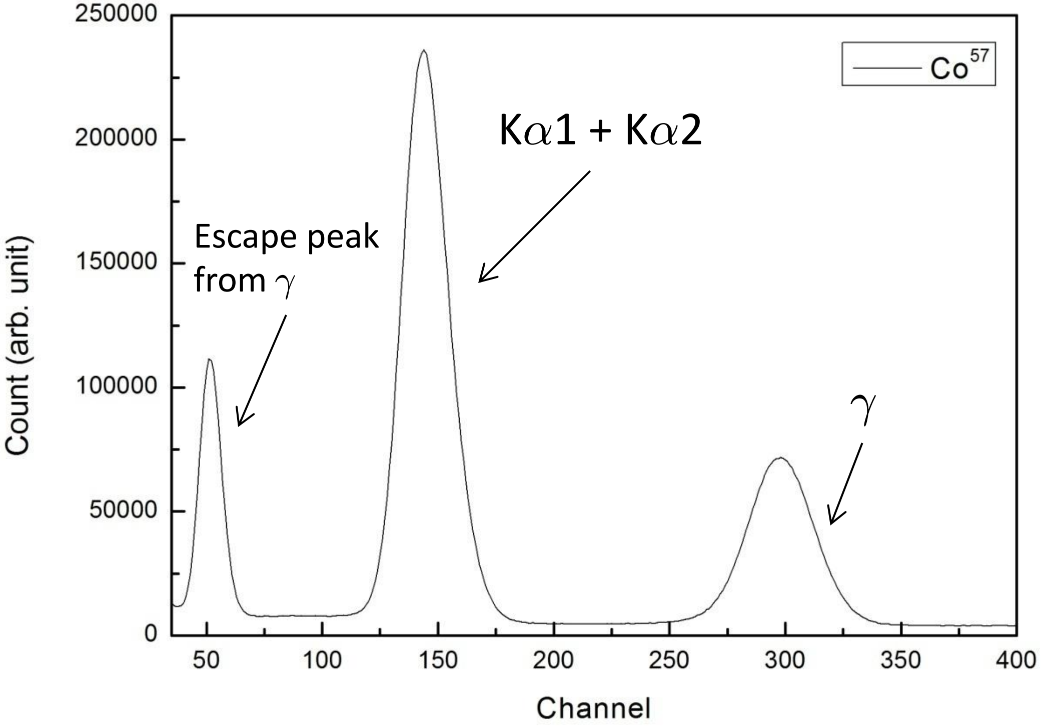
with W = 35 eV/pair

Example of X-ray spectroscopy with proportional counter



^{57}Co

Energie (keV)	Intensité	Type
0.615	0.068	Ll
0.628	0.046	Lη
0.705	0.062	Lα2
0.705	0.56	Lα1
0.708	0.0038	Lβ6
0.717	0.42	Lβ1
0.792	0.022	Lβ4
0.792	0.034	Lβ3
6.266	1.69E-05	Kα3
6.391	16.4	Kα2
6.404	32.6	Kα1
7.058	3.88	Kβ1
7.058	1.99	Kβ3
7.108	0.00206	Kβ5
7.112	2.20E-07	Kβ4
14.413	9.16	γ



Measurement of X-rays from ^{57}Co with a proportional counter LND 45427 (97% krypton- 3% CO_2)
Typical resolution is about 16-20 %

Escape peaks

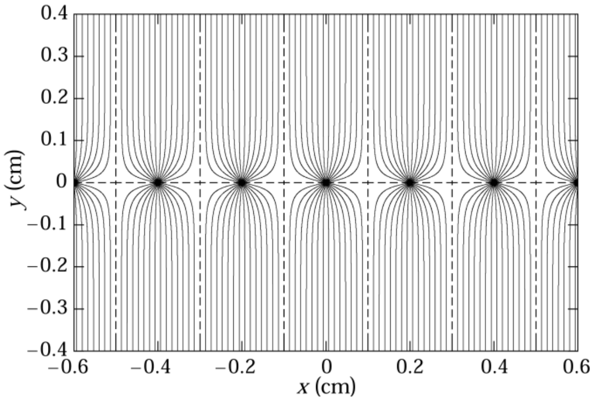
- After a photoelectric effect → If initial X-ray such as $E_{RX} > B_K$ → emission of an electron from the K shell → electron rearrangement by emission of an X-ray with energy $B_K - B_L$ which can escape
- If escape → escape peak in $E_{RX} - (B_K - B_L)$
- If detected→ total absorption peak
- If initial X-ray such as $B_L < E_{RX} < B_K$ → emission of an electron from the L shell → electron rearrangement by emission of an X-ray with energy $B_L - B_M$ which **cannot** escape (too small energy)
- The escape energies are 2.9, 12.4 and 29.2 keV for Ar, Kr and Xe respectively

B_K(Ar,Kr,Xe) = 3.2,14.3,34.6 B_L(Ar,Kr,Xe) = 0.3,1.9,5.5

Examples of proportional counter for X-ray spectroscopy

Cylindrical Side Window Proportional Counters from LND

Multi-wire Proportional counters as tracking devices

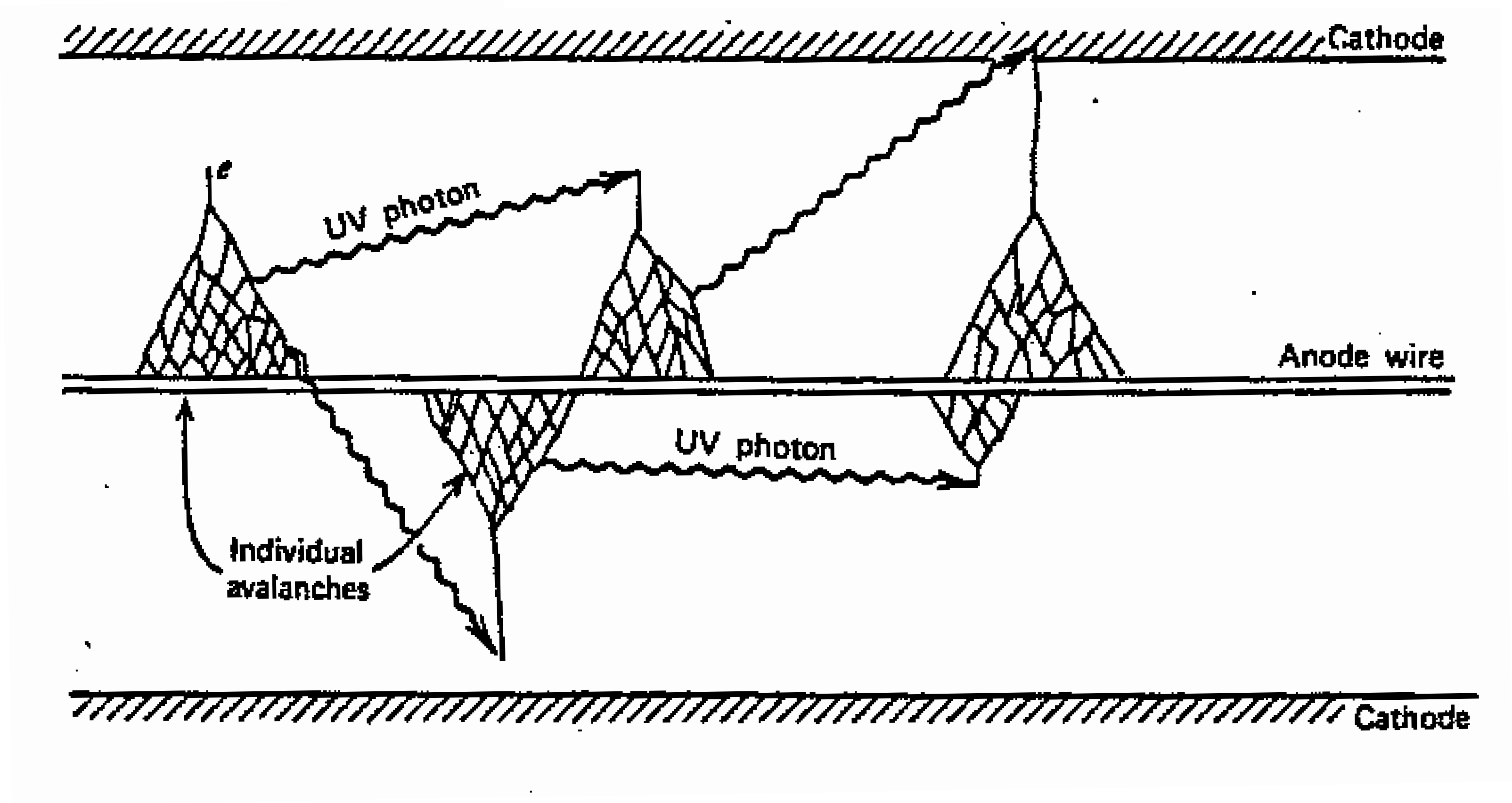


- Two cathodes planes with a series of anode wires stretched between the cathode planes
- The electric field geometry close to the anode wires is very similar to the field in an unique proportional counter → each individual anode wire behaves as a proportional counter
- The wire number has position information → mainly used for charged tracks

Geiger-Müller counter (GM)

- Detector developed in 1928 by Geiger and Müller → always used in present time due to its simplicity, low cost and ease of operation
- For a GM → high U_0 → high multiplication coefficient M (of about 10^6 - 10^8) → high excitation probability for the molecules of the gas → high deexcitation probability by emission of UV photons → high absorption probability for an UV by photoelectric effect → emission of an e^-
- Each avalanche induces at least another one → chain reaction
- The discharge is thus maintained by UV radiations

Avalanche mechanism in a Geiger tube



Stop of the discharge

- The stop of the discharge originates in the positive ions created during the avalanche
- Ions have a small mobility → essentially motionless during time necessary to collect all e-
- When the concentration of positive ions is sufficiently high → reduction of the electric field in the vicinity of the anode below E_c → avalanche stops
- For a fixed applied voltage the discharge always stops after developing about the same total charge ↔ independent of the number of ion pairs created by the initial radiation
- The Geiger tube is only a particle counter

Quenching gas (1)

- After discharge → positive ions slowly arrive at the cathode
- They are neutralized by combining with e^- from the cathode → energy equal to the ionization energy of the gas minus the energy required to extract e^- from the cathode (work function) is liberated
- If this energy is larger than the cathode work function → another e^- from the cathode can be ejected (with a small probability)
- The number of ions is huge → even though the probability is small → at least one such free e^- is generated → second full Geiger discharge
- The cycle will be infinitely repeated
- Phenomenon more « critic » than for a proportional counter for which the number of ions is too small → weak probability of secondary avalanche (and even though it happens → pulse largely less intense than the initial pulse)

Quenching gas (2)

- A quench gas is added (characterized by a low ionization potential and a more complex molecular structure than the primary gas: 5-10% of ethyl alcohol for example)
- Positive ions collide with molecules of quench gas and due to difference in ionization energy → due to the difference of ionization potential → transfer of positive charge to the quench gas molecule → original ions are neutralized
- Positive ions of the quench gas drift to the cathode
- At the cathode → neutralized → energy excess is going into dissociation of the molecules (no liberation of free electron) → no e^- liberated → no additional avalanches are formed
- Dissociation of quench gas → finite lifetime of the tube ($\sim 10^{10}$ discharges)

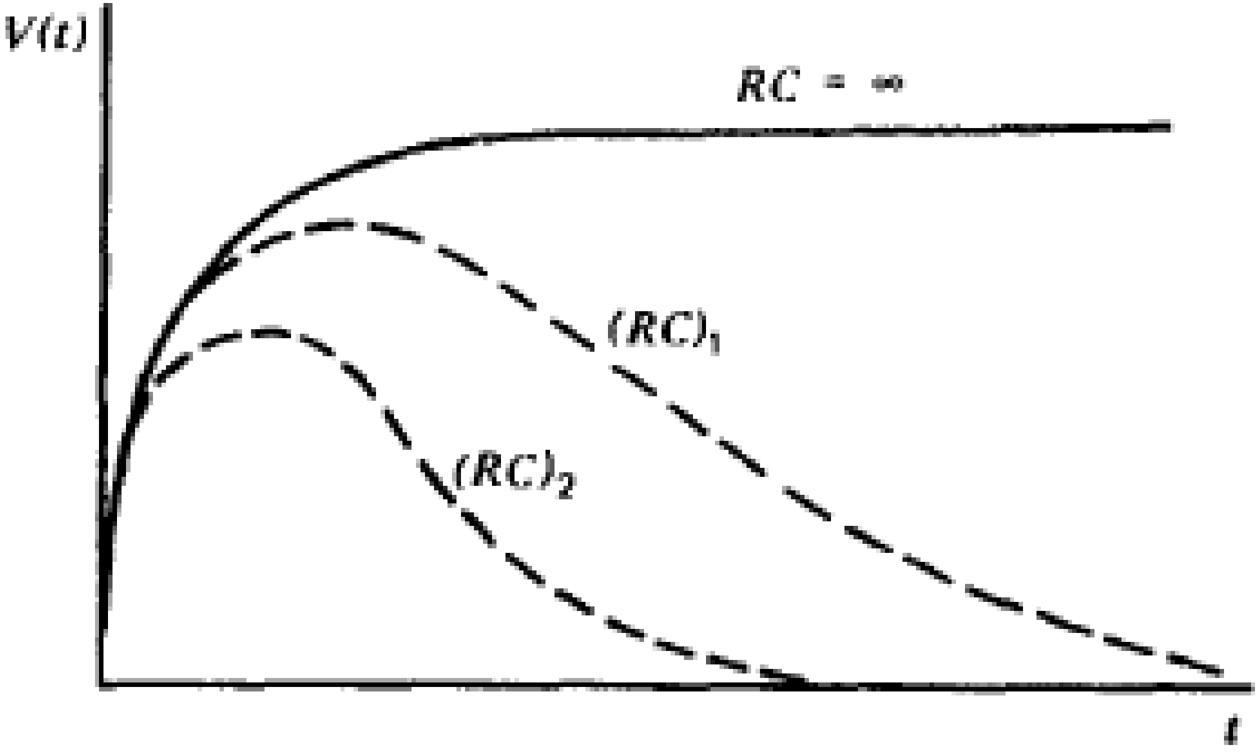
Quenching gas (3)

- To avoid this problem of limited life time → use of Cl_2 or Br_2
- Same principle of molecule dissociation but spontaneous recombination after some time → in principle infinite life time
- However other mechanisms limit the GM life time (ex: modification of the anode surface by ionic deposit)

Charges collection

- Same principle as for a proportional counter but a little bit more complex
- The avalanches are formed along all anode
- The mechanism is more complex due to the modification of the electric field due to space charges
- The collection time of the e^- is a little bit longer than for an unique avalanche but stays very short compared to the collection time of the ions
- The collection time of the ions is long → the maximum will depend on the time constant *RC* of the circuit

Shape of the pulse

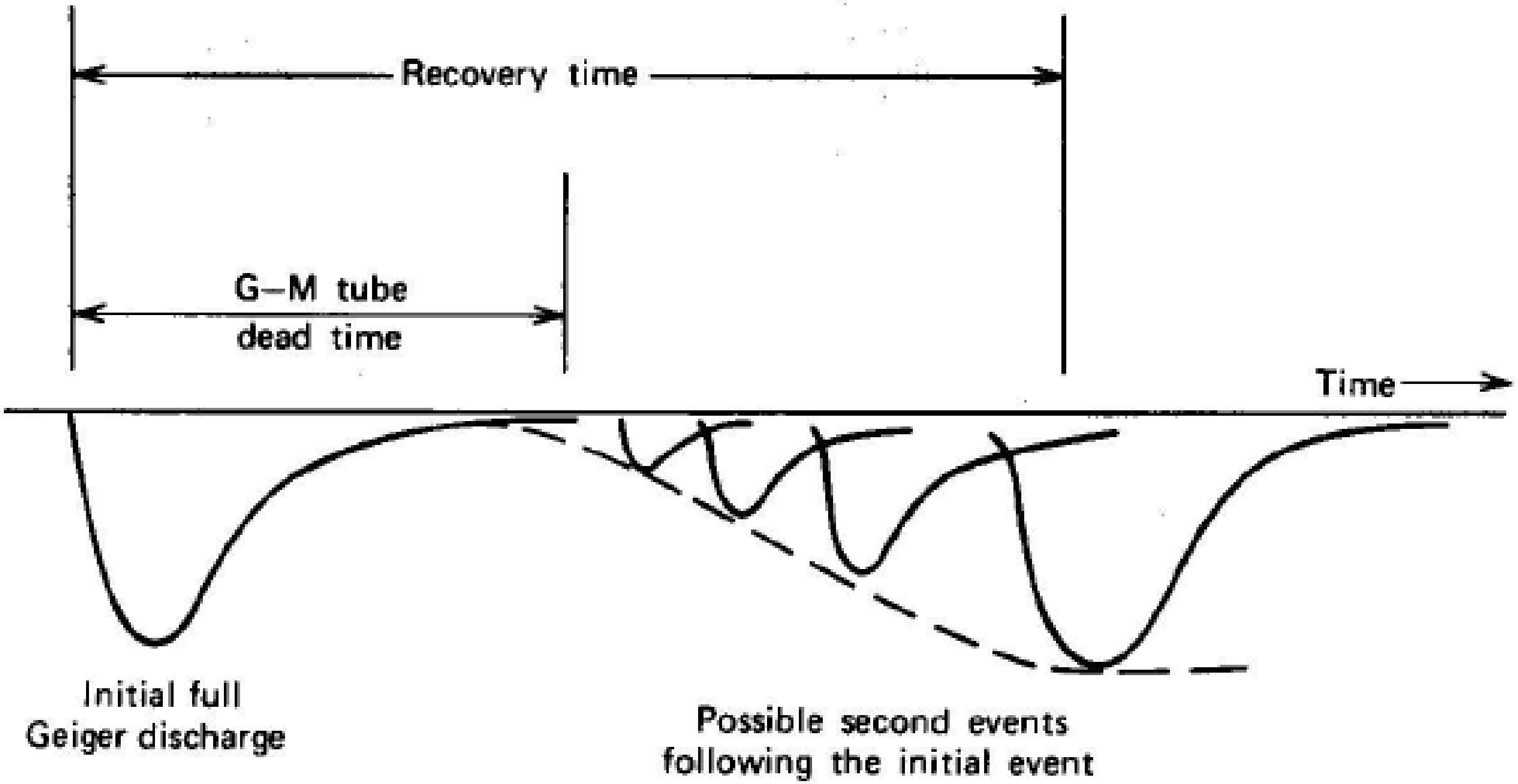


$(RC)_2 < (RC)_1 < RC = \infty$

Dead time and restitution time

- The accumulation of a positive space charge which is at the basis of the discharge stop does not allow to generate a new discharge before the (at least partially) elimination of this space charge
- If an ionizing particle induces a discharge → the following particle will induce a new discharge only if it arrives after a certain time (dead time $\sim$ 200 μs)
- The drift of the positive charge to the cathode allows to the electric field close to the anode to exceed again the critical value → a new discharge can then happen but with a smaller amplitude of the signal because of the weaker electric field
- The pulse reaches its « normal » value only if the new discharge occurs after a certain time called restitution time $\sim$ 1 ms

Illustration of dead time and restitution time



GM applications

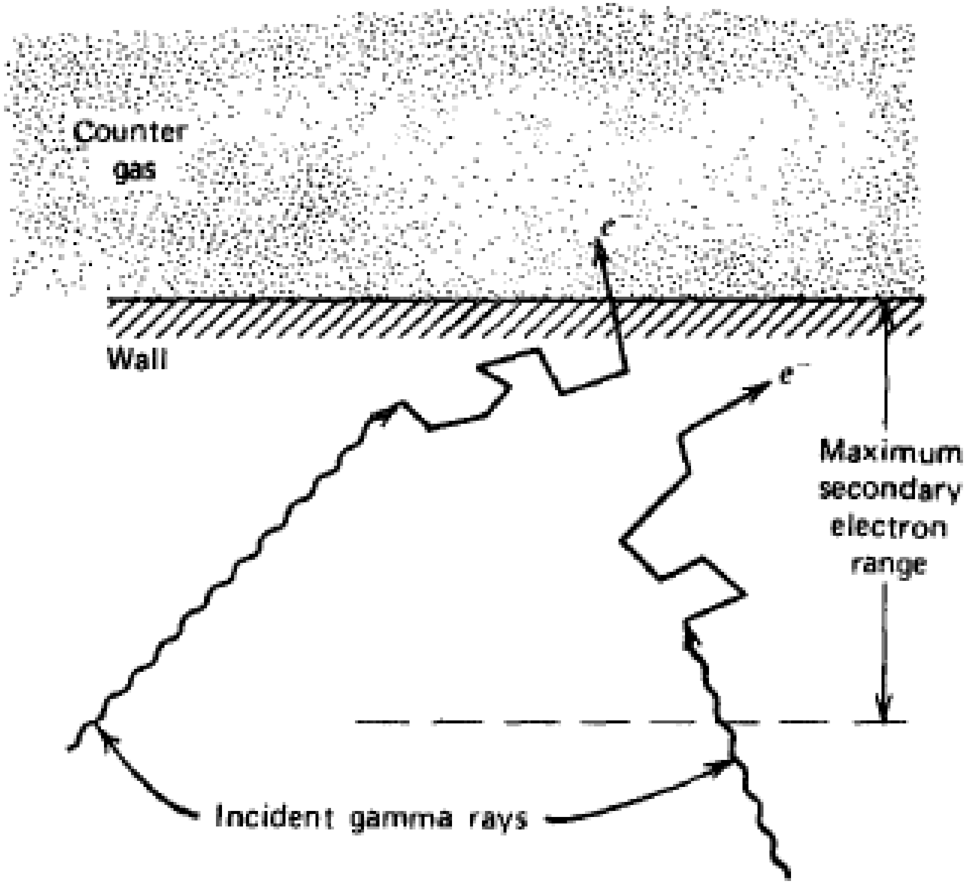
- GM allows the detection of α (rarely) and β when they have a thin entrance window

- They also allow the detection of γ → the interaction of the gammas with the wall produces electrons by photoelectric effect or Compton effect → the electrons that leave the wall and enter into the gas give rise to ionizations → GM signal

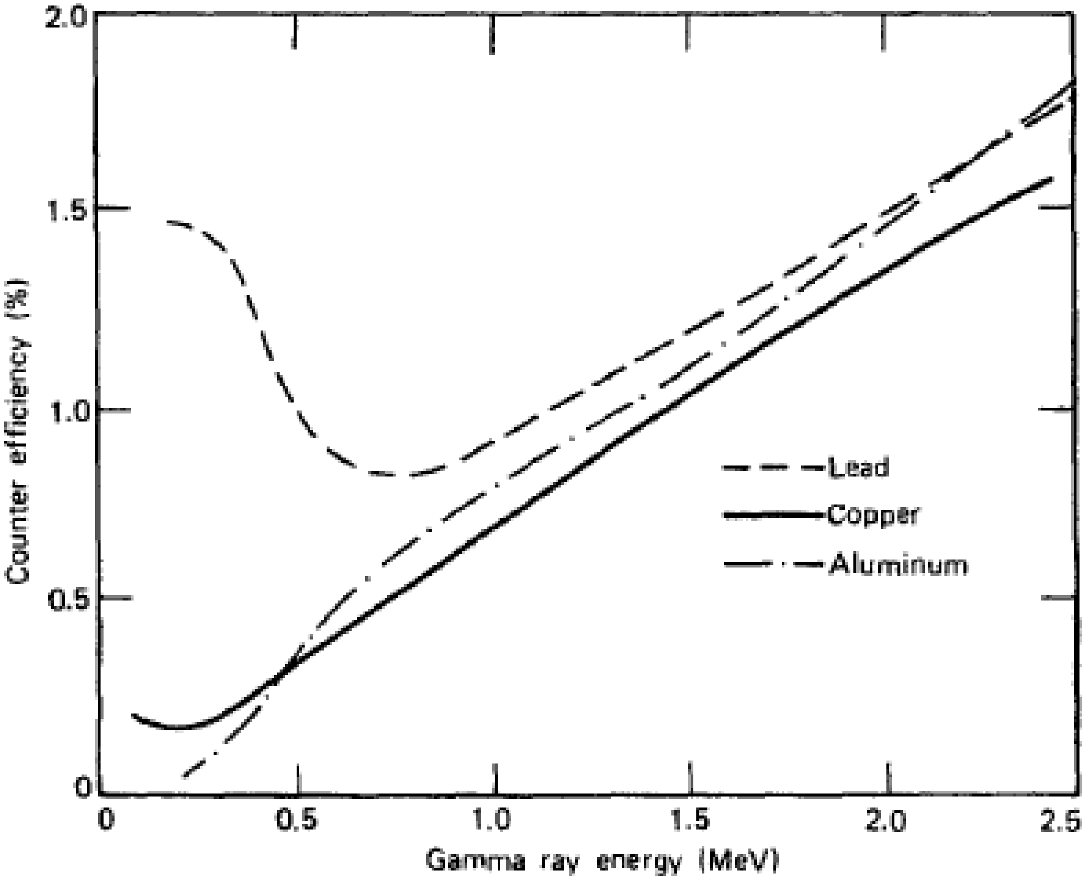
γ detection with GM

- The efficiency of a GM for γ counting depends on 2 factors →
  1. The probability that the γ interacts with the wall and produces an e^-
  2. The probability that the e^- reaches the gas before the end of its path (depends on the work function of the medium of the wall)
- Only the most internal layer of the wall contributes to the e^- production
- This region has a thickness equivalent to the maximal range of the e^- created inside the wall → the increase of the thickness does not increase the efficiency
- On the contrary the efficiency ↘ if the thickness is > than the range due to the absorption of the γ in the external layers of the wall
- The interaction probability ↗ when the medium Z ↗ → large Z are chosen

Illustration of the γ detection with a GM



GM efficiency for the γ detection



In all cases → small efficiency

Example of Geiger-Müller counter

Model TGS-146 from Hitachi Aloka Medical Ltd

Summary of applications of the gas detectors

- Ionization chamber → dosimetry (all particles), detection of α and β and possibly of γ when a high pressure is considered

- Proportional counter → spectroscopy α and proton (the size of the detector must be larger than the range of the particule (otherwise only detection) → for Ar with a thickness of 5 cm with $p = 1$ atm and $T = 20$°C → $E_p < 1.5$ MeV and $E_\alpha < 6$ MeV), detection of β, spectroscopy X, detection of neutrons

- Geiger-Müller counter→ detection of α, β and γ