Gas detectors: general principles

24/1:
- reminder how they work,
- history,
- ionisation,
- electric field,
- electron transport,
- mean gas gain,

25/1:
- gas gain fluctuations,
- ion transport,
- signals.
How they work

Gas-based detectors all work according to much the same principles:

- a charged particle passing through the gas ionises a few gas molecules;

- the electric field in the gas volume transports the ionisation electrons and provokes multiplication;

- the movement of electrons and ions leads to induced currents in electrodes;

- the signals are processed and recorded.
At the 100 μm – 1 mm scale

- Example:
  - CSC-like structure,
  - Ar 80% CO₂ 20%,
  - 10 GeV μ.

- Electron are shown every 100 collisions, but have been tracked rigorously.

- Ions are not shown.
A brief history
Geiger counter

- Detects radiation by discharge;
- can count $\alpha$, $\beta$ and $\gamma$ particles (at low rates ...);
- no tracking capability.
- 1908: Ernest Rutherford and Hans Geiger
- 1928: Hans Geiger and Walther Müller

A Geiger-Müller counter built in 1939 and used in the 1947-1950 for cosmic ray studies in balloons and on board B29 aircraft by Robert Millikan et al.

Made of copper, 30 cm long
Motivation for the Geiger counter

In considering a possible method of counting the number of $\alpha$-particles, their well-known property of producing scintillations in a preparation of phosphorescent zinc sulphide at once suggests itself.

The doubt, however, at once arises whether every $\alpha$-particle produces a scintillation, for it is difficult to be certain that the zinc sulphide is homogeneous throughout. No confidence can be placed in such a method of counting the total number of $\alpha$-particles (except as a minimum estimate), α detection by eye using ZnS scintillation suffers from efficiency losses + is laborious.

It has been recognised for several years that it should be possible by refined methods to detect a single $\alpha$-particle by measuring the ionisation it produces in its path.

We then had recourse to a method of automatically magnifying the electrical effect due to a single $\alpha$-particle. For this purpose we employed the principle of production of fresh ions by collision. In a series of papers, Townsend* has worked out the conditions under which ions can be produced by collisions with the neutral gas molecules in a strong electric field. The effect is best shown in gases at a pressure of several millimetres of mercury.

Ionisation signal is usable but small ($z^2$ !)

Use multiplication at low pressure as discovered in 1901 by JS Townsend.

“ion” = electron here.

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* 'Phil. Mag.,' February, 1901; June, 1902; April, 1903; September and November, 1903.

[E. Rutherford and H. Geiger, An Electrical Method of Counting the Number of $\alpha$-Particles from Radio-Active Substances, Proc. R. Soc. Lond. A 81 (1908) 141-161]
From Tube to TPC

Geiger

MDT
Atlas

MWPC

Drift electrode

Cathode wires

Anode wires

Read-out plane

Cathode plane

Anode wires

Cathode plane
MWPC

- First gaseous tracking device
- 1968: Georges Charpak

Georges Charpak (1924-1992-2010)

One of the NA60 muon chambers
TPC

- Typically very large
- Almost empty inside
- Excellent for dealing with large numbers of tracks

- 1976: David Nygren (for PEP4)
MSGC: an early MPGD

- Built using solid-state techniques;
- good resolution;
- poor resistance to high rates.

- 1988: Anton Oed

![Anode](image1)
![Cathode](image2)
![Substrate](image3)
Micromégas

- Fast, rate tolerant tracking device
- 1994: Yannis Giomataris and Georges Charpak

Wire diameter: 18 µm,
Pitch: 63 µm, Gap: 192 µm

Yannis Giomataris

[Purba Bhattacharya et al., 10.1016/j.nima.2013.07.086; ILC NewsLine]
Muon tomography

- Tower structure and water level are visible.
- Portable system (30 W).

[Sébastien Procureur,
Simon Bouteille,
David Attié]
GEMs

- Acts as a “pre-amplifier”
- 1996: Fabio Sauli

A few electrons enter here

E \sim 2000 \text{ V/cm}

Gas

E \sim 80 \text{ kV/cm}

Metal

E \sim 3000 \text{ V/cm}

Dielectric

Many electrons exit here

Fabio Sauli
Ionisation
1896: Ionisation by radiation

Early in the study of radioactivity, ionisation by radiation was recognised:

” Becquerel discovered in 1896 the special radiating properties of uranium and its compounds. Uranium emits very weak rays which leave an impression on photographic plates. These rays pass through black paper and metals; they make air electrically conductive. “

[Pierre Curie, Nobel Lecture, June 6\textsuperscript{th} 1905]

“A sphere of charged uranium, which discharges spontaneously in the air under the influence of its own radiation, retains its charge in an absolute vacuum. The exchanges of electrical charges that take place between charged bodies under the influence of the new rays, are the result of a special conductivity imparted to the surrounding gases, a conductivity that persists for several moments after the radiation has ceased to act.”

[Antoine Henri Becquerel, Nobel Lecture, December 11\textsuperscript{th} 1903]
Electronic losses at low energy

- Nuclear effects abound at very low energy.
- Numerous models: SRIM, MSTAR, CasP, PASS ...

\[
\frac{dE}{dx} = 20 \frac{\text{MeV cm}^2}{\text{mg}} \times 2.7 \frac{\text{g}}{\text{cm}^3} = 5.4 \frac{\text{MeV}}{\mu\text{m}}
\]

[Ref: Helmut Paul, https://www-nds.iaea.org/stopping/]
1930-1933: EM energy loss

1930 - Hans Bethe, non-relativistic quantum calculation:

The loss in kinetic energy per centimeter path is

\[- \frac{dT}{dx} = N E = \frac{4 \pi e^4 z^2 N}{m v^2} \ln \frac{(2) m v^2}{c R h} .\]

[Christian Møller (1904-1980): average atomic ionisation energy $E$: largest energy transfer per collision $W$:]

1931 - Christian Møller solves relativistic $e^-$ scattering.

1932 - Hans Bethe, relativistic quantum calculation:
Compare PDG with ionisation models

- **Heed**, a photo-absorption & ionisation model, finds for a minimum ionising $\mu^\pm$:
  - Peak: $n_e = 41/\text{cm}$
  - “Mean”: $n_e = 72/\text{cm}$

- **Degrad**, an e$^-$ transport program, finds for an e$^-$ at the same $\beta\gamma$:
  - Peak: $n_e = 50/\text{cm}$
  - “Mean”: $n_e = 62/\text{cm}$

- Mean is ill-defined due to rare but large deposits.

![Graph showing frequency of electrons per cm with PDG and ionisation models compared]
Energy loss fluctuations

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

[Diagram: Richard Talman, NIM A 159 (1979) 189-211]
Clustering – primary interactions

- Electrons are not evenly spaced, not even exponentially:
  
- From ILD TPC test beam studies:
  - 4 × 2 InGrid Octopuce,
  - pixels: 55 × 55 µm²,
  - T2K gas: Ar 95 %, CF₄ 3 %, iC₄H₁₀ 2 %;
  - DESY II, 5 GeV e⁻.

[Michael Lupberger, AIDA-PUB-2014-010, Robert Menzen, AIDA-THESIS-2013-001]
\( \delta \)-electrons

- Deposits are not always “lumps”:

- Laboratory tests:
  - modified MediPix;
  - pixels: \( 55 \times 55 \text{ \( \mu \text{m} \)^2} \);
  - \( \text{He} \) 80 \%, \( \text{iC}_4\text{H}_{10} \) 20 \%.

[Harry van der Graaf and co-workers (2004)]
Virtual photon exchange

Charged particle

Ar atom

$\gamma^*$

$\ll 1 \text{ mm}$

$1 \text{ mm}$
Core formulae PAI model

Key: photo-absorption cross section \( \sigma_\gamma(E) \)

\[
\frac{\beta^2 \pi \alpha}{d} \frac{d \sigma}{d E} = \frac{\sigma_\gamma(E)}{E} \log\left(\frac{1}{\sqrt{(1-\beta^2 \epsilon_1)^2 + \beta^4 \epsilon_2^2}}\right) + \text{Relativistic rise}
\]

\[
\frac{1}{N \hbar c} \left[ \beta^2 - \left( \frac{\epsilon_1}{|\epsilon_1|^2} \right) \theta + \frac{\sigma_\gamma(E)}{E} \log\left( \frac{2 m_e c^2 \beta^2}{E} \right) \right]
\]

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

With:

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

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

\[
\theta = \arctan \frac{1 - \epsilon_1 \beta^2}{\epsilon_2 \beta^2}
\]

Cross section to transfer energy \( E \)

Черенков radiation

Resonance region

Rutherford scattering
Photo-absorption in Ar (Heed)

Argon has 3 shells, hence 3 groups of lines:

- K = 1s
- L1 = 2s
- L2 = 2p 1/2
- L3 = 2p 3/2
- M1 = 3s
- M2 = 3p 1/2
- M3 = 3p 3/2

[Plot from Igor Smirnov]
Importance of the PAI model terms

- All electron orbitals (shells) participate:
  - outer shells: frequent interactions, few electrons;
  - inner shells: few interactions, many electrons.
- All terms in the formula are important.

De-excitation

Fluorescence  Coster-Kronig  Auger

References:
Electric fields
1600: “Electric force”

- 1544: William Gilbert born in Colchester
- 1600: De magnete, magneticisque corporibus, et de magno magnete tellure.
- Concluded that the Earth is a magnet and credited with the first use of the term “electric force”:
  
  vim illam electricam nobis placet appellare quae ab humore provenit

- 1601: Physician to Elizabeth I and James I.

[Guilielmi Gilberti, De magnete ..., excudebat Petrus Short anno MDC, Londini, courtesy Universidad Complutense de Madrid and Google books]
Field calculation techniques

- **Closed expressions, “analytic method”:**
  - almost all 2d structures of wires, planes + periodicities;
  - dielectrics and space/surface charge are laborious;
  - fast and precise, if applicable.

- **Finite element method:**
  - 2d and 3d structures, with or without dielectrics;
  - several major intrinsic shortcomings.

- **Integral equations or Boundary element methods:**
  - equally comprehensive without the intrinsic flaws;
  - technically challenging and emerging;
  - consumes more CPU time than FEM, but catching up.

- **Finite differences:**
  - used for iterative, time-dependent calculations.
1814: Cauchy-Riemann equations

Express the existence of a derivative of a complex analytic function \( f = u + i \, v \):

\[
\frac{\partial f}{\partial x} = \frac{\partial u}{\partial x} + i \frac{\partial v}{\partial x} = \frac{\partial f}{\partial i\, y} = -i \frac{\partial u}{\partial y} + \frac{\partial v}{\partial y}
\]

implies that the real part \( u \) is harmonic:

\[
\frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 v}{\partial x \, \partial y} = \frac{\partial^2 v}{\partial y \, \partial x} = -\frac{\partial^2 u}{\partial y^2} \quad \Rightarrow \quad \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = \nabla^2 u = 0
\]

Reference: A.L. Cauchy, *Sur les intégrales définies* (1814). This *mémoire* was read in 1814, but only submitted to the printer in 1825.
1749: 2d flow of liquids

Jean le Rond d'Alembert takes part in a hydrodynamics contest in Berlin. Euler gives the price to Jaques Adami.

d'Alembert and Euler don't speak for 10 years, but:

59. On peut encore trouver $M$ & $N$ par la méthode suivante qui est un peu plus simple. Puisque $\frac{dp}{dz} = -\frac{dq}{dx}$

& $\frac{dp}{dx} = \frac{dq}{dx}$, donc $qdxdz + pdz$ & $pdz - qdz$ feront des différentielles complètes.


Stigler's law

“no scientific discovery is named after its original discoverer”
Why not 3d?

- The complex numbers \((\mathbb{IR}^2, +, \times)\) form a field, like the real numbers \((\mathbb{IR}, +, \times)\), but \((\mathbb{IR}^3, +, \times)\) does not. As a result, 2d arithmetic can be done with complex numbers, but there is no 3d equivalent for this.

- It can be proven that only \(\mathbb{IR}\) and \(\mathbb{C}\) can form a commutative, associative division algebra.

- \((\mathbb{IR}^4, +, \times)\) can be made into a non-commutative division algebra known as quaternions, but this does not help since \(\nabla \cdot E\) links all dimensions.

Caspar Wessel (1745-1818)
Jean-Robert Argand (1768-1822)
Johann Carl Friedrich Gauss (1777-1855)
Sir William Rowan Hamilton (1805-1865)
Charles Sanders Peirce (1839-1914)
Georg Frobenius (1849-1917)
Aircraft wings – finite elements

“Stiffness and Deflection Analysis of Complex Structures”, a study in the use of the finite element technique (then called “direct stiffness method”) for aircraft wing design.

\[
[K] = \frac{6EI}{Lh^2(1 + 4n)} \begin{bmatrix}
\frac{4}{3} (1 + n) & 0 & 0 & 0 & 0 & 0 \\
-(h/L) & 0 & h^2/L^3 & 0 & 0 & 0 \\
(2/3) (1 - 2n) & 0 & -(h/L) & (4/3) (1 + n) & 0 & 0 \\
0 & 0 & 0 & 0 & h/L & 0 \\
h/L & 0 & -(h^2/L^3) & h/L & 0 & h^2/L^2
\end{bmatrix}
\]

neBEM's Green's functions

- neBEM has only 3 Green's functions:
  - rectangle;
  - right-angled triangle;
  - line segment.

- The Green's functions have been computed by integrating a uniform charge distribution across the element.

- This avoids the nodal charges found in several BEM methods. But the joints between elements still have a jump.
Electron transport
Mean free path in argon

- Literature will tell you
  - $e^-$ cross section Ar atom: $\sigma \approx 1.5 \times 10^{-16}$ cm$^2$
  - atoms per unit volume: $n_0 \approx 2.7 \times 10^{19}$ atoms/cm$^3$

- Mean free path for an electron?
  - An electron hits all atoms of which the centre is less than a cross section $\sigma$ radius from its path;
  - over a distance $L$, the electron hits $n_0 \sigma L$ atoms;
  - mean free path = distance over which it hits 1 atom;
    \[
    \lambda_e = \frac{1}{(\sigma n_0)} \approx 2.5 \mu m
    \]
  - much larger than
    - 4 nm distance between atoms, and
    - 140-600 pm typical gas molecule diameters.
MPGDs and the mean free path

- Recall:
  - Mean free path of electrons in Ar: 2.5 µm,

- Compare with:
  - Micromegas mesh pitch: 63.5 µm
  - GEM polyimide thickness: 50 µm
  - Micromegas wire diameter: 18 µm
  - GEM conductor thickness: 5 µm

- Hence:
  - mean free path approaches small structural elements;
  - such devices should be treated at a molecular level.
Velocity in electric fields

Imagine that an electron stops every time it collides with a gas molecule and then continues along $E$.

To cover a distance $\lambda_e$ it will need a time $t$:

$$\frac{1}{2} \frac{qE}{m_e} t^2 = \lambda_e, \quad t = \sqrt{\frac{2\lambda_ee}{qE}}, \quad \bar{v} = \frac{\lambda_e}{t} = \sqrt{\frac{\lambda_ee}{2m_e}}$$

which gives:

$$\bar{v} \approx 13 \text{ cm/\mu s} \quad \text{for} \quad E = 1 \text{ kV/cm}$$
Drift velocity in argon

Compare with a Magboltz calculation for pure argon:

\[ \sqrt{E} \] dependence is not too far off, although linearly proportional is more common at low field),

BUT

the velocity is \textit{vastly} overestimated! Magboltz finds a velocity that is \textit{30 times} smaller ...

WHY?
Adding CO$_2$

- CO$_2$ makes the gas faster, dramatically.

- Drift velocities calculated by Magboltz for Ar/CO$_2$ at 3 bar. 
  (Note where the arrow is !)
**CO$_2$ – vibration modes**

- CO$_2$ is linear: O – C – O
- Vibration modes are numbered $V(ijk)$:
  - $i$: symmetric,
  - $j$: bending,
  - $k$: anti-symmetric.

![Diagram of CO$_2$ vibrations](image)
Electrons in $\text{Ar}/\text{CO}_2$ at $E=1$ kV/cm
Electrons in Ar/CO$_2$ at $E=1$ kV/cm

40% CO$_2$

50% CO$_2$

Starting point
Drift velocity vs Mean velocity

- Drift velocity $v_D$: distance effectively travelled $\div$ time needed.

- Compare rabbit and turtle:

\[ v_D = \bar{v} \]

\[ v_D \ll \bar{v} \]
Diffusion

- The combination of a high velocity and low drift velocity implies that the electrons scatter a lot.

- Diffusion = RMS of the difference between the actual and the average movement

In a homogeneous field, if the diffusion over 1 cm of drift is 100 µm, how large is the diffusion over 1 m?
Adding CO$_2$

- Transverse diffusion is much reduced by CO$_2$.
- Calculated by Magboltz for Ar/CO$_2$ at 3 bar.
Some quencher gases can attach electrons.

Energy-momentum conservation: 3-body or dissociation.

Examples:
- $O_2$: mostly 3-body $O_2^-$ and at higher $\epsilon$ 2-body dissociative;
- $H_2O$: $[H_2O]_n$ has positive electron affinity, $H_2O$ probably not;
- $CF_4$: mostly dissociative $F^- + CF_3$, $F + CF_3^-$ (below 10 eV);
- $SF_6$: $SF_6^- < 0.1$ eV, $\sigma=10^{-18}$ cm$^2$, then $F^- + SF_n^-$ (n=3, 4, 5);
- $CS_2$: negative ion TPC;
- $CO_2$: $O^-$, $[CO_2]_n^-$ but no $CO_2^-$ (4 eV and 8.2 eV).
\( \text{CO}_2 \) – dissociative attachment

- \( \text{CO}_2 \) has a tiny attachment cross section at low energy.

- The 4 eV peak is linked to a short-lived \( ^2\Pi_u \) shape resonance which decays 
  \( e^- \text{CO}_2 \rightarrow \text{CO} + \text{O}^-; \)
  
  [A. Moradmand et al. (2013) 10.1103/PhysRevA.88.032703]

- The 8.2 eV peak is thought to be a Feshbach resonance.

Note the change in vertical scale!
Feshbach and Shape resonances

- Feshbach: e⁻ attached to electronically excited CO₂* states of the neutral CO₂ molecule.
- Shape: e⁻ trapped within barrier.

Attachment in $\text{CO}_2$

$\text{CO}_2$ is a linear molecule:

hybrid orbitals only, p-orbitals not shown
Calculating transport properties

- One can of course measure every mixture one needs …

- … but it would be far more efficient if one could compute the transport properties of arbitrary mixtures.
1935: Electron energy distribution

- Calculation of the electron energy distribution
- allowing for energy loss in elastic collisions;
- detailed balancing of energy and momentum gain (E-field, diffusion) and loss (elastic collision);
- velocity dependent cross section;
- use of Legendre expansion (crediting H.A. Lorentz, 1916):

\[
f(x, v, \omega) = f_0(x, v) + P_1(\cos \omega)f_1(x, v) + P_2(\cos \omega)f_2(x, v) + \cdots
= f_0(x, v) + (\xi/v)f_1(x, v) + \cdots.
\]

\(P_1, P_2\) : Legendre polynomials

The function \(f_0\) determines the random distribution in velocity, and \(f_1\) determines the electron drift. The higher terms in the series are nearly always very small and do not correspond to any simple physical property of the distribution, but serve simply to improve the form of the distribution function.

[Philip M. Morse, W.P. Allis and E.S. Lamar, Velocity Distributions for Elastically Colliding Electrons, Phys. Rev. 48 (1935) 412–419]
1962: Numerical e\textsuperscript{-} transport

- Iterative approach, allowing for inelastic cross section terms:
  - educated guess of cross sections (elastic & inelastic);
  - \textbf{numerically} solve the Boltzmann equation (no moments);
  - compare calculated and measured mobility and diffusion;
  - adjust cross sections.

“... more than 50,000 transistors plus extremely fast magnetic core storage. The new system can simultaneously read and write electronically at the rate of 3,000,000 bits of information a second, when eight data channels are in use. In 2.18 millionths of a second, it can locate and make ready for use any of 32,768 data or instruction numbers (each of 10 digits) in the magnetic core storage. The 7090 can perform any of the following operations in one second: 229,000 additions or subtractions, 39,500 multiplications, or 32,700 divisions. “ (IBM 7090 documentation)

A large number of cross sections for 60 molecules...

- Numerous organic gases, additives, *e.g.* \( \text{CO}_2 \):
  - elastic scattering,
  - 44 inelastic cross sections (5 vibrations and 30 rotations + super-elastic and 9 polyads),
  - attachment,
  - 6 excited states and
  - 3 ionisations.

- noble gases (He, Ne, Ar, Kr, Xe):
  - elastic scattering,
  - 44 excited states and
  - 7 ionisations.
LXcat (pronounced elecscat) is an open-access website for collecting, displaying, and downloading ELECtron SCATtering cross sections and swarm parameters (mobility, diffusion coefficient, reaction rates, etc.) required for modeling low temperature plasmas. [...]”

[http://www.lxcat.laplace.univ-tlse.fr/]
LXcat people

- Art Phelps,
- Leanne Pitchford – Toulouse,
- Klaus Bartschat – Iowa,
- Oleg Zatsarinny – Iowa,
- Michael Allan – Fribourg,
- Steve Biagi
- ...

Art Phelps
Leanne Pitchford
Michael Allan
Klaus Bartschat
Gas gain
1901: Gas multiplication

John Townsend:

Let a force $X$ be applied to $N_0$ negative ions in a gas at pressure $p$ and temperature $t$. Let $N$ be the total number of negative ions after the $N_0$ ions have travelled a distance $x$. The new negative ions travel with the same velocity as the original $N_0$ ions, so that all the negative ions will be found together during the motion. The number of negative ions produced by $N$ ions travelling through a distance $dx$ will be $\alpha Ndx$; where $\alpha$ is a constant depending on $X$, $p$, and $t$.

Then

$$dN = \alpha Ndx.$$ 

Hence

$$N = N_0 e^{\alpha x}.$$

[J.S. Townsend, “The conductivity produced in gases by the motion of negatively charged ions”, Phil. Mag. 6-1 (1901) 198-227. If access to the Philosophical Magazine is restricted, then consult a German-language abstract at http://jfm.sub.uni-goettingen.de/.]
Mean size of the avalanche

- Townsend coefficient $\alpha$: probability per unit length that an electron creates an additional electron.

- Avalanches grow proportionally to their size:

\[
\frac{\text{d} n(x)}{\text{d} x} = n(x) \alpha(x) \quad \text{d} x
\]

\[
n(x) = n(0) e^{\int_0^x \alpha(y) \text{d} y}
\]

- $\alpha$ Depends on the electric field which in turn varies across the detector, symbolically written here as $x$, and also on pressure and temperature.

- Intuitively, gain is merely a matter of ionisation.
$\alpha(\text{Ar-CO}_2)$

- $\alpha = \text{number of e}^-$ an avalanche e$^-$ creates per cm.

- Adding CO$_2$ reduces the gain.

- Calculated by Magboltz for Ar/CO$_2$ at 3 bar.
Does this reproduce the measurements?

\( \text{Ar - CH}_4 \) vs \( \text{Ar - CO}_2 \)

- **Ar - CH\(_4\)**: Measurements and calculations using Townsend coefficient.
- **Ar - CO\(_2\)**: Different CO\(_2\) concentrations (5%, 10%, 15%, 20%) shown with varying gain vs anode potential.
Level diagram argon and admixtures

Ionisation energies of the admixtures

Ionisation

Excimers

Ground state

Diss. ground
Simplified Penning model

Take small steps until the energy has been used up

\[ \text{Ar}^* \rightarrow \text{Ar}_2^+ + e^- \rightarrow \text{CO}_2^+ + e^- \]

- Energy absorbed, no ionisation
- Radiation trapping, photo-ionisation

Frans Michel Penning (1894-1953)
Radiation trapping

- Photons emitted by radiative decay to ground of excited noble gas atoms have a high probability of being re-absorbed and subsequently re-emitted by the noble gas: radiation trapping.

- Eventually, after many absorption/emission cycles, the photons are absorbed by a quencher gas molecule.

- Excited states can effectively have a long lifetime.
Direct vs Exchange ionisation

Direct ("radiative")

Exchange ("Auger")

atomic levels

Ar CO₂

atomic levels

Ar CO₂
Simplified Penning model (cont'd)

Let $A$ be a noble gas and $B$ a quencher, $A^*$ is excited with excitation energy $> \text{ionisation energy of } B^+$.

In a time-step $dt$, $A^*$ produces $n \, dt$ electrons:

- $A^*$ collides with $B$ and transfers its excess energy, or
- $A^*$ decays and radiatively ionises $B$

\[ n = p \, c \, \frac{f_{B^+}}{\tau_{A^*B}} + f_{\text{rad}} \]

or ... $A^*$ survives with probability:

\[ 1 - \frac{dt}{\tau_P}, \quad \frac{1}{\tau_P} = p \, c \, \frac{f_{B^+} + f_{\overline{B}}}{\tau_{A^*B}} + \frac{1}{\tau_{A^*}} \]

$p = \text{pressure}$
$c = \text{quencher fraction}$
$f_{B^+} = \text{collision transfer}$
$f_{\overline{B}} = \text{collision loss}$
$f_{\text{rad}} = \text{radiative decay}$
$\tau_{A^*B} = \text{collision time}$
$\tau_{A^*} = \text{decay time}$
Simplified Penning model (cont'd)

- Summing to get the number of electrons from $A^*$:

\[
r(p,c) = ndt + ndt \left( 1 - \frac{dt}{\tau_p} \right) + ndt \left( 1 - \frac{dt}{\tau_p} \right)^2 + ... \\
= n \tau_p
\]

Nothing happened in the first step

- $r(p,c)$ is the fraction of the excitation frequency to be added to the ionisation frequency in order to correct the Townsend coefficient for the Penning effect.

- There are only two a priori unknown parameters:
  - $f_{\text{rad}}$: radiative ionisation probability,
  - $f_{B^+}$: collision ionisation probability.
Determining the Penning parameters

The Penning transfer rate \( r(p,c) \) is measured by finding, in experimental data, the fraction of excitations to be added to \( \alpha \):

\[
G = \exp \int \alpha \left( 1 + r(p,c) \frac{v_{\text{exc}}}{v_{\text{ion}}} \right)
\]

The model parameters may be found by fitting:

\[
\begin{align*}
r(p,c) &= \frac{pc f_{B^+}/\tau_{AB} + p(1-c)f_{A^+}/\tau_{AA} + f_{\text{rad}}/\tau_{A^*}}{pc(f_{B^+} + f_{B})/\tau_{AB} + p(1-c)(f_{A^+} + f_{A})/\tau_{AA} + 1/\tau_{A^*}} \\
A^* &\rightarrow B^+ \quad A^* \rightarrow A^+ \quad A^* \rightarrow A \gamma
\end{align*}
\]
Data covers 5 orders of magnitude!

- Current reference is taken at the ionisation level.
- Main source of error: ~5%.
Ar-CO$_2$ transfer rates

- Penning parameter fits with data from Tadeusz Kowalski et al. 1992 and 2013.
- At $p = 1070$ hPa.

[10.1016/0168-9002(92)90305-N, 10.1016/j.nima.2014.09.061]
Gas gain fluctuations
If the distance between ionisations fluctuates exponentially with a mean of $1/\alpha$ (reciprocal of the Townsend coefficient), then, the avalanche size fluctuates (nearly) exponentially:

$$p(n) = \frac{1}{\bar{n}} \left| 1 - \frac{1}{\bar{n}} \right|^{n-1}$$

George Udny Yule (1871-1951)

Statistics Yule-Furry

- Yule-Furry is exponential for large mean avalanche sizes:

\[ p(n) = \frac{1}{\bar{n}} \left( 1 - \frac{1}{\bar{n}} \right)^{n-1} \approx e^{-n/\bar{n}} \]

- Mean: \( \bar{n} \)
- RMS: \( \bar{n} \sqrt{1 - 1/\bar{n}} \approx \bar{n} \)
S.C. Curran (1949)

S.C. Curran et al. measured the pulse height distribution in a cylindrical counter ($d = 150 \, \mu m$ wire, $Ar 50\% CH_4 50\%$, $p = 670\, mbar$) at $G \sim 10^4-10^5$:

\[ p(n) = \sqrt{n} e^{-n} \]

\[ f \equiv \left| \frac{\sigma}{\bar{n}} \right|^2 \approx \frac{2}{3} \]
Pólya distribution

- When mathematicians speak of a Pólya distribution, they refer to a negative binomial distribution.

- Avalanche papers may mean a $\Gamma$-distribution:

$$P(g) \propto g^\theta e^{-(1+\theta)g}$$

Note: we sometimes shift $\theta$ by one unit!

- and sometimes make reference to a 1923 paper which deals with railway accidents, diseases and flowers.

[F. Eggenberger and G. Pólya, Über die Statistik verketteter Vorgänge, Zeitschrift für Angewandte Mathematik und Mechanik 3 (1923) 279-289.]
Hump – good or bad?

- Smaller gain fluctuations:
  - better energy resolution.

- Smaller probability of small gain:
  - higher detection efficiency.

- Smaller probability of high gain:
  - fewer discharges.

\[ f \equiv \frac{\sigma^2}{\bar{n}^2} \]
Assumptions

- Yule-Furry follows if one assumes:
  - probability to ionise over a distance $dx$ is $\alpha \, dx$
  - distance between ionisations fluctuates exponentially with mean $1/\alpha$.
- no history: Townsend coefficient $\alpha$ is constant,
- no attachment losses.
Two schools of thought ...

- The distance between ionisations does not simply vary exponentially (e.g. the Raether group).

- The Townsend coefficient is not constant (e.g. Byrne, Lansiart & Morucci).
Minimum step length

Imposing a minimum distance between ionisations adds a hump.

These are not exponentials.
Mean and Minimum step size

Mean distance between successive ionisations:

\[ \bar{\lambda} = \frac{1}{\alpha} \]

Minimum distance between successive ionisations:

\[ \lambda_{\text{min}} > \frac{IP}{E} \]

Define

\[ \frac{\bar{\lambda}}{\lambda_{\text{min}}} = \frac{E}{\alpha IP} = \kappa \]

- Large \( \kappa \) minimum distance has no effect → exponential
- \( \kappa \approx 1 \) little room for fluctuations → hump
Heinz Raether's group (Hamburg)

- After ionisation, electrons have to travel a minimum distance before their energy again suffices to ionise.

- \( \kappa = \frac{E}{\alpha IP} \) is an indicator of the avalanche shape.

- Lothar Frommhold (1956)
  \( \kappa = 12-110: \) exponential

- Hans Schlumbohm (1958)
  \( \kappa > 23: \) exponential
  \( 23 > \kappa > 10: \) levels off towards small sizes
  \( 10 > \kappa: \) a maximum appears

- Werner Legler (1961)
  any \( \kappa \) model calculation.
Hans Schlumbohm (1958)

Dimethoxymethane spectra: increasing $E$, decreasing $p$ and $d$ and ~constant mean gain.

The Magnettrommelrechner (1961)

Excellent agreement ... but no closed form

\[ \kappa = 5.3 \]

Abb. 5. Lawinenverteilung in Methylal nach Schlumbohm \(^8\). 
\( E/p = 186.5 \text{ Volt/cm} \cdot \text{Torr, } \alpha \cdot U_i/E = 0.19 \). Ausgezogene Kurve: Theoretische Verteilung im Modellgas für \( \alpha x_0 = 0.18 \).
The alternative school

Townsend coefficient not constant ...
A. Lansiart & J.P. Morucci (1962)

- Small avalanches are composed of electrons that
  - have ionised less, hence
  - have more energy, hence
  - will ionise more easily.

- They modeled this with an avalanche size-dependent $\alpha$:
  $$\alpha(n) = \alpha(0) \left(1 + \frac{k}{n}\right)$$

- Implies that $f = (\sigma/\mu)^2 = 1/(1+k) < 1$, in agreement with Curran's measurements.

- Electron energy distribution continues to decrease, without reaching an equilibrium.
Werner Legler's response (1967)

“To do this in general one has to use an ionization coefficient $\alpha(n, x)$ which depends not only on $n$ but also on the distance $x$ the avalanche has covered from the starting point (cathode) of the primary electron.

Besides the experimental doubts, the introduction instead of $\alpha(n, x)$ of an ionization coefficient which depends on $n$ only leads to serious theoretical difficulties.

The suppression of the dependence on $x$ means that the electron swarm has constant ionization probability between successive ionizations and relaxation effects are neglected, completely contrary to the intention of Cookson and Lewis.

Furthermore, a dependence of the ionization coefficient on $n$ alone is understandable only if there are space-charge effects, and these are quite negligible at the beginning of the avalanche development.”

Г.Д. Алхазов (1970)


Classic paper – examines various geometries, and the ionisation probability as function of distance travelled.

[...] indeed there exists some correlation between $\alpha$, and $K$ [number of electrons already in the avalanche] but it has a much more complicated form as compared to that in eq. (3) [$\alpha \propto 1 + \mu/K$] so that the assumption that the ionization probability depends only on $K$ is in principle unsuitable for the description of the electron avalanche statistics. [...] the distribution of the number of electrons in the single avalanche in uniform fields deviates from a Polya distribution. [...] In proportional cylindrical counters the distribution is in close agreement with a Polya one.
Monte Carlo approach – a way out?

- Analytic models are precious for the insight they afford.

- But the complexity of real gases and detectors make realistic models unwieldy:
  - inelastic collisions (vibrations, rotations, polyads);
  - excitations and Penning transfers;
  - ionisation;
  - attachment;
  - intricate, position-dependent $E$ and $B$ fields.

- Predictions for experiments are more practical using a Monte Carlo approach, here based on Magboltz.
Pure argon: Magboltz distribution

With increasing $E$, $\kappa = E/\alpha . \text{IP}$ decreases: the size distribution becomes more rounded:

![Graphs showing multiplications at different fields with exponential and Polya fits.](image-url)
Distance between ionisations

- The distance between successive ionisations oscillates, shown here for Ar (also happens in CH$_4$ for instance).
- Why?

Ar, $E = 30$ kV/cm

[Magboltz calculations by Heinrich Schindler]
Relative variance $f \equiv \sigma^2 / \bar{n}^2$

- $f > 1$ attachment
- $f = 1$ exponential
- $f = 0$ no spread

$f \leftrightarrow \kappa$ translation:
- $\kappa \gg 20 \quad f \approx 1$
- $\kappa < 10 \quad f \downarrow 0$
MC verification: methane

- Schlumbohm (data)
- Cookson and Lewis (data)

Monte Carlo and statistical error
Experimental setup

Vessel mounted on motors

See: 10.1016/j.nima.2010.09.072
Single-electron spectra

**blue**: Pólya signal + Gaussian noise fit;

**red**: Monte Carlo (Magboltz), not fits!

Ar 95 % iC$_4$H$_{10}$ 5 %, E=28.12 kV/cm,
Ne 95 % iC$_4$H$_{10}$ 5 %, E=26.25 kV/cm,
He 95 % iC$_4$H$_{10}$ 5 %, E=26.25 kV/cm,

He: $f \sim 0.35$

Ar: $f \sim 0.60$

Ne: $f \sim 0.35$
Ion transport
Ions

- Avalanches produce not only electrons, but also ions – at least as many.

- Detectors like Micromegas and wire chambers get their signal mostly from ion motion (→ Signals).

- Hence we better know the basics of ions:
  - how fast do the ions move?
  - are they subject to diffusion?
  - which ions are moving?
\( \text{Ar}^+ \) and \( \text{Ne}^+ \) mobility \( \equiv \frac{v_D(E)}{E} \)

The mobility of e.g. noble gas ions in their parent gas has been measured:

\[ \text{HW Ellis et al., At. data nucl. data tables 17 (1976) 177-210 (compilation)} \]
Avalanche products

- $\text{Ar}^+ \text{ dominates in Ar-CO}_2$, $\text{CO}_2^+ \text{ dominates in Ne-CO}_2$ below 150 kV/cm:
Electron-impact cross sections

- $\text{CO}_2^+$ and $\text{Ar}^+$ compete.
- $\text{Ne}^+$ has higher threshold and is produced less.
- Mix: Ne 90 % CO$_2$ 10 %

[Pure gases, data from LXcat]
Ion induced signals

One can calculate the current induced on the pads of a TPC by ions moving from the anode wires to the field wires where they give a signal.

Example: NA49 TPC.
How about $\text{Ne}^+$ in Ne?

$\text{Ne}^+$ ions in Ne come reasonably close to the measurements ...

we've used it for years ...

but does it make sense?

NA49 TPC: Ne 90 % $\text{CO}_2$ 10 %.

[Data: Rainer Renfordt]

Time taken by an ion from anode wire to field wire [µs]
Consider a charge transfer reaction $A^+ B \rightarrow A B^+$:
- rate $\propto$ density of B molecules $N_B \,[1/cm^3]$;

The proportionality factor is called rate constant, $k$:
- rate $= k \,[cm^3/s] \, N_B \,[1/cm^3]$.
- The reaction time $\tau$ is the reciprocal of the rate.

Example: $Ar^+$ in Ar (resonant charge exchange)
- $k = 4.6 \times 10^{-10} \, cm^3/s$, $N \approx 2.45 \times 10^{19}/cm^3$,
- rate $= 1.1 \times 10^{10}/s$, $\tau = 100 \, ps$,
- Main effect: reduces mobility.
Thermal collision frequency

Mean relative velocity:

\[ \bar{v}_{\text{rel}} = \sqrt{\frac{8 k_B T}{\pi \mu}} \approx 570 \text{ m/s} \]

Values for Ar-Ar\(^+\) at 300 K and 1 atm, \(\mu\): reduced mass for Ar, \(\sigma\): empiric momentum transfer cross section \(\Omega^{(1,1)} = 157 \times 10^{-16} \text{ cm}^2\).

Multiplying with the cross section \(\sigma\) gives the rate constant:

\[ k = \sigma \bar{v}_{\text{rel}} \approx 9 \times 10^{-10} \text{ cm}^3/\text{s} \]

Combining with the number density gives the reaction time:

\[ \tau = \frac{1}{N \sigma \bar{v}_{\text{rel}}} = \frac{k_B T}{p} \frac{1}{\sigma \bar{v}_{\text{rel}}} = \frac{1}{p \sigma} \sqrt{\frac{\pi \mu k_B T}{8}} \approx 46 \text{ ps} \]

(cf Ar\(_2\))
3-body reactions

- Bound state formation requires the evacuation of excess energy & momentum through internal degrees of freedom (rotation, vibration), or via a “helper”.

- The rate constant in 3-body reactions has the unit of cm$^6$/s.

- Example 1: $\text{Ar}^+ + \text{Ar} + \text{Ar} \rightarrow \text{Ar}^+ \cdot \text{Ar} + \text{Ar}$
  - $k = 2.3 \times 10^{-31}$ cm$^6$/s, assuming $N \approx 2.45 \times 10^{19}$/cm$^3$
  - rate = $k N^2 = 1.3 \times 10^8$/s, $\tau = 7$ ns

- Example 2: $\text{CO}_2^+ + \text{CO}_2 + \text{CO}_2 \rightarrow \text{CO}_2^+ \cdot \text{CO}_2 + \text{CO}_2$
  - $k = 2.4 \times 10^{-28}$ cm$^6$/s
  - rate = $k N^2 = 1.4 \times 10^{11}$/s, $\tau = 7$ ps
Ions drifting in pure Ar

In pure argon, dimers are formed:

\[ \text{Ar}^+({}^2\text{P}^{0}_{3/2}) + 2\text{Ar} \rightarrow \text{Ar}^+\cdot\text{Ar} + \text{Ar} \]

\[ k = 2.3 \pm 0.1 \times 10^{-31} \text{ cm}^6/\text{s}, \ 7 \text{ ns} \]

Note: dimers move faster than ions due to \( \text{Ar} \leftrightarrow \text{Ar}^+ \) resonant charge exchange.

[Ref: P.N.B. Neves et al. 10.1063/1.3497651]
He, Xe, N$_2$

Principal reactions involving CO$_2$

- **Ar$^+$**: charge exchange, $\tau \approx 0.85$ ns
  - Ar$^+$ + CO$_2$ $\rightarrow$ Ar + CO$_2^+$

- **Ne$^+$**: charge transfer in 2-steps, $\tau \approx 8$ ns
  - Ne$^+$ + CO$_2$ $\rightarrow$ Ne + CO$^+$ + O
  - CO$^+$ + CO$_2$ $\rightarrow$ CO + CO$_2^+$

- **CO$_2$**: 3-body association, 7-20 ps
  - CO$_2^+$ + 2CO$_2$ $\rightarrow$ CO$_2^+$•CO$_2$ + CO$_2$

- [For 10 % CO$_2$, atmospheric pressure, room temperature]
\[
\text{Clear}[n\text{Xe}, n\text{Xe}2, n\text{Xe}C2H6, n\text{C}2H4, n\text{C}2H5, n\text{C}2H6]
\]

\[
\text{evol} = \text{Assuming}[[\{r\text{Xe}Xe2 > 0, r\text{Xe}2XeC2H6 > 0, r\text{Xe}C2H4 > 0, r\text{Xe}C2H5 > 0, \\
\text{rXe}C2H6 > 0, n0\text{Xe} > 0, n0\text{C}2H4 > 0, x > 0\},
\]

\[
\text{Simplify}[\text{DSolve}[
\{n\text{Xe}'[x] = -(r\text{Xe}Xe2 + r\text{Xe}C2H4 + r\text{Xe}C2H5 + r\text{Xe}C2H6) n\text{Xe}[x], \\
n\text{Xe}[0] = n0\text{Xe},
\text{nXe}2'[x] = r\text{Xe}2\text{Xe}2 n\text{Xe}[x] - r\text{Xe}2\text{Xe}C2H6 n\text{Xe}2[x],
\text{nXe}2[0] = 0,
\text{nXeC2H6}'[x] = r\text{Xe}2\text{Xe}C2H6 n\text{Xe}2[x],
\text{nXeC2H6}[0] = 0,
\text{nC2H4}'[x] = r\text{Xe}C2H4 n\text{Xe}[x],
\text{nC2H4}[0] = n0\text{C}2H4,
\text{nC2H5}'[x] = r\text{Xe}C2H5 n\text{Xe}[x],
\text{nC2H5}[0] = 0,
\text{nC2H6}'[x] = r\text{Xe}C2H6 n\text{Xe}[x],
\text{nC2H6}[0] = 0\},
\{n\text{Xe}[x], n\text{Xe}2[x], n\text{Xe}C2H6[x], n\text{C}2H4[x], n\text{C}2H5[x], n\text{C}2H6[x]\}, x]]
\]

\[
\text{CForm}[%]
\]

\[
\left\{\begin{array}{l}
n\text{C}2\text{H}4[x] \rightarrow \left(1 - e^{-(r\text{Xe}C2H4 + r\text{Xe}C2H5 + r\text{Xe}C2H6 + r\text{Xe}Xe2) x}\right) n0\text{Xe} r\text{Xe}C2H4 + \\
n0\text{C}2H4 \frac{(r\text{Xe}C2H4 + r\text{Xe}C2H5 + r\text{Xe}C2H6 + r\text{Xe}Xe2)}{(r\text{Xe}C2H4 + r\text{Xe}C2H5 + r\text{Xe}C2H6 + r\text{Xe}Xe2)},
\end{array}\right.
\]

\[
n\text{C}2\text{H}5[x] \rightarrow -\frac{-1 + e^{-(r\text{Xe}C2H4 + r\text{Xe}C2H5 + r\text{Xe}C2H6 + r\text{Xe}Xe2) x}}{r\text{Xe}C2H4 + r\text{Xe}C2H5 + r\text{Xe}C2H6 + r\text{Xe}Xe2} n0\text{Xe} r\text{Xe}C2H5
\]
Reaction dynamics in Ar CO$_2$

Reactions:
- $\text{Ar}^+ + \text{CO}_2 \rightarrow \text{Ar} + \text{CO}_2^+$
- $\text{CO}_2^+ + 2\text{CO}_2 \rightarrow \text{CO}_2^+\cdot\text{CO}_2 + \text{CO}_2$
- $\text{Ar}^+ + 2\text{Ar} \rightarrow \text{Ar}^+\cdot\text{Ar} + \text{Ar}$

Parameters:
- $p = 1$ bar
- Mix: 90% Ar + 10% CO$_2$
Situating cluster ions

- Chemically bound molecules: 0.75 - 11.1 eV
  - covalent or ionic bond.

- Cluster ions: 0.09 - 1.7 eV
  - bound by charge-induced dipole forces,
  - constituents retain their identity.

- van der Waals molecules: 0.0009 - 0.1 eV
  - bound by van der Waals forces
  - observed at low temperatures.

[B.M. Smirnov, “Cluster Ions and Van Der Waals Molecules,” CRC press]
Binding energy of \( \text{CO}_2 \) cluster ions

- Binding energy when successively adding more \( \text{CO}_2 \):
  - \( \text{CO}_2^+ \cdot \text{CO}_2 \): 0.60 eV (16.2 kcal/mol)
  - \( \text{CO}_2^+ \cdot 2\text{CO}_2 \): 0.26 eV (6.0 kcal/mol)


- \( \text{CO}_2^+ \cdot \text{CO}_2 \): 0.51 eV (11.8 ± 1.0 kcal/mol)
- \((\text{CO}_2)_2^+ \cdot \text{CO}_2 \): 0.14 eV (3.3 ± 1.4 kcal/mol)
- \((\text{CO}_2)_3^+ \cdot \text{CO}_2 \): 0.12 eV (2.8 ± 1.4 kcal/mol)


(Conversion: 1 kcal/mole = 0.043 eV)
Life cycle of $\text{CO}_2^+\cdot(\text{CO}_2)_n$

- $\text{CO}_2^+\cdot\text{CO}_2$ has a dissociation energy of 0.6 eV
  - far above thermal energies at 1 bar (35 meV);
  - it is a long-lived cluster – calculated lifetime = 5 ns.
  [B.M. Smirnov, “Cluster Ions and Van Der Waals Molecules,” CRC press]

- This is much longer than the formation time $\tau = 7\text{-}20$ ps via 3-body association in 10 % CO$_2$ with Ar + CO$_2$ as “helpers”.

- Hence, any isolated CO$_2^+$ rapidly binds again.

- $\text{CO}_2^+\cdot(\text{CO}_2)_n$ probably lives shorter but will recombine. The cluster size $n$ will therefore fluctuate at the ns time scale.
Ne\(^+\) in Ne ... did it make sense?

- The avalanche produced little Ne\(^+\) to begin with;
- \(\text{IP}_{\text{Ne}^+} > \text{IP}_{\text{CO}_2^+}\): Ne\(^+\) took 8 ns to generate a CO\(_2^+\);
- which transformed to CO\(_2^+\)•CO\(_2\).
- In nearly pure Ne, there could be some Ne\(_2^+\).
Experimental check

Remains showing that experiments indeed observe CO$_2^+$(CO$_2$)$_n$ and not e.g. Ar or CO$_2^+$ as assumed.

This we do by comparing:
- mobility for lots of mixing fractions (data);
  WITH
- mobility of CO$_2^+$ in pure gases (literature);
- mobility of CO$_2^+$(CO$_2$)$_n$ in pure gases (mass-mobility);
- mobility of CO$_2^+$(CO$_2$)$_n$ in CO$_2$ (literature);
- mobility of Ar$^+$ and Ne$^+$ (literature);
  USING
- the Blanc interpolation formula.
Mass-mobility in pure Ar and Ne
Blanc's mobility interpolation

\[ \frac{1}{K_0} \frac{K_{\text{mix}}}{K_0} = f_{\text{CO}_2} \frac{K_{\text{CO}_2}}{K_0} + f_{\text{Ar}} \frac{K_{\text{Ar}}}{K_0} \]

1/$K_0$ = $E/\nu_D$
reciprocal of mobility for $E \downarrow 0$

Blanc diagram for Ar-CO$_2$

- **Coxon**: pure CO$_2$
- **Schultz**: 1 atm
- **Coimbra**: 0.01 atm, smaller clusters?
- **NA49**: 1 atm
- **ALICE**: 1 atm, water clusters?
Blanc diagram for Ne-CO$_2$

Like in Ar-CO$_2$, CO$_2^+$ forms clusters in Ne-CO$_2$. 
How about alkanes?

- Ar 90 % - C\textsubscript{2}H\textsubscript{6} 10 %, at low pressure.
- Expect Ar\textsuperscript{+} or C\textsubscript{2}H\textsubscript{6} but ... none are seen – why?

[André Cortez et al. 10.1088/1748-0221/8/12/P12012]
Ar-CH₄

Short lived
Long lived

No further reactions reported

Ar

CH₄

Ar⁺

CH₂⁺

CH₃⁺

CH₄⁺

C⁺

CH⁺

C₂⁺

C₂H⁺

C₂H₂⁺

C₂H₃⁺

C₂H₄⁺

C₂H₅⁺

C₂H₆⁺

C₂H₇⁺

C₂H₈⁺

C₃⁺

C₃H⁺

C₃H₂⁺

C₃H₃⁺

C₃H₄⁺

C₃H₅⁺

C₃H₆⁺

C₃H₇⁺

C₃H₈⁺

Ar⁺

CH₄⁺

C₃H₄⁺

C₃H₅⁺

C₃H₆⁺

C₃H₇⁺

C₃H₈⁺

Ar⁺

CH₄⁺

C₃H₄⁺

C₃H₅⁺

C₃H₆⁺

C₃H₇⁺

C₃H₈⁺

slow

impact

ion-CH₄ and ion-Ar interactions

15%

85%

42%

45%
Summary electrons

- Quenchers play a major role in electron transport:
  - increase drift velocity;
  - decrease diffusion.

- Some quenchers increase the gain:
  - Penning effect;
  - gain fluctuations are influenced by quenchers.
Summary ions

- Avalanches ionise the constituent gases, and the initial ions undergo a staggering sequence of reactions.

- In Ar-CO$_2$ and Ne-CO$_2$ mixtures, the signal ions are CO$_2^+$•(CO$_2$)$_n$ clusters, which are slower than CO$_2^+$;
- water forms larger clusters, further reducing the mobility;
- pure noble gases form dimers, Ar$_2^+$, Ne$_2^+$ which are faster than Ar$^+$ and Ne$^+$ due to resonant charge exchange;
- Xe forms dimers, trimers and probably bigger objects;
- alkanes combine to form heavier molecules.

- There is room for theses in this field.