lectures on detectors for high energy physic, astro-particle physic and nuclear physic

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• Claus Grupen, Particle Detectors, (Cambridge University Press, 1996)
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• Lectures from: J.Chauveau, M.-H.Schune et A.Stocchi, Ph.Schwemling, Th.Patzak, Ch.Joram, O.Ullaland… and many discussion with colleagues!!
• Bruno Rossi, High energy particles (Prentice-Hall, 1952)
Lecture on Gaseous detectors
Outline: Reminder
- Ionisation in gas
- Electrons and ions mobility in gas
- Pure gas and gas mixture properties
- Dependences of signal on geometry and applied voltage
- Proportional, streamer and Geiger-Muller modes
- Quencher / gain variation
- δ-ray

Practical examples: applying our knowledge (finally!)
- Few examples of gaseous detectors (including some information on diffusion in gas):
  - MWPC, RPC, MSGC, GEM, Micromegas,
  - drift chambers, TPC, straw (pailles)

Conclusions
Summary on interactions

During first lectures, we have seen that:

**What a particles detector should do:**
Measure of: $E$, $p_{x,y,z}$ (i.e. angular measurement), $x$, $y$, $z$, $dE/dx$, id. (mass), charge, time,…

Which particle would we see in our detectors: $e$, $\mu$, $\gamma$, $\pi$, $K$, proton, n, jets (at high energy), $(\nu)$, $\alpha$ (=He$^{2+}$), $\beta^{+/−}$ (=e$^{+/−}$)

**Energy loss/interactions in matter:**
for charged particles: ionisation, described by Bethe-Bloch formula (*): $10^{-1} \lesssim \beta \gamma \lesssim 10^{4}$

Remark: a m.i.p. particle looses $\sim$ 2 MeV/(g/cm$^2$)
for e$^{+/−}$ above radiation $E_{e}^{c} \sim 660$ MeV/(Z+1.2)
for $\mu^{+/−}$ $E_{\mu}^{c} \sim 7000$ GeV/(Z+2.1)$^{0.89}$

for $\gamma$:
photoelectric effect: $E_{\gamma} \lesssim 1$ MeV
Compton diffusion: $10$ keV $\lesssim E_{\gamma} \lesssim 10$ MeV
pair creation: $2.m_{e} \lesssim E_{\gamma}$

for hadrons, there is also strong interaction: $\sigma_{inel} \approx \sigma_{0}A^{0.7}$, $\sigma_{0} \approx 35$ mb

Radiation interactions and multiple scattering are characterized by: $X_{0} = \frac{716.4 \text{ g.cm}^{-2}A}{Z(Z+1)\ln(287/\sqrt{Z})}$

strong interaction by: $\lambda_{I} \approx 35(\text{g.cm}^{-2})A^{1/3}$

(*): with some correction for e$^+/e^−$
Mean energy loss in matter (heavy part.)

- **“decrease”**, classical effect: as the particle speed decreases it has more time to ionise matter.
- Large minimum around $\beta \gamma \sim 3$
- Relativistic increase: transverse electric field is proportional to $\gamma$; when energy increases, distant collisions are more probable.
- “Plateau”: when impact parameter is of the order of atomic distances polarisation effects (and thus correction) are getting more important.
- Large $dE/dx$ ($\delta$-ray): may be considered as new particle or simply $dE/dx$. 

![Graph showing energy loss in matter with annotations](image)
Interaction of $\gamma$ and electrons in matter

Photoelectric effect $\rightarrow$ pair creation $\rightarrow$ Compton diffusion

$E_{c}^{\mu} \sim E_{c}^{e} \cdot (m_{\mu}/m_{e})^{2} \approx 100$ GeV
Dependence of “density factor” with pressure (for H₂)

\[ \omega^2 = \frac{n e^2}{\varepsilon_0 m} \]

\( n = \#_{\text{el.}}/\text{cm}^3 \)

**Fig. 4.** Ionization loss of \( \mu \)-mesons in various gases. The broken curves give the values of \((1/\rho)(dE/dx)\) which would be obtained without the density effect.
At high energies ($E > E_c$) radiation phenomena's could be describe by a coefficient of absorption: after going through a certain amount of matter of thickness $x$, there is only $e^{-x/L}$ initial particles remaining. $L$ is written $X_0$ EM process and $\lambda_I$ for hadronic process. Unit is cm or g/cm$^2$.

Remark: $\lambda_I > X_0$ for $Z > 6$.

Unit:

$\lambda_I \approx 35 (g/cm^2) A^{1/3}$

And $N.A. = \rho. N_a$ so $\lambda_I/\rho$ in cm varies like $A^{-2/3}$

$$X_0 = \frac{716.4 (g/cm^2) A}{Z(Z+1) \ln(287/\sqrt{Z})}$$

$\lambda_I > X_0$ for $Z > 6$ thus for a given material, electrons and photons are more efficiently absorbed than hadrons.

For material above $Z = 50$:

$\lambda_I > 10 \times X_0$

For lead: $\lambda_I / X_0 \sim 0.12 Z^{4/3} \sim 30$
Electromagnetic shower

E=300 GeV

Hadronic shower

E=300 GeV

Low air quantity in equivalent $X_0$...

Total amount of air at sea level $\sim 23.X_0$
Implication: the hadronic showers

In an hadronic shower, there will be production of many $\pi$, K and neutrons. $\pi^0$ will give an EM component (from 15 to 20% of initial E), some of the $\pi$ et K at low energies will give – by decay - $\mu$, $\nu$. Neutrons are difficult to detect (neutral, heavy part.) and will escape. This gives with neutrino the invisible energy of the shower.

Multiplicity varies with $E \propto \ln(E)$

$\sigma_{inel} \approx \sigma_0 A^{0.7}$  $\sigma_0 \approx 35 \text{ mb}$

~ independant of the energie above 1GeV for p, $\pi$, K…

Remark: energy profil deposition are different between EM and Had. showers: higher multiplicity for hadronic interaction at the begining of the shower development.

secondaries: $p_t \approx 0.35 \text{ GeV/c}$
How the hadronic shower is produced?

Secondary particles production in hadronic showers are coming from “spallation”:

Fig. 6. Step I: Development of an “internuclear cascade”. From one nucleus an intranuclear cascade releases a few high energetic spallation products, which are able to initiate further intranuclear cascade processes. Step II: The highly excited nuclei remaining from each intranuclear cascade deexcite.
( parenthesis
Super-Kamiokande experiment (Japan)

~11:150 PM
~50 k-tonnes ultra pure water
H₂O : 1.X₀ₑₐᵤ = 36 g/cm² (= 36 cm)

n=1.33 => θ₉ₑₐₑ₀ ≈ 40°

Detection of Cerenkov rings produced in water.

Neutrino energy ~1.5 GeV
=> energy of μ and e
in Super-K \(\leq 1.5\) GeV

Reminder: \(E_{C_\mu} \sim < 1.5\) GeV.
"Range" of particle in matter

\[ \frac{dE}{dx} = \sum w_i \frac{dE}{dx} \]

\( w_i = \text{fractional mass of element } \#i \)

\( \sim 400 \text{ g/cm}^2 (\approx 4 \text{m in water}) \)

Slow decrease due to (rare) interaction with high momentum transfer.

Fast brake due to \( \frac{dE}{dx} \) variation like \( \beta^{5/3} \).

This is the Bragg peak

\[ E_\mu \sim 1 \text{ GeV} \]
CONES OF CHERENKOV LIGHT are emitted when high-energy neutrinos hit a nucleus and produce a charged particle. A muon-neutrino (top) creates a muon, which travels perhaps one meter and projects a sharp ring of light onto the detectors. An electron, produced by an electron-neutrino (bottom), generates a small shower of electrons and positrons, each with its own Cherenkov cone, resulting in a fuzzy ring of light. Green dots indicate light detected in the same narrow time interval.
PM and HPD (Hybrid Photo Diodes)

Photo Multiplier Tube

- photocathode
- focusing electrodes
- accelerating electrode
- first dynode
- multiplier
- anode
- window
- input optics
- envelope
- last dynode
- foot
- pumping stem
- base
- key

Remove dynodes and anode, add silicon sensor inside tube

Hybrid Photo Diode

- photocathode
- focusing electrodes
- electron
- silicon sensor
- ΔV

~4000 to 5000 electrons-holes pairs → good energy resolution
parenthesis)
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Conclusions
Electrons and ions drift in gas

First case:
A $m.i.p$ particle. in 1 cm of gas (Ar) will create $\sim 30$ e-/ions pairs.

Question: What is the mean energy required to create an e-/ion pair?
(see PDG Booklet)

If we collect all these charges, we measure:
$V = ne/C$  \hspace{1cm} (\leftarrow Q = C.V)$

Assuming:
$C = 10\text{pF}$, $n = 30 \Rightarrow V \sim \mu\text{-volt (to small)}$

Gas density $\rho$, of the order of $0.001$
So $dE/dx \sim 0.001 \times 1 \times 2 \sim 2\text{ keV}$
More precise calculation gives $4\text{ keV}$ in Ar.

In general, primary electrons have enough energy to locally ionise the gas:
In total, $n_T \approx 3\times \text{ to } 5\times n_{\text{primaire}}$

In summary:

- $V = ne/C$
- $C = 10\text{pF}$, $n = 30 \Rightarrow V \sim \mu\text{-volt (to small)}$
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<thead>
<tr>
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<tr>
<td>H(_2) gas</td>
<td>1</td>
<td>1.00794</td>
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<td>6.00</td>
<td>≈ 0.32</td>
<td>≈ 18.95</td>
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</table>

For Air, \((20^\circ C, 1\text{ atm.}, [STP])\):

- Density \( ^{g/cm^2} \) = 0.49919 g/cm\(^2\)
- Density \( ^{g/L} \) = 62.0 g/L
- Refractive index \( ^{n} \) = 1.33

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<td>8</td>
<td>18.0152</td>
<td>0.55509</td>
<td>60.1</td>
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<td>36.1</td>
<td>1.00</td>
<td>373.15</td>
<td>1.33</td>
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</tbody>
</table>

\(^{a}\) Nuclear, \(^{b}\) dE/dx, \(^{c}\) Density, \(^{d}\) Liquid boiling point, \(^{e}\) Refractive index.
Total number of electron/ion pairs

\[ n_{total} = \frac{\Delta E}{W_i} = \frac{dE}{dx} \frac{\Delta x}{W_i} \]

\[ n_{total} \approx 3 \ldots 4 \cdot n_{primary} \]

\( W_i \) = energy needed for one pair

# of primary pairs in some common gas (and \( W_i \))

\[ \overline{Z} \]

(mean \( Z \))

(Lohse and Witzeling, Instrumentation in High Energy Physics, World Scientific, 1992)
Remark on e-/ion pair production and on energy resolution

Different ways to produce pairs (p= incident particle):

Excitation: \(X+p \rightarrow X^*+p \) then \(X^* \rightarrow X^++e^-\)

Ionisation: \(X+p \rightarrow X^++p+e^-\)

*Penning* effect: \(Ne^*+Ar \rightarrow Ne+Ar^++e^-\)

direct desexcitation is “very low” and happen through collision with Ar.

Resolution on energy will be (mean value):

\[
R = 2.35 \sqrt{\frac{F.w_i}{\Delta E}}
\]

with:

\(F = Fano\) factor ; \(F<1\) due to non independent ionisations

\(\Delta E = \) energy deposited

\(2.35 \approx 2\sqrt{2}\sqrt{\ln2}\) (FWHM coef.)

Depending of the gas, we measure \(F\) from 0.15 to 0.4 (constant changing with material): Ar (0.2); Ar+5%Xe (0.14); Ar+5%Kr (0.37), etc.
Development of signal in a ionisation chamber

Fig. 2.1. Parallel-plate ionization chamber (schematic).

\[ V = \frac{ne}{C} \quad (\leftarrow Q = C.V) \]

Fig. 2.2. Time development of a voltage pulse \( \Delta U(t) \) from ionization chamber for resistance \( R = \infty \).

\[ -\frac{N.e}{C} \quad \frac{z_0}{d} \]

\[ -\frac{N.e}{C} \]

N=number of charges created
C=capacity (hyp. R=\( \infty \))
In practice all these quantities will fluctuate and will depend on e-/ions drift velocity; so will depend on gas properties, conditions (E, pressure, etc.), B, etc.
Lecture #4
Gaseous detectors

Outline:
- Ionisation in gas
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conclusion
Electrons and ions mobility in gas

When created, electrons and ions will drift in the gas. Drift velocity is very different for electrons w.r.t. ions since their masses are very different. We define: \( v_{\text{drift \pm}} = \mu^{\pm} \cdot E \)

**For ions:**
Mean velocity is \( v^+ \propto E/P \)
with: \( E = \) electric field and \( P = \) gas pressure.

For ions, mobility is \( \mu^+ (=v^+/E, \text{by definition}) \) and is \( \sim \) constant since ions do not increase their energy between two collisions.

**For electrons:**
\[ v^- = \left( \frac{e}{2m} \right) E \cdot \tau \]  (Townsend)
with: \( \tau = \text{mean time between two collisions} \)
\( v^- \) goes up to few \( 10^6 \) cm/s

But \( \sigma \), so \( \tau \), varies rapidly with \( E \) for electrons
(in particular when \( \lambda_e \sim \lambda_{e-\text{atomique}}, \) Ramsauer effect)
(Often) drift velocity of \( e^- \) increases rapidly for low field, and then saturate. This is interesting for application in drift chambers.
## Mobility of ions in some gas mixture

<table>
<thead>
<tr>
<th>Gas</th>
<th>Ion</th>
<th>Mobility $\mu^+$ (cm$^2$/V·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>He$^+$</td>
<td>10.2</td>
</tr>
<tr>
<td>Ar</td>
<td>Ar$^+$</td>
<td>1.7</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>H$_2$O$^+$</td>
<td>0.7</td>
</tr>
<tr>
<td>Ar</td>
<td>(OCH$_3$)$_2$CH$_2^+$</td>
<td>1.51</td>
</tr>
<tr>
<td>Iso-C$<em>4$H$</em>{10}$</td>
<td>(OCH$_3$)$_2$CH$_2^+$</td>
<td>0.55</td>
</tr>
<tr>
<td>(OCH$_3$)$_2$CH$_2$</td>
<td>(OCH$_3$)$_2$CH$_2^+$</td>
<td>0.26</td>
</tr>
<tr>
<td>Ar</td>
<td>IsoC$<em>4$H$</em>{10}^+$</td>
<td>1.56</td>
</tr>
<tr>
<td>Iso-C$<em>4$H$</em>{10}$</td>
<td>IsoC$<em>4$H$</em>{10}^+$</td>
<td>0.61</td>
</tr>
<tr>
<td>Ar</td>
<td>CH$_4^+$</td>
<td>1.87</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>CH$_4^+$</td>
<td>2.26</td>
</tr>
<tr>
<td>Ar</td>
<td>CO$_2^+$</td>
<td>1.72</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>CO$_2^+$</td>
<td>1.09</td>
</tr>
</tbody>
</table>

$\mu^+ = v^+ / E$ (by definition)

**Unit:**

$v^+ / E$ (cm/s)/(V/cm)

If $E=1000$ V/cm so

$\mu^+ = 1.72$ cm$^2$/V·s

i.e. **1.72 cm/ms**

**ions**
Mobility of **electrons** in some gas mixture: Garfield simulation

Drift velocity of ionisation e-

\[ v_0 \text{ [cm/μsec]} \]

\[ E \text{ [V/cm]} \]

- Ar 80% CO₂ 20% Coll 10
- Ar 93% CO₂ 7% Coll 10

About ~1000 times speed of ions
Mobility of electrons in gas

\[ \sigma = \text{cross section} \]

\[ \lambda = \frac{\text{fraction of energy loss}}{\text{collision}} \]

\[ \approx 2m_e/m_{\text{mol.}} \]

(CH\textsubscript{4} polyatomique gas)

Normal condition of T and P

One can show that

\[ v_D^2 = \frac{eE}{mN\sigma} \frac{\lambda}{2} \]
Outline:
- Ionisation in gas
- Electrons and ions mobility in gas
- Pure gas and gas mixture properties
- Dependences of signal on geometry and applied voltage
- Proportional, streamer and Geiger-Muller modes
- Quencher / gain variation
- δ-ray

Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
- MWPC, RPC, MSGC, GEM, Micromegas,
- drift chambers, TPC, straw (pailles)

conclusion
“Attachment time” of electrons in gas

Coefficient, number of collisions, and average time for electron attachment in several gases under normal conditions\(^{12,18,21}\)

<table>
<thead>
<tr>
<th>Gas</th>
<th>h</th>
<th>N</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(_2)</td>
<td>6.2 × 10(^{-9})</td>
<td>2.2 × 10(^{11})</td>
<td>0.71 × 10(^{-3})</td>
</tr>
<tr>
<td>O(_2)</td>
<td>2.5 × 10(^{-5})</td>
<td>2.1 × 10(^{11})</td>
<td>1.9 × 10(^{-7})</td>
</tr>
<tr>
<td>H(_2)O</td>
<td>2.5 × 10(^{-5})</td>
<td>2.8 × 10(^{11})</td>
<td>1.4 × 10(^{-7})</td>
</tr>
<tr>
<td>Cl</td>
<td>4.8 × 10(^{-4})</td>
<td>4.5 × 10(^{11})</td>
<td>4.7 × 10(^{-9})</td>
</tr>
</tbody>
</table>

“Attachment time” \(t\) is: \(t = (hN)^{-1}\)

\(h\) = attachment probability (\(\sim 0\) for noble gas and for hydrogen)
\(N\) = # of collision per unit of time

**Num. application:** in oxygen and resp. in water, mean “attachment time” is only of the order of 190 ns and resp. 140 ns! In CO\(_2\) it is of the order of milli-sec.

**Other gas:** 1% of air in Argon will remove 1/3 of electrons per cm of drift (at E=500 V/cm).

(remember \(\sim 1\) cm per \(\mu\)s)
Some gas properties

Table 4. Properties of gases at normal conditions: density $\rho$, minimal energy for excitation $E_{\text{ex}}$, minimal energy for ionization $E_i$, mean effective ionization potential per atomic electron $I_0 = 1/Z$, energy loss $W_i$ per ion pair produced, minimal energy loss $(dE/dx)_0$, total number of ion pairs $n_T$ and number of primary ions $n_p$ per centimetre of path for minimum ionizing particles [SA 77]

<table>
<thead>
<tr>
<th>Gas</th>
<th>$Z$</th>
<th>$A$</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$E_{\text{ex}}$ (eV)</th>
<th>$E_i$ (eV)</th>
<th>$I_0$ (eV)</th>
<th>$W_i$ (eV)</th>
<th>$(dE/dx)_0$ (MeV/g cm$^{-2}$)</th>
<th>$n_p$ (cm$^{-1}$)</th>
<th>$n_T$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>2</td>
<td>2</td>
<td>$8.38 \times 10^{-5}$</td>
<td>10.8</td>
<td>15.9</td>
<td>15.4</td>
<td>37</td>
<td>4.03</td>
<td>5.2</td>
<td>9.2</td>
</tr>
<tr>
<td>He</td>
<td>2</td>
<td>4</td>
<td>$1.66 \times 10^{-4}$</td>
<td>19.8</td>
<td>24.5</td>
<td>24.6</td>
<td>41</td>
<td>1.94</td>
<td>5.9</td>
<td>7.8</td>
</tr>
<tr>
<td>N$_2$</td>
<td>14</td>
<td>28</td>
<td>$1.17 \times 10^{-3}$</td>
<td>8.1</td>
<td>16.7</td>
<td>15.5</td>
<td>35</td>
<td>1.68</td>
<td>10</td>
<td>56</td>
</tr>
<tr>
<td>O$_2$</td>
<td>16</td>
<td>32</td>
<td>$1.33 \times 10^{-3}$</td>
<td>7.9</td>
<td>12.8</td>
<td>12.2</td>
<td>31</td>
<td>1.69</td>
<td>22</td>
<td>73</td>
</tr>
<tr>
<td>Ne</td>
<td>10</td>
<td>20.2</td>
<td>$8.39 \times 10^{-4}$</td>
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<td>21.5</td>
<td>21.6</td>
<td>36</td>
<td>1.68</td>
<td>12</td>
<td>39</td>
</tr>
<tr>
<td>Ar</td>
<td>18</td>
<td>39.9</td>
<td>$1.66 \times 10^{-3}$</td>
<td>11.6</td>
<td>15.7</td>
<td>15.8</td>
<td>26</td>
<td>1.47</td>
<td>29.4</td>
<td>94</td>
</tr>
<tr>
<td>Kr</td>
<td>36</td>
<td>83.8</td>
<td>$3.49 \times 10^{-3}$</td>
<td>10.0</td>
<td>13.9</td>
<td>14.0</td>
<td>24</td>
<td>1.32</td>
<td>22</td>
<td>192</td>
</tr>
<tr>
<td>Xe</td>
<td>54</td>
<td>131.3</td>
<td>$5.49 \times 10^{-3}$</td>
<td>8.4</td>
<td>12.1</td>
<td>21.1</td>
<td>22</td>
<td>1.23</td>
<td>44</td>
<td>307</td>
</tr>
<tr>
<td>CO$_2$</td>
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<td>44</td>
<td>$1.86 \times 10^{-3}$</td>
<td>5.2</td>
<td>13.7</td>
<td>13.7</td>
<td>33</td>
<td>1.62</td>
<td>34</td>
<td>91</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>10</td>
<td>16</td>
<td>$6.70 \times 10^{-4}$</td>
<td>15.2</td>
<td>13.1</td>
<td>28</td>
<td>2.21</td>
<td>1.48</td>
<td>16</td>
<td>53</td>
</tr>
<tr>
<td>C$<em>4$H$</em>{10}$</td>
<td>34</td>
<td>58</td>
<td>$2.42 \times 10^{-3}$</td>
<td>10.6</td>
<td>10.8</td>
<td>23</td>
<td>1.86</td>
<td>4.50</td>
<td>46</td>
<td>195</td>
</tr>
</tbody>
</table>

$\rho$(gaz) $\sim \rho$(solid/liquid)/1000

$n_p$ is used for **efficiency calculation**

$n_T$ is used for **signal calculation**

$x2 \rightarrow x5$
**Energy needed for creating and electron-ion pair**

Table 1.3. Energy $W$ spent, on the average, for the creation of one ionization electron in various gases and gas mixtures [CHR 71]; $W_\alpha$ and $W_\beta$ are from measurements using $\alpha$ or $\beta$ sources, respectively. The lowest ionization potential is also indicated.

<table>
<thead>
<tr>
<th>Gas</th>
<th>$W_\alpha$ (eV)</th>
<th>$W_\beta$ (eV)</th>
<th>$I$ (eV)</th>
<th>Gas mixture$^a$</th>
<th>$W_\alpha$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>36.4</td>
<td>36.3</td>
<td>15.43</td>
<td>Ar (96.5%) + C$_2$H$_6$ (3.5%)</td>
<td>24.4</td>
</tr>
<tr>
<td>He</td>
<td>46.0</td>
<td>42.3</td>
<td>24.58</td>
<td>Ar (99.6%) + C$_2$H$_2$ (0.4%)</td>
<td>20.4</td>
</tr>
<tr>
<td>Ne</td>
<td>36.6</td>
<td>36.4</td>
<td>21.56</td>
<td>Ar (97%) + CH$_4$ (3%)</td>
<td>26.0</td>
</tr>
<tr>
<td>Ar</td>
<td>26.4</td>
<td>26.3</td>
<td>15.76</td>
<td>Ar (98%) + C$_3$H$_8$ (2%)</td>
<td>23.5</td>
</tr>
<tr>
<td>Kr</td>
<td>24.0</td>
<td>24.05</td>
<td>14.00</td>
<td>Ar (99.9%) + C$_6$H$_6$ (0.1%)</td>
<td>22.4</td>
</tr>
<tr>
<td>Xe</td>
<td>21.7</td>
<td>21.9</td>
<td>12.13</td>
<td>Ar (98.8%) + C$_3$H$_6$ (1.2%)</td>
<td>23.8</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>34.3</td>
<td>32.8</td>
<td>13.81</td>
<td>Kr (99.5%) + C$_4$H$_8$-2 (0.5%)</td>
<td>22.5</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>29.1</td>
<td>27.1</td>
<td>12.99</td>
<td>Kr (93.2%) + C$_2$H$_2$ (6.8%)</td>
<td>23.2</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>26.6</td>
<td>24.4</td>
<td>11.65</td>
<td>Kr (99%) + C$_3$H$_6$ (1%)</td>
<td>22.8</td>
</tr>
<tr>
<td>C$_2$H$_2$</td>
<td>27.5</td>
<td>25.8</td>
<td>11.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>35.0</td>
<td>33.8</td>
<td>12.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$O</td>
<td>30.5</td>
<td>29.9</td>
<td>12.60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The quoted concentration is the one that gave the smallest $W$. 
### Application

How many primary and secondary pairs will be created for a \textit{m.i.p.} particle in a mixture of Ar:Butane = 70:30 at normal condition (NTP)?

<table>
<thead>
<tr>
<th>Gas</th>
<th>(Z)</th>
<th>(A)</th>
<th>(\rho) (g/cm(^3))</th>
<th>(E_{\text{ex}}) (eV)</th>
<th>(E_i) (eV)</th>
<th>(I_0) (eV)</th>
<th>(W_i) (eV)</th>
<th>((dE/dx)_0) (MeV/g cm(^{-2}))</th>
<th>(\eta_p) (cm(^{-1}))</th>
<th>(\eta_T) (cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)</td>
<td>2</td>
<td>2</td>
<td>(8.38 \times 10^{-5})</td>
<td>10.8</td>
<td>15.9</td>
<td>15.4</td>
<td>37</td>
<td>4.03</td>
<td>0.34</td>
<td>5.2</td>
</tr>
<tr>
<td>He</td>
<td>2</td>
<td>4</td>
<td>(1.66 \times 10^{-4})</td>
<td>19.8</td>
<td>24.5</td>
<td>24.6</td>
<td>41</td>
<td>1.94</td>
<td>0.32</td>
<td>5.9</td>
</tr>
<tr>
<td>N(_2)</td>
<td>14</td>
<td>28</td>
<td>(1.17 \times 10^{-3})</td>
<td>8.1</td>
<td>16.7</td>
<td>15.5</td>
<td>35</td>
<td>1.68</td>
<td>1.96</td>
<td>10</td>
</tr>
<tr>
<td>O(_2)</td>
<td>16</td>
<td>32</td>
<td>(1.33 \times 10^{-3})</td>
<td>7.9</td>
<td>12.8</td>
<td>12.2</td>
<td>31</td>
<td>1.69</td>
<td>2.26</td>
<td>22</td>
</tr>
<tr>
<td>Ne</td>
<td>10</td>
<td>20.2</td>
<td>(8.39 \times 10^{-4})</td>
<td>16.6</td>
<td>21.5</td>
<td>21.6</td>
<td>36</td>
<td>1.68</td>
<td>1.41</td>
<td>12</td>
</tr>
<tr>
<td>Ar</td>
<td>18</td>
<td>39.9</td>
<td>(1.66 \times 10^{-3})</td>
<td>11.6</td>
<td>15.7</td>
<td>15.8</td>
<td>26</td>
<td>1.47</td>
<td>2.44</td>
<td>29.4</td>
</tr>
<tr>
<td>Kr</td>
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<td>83.8</td>
<td>(3.49 \times 10^{-1})</td>
<td>10.0</td>
<td>13.9</td>
<td>14.0</td>
<td>24</td>
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</tr>
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<td>Xe</td>
<td>54</td>
<td>131.3</td>
<td>(5.49 \times 10^{-1})</td>
<td>8.4</td>
<td>12.1</td>
<td>21.1</td>
<td>22</td>
<td>1.21</td>
<td>6.76</td>
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</tr>
<tr>
<td>CO(_2)</td>
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<td>(1.86 \times 10^{-1})</td>
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<td>13.7</td>
<td>13.7</td>
<td>33</td>
<td>1.62</td>
<td>3.01</td>
<td>34</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>10</td>
<td>16</td>
<td>(6.70 \times 10^{-1})</td>
<td>15.2</td>
<td>13.1</td>
<td>28</td>
<td>2.21</td>
<td>1.48</td>
<td>16</td>
<td>53</td>
</tr>
<tr>
<td>C(_4)H(_10)</td>
<td>34</td>
<td>58</td>
<td>(2.42 \times 10^{-1})</td>
<td>10.6</td>
<td>10.8</td>
<td>23</td>
<td>1.86</td>
<td>4.50</td>
<td>46</td>
<td>195</td>
</tr>
</tbody>
</table>
How many primary and secondary pairs will be created for a \( m.i.p. \) particle in a \( \text{Ar:Butane mixture 70:30, at normal condition (NTP)} \)?

<table>
<thead>
<tr>
<th>Gas</th>
<th>( Z )</th>
<th>( A )</th>
<th>( \rho ) (g/cm(^3))</th>
<th>( E_{\text{ex}} ) (eV)</th>
<th>( E_{\text{i}} ) (eV)</th>
<th>( I_{0} ) (eV)</th>
<th>( W_{i} ) (eV)</th>
<th>( (dE/dx)_{0} ) (MeV/g cm(^{-2}))</th>
<th>( (keV/cm) )</th>
<th>( n_{p} ) (cm(^{-1}))</th>
<th>( n_{T} ) (cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_{2} )</td>
<td>2</td>
<td>2</td>
<td>( 8.38 \times 10^{-5} )</td>
<td>10.8</td>
<td>15.9</td>
<td>15.4</td>
<td>37</td>
<td>4.03</td>
<td>0.34</td>
<td>5.2</td>
<td>9.2</td>
</tr>
<tr>
<td>( \text{He} )</td>
<td>2</td>
<td>4</td>
<td>( 1.66 \times 10^{-4} )</td>
<td>19.8</td>
<td>24.5</td>
<td>24.6</td>
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<td>1.94</td>
<td>0.32</td>
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<tr>
<td>( \text{N}_{2} )</td>
<td>14</td>
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<td>( 1.17 \times 10^{-3} )</td>
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<td>12.8</td>
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<td>1.69</td>
<td>2.26</td>
<td>22</td>
<td>73</td>
</tr>
<tr>
<td>( \text{Ne} )</td>
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<td>( 8.39 \times 10^{-4} )</td>
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<td>21.5</td>
<td>21.6</td>
<td>36</td>
<td>1.68</td>
<td>1.41</td>
<td>12</td>
<td>39</td>
</tr>
<tr>
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<td>15.8</td>
<td>26</td>
<td>1.47</td>
<td>2.44</td>
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<tr>
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<td>8.4</td>
<td>12.1</td>
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<td>1.23</td>
<td>6.76</td>
<td>44</td>
<td>307</td>
</tr>
<tr>
<td>( \text{CO}_{2} )</td>
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<td>44</td>
<td>( 1.86 \times 10^{-3} )</td>
<td>5.2</td>
<td>13.7</td>
<td>13.7</td>
<td>33</td>
<td>1.62</td>
<td>3.01</td>
<td>34</td>
<td>91</td>
</tr>
<tr>
<td>( \text{CH}_{4} )</td>
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<td>16</td>
<td>( 6.70 \times 10^{-4} )</td>
<td>15.2</td>
<td>13.1</td>
<td>28</td>
<td>2.21</td>
<td>1.48</td>
<td>16</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>( \text{C}<em>{4}\text{H}</em>{10} )</td>
<td>34</td>
<td>58</td>
<td>( 2.42 \times 10^{-3} )</td>
<td>10.6</td>
<td>10.8</td>
<td>23</td>
<td>1.86</td>
<td>4.50</td>
<td>46</td>
<td>195</td>
<td></td>
</tr>
</tbody>
</table>

\( W_{i} \) (\( \text{Ar} \)) = 26 eV \hspace{2cm} dE/dx (\( \text{Ar} \)) = 2.44 keV/cm \hspace{2cm} n_{p} (\( \text{Ar} \)) = 29.4 /cm

\( W_{i} \) (\( \text{C}_{4}\text{H}_{10} \)) = 23 eV \hspace{2cm} dE/dx (\( \text{C}_{4}\text{H}_{10} \)) = 4.50 keV/cm \hspace{2cm} n_{p} (\( \text{C}_{4}\text{H}_{10} \)) = 46 /cm

So for this mixture, we have:

\[ n_{T} = (2440/26) \times 0.7 + (4500/23) \times 0.3 = 124 \text{ pairs/cm} \]
\[ n_{p} = 29.4 \times 0.7 + 46 \times 0.3 = 34 \text{ pairs/cm} \]

i.e. a distance \( \sim 300 \mu \text{m} \) between each **primary** pair (and a factor \( \sim 3.5 \) from \( n_{T} \) to \( n_{p} \))
Outline:

- Ionisation in gas
- Electrons and ions mobility in gas
- Pure gas and gas mixture properties
- Dependences of signal on geometry and applied voltage
- Proportional, streamer and Geiger-Muller modes
- Quencher / gain variation
- \( \delta \)-ray

Practical examples: applying our knowledge!

Few examples of gaseous detectors (including some information on diffusion in gas):

- MWPC, RPC, MSGC, GEM, Micromegas,
- drift chambers, TPC, straw (pailles)

conclusion
Signal for different practical configurations

Different cases should be considered in order to understand where the signal comes from. It will depend on:

- chamber geometry
- electric field intensity
- (front-end electronic)

1\textsuperscript{st} case: chamber with // plates

Signal comes from variation of electrostatic energy stored in the capacitor:

$$\Delta \left( \frac{1}{2} CU^2 \right) + \int_{Z_{\text{min}}}^{Z_{\text{max}}} NqE.dz = 0 \Rightarrow CU_0 \Delta U = -NqE.\Delta z$$

Thus for electrons: \( \Delta U^- = -Nez_0 / Cd \) and for ions: \( \Delta U^+ = -Ne(d - z_0) / Cd \)

Drift time is:

$$\Delta t^{+/−} = \int \frac{dz}{v_D^{+/−}} \Rightarrow \Delta t^− = \frac{z_0}{v_D^-}$$

It is \( \sim 10 \mu s \) for electrons and \( \sim 6 \text{ms} \) for ions in 5cm of Argon, \( E=500 \text{ V/cm} \)

\( (E=U/d) \)
2\textsuperscript{nd} case: Case of a cylinder geometry \textbf{without amplification} (low E field) : \textit{ionisation chamber}

Typical example
b=10 mm, a(anode=wire)=10\,\mu m

As before (for electrons):

\[ \Delta \left( \frac{1}{2} C U^2 \right) + \int_{r_a}^{r_i} NqE \, dr = 0 \]

with:

\[ E(r) = \frac{U_0}{r \ln(r_b/r_a)} \]

Then we have:

\[ \Delta U^- = -\frac{N.e}{C} \frac{\ln(r_i/r_a)}{\ln(r_b/r_a)} \]

and:

\[ \Delta U^+ = -\frac{N.e}{C} \frac{\ln(r_b/r_i)}{\ln(r_b/r_a)} \]

Thus:

\[ \frac{\Delta U^+}{\Delta U^-} = \frac{\ln(r_b/r_i)}{\ln(r_i/r_a)} \text{ always } < 1 \]

typically \sim 0.1

\Rightarrow \text{signal comes from electrons!!}
3rd case: High $E$ field: avalanche on -anode- wire

- It is almost mandatory to “multiply” electrons obtained from first ionisation (from $\sim 10$ to $\sim 100$)
- These electrons will drift to wire thanks to electric field
- Close to central wire ($\sim$few times wire radius) they “fill” an important acceleration,

The electrons energy increases $\Rightarrow$ ionisation by collision amplifying the phenomena
(timescale of the amplification: few ns)

(F. Sauli, CERN 77-09)
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(F. Sauli, CERN 77-09)
**3rd case:** Case of a cylinder geometry with amplification (high E field): proportional chamber

Typical example

\[ b = 10 \text{ mm}, \ a (\text{anode}=\text{wire}) = 10 \mu \text{m} \]

Above some threshold \( E \), each e- Accelerate and will also ionise the gas.

\[
E(r) = \frac{U_0}{r \ln(r_b/r_a)}
\]

We get (H. Fischer, 1975):

\[ \sim 6,9 \times 10^4 \text{V/cm.atm}, \text{methane (CH}_4\text{)} \]
\[ \sim 10,0 \times 10^4 \text{V/cm.atm, propane (C}_3\text{H}_8\text{)} \]

Avalanche appears in last tenth of microns \( (=n\lambda \sim r_a) \), when the ratio is \( \sim 7 \) => **signal comes from ions** !! Still: \( t_{ions} \sim \text{ms et } t_e \sim \text{ns.} \)
Output pulse duration varies with the (integration) time constant of the front-end electronic.

Signal in a proportional counter

T = max. drift time of ions (μs)

Charge preamplifier: Signals varies with preamplifier

(F. Sauli, CERN 77-09)
Working condition of a wire chamber

Variation of the electric field along the axis perpendicular to the wire plane and centred on one wire in a multiwire proportional chamber (x), and along the direction parallel to the wire plane (y) \textsuperscript{38).}
Charge multiplication: *Townsend* coefficients

When increasing $E$, an electron will create an “new” electrons:

$$n = n_0 e^{\alpha(E)x} \quad \text{or} \quad n = n_0 e^{\alpha(r)x} \quad \alpha = \text{first Townsend coefficient}$$

(varies with $E$, i.e. with $r$)

$$\alpha = \frac{1}{\lambda} \quad \text{with } \lambda = \text{mean free path of electrons}$$

since $\alpha \neq \text{cte} \Rightarrow A = \frac{n}{n_0} = \exp \left[ \int_{a}^{r_C} \alpha(r) dr \right] \quad \text{Gain} \quad A \approx k e^{CV_0}$$

Valid when the applied voltage is “above” the proportional zone: $A$ varies like $\exp(V_{\text{anode}})$.

- $\alpha$ should be measured for all gas (modelling by Rose and Korff).
  Above a gain of the order of $\sim 10^8$, there is a spark (*this is the Raether limit*).

- Voltage where the avalanche starts depend on gas (mixture) and is of the order of $\sim 10^4$ V/cm.atm ($\propto E/p$ -pressure p-)

- There is a 2nd *Townsend* coefficient $\gamma$, describing the influence of created photons during the avalanche, on the amplification.
  Thus: $A \rightarrow A_\gamma = A/(1-A\gamma)$. When $\gamma < 1/A$ we are in the limited proportional region. Above there is spark region (Geiger-Muller).
Outline:

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- Quencher / gain variation
- δ-ray

Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
- MWPC, RPC, MSGC, GEM, Micromegas,
- drift chambers, TPC, straw (pailles)

conclusion
I: too small voltage: recombination of pairs.

II: ionisation chamber. Charge collection without amplification.

IIIa: proportional mode. Signal is amplified and proportional to deposit ionisation. Gain goes from $10^4$ to $10^5$. Gain $\uparrow$ expon. with anode voltage.

IIIb: streamer mode. Secondary avalanches induced by first -principal- avalanche. Large quenching needed or pulsed HV. Gain of the order of $\sim 10^{10}$.

Geiger-Müller principle

**Figure 7-1** The mechanism by which additional avalanches are triggered in a Geiger discharge.

UV photons coming from first avalanche could also eject electrons (photoelectric effect) which will also induce a new avalanche.
Avalanche in *streamer* mode

**NORMAL AVALANCHE**

**STREAMER**

Avalanche simulation

Fig. 5 Two dimensional display of a simulated drift process of one electron from starting point to anode wire surface.

Fig. 6 Two dimensional display of a simulated electron avalanche.

Fig. 7 Two dimensional displays of a simulated electron avalanche. Shading shows the density of electrons in the avalanche.
Lecture #4
Gaseous detectors

Outline:
- Ionisation in gas
- Electrons and ions mobility in gas
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Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
- MWPC, RPC, MSGC, GEM, Micromegas,
- drift chambers, TPC, straw (pailles)

conclusion
- Polyatomic gas (with some vibration et rotation modes) where the energy coming from UV photons could be absorbed by collision or dissociation.

- Some quencher gas often used: methane CH$_4$, isobutane C$_4$H$_{10}$, ethanol, CO$_2$ (sometimes water…)

- Many mixtures tested… (see F.Sauli, 1977)

- “Magic gas” : 70% Ar, isobutane 29.6%, Freon 0.4% . High gains possible.
Problems induced by quencher gas

Quencher debris (polyatomic gas) could deposit and polymerise on the wire.

In general debris isolate. At the end, they could modify the functioning of the detector (modify working conditions, or sparks and large charge deposit).
Lecture #4
Gaseous detectors

Outline:
- Ionisation in gas
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- Quencher / gain variation
- δ-ray

Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
  - MWPC, RPC, MSGC, GEM, Micromegas,
  - drift chambers, TPC, straw (pailles)

Conclusion
Range of electrons (δ-ray) in gas

For $E \lesssim$ few 100 keV, range $R_p$ of ejected electrons could be parameterised by:

$$R_p \sim 0.71 E^{1.72} \quad (E \text{ in MeV})$$

and $R_p \sim R_{\text{Bethe-Bloch}} / (2 \text{ to } 3)$ because of fluctuation...

The angular emission of δ-ray of energy $E$ is:

$$\cos^2(\theta) = \frac{E}{E_M} \ll 1$$

valid since $N(E \geq E_0) \sim \text{cte}/E_0$
Up to now, what do we learned?

Electrons drift ~100 to ~1000 faster than ions. Drift time of electrons is ~5 cm/μs

Noble gas do not “attach” e- but to a certain extend, O₂ and H₂O could be considered as unwanted component

At high $E$ field, electrons induce an avalanche when E field is high enough. Signal may come from e- or ions depending of the geometry and the field.

An ionisation chamber goes through a proportional mode, a streamer mode then a Geiger-Muller mode (when increasing high voltage).

*Quencher* gas is used to avoid avalanche to become sparks (like in G-M mode).
There exist also other “tricks” (see application).

We will also see that transverse diffusion of electrons is about ~1cm/m (a magnetic field B // E decrease the transverse diffusion)

etc, etc…

**We still have to see practical applications to this “theory”!!**
Gain (amplification) of the gaseous detector will depend on:

- Component stability (in %), applied voltage, temperature

- Anode wire centering -positioning- in the detector (cylinder, w.r.t. to other wires), wire diameter variations, pitch variations (if several wires like for MWPC)

- Drift of (slow) ions which may induce a space charge effect. Also if large amplification, we may have a large space charge effect (from electron)

- Anode and cathode surface deterioration (deposit of debris, sparks…): “aging”

- Fluctuations of initial charge creation

etc.

Remark: gain will drop close to the end-plug (where the wire is attached: crimped, glued…)
All this can be parameterised and measured

Order of magnitude: drift over 1m ⇒ σ ≈ 1 cm

Drift velocity: few cm/μs
Detection (in)efficiency: importance of ions space charge

One could have a ~100% efficiency.

But at high flux, ions could not escape between collisions (on an accelerator).
Outline:
Ionisation in gas
Electrons and ions mobility in gas
Pure gas and gas mixture properties
Dependences of signal on geometry and applied voltage
Proportional, streamer and Geiger-Muller modes
Quencher / gain variation
δ-ray

Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
MWPC, RPC, MSGC, GEM, Micromegas, drift chambers, TPC, straw (pailles)

conclusion
Multi-Wire Proportional Chamber (MWPC)

Typical values:
L=8 mm, d=2 mm,
Wire diameters: 20-30 μm
in general, L/d ≈ 3-4

Spatial resolution :
\[ \sigma = \frac{d}{\sqrt{12}} \approx 600 \mu m \]
Simple solution:
two planes of crossing wires (90°). Because of ambiguities only possible if the multiplicity is not too high (otherwise combinatorial problems)

Also: wires with small stereo angles (or U, V, Z planes, etc.)

One may also use the time resolution.
e.g.: ITC of ALEPH, resolution ≈3 cm (100 ps)

**Remark about wire sag:**

\[ x(L/2) = s_g = \frac{L^2 \cdot g \cdot \rho \cdot \sigma}{8T} \]

with \( \sigma = \) wire section (mm²), \( T = \) stretching (kg)

Tungsten: \( s_g \approx 300 \mu m \)

for \( L = 5m \) and \( \Phi = 100 \mu m \), \( T = 350g \)

Deformation (!) if: \( Tc/\sigma > 200 \) to 400 kg/mm² for W⁶²
Other possible solution

One divide cathode planes in strips, each, readout individually
Resistive Plate Chamber (RPC)

No more wires (pillars to maintain space)

Timing resolution varies from 1 to 2 ns. Why?

Could be improved by inserting several slices.

Careful running conditions since it is close to streamer mode.

Gas: $C_2F_4H_2, (C_2F_5H) + \text{few \% isobutane}$
Physics behind their operation

\[ \tau = 2R_b \left( \frac{C_b}{2} + C_g \right) = 2\rho_b \frac{d}{S} \left( \frac{1}{2} \varepsilon_0 \varepsilon_r \frac{S}{d} + \varepsilon_0 \frac{S}{g} \right) = \rho_b \varepsilon_0 \left( \varepsilon_r + 2\frac{d}{g} \right) \]

Could be useful for RDS1 community

V. Peskov et al., Resistive gaseous detector (ed. Wiley-VCH)
Micro-Strip Gaz Chamber (MSGC)

Considered by CMS experiment, but aging problems…(replace by Si)

Ar:DME 50:50
Resolution ~30 to 40μm
Gain <10000

Field geometry

Glass DESAG AF45 + S8900 semiconducting glass coating, \( \rho = 10^{16} \, \Omega/\square \)

Fast ion evacuation \( \rightarrow \) high rate capability \( \approx 10^6 \, /{(\text{mm}^2 \cdot \text{s})} \)
Micro-Strip Gaz Chamber (MSGC)

Considered by CMS experiment, but aging problems…(replace by Si)
Signal zone (drift zone) and amplification zone are separated!

**Gaz Electron Multiplier (GEM)**

- **Limitations:**
  - shorts in one “hole” => short on the full area
  - Gain limitation?

Amplification gap of ~ 2mm => signal width ~20ns
Gaz Electron Multiplier (GEM)

Construction complexity?

THE DISCHARGE VOLTAGE (MAXIMUM GAIN) INCREASES IN CASCADED MULTI-MPGD

TRIPLE GEM:

DRIFT

\[ E_D \quad \text{DRIFT} \]

GEM 1

\[ E_{T1} \quad \text{TRANSFER 1} \]

GEM 2

\[ E_{T2} \quad \text{TRANSFER 2} \]

GEM 2

\[ E_I \quad \text{INDUCTION} \]

READOUT

DISCHARGE PROBABILITY VS GAIN:

\[ Q \approx 4 \times 10^6 \]

\[ Q \approx 8 \times 10^8 \]

S. Bachmann et al, NIMA479(2002)294
COMPUTED FIELD NEAR THE CATHODE RIMS IN GEM

$V_{\text{GEM}} = 375 \text{ V}$  $V_{\text{T}} = V_{\text{I}} = 3.5 \text{ kV/cm}$

Filippo Resnati, Personal communication today

160 kV/cm

FIELD EMISSION AND/OR IONIZATION

WAITING FOR A DEDICATED FULL GAIN CALCULATION “A LA MSGC”
In few years, many improvements in these detectors construction: mainly using industrial lithography process.

- e- trajectory in the amplification zone.
- e- are scattered, so ions will be catch by the grid -micromesh- (they go back).
- Ions disappeared in about ~100ns
e- trajectory in the amplification zone. e- are scattered, so ions will be catch by the grid -micromesh- (they go back). Ions disappeared in about ~100ns
Drift gap of ~5mm => possibility to do a micro-TPC track reconstruction

Not shown: resistive strip (HV) + insulator layers on top of strips plane
Micromegas (micro-) TPC mode

Several strips hit due to transverse diffusion (depends on strip width, etc.)

In MM gas, ~1 ionization cluster each ~200 microns of track.
Micromegas (micro-) TPC mode

In MM gas, ~1 ionization cluster each ~200 microns of track.

Time information

=> TPC mode needed

Track angle (deg.)

angular range of the NSW
Micromegas 4 gaps chamber/module when finished
Micromegas detectors could be opened for repairing them. *Mesh attached to the drift panel*…
Gain calculation (correction parameters)

\[ G = e^\int \alpha_{Pen}(E(r)) \, dr \]

- \( \text{Ar}^* + \text{CO}_2 \rightarrow \text{Ar} + \text{CO}_2^+ + e^- \)
- \( \text{Ar}^* \, 3p^53d \) (13.8 eV) and higher level excitations can ionise \( \text{CO}_2 \) (13.77 eV)

\[ \alpha_{Pen} = \alpha \left( 1 + r_{Pen} \frac{f_{\text{exc}}}{f_{\text{ion}} f_{\text{mix}}} \right) \]

- Townsend coefficients (\( \alpha \)), production frequencies of the ionisations and excitations calculated with Magboltz
- \( r_{Pen} \): Penning transfer rate

Feedback correction for the over-exponential increases in gas gain

\[ G_{total} = G / (1 - \beta G) \]
18/45 Standard Woven:

- Wire diameter 18 µm
- Edge to Edge 45 µm
- Axis to Axis 63 µm

The wires have the maximum field is 112 kV/cm

The drift gap, amplification gap are the same

on the YZ plane, through a wire
Figure 7: Cross Section of argon and carbon dioxide as a function of energy. These graphs are taken from the Magboltz 7.1 database for gas properties.
One need an external time stamp (trigger) taken as a reference for the time measurement provided by the drift chamber.

Resolution:
from few tenth of μm, knowing gas properties: r-t relation
(non linear effect like Ramsauer effect, electronics, diffusion -trajectory fluctuations-, Lorentz angle…)

---

Drift chambers

scintillator

low field region

high field region

drift

gas amplification

\( \chi \)

DELAY

Stop
Start

TDC
Useful parameters of drift chambers

• One need fewer wires:
  – Cost
  – Mechanical structure less constrained w.r.t. M.W.P.C.
  – Good transverse resolution thanks to a good r-t relationship knowledge

• Large possible volumes

• But:
  – They need an external trigger
  – Electronic may be more complex than MWPC (which signal are we looking at?)
  – Slow detectors (drift time up to few 100ns, even ~1μs)
Diffusion and drift

- En l’absence de champ externe (E ou B), les électrons diffusent sous l’effet des collisions avec les atomes :

\[
\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{-\left(\frac{x^2}{4Dt}\right)} \, dx
\]

le \( \sigma \) équivalent = \( \sigma_x(t) = \sqrt{2Dt} \) \( \text{or} \) \( D = \frac{\sigma_x^2(t)}{2t} \)

\( D \): diffusion coefficient en \( \text{cm}^2/\text{sec} \)

\( \sigma_x \)

Ordre de grandeur : dérive de 1m \( \Rightarrow \sigma \approx 1 \text{ cm} \)

Il y a aussi une dérive longitudinal, i.e. un étallement en temps
**Diffusion and drift**

Order of magnitude of *transverse* diffusion:
- drift over 1 cm $\Rightarrow \sigma \approx 0.1$ to 0.01 cm
- drift over 1 m $\Rightarrow \sigma \approx 1$ to 10 cm

Mean position value stays identical but signal is smeared.
Diffusion and drift

when we have together a $E$ and $B$ fields

Longitudinal diffusion (in $B$ field direction) doesn’t change

But in transverse plane, electrons are spinning -following- “around” $B$ field line

$\Rightarrow$ diffusion coefficient is:

$$D_T(B) = \frac{D_0}{1 + \omega^2 \tau^2}$$

$\sigma \propto \sqrt{D}$

with $\omega = eB/m$ cyclotron frequency

Transverse diffusion $\sigma$ (µm) for a drift of 15 cm in different Ar/CH$_4$ mixtures

(A. Clark et al., PEP-4 proposal, 1976)

(this phenomena is used in TPC -Time Projection Chamber-)
when we have (a $E$ and) $B$ fields

$\Rightarrow$ Lorentz angle between $E$ and drift velocity of e-

$$\vec{E} \perp \vec{B}$$

$$\tan \alpha_L = \omega \tau = v_{\text{drift-e.}} \cdot (B/E)$$

$\alpha_L$: Lorentz angle

$$\omega = \frac{e\vec{B}}{m}$$ cyclotron frequency

Typical angle $\sim$30 degrees for $B=1$Tesla and $E=0.5$kV/cm in Ar:C$_4$H$_{10}$:methylal (67:30:3)
Increase each electron trajectory length $\Rightarrow \Delta t$ to be measure

Example for Atlas drift chambers: up to 20ns over $\sim$700ns in total (Ar:CO$_2$ : 93:7, 3 bars)

As the gas is “faster” $\alpha_L$ increases (collisions -diffusion- are limiting this effect)
Drift chambers: different geometries
Example of a multipurpose detector on a collider: ATLAS at the LHC

- **Internal det.** ($\lesssim 0.5 \times_0$):
  - 6 pt. Si. and 30 pt. TRT
- **EM calorimeter** ($>20.\times_0$)
- **Had. calorimeter** (~11.$\lambda_t$)
- **Muon system** (Feet of the experiment, muon acceptance $>95\%$)
- **Internal solenoid magnet** ($\int Bdl \sim 2T.m$)
- **Magnet return yoke**
- **External toroid magnet** ($\int Bdl \sim 5T.m$)
Drift chambers : ATLAS geometry

b=15 mm, a(anode=fil)=50μm
L from 2 to 6 m

Ar:CO₂ 93:7
p = 3 bar => ~3×100 pairs/cm (n_{Total})
V ~ 3000V (2.10⁵ V/cm)
Gain: 2.10⁴
Max drift time of e⁻ : 700ns, i.e. “slow” good for Lorentz angle limitation
\( v \sim 3\text{cm/μs} = 30\text{μm/ns} \)
Centring of wire < 100μm all along the tube (20μm at the end-plug)
Threshold at the ~25^{th} e⁻
\( \sigma \sim 80 \, \mu\text{m} / \text{tube} \) => combining tubes of one chamber gives ~50μm locally
b=15 mm, a(anode=fil)=50μm
L from 2 to 6 m

dE/dx(μ) = 14 keV
i.e. several e- clusters

Arrival time fluctuation of each e-cluster on the anode wire
Sag measurement in Atlas muon spectrometer

MDT are sensitive to Lorentz angle (in $B$ field), up to 20ns delay over 680ns (not for CSC chambers).

$\sigma \sim 80\,\mu$m/tube, and combining them by $2 \times 3$ or $2 \times 4$ tubes within a chamber: $\sigma \sim 60\,\mu$m locally

Also an angular measurement (vector) $\sim 200\,\mu$rad.  

$\varepsilon_{\text{tube}} \sim 95\%$ (half from tube wall, half track centred w.r.t. wire)
Mean # of e- from ionisation (<\sim 400)

Inefficiency = f(radius)
close to tube walls, because of δ-ray!
Remark: bad resolution for tracks centred on the wire
Example: Aleph TPC (gas: Ar/CH$_4$ 90/10)

$N_{\text{samples}}$: 338, wire spacing 4 mm

dE/dx resolution: 5% for m.i.p.

Each track gives $\sim$338 measurements for a given particle seen in the detector (Time Projection Chamber – TPC –).

Limiting factor comes from fluctuation “Landau tails”.

**ALEPH**

- w ~ 0.4 MeV/(g/cm$^2$)
- $\pi$/$K$
- $e/\pi$
- $p/K$
- $K$
- $e$
- $p$

\[ \text{log scale !} \]
\[ \text{linear scale !} \]
Slow detector: $\sim 100\mu s$

Space charge problem: between two “collisions” (bunch) one activates an intermediate grid (at a given potential) in order to avoid ions to drift back to the drift space.

TPC: example of dE/dx measurement
How does straw tubes work?

Example an LHC experiment:
>350000 straws of Ø=4mm, L_{max}=150cm
Particle flux: 200 kHz/cm => occupancy ~ 25%
Gas with 3 components: 70% Xe + 20% CF₄ + 10% CO₂ (±2%)
  Xe for a good X-ray absorption (∝Z³; Z=54)
  CF₄ fast gas (+ plastic foils for trans. radiation)
  CO₂ as a quencher (auto-limited streamer mode, i.e. close to)
\[ \Delta E/\Delta x_{m.i.p.} \sim 2 \text{ keV} \]
Lorentz angle ~ 30° (B_{solenoid}=2T)
Wire diameter 30μm (gain limitation to 4.10⁴)
streamer fraction ~ 7% (if 5% more of Xe => streamer event fraction ~ 2%)
Temperature variation < 10 deg. (Δg/g<2%)
Wire centring ≲ 200μm
Anode HV: 1570 ± 30 V (if higher streamer)
Maximum collection time ~40ns
Threshold for drift time measurement at 200 eV (i.e. 8000 e-) : σ~150μm ↔ 8ns
Threshold of soft X-ray detection: 6.5 keV.

\[ \text{For } \varepsilon_g=90\% \text{ we get 8\% of } \pi \Rightarrow \text{rejection > 10} \]
extc, etc...
Heat produced ~400W. Cooling using CO₂. Temp. <50° on electronics
Transition Radiation Detector

Discriminating $e/\pi$

$0 \sim 1/\gamma$ so $\sim \mu$-radian for $e$ of about 10 GeV.

Also $N\gamma \sim 0.5\% Z^2$
For each “radiator”.

Soft X-ray emission associated of few keV.

Assembly of plastic foils (reinforced) and straws of 5mm diameter
Asking to keep 95% of e\textsuperscript{-} (the wanted signal) we get ~4% de π in the final sample.

Without plastic foils energy loss is almost the same for π or electrons.

X-ray absorbed in ~1mm (if Argon gas)

M.L. Cerry et al.  
Phys. Rev. 10(1974)3594
Simulation of $H^0 \rightarrow ZZ^* \rightarrow e^+ e^- \mu^+ \mu^-$ in ATLAS

$E_{\text{Center of mass}} = 14$ TeV

We observe that:

- lot of track (~2000), high occupancy (for straw but not for Si)
- curved tracks ($B$ field ≠ 0)
- $e^+/e^-, \mu^+/\mu^-$ ~ straight track
- lot of hit on first 3 inner layers and then less and less
- lot of aligned hit at large radius
- red hits (?) at large radius

Each blue/red point is a single hit in the Atlas Inner Detector
Conclusions

We have seen:
• Signal formation and detection (including fluctuations)
• Velocity(electrons) $\sim$100 to $\sim$1000× velocity(ions). Drift time of electrons is $\sim$5 cm/μs
• Working condition of a ionisation chamber goes from *proportionnel* mode, then *streamer* mode, then *Geiger-Muller* mode (when increasing HV)
• *quencher* gas is used to avoid sparks (risk of deterioration for some detectors)
• …/… other effects …/…
• We (you!) have understood how work the following gaseous detector:
  MWPC, drift chambers, RPC, MicroMegas (i.e. new detectors MPGD ), …
• We are able to understand (!!!):
  TPC (e.g. DELPHI/ALEPH),
  central tracker (e.g. ATLAS/CMS or others!)
  muon system

etc, etc…
Moral #1:
Discuss with specialists (physicists and engineers and technicians) in order to understand a detector, and before starting a new one!!

Moral #2:
An experiment could be built only with an experienced team (with know-how). Otherwise one may “re-invent the wheel”…

Moral #3:
There is no unique universal detector (unfortunately). One need to test the detector (also simulate it) in real conditions in order to understand/optimize the working conditions (prototype).

etc…
Signal collection: typical characteristics for different detectors

### Table 28.1: Typical spatial and temporal resolutions of common detectors. Revised September 2003 by R. Kadel (BNL).

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Resolution Time (rms)</th>
<th>Dead Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubble chamber</td>
<td>10–150 $\mu$m</td>
<td>50 ms$^a$</td>
</tr>
<tr>
<td>Streamer chamber</td>
<td>300 $\mu$m</td>
<td>100 ms</td>
</tr>
<tr>
<td>Proportional chamber</td>
<td>50–300 $\mu$m$^b,c,d$</td>
<td>200 ns</td>
</tr>
<tr>
<td>Drift chamber</td>
<td>50–300 $\mu$m</td>
<td>100 ns</td>
</tr>
<tr>
<td>Scintillator</td>
<td>—</td>
<td>100 ps/n$^f$</td>
</tr>
<tr>
<td>Emulsion</td>
<td>1 $\mu$m</td>
<td>—</td>
</tr>
<tr>
<td>Liquid Argon Drift [Ref. 6]</td>
<td>$\sim$175–450 $\mu$m</td>
<td>$\sim$200 ns</td>
</tr>
<tr>
<td>Gas Micro Strip [Ref. 7]</td>
<td>30–40 $\mu$m</td>
<td>&lt; 10 ns</td>
</tr>
<tr>
<td>Resistive Plate chamber [Ref. 8]</td>
<td>$\lesssim$10 $\mu$m</td>
<td>1–2 ns</td>
</tr>
<tr>
<td>Silicon strip</td>
<td>pitch/(3 to 7)$^g$</td>
<td>$h$</td>
</tr>
<tr>
<td>Silicon pixel</td>
<td>2 $\mu$m$^i$</td>
<td>$h$</td>
</tr>
</tbody>
</table>

$^a$ Multiple pulsing time.
$^b$ 300 $\mu$m is for 1 mm pitch.
$^c$ Delay line cathode readout can give $\pm$150 $\mu$m parallel to anode wire.
$^d$ Wire spacing/$\sqrt{2}$.
$^e$ For two chambers.
$^f$ $n =$ index of refraction.
$^g$ The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim$25 $\mu$m) with pulse-height-weighted center finding.
$^h$ Limited by the readout electronics [9]. (Time resolution of $\lesssim$25 ns is planned for the ATLAS SCT.)
$^i$ Analog readout of 34 $\mu$m pitch, monolithic pixel detectors.

From PDG.

**Remark:** Time collection of signal is related to drift time of charged carriers (deposit energy is almost instantaneous: ps in liquid/solid, ns in gas).

Choice of electronics also determine total collection time of signal.
Veresatile detection volume. Choice of gas depend of nuclear that you want to detect.

ACTAR TPC
a versatile instrument for nuclear physics

J. Giovinazzo - CENBG
and the ACTAR TPC collaboration

▷ what is ACTAR TPC
▷ General design
▷ Characterization
▷ Status
Elongated gas detection volume with 2 readout area (read from below)

TPC mode (i.e. elx with timing information)

Veratile detection volume. Choice of gas depend on nuclear that you want to detect.

“reaction” chamber
128x128 pads collection plane large transverse tracks

“decay” chamber
256x64 pads collection plane short transverse tracks, larger implantation depth
Detector characterization:

i.e. which gain (relatively or better absolutely)

How to do that?
Detector characterization:
i.e. which gain (relatively or better absolutely)

How to do that?