Ionization detectors

- incoming particle
- ionization track

**Ionization track**

- ion/e⁻ pairs

Minimum-ionizing particles (Sauli. IEEE+NSS 2002)

different counting gases:

<table>
<thead>
<tr>
<th>GAS (STP)</th>
<th>Helium</th>
<th>Argon</th>
<th>Xenon</th>
<th>CH₄</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>dE/dx (keV/cm)</td>
<td>0.32</td>
<td>2.4</td>
<td>6.7</td>
<td>1.5</td>
<td>3.9</td>
</tr>
<tr>
<td>&lt;n&gt; (ion pairs/cm)</td>
<td>6</td>
<td>25</td>
<td>44</td>
<td>16</td>
<td>55</td>
</tr>
</tbody>
</table>

ionization process: Poisson statistics

detection efficiency \( \varepsilon \) depends on average number \(<n>\) of ion pairs

\[
\varepsilon \leq 1 - e^{-<n>}
\]

\[
\Delta E \propto <n>
\]

\[
\approx \text{linear for } \Delta E \ll E
\]
### Effective ionization energies

#### Excitation and ionization characteristics of various gases

<table>
<thead>
<tr>
<th></th>
<th>Excitation potential [eV]</th>
<th>Ionization potential [eV]</th>
<th>Mean energy for ion-electron pair creation [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>10.8</td>
<td>15.4</td>
<td>37</td>
</tr>
<tr>
<td>He</td>
<td>19.8</td>
<td>24.6</td>
<td>41</td>
</tr>
<tr>
<td>N₂</td>
<td>8.1</td>
<td>15.5</td>
<td>35</td>
</tr>
<tr>
<td>O₂</td>
<td>7.9</td>
<td>12.2</td>
<td>31</td>
</tr>
<tr>
<td>Ne</td>
<td>16.6</td>
<td>21.6</td>
<td>36</td>
</tr>
<tr>
<td>Ar</td>
<td>11.6</td>
<td>15.8</td>
<td>26</td>
</tr>
<tr>
<td>Kr</td>
<td>10.0</td>
<td>14.0</td>
<td>24</td>
</tr>
<tr>
<td>Xe</td>
<td>8.4</td>
<td>12.1</td>
<td>22</td>
</tr>
<tr>
<td>CO₂</td>
<td>10.0</td>
<td>13.7</td>
<td>33</td>
</tr>
<tr>
<td>CH₄</td>
<td>13.1</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>C₄H₁₀</td>
<td>10.8</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>

Mean energy per ion pair larger than IP because of excitations.

Large organic molecules have low-lying excited rotational states → excitation without ionization through collisions.
Charge transport in gas

Electric field \( E = \Delta U / \Delta x \) separates positive and negative charges.

charge diffusion in electric field

\[
\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi \cdot D \cdot t}} \cdot \exp \left\{ -\frac{(x-w \cdot t)^2}{4 \cdot D \cdot t} \right\}
\]

- \( w = \frac{e}{2m} \cdot E \cdot \tau \) drift velocity
- \( \tau = \lambda / \langle v \rangle \) mean time between collisions
- \( D = \mu \cdot \frac{k \cdot T}{e} \) mobility

There is a cycle of acceleration and scattering/ionization etc.

Drift \( w \) and diffusion \( D \) depend on field strength \( E \) and gas pressure \( \rho \)

\[
w = w(E/\rho) \quad \bar{D} = \bar{D}(E/\rho)
\]
**Ion mobility**

 Ion mobility $\mu^+ = \omega^+ / E$

For ions there is an interplay between acceleration and collisions. Ion mobility is independent of field for a given gas at $\rho$, $T = \text{const.}$

<table>
<thead>
<tr>
<th>GAS</th>
<th>ION</th>
<th>$\mu^+$ (cm$^2$ V$^{-1}$ s$^{-1}$) @STP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>$\text{Ar}^+$</td>
<td>1.51</td>
</tr>
<tr>
<td>$\text{CH}_4$</td>
<td>$\text{CH}_4^+$</td>
<td>2.26</td>
</tr>
<tr>
<td>Ar+$\text{CH}_4$ 80+20</td>
<td>$\text{CH}_4^+$</td>
<td>1.61</td>
</tr>
</tbody>
</table>

$\omega^+ \sim 10^{-2}$ cm/μs

$\omega^- \sim 10^1$ cm/μs

E. McDaniel and E. Mason; The mobility and diffusion of ions in gases (Wiley 1973)
Electron mobility

In general, the mobility of electrons is not constant, but depend on on their kinetic energy and varies with the electric field strength.

Drift velocities of electrons in Argon-Methan mixtures

Drift velocities of electrons in different gases
Amplification counters

- single-wire gas counter

- gas counters may be operated in different operation modes depending on the applied high voltage.
An ionization chamber is operated at a voltage which allows full collection of charges, however below the threshold of secondary ionization (no amplification).

For a typical field strength 500 V/cm and typical drift velocities the collection time for 10 cm drift is about 2 μs for e− and 2 ms for the ions.

Time evolution of the signals for one e− ion pair:
The motion of charges induces an apparent current in the electrodes. Ion causes the same signal as the electron = same sign, same amplitude, but much slower.

\[ i = \frac{q}{V_0} \frac{dV}{ds} \frac{ds}{dt} \]
Ionization chamber

- no gas gain
- charges move in electric field
- induced signal is generated during drift of charges
- induced current ends when charges reach electrodes

additional ‘Frisch grid’:
- electrons drift towards Frisch grid and induce a signal but not on the anode.
- when electrons pass the Frisch grid, a signal is induced on anode.
- the angular dependence of the electrons is removed from anode signal
Signal generation in ionization counters

primary ionization in gases: \( I \approx 20\text{–}30 \text{ eV/IP} \)

energy loss \( \Delta \varepsilon \):
\[ n = n_1 = n_e = \Delta \varepsilon / I \]

force:
\[ F_e = -eU_0/d = -F_1 \]

energy content of capacity \( C \)
1) \( W(t) = \frac{C}{2} [U_0^2 - U^2(t)] \approx C \cdot U_0 \cdot \Delta U(t) \)
2) \( W(t) = n_e F_e [x_e(t) - x_0] + n_I F_I [x_I(t) - x_0] \)
\[ = + \frac{n \cdot eU_0}{d} [x_I(t) - x_e(t)] \]

\( \Delta U(t) = \frac{W(t)}{C \cdot U_0} = \frac{n \cdot e}{C \cdot d} [w^+(t) - w^-(t)](t - t_0) \)

total signal: electron & ion components
Time-dependent signal shape

total signal: electron & ion components

\[ \Delta U(t) = \frac{\Delta \varepsilon}{C \cdot d} [w^+(t) - w^-(t)](t - t_0) \]

\[ |w^+(t)| \sim 10^{-3} \cdot |w^-(t)| \]

drift velocities \((w^+ > 0, w^- < 0)\)

Both components measure \(\Delta \varepsilon\) and depend on position of primary ion pair

\[ x_0 = w^+ \cdot (t_e - t_0) \]

for fast counting use only electron component!
Proportional counter

Gas amplification factor (typical $10^4$–$10^6$) is constant

Anode wire: small radius $R_A \approx 50 \, \mu m$ or less
Voltage $U_0 \approx (300\text{-}500) \, V$

Field at $r$ from the wire

$$E(r) = \frac{U_0}{\ln(R_C/R_A)} \cdot \frac{1}{r}$$

Avalanche $R_I \rightarrow R_A$, several mean free paths needed
Pulse height mainly due to positive ions ($q^+$)
The primary produced electrons drift the anode wire and reach the area of high electrical field strength. If a critical field strength is reached, a secondary ionization produces electrons in an avalanche.

**time sequence of the signal evolution**

- **primary ionization**
- **secondary ionization**
- **pos. ions drift due to secondary ionization**

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Indian Institute of Technology Ropar  Hans-Jürgen Wollersheim - 2017
### Proportional counter

- Target
- Entrance window \( \sim \varphi_{\text{lab}} \), \( \sim \tan \vartheta_{\text{lab}} \)
- \( V_0 \sim 500 \text{ V} \)
- Pressure \( p = 5-10 \text{ Torr} \)
- \( \sim 3 \text{ mm gap anode-cathode} \)
- Delay line, \( \Delta t \sim \tan \vartheta \)
- \( \Delta \text{time} \rightarrow \)
Multi-Wire Proportional Chamber

A multi-wire proportional chamber detects charged particles and gives positional information on their trajectory.

- **time resolution:** fast anode signals ($t_{\text{rise}} \sim 0.1$ ns)
- **position resolution:** for $d = 2$ mm $\sigma_x = 50$-$300$ μm (weighted with charges)

...
Multi-Wire Proportional Chamber

[Diagram showing the principles of a multi-wire proportional chamber, including cathode strips, anode wires, charged particle tracks, and signal distributions.]

Center of gravity determined with $\sigma_y = 50 - 300 \, \mu m$
**Time Projection Chamber**

- **Principle:** Time Projection Chambers are based on the drift of the charge carriers with constant drift velocity \( v_D \) in a homogenous E-field \( (E = -dU/dz) \).

- **typical parameters:** \( E \sim 1 \text{ kV/cm}, \ v_D \sim 1-4 \text{ cm/\mu s}, \ \Delta z \sim 200 \text{ \mu m} \)

- **3-dim. traces:** \( z \) from the drift time, \( (x,y) \) from the segmented anode
Geiger-Müller counter

- The discharge is not any more localized
- The number of charge carriers is not any more related to the primary ionization
- The gas amplification amounts to $10^8$-$10^{10}$