Gas Detectors
[the oldest detectors]

Basic principle:

- **gas ionization** from radiation interaction;
- **electric signal** originated by ion-electron pairs collected through an electric field.

- Ionization chambers
- Proportional counters
- Geiger Muller counters

*Same basic principle, different intensity of applied electric field*
Ionization Process

Primary Ionization Track (Gases)

Pair formation:
- direct interaction
- secondary process
  (very energetic electrons can ionize …)

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

<table>
<thead>
<tr>
<th>GAS (STP)</th>
<th>Helium</th>
<th>Argon</th>
<th>Xenon</th>
<th>CH$_4$</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>n (ion pairs/cm$^2$)</td>
<td>6</td>
<td>25</td>
<td>44</td>
<td>16</td>
<td>55</td>
</tr>
</tbody>
</table>

Statistical ionization process: Poisson statistics
Detection efficiency $\varepsilon$ depends on average number $<n>$ of ion pairs

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

<table>
<thead>
<tr>
<th>GAS (STP)</th>
<th>thickness</th>
<th>$\varepsilon$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>1 mm</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>2 mm</td>
<td>70</td>
</tr>
<tr>
<td>Argon</td>
<td>1 mm</td>
<td>91.8</td>
</tr>
<tr>
<td></td>
<td>2 mm</td>
<td>99.3</td>
</tr>
</tbody>
</table>

Higher $\varepsilon$ for slower particles
average energy per pair production: weak dependence on gas and particle type

Example: $E_p \sim 1 \text{ MeV}$

$\# \text{ pairs} \sim 30000$
Ions/electrons suffer of multiple collisions with gas molecules and lose energy \( \Rightarrow \) thermal equilibrium with gas, recombination, ... loss of signal

**Free Charge Transport in Gases**

1D Diffusion equation \( \rightarrow P(x) = \frac{1}{N_0} \frac{dN}{dx} \)

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

\[
\langle x \rangle_{rms} := \sqrt{\langle x^2 \rangle} = \sigma_x = 2Dt
\]

\( D \) diffusion coefficient, \( <v> \) mean speed, \( \lambda \) mean free path

**Thermal velocities** :

\[
<v> = \sqrt{\frac{8kT}{\pi m}} = \sqrt{\frac{8}{3\pi}} \sqrt{\langle v^2 \rangle}
\]

Maxwell+ Boltzmann velocity distribution

\( D(\text{ion}) \ll D(e^-) \) Small ion mobility

H. Schröder
Driven Charge Transport in Gases

Electric field $E = \Delta U / \Delta x$ separates +/− charges

Net effect: superposition of thermal velocity (random) and drift velocity (ordered)

$$v = \frac{e}{2m} E \cdot \tau \quad \text{drift velocity}$$

$$\tau = \frac{\lambda}{\langle v \rangle} \quad \text{mean collision time}$$

$$\bar{D} = \mu \cdot \frac{kT}{e} \quad \mu := \frac{v}{E} \quad \text{mobility}$$

Cycle: acceleration − scattering

Drift and diffusion depend on field strength and gas pressure $p$ (or $\rho$).

$$v = v(E/p); \quad \bar{D} = \bar{D}(E/p)$$

Electric Field is needed to efficiently collect the charges from interaction place
Ion Mobility

Ion mobility $\mu^+ = \frac{v^+}{E}$

Typically independent of field, for a given gas at $p, T = \text{const.}$

**Typical ion drift velocities** (Ar + CH$_4$ counters):

$v^+ \sim (10^{-2} - 10^{-5}) \text{ cm/s } \mu\text{s}$

**slow!**

$\nu_{\text{drift}} \propto \mu \frac{E}{p}$

**Typical values:**

$v_{\text{drift}} = 1 \text{ m/s}$

Transit time (1 cm distance) = 1 ms !!!

E. McDaniel and E. Mason

The mobility and diffusion of ions in gases (Wiley 1973)
Electron Transport

Multiple scattering/acceleration produces effective spectrum $P(\varepsilon)$
→ calculate effective $\lambda$ and $\tau$. [reduced mass compared to ions]

Gas admixture

- $90\%$ Ar + $10\%$ methane
- $10\%$ Ar + $90\%$ methane

Simulations

Drift Velocity cm/μs

Electric Field kV/cm

$V_{\text{drift}} \sim 10^3 \, V^+$

$10\%$ Ar + $90\%$ methane

$90\%$ Ar + $10\%$ methane

Udo Schröder

Region of operation of gas detectors

Nr. Collected Ions vs. Voltage

1. Radiation creates pairs that recombine before reaching the electrodes
   Loss of original Signal

2. The created pairs can reach the electrodes with help of the voltage V.
   Plateau forms. Ionization Chamber
   Signal proportional to primary ionization

3. Over a certain Voltage, secondary electrons are created. Near the electrode proportional to the incoming energy Proportional Counter
   Signal proportional to primary+secondary ionization

4. Region of limited proportionality

5. Discharge in the full gas.
   Geiger-Müller Detector
   Same Signal independent of energy

Region of operation depends on ⇒

1. Form of chamber (cylindrical, flat, spherical, ...)
2. Size of wires (in cylindrical counters)
3. Gas type (mixture)
4. Gas Pressure
5. Level of high voltage

Normally counters are manufactured to work in one region ONLY
Ionization Chamber: the simplest gas detector

Ionisation chamber:
Two electrodes “parallel” with opposite charge.

General constituents:
- Container filled with gas
- Two isolated electrodes
- High Voltage

Choice of gas:
- air (γ detection)
- Ar (more dense) to increase ionization probability (p ~ 1 atm)

Mode of operation:
- current mode [average rate info]
- pulse mode [info on individual event]

Measured current is true indication of rate of formation of charges

$E = \text{constant}$

$E \sim \frac{1}{r}$

10-100 V
Signal type and size: $\alpha$ particle $E_\alpha = 3\ MeV$

$w = 30\ eV \Rightarrow n = E_\alpha / w = 10^5$ e-ions

Fill Gas: He, N$_2$, Ar, Kr, Xe, ...

Detection Efficiency: ~100% for charged particles

~1% for photons *(low density and Z !!!)*

Very low outputs ($10^{-4}$ V) $\Rightarrow$ require high amplification

A typical gas counter has a capacitance of about 50 pF, and the charge will be collected in a time of the order of 1 $\mu$s. If all the charge created by the 3-MeV particle is collected, the voltage and current expected are of the order

\[
V = \frac{Q}{C} \approx \frac{10^5 \times 1.6 \times 10^{-19} \text{C/el}}{50 \times 10^{-12} \text{F}} \approx 0.5 \times 10^{-3} \text{V} \approx 0.5 \text{mV}
\]

\[
i = \frac{Q}{t} \approx \frac{10^5 \times 1.6 \times 10^{-19}}{10^{-6}} \text{A} \approx 1.6 \times 10^{-8} \text{A}
\]

**SMALL signals, amplification is needed!**
Figure 3.4.2: (a) Parallel plate ion chamber and a two dimensional view of electric field inside its active volume. The curved electric field at the sides may induce nonlinearity in the response. (b) Cylindrical ion chamber and a two dimensional view of radial electric field in its active volume. The increased flux of electric lines of force near the positively charged anode wire greatly enhances the electron collection efficiency.
Signal Generation in Ionization Counters

Primary ionization: Gases $l \approx 20-30$ eV/IP, Si: $l \approx 3.6$ eV/IP, Ge: $l \approx 3.0$ eV/IP

Energy loss $\Delta \varepsilon$: $n = n_I = n_e = \Delta \varepsilon / l$

number of primary ion pairs $n$ at $x_0$, $t_0$

Force: $F_e = -eU_0/d = -F_l$

Force acting to move charges to electrodes

Energy content of capacitor $C$:

1) $W(t) = \frac{C}{2} \left[ U_0^2 - U(t)^2 \right] \approx CU_0 \Delta U(t)$

2) $W(t) = n_e F_e \left[ x_e(t) - x_0 \right] + n_l F_l \left[ x_I(t) - x_0 \right]$

$= + \frac{neU_0}{d} \left[ x_I(t) - x_e(t) \right]$

$= \frac{W(t)}{CU_0} = \frac{ne}{Cd} \left[ v^+(t) - v^-(t) \right] (t - t_0)$

$\tau = RC \gg t_c$

signal rise time depends on charge collection time $t_c$

Time dependent signals observed in the detector
Time-Dependent Signal Shape

\[ \Delta U(t) = \frac{\Delta \varepsilon}{C_d} \left[ v^+(t) - v^-(t) \right] (t - t_0) \]

Total signal: e & l components

\[ |v^+(t)| \sim 10^{-3} |v^-(t)| \]
Drift velocities

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

\[ x_0 = v^- (t_e - t_0) \]
Use electron component only for fast counting.
The pulse is chopped at a convenient time by a shaping circuit.
Ionization Chamber pulse mode operation with Frisch grid

The fine meshing grid removes the pulse-amplitude dependence on position of interaction:

- The grid is maintained to intermediate potential and is transparent to electrons
- Incident radiation directed only into active volume Cathode-Grid

The signal derives from electrons drift only
⇒ NO dependence on slow ion motion !!!

in PRISMA @LNL

NO resistor ⇒ NO measurable signal

Shield

Incident radiation

Frisch Grid

Anode

Cathode

<table>
<thead>
<tr>
<th>V_R(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>y/u^-</td>
</tr>
<tr>
<td>d/u^-</td>
</tr>
</tbody>
</table>

R

C

d = 1.6 cm

d = 16 cm

NO resistor
⇒ NO measurable signal
ICs have excellent resolution in E, Z, A of charged particles but are slow detectors. Gas IC need very stable HV and gas handling systems.

Energy resolution

$$\sigma^2_{\varepsilon} = F \langle n_{ip} \rangle = F \frac{\Delta \varepsilon}{I}$$

F<1 Fano factor
Ionisation chamber as Smoke Detector

1 $\mu$Cu (~ 0.3 $\mu$g) of $^{241}$Am
$\tau = 432$ y

- $\alpha$ passing through ionization air-chamber
  produce constant current
- smoke absorbs $\alpha$'s $\Rightarrow$ reduced ionization, lower signal, alarm ..
- $\alpha$'s have low penetrability: they are stopped by the plastic of detector
NEUTRON detectors

Detection of secondary events produced in

- nuclear reactions: (n,p), (n,α), (n,γ), (n,fission)
- nuclear scattering from light charged particles, than detected

For slow and thermal n:

(n,p) and (n,α) mostly ...

**Best reaction:** $^{10}\text{B} + n \rightarrow ^7\text{Li}^* + \alpha$

$\gamma = 0.48$ MeV

- Natural abundance of $^{10}\text{B}$ is high: 20%
  $\Rightarrow$ material enriched with $^{10}\text{B}$ increase the efficiency

- Exotermic reaction:
  it occurs also for very low n energy

For $E_n = 0.025$ eV, $\sigma = 3770$ b !!

$\Rightarrow$ ideal for n detection

$\Rightarrow$ useful for measuring the flux of thermal n
Ionization chamber/proportional counters filled with BF$_3$ gas [typical sized tubes: e.g., 2 - 5 cm diameter]

- BF$_3$ gas, enriched to >90% of $^{10}$B
- Operated as proportional or G-M counter

Only determination of interaction, NOT energy

The wall effect

Wall effect prevents precise energy measurements

\[
\text{n + } ^{10}\text{B} \rightarrow (^{11}\text{B})^* \\
\rightarrow ^{7}\text{Li}^* + ^4\text{He}, Q = 2.31 \text{ MeV} \ [94\%] \\
\text{K.E. } 0.84 \text{ MeV} + 1.47 \text{ MeV} \\
\rightarrow ^{7}\text{Li} + ^4\text{He}, Q = 2.79 \text{ MeV} \ [6\%]
\]

Paraffine as moderator

Ideal response: large tube, all reaction products absorbed in gas volume.

Real Response

Wall effect

Due to partial energy deposition of lost ion
Proportional Counters

Basic Principle: signal multiplication to amplify charge produced by original (e-, ion) pair

⇒ Avalanche Formation:
by increasing $E$ electrons acquire kinetic energy to ionize ...

$E_{\text{threshold}} \sim 10^6 \text{ V/m, } p \sim 1 \text{ atm}$

\[
\frac{dn}{n} = \alpha \, dx
\]

fractional increase of electrons per unit path length $dx$

$n(x) = n(0)e^{\alpha x}$
density of electrons increases exponentially in the direction of motion of the avalanche

$\alpha = 0$ if $E < E_{\text{th}}$

$\alpha \propto E$ if $E > E_{\text{th}}$

Figure 6.1: A plot of the first Townsend coefficient as a function of electric field strength for a typical gas.
Fig. 2. Townsend coefficient vs. reduced electric field. The six curves are obtained for Ar–CO$_2$ mixtures spanning from 100–0% to 0–100% relative percentages. The thin dot–dashed lines are the predictions of Eq. (8) with the parameters $A$ and $B$ have been fitted separately for the pure gases. The heavy dashed lines are obtained from a two-dimensional fit of the entire data set with the same formula (see text).
Best Geometry: Cylindrical

**Polarity** is very important: electrons must be attracted to the center.

Electromagnetic field inside cylindrical chamber:

\[ E(r) = \frac{V_0}{\ln \left(\frac{b}{a}\right)} \frac{1}{r} \]

- \( a \) = anode radius
- \( b \) = cathode radius

**Example:**

\( V = 2000 \text{ V} \)
\( a = 0.008 \text{ cm} \) ⇒ \( E(a) = 10^6 \text{ V/m} \)
\( b = 1 \text{ cm} \)

**N. B.** in planar geometry equivalent field requires \( V \sim 10^5 \text{ Volt} \)

Electrons are more mobile than ions ⇒ Avalanche looks like a liquid drop with electrons at the head.
Uniform multiplication is obtained only in a confined region

\[ d \sim 5a \]

**Monte Carlo simulation**

Pulse signal from a cylindrical proportional counter

\[ \tau = RC \]

The pulse is usually cut by an RC differentiating circuit

\[ V(t) = -\frac{q}{4\pi\epsilon l} \ln \left(1 + \frac{\mu CV_0}{\pi\epsilon a^2} t\right) = -\frac{q}{4\pi\epsilon l} \ln \left(1 + \frac{t}{t_0}\right) \]
Total Charge produced

\[ Q = n_0 e^M \]

Gas multiplication Factor

\[ M = 10^2 - 10^4 \]
Multi Wire Proportional Counter

Detector sensitive to position of radiation interaction:
- 2 planes of wires (anodes and coathods)
- $\Delta x \sim 2-3$ mm
- size $\sim 1 \text{ m}^2$

Wire read-out may be very complicated
$\Rightarrow$ read-out of more than one wire at just one end
Position reconstructed by charge division

Electric field lines and constant potential energy surface
Read-Out methods

1. **Separate wire read-out**
   - complicated and costly (too many wires)

1. **Analog methods**:
   - center of gravity
   - charge division

**Center of gravity**

Chatode in strips:
Signals from each strip is stored and center of gravity is calculated

\[ y = \frac{\sum (Q_i - b)y_i}{\sum (Q_i - b)} \]

**Charge Division**

Charge collected at the two ends of the resistive anode is divided in proportion to the length of the wire from the point at which the charge is injected

\[ \frac{y}{L} = \frac{Q_A}{Q_A + Q_B} \]

\[ y = L \frac{Q_A}{Q_A + Q_B} \]
MWPPAC: the Focal plane detector of the PRISMA spectrometer at LNL Laboratory (Padova)

- **3 electrode structure**
  - Central cathode
  - 2 anodic wire planes (X and Y)
- **Cathode**: 3300 wires of 20 µm, 0.3 mm spacing, negative high voltage: 500-600 V
- **X plane**: 10 x 100 wires each, 1 mm spacing
- **Y plane**: common to all cathode, 130 wires, 1 m long, 1 mm steps
- **Spatial resolution**:
  - $\Delta X \sim 1\text{mm}$
  - $\Delta Y \sim 2\text{mm}$
Focal Plane Detectors of PRISMA: in-beam tests

MWPPAC ($\epsilon \sim 100\%$)

**X position (channels)**

- $\Delta t \sim 300$ ps
- $\Delta X = 1$ mm
- $\Delta Y = 2$ mm

**Y position (channels)**

- different shapes due to PRISMA optics
- focusing in Y (QUADRUPOLE)

**Dispersion in X (DIPOLE)**

**IC**

- $195$ MeV $^{36}$S + $^{208}$Pb, $\Theta_{lab} = 80^\circ$
- $\Delta E$ (a.u.)
- $Z=28$

- $240$ MeV $^{56}$Fe+$^{124}$Sn, $\Theta_{lab} = 70^\circ$
- $\Delta E$ (a.u.)
- $Z=16$
- $\Delta E/E < 2\%$
- $\Delta Z/Z \sim 60$

- $Z=26$
Proportional Scintillator Counter

Hybrid detector !!!

With noble gases

75-97 % of energy gained by electrons from electric field is converted into light

Energy resolution for low radiation is 2 times better than with ordinary proportional counters
**Geiger-Muller Counters**

for High Electric Fields:

Secondary avalanches are produced by photons emitted by excited atoms

\[ M \sim 10^{10} \]

*Entire volume gas is involved in the process*

⇒ Loss of information on space

⇒ Loss of information on energy (NO spectroscopy)

⇒ identical output

Fill Gas: He, Ne or Ar

Noble gases

To avoid formation of negative ions being based on multiplication process

400-1200 V depending on the gas
portable instruments for radiation monitoring

Two window types:
- Glass: Resistant, no α detection
- Mica: Fragile, possible α detection
Dead Time

The Geiger discharge stops when an **high ions (+) concentration** reduces the field E below the multiplication threshold

![Diagram of Geiger discharge and recovery time](image)

Second full pulse appears when **ALL** ions (+) are collected to the cathode

⇒ G-M tubes are limited to application with **low counting rates**

**Method to improve effective counting range**

1. **Time-to-first-count-method:**
   - The high voltage is switched between two values:
     - **Normal** operating voltage
     - **Lower** value below avalanche threshold

2. **Self-Quencing:**
   - addition of quench gas (5-10%)
   - with complex molecule absorbing UV photons (ethyl alcohol …)

Quenching gas is consumed (molecule disassociate) ⇒ Limit $10^9$ counts