EDIT 2011

Excellence in Detectors and Instrumentation Technologies
CERN, Geneva, Switzerland - 31 January - 10 February 2011

GASEOUS DETECTORS FUNDAMENTS

Fabio Sauli
TERA Foundation and CERN
ENERGY LOSS OF CHARGED PARTICLES

DIFFERENTIAL ENERGY LOSS AS A FUNCTION OF VELOCITY

Reduced units:

\[ \chi \left( g \ cm^{-2} \right) = \rho \left( g \ cm^{-3} \right) l \ (cm) \]

\[ \frac{dE}{d\chi} = \frac{1}{\rho} \frac{dE}{dx} \quad \rho : \text{density} \]

Expressed in MeV g\(^{-1}\) cm\(^2\), the differential energy loss is equal within a factor of two for all materials (except \( H_2 \)).
IONIZATION ENERGY LOSS OF CHARGED PARTICLES IN GASES

MAIN PARAMETERS:

| Gas   | Density, mg cm^{-3} | $E_x$ eV | $E_I$ eV | $W_I$ eV | $dE/dx|_{min}$ keV cm^{-1} | $N_P$ cm^{-1} | $N_T$ cm^{-1} |
|-------|----------------------|----------|----------|----------|----------------------------|----------------|----------------|
| Ne    | 0.839                | 16.7     | 21.6     | 30       | 1.45                       | 13             | 50             |
| Ar    | 1.66                 | 11.6     | 15.7     | 25       | 2.53                       | 25             | 106            |
| Xe    | 5.495                | 8.4      | 12.1     | 22       | 6.87                       | 41             | 312            |
| CH$_4$| 0.667                | 8.8      | 12.6     | 30       | 1.61                       | 37             | 54             |
| C$_2$H$_6$ | 1.26 | 8.2      | 11.5     | 26       | 2.91                       | 48             | 112            |
| iC$_4$H$_{10}$ | 2.49 | 6.5      | 10.6     | 26       | 5.67                       | 90             | 220            |
| CO$_2$| 1.84                 | 7.0      | 13.8     | 34       | 3.35                       | 35             | 100            |
| CF$_4$| 3.78                 | 10.0     | 16.0     | 54       | 6.38                       | 63             | 120            |

Detection efficiency: $\varepsilon = 1 - P_0^n = 1 - e^{-n}$

Total number of ion pairs: $n_T = \frac{\Delta E}{W_i}$

Minimum ionizing particles in Argon NTP:

- $dE/dx$: 2.5 keV/cm
- $n_p$: 25 ion pairs/cm

$\Delta E = 2.5$ keV/cm  $w_i = 25$ eV  $n_T \approx 100$ ip/cm

Detection efficiency:

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>$\varepsilon$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91.8</td>
</tr>
<tr>
<td>2</td>
<td>99.3</td>
</tr>
</tbody>
</table>


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PROGRAM HEED: NUMBER OF PRIMARY INTERACTIONS (CLUSTERS) IN GASES AT STP

EXPERIMENTAL CLUSTER SIZE PROBABILITY:

I. B. Smirnov, Nucl. Instr. and Meth. A554 (2005) 474

http://consult.cern.ch/writeup/heed/

PROBABILITY AND RANGE OF DELTA ELECTRONS

PROBABILITY FOR AN ELECTRON OF ENERGY $> E$:

\[ \frac{d\sigma}{dx} \text{ cm}^{-1} \]

\[ E \text{ (eV)} \]

\[ > E \]

ARGON (NTP)

Minimum ionization

Rutherford

ELECTRON RANGE IN ARGON STP:

I. B. Smirnov,
Nucl. Instr. and Meth. A554(2005)474

F. Lapique and F. Piuze,
Nucl. instr. and Meth. 175(1980)297
CONSEQUENCES OF IONIZATION STATISTICS

LANDAU DISTRIBUTION OF ENERGY LOSS:
POOR ENERGY LOSS RESOLUTION

For a Gaussian distribution:

\[ \sigma_N \sim 21 \text{ i.p.} \quad \text{FWHM} \sim 50 \text{ i.p.} \]

G. Charpak et al, Nucl. Instr. and Meth. 167 (1979) 455
DETECTION OF PHOTONS

PHOTON ABSORPTION

\[ I = I_0 e^{-\frac{x}{l}} \]

\( l \): absorption length

\[ \varepsilon = \frac{I_0 - I}{I_0} = 1 - e^{-\frac{x}{l}} \]

Conversion efficiency:

PHOTOELECTRIC: Interaction with an electronic shell with emission of a photoelectron. The excited atom/molecule returns to ground state through fluorescence or radiation-less (Auger) process.

COMPTON: Scattering of the photon by quasi-free electrons; can be coherent or incoherent

PAIR PRODUCTION: Conversion in a \( e^+e^- \) pair in the field of the atom/molecule. Possible for \( E_\gamma > 2 m_e = 1.022 \text{ MeV} \)
DETECTION OF PHOTONS

http://xdb.lbl.gov/
http://henke.lbl.gov/optical_constants/
PHOTON ABSORPTION: VISIBLE TO ULTRAVIOLET

MOLECULAR GASES: ABSORPTION CROSS SECTIONS

Noble Gases: Photoionization Above Threshold

H. S. W. Massey, Electronic and Ionic impact Phenomena (Oxford Press 1969)

PHOTOSENSITIVE VAPOURS:
TEA (Triethylamine, \((C_2H_5)_3N\)) \(E_i=7.5\) eV
TMAE (Tetrakis (dimethylamine) ethylene, \([(CH_3)_2N]_2C\)) \(E_i=5.6\) eV
SOFT X-RAYS

ABSORPTION LENGTH IN GASES (STP) VS PHOTON ENERGY

- Example:
  - $^{55}\text{Fe}$ 5.9 keV X-rays in Argon
  - $l = 2 \text{ cm}$

In a 1 cm thick counter:
\[ \varepsilon \sim 0.4 \]
Fluorescence photons can convert far from the primary interaction, or escape from the sensitive volume (escape peak):

**X-RAY ABSORPTION SPECTRUM**

$^{55}\text{Fe}$ X-Rays (5.9 keV) in Argon:
DRIFT AND DIFFUSION OF CHARGES IN GASES

E = 0: THERMAL DIFFUSION (Ions and electrons):

Maxwell energy distribution: \[ F(\varepsilon) = C\sqrt{\varepsilon} e^{-\frac{\varepsilon}{KT}} \]

E > 0: CHARGE TRANSPORT AND DIFFUSION

Drift velocity: \[ w = \frac{\Delta x}{\Delta t} \]

Diffusion: \[ \sigma = \sqrt{2Dt} = \sqrt{2D}\frac{x}{w} \]

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MOBILITY: RATIO OF VELOCITY AND FIELD

IONS MOBILITY (NTP: 300 K, 760 mm Hg)

<table>
<thead>
<tr>
<th>GAS</th>
<th>ION</th>
<th>$\mu^+$(cm$^2$s$^{-1}$V$^{-1}$)</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>CH$_4$</td>
<td>CH$_4^+$</td>
<td>2.26</td>
</tr>
<tr>
<td>Ar</td>
<td>CH$_4^+$</td>
<td>1.87</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>CO$_2^+$</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Ar-CH$_4$, $E$=1kV cm$^{-1}$  \(w^+ = 1.87\) cm ms$^{-1}$

IONS MOBILITY IN NITROGEN:

\[ \mu^+ = \frac{w^+}{E} \]

\[ \text{GAS} \quad \text{ION} \quad \mu^+(\text{cm}^2\text{s}^{-1}\text{V}^{-1}) \]

\[ \text{He} \quad \text{He}^+ \quad 10.2 \]

\[ \text{Ar} \quad \text{Ar}^+ \quad 1.7 \]

\[ \text{CH}_4 \quad \text{CH}_4^+ \quad 2.26 \]

\[ \text{Ar} \quad \text{CH}_4^+ \quad 1.87 \]

\[ \text{CO}_2 \quad \text{CO}_2^+ \quad 1.09 \]

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*S. C. Brown
Basic Data in Plasma Physics (Wiley, New York 1959)*
ELECTRONS DRIFT VELOCITY

DRIFT VELOCITY:

DIFFUSION:

ELECTRON-MOLECULE CROSS SECTION
Charge transport processes are determined by the various electron-molecule cross sections:

MAGBOLTZ:
Montecarlo program to compute electron drift and diffusion


http://rjd.web.cern.ch/rjd/cgi-bin/cross
ENERGY DISTRIBUTION AT INCREASING FIELDS:

EQUAL FIELD, DIFFERENT GAS:

SAME GAS, INCREASING FIELD:
ELECTRONS DRIFT AND DIFFUSION

DRIFT VELOCITY IN ARGON-METHANE MIXTURES

EXAMPLE: Ar-CH₄ 90-10), STP, E=1kVcm⁻¹

\[ w^- = 2.5 \text{ cm } \mu \text{s}^{-1} \]
\[ \sigma_T = 600 \text{ } \mu \text{m} \]
\[ \sigma_L = 200 \text{ } \mu \text{m} \]
\[ \frac{w^-}{w^+} \approx 10^3 \]

Computed with MAGBOLTZ

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ATTACHMENT CROSS SECTION OF OXYGEN:

ELECTRONS SURVIVING AFTER 20 CM DRIFT (E = 200 V/cm):
HIGH FIELD-INELASTIC COLLISIONS

ELECTRON CROSS SECTIONS IN ARGON:

ELECTRONS ENERGY DISTRIBUTION IN ARGON AT INCREASING FIELDS:

**EXCITATION 11.6 eV**

**IONIZATION 15.7 eV**

**$E_x = 10.6$ eV**  **$E_i = 15.7$ eV**

**$1 \text{ kV cm}^{-1}$**

**$5 \text{ kV cm}^{-1}$**

**$100 \text{ kV cm}^{-1}$**
HIGH FIELD-INELASTIC COLLISIONS

MAIN ELECTRON-MOLECULE INELASTIC PROCESSES:

1) A+e \rightarrow A^+e+e  
   Ionisation by electronic impact.
2) A+e \rightarrow A^+e  
   Excitation by electronic impact.
3) A^+e \rightarrow A+e  
   Deexcitation by electronic collision.
4) A+\nu \rightarrow A^*  
   Photo-excitation (absorption of light).
5) A^* \rightarrow A+\nu  
   Photo-emission (radiative deexcitation).
6) A+\nu \rightarrow A^+e  
   Photolionisation.
7) A^+e \rightarrow A+\nu  
   Radiative recombination.
8) A^+e+B+e \rightarrow A+B  
   Three body recombination.
9) A^+B \rightarrow A+B^*  
   Collisional deexcitation.
10) A^+B \rightarrow A+B^+e  
    Penning effect.
11) A^+B \rightarrow A+B^+  
    Charge exchange.
12) A^+e+B \rightarrow A^++B^+e  
    Ionisation by ionic impact.
13) A+B \rightarrow A^+B  
    Excitation by atomic impact.
14) A+B \rightarrow A^+B+e  
    Ionisation by atomic impact.
15) A+e \rightarrow A^-  
    Formation of negative ions.
16) A^- \rightarrow A+e  
    Electrons release by negative ions.
17) A^++A \rightarrow A^++e  
    Associative ionisation.
18) A^++2A \rightarrow A^+e  
    Molecular ion formation.
19) A^++A+A \rightarrow A^+e  
    Excimer formation.
20) A^++A \rightarrow A+A+\nu  
    Radiative excimer dissociation.
21) (XY)^* \rightarrow X+Y^*  
    Dissociation.
22) (XY)^+e \rightarrow X+Y^*  
    Recombinational dissociation.

J. Meek and J. D. Cragg, Electrical Breakdown of Gases (Clarendon Press, Oxford 1953)

ENERGY SHARING BETWEEN COLLISION PROCESSES:

L. B. Loeb, Basic Processes of Gaseous Electronics (UC Berkeley Press, 1961)
CHARGE MULTIPLICATION

CHARGE MULTIPLICATION IN UNIFORM FIELD

Mean free path for ionization:

$$\lambda = \frac{1}{N \sigma}, \quad N: \text{molecules/cm}^3$$

Townsend coefficient:

$$\alpha = \frac{1}{\lambda}, \quad \text{Ionizing collisions/cm} \quad \frac{\alpha}{\mathbb{P}} = f\left(\frac{E}{\mathbb{P}}\right)$$

Incremental increase of the number of electrons in the avalanche:

$$dn = n \alpha dx$$

Multiplication factor (Gain):

$$M(x) = \frac{n}{n_0} = e^{\alpha x}$$

Maximum Avalanche size before discharge (Raether limit):

$$Q_{\text{MAX}} \approx 10^7 e$$

\textit{S.C. Brown, Basic Data of Plasma Physics (MIT Press, 1959)}

\textit{H. Raether, Electron Avalanches and Breakdown in Gases (Butterworth 1964)}
TOWNSEND COEFFICIENT FOR Ar, CH₄ and Ar-CH₄:

(COMPUTED WITH MAGBOLTZ)
**CHARGE INDUCTION - IONIZATION CHAMBER**

**SIGNAL DEVELOPMENT BY A MOVING CHARGE +Q**

Charge induced on each electrode by +Q moving through the difference of potential $dV$:

$$dq = Q \frac{dV}{V_0} = Q \frac{ds}{s_0}$$

Integrating over $s$ (or time $t$):

$$q(s) = \frac{Q}{s_0} s \quad q(t) = \frac{Q}{s_0} wt \quad i(t) = \frac{dq}{dt} = \frac{Q}{s_0} w$$

Electrons- ion pair (-Q and +Q) released at the same distance $s$ from the cathode:

- For $0 \leq t \leq T^-:
  $$q(t) = Q \left( \frac{w^- t}{s_0} + \frac{w^+ t}{s_0} \right)$$

- For $T^- \leq t \leq T^+$:
  $$q(t) = Q \left( \frac{s - s_0}{s_0} + \frac{w^+ t}{s_0} \right)$$

$$q(T^+) = Q$$

$w^-$ ($w^+$): electron (ion) drift velocity
$T^-$ ($T^+$): total electron (ion) drift time
(+Q on cathode, -Q on anode)

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PARALLEL PLATE COUNTERS:

Increase in the number of charges after a path \( ds \):

\[
dn = n_0 c_0 ds \\
n = n_0 e^{c_0 s}
\]

Charge induced by electrons:

\[
dq^- = -en_0 e^{c_0} \frac{ds}{s_0}
\]

\[
q^-(s) = \frac{en_0}{\alpha s_0} (e^{c_0 s} - 1) = \frac{en_0}{\alpha s_0} e^{c_0 s} = \frac{en_0}{\alpha s_0} e^{c_0 s}
\]

\[
i^- (t) = \frac{dq^-}{dt} = \frac{en_0 w^-}{s_0} e^{c_0 t} = \frac{en_0}{T^-} e^{c_0 t}
\]

Current signal induced by ions:

\[
i^+(t) = \frac{en_0}{T^+} \left( e^{c_0 t} - e^{c_0 t} \right) \\
\quad 0 \leq t \leq T^-
\]

\[
i^+(t) = \frac{en_0}{T^+} \left( e^{c_0 t} - e^{c_0 t} \right) \\
\quad T^- \leq t \leq T^+
\]

\[
\frac{1}{w^+} = \frac{1}{w^-} + \frac{1}{w}
\]
THIN ANODE WIRE

Cathode radius $b$

Anode radius $a$

ELECTRIC FIELD AND POTENTIAL:

$$E(r) = \frac{CV_0}{2\pi \varepsilon_0} \frac{1}{r}$$

$$V(r) = \frac{CV_0}{2\pi \varepsilon_0} \ln \frac{r}{a}$$

$$C = \frac{2\pi \varepsilon_0}{\ln(b/a)}$$

capacitance per unit length
PROPORTIONAL COUNTER

AVALANCHE DEVELOPMENT:

CHARGE SIGNAL INDUCTION:

\[ q^- = \frac{Q}{V_0} \int_a^{a+\lambda} \frac{dV}{dr} = -\frac{QC}{2\pi\varepsilon_0} \ln \frac{a+\lambda}{a} \]

\[ q^+ = \frac{Q}{V_0} \int_a^{a+\lambda} \frac{dV}{dr} = -\frac{QC}{2\pi\varepsilon_0} \ln \frac{b}{a+\lambda} \]

\[ q = q^- + q^+ = -\frac{QC}{2\pi\varepsilon_0} \ln \frac{b}{a} = -Q \]

\[ q^- = \ln(a+\lambda) - \ln a \approx 0.01 \]

\[ q^+ = \ln b - \ln(a+\lambda) \approx 0.01 \]

99% of signal due to positive ions

\[ q(t) = -\frac{QC}{2\pi\varepsilon_0} \ln \left( 1 + \frac{\mu^+CV_0}{2\pi\varepsilon_0} t \right) = -\frac{QC}{2\pi\varepsilon_0} \ln \left( 1 + \frac{t}{t_0} \right) \]

CHARGE SIGNAL: POSITIVE ION TAIL

RC differentiation for faster response

S. C. Curran and J. D. Craggs, Counting Tubes (Butterworth 1949)

F. Sauli, Principles of Operation of Multiwire Proportional and Drift Chambers (CERN 77-09)
PROPORTIONAL COUNTERS: OPERATING REGIMES

\[ \ln M \]

Voltage

\[ n_1 \]

\[ n_2 \]

Attachment

Collection

IONIZATION CHAMBER

PROPORTIONAL COUNTER

Multiplication

Streamer

Saturation

Breakdown
MULTIWIRE PROPORTIONAL CHAMBER

TWO-DIMENSIONAL COORDINATE READOUT
Center of gravity of induced signals on cathodes

\[ X = \sum \frac{X_i A_i(X)}{A(X)} \quad Y = \sum \frac{Y_i A_i(Y)}{A(Y)} \]

G. Charpak et al, Nucl. Instr. and Meth. 62(1968)235

G. Charpak and F. Sauli, Nucl. Instr. and Methods 113(1973)381
DRIFT CHAMBER

MWPC WITH A FIELD-SHAPING WIRE BETWEEN ANODES, TO AVOID LOW-FIELD REGIONS

SPACE-TIME CORRELATION (RIGHT-LEFT AMBIGUITY):

A. H. Walenta, J. Heintze and B. Scürlein, Nucl. Instr. and Meth. 92(1971)373

ELECTRIC FIELD AND DRIFT PROPERTIES CALCULATIONS: GARFIELD

Rob Veenhof
LABORATORY: STRAWS AND DRIFT TUBES

SINGLE WIRE PROPORTIONAL COUNTERS

STRAWs ARRAYS:

Anatoli Romaniouk: ATLAS Transition Radiation Tracker (TRT)
Hans Danielsson: NA62 Straw Detectors
Joerg Dubbert: ATLAS Monitored Drift Tubes (MDT)
LABORATORY: MICROPATTERN GAS DETECTORS

MICROME GAS and GRIDPIX

GAS ELECTRON MULTIPLIER (GEM)

Paul Colas
Harry van der Graaf

Gianni Bencivenni
AND NOW, PUT YOUR HANDS ON (CAREFULLY)!