Gas Detectors

22.104 Spring 2002
Gas Detectors as Two Part Problems

- Detection medium
  - interaction where radiation interaction occurs
  - detection medium where by-products of interaction interact
  - usually same medium, but can also have an interaction medium not the gas

- Motion of electrons and ions in gas under influence of electric field

- Detection and measurement of electron and ion motion
Electroscope
Ionization Processes

- Assume a charged particle, $p_c$ incident on gas
  
  - in case of $\gamma$'s we have photoelectric, Compton or pair production to get an electron

- Possible processes

\[
p_c \rightarrow X \rightarrow X^* + p_c
\]

\[
\sigma \approx 10^{-17} \text{ cm}^2
\]

de-excite by Penning Effect

\[
X^* + X \rightarrow X^+ + p_c + e^-
\]

or, can have direct ionization

\[
p_c \rightarrow X \rightarrow X^+ + p_c + e^-
\]

\[
\sigma \approx 10^{-16} \text{ cm}^2
\]
Diffusion Relations

\[ \sigma (r) = \sqrt{6}Dt \]

\[ D = \frac{1}{3}v\lambda \]

\[ \lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma_0 p} \]
Drift in Electric Fields

\[ v = \frac{e}{2m} E \tau \]

where

\( E \) = electric field

\( \tau \) = time between collisions

\[ v_{\text{average}} = \sqrt{\frac{8kT}{\pi m}} \]

\( \approx 10^6 \) cm/s for electrons

\( \approx 10^4 \) cm/s for ions
Additions of Complex Molecules to Noble Gasses

- Noble gasses have closed shells, so no excitations at low energies.
- Add complex molecule such as CH$_4$ which can get energy from electron
- Result is that CH$_4$ “cools” electron so that the time between collisions goes up and as a result, the drift velocity goes up and the electron picks up more energy from the applied field
- In addition, molecule may absorb in the UV
Drift Velocities in Mixtures

Drift velocity in Argon Methane Mixture

Drift velocity in Argon Ethylene Mixture
Xe-CH$_4$ Drift Velocity
Xe-CH$_4$ Diffusion
Xe-He Diffusion

Diagram showing the diffusion square root (cm) vs. time for different percentages of Xe and He.
X-He Drift Velocity
Parallel Plate Ionization Chamber

\[ \frac{\Delta Q}{\Delta t} = \frac{qV}{L} (v_- + v_+) \]

\[ t = \frac{L - x}{v_-} \]

\[ \Delta Q \]

\[ t \]
Frisch Grid

\[ L \]

\[ x \]

\[ E \]

\[ V \]

\[ E_F \gg E \]
# Ionization Properties of Some Gasses

<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></td>
<td>13.1</td>
<td>28</td>
</tr>
<tr>
<td>C₄H₁₀</td>
<td></td>
<td>10.8</td>
<td>23</td>
</tr>
</tbody>
</table>
Parasitic Effect in Ionization Chambers

- Recombination effect
- Space charge limitations
- Mechanical vibration
- Electronic noise
## Recombination in Ionization Chambers

<table>
<thead>
<tr>
<th>Type of chamber</th>
<th>Dimensions</th>
<th>V</th>
<th>Ionization density</th>
<th>Air (1 atm)</th>
<th>Argon (1 atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>I.P./cc/sec.</td>
<td>A/cc</td>
<td>I.P./cc/sec.</td>
</tr>
<tr>
<td>Plane parallel</td>
<td>d = 5 cm</td>
<td>1,000</td>
<td>$1.6 \times 10^8$</td>
<td>$2.5 \times 10^{-11}$</td>
<td>$6 \times 10^{15}$</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>a = 1 cm, b = 10 cm</td>
<td>1,000</td>
<td>$8 \times 10^6$</td>
<td>$1.3 \times 10^{-12}$</td>
<td>$8 \times 10^{14}$</td>
</tr>
<tr>
<td>Spherical</td>
<td>a = 1 cm, b = 10 cm</td>
<td>1,000</td>
<td>$10^6$</td>
<td>$1.5 \times 10^{-13}$</td>
<td>$1.3 \times 10^{14}$</td>
</tr>
</tbody>
</table>

Values for 1% loss
# Saturation in Ionization Chambers

<table>
<thead>
<tr>
<th>Type of chamber</th>
<th>Dimensions</th>
<th>( V )</th>
<th>Ionization density A/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane parallel</td>
<td>( d = 5 \text{ cm} )</td>
<td>1,000</td>
<td>( 10^{-9} )</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>( a = 1 \text{ cm} ) ( b = 10 \text{ cm} )</td>
<td>1,000</td>
<td>( 2 \times 10^{-11} ) (outer electrode +ve) ( 3 \times 10^{-10} ) (outer electrode -ve)</td>
</tr>
<tr>
<td>Spherical</td>
<td>( a = 1 \text{ cm} ) ( b = 10 \text{ cm} )</td>
<td>1,000</td>
<td>( 2 \times 10^{-12} ) (outer electrode +ve) ( 6 \times 10^{-10} ) (outer electrode +ve)</td>
</tr>
</tbody>
</table>
Fano Factor

Number of ion pairs formed is \( \frac{E}{w} \), where \( w \sim 30 \text{ eV} \)

Expect a variance of:

\[
\sqrt{\frac{E}{w}}
\]

or a fractional variance of:

\[
\sqrt{\frac{w}{E}}
\]

But, with Fano factor, we get:

where \( F \sim 0.1 - 0.2 \)

\[
\sqrt{\frac{wF}{E}}
\]
## Fano Factors In Gasses

<table>
<thead>
<tr>
<th>Gas Composition</th>
<th>Fano Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar 100%</td>
<td>0.2 ± 0.01</td>
</tr>
<tr>
<td>Ar + 80% Xe</td>
<td>&lt;0.40 ± 0.03</td>
</tr>
<tr>
<td>Ar + 24% Xe</td>
<td>&lt;0.23 ± 0.02</td>
</tr>
<tr>
<td>Ar + 20% Xe</td>
<td>&lt;0.16 ± 0.02</td>
</tr>
<tr>
<td>Ar + 5% Xe</td>
<td>&lt;0.14 ± 0.03</td>
</tr>
<tr>
<td>Ar + 5% Kr</td>
<td>&lt;0.37 ± 0.06</td>
</tr>
<tr>
<td>Ar + 20% Kr</td>
<td>&lt;0.12 ± 0.02</td>
</tr>
<tr>
<td>Ar + 79% Kr</td>
<td>&lt;0.13 ± 0.02</td>
</tr>
<tr>
<td>Xe 100%</td>
<td>&lt;0.15 ± 0.01</td>
</tr>
<tr>
<td>Kr 100%</td>
<td>&lt;0.19 ± 0.02</td>
</tr>
<tr>
<td>Kr + 1.3% Xe</td>
<td>&lt;0.19 ± 0.01</td>
</tr>
<tr>
<td>Kr + 20% Xe</td>
<td>&lt;0.21 ± 0.02</td>
</tr>
<tr>
<td>Kr + 40% Xe</td>
<td>&lt;0.22 ± 0.01</td>
</tr>
<tr>
<td>Kr + 60% Xe</td>
<td>&lt;0.21 ± 0.01</td>
</tr>
<tr>
<td>Kr + 95% Xe</td>
<td>&lt;0.21 ± 0.01</td>
</tr>
</tbody>
</table>
Cylindrical Counter
Cylindrical Fields

\[ E \sim \frac{1}{r} \]

Diagram showing a cylindrical field with an anode and a cathode, and a graph indicating the relationship between the electric field and distance, \( r \).
Avalanche Development
Pulse Development in Cylindrical Detector

\[ v\left(\frac{a}{b} T\right) \approx \frac{Q}{2\pi C} \, , \]

Graph showing the pulse development over time with different time constants (\(\tau\)) as indicated on the graph.
Operating Region of Gas Detector

![Graph showing the operating region of a gas detector](image-url)
Properties of several gases used in proportional counters (from different sources, see the bibliography for this section). Energy loss and ion pairs per unit length are given at atmospheric pressure for minimum ionizing particles.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Z</th>
<th>A</th>
<th>$\delta$ (g/cm³)</th>
<th>$E_{\text{ex}}$ (eV)</th>
<th>$E_{\text{i}}$ (eV)</th>
<th>$I_0$ (keV/cm)</th>
<th>$W_{\text{i}}$ (MeV/g cm⁻²)</th>
<th>$\text{dE/dx}$ (keV/cm)</th>
<th>$n_{\text{p}}$ (i.p./cm) (^\text{a)})</th>
<th>$n_{\text{T}}$ (i.p./cm) (^\text{a)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>1</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>N₂</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>O₂</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>
<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>4.60</td>
<td>(22)</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>12.1</td>
<td>22</td>
<td>1.23</td>
<td>6.76</td>
<td>44</td>
</tr>
<tr>
<td>CO₂</td>
<td>22</td>
<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>
</tr>
<tr>
<td>CH₄</td>
<td>10</td>
<td>16</td>
<td>$6.70 \times 10^{-3}$</td>
<td>15.2</td>
<td>13.1</td>
<td>13.1</td>
<td>28</td>
<td>2.21</td>
<td>1.48</td>
<td>16</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>34</td>
<td>58</td>
<td>$2.42 \times 10^{-3}$</td>
<td>10.6</td>
<td>10.8</td>
<td>10.8</td>
<td>23</td>
<td>1.86</td>
<td>4.50</td>
<td>(46)</td>
</tr>
</tbody>
</table>

\(^{a)}\ i.p. = ion pairs
X-ray Absorption in Gasses
Neutron Detection

- Use gas filling with large cross-section
  - He-3
  - BF$_3$

- Coat wall of chamber with thin layer of fissionable material and detect fission products
Higher Energy Gammas

- Interaction in non-gaseous medium
  - interact in wall
  - Distribute conversion material in form of meshes, thin tubes, or sheets within gas volume
PWR Out of Core Instruments
PWR Ranges

- Source start-up range
- Intermediate range
- Power range

Typical neutron flux in n/cm² · s (out-of-core)
Instrument Requirements

- **Start-up**
  - gamma Flux dominates
  - require discrimination against gammas
  - pulse mode possible

- **Intermediate**
  - gamma still important
  - switch to current mode
  - reject gammas
    - » CIC
    - » MSV

- **Full Power**
  - gammas not important
  - simplicity for safety
  - ion chambers
Compensated Ion Chamber

\[ \text{Signal} = I_1 - I_2 \]
Mean Square Value Counter

\[ \sigma_{I}^{2}(t) = \frac{rQ^{2}}{T} \]
BWR Ranges

- Source start-up range
- Intermediate range
- Power range

Typical neutron flux in n/cm² • s (in-core)
BWR In-Core Fission Counter
Memory Effects

![Graph showing normalized residual current vs. time after irradiation](image)
Operating Voltages
Self powered Neutron Detector
Some Special Cases

- Multiwire Proportional Counter
  - 2 dimensional readout of position
  - avalanche gap chamber
  - radial drift field chamber

- Gas Scintillator
Multiwire Proportional Chamber
2-Dimensional Readout of MWPC
Avalanche Gap Chamber

\[ G = k e^x \]

Beta Source

Avalanche Gap (high field)

Drift Region

High Amplification

Low Amplification

MWPC
Radial Drift Field Chamber

Scattered X-Ray

Incident X-Ray Beam

Radial Drift Interaction Region

Transfer Region

MWPC
Gas Scintillator

- Incident Radiation
- X-Ray Interaction
- Electron Drift
- Light Production (160 nm in Xe)
- Drift Region
- Light Gap
- Light Detectors (PMTs)
Gas Scintillator Properties

- Can get very large amount of light without charge multiplication
- Energy resolution better than conventional scintillators
- Can be operated as position sensitive detectors

\[ L = 4000 \left( \frac{E}{p} - 1.3 \right) px \text{ photons/keV} \]

$E$ in kV/cm
$p$ in atmospheres
$x$ gap width in cm

10000 photons/keV vs 40 in NaI!)}