• **Introduction**
  – Overview of detector systems
  – Sources of radiation
    • Radioactive decay
    • Cosmic Radiation
    • Accelerators

• **Interaction of Radiation with Matter**
  – General principles
  – Charged particles
    • heavy charged particles
    • electrons
  – Neutral particles
    • Photons
    • Neutrons
    • Neutrinos

• **Definitions**

• **Detectors for Ionizing Particles**
  – Principles of ionizing detectors
  – Gas detectors
    • Principles
    • Detector concepts
Review of Previous Lecture
Absorption of Photons

- Photoelectric effect:

- Compton scattering

- Pair production near nuclei
Interaction of Neutrons

- No electric charge $\rightarrow$ no Coulomb interaction
- Only strong force with nuclei in matter
- High energy neutrons have to come within $\approx 10^{-13}$ cm of the nucleus $\rightarrow$ very penetrating
- Several different interaction processes:
  - Elastic scattering: Principal mechanism of energy loss in the range of MeV
  - Inelastic scattering: Nucleus is left in an excited state which later decays by radiative emission. Energy of neutron has to be high enough for excitation (typically $> 1$ MeV)
  - Radiative neutron capture: cross section $\propto 1/v$ $\rightarrow$ only takes place for slow neutrons, resonance peaks superimposed
  - Other nuclear reaction: caption of neutron + emission of charged particle, typically in the range of eV to keV, cross section $\propto 1/v$ + resonances
  - Fission: most likely at thermal energies
  - High energy hadron shower production: only for very high energy neutrons ($> 100$ MeV)
Neutrino Measuring Techniques

- Radio chemical method
  - Detection via radioactive reaction products
  - Only sensitive on $\nu_e$!!

- Measurement of the partner lepton
  - Sensitive on $\nu_e$ and $\nu_\mu (+ \nu_\tau)$
  - Momentum of $\nu$ has to be sufficient

- Elastic Scattering
  - Detection of the scattered electron

- Deuteron breaking
  - Detection of the nucleons
 Definitions

“Old” ionization detectors
Gas Detectors
Sensitivity

• is the minimum magnitude of input signal required to produce a specified output signal having a specified signal-to-noise ratio

• Usually given by:
  – the cross section for ionization reactions in the detector
  – the detector mass
  – the inherent detector noise
  – the protective material surrounding the detector

\[ \text{determines the probability that (part of) the energy of the incoming radiation is transformed in the form of ionization} \]
\[ \text{signal > noise} \]
\[ \text{entrance threshold} \]
Energy Resolution

- **Width** of the **probability distribution** function of the **measured observable** for a given physical value
- For detectors designed to measure the energy of the incident radiation the **energy resolution** is the most important quantity
- The resolution is quantified in terms of the **full width at half maximum** of the peak:
  \[ R = \frac{\Delta_{\text{FWHM}} E}{E} = 2.35 \frac{\sigma(E)}{E} \]
- Two peaks closer together than the FWHM are usually considered **not resolvable**
- \( \Delta E \) includes all type of noise sources:
  \[ (\Delta E)^2 = (\Delta E_{\text{stat}})^2 + (\Delta E_{\text{det}})^2 + (\Delta E_{\text{elect}})^2 + \ldots \]
Energy Resolution and Fano Factor

- The mean number of ionizing events $J$ is given by the mean energy required to produce an ionization $w$ ($w > $ B.E.):
  \[ J = \frac{E}{w} \]
- $w$ depends on the material
- To calculate the fluctuations one would typically take the Poisson distribution which yields:
  \[ \text{var} = J \]
- This implies that the ionization processes are all statistically independent, which is not true
- U. Fano calculated the variance for large $J$ and found:
  \[ \text{var} = \sigma^2 = FJ \]
- $F$ is the Fano factor describing the deviation of the variance from a Poisson distribution
- This gives for the resolution:
  \[ R = 2.35 \frac{\sqrt{FJ}}{J} = 2.35 \sqrt{\frac{Fw}{E}} \]
- For $F = 1$ the variance is the same as the Poisson distribution
The Fano Factor

- Because the Fano factor describes corrections in the statistical fluctuations in the process of ionization, it gives the best energy resolution a detector can reach.
- It is material dependent and varies strongly:
  - scintillators ≈ 1
  - gases < 1
  - semiconductors ≈ 0.1 (theoretically)
- Measuring the Fano factor not easy because all other noise sources have to be reduced → typically an upper limit for the Fano factor is given.
- F is in addition a function of the temperature and, below 1 keV, also of the energy of the incoming particle.
Detector Response

- In general the detector response describes the dependence of the expectation value of a measured quantity on the physical quantity.
- Ideally the relation between the physical quantity and the measured quantity is linear (this is not necessary but makes life easier).
- Due to the limited resolution of the detector the result will always convoluted with the resolution.
- Be careful: the response of a detector may vary with the type of radiation it detects.
The Response Function

• Spectrum of pulse heights observed from the detector for a monoenergetic beam

• Ideal case: delta function and linear behavior for different energies \(\Rightarrow\) 1-to-1 correspondence between the measured quantity and the particles physical quantity

• Typically (much) more complicated:
  – e.g.: electrons on a thick detector:
    • main component: Gaussian distribution
    • some electrons scatter out of detector \(\Rightarrow\) low energetic tail
    • bremsstrahlung \(\rightarrow\) photons leave detector \(\Rightarrow\) low energetic tail
  – e.g.: photons on the same detector: \(\Rightarrow\) next page
The Response Function

- Superposition of photoelectric effect, Compton scattering and pair production

\[ PH(E) = \int S(E') R(E, E') dE' \]

\( PH \): pulse height distribution, \( R(E, E') \) response function, \( S(E') \) incident spectrum, \( E' \) incident energy
Response Time

- **Time between the arrival** of the particle and the signal formation
- Important for **dedicated time measurements** (e.g. time-of-flight detectors)
- Must be considered when triggering on events in different detector components
Dead Time

- Finite time required by a detector to process an event, during which no additional signal can be registered.

- Two cases:
  - detector is insensitive → non-extendable/paralyzable dead time
  - detector stays sensitive → extendable or paralyzable dead time (e.g. rate of a Geiger-Müller counter drops at very high dosis)
Dead time

• Non-extendable dead time:

\[ mT = k + mk\tau \]
\[ \iff m = \frac{k/T}{1 - (k/T)\tau} \]

\( m \): true count rate, \( T \): measuring time, \( k \): measured counts, \( \tau \): dead time

• Extendable dead time:

\( P(t) \): distribution of time intervals between random events with rate \( m \)

\[ P(t) = m \exp(-mt) \]

only events arriving later than \( \tau \) are recorded

\[ P(t > \tau) = m \int_{\tau}^{\infty} \exp(-mt) dt = \exp(-m\tau) \]

\[ k = mT \exp(-m\tau) \]
Measuring dead time

- “Two-source” technique (for the non-extended case):

\[
\begin{align*}
n_{1/2} &= \frac{R_{1/2}}{1 - R_{1/2}\tau} \\
n_1 + n_2 &= \frac{R_{12}}{1 - R_{12}\tau}
\end{align*}
\]

\[
\Rightarrow \frac{R_{12}}{1 - R_{12}\tau} = \frac{R_1}{1 - R_1\tau} + \frac{R_2}{1 - R_2\tau}
\]

\[
\Leftrightarrow \tau = \frac{R_1 R_2 - [R_1 R_2 (R_{12} - R_1)(R_{12} - R_2)]^{1/2}}{R_1 R_2 R_{12}}
\]

- Large errors (5 - 10%)
- Experimentally difficult
- Better: use of two oscillators:

Non-extendable dead time

\[
f_{12} = \begin{cases} 
    f_1 + f_2 - 2f_1 f_2 \tau & \text{for } 0 < \tau < T / 2 \\
    1 / T & \text{for } T / 2 < \tau < T
\end{cases}
\]

with T: period of faster osc.

Extendable dead time

\[
f_{12} = \begin{cases} 
    f_1 + f_2 - 2f_1 f_2 \tau & \text{for } 0 < \tau < T \\
    0 & \text{for } T < \tau
\end{cases}
\]

Equal for \( f < (2\tau)^{-1} \)

\[
\tau = \frac{t_m}{2} \frac{R_1 + R_2 - R_{12}}{R_1 R_2}
\]
Detector Efficiency

- Two definitions:
  - **absolute efficiency** $E_{\text{tot}}$
  - **intrinsic efficiency** $E_{\text{int}}$

  $$E_{\text{tot}} = \frac{\text{events registered}}{\text{events emitted by source}}$$

- Example: cylindrical detector with a point source at a distance $d$ on the axis of the detector

  $$P(\theta)d\Omega = \frac{d\Omega}{4\pi}$$

  $$dE_{\text{tot}} = \left[1 - \exp\left(\frac{-x}{\lambda}\right)\right] \frac{d\Omega}{4\pi}$$

- If $x$ does not vary too much:
  $$E_{\text{tot}} \approx E_{\text{int}} E_{\text{geom}} \approx \text{efficiency} \cdot \text{acceptance}$$

  $$E_{\text{int}} = \frac{\text{events registered}}{\text{events impinging on detector}}$$
“Old” ionization detectors

- Photo emulsion
- Cloud chamber
- Bubble chamber
- Spark chamber
Ionization tracks can be measured in photo emulsions. With a microscope the darkening of the film is measured.

Space resolution $\approx 1\mu m$

Slow heavy particles make more ionization as fast light particles

(about $10^{13}$ fields like this one!)
Cloud chamber

Ionization as condensation or evaporation nucleus: cloud or bubble chamber

Langsame schwere Teilchen machen mehr Ionisation als schnelle leichte Teilchen

Zeuthener Nebelkammer
Bubble chamber

Big European Bubble Chamber

Spuren durch Magnetfeld gekrümmt

D.A. Glaser, Nobelpreis 1960
Spark chamber

Between 2 plates with high voltage a spark emerges along the ionization track

Problems for modern detectors:

- Too slow
- Needs trigger for high voltage at plates
- Spark makes electromagnetic debris
- Difficult to read out electronically

Is also true for emulsion, cloud and bubble chamber
Transport of Electrons / Ions in Gases

- Ionization mechanisms
- Diffusion
- Drift
- Losses
Ionization Mechanisms in Gases

- Energy loss of charged particles in matter divided in two types:
  - excitation: \[ X + p \rightarrow X^* + p \rightarrow \text{Penning effect} \]
  - ionization: \[ X + p \rightarrow X^+ + p + e^- \]

- Additional effect in gases: Penning Effect
  \[ \text{Ne}^* + \text{Ar} \rightarrow \text{Ar}^+ + e^- \]
  In certain atoms, metastable states are excited which may deexcite via the ionization of a second atom

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

\[ \text{Helium} \]
Ionization of Gases

Often the resulting primary electron will have enough kinetic energy to ionize other atoms.

Primary ionization

\[ n_{\text{primary}} \cdot \approx 4 \quad \ldots \quad 30 \] pairs/cm

\[ \Delta E/\text{pair} \approx 20 - 40 \text{ eV} \]

Total ionization

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

Primary and secondary ion pair production given at atmospheric pressure and for mips

\[ \frac{N_{\text{total}}}{cm} \approx 5 \cdot Z \]

or, about 100 e\(^{-}\)/cm in argon gas

\[ = 1.6 \times 10^{-17} \text{ C} \]
Cluster parameters

Cluster distance

Number of primary electrons per cluster

He + 10% i-C$_4$H$_{10}$ at STP
## Mean Energy for Electron-Ion Pair Production

<table>
<thead>
<tr>
<th></th>
<th>Excitation potential [eV]</th>
<th>Ionization potential [eV]</th>
<th>Mean energy for ion-electron creation [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)</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>N(_2)</td>
<td>8.1</td>
<td>15.5</td>
<td>35</td>
</tr>
<tr>
<td>O(_2)</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>CO(_2)</td>
<td>10.0</td>
<td>13.7</td>
<td>33</td>
</tr>
<tr>
<td>CH(_4)</td>
<td></td>
<td>13.1</td>
<td>28</td>
</tr>
<tr>
<td>C(<em>4)H(</em>{10})</td>
<td></td>
<td>10.8</td>
<td>23</td>
</tr>
</tbody>
</table>
• Spatial distribution (1D) of charges after time \( t \) is:

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

with \( N_0 \): total number of charges, \( x \): distance from creation, \( D \): diffusion coeff.

• This gives the rms spread in \( x \) and in three dimensions to:

\[
\sigma(x) = \sqrt{2Dt} \quad \Leftrightarrow \quad \sigma(r) = \sqrt{6Dt}
\]

• Diffusion coeff. is:

\[
D = \frac{1}{2} v \lambda \quad \text{for an ideal gas:} \quad \lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma_0 p}
\]

\[
D = \frac{2}{3} \frac{1}{p \sigma_0} \sqrt{\frac{(kT)^3}{m}}
\]

with \( \lambda \): mean free path, \( p \): pressure, \( \sigma_0 \) total collision cross section
Diffusion

diffusion of ions is almost gas independent

diffusion of electrons is strongly gas dependent
Drift

- In the presence of an electric field, the electrons and ions are accelerated along the field lines.
- Acceleration is interrupted by collisions with the gas molecules, resulting in "stop and go" traffic. The maximum average velocity is limited, called drift velocity $v_D$.
- Mobility $\mu = \frac{v_D}{E}$.
- For positive ions $v_D \propto \frac{E}{p}$ (called reduced electric field), $\mu$ is constant for $p$ constant.
- For ideal gases, $D/\mu = \frac{kT}{e}$ (Einstein relation).
- For electrons $v_D \propto E$.
- Velocities of a few times $10^6$ cm/s at electric fields of 1 kV/cm-atm can be achieved before saturation.
Drift

• Derivation of drift velocity:
  – The collision rate $1/\tau$ is proportional to the density of the gas $N$ (gas atoms / m$^3$) and the instantaneous velocity
    \[
    \frac{1}{\tau} = N\sigma v
    \]
  – The displacement of the electron vs. time is:
    \[
    x(t) = \frac{1}{2} \frac{e}{m} E t^2
    \]
  – The time between collisions is determined by the probability of collisions:
    \[
    dP = \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right) dt
    \]
  – Averaging $x$ overt time gives:
    \[
    \langle x \rangle = \int \frac{1}{2} \frac{q_e}{m} E t^2 \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right) dt = \frac{q_e}{m} E \tau^2
    \]
  – Which leads to the average drift velocity:
    \[
    \langle v \rangle = \frac{\langle x \rangle}{\tau} = \frac{q_e}{m} E \tau \equiv \mu E
    \]
  • Because $\tau$ is inversely proportional to the density of the gas $\Rightarrow v \propto E/p$
  • Typically the mobility is given at standard pressure $\Rightarrow$
    \[
    v_D = \mu p_0 \frac{E}{p}
    \]
  • Drift velocity is often plotted vs. the reduced field $E/p$
Drift of electrons

- Often the drift velocity is also given in terms of the fractional energy loss $\lambda(\varepsilon)$, with $\varepsilon$ the energy of the electron

$$v_D = \sqrt{\frac{eE}{mN\sigma}} \sqrt{\frac{\lambda}{2}}$$

- Because $\sigma(\varepsilon)$ and $\lambda(\varepsilon)$ show a strong energy dependence on the electron energy in typical electrical fields, the electron drift velocity shows a strong and complex variation with the applied electrical field
Typical electron drift velocity: **5-10 cm / µs**

**Microscopic velocity** is approx. 100 times larger

Noble gases with small electro negativity are useful

- Noble gases (Ar/Ne) are typically the main component
- Admixture of CO$_2$, CH$_4$, Isobutane etc. for “quenching” (see later)
Drift of ions

• The drift velocity of ions is given by the same expression as derived above:

\[ v_D = \mu p_0 \frac{E}{p} \]

• For gas mixtures:

\[ \frac{1}{\mu} = \sum_k \frac{c_k}{\mu_k} \]

with \( c_k \): concentration per volume, \( \mu_k \): mobility of component

• At 1 kV/cm ions are 1000 times slower than electrons

\begin{array}{|c|c|c|}
\hline
\text{Gas} & \text{Ion} & \mu \ [\text{cm}^2/\text{Vs}] \\
\hline
\text{He} & \text{He}^+ & 10.2 \\
\text{Ar} & \text{Ar}^+ & 1.7 \\
\text{Ar} & \text{CH}_4^+ & 1.87 \\
\text{CH}_4 & \text{CH}_4^+ & 2.26 \\
\text{Ar} & \text{CO}_2^+ & 1.72 \\
\text{CO}_2 & \text{CO}_2^+ & 1.09 \\
\hline
\end{array}

• The drift velocity of positive ions is linear vs. the reduced electric field up to very high fields
Diffusion and Drift

- \( \sigma_x \propto \sqrt{t} \propto \sqrt{s} \)
- At 1kV/cm and 1 Atm pressure the thermodynamic limit is 70 \( \mu \)m for 1 cm drift
- without electric field the diffusion of e\(^-\) would be equal to t.d. limit
- microscopic energy of the e\(^-\) due to the electric field increases diffusion

**Electric Field**

- \( \Delta s, \Delta t \)
- s

\[ s \]

- \( \sigma_x \) depends on \( E/p \) and scales with \( \sqrt{p} \)
- Gases with a large fractional energy loss like CH\(_4\) \( \Rightarrow \) small electron energy \( \Rightarrow \) low diffusion
- For Argon the fractional energy loss is small \( \Rightarrow \) large electron energy \( \Rightarrow \) large diffusion

**Graph**

- Longitudinal diffusion (\( \mu \)m) [1 cm drift] vs. \( E/P \) (V/cm Atm)
- CH\(_4\)
- A-CH\(_4\)
- A
- DME
- Thermal Limit
Drift and Diffusion in E and B fields

- Typically the detectors are operated in strong magnetic fields to measure the momentum of the particles \( \Rightarrow \) drift and diffusion are driven by \( \vec{E} \times \vec{B} \) effects.

- Look at 2 special cases:
  
  \[ \vec{E} \perp \vec{B} \]

\[ \tan \alpha_L = \omega \tau \]

\( \alpha_L \): Lorentz angle

\[ \omega = \frac{eB}{m} \]

\( \omega \): cyclotron frequency
The longitudinal diffusion (along B-field) is unchanged. In the transverse projection the electrons are forced on circle segments with the radius $v_T/\omega$. The transverse diffusion coefficient appears reduced

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

Very useful... see later!
Recombination and Electron Attachment

- Two processes hinder the free propagation of electrons and ions:
  - recombination:
    \[ X^+ + e^- \rightarrow X + h\nu \]
    \[ X^- + Y^+ \rightarrow XY + h\nu \]
    solution: use an **electric field** which is high enough to separate positive and negative charged particles from each other

- electron attachment (for gases with high electro negativity):
  \[ e^- + X \rightarrow X^- + h\nu \]
  solution: use **Nobel gases** as main component
Avalanche Multiplication

- Multiplication in gas detectors occurs when the primary ionization electrons gain sufficient energy before they interact with the gas to further ionize gas molecules, the secondary electrons create tertiary ionization and so on → avalanche.
- Because of the greater mobility of electrons the avalanche has the form of a liquid drop with the electrons near the head.

Different stages in the gas amplification process next to the anode wire.

Cloud track picture of a single electron avalanche.
Avalanche Multiplication

- **First Townsend coefficient**: $\alpha := 1/\lambda$, probability of an ionization per unit path length
- **Multiplication factor** or gas gain $M$ is defined as:

$$M = \frac{n}{n_0} = \exp\left(\int_{r_1}^{r_2} \alpha(x) dx\right)$$

- Physically the gas gain is limited to $M < 10^8$ or $\alpha x < 20$ after which breakdown occurs

\[
\frac{\alpha}{p} \text{ vs. } \frac{E}{p}
\]

\[
\frac{\alpha}{p} (\sigma) \text{ vs. electron energy}
\]
Avalanche Multiplication

- Typically avalanche multiplication is used in tube detectors because of the $1/r$ dependence of the electric field.

- At which radius starts avalanche multiplication?
  - Assume that a “critical field” of 50 kV/cm is needed:
    \[ r_c = \frac{1}{E_c} \frac{V_0}{\ln(b/a)} \]
  - With a wire diameter of 25 µm, an outer radius of 25 mm and 1 kV applied one gets a critical radius of approx. 30 µm \(\Rightarrow\) avalanche region is $10^{-6}$ of the chamber volume.
De-excitation of a noble gas is only possible via the emission of a photon. If the photon energy is above the ionization threshold for other molecules in the set-up, new avalanches will be created.

→ Permanent discharges

Add poly-atomic gases as quenchers.

What the water molecule can do.
Choice of Fill Gas

• Requirements:
  – low working voltage
  – high gain
  – good proportionality
  – high rate capability

• Not achievable with a single gas ➔ mixtures
  – Nobel gasses as main component ➔ very low electric field intensity to create avalanches (typ. Argon)
  – Problem: above a gain of $10^3$ – $10^4$ continuous discharge arises because of high excitation energy (11.6 eV)
  – Solution: add quenchers (methane, alcohol, CO$_2$, BF$_3$) to absorb radiated photons ➔ gain of $10^6$ possible ➔ but quenchers dissociate
  – Problem: Organic dissociated quenchers form solid or liquid polymers around the anode and cathode of the detector. Ions have to diffuse through this layer ➔ for high rates a space charge builds up which can cause a continuous discharge
  – Solution: Add a small amount of nonpolymerizing agent such as methylal or propylic alcohol