Experimental Techiques in Particle Physics

Overview of Detectors

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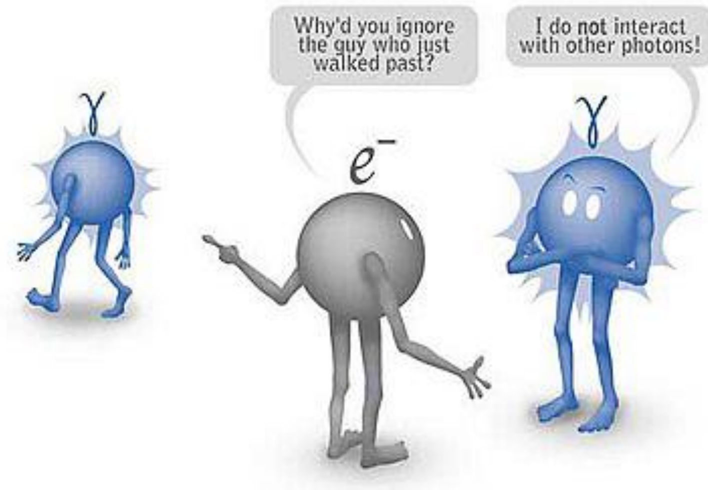
Basics of Particle Detection (I)

- **Detection** is the counting of particles in other words:
  “Is there a particle?”
- **Identification** is the measurement of its **properties**.
- Particles can only be detected through their interaction with “something” e.g. the detector material.
- The effect(s) of the interaction is registered by the detector, not the particle itself.



Basics of Particle Detection (II)

- Quote Claus Grupen: “Every effect of particles or radiation can be used as a working principle for a particle detector.”
- Precise understanding of the interactions inducing effects and the knowledge of the processes leading to subsequent signals in particle detectors is key.
- One has to deduce the information about the particle from the interaction.

Basics of Particle Detection (III)

- Main method of particle detectors
  - Detection and identification of particles with mass m_0 and charge z.
  - Usually z = ±1 in particle physics, but not in nuclear physics, heavy ion physics or cosmic rays.

- Methods of particle identification:
  - Measure the bending radius ρ in a magnetic field B ($\vec{\rho} \perp \vec{B}$):
  - $$\frac{m\,v^2}{\rho} = z \cdot e \cdot v \cdot B \quad \Rightarrow \quad \rho = \frac{p}{z\,e\,B} \propto \frac{\gamma\,m_0\,\beta\,c}{z}$$

    With p being the momentum and $\beta = \frac{v}{c}$ respectively $\gamma = \frac{1}{\sqrt{1-\beta^2}}$

Basics of Particle Detection (IV)

Particle detectors exploit the following types of interactions:

- Ionization and excitation caused by charged particles
- Bremsstrahlung: emission of photons from accelerated charged particles
- Photon scattering and photon absorption
- Cherenkov radiation
- Nuclear interaction of imminent hadrons with nuclei in material
- Weak interaction (only detection method for neutrinos)
- Usually more than one interaction process happens if the particle is not immediately absorbed

Particle Detectors: Overview (I)

Possible Classifications:

- Measured particle variable:
  - Energy,
  - Momentum,
  - Time,
  - Position,
  - Particle type, …
- Detected quantity:
  - Electric charge,
  - Light, …
- Detecting material:
  - Semiconductor,
  - Gas,
  - Scintillator, …

Particle Detectors: Overview (II)

No 1:1 correspondence among different types:

- Scintillators can measure
  - Time,
  - Energy,
  - Position, …
- Position can be measured using
  - Semiconductor,
  - Gas,
  - Scintillator, …
- Detectors differ in
  - Resolution,
  - Sensitivity, …

Detector Types

Criteria for Choice:

- Sensitivity
  - Detection probability (efficiency)
- Resolution
  - Precision of measured variable (energy, time, position, …)
- Noise
  - How often is a particle faked?
- Speed
  - How fast is the signal and how long does it take to be sensitive again (dead time)?
- Radiation hardness
  - How robust is the detector to radiation (LHC)?
- Price
  - How much does it cost? This often defines the size of the detector.

Sensitivity

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

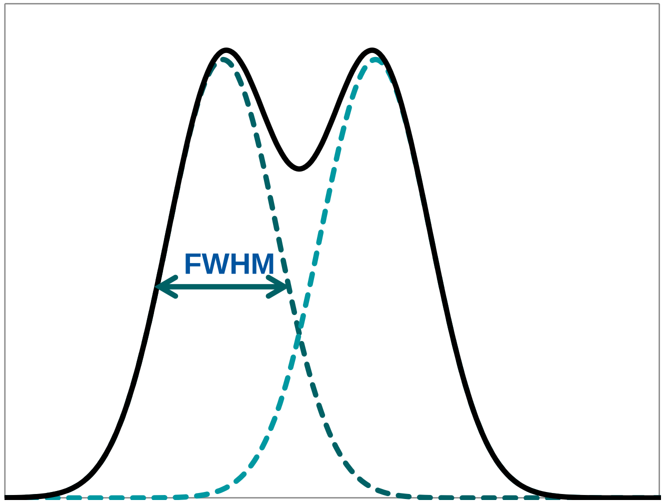
- Usually given by:
  - the cross section for ionization reactions in the detector
  - the detector mass
  - the inherent detector noise versus signal height
  - the protective material surrounding the detector => entrance threshold

determines the probability that (part of) the energy of the incoming radiation is transformed in the form of ionization

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:

$$R = \frac{\Delta E}{E} = \frac{2.35\,\sigma(E)}{E} \qquad (\Delta E = FWHM)$$



- Two peaks closer together than the FWHM are usually considered not resolvable

- ΔE includes all type of noise sources:

$$(\Delta E)^2 = (\Delta E_{statistic})^2 + (\Delta E_{detector})^2 + (\Delta E_{electronics})^2 + \ldots$$

Energy Resolution

- The mean number of ionizing events J is given by the mean energy required to produce an ionization w and the deposited energy E:

$$J = E / w$$

  - w depends on the material
- To calculate the fluctuations one would typically take the Poisson distribution which yields:

$$var = \sigma^2 = J$$

$$R = 2.35 \sqrt{\frac{w}{E}}$$

- This implies that the ionization processes are all statistically independent

- Typical values are for 1 MeV gammas
  - NaI detector ca. 8 – 9 %
  - Ge detector ca. 0.1 %

Energy Resolution and Fano Factor

- U. Fano calculated the variance for large J and found:

$$var = \sigma^2 = FJ$$

- F is the Fano factor describing the deviation of the variance from a Poisson distribution

- This gives for the resolution:

$$R = 2.35\frac{\sqrt{F \cdot J}}{J} = 2.35\sqrt{\frac{F \cdot w}{E}}$$

- For F = 1 the variance is the same as the Poisson distribution

Fano Factor

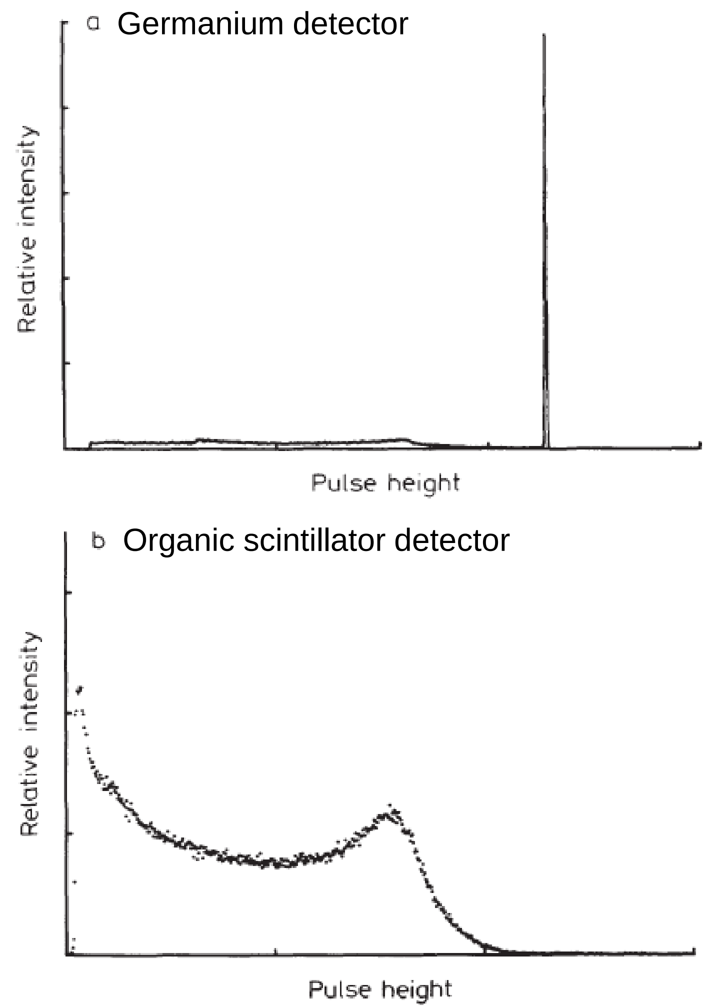
- Because the Fano factor describes corrections in the statistical fluctuations in the process of ionization, it gives the best energy resolution a detector can reach
- It is material dependent and varies strongly:
  - scintillators ≈ 1
  - gases < 1
  - semiconductors ≈ 0.1 (theoretically)
- Measuring the Fano factor is not easy because all other sources of noise 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

- The response function of a detector at a given energy is determined by the different interactions of the incident radiation with the detector and its design and geometry
- 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 be 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 => 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 => low energetic tail
  - Bremsstrahlung: photons leave detector => low energetic tail
- Superposition of photoelectric effect, Compton scattering and pair production



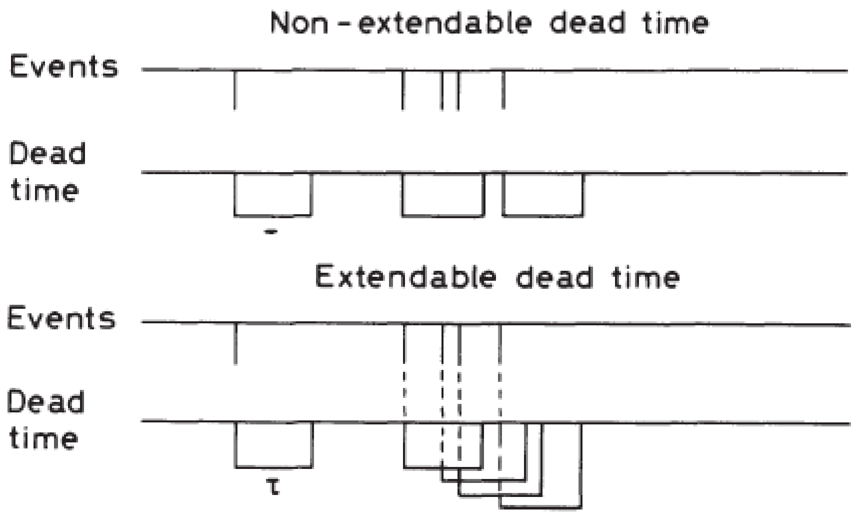
Source: W.R. Leo

Response Time

- The response time is the time which a detector takes to form a signal
- This is the time between the arrival of the particle and the signal formation
- Important for dedicated time measurements (e.g. time-of-flight detectors)
  - For good timing, it is necessary that the signal is quickly formed into a sharp pulse
- The response time contributes to the dead time of the detector
- Must be considered when triggering on events in different detector components

Dead Time (I)

- Finite time τ required by a detector to process an event.
- Related to the duration of the pulse signal.
  - But entire detection system must be taken into account.
- Two cases can be distinguished:
  - detector is insensitive after first event until end of dead time
    => non-extendable or non-paralyzable dead time
  - detector stays sensitive after first event
    => extendable or paralyzable dead time
    (e.g. rate of a Geiger-Müller counter drops at very high dose)



Source: W.R. Leo

Non-extendable Dead Time

- During the non-extendable dead time a second event is simply undetected
- So de facto some events are lost or in other words the actual measuring time is shortened by $k\,\tau$

$$m = \frac{k}{T - k\,\tau}$$

$$m = \frac{\left(k/_T\right)}{1 - \left(k/_T\right)\tau}$$

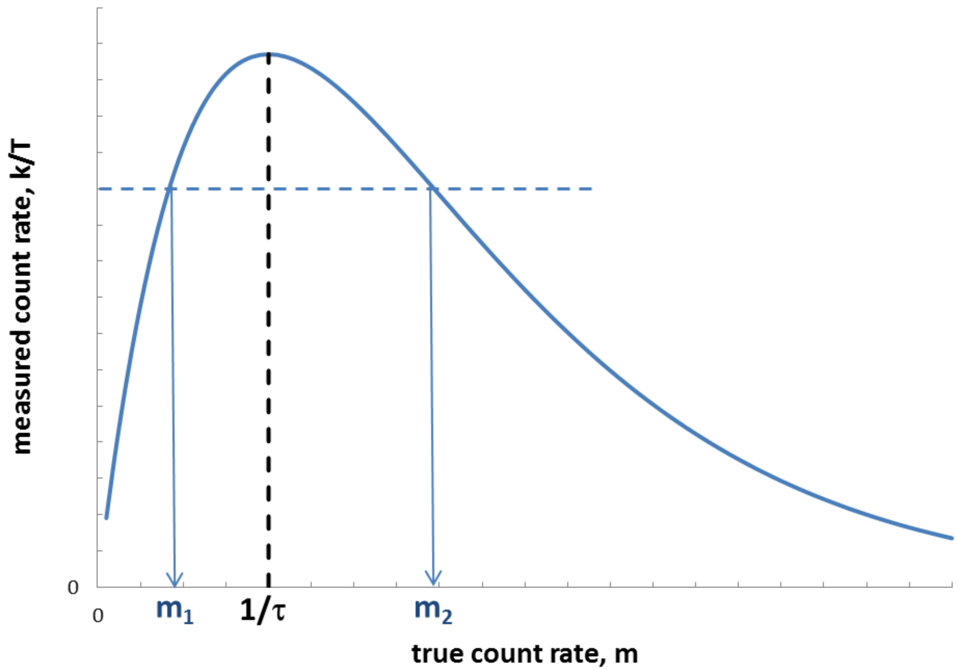
m: true count rate, T: total measuring time,
k: measured counts, τ: dead time

Extendable Dead Time

- In the case of extendable dead time only counts which arrive at time intervals greater than τ are recorded.
- The distribution of time intervals P(t) of decay events with rate m (i.e. decay constant) is given by $P(t) = m\, e^{-m \cdot t}$
- As only events arriving later than τ are recorded:

$$P(t > \tau) = m \int_{\tau}^{\infty} e^{-m \cdot t} dt = e^{-m \cdot \tau}$$

- So the number of events observed is the fraction of m T (= true number of counts) whose arrival times satisfies the equation above:
$k = (m\, T)\, e^{-m \cdot \tau}$
- The solution is found numerically
  - Be aware that 2 solutions exist



Measuring Dead Time

- "Two-source" technique (for the non-extendable case):

$$n_1 = \frac{R_1}{1-R_1\cdot\tau} \qquad n_2 = \frac{R_2}{1-R_2\cdot\tau} \qquad n_1 + n_2 = \frac{R_{12}}{1-R_{12}\cdot\tau}$$

$$\Rightarrow \frac{R_{12}}{1-R_{12}\cdot\tau} = \frac{R_1}{1-R_1\cdot\tau} + \frac{R_2}{1-R_2\cdot\tau}$$

$$\Rightarrow \tau = \frac{R_1 R_2 - \sqrt{R_1 R_2 (R_{12}-R_1)(R_{12}-R_2)}}{R_1\cdot R_2\cdot R_{12}}$$

  - R_1, R_2 and R_{12} are the observed count rates whereas n_1, n_2, are the true count rates
  - Large errors (5 – 10 %)
  - Experimentally difficult, e.g. positioning of the two sources
  - Alternativ: replace one source with a pulser of frequency $f < {}^{1}/_{(3\,\tau)}$
- For extendable case typically done with 2 oscillators (see e.g. W.R. Leo)
  - But care must be taken that the form of the pulses are as a close as possible to those of the detector and that the frequencies are stable

Detector Efficiency

- Two definitions:
  - absolute efficiency Eff_{tot}
  - intrinsic efficiency Eff_{int}

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

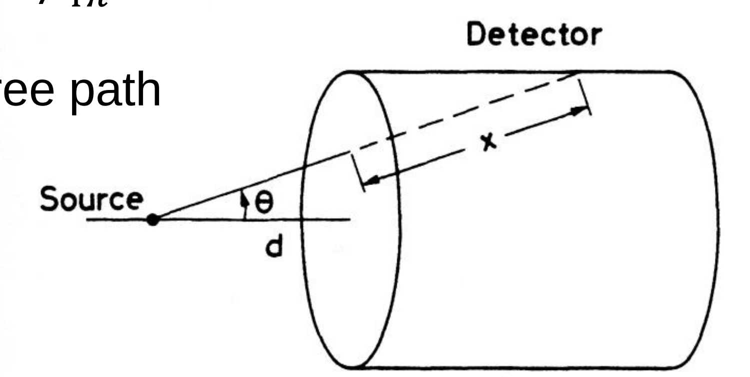
- Example: cylindrical detector with a point source at a distance d on the axis of the detector
  - Probability of emission into angle θ: $P(\theta)d\Omega = {}^{d\Omega}/_{4\pi}$

$$dEff_{tot} = (1 - e^{-x/\lambda})\frac{d\Omega}{4\pi}$$ with λ the mean free path

  - Factorization: $Eff_{tot} \cong Eff_{int} \cdot Eff_{geom}$

$$\cong efficiency \cdot acceptance$$

$$Eff_{int} = \frac{events\ registered}{events\ impinging\ on\ detector}$$



Source: W.R. Leo

Particle Detectors: Overview

Detector types discussed during this course:

- Visual detectors
- Semiconductor detectors
- Gas ionisation detectors
- Scintillators
- Calorimeters
- Particle identification

Visual detectors

- Particle tracks are recorded by photographs
  - Cloud chamber
  - Bubble chamber
  - Spark chamber
  - Nuclear track detectors

- Particles directly recorded within photo-sensitive material
  - Emulsions
  - CR39

- Main disadvantage:
  - Tracks informative is not available in electronic form

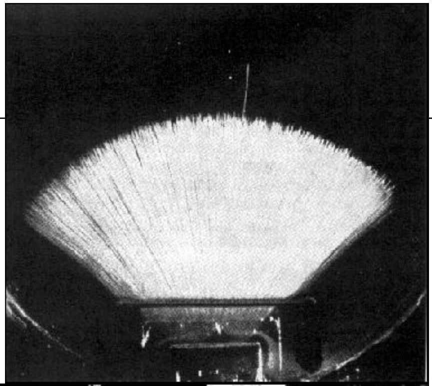
- Today: Digitization of tracks using automized scanning

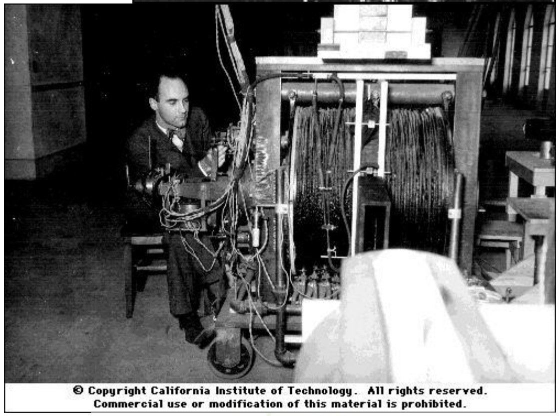
Cloud Chamber

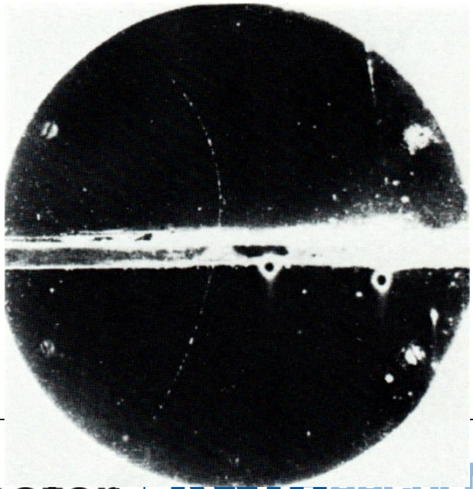
- 1911 Wilson, Nobel prize 1927
- Chamber with saturated atmosphere (water, alcohol)
- Charged particles generate ionization track
  - Condensation nuclei => track of cloud droplets

Discovery of the positron:

- 1932 Anderson, Nobel prize 1936
- Balloon experiment using cosmic radiation, exploiting magnetic field!
- Particle goes upwards (energy loss in plate!)
- Bending direction => positive charge
- Too little ionization for proton, would be stopped in plate
  - Electron with positive charge => Positron

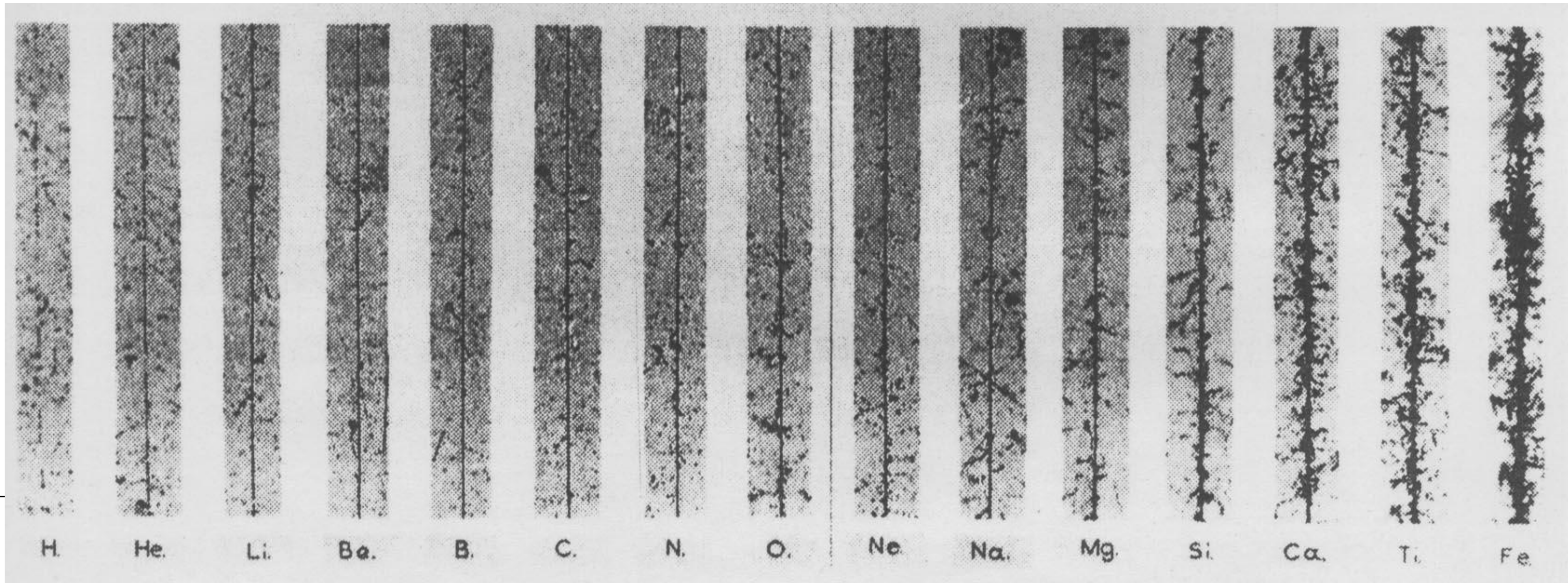




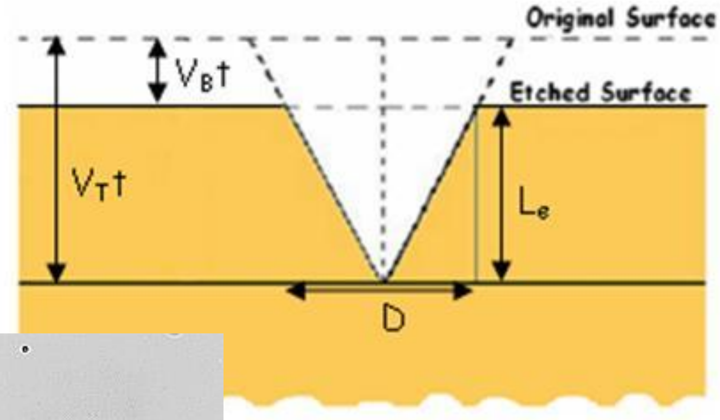


Emulsions

- Oldest „technology“ to visualize particles
  - Discovery of radioactivity by Becquerel
- AgBr or AgCl crystals in gelantine substrate
  - exposure of silver crystals by the ionization track
  - Fixation => pure silver => black track
- Spatial resolution:
  - Size of silver grains ca. 0.2 µm
  - Resolution better than 1 µm

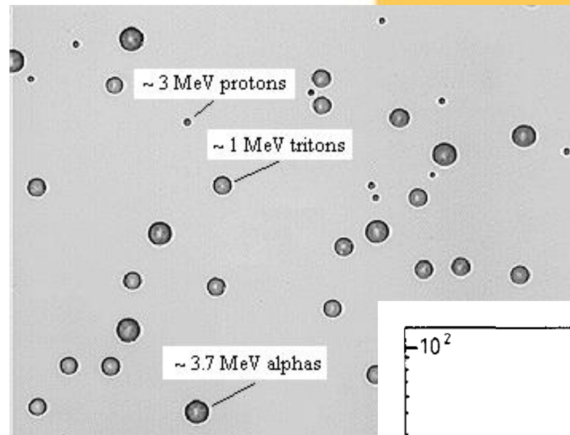


CR-39® Nuclear Track Detectors



Polyallyldiglycolcarbonat (PADC)

- Particle produces ionization along its track.
- Deposited energy is dissipated into heat.
- Chemical and mechanical properties of target material is changed along latent track.
- Along the latent track the etching rate is higher compared to the unirradiated pristine material.
- After e.g. several hours in 6n NaOH tracks of several µm diameter visible under microscope are formed.



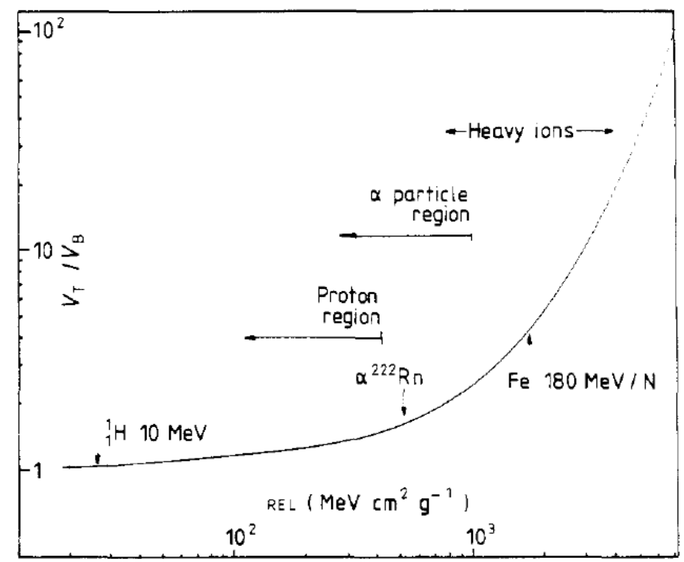
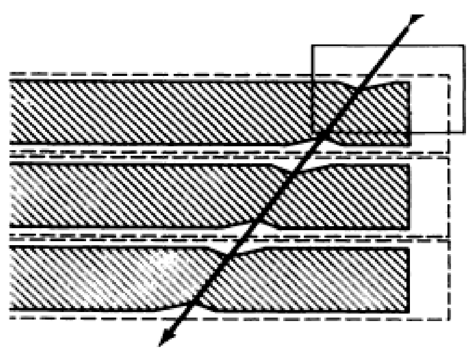


Figure 2 Response curve for CR-39 indicating the position of protons, α particles and heavy ions

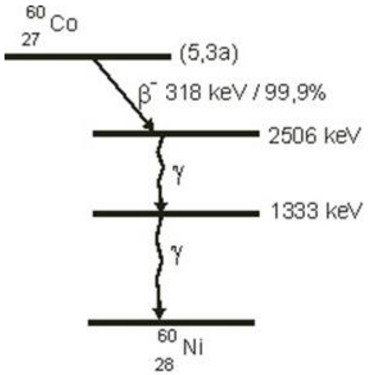


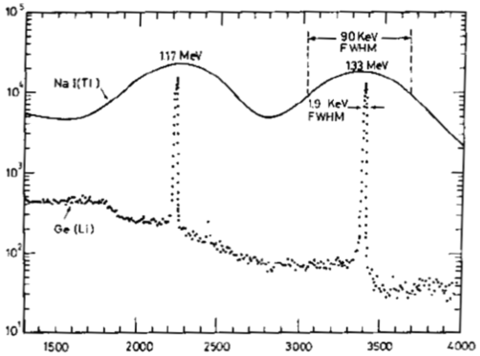
Source: Phys. Technol., Vol 13. 1982.

Semiconductor Detectors (I)

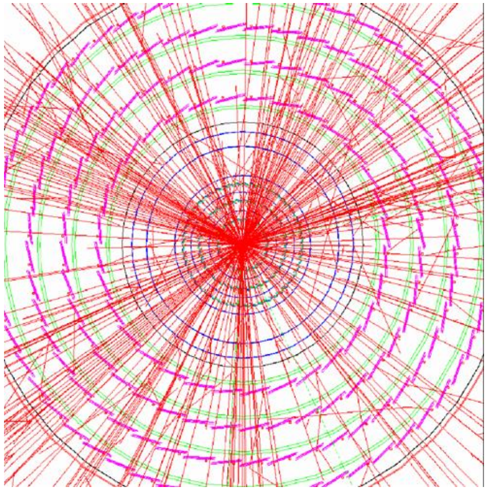
Applications:

- In nuclear physics mainly for energy spectroscopy





- In particle physics mainly for tracking and vertexing



Semiconductor Detectors (II)

History:

- 1951: First detector from Germanium pn-diode (Mc Kay)
- 1960: pin-detector from silicon for β- and γ-spectroscopy (Pell)
- 1980: Planar Si-diode as tracking detector in particle physics (Kemmer)

- General properties of semiconductor detectors:
  - Small ionization energy (w≈3 eV) → large primary charge
  - High material density → high multiple scattering and photon conversion
  - Lithographic structuring (microchip technology) → precise position resolution
  - Silicon technology → High integration with read-out electronics possible

Semiconductor Detectors (III)

Materials (I):

- Germanium:
  - + Small band gap ($E_g \approx 0.7\ eV$) → very good energy resolution
  - — High thermal noise at room temperature → cooling with liquid nitrogen (77 K)
  - Applications: nuclear spectroscopy
- Silicon:
  - + Band gap ($E_g \approx 1.1\ eV$) → operation at room temperature possible
  - + Processes of microchip industry usable
  - Applications: mainly position measurements (tracking, vertexing)
- Carbon (CVD diamond):
  - + Band gap ($E_g \approx 5.5\ eV$) → small thermal noise → works even without depletion!
  - + High radiation hardness
  - — Very expensive
  - Applications: in harsh radiation environment (near the beam)

Semiconductor Detectors (III)

Materials (II):

- Gallium Arsenide (III-V semiconductor):
  - \+ More radiation hard than silicon
  - – Expensive
  - – Poisonous
  - Application: Was investigated for LHC (high radiation)

- Cadmium Telluride (II-VI semiconductor):
  - \+ High atomic number → High photon conversion efficiency
  - Application: X-ray and gamma-spectroscopy

- More: ZnS, InP, HgI…

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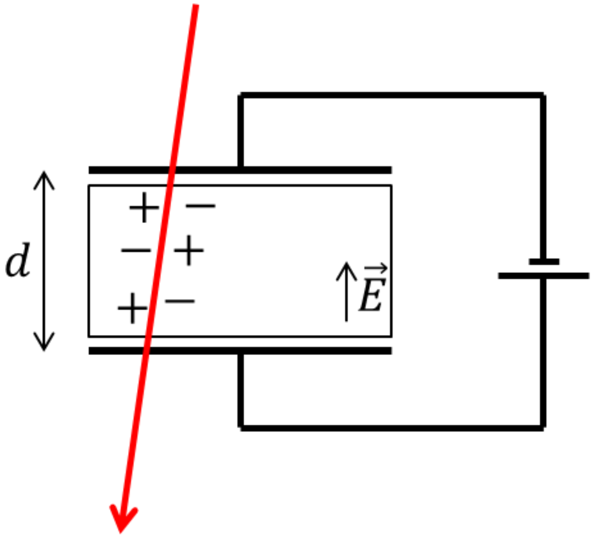
Operation and detection principle:

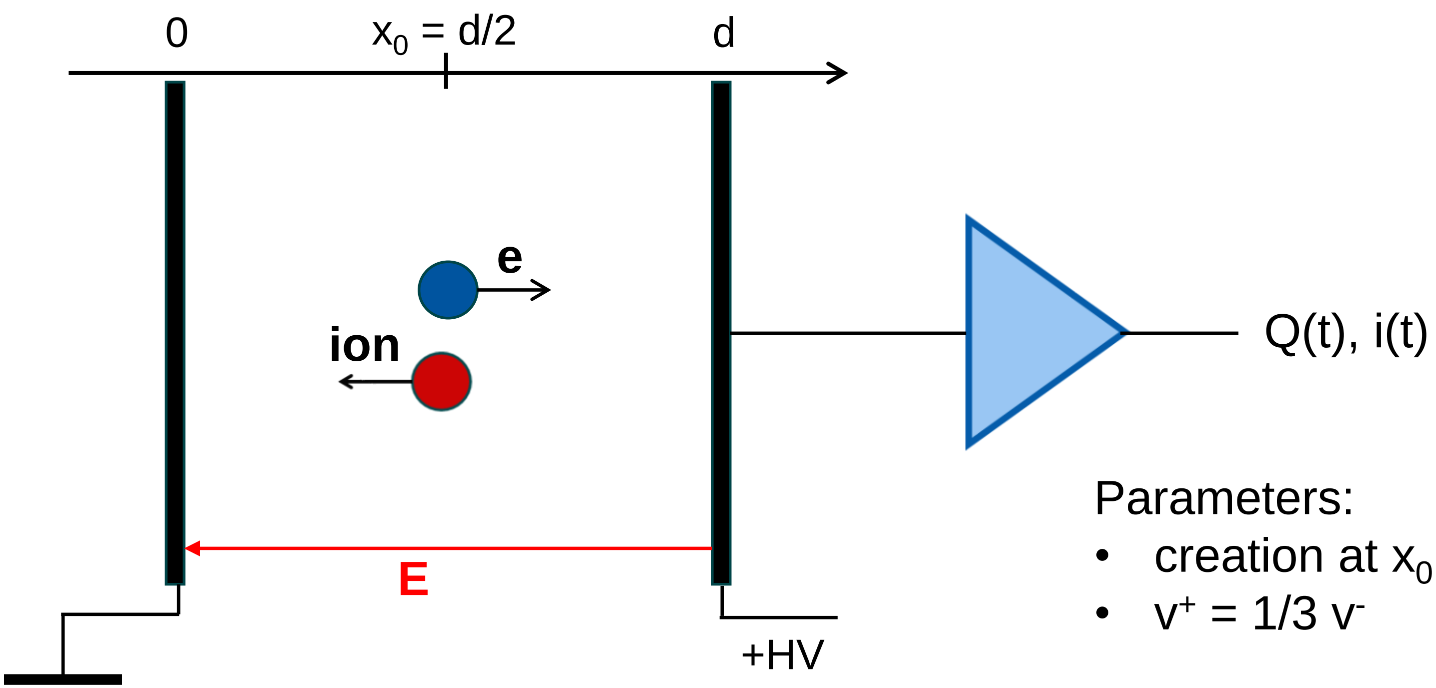
- External voltage applied across detector volume
- Traversing particle generates electron-ion pairs
- The electrons drift to the anode and the ions to the cathode and generate a signal
- So the chain is as follows:
  deposited energy → moving charge → induced charge → output signal



Signal Generation (I)

- When do we see a signal at the preamplifier?
  - ~~When the electrons reach the contacts?~~
  - ~~When the ions reach the backside?~~

    Popular answer
  - Immediately when the ion/electron pair is created and the charges start to move?



Parameters:

- creation at $x_0 = d/2$
- $v^+ = 1/3\ v^-$

Signal Generation (II)

- The charge induced on the electrode by a point charge q is $Q = -q\ \varphi_0(x)$
- And the induced current is given by $i = -\frac{dQ}{dt} = q\ \vec{v}\ \vec{E}(x)$
- For the simple case given above: $\vec{E} = -\frac{U_0}{d}\ \overrightarrow{e_x}$ with $C = \frac{\epsilon\ \epsilon_0\ A}{d}$
- $i_S{}^{\pm} = q^{\pm}\ \vec{E}\ \overrightarrow{v^{\pm}} = -\frac{q^{\pm}\ U_0}{d}\ \overrightarrow{e_x}\ \overrightarrow{v^{\pm}} = \frac{e\ U_0}{d}\ v^{\pm}$

Signal Generation (III)

- $T^- = \frac{d - x_0}{v^-} \qquad T^+ = \frac{x_0}{v^+}$

⇒ Total collected charge is

⇒ $$Q_S{}^{tot} = Q_S{}^- + Q_S{}^+ = -\frac{e}{d}\left(\int_0^{T^-} v^-\,dt + \int_0^{T^+} v^+\,dt\right) =$$
$$= -\frac{e}{d}\,v^-\left(\frac{d - x_0}{v^-}\right) - \frac{e}{d}\,v^+\left(\frac{x_0}{v^+}\right) = -\boldsymbol{e}$$

⇒ Due to the large differences in drift velocities between electrons and ions:

⇒ $i_S{}^- = \frac{e}{d}\,v^- \quad \gg \quad i_S{}^+ = \frac{e}{d}\,v^+$

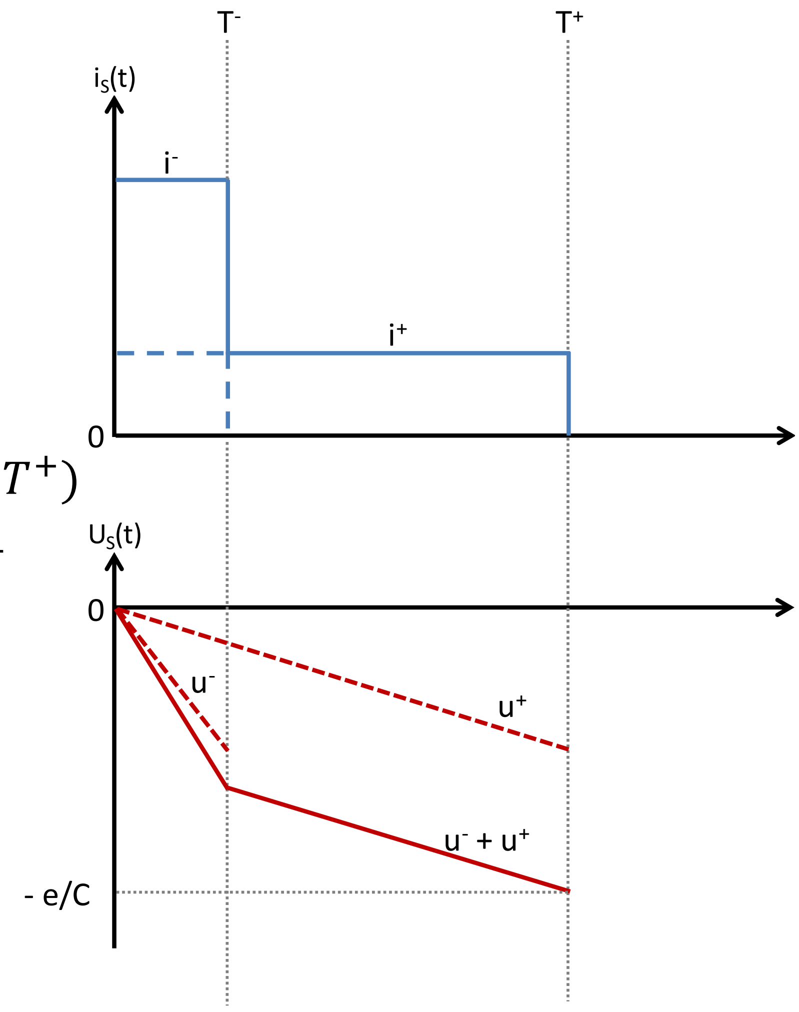
⇒ This means that the signal current does not depend on x_0, the place where the charges were generated

Signal Generation (IV)

$$dU_S^{\pm} = \frac{1}{C}\, dQ_S^{\pm} = \frac{1}{C}\, i_S^{\pm} dt = -\frac{e}{C\,d}\, v^{\pm}\, dt$$

$$U_S(t) = U_S^{-}(t) + U_S^{+}(t)$$

$$= \begin{cases} -\frac{e}{C\,d}(v^{-} + v^{+})t & for\ 0 < t < \min(T^{-}, T^{+}) \\ -\frac{\boldsymbol{e}}{\boldsymbol{C\,d}}(\boldsymbol{d} - \boldsymbol{x_0} + \boldsymbol{v^{+}t}) & \boldsymbol{for\ T^{-} < t < T^{+}} \\ -\frac{e}{C\,d}(x_0 + v^{-}t) & for\ T^{+} < t < T^{-} \end{cases}$$



Due to very different drift velocities $v^{-} \gg v^{+}$
=> $T^{-} \ll T^{+}$
=> $T^{-} < t < T^{+}$ is valid

- Thank you for your attention.
- See you again in 2 weeks for lecture 7 about semiconductor detectors.