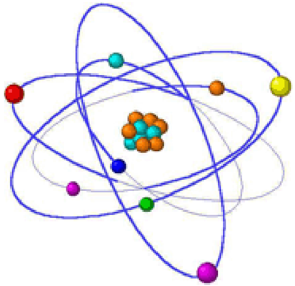
Radioisotope and Radiation Applications (FS2013)



Radiation Detectors (Week 1b, 2nd part)

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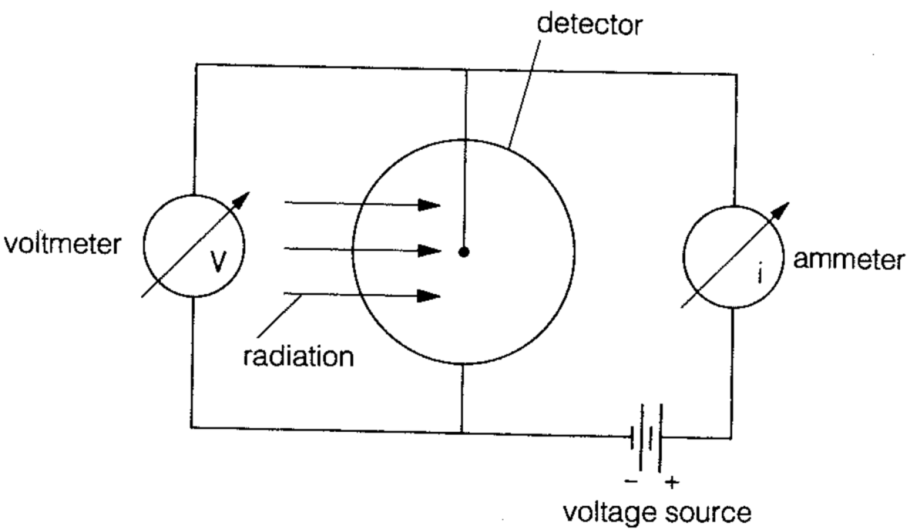
Radiation Detectors: Table of Contents

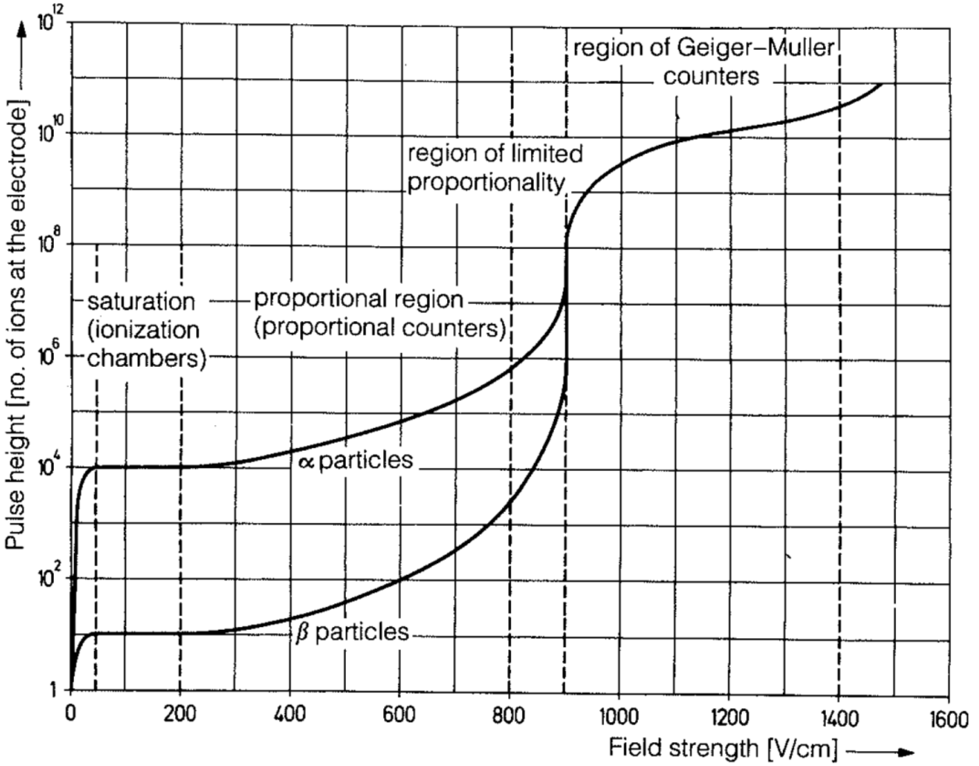
General Properties of Detectors

- **Motivation:**
  - **a)** Ionising radiation as normally used cannot be observed by the unaided human senses!
  - **b)** Detectors constitute an essential (end) part of nearly all applications described later!
- Principle: Measure radiation interaction with matter, i.e., ionization, excitation, induced (nuclear) reactions, ...
- Activity (A) and counting rate (I'):
  - counting rate: $$I' = I + I_0 = \eta A + I_0 = \eta_1 A_1 + \eta_2 A_2 + \ldots + I_0$$
  - with background counting rate I_0
  - and efficiency given by: $$\eta = H \cdot (1-S) \cdot (1+B) \cdot G \cdot (1-W) \cdot \eta_i \cdot (1-D)$$

  H=frequency of decay mode, S=self-absorption, B=contribution from backscattering, G=geometry, W=absorption in air and counter window, η_i=internal counting efficiency, D=correction for dead time τ
- True interaction rate I given from counting rate I^* by: $$I = \frac{I^*}{1 - I^* \cdot \tau}$$
- Characteristics of detectors: range, resolution, detection efficiency ($\varepsilon_i = \eta_i \cdot (1\text{-}D)$)

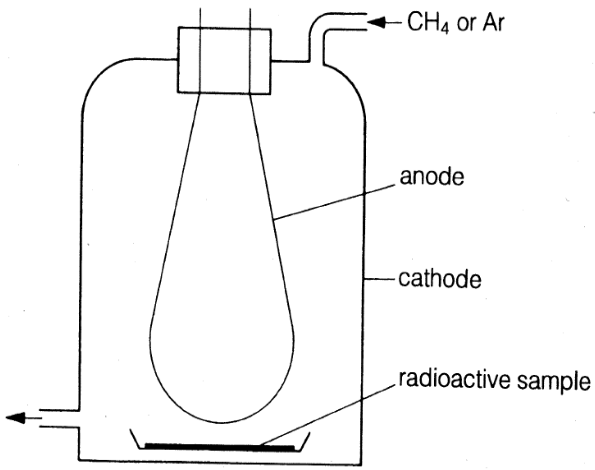
Gas-filled Detectors (1)



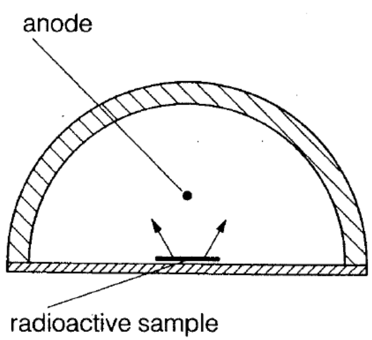


- Arrangement of a gas-filled ionization detector: measurement of ion pairs created by the incident radiation.
- Pulse height (total # of ion pairs) depends on the electric field strength (or voltage).

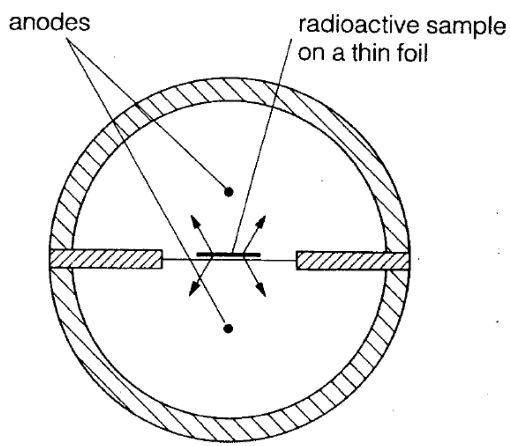
Gas-filled Detectors (2)



Windowless Flow counter (proportional counter)



2π counter



4π counter

❑ Ionization chambers:

- all the electrons are collected at the cathode
- (e.g.) an α-particle with E_α=3.5 MeV produces $N = E_\alpha/E_1=10^5$ ion pairs in air (E_1~35 eV)
- β-particles can hardly be measured
- Used to measure α-emitters, fission fragments, for calibration of radioactive sources, radiation monitoring

❑ Proportional counters:

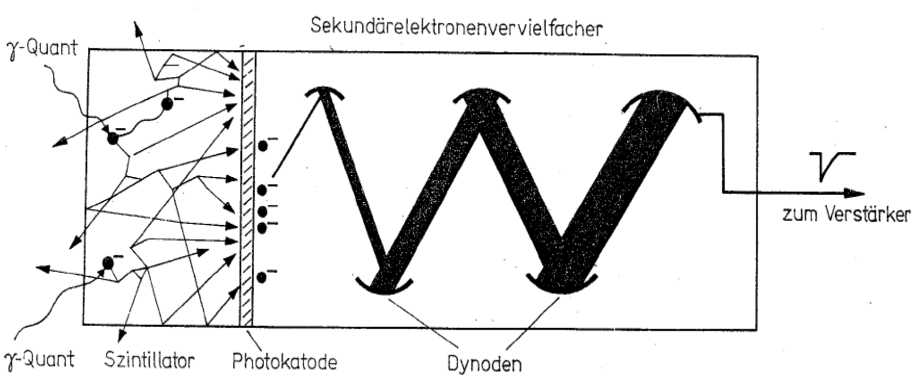
- Gas amplification by factors between ~$10^3 - 10^5$
- α-radiation measured at low voltages
- β-radiation measured at high voltages
- # of primary electrons proportional to energy of radiation
- Due to low dead times (~μs) high counting rates

❑ Geiger-Müller (GM-) counters:

- A single ionization in the gas leads to a discharge over the whole counter
- Dead times between 100μs and 500μs
- No further amplification needed
- Measurement of α-, β- and γ-radiation (η_i^γ~1%)

Scintillation Detectors

Photomultiplier



Scintillation detector (schematically)

- Scintillation: excited electrons jump back to lower energy states and create little flashes in transparent material.
- Examples of solid and liquid scintillators:
  - Inorganic crystals: NaI(Tl) and CsI(Tl) crystals, ZnS(Ag)
  - Organic crystals: Anthracene, trans-Stilbene
  - Liquids: p-Terphenyl (5g) in 1l of toluene
- Often a secondary scintillator is used as a wavelength shifter.
- Applied mainly for measurement of:
  - γ-radiation, also X-rays
  - β-radiation
- Main advantage: high counting efficiency.
- A Cherenkov detector is an advanced scintillation counter: Cherenkov radiation when $(v/c) > (1/n)$.

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Semiconductor Detectors

- Principle (similar to ionization chambers):
  - Incident radiation creates electron-hole pairs in the valence and conduction band.
  - Electric field drives electrons and holes to electrodes and causes a pulse in an outer circuit.
- Materials most frequently used are Si and Ge (band energy gap 1.09eV and 0.79eV, resp.).
- Advantages:
  - Low excitation energy per pair (Si: 3.6eV, Ge:2.8eV) provides for a high energy resolution.
  - Good time resolution between 0.1ns and 1 μs.
  - Relatively high density of Si/Ge causes high energy loss: detectors can be small.
  - Applicable to measure all charged particles and γ-radiation.
- Two problems:
  - Thermal noise increases strongly with temperature (solution: cooling).
  - Impurities lead to a leakage current (solution: high-purity crystals).

Neutron Detection

- Principle: detection by production of secondary ionizing radiation
  - Low-energy neutrons by (n,p) or (n,α) reactions or nuclear fission,e.g.,$^{3}He(n,p)^{3}H$, $^{10}B(n,\alpha)^{7}Li$, $^{235}U(n,f)$.
  - High-energy neutrons via recoiling ions, preferably protons.
  - The produced charged particles can be measured in the detector types discussed before.
- Ionization chambers:
  - Can be covered on the inner surface with a thin layer of ^{10}B or ^{235}U.
  - Can be filled with $^{10}BF_3$ or ^{3}He, or may be filled with a gas containing hydrogen.
- Proportional counters can also be filled with $^{10}BF_3$ or ^{3}He or H_2 or polyethylene.
- Scintillators:
  - As ^{6}Li or ^{10}B can be incorporated in scintillators, slow neutrons can be detected via the $^{6}Li(n,\alpha)^{3}H$ or $^{10}B(n,\alpha)^{7}Li$ reactions. Crystals of ^{6}LiI are also used.
  - Fast neutron spectra can be determined via proton recoil in large organic solid or liquid scintillators.
  - Very low neutron fluxes can be measured by scintillators containing Gd via Gd(n,γ) reactions.
- On the surface of semiconductor detectors compounds containing ^{6}Li or ^{235}U may be deposited.
- Activation methods: neutron fluxes can also be determined via (n,γ) reactions and subsequent measurement of the induced activity.

Track Detectors

- Principle: length and curvature of the track reveal energy and charge of the particle.
- Photographic methods:
  - Photographic plates are the oldest track detectors (Becquerel 1896).
  - Photographic emulsions on plates or films indicate the position of radionuclides (autoradiography).
- Dielectric track detectors:
  - Heavy ionizing particles produce tracks (cylindrical channels) with dimensions about 1 to 10nm which become visible under a normal microscope after etching.
- Cloud (Wilson) chambers:
  - In a chamber filled with saturated gas condensation occurs along ion tracks.
- Bubble chambers:
  - In a superheated liquid charged particles create vapor bubbles along their tracks.
- Spark chambers:
  - Consist of a stack of conducting plates separated by a gas (He, Ne) gap. When an ionising particle passes through the detector, a trigger system applies a high voltage between each pair of neighbouring plates. Thus sparks on the trajectory of the particle are produced, which can be seen or photographed through the side.

Dosimeters

- Thermoluminescence dosimeter (TLD):
  - Principle: In certain crystals the electrons and holes produced by radiation are trapped on the impurities. Hence energy is stored in the crystal, which can later be released in the form of light by thermal or optical stimulation.
  - Examples: LiF, CaF_2 with Mn as impurity.
  - Emitted light can be measured as a function of temperature (TL-curve or glow curve).
- Film Badges:
  - Consist of (layers of) photographic film covered partly by various foils of plastic, aluminum and cadmium.
  - Thus information about the type and energy of the radiation is obtained.
  - Boron loaded films allow registration of thermal neutrons.
  - Highly energetic particles produce tracks in the film.
- Pocket Ion Chambers:
  - The initially charged "ball-pen" is discharged by exposure to radiation.
  - Cannot detect α- and low-energy β-radiation.

Choice of Detectors

Detectors must be chosen according to radiation to be measured !

Table: Suitability of detectors for the measurement of various kinds of radiation.

Kind of radiation	Ionization chambers	Proportional counters	Geiger–Muller counters	Scintillation detectors	Semiconductor detectors
α radiation	Favourable	Flow counters very favourable	Unfavourable	Liquid scint. favourable	Si barrier detectors favourable
High-energy β radiation (>1 MeV)	Unsuitable	Suitable	Favourable	Organic cryst. favourable	Si barrier detectors suitable
Low-energy β radiation (<0.5 MeV)	Unsuitable	Favourable	Unfavourable	Liquid scint. very favourable	Si barrier detectors favourable
High-energy γ radiation (>0.1 MeV)	Unsuitable	Unsuitable	Unfavourable	NaI(Tl), CsI(Tl) crystals very favourable	i-Ge, Ge(Li) detectors very favourable
Low-energy γ radiation (<0.1 MeV) and X-rays	Unsuitable	Suitable	X-ray counters favourable	NaI(Tl), CsI(Tl) crystals favourable	Si(Li) detectors very favourable

Special Topics

Spectrometry:

- α- and γ-particles from nuclear (2 body) decays have sharp energies and can be used for identification of radionuclides.
- Detectors for spectrometry are combined with (pre)amplifiers and multichannel analysers.
- Analysis with computer: peak search, energy calibration, radionuclide identification.

Relative and absolute activities:

- In order to measure relative activities, η must just be constant.
- For determination of absolute activities, η must be exactly known (by calculation or calibration).

Coincidence and anti-coincidence circuits (two detectors needed):

- Coincidence studies are very useful for investigations of decay schemes.
- Anticoincidence measurements to reduce background (veto-counters).

Low-level counting requires reduction of background:

- Heavy detector shielding.
- Underground location to reduce cosmic radiation background.

Measurement Error and Statistics

- To all measured values an accurate error must be assigned:
  - Statistical errors
  - Systematic errors
  - The propagation of errors must be properly followed.
- Analysis of data (1):
  - (Weighted) mean: $\bar{x} = \frac{1}{w} \sum_{i=1}^{N} w_i\, x_i \; ; w = \sum_{i=1}^{N} w_i \; ; w_i = \frac{1}{\sigma_i^{\,2}}$; sample s.d.: $s = \sqrt{\frac{\frac{1}{(N-1)} \sum_{i=1}^{N} w_i \left(x_i - \bar{x}\right)^2}{\frac{w}{N}}}$
- Analysis of data (2) based on a statistical model:
  - Binominal distribution
  - Poisson distribution
  - Gaussian or normal distribution
  - Distribution free approaches
- Finally uncertainties and the corresponding confidence limits must be stated.

Summary

- Ionising radiation as normally used cannot be observed by the unaided human senses.
- Detectors constitute an essential (end) part of nearly all applications described later.
- Principle: radiation interacts with matter of the detector.
- There is a variety of detector types.
- Detectors must be chosen according to the radiation to be measured.
- Detectors must be understood (also to identify malfunctions), especially: proper errors must be assigned to the data including confidence limits.

Literature / WWW-reference

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