Radiation detection implies that the radiation interacts (e.g. leaves at least part of its energy) in the material. A specific material is chosen, because of its intrinsic properties (e.g. how sensitive it is to the type of radiation one want to measure), but it also depends on what information we need to extract from the measurement.

At some point: the induced signal is converted into an electronic signal, which similarly needs to be converted into a number (digital).
The Geiger-Mueller counter is an electronic way of measuring radioactive decay (Becquerel used photographic plates.)
Question –

In designing instrumentation to measure the properties of an energetic particle accurately, one encounters a fundamental constraint.

What is it?

Hint: especially relevant if multiple properties are to be measured
Basic principle of Interaction

\[ \Delta E = E_i - E_f \]

Energy deposited in the material

Because some energy has to be deposited, the particle, after measurement, has different properties.
  - slightly less energy
  - slightly different direction
The Atlas Detector (Large Hadron Collider)
Interactions

**Charged Particles** (α- and β-radiations, but also all ions for example):
A charged particle loses energy in the material by kicking out (ionizing) some electrons from the atoms of the material (Coulomb force).
→ Collect the electrons: generate an electronic signal!

**Neutrons:**
Neutrons are not charged, they don’t interact with the electrons!
Interaction happens only at the nucleus level... much less likely.
→ Induce recoil of the nucleus/ion, then see “Charged Particles”

**γ’s (electromagnetic radiation):**
γ’s are high-energy photons. Do not carry charge.
Interactions with the electrons present in the material, but not through the Coulomb force.
→ Collect the electrons, electronic signal
Charged Particles

Differential energy loss for this particle type within a specific material type, divided by the corresponding differential path length as a function of the energy.

\[ S = - \frac{dE}{dx} (E) \]

Note: \( x \) is often density*length \( \rightarrow \) units of mass/area)

The energy loss is deposited in the material with the highest deposit near the end of the range (Bragg peak)

A charged particle has a certain range in the material. \( S \) increases as the velocity of the particle decreases.

One application: cancer radiotherapy (ion beam, implanted radiosource…)
Example Energy Loss in Material by Charged Particles

dx [mg/cm²] already includes the density of the material

→ Can be transformed into a number [atoms/cm²]

Helium ions lose more energy than Hydrogen ions in a given material

Shorter range → Thinner detector

**Figure 2-3** Specific energy loss as a function of energy for hydrogen and helium ions. $E_m$ indicates the energy at which $dE/dx$ is maximized. (From Wilken and Fritz.²)
Lab 4  Energy Loss (dE/dX) by Alpha Particles

Measure how Energy of alpha changes (dE) as a function of different air pressures (dX)
Interaction of $\gamma$-radiation with matter
(Labs 1,2,3,6)

**Photoelectric effect:**

Atomic electron absorbs the energy and momentum of the $\gamma$ photon (simultaneous energy and momentum conservation possible due to participation of atomic nucleus)

$$\gamma + e^- \rightarrow e^-^*$$

**Compton effect:**

$\gamma$-photon is scattered off a free (or quasi-free) electron in the material. Energy and momentum are conserved in the scattering process.

$$\gamma + e^- \rightarrow \gamma' + e^-^*$$

**Pair production effect:**

Production of a matter / antimatter pair by the $\gamma$-photon in the Coulomb field of the atomic nucleus. Threshold: incident $\gamma$-energy has to be larger than the rest mass of particles produced.

$$\gamma + \text{atomic nucleus} \rightarrow e^+ + e^-$$
Interaction (energy transfer) mechanisms in detectors (II)

2. Scintillators (ex: NaI detector)

Photon emissions result from excited or ionized electrons returning to their initial orbit (or when other electrons are filling their positions).

→ emission of secondary electromagnetic radiation (but with lower energy): scintillation

1. γ-radiation hits scintillator and interacts with electrons

2. γ-energy absorbed and distributed on many excited electrons/atoms

3. De-excitation leads to production of many low energy photons (ultraviolet → Visible light)
Photo(multiplier) tubes
Putting it all together

Typically 10's-1000's Gammas/second (one shown here)

e- looses energy and generates low energy photons (see earlier slide).

Some of these photons strike the PMT and about 1 in 5 creates a photoelectron at the photocathode

Amplification (see earlier slide)

\( \gamma \) interacts in scintillator
Transfers some or all energy to an e- (and perhaps an e+)
See previous slide

Glass envelope with special coating on inside. Called the photocathode

In how many places can photoelectrons be created? Where?
Electronics

Once we have an electronic signal (proportional to the energy deposited in the detector), we need to convert it into a “useful” signal.

In the ADC, the voltage is converted into a (channel) number that can be read by a MCA (Multi-Channel Analyzer) → Spectrum

One event with energy deposited in a way that the produced voltage is attributed to channel number 109
Example: Gamma Spectra
SemiConductor Detectors

Silicon Junction
- Insulating ring
- Metallized surface
- Silicon wafer
- Metal case
- Connector

Germanium Detector
- Cooling
- Ge Crystal
- Cryostat (LN2, 77K)

Silicon Array (LEDA)

Germanium Array (GammaSphere)
Interaction (energy transfer) mechanisms in detectors (I)

What detector? Which response? What signal?

As seen previously, (all or part of) the radiation energy (e.g. kinetic energy) is transferred at some point to the electrons in the material (excitation or ionization).

1. Semi-Conductors

Silicon detectors are commonly used to detect charged particles, whereas Germanium detectors can be used to detect $\gamma$-rays.

→ Based on a similar principle

By applying a voltage, the charges can be collected (electronic pulse)
NaI VS Germanium detector (I)

NaI detectors are fairly efficient in detecting $\gamma$-rays, however their energy resolution is only around 7%:

$$\frac{\Delta E}{E} \sim 7\%$$

Germanium detectors are usually less efficient than NaI’s (lower probability of interaction), but they have a much better energy resolution:

$$\frac{\Delta E}{E} \sim 0.5\%$$

Most of the time:
No detector is ideal! Choice of a given detector usually depends on the application.
Background

The real world is not background free…

Main sources:
- cosmic radiations
- natural radioactivity

Real detector (Photopeak for example) in an ideal world

Real detector in the real world

We have to subtract the background that is not induced by our photopeak signal…

Background

The real world is not background free…

Main sources:
- cosmic radiations
- natural radioactivity

Real detector (Photopeak for example) in an ideal world

Real detector in the real world

We have to subtract the background that is not induced by our photopeak signal…
Other detectors…

There are other types of detectors (but the basic principle of interaction remains the same: ionization or excitation).

- Ionization chamber, Proportional counters, Drift Chambers
- Solid-state detectors (other than Silicon and Germanium)
- Neutron detectors
- Cerenkov detectors
- Bolometers…
Ice as Detector ICECUBE experiment
Search for Galactic and Extra-Galactic Neutrinos
Atmosphere as the Detector

The Pierre Auger Observatory – Mendoza Province Argentina
Detector is the size of Rhode Island

Use the atmosphere as the detector for extremely High Energy “particles.

Scintillation Light Produced in the atmosphere is proportional to the energy of the primary particle
Detector Configuration for $10^{19}$ eV

- **Calibration Facilities**
  - LIDAR
  - APF
  - HAM

- **Fluorescence Detectors**
  - 4 Telescope enclosures
  - 6 Telescopes per enclosure
  - 24 Telescopes total
  + Atmospheric Monitoring System

- **Surface Detector Array**
  - 1600 detector stations
  - 1.5 Km spacing
  - 3000 Km²

- **Radiosonde Launch**

The diagram shows the locations of various facilities and detectors, including LOMA AMARILLA, LEONES, COIHUECO, LIDAR, APF, HAM, CLF, XLF, MORADOS, and Star Mon., along with the 1600 detector stations arranged in a grid with 1.5 Km spacing covering 3000 Km².
A Water Cherenkov Station

- Communications antenna
- GPS antenna
- Electronics enclosure
- Solar panels
- Battery box
- 3 photomultiplier tubes looking into the water collect light left by the particles
- Plastic tank with 12 tons of very pure water
Proportional to \( \frac{dE}{dX} \)
(but on PeV scale!)

High Energy Cosmic Ray
\( 10^{19} \) eV

Nuclear Physics (Alpha particle)
\( 10^6 \) eV

Figure 2-2  The specific energy loss along an alpha track.
A simpler Detector with same properties.

Photomultiplier

Detector

6.6x10^5 eV
Extra Slides
Energy dependence of the various $\gamma$-ray interactions

- Photoelectric effect
- Compton effect
- Pair production (notice threshold @ 2 x 0.511MeV)