Radiation (Particle) Detection and Measurement

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).
Examples of Radiation Detectors

Example 1: Geiger Mueller Tube

Example 2 LHC ATLAS particle Detector
Computer Based System  Data Acquisition system

Detector

PC + Windoze 7 Operating System

Data Acquisition System Ortec MCA-2K Measures, Accumulates Data

Amp

Interface Program (Ortec Maestro) Displays Data GUI interface to Hardware

PH-326 Student

> Time
Basic principle of Interaction

Because some energy has to be deposited, the particle, after measurement, has different properties.
- slightly less energy
- slightly different direction
The oscilloscope is wired into the experiment using tees. Why do I want you to do that?
The oscilloscope is wired into the experiment using tees. Why do I want you to do that? So you can look at the signals anytime without disturbing the experiment.
How can $\gamma$-radiation with matter?

You will measure lots of gamma rays in your experiments.

\[ \gamma^{\prime} \rightarrow e^{-} \rightarrow e^{-} \]

\[ \gamma^{\prime} \rightarrow e^{-} \rightarrow e^{-} \]

\[ \gamma \rightarrow e^{+} \rightarrow e^{-} \]

atomic nucleus

atomic nucleus

atomic nucleus

atomic nucleus
How can $\gamma$-radiation with matter?

**Photoelectric effect:**

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

**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.

(PHGN326 Lab #3)

**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.
Interaction (energy transfer) mechanisms in detectors (II)

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. $\gamma$-radiation hits scintillator and interacts with electrons

2. $\gamma$-energy absorbed and distributed on many excited electrons/atoms

3. De-excitation leads to production of many low energy photons (ultraviolet $\rightarrow$ Visible light)
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)

Putting it all together

$\gamma$ (MeV)

$e^-$

$\gamma$ interacts in scintillator

Transfers some or all energy to an $e^-$ (and perhaps an $e^+$)

See previous slides

Scintillator

Glass envelope with special coating on inside.

Called the photocathode

Electron Multiplier (photomultiplier tube)

Electron (called a photoelectron)

Electronic Amplifier

Current pulse

V~$E_\gamma$ deposited

In how many places can photoelectrons be created? Where?
Photo(multiplier)tubes

The Photomultiplier Tube

- Incident Light
- Semi-transparent Photocathode
- Photoelectron Trajectories
- Dynodes
- Focusing Electrodes
- Electron Multiplier
- Anode

Figure 1

- Focusing Electrode
- Voltage Dropping Resistors
- Power Supply
- Output Meter
- Photomultiplier Tube
- Window
- Photocathode
- Anode
- Incoming photon
A simpler Detector with same properties.

Photomultiplier

Detector

6.6 \times 10^5 \text{ eV}
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
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

detector resolution

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…
Super Kamiokonda Neutrino Experiment (Japan)
Ice as Detector ICECUBE experiment
Search for Galactic and Extra-Galactic Neutrinos
FIG. 4. The two observed events from (a) August 2011 and (b) January 2012. Each sphere represents a DOM. Colors represent the arrival times of the photons where red indicates early and blue late times. The size of the spheres is a measure for the recorded number of photo-electrons.

Estimated Energy $\sim 1 \text{ PeV}$
Earth’s Atmosphere

Largest possible calorimeter in the world.
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
Pierre Auger Observatory

Primary particle

Fluorescence light - isotropic

Cherenkov light

Water-Cherenkov detectors

1.5 km

<8 km>

not to scale
Proportional to $dE/dX$ (but on PeV scale!)

**Figure 2.2**
The specific energy loss along an alpha track.

10$^6$ eV

Nuclear Physics
(Alpha particle)

10$^{19}$ eV

High Energy Cosmic Ray

Energy Estimate:
$E_m = (7.11 \pm 0.10) \times 10^{19}$ eV
$X_m = 1.14 \pm 0.06$ g/cm$^2$
$\chi^2$ for $1t-19$ is 1.91

Shower size
Longitudinal Profile Event 93431

10$^{19}$ eV

$E_m = 2.25 \pm 0.05$ eV
Anisotropy Hints $> 60$ EeV

$E > 5.7 \times 10^{19} \text{ eV}$  $20^\circ$ smoothing

$\approx 5 \sigma$ pretrial

$\approx 3 \sigma$ pretrial

Telescope Array

Auger Observatory
Neutrino & UHECR Coincidence

?
Fluorescence from SPACE

~170,000 km$^2$ (400 km alt)

60 deg FOV
Launch April 25th 2017
(4/24 23:50 UTC)
Towards Space Probes of UHE Cosmic Rays & Neutrinos

JEM-EUSO

EUSO-Balloon

Mini-EUSO

EUSO-SPB1

EUSO-SPB2

K-EUSO

EUSO-KLYPVE 400km
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