Introduction to Detectors in Nuclear Physics

Simona Malace
Jefferson Lab
→ Interaction of particles with matter

  Neutral particles: photons, neutrons
  Charged particles: heavy (mass >> $m_e c^2$), light (electrons/positrons)

→ Detectors: going from the theory of passage of particles through matter to particle detection

  Tracking detectors: Drift Chambers
  Particle identification detectors: Calorimeters, Cherenkov counters

→ What goes into designing/maintaining a detector?

→ References
Neutral Particles Go Through Matter

- Particle detection relies on understanding particles’ interaction with matter

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**Photoelectrons are ejected from metals in response to photon radiation incident on surface**

\[ T_e = h\nu - w \]

where \( w \) = material work function

<table>
<thead>
<tr>
<th>Material</th>
<th>Work Function (eV)</th>
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<tbody>
<tr>
<td>Al</td>
<td>4.08</td>
</tr>
<tr>
<td>Pb</td>
<td>4.14</td>
</tr>
<tr>
<td>Zn</td>
<td>4.31</td>
</tr>
<tr>
<td>Fe</td>
<td>4.50</td>
</tr>
<tr>
<td>Cu</td>
<td>4.70</td>
</tr>
<tr>
<td>Ag</td>
<td>4.73</td>
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**Practical example:**

Will 300 nm photons eject photoelectrons from silver?

Answer: No. \( w_{Ag} = 4.73 \text{ eV}; \ h\nu/\lambda > 4.73 \text{ eV} \Rightarrow \lambda < h\nu/4.73 = 1240/4.73 = 262 \text{ nm} \)
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Particle detection relies on understanding particles’ interaction with matter.

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Via the photoelectric effect the full energy of the photon is transferred to the material (detector) → useful in spectroscopy.

662 keV photon emitted by $^{137}$Cs interacts with NaI.
Neutral Particles Go Through Matter

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The fundamental interaction that leads to conversion of photons into electrons in a PMT is the photoelectric effect.
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Photon scatters off atomic electrons that can be considered essentially free and deposits just part of its energy in the material.

\[ T_{\text{max}} = \frac{2E_\gamma^2}{(mc^2+2E_\gamma)} \]

\[ E_{\gamma'} = \frac{E_\gamma}{1 + (E_\gamma/m_e c^2)(1 - \cos \theta)} \]
Neutral Particles Go Through Matter

- Particle detection relies on understanding particles' interaction with matter.

## Neutral Particles

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\[
T_{\text{max}} = \frac{2E_\gamma^2}{mc^2+2E_\gamma}
\]

- Compton edge can be used to gain match scintillators for use in trigger configurations.
Neutral Particles Go Through Matter

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Photons create electron-positron pairs in the field of a nucleus (electron)

hv > 1.02 MeV
Neutral Particles Go Through Matter

- Particle detection relies on understanding particles’ interaction with matter

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Photons create electron-positron pairs in the field of a nucleus (electron)

hv > 1.02 MeV

Electromagnetic shower in your electromagnetic calorimeter
Neutral Particles Go Through Matter

Now to put it all together:

\[
\mu/\rho = x^{-1}\ln(I_0/I)
\]

Mass attenuation coefficient: \( \mu \)
Material density: \( \rho \)
\( I, I_0 \): outgoing and incoming photon intensity
\( x \): mass thickness (linear thickness * density)

- Low-energy photon beams get attenuated primarily through photoelectric absorption
- Mid-energy photon beams get attenuated primarily though Compton scattering
- High-energy photon beams get attenuated through pair production
<table>
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<th>Mechanism</th>
<th>Heavy particles</th>
<th>Light particles</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision with atomic electrons</td>
<td>♦</td>
<td>♦</td>
<td>Leads to ionization/excitation of medium</td>
</tr>
<tr>
<td>Elastic scattering off nuclei</td>
<td>♦</td>
<td>♦</td>
<td>Leads to multiple scattering of incident particle, Bremsstrahlung photon production</td>
</tr>
<tr>
<td>Cherenkov radiation</td>
<td>♦</td>
<td>♦</td>
<td>Emitted if velocity of incident particle is larger than that of light in the medium</td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td>♦</td>
<td>♦</td>
<td>Emitted when incident particle accelerated/decelerated in Coulomb field of nucleus; initiates electromagnetic showers</td>
</tr>
<tr>
<td>Hadronic reactions</td>
<td>♦</td>
<td></td>
<td>Energy loss through inelastic collisions between hadrons and nuclei</td>
</tr>
<tr>
<td>Transition radiation</td>
<td></td>
<td>♦</td>
<td>X-rays are emitted when ultra-relativistic particles ($\gamma &gt; 1000$) pass the boundary between media with different refractive indices</td>
</tr>
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Heavy Charged Particles Go Through Matter

Mean rate of energy loss of the charged particle per g cm$^{-2}$ of medium traversed

- Coulomb scattering off medium’s atomic electrons lead cause for energy loss by heavy charged particles for $\beta\gamma \sim 0.1 – 1000$

- Stopping power parametrized via Bethe-Bloch equation

- Low-energy heavy charged particles have a well defined range in matter

- Scattering of atoms nuclei not a significant source of energy loss but leads to slight trajectory changes (multiple scattering)
Heavy Charged Particles Go Through Matter

- The quantum-mechanical parametrization of the energy loss by heavy particles as they go through matter and engage in inelastic collisions with the atomic electrons is condensed in the Bethe-Bloch formula:

\[
\frac{dE}{dX} = 4 N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{2} \ln \left( \frac{2m_e c^2}{I^2} \right) T_{\text{max}}^2 \frac{1}{2} \frac{1}{\beta^2 - 1}
\]

**Energy loss per unit distance (stopping power)**

- The energy loss per unit distance (stopping power) is given by the Bethe-Bloch formula, which involves several parameters:

  - \( dE/dX \): Energy loss per unit distance
  - \( N_A \): Avogadro's number
  - \( r_e \): Classical electron radius
  - \( m_e \): Electron mass
  - \( c \): Speed of light
  - \( Z \): Atomic number
  - \( A \): Atomic weight
  - \( I \): Mean excitation potential
  - \( z \): Electrical charge
  - \( \beta \): Velocity relative to that of light in vacuum
  - \( \gamma \): Lorentz factor
  - \( T_{\text{max}} \): Maximum energy transfer in a single collision

**Incident heavy particle characteristics:**

- \( z \) = electrical charge
- \( \beta = v/c \) = velocity relative to that of light in vacuum
- \( \gamma = (1-\beta^2)^{-1/2} \)
- \( T_{\text{max}} \) = maximum energy transfer in a single collision

**Matter’s characteristics:**

- \( Z \) = atomic number
- \( A \) = atomic weight
- \( I \) = Mean excitation potential (related to the average orbital frequency of the atomic electrons)
Main features of the Bethe-Block formula

- Valid (within few percent) from $\beta\gamma$ from $\sim 0.1$ to $\sim 1000$

- At small $\beta\gamma$ the rate of energy loss is rapid: goes like $\beta^{-3/5}$ (slow particles spend more time in the atom’s electric field)

- At $\beta\gamma$ between $\sim 3$ and $\sim 4$ the rate of energy loss reaches a minimum: a muon with a momentum of $\sim 300-400$ MeV it’s a Minimum Ionizing Particle (MIP)

- At large $\beta\gamma$ $dE/dx$ increases as $\ln\beta^2\gamma^2$; this “relativistic rise” is somewhat quenched (-$\delta/2$ term in the Bethe-Bloch eq.) due to the polarization of the medium by the field of the particle – density correction
Particles with the same velocity have similar rates of energy loss in different materials (slow decrease with increasing Z).

The minimum occurs indeed between $\beta\gamma$ of 3 and 4 and the energy loss varies between 1 and 2 MeV cm$^2$/g for most materials.

**Practical example:**

*Cosmic muons are pretty much MIPs so if you want to know what’s their energy loss in a 5 cm slab of aluminum:*

- Find $dE/dx$ for cosmic muons in Al: ~ 1.6 MeV cm$^2$/g
- Find the density of Al: $\rho_{Al} = 2.7$ g/cm$^3$

Cosmic $\mu$ will lose ~ 4.32 MeV per cm so ~21 MeV in 5 cm of Al.
Heavy Charged Particles Go Through Matter: Application to Particle Identification

Practical example:

From the $dE/dx$ curves one can identify particles by extracting their mass if the momentum is known or one can gain knowledge about the momentum of the particle if the particle type is known.

- $dE/dx$ measurements by a Time Projection Chamber (ALICE, CERN): particles are identified by comparing the energy they deposit in the drift gas to the expected $dE/dx$ value computed using the Bethe-Bloch formula with an assumption about mass.

- Pions are separated from kaons for momenta up to $p \sim 0.7$ GeV/c.
- Proton/antiproton band starts to overlap with the pion/kaon band at $p \approx 1$ GeV/c.

Electrons/positrons look different...
Bethe-Bloch formula gives the mean energy loss via excitation and ionization for heavy charged particles with $\beta\gamma$ roughly between 0.1 and 1000.

To find out the mean distance a particle will travel in a given material until it’s stopped due to collision induced energy losses, integrate the Bethe-Bloch equation from the particle’s energy $E$ to 0:

$$R = \int_{E}^{0} \frac{dE}{dE/dx}$$

**Practical examples:**

- A 200 MeV muon will travel in Pb $\sim 80/11.34 \sim 7$ cm
- A 700 MeV kaon will travel in Pb $\sim 195/11.34 \sim 17$ cm
Heavy Charged Particles Go Through Matter: the Bragg Curve

- Heavy particles slow down as they go through matter so their rate of energy loss will change; they will lose more energy per unit length towards the end of their path through matter.
Heavy Charged Particles Go Through Matter: the Bragg Curve

- Heavy particles slow down as they go through matter so their rate of energy loss will change; they will lose more energy per unit length towards the end of their path through matter.

- The nature of the $dE/dx$ dependence of the penetration depth has important applications in the medical field: treatment of tumors.

Different penetration depths are achieved with different proton energies.
Heavy Charged Particles Go Through Matter: Fluctuations in Energy Loss

Mean versus Most Probable

- Two particles of the same type with the same energy will not lose the same amount of energy in the same material: the energy loss process is statistical
  - The Landau-Vavilov functions give the distribution of the rate of energy loss in absorbers of finite thickness
  - The Bethe-Bloch formula gives the mean rate of energy loss
Heavy Charged Particles Go Through Matter: Fluctuations in Energy Loss

**Mean versus Most Probable**

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**Thin absorber/low density:** few collisions, some with high energy loss

**Thick absorber/high density:** many collisions, some with high energy loss
Electrons/Positrons Go Through Matter

- Few differences between electrons/positrons and heavier charged particles in terms of rate of energy loss

Processes that contribute to energy losses:

- Bremsstrahlung
- Ionization
- Moller scattering (electron – orbital electron scattering)
- Bhabha scattering (positron – orbital electron scattering)
- Annihilation

Electrons lose energy predominantly by bremsstrahlung
Electrons/Positrons Go Through Matter

- Few differences between electrons/positrons and heavier charged particles in terms of rate of energy loss

Processes that contribute to energy losses:

- **Bremsstrahlung**

 Photon emission by an electron accelerated in the Coulomb field of a nucleus

\[
\frac{dE}{dx} = 4\alpha N_A \frac{z^2 Z^2}{A} \left( \frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} \right)^2 E \ln \frac{183}{Z^{1/3}}
\]

\[X_0 \approx \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}\]

Radiation Length, \(X_0\): the distance over which the electron energy is reduced by 1/e due to radiation losses only

Fractional energy loss per radiation length in lead as a function of the electron energy
Electrons Go Through Matter: Bremsstrahlung

- Critical energy: \( \left. \frac{dE}{dx} \right|_{\text{brems}} = \left. \frac{dE}{dx} \right|_{\text{ion}} \)

Practical example:
- \( E_c \) for an electron in Cu: 20 MeV
- \( E_c \) for a pion in Cu: 1.5 TeV
Electrons Go Through Matter: Ionization, Example of Application to Detectors

- Information about where the particle is at in space can be obtained by using a drift chamber which measures the drift time of electrons created via ionization (primary, secondary etc.) of gases.

- Time measurement started by an external, fast detector.

- Electrons that result from ionization processes drift to the anode (sense wire), in the field created by the cathodes.

- The electrons arrival at the anode stops the time measurement.

\[ x = \int_{t_0}^{t_1} v \, dt \]

\( v = \text{drift velocity} \)
Electrons Go Through Matter: Ionization, Example of Application to Detectors

Hall C, SHMS
Electrons Go Through Matter: Bremsstrahlung, Application to Detectors

- Electromagnetic showers: Bremsstrahlung radiation by electrons + electron-positron pair formation by energetic photons

Simple, approximate model for electromagnetic shower formation

- After 1 radiation length: 1 Bremsstrahlung photon and 1 electron
- After 2 radiation lengths: 1 photon, 2 electrons, 1 positron – 4 particles total
- After 3 radiation lengths: 2 photons, 3 electrons, 2 positrons – 8 particles total

Number of particles after \( t \) radiation lengths: \( 2^t \)

Average energy per particle after \( t \) radiation lengths: \( E_0 / 2^t \)
Electrons Go Through Matter: **Bremsstrahlung**, Application to Detectors

- Electromagnetic showers: **Bremsstrahlung radiation** by electrons + **electron-positron pair formation** by energetic photons

Simple, approximate model for electromagnetic shower formation

- Assuming the shower abruptly stops at $E_c$:

  \[
  \frac{E_0}{2t_{\text{max}}} = E_c \quad \rightarrow \quad t_{\text{max}} = \frac{\ln E_0 / E_c}{\ln 2}
  \]

  **Longitudinal shower progression**

  **Transverse shower progression**: Moliere radius, $R_M = \frac{21\text{MeV}}{E_c} X_0$

**Practical example:**

10 GeV electrons in lead glass:

- Lead glass: $E_c = 11.8$ MeV, $X_0 = 2.4$ cm
- $t_{\text{max}} \sim 10$, $R_M = 4.3$ cm
Electrons Go Through Matter: **Bremsstrahlung, Application to Detectors**

- Electromagnetic showers: *Bremsstrahlung radiation* by electrons + *electron-positron pair formation* by energetic photons

However, the electromagnetic shower development it’s more complicated than this simple picture, need a Monte Carlo simulation to calculate it all.

Longitudinal profile of showers created by electrons in lead tungstate

Transverse (radial) profile of showers created by electrons in lead tungstate
Electrons Go Through Matter: Electromagnetic Showers via Monte Carlo Simulation

Electrons going through lead glass

2 GeV

5 GeV

10 GeV

80 GeV

Simulation from the OPAL collaboration
Electrons Go Through Matter: Electromagnetic Calorimeters, Hall C

- Particles that shower deposit their entire energy in the calorimeter
- Particles that don’t deposit just a fraction
Cherenkov Radiation

- A coherent wavefront of photons emerges when a charged particle travels faster than the speed of light in a given medium.

\[ \nu_{\text{particle}} > \frac{c}{n} \]

where \( n = \text{medium's index of refraction} \)

\[ \cos \theta = \frac{1}{\beta n(\lambda)} \]

angle of cone of Cherenkov photons

\[ \frac{dN}{d\lambda dx} = \frac{2\pi z^2 \alpha}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) \]

number of Cherenkov photons created per path length, per wavelength

**Practical example:**

- Pions with momentum larger than \( 0.140/\sqrt{1.00045^2 - 1} = 4.6 \text{ GeV} \) will make Cherenkov light in CO\(_2\) at 1 atm.

- Electrons make a cone of \( \sim 1.7 \text{ deg} \) in CO\(_2\) at 1 atm.
Cherenkov Radiation: Application to Detectors

- Cherenkov detector
  - Tank filled with gas
Cherenkov Radiation: Application to Detectors

- Cherenkov detector
  - Tank filled with gas
Cherenkov Radiation: Application to Detectors

- Cherenkov detector
  - Tank filled with gas
  - Mirrors
Cherenkov Radiation: Application to Detectors

Cherenkov detector

- Tank filled with gas
- Mirrors
Cherenkov Radiation: Application to Detectors

- Cherenkov detector
  - Tank filled with gas
  - Mirrors
  - PMT

Photomultiplier tube (PMT)

Quantum efficiency versus wavelength of various photocathodes
Cherenkov Radiation: Application to Detectors

- Cherenkov detector
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  - PMT

Pulse amplitude in mV from 1 photoelectron
Cherenkov Radiation: Application to Detectors

- Cherenkov detector
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  - PMT

Pulse amplitude in mV from 1 photoelectron

Calibration constant
Cherenkov Radiation: Application to Detectors

- Cherenkov detector
  - Tank filled with gas
  - Mirrors
  - PMT

Number of photoelectrons when few GeV electrons go through the gas

Pulse amplitude in mV from 1 photoelectron

Calibration constant
Cherenkov, Calorimeter Detectors: Particle Identification

- Typical electron-pion separation in Hall C using Cherenkov and Calorimeter detectors response

Diagram showing calorimeter energy deposition with Cherenkov cut > 2 photoelectrons.
Let’s say a Cherenkov detector  From my work on the SoLID Cherenkov detectors simulation ~ 8 years ago

Few things to worry about and include in your simulation:

→ radiator: index of refraction, transmittance...

→ Optics: mirror dimensions/shape, where in the tank do you place mirrors, collection efficiency

→ Mirror reflectivity

→ PMTs: quantum efficiency parametrization, magnetic field induced losses

→ Determine tolerances by running the simulation with small displacements in key parameters

→ When putting it all together: is it practical + cost effective, serviceable?
Designing a Detector

Let’s say a Cherenkov detector

From my work on the SoLID Cherenkov detectors simulation ~ 8 years ago
Designing a Detector

Let's say a Cherenkov detector

From my work on the SoLID Cherenkov detectors simulation ~ 8 years ago

Index of refraction not well measured: study sensitivity of photoelectron yield to the value of n “plugged” in the simulation
Designing a Detector

Let’s say a Cherenkov detector

From my work on the SoLID Cherenkov det

Collection efficiency not universally great…
Designing a Detector

Let’s say a Cherenkov detector  

From my work on the SoLID Cherenkov detectors simulation ~ 8 years ago

![Composite Mirror Applications](image)

- **Cost:** $276,925
- **Shipping and Handling:** included
- **Delivery Schedule:** 6 months from order
- **Terms:** 30% down with Order
  
  20% with receipt of tooling in place, approximately month 4 of the program schedule.

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**Coating by CMA**

- **Upper edge width:** 43.0998 cm
- **Length:** 104.11 cm
- **Lower edge width:** 22.2419 cm

---

**Graphs demonstrating reflectivity vs. wavelength for different Coatings**

- **LHCb17**
- **LHCb27**
- **LHCb32**
- **LHCb37**
- **LHCb28**
- **LHCb29**
- **LHCb30**
- **LHCb31**
- **LHCb32**
Designing a Detector

Let’s say a Cherenkov detector

Measure PMT loss of signal in magnetic field

Design a mu-metal shield
Maintaining/Commissioning a Detector

From my work on the SHMS quartz plane
Maintaining/Commissioning a Detector

From my work on the SHMS quartz plane

[Graph showing spectral data with various curves labeled 250 um, 500, 900, and 1000]

[Images of a detector device, one labeled 'NO' and another labeled 'YES']
Maintaining/Commissioning a Detector

From my work on the SHMS quartz plane
Maintaining/Commissioning a Detector

From my work on the SHMS quartz plane
Maintaining/Commissioning a Detector

From my work on the SHMS quartz plane

Curing time for per side... 7 days
Maintaining/Commissioning a Detector

From my work on the SHMS quartz plane
Maintaining/Commissioning a Detector

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From my work on the SHMS quartz plane

Maintaining/Commissioning a Detector

![Graphs showing amplitude vs. PMT for SHMS 52Y3, 52Y4, 52Y5, 52Y6, 52Y7, 52Y8, with different symbols for pions, kaons, and protons.](image)
References

Techniques for Nuclear Physics – Leo

JINST – CERN technical publications


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