Detectors in Particle Astrophysics

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Nepomuk Otte
School of Physics &
Center for Relativistic Astrophysics
Georgia Institute of Technology
Plan

• Why a lecture on detector physics?
• A particle physics experiment: requirements
• Interaction of ionizing radiation with matter
• Detector Technologies
  • Scintillators
  • Photon detectors
  • Semiconductor detectors
Why you should know about Detector Physics!

Because this is how you understand the instrument

Helps in several aspects:

- Understanding the physical limits of the experiments
- Development of new analysis methods
- Making non standard measurements

....

You can design a new experiment
This lecture can only serve as a starting point
If you want to learn more

Try the reviews published by the particle data group:
  http://pdg.lbl.gov/

Or any other good book about detectors in high energy physics

  Radiation Detection and Measurement by Knoll
  Particle Detectors by Claus Grupen & Boris Schwartz
  Detectors for Particle Radiation by Konrad Kleinknecht
Particle Detectors: Requirements

What you want to know:

- Particle detection
- Momentum / energy measurement
- Particle identification
- Arrival direction
- Measurements of particle decay length
- ...

You need to know:

1. How particles “interact” in matter
2. How materials “respond”
3. What technologies exist to “read out” detector medium

To extract this information
Things can become pretty complex
Most often a common Principle

Tracker

Anticoincidence shield

Conversion foils

Particle tracking

Calorimeter
Neutrino Astrophysics

Antares

Tracker and Calorimeter in one

Ice Cube
Pierre Auger Observatory

Detection of cosmic rays above $10^{16}$ eV

Tracker and Calorimeter in one

24 telescopes in total
Air Showers

Use measured air shower characteristics for:
- calorimetry
- particle ID
- tracking

Readout:
- Fluorescence light
- Cherenkov light
- Particles
- Radio

Not like in a laboratory
Remote places
Weather
Inhomogenous detector medium
Background (light from the sky)
Interaction of ionizing radiation with matter

Heavy charged particles (everything but electrons)

Electrons/positrons

Photons
Charged particles $\neq$ electrons
Energy Loss of heavy (M\(\gg m_e\)) charged Particles in Matter

- Energy loss described by Bethe-Bloch formula
- Ionisation through inelastic scattering & atomic excitation
- Global minimum in \(dE/dX\) @ \(\beta y \approx 3.5\) -> Minimum Ionizing Particle (MIP)
- \(dE/dx\) at minimum \(\sim 2\) MeV cm\(^2\) / g (multiply with density and thickness of material to get total energy loss)
- \(dE/dx\) \(\sim Z\) with \(Z=\)atomic number of absorber
- \(dE/dx\) \(\sim z^2\) with \(z=\)charge of incident particle
- Hadronic interactions come in addition (needed for shower development)

What would you chose?

**High density and high Z?**

**or**

**Low density and low Z?**
Small Angle Scattering (also for electrons)

- **single scattering for very thin absorbers:**
  
  Rutherford-Scattering:  
  \[
  \frac{d\sigma}{d\Omega} \sim \frac{1}{\sin^4 \frac{\theta}{2}}
  \]

- **multiple scattering: \( N < 20 \)**
  Difficult to describe

- **multiple scattering \( N > 20 \)**
  
  Statistical treatment: Molière-theory

  \[
  \left[ \langle \Theta^2 (x) \rangle \right]^{1/2} = \frac{13.6 \text{ MeV}}{\beta \cdot p \cdot c} \cdot z \sqrt{\frac{x}{X_0}} \cdot \left( 1 + 0.038 \ln \frac{x}{X_0} \right)
  \]

  \( X_0 = \text{radiation length} = \text{material constant} \quad \sim \frac{1}{Z^2} \)

  Central 98% are normal distributed

  **Limit for resolving momentum, vertex, and arrival direction**
Electrons
Energy Loss of Electrons

Modified Bethe-Bloch:

Scattering of same type of particle
masses are the same

In addition to ionisation
Bremsstrahlung

\[
\frac{dE}{dX} = \left. \frac{dE}{dX} \right|_{\text{Ion}} + \left. \frac{dE}{dX} \right|_{\text{Brems}}
\]

Critical energy: \( \frac{dE}{dx}_{\text{Ion}} = \frac{dE}{dx}_{\text{Brems}} \)

\( E_c = 560 \text{MeV/Z} \)
Energy Loss due to Bremsstrahlung

Probability \( \sim \frac{1}{m_e^2} \frac{1}{E_\gamma} \)

\[ -\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} \cdot r_e^2 \cdot E \ln \frac{183}{Z^{1/3}} = \frac{E}{X_0} \]

Radiation length \( X_0 = \frac{716.4 \cdot A}{Z(Z + 1) \ln(287/\sqrt{Z})} \) [g/cm\(^2\)]

Energy loss by Bremsstrahlung: \( \sim Z^2 \)

\( \sim N_A/A \hat{=} \) Nuclear density

Exponential energy loss \( \frac{dE}{dx} = \frac{E}{X_0} \rightarrow E(X) = E_0 \exp \left( -\frac{x}{X_0} \right) \)
Photons
Interaction of Gamma-Rays with Matter

- Photoelectric effect
- Compton scattering
- Pair production

In general absorption:
- Attenuation of photon intensity

\[ I(x) = I_0 \exp(-\mu x) \]

\( \mu \) = Attenuation coefficient

\( \sigma_{\text{p.e.}} \) = Atomic photoelectric effect (electron ejection, photon absorption)
\( \sigma_{\text{Rayleigh}} \) = Rayleigh (coherent) scattering–atom neither ionized nor excited
\( \sigma_{\text{Compton}} \) = Incoherent scattering (Compton scattering off an electron)
\( \kappa_{\text{nuc}} \) = Pair production, nuclear field
\( \kappa_e \) = Pair production, electron field
\( \sigma_{\text{g.d.r.}} \) = Photonuclear interactions, most notably the Giant Dipole Resonance [46]. In these interactions, the target nucleus is broken up.
Interaction of Photons in Matter

- **Attenuation of intensity**
  \[ I(x) = I_0 e^{-\mu x} \] \( \mu \) = attenuation coefficient

- **Photoeffect**
  - Photon energy > binding energy of electron
    - \( \mu \sim Z^5/E_y^{7/2} \)

- **Compton scattering**
  - Relevant between \(~100\) keV and \(~\) few MeV
    - \( \mu \sim Z/E_y \)

- **Pair creation**
  - Relevant above kinematically allowed threshold: \( E_y > 2m_e \)
    - \( \mu \sim Z^2/E_y \approx 9/(7X_0) \)

Large Z helps
And…
Cherenkov Effect

- Not important for energy loss but very important mechanism in most astroparticle experiments

\[ \cos \theta_c = \left( \frac{1}{n\beta} \right) \]

or

\[ \tan \theta_c = \sqrt{\beta^2 n^2 - 1} \approx \sqrt{2\left(1 - \frac{1}{n\beta}\right)} \]

for small \( \theta_c \), e.g. in gases.

\[ \frac{d^2 N}{dE dx} = \frac{\alpha z^2}{\hbar c} \sin^2 \theta_c = \frac{\alpha^2 z^2}{r_e m_e c^2} \left(1 - \frac{1}{\beta^2 n^2(E)}\right) \approx 370 \sin^2 \theta_c(E) \text{ eV}^{-1}\text{cm}^{-1} \]

\[ \frac{d^2 N}{dx d\lambda} = \frac{2\pi \alpha z^2}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) \]
Ionization $\rightarrow$ free electrons?
Ionization yield

- $E_I = $ Ionization energy
- $W = <E_{\text{e-ion pair}}>$
- $W > E_I$
- $N_p = $ primary generated e-/Ion pairs (per cm)
- $N_T = \Delta E/W > N_p = $ total ionization yield (per cm)

Want that large for energy measurements

For MIPs

A number to remember: Silicon $W \sim 3.6$ eV
Why large $N_T$? -->Example: Energy measurements

$N = \text{Number of pairs generated after energy loss } E$

$E \sim N$ and $\Delta E \sim \sqrt{N}$

Energy loss is a statistical process

$\rightarrow$ energy resolution $\frac{\Delta E}{E} \sim \frac{\sqrt{N}}{N} \sim \frac{1}{\sqrt{N}}$

Note that energy resolution also depends on the energy of the primary

$\rightarrow \frac{\Delta E}{E} \sim \frac{1}{\sqrt{N}} \sim \frac{1}{\sqrt{E}}$

Under the condition that all the energy is deposited in the detector $\rightarrow$ energy resolution improves with increasing particle energy
Semiconductor Detectors

How many electron/hole pairs are produced by a MIP going through 300 um thick silicon?
Scintillators

- Organic scintillators
- Inorganic scintillators
- Scintillating gases
  Some of the ionized electrons can produce light in some materials

If material is transparent --> light can be detected with photon detector

Scintillation mechanisms are complicated and not fully understood -> several contributions with different time constants.
What makes a good Scintillator

- High conversion efficiency of deposited energy into photons
- Light yield should be proportional to deposited energy over as wide a range as possible
- Medium should be transparent to the wavelength of its own emission
- Fast decay time of the induced luminescence
- Good optical quality and available in large quantities
- Index of refraction ~1.5 to allow good coupling to photo detector (glass surface)

Difficult to achieve everything simultaneous
Organic scintillators (plastic)

- Organic (aromatic) molecules
- $\pi$-electron structure
- Large band gap between $S_0$ and $S_1 \sim 3-4$ eV
  - Molecules normally in $S_0$ state
  - Excitation into multiple possible configuration
  - Rapid deexcitation (radiationless) into $S_1$ state
- Fluorescence $S_{10} \rightarrow S_0$
  - Time constant $\tau$
  - Intensity $I(t) = I_0 e^{-t/\tau}$
  - $\tau \sim \text{ns}$
- Phosphorescence $T_1$ to $S_0$
  - $\tau \sim \text{ms}$
  - Excitation back into $S_1$ possible
Transmission and Absorption

is used as wavelength shifter

e.g. matching to spectral response of photo detector
## Typical characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.03 g/cm³</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.58</td>
</tr>
<tr>
<td>$\chi_0$</td>
<td>44 cm</td>
</tr>
<tr>
<td>Light yield</td>
<td>100 eV/γ</td>
</tr>
<tr>
<td>Attenuation length</td>
<td>1-2 m</td>
</tr>
<tr>
<td>decay time</td>
<td>2-3 ns</td>
</tr>
<tr>
<td>$\lambda_{\text{max}}$</td>
<td>~400 nm</td>
</tr>
</tbody>
</table>
Inorganic scintillators

- Much higher density than organic scintillators 
  ~3-4 g/cm³
  - High stopping power
  - High conversion efficiency for electrons/photons
  - **Good for energy measurements (calorimetry)**
- Bandgap of 5-10 eV
- Some crystals are intrinsic scintillators others require dopant (Thallium or Cerium)
- Need activator in the band gap
  - Need several excited states in the activator
- Exitons (bound electron/hole pairs) are created
  - Large lifetime
- Exitons de-excite via activators
- **Decay time constant ~10⁻⁷ s**
- Much less quenching than in organic scintillators
Characteristics of typical inorganic scintillators

Table 28.4: Properties of several inorganic crystal scintillators. Most of the notation is defined in Sec. 6 of this Review.

<table>
<thead>
<tr>
<th>Parameter: $\rho$ MP $X_0^<em>$ $R_M^</em>$ $dE/dx$ $\lambda_I^*$ $\tau_{\text{decay}}$ $\lambda_{\text{max}}$ $n^\dagger$</th>
<th>Relative output$^\ddagger$</th>
<th>Hygroscopic?</th>
<th>$d(\text{LY})/dT$ $^\circ/\circ C^\ddagger$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units: g/cm$^3$ °C cm cm MeV/cm cm ns nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaI(Tl) 3.67 651 2.59 4.13 4.8 42.9 230 410 1.85 100 yes −0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BGO 7.13 1050 1.12 2.23 9.0 22.8 300 480 2.15 21 no −0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BaF$_2$ 4.89 1280 2.03 3.10 6.6 30.7 630$^s$ 300$^s$ 1.50 36$^s$ no −1.3$^s$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9$^f$ 220$^f$ 3.4$^f$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.4$^f$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Csl(Tl) 4.51 621 1.86 3.57 5.6 39.3 1300 560 1.79 165 slight 0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Csl(pure) 4.51 621 1.86 3.57 5.6 39.3 35$^s$ 420$^s$ 1.95 3.6$^s$ slight −1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6$^f$ 310$^f$ 1.1$^f$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PbWO$_4$ 8.3 1123 0.89 2.00 10.2 20.7 30$^s$ 425$^s$ 2.20 0.083$^s$ no −2.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10$^f$ 420$^f$ 0.29$^f$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSO(Ce) 7.40 2050 1.14 2.07 9.6 20.9 40 420 1.82 83 no −0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSO(Ce) 6.71 1950 1.38 2.23 8.9 22.2 600$^s$ 430 1.85 3$^s$ no −0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Numerical values calculated using formulae in this review.
$^\dagger$ Refractive index at the wavelength of the emission maximum.
$^\ddagger$ Relative light output measured for samples of 1.5 $X_0$ cube with a Tyvek paper wrapping and a full end face coupled to a photodetector. The quantum efficiencies of the photodetector is taken out.
$^\circ C$ Variation of light yield with temperature evaluated at the room temperature.
$f = \text{fast component}, \: s = \text{slow component}$

40,000 ph/MeV
Emission spectra of a few scintillators

Response of photon detector and emission spectrum should match
Photomultipliers PMT

- Absorption of photon and emission of a photoelectron (Photoeffect)
  1. absorption of photon and energy transfer to one electron
  2. electron migrates to the surface
  3. escape of the electron from the surface
  4. multiplication of electron in dynode structure -> gains of several million possible

PMT handbook available for download

The world biggest Kamiokande
Photocathode

- Photoeffect

- Electron migration through cathode material
  - Minimize energy losses: electron must have enough kinetic energy to overcome work function $\phi$
  - “escape depth” depth from which electrons make it to the surface
    - In metals a few nm
    - In semiconductors up to 25nm
    - Small compared to absorption length of visible light

Surface activation with Cs

Photocathode = Semiconductor + alkali metals
Quantum Efficiency

\[ QE = \frac{\text{photoelectrons}}{\text{photons at cathode}} \]

Some cathodes now reach efficiencies of 35% or more. First PMT had an efficiency of 0.4%
Electron Multiplication

Electrons are accelerated
-→ bombard dynodes
-→ secondary electron emission
-→ only a few of the electrons make it out of the dynode

Alkali antimoide
Beryllium oxide BeO
Magnesium oxide (MgO)
Gallium phosphide (GaP)
Gallium Arsenide phosphide (GaAsP)

Nickel, stainless steel, or copper-beryllium alloy

$$\delta = \frac{\text{number of electrons emitted}}{\text{primary incident electron}}$$

Typically 4-5