Scintillation Detectors
Particle Detection via Luminescence

Kolanoski, Wermes
Scintillators – General Characteristics

Principle:
- dE/dx converted into visible light
- Detection via photosensor
  [e.g. photomultiplier, human eye …]

Main Features:
- Sensitivity to energy
- Fast time response
- Pulse shape discrimination

Requirements
- **High efficiency** for conversion of exciting energy to fluorescent radiation
- **Transparency** to its fluorescent radiation to allow transmission of light
- **Emission of light** in a spectral range detectable for photosensors
- **Short decay time** to allow fast response
Inorganic Crystals

Materials:
- Sodium iodide (NaI)
- Cesium iodide (CsI)
- Barium fluoride (BaF$_2$)
...

Mechanism:
- Energy deposition by ionization
- Energy transfer to impurities
- Radiation of scintillation photons

Time constants:
- Fast: recombination from activation centers [ns ... μs]
- Slow: recombination due to trapping [ms ... s]
Inorganic Crystals

Example CMS
Electromagnetic Calorimeter

Crystal growth

PbWO\textsubscript{4} ingots

One of the last CMS end-cap crystals
Inorganic Crystals – Time Constants

Exponential decay of scintillation can be resolved into two components ...

\[ N = Ae^{-t/\tau_f} + Be^{-t/\tau_s} \]

\( \tau_f \) : decay constant of fast component  
\( \tau_s \) : decay constant of slow component
Inorganic Crystals – Light Output

Scintillation Spectrum for NaI and CsI

Strong Temperature Dependence [in contrast to organic scintillators]
Scintillation in Liquid Nobel Gases

Materials:
- Helium (He)
- Liquid Argon (LAr)
- Liquid Xenon (LXe)

Decay time constants:
- Helium: \( \tau_1 = 0.02 \, \mu\text{s}, \tau_2 = 3 \, \mu\text{s} \)
- Argon: \( \tau_1 \leq 0.02 \, \mu\text{s} \)

![Diagram]

- 
  - Excitation: \( A \rightarrow A^* \)
  - Collision: \( A^* \rightarrow A_2^{*} \)
  - Ionization: \( A \rightarrow A^* \)
  - Ionized molecules: \( A_2^{*} \)
  - Excited molecules: \( A^* \)
  - De-excitation and dissociation: \( A_2^{*} \rightarrow A \)
  - Recombination: \( e^- \)
  - UV:
    - LAr: 130 nm
    - LKr: 150 nm
    - LXe: 175 nm
Inorganic Scintillators – Properties

Numerical examples:

NaI(Tl) \( \lambda_{\text{max}} = 410 \text{ nm}; \ h\nu = 3 \text{ eV} \)\
photons/MeV = 40000\
\( \tau = 250 \text{ ns} \)

PBWO\(_4\) \( \lambda_{\text{max}} = 420 \text{ nm}; \ h\nu = 3 \text{ eV} \)\
photons/MeV = 200\
\( \tau = 6 \text{ ns} \)

Scintillator quality:

Light yield – \( \varepsilon_{\text{sc}} \equiv \) fraction of energy loss going into photons

e.g. NaI(Tl) : 40000 photons; 3 eV/photon \( \Rightarrow \) \( \varepsilon_{\text{sc}} = 4 \cdot 10^4 \cdot 3 \text{ eV}/10^6 \text{ eV} = 11.3\% \)
PBWO\(_4\) : 200 photons; 3 eV/photon \( \Rightarrow \) \( \varepsilon_{\text{sc}} = 2 \cdot 10^2 \cdot 3 \text{ eV}/10^6 \text{ eV} = 0.06\% \)
[for 1 MeV particle]
Organic Scintillators

Aromatic hydrocarbon compounds:

- e.g. Naphtalene \([C_{10}H_8]\)
- Antracene \([C_{14}H_{10}]\)
- Stilbene \([C_{14}H_{12}]\)

... Very fast!
[Decay times of O(ns)]

Scintillation light arises from delocalized electrons in \(\pi\)-orbitals ...

Transitions of 'free' electrons ...
Organic Scintillators

Molecular states:

Singlet states
Triplet states

Fluorescence in UV range
[~ 320 nm]

Fluorescence: \( S_1 \rightarrow S_0 [< 10^{-8} \text{ s}] \)
Phosphorescence: \( T_0 \rightarrow S_0 [> 10^{-4} \text{ s}] \)

Absorption in 3-4 eV range
Organic Scintillators

Transparency requires:

**Shift of absorption and emission spectra ...**

Shift due to

**Franck-Condon Principle**

Excitation into higher vibrational states
De-excitation from lowest vibrational state

Excitation time scale : $10^{-14}$ s
Vibrational time scale : $10^{-12}$ s
$S_1$ lifetime : $10^{-8}$ s
Plastic and Liquid Scintillators

In practice use ...

solution of organic scintillators
[solved in plastic or liquid]
+ large concentration of primary fluor
+ smaller concentration of secondary fluor
+ ...

Scintillator requirements:

Solvable in base material
High fluorescence yield
Absorption spectrum must overlap with emission spectrum of base material
Plastic and Liquid Scintillators

A

Energy deposit in base material → excitation

Solvent

Excitations

S\text{0A}

S\text{1A}

S\text{0B}

S\text{1B}

S\text{0C}

S\text{1C}

Primary fluorescent
- Good light yield ...
- Absorption spectrum matched to excited states in base material ...

B

Primary Fluor

C

Secondary fluorescent

Wave length shifter

S\text{0A} \rightarrow S\text{1A} \rightarrow S\text{0B} \rightarrow S\text{1B} \rightarrow S\text{0C} \rightarrow S\text{1C}
Wavelength Shifting

Principle:
Absorption of primary scintillation light
Re-emission at longer wavelength
Adapts light to spectral sensitivity of photosensor

Requirement:
Good transparency for emitted light
Organic Scintillators – Properties

Light yield:
[without quenching]

\[ \frac{dL}{dx} = L_0 \frac{dE}{dx} \]

Quenching:
non-linear response due to
saturation of available states

Birk's law:

\[ \frac{dL}{dx} = L_0 \frac{dE}{dx} \frac{1 + kB \frac{dE}{dx}}{1 + kB \frac{dE}{dx}} \]

[kB needs to be determined experimentally]

Also other
parameterizations ...

Response different
for different particle types ...
Scintillation Counters – Setup

Scintillator light to be guided to photosensor

- Light guide
  [Plexiglas; optical fibers]
  
  Light transfer by total internal reflection
  [maybe combined with wavelength shifting]

Liouville's Theorem:

Complete light transfer impossible as $\Delta x \Delta \theta = \text{const.}$
[limits acceptance angle]

Use adiabatic light guide like 'fish tail';

- appreciable energy loss
Photon Detection

Purpose: Convert light into a detectable electronic signal

Principle: Use photo-electric effect to convert photons to photo-electrons (p.e.)

Requirement:
High Photon Detection Efficiency (PDE) or Quantum Efficiency; \( Q.E. = \frac{N_{p.e.}}{N_{\text{photons}}} \)

Available devices [Examples]:
- Photomultipliers [PMT]
- Micro Channel Plates [MCP]
- Photo Diodes [PD]
- Hybrid Photo Diodes [HPD]
- Visible Light Photon Counters [VLPC]
- Silicon Photomultipliers [SiPM]
Photomultipliers – Dynode Chain

Electrons accelerated toward dynode
Further electrons produced ➔ avalanche
Secondary emission coefficient:
\( \delta = \frac{\text{#(e\textsuperscript{-} produced)}}{\text{#(e\textsuperscript{-} incoming)}} \)

Typical:
\[ \delta = 2 - 10 \]
\[ n = 8 - 15 \]
\[ \Rightarrow G = \delta^n = 10^6 - 10^8 \]

Gain fluctuation:
\[ \delta = kU_D; \ G = a_0(kU_D)^n \]
\[ \frac{dG}{G} = ndU_D/U_D = ndU_B/U_B \]
Optimization of

PMT gain
Anode isolation
Linearity
Transit time

B-field dependence

PM’s are in general very sensitive to B-fields!
Even to earth field (30-60 μT). μ-metal shielding required.
Photomultipliers – Photocathode

γ-conversion via photo effect...

Photon

entrance window

photo cathode

Electron

4-step process:
- Electron generation via ionization
- Propagation through cathode
- Escape of electron into vacuum

Q.E. ≈ 10-30%
[need specifically developed alloys]

Bialkali: SbRbCs; SbK₂Cs
Photomultipliers – Energy Resolution

Energy resolution influenced by:

**Linearity of PMT:** at high dynode current possibly saturation by space charge effects; $I_A \propto n_Y$ for 3 orders of magnitude possible ...

**Photoelectron statistics:** given by poisson statistics.

$$P_n(n_e) = \frac{n_e^n e^{-n_e}}{n!} \quad \text{with } n_e \text{ given by } \frac{dE}{dx} ...$$

$$\sigma_n/\langle n \rangle = 1/\sqrt{n_e}$$

**Secondary electron fluctuations:**

$$P_n(\delta) = \frac{\delta^n e^{-\delta}}{n!} \quad \text{with dynode gain } \delta; \quad \text{and with } N \text{ dynodes } ...$$

$$\sigma_n/\langle n \rangle = 1/\sqrt{\delta}$$

$$\left( \frac{\sigma_n}{\langle n \rangle} \right)^2 = \frac{1}{\delta} + \ldots + \frac{1}{\delta^N} \approx \frac{1}{\delta - 1} \quad \text{... important for single photon detection}$$

For NaI(Tl) and 10 MeV photon; photons/MeV = 40000; $\eta = 0.2$; Q.E. =0.25

$$n_e = 20000$$

$$\sigma_n/\langle n \rangle = 0.7\%$$
Silicon Photomultipliers

Principle:

Pixelized photo diodes
operated in Geiger Mode

Single pixel works as a binary device

Energy = #photons seen by
summing over all pixels

Features:

Granularity : 10^3 pixels/mm^2
Gain : 10^6
Bias Voltage : < 100 V
Efficiency : ca. 30 %

Works at room temperature!
Insensitive to magnetic fields
Scintillation Counters – Setup

Supplies which power the readout are mounted in an external steel box which has the cross-section of the support girder and which also contains the external connections for power and other services for the electronics (see section 4).

Finally, the calorimeter is equipped with three calibration systems: charge injection, laser, and a Cs radioactive source. These systems test the optical and digitised signals at various stages and are used to set the PMT gains to a uniformity of ±(% (see section 4).

5.3.1.2 Mechanical structure

Photomultiplier
Wavelength-shifting fibre
Scintillator
Steel

Source tubes

Figure 5.9: Schematic showing how the mechanical assembly and the optical readout of the tile calorimeter are integrated together. The various components of the optical readout, namely the tiles, the fibres, and the photomultipliers, are shown.

The mechanical structure of the tile calorimeter is designed as a self-supporting, segmented structure comprising 17 modules, each subtending 30–60 degrees in azimuth, for each of the three sections of the calorimeter. The module sub-assembly is shown in figure 5.9.

Each module contains a precision-machined strong-back steel girder, the edges of which are used to establish a module-to-module gap of ±0.1 mm at the inner radius. To maximise the use of radial space, the girder provides both the volume in which the tile calorimeter readout electronics are contained and the flux return for the solenoid field. The readout fibres, suitably bundled, penetrate the edges of the girders through machined holes, into which plastic rings have been precisely mounted. These rings are matched to the position of photomultipliers. The fundamental element of the absorber structure consists of a 20 mm thick master plate, onto which 1 mm thick spacer plates are glued in a staggered fashion to form the pockets in which the scintillator tiles are located. The master plate was fabricated by high-precision die stamping to obtain the dimensional tolerances required to meet the specification for the module-to-module gap.

At the module edges, the spacer plates are aligned into recessed slots, in which the readout fibres run. Holes in the master and spacer plates allow the insertion of stainless-steel tubes for the radioactive source calibration system.

Each module is constructed by gluing the structures described above into sub-modules on a custom stacking fixture. These are then bolted onto the girder to form modules, with care being taken to ensure that the azimuthal alignment meets the specifications. The calorimeter is assembled by mounting and bolting modules to each other in sequence. Shims are inserted at the inner and outer radius load-bearing surfaces to control the overall geometry and yield a nominal module-to-module azimuthal gap of ±0.1 mm and a radial envelope which is generally within ±1 mm of the nominal one.
Scintillation Counters – Applications

Time of flight (ToF) counters
Energy measurement (calorimeters)
Hodoscopes; fibre trackers
Trigger systems

ATLAS Minimum Bias Trigger Scintillators

Particle track in scintillating fibre hodoscope
CMS – Crystal Calorimeter (ECAL)

Scintillator : PBW04 [Lead Tungsten]  
Photosensor : APDs [Avalanche Photodiodes]

Number of crystals: ~ 70000  
Light output: 4.5 photons/MeV
CALICE – Analogue HCAL

1m³-Prototype
38 layers

Sandwich structure:
- Scintillator Tiles+WLS+SiPMs (.5 cm)
- Stainless steel absorber (1.6 cm)

Scintillator : Plastic
Photosensor : SiPMs