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 $\rightarrow$ excitation

<table>
<thead>
<tr>
<th>Solvent</th>
<th>$S_0A$</th>
<th>$S_1A$</th>
<th>$\gamma_A$</th>
<th>$S_0B$</th>
<th>$S_1B$</th>
<th>$\gamma_B$</th>
<th>$S_0C$</th>
<th>$S_1C$</th>
<th>$\gamma_C$</th>
</tr>
</thead>
</table>

**B**

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

**C**

Secondary fluorescent
Wave length shifter
## Plastic and Liquid Scintillators

### Some widely used solvents and solutes

<table>
<thead>
<tr>
<th></th>
<th>solvent</th>
<th>secondary fluor</th>
<th>tertiary fluor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Liquid scintillators</strong></td>
<td>Benzene</td>
<td>p-terphenyl</td>
<td>POPOP</td>
</tr>
<tr>
<td></td>
<td>Toluene</td>
<td>DPO</td>
<td>BBO</td>
</tr>
<tr>
<td></td>
<td>Xylene</td>
<td>PBD</td>
<td>BPO</td>
</tr>
<tr>
<td><strong>Plastic scintillators</strong></td>
<td>Polyvinylbenzene</td>
<td>p-terphenyl</td>
<td>POPOP</td>
</tr>
<tr>
<td></td>
<td>Polyvinyltoluene</td>
<td>DPO</td>
<td>TBP</td>
</tr>
<tr>
<td></td>
<td>Polystyrene</td>
<td>PBD</td>
<td>BBO</td>
</tr>
</tbody>
</table>

![Polystyrene](image)

![p-Terphenyl](image)

![POPOP](image)
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

<table>
<thead>
<tr>
<th>Scintillator Material</th>
<th>Density [g/cm$^3$]</th>
<th>Refractive Index</th>
<th>Wavelength [nm] for max. emission</th>
<th>Decay time constant [ns]</th>
<th>Photons/MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphtalene</td>
<td>1.15</td>
<td>1.58</td>
<td>348</td>
<td>11</td>
<td>$4 \cdot 10^3$</td>
</tr>
<tr>
<td>Antracene</td>
<td>1.25</td>
<td>1.59</td>
<td>448</td>
<td>30</td>
<td>$4 \cdot 10^4$</td>
</tr>
<tr>
<td>p-Terphenyl</td>
<td>1.23</td>
<td>1.65</td>
<td>391</td>
<td>6-12</td>
<td>$1.2 \cdot 10^4$</td>
</tr>
<tr>
<td>NE102*</td>
<td>1.03</td>
<td>1.58</td>
<td>425</td>
<td>2.5</td>
<td>$2.5 \cdot 10^4$</td>
</tr>
<tr>
<td>NE104*</td>
<td>1.03</td>
<td>1.58</td>
<td>405</td>
<td>1.8</td>
<td>$2.4 \cdot 10^4$</td>
</tr>
<tr>
<td>NE110*</td>
<td>1.03</td>
<td>1.58</td>
<td>437</td>
<td>3.3</td>
<td>$2.4 \cdot 10^4$</td>
</tr>
<tr>
<td>NE111*</td>
<td>1.03</td>
<td>1.58</td>
<td>370</td>
<td>1.7</td>
<td>$2.3 \cdot 10^4$</td>
</tr>
<tr>
<td>BC400**</td>
<td>1.03</td>
<td>1.58</td>
<td>423</td>
<td>2.4</td>
<td>$2.5 \cdot 10^2$</td>
</tr>
<tr>
<td>BC428**</td>
<td>1.03</td>
<td>1.58</td>
<td>480</td>
<td>12.5</td>
<td>$2.2 \cdot 10^4$</td>
</tr>
<tr>
<td>BC443**</td>
<td>1.05</td>
<td>1.58</td>
<td>425</td>
<td>2.2</td>
<td>$2.4 \cdot 10^4$</td>
</tr>
</tbody>
</table>

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA
Organic Scintillators – Properties

![Graphs showing the relative light output of NE104 and NE110 scintillators versus wavelength.](image)

- NE104
- NE110

Wavelength [nm] vs. Relative Light Output [arbitrary units]
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:
\[
\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + kB \frac{dE}{dx}}
\]

[kB needs to be determined experimentally]

Also other parameterizations ...

Response different for different particle types ...
## Scintillators – Comparison

<table>
<thead>
<tr>
<th>Inorganic Scintillators</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>high light yield [typical; $\epsilon_{sc} \approx 0.13$]</td>
<td>complicated crystal growth</td>
</tr>
<tr>
<td></td>
<td>high density [e.g. PBWO$_4$: 8.3 g/cm$^3$]</td>
<td>large temperature dependence</td>
</tr>
<tr>
<td></td>
<td>good energy resolution</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Organic Scintillators</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>very fast</td>
<td>lower light yield [typical; $\epsilon_{sc} \approx 0.03$]</td>
</tr>
<tr>
<td></td>
<td>easily shaped</td>
<td>radiation damage</td>
</tr>
<tr>
<td></td>
<td>small temperature dependence</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pulse shape discrimination possible</td>
<td></td>
</tr>
</tbody>
</table>

Expensive

Cheap
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
Scintillation Counters – Setup
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; $Q.E. = \frac{N_{p.e.}}{N_{photons}}$

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

Principle:

Electron emission from photo cathode
Secondary emission from dynodes; dynode gain: 3-50 \([f(E)]\)

Typical PMT Gain: > 10^6
[PMT can see single photons ...]
**Photomultipliers – Photocathode**

γ-conversion
via photo effect ...

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

Q.E. ≈ 10-30%
[need specifically developed alloys]
Photomultipliers – Dynode Chain

Multiplication process:
Electrons accelerated toward dynode
Further electrons produced → avalanche
Secondary emission coefficient:
\[ \delta = \#(e^-\text{produced})/\#(e^-\text{incoming}) \]

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

Gain fluctuation:
\[ \delta = kU_D; \ G = a_0(kU_D)^n \]
\[ \frac{dG}{G} = n \frac{dU_D}{U_D} = n \frac{dU_B}{U_B} \]
Photomultipliers – Dynode Chain

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 – Energy Resolution

Energy resolution influenced by:

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

Photoelectron statistics: given by poisson statistics.

\[
P_n(n_e) = \frac{n_e^n e^{-n_e}}{n!}
\]

with $n_e$ given by $dE/dx$ ...

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

Secondary electron fluctuations:

\[
P_n(\delta) = \frac{\delta^n e^{-\delta}}{n!}
\]

with dynode gain $\delta$; and with $N$ dynodes ...

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

\[
\left(\frac{\sigma_n}{\langle n \rangle}\right)^2 = \frac{1}{\delta} + \ldots + \frac{1}{\delta^N} \approx \frac{1}{\delta - 1}
\]

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

\[
n_e = 20000\quad \sigma_n/\langle n \rangle = 0.7\%
\]

$\sigma_n/\langle n \rangle$ dominated by first dynode stage ...

... important for single photon detection
Photomultipliers – Energy Resolution

For detection of single photons

Large $\delta$!

... yields better energy resolution
Micro Channel Plate

"2D Photomultiplier"

Gain: $5 \cdot 10^4$

Fast signal [time spread ~ 50 ps]

B-Field tolerant [up to 0.1T]

But: limited life time/rate capability
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
Silicon Photomultipliers

HAMAMATSU
MPPC 400Pixels

One of the first SiPM
Pulsar, Moscow
Silicon Photomultipliers
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
H1 – Spaghetti Calorimeter

Scintillator : BICRON BCF-12
Photosensor : Photomultipliers
CMS – Crystal Calorimeter (ECAL)
CMS – Crystal Calorimeter (ECAL)

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

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

1m$^3$-Prototype
38 layers

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

Scintillator : Plastic
Photosensor : SiPMs

2006/2007 CERN Testbeam
[2008/09, Fermilab]
CALICE – Scintillator ECAL

Scintillator layers: 2 mm
Tungsten layers: 3 mm

X/Y-Strips: 1 x 4 cm²
Granularity: 1 x 1 cm²

Readout: MPPC
Channels: ~ 10⁷

Particle

SiPM r/o with WLS

Scintillator

SiPM [1600 pixels]
Some examples of liquid scintillator based detectors

Borexino (low energy solar neutrino detector and geo-neutrino)

KamLAND (reactor neutrino detector and geo-neutrino)

Double Chooz (reactor neutrino detector)

Daya Bay (reactor neutrino detector)

Reno (reactor neutrino detector)

Planned: SNO+ and JUNO
PMT’s on the sphere surface
Vessel before inflation (viewed by CCD cameras)
Vessel after inflation (viewed by CCD cameras)
Detector fully filled on May 15\textsuperscript{th}, 2007: DAQ starts

LAKN –
Low Argon and Krypton Nitrogen

Ultra-pure water

Liquid scintillator

Ultra-pure water

Photos taken with one of 7 CCD cameras placed inside the detector
Solid State Detectors (SSD)

Ionization chamber medium could be gas, liquid, or solid
- Gas $\Rightarrow$ electron and ion pairs; Semiconductor $\Rightarrow$ electron and hole pairs

<table>
<thead>
<tr>
<th></th>
<th>Gas</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Atomic number (Z)</td>
<td>Low</td>
<td>Moderate (Z=14)</td>
</tr>
<tr>
<td>Ionization Energy ($\varepsilon_1$)</td>
<td>Moderate ($\approx$ 30 eV)</td>
<td>Low ($\approx$3.6 eV)</td>
</tr>
<tr>
<td>Signal Speed</td>
<td>Moderate (10ns-10$\mu$s)</td>
<td>Fast (&lt;20 ns)</td>
</tr>
</tbody>
</table>

Solid State Detectors
- Energy ($E$) to create e-h pairs 10 times smaller than gas ionization $\Rightarrow$ increase charge $\Rightarrow$ good $E$ resolution

\[ \frac{\Delta E}{E} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E/\varepsilon_1}} \propto \sqrt{\varepsilon_1} \]

- Greater density
  - Reduced range of secondary electron $\Rightarrow$ excellent spatial resolution
  - Average $E_{\text{loss}} \approx$390eV/ $\mu$m $\approx$108 e-h/ $\mu$m (charge collected is a function of thickness D but no multiplication)

- To minimize multiple scattering D should be small, 300 $\mu$m $\approx$32,000 e-h pairs yields good S/N
Principle of Operation

- Goal: precise charged particle position measurement
- Use ionization signal \((dE/dx)\) from charged particle passage

- In a semiconductor, ionization produces electron hole (e-h) pairs
- Use an electric field to drift the e and h to oppositely charged electrodes
- Problem: in pure intrinsic (undoped) silicon, there are more free charge carriers than those produced by a charged particle.
  Ex.: in this volume have \(4.5 \times 10^8\) free charge carriers and only \(3.2 \times 10^4\) produced by MIP particle
- Problem: electron–hole pairs quickly re-combine
- Solution: Deplete the free charge carriers and collect e (or h) quickly by exploiting the properties of a p-n junction (diode)
Semiconductor: Band Gap

When isolated atoms are brought together to form a lattice, the discrete atomic states shift to form energy bands.

If the gap is large, the solid is an insulator. If there is no gap, it is a conductor. A semiconductor results when the gap is small.

Ge 0.7 eV  GaAs  1.4 eV  Si  1.1 eV  Diamond 4.5 eV
The PN Junction

**Space Charge Region:** When n and p type silicon are brought together ⇒ gradient of electron and hole densities ⇒ migration of majority carriers across the junction which leaves a region of net charge of opposite sign on each side, called the space-charge region or depletion region (depleted of free charge carriers). The electric field in the region prevents further migration of carriers ⇒ potential difference Φ=V_{bi} (built in potential).

**Junction:** Interface where the p- and n-type materials meet.

**N_A & N_D:** Negative and positive doping (n/cm³), usually ≈ 10^{15} – 10^{20}/cm³.

**p–n e-field**

![Diagram of PN Junction](image)
The pn junction is considered biased when an external voltage is applied. There are two types of biasing: Forward bias and Reverse bias. **biased p-n junction**
Charge collection

- Electron and hole pairs created in the depletion region move under the E field

\[ v_{e,h}(x) = \mu_{e,h} E(x) \]
\[ \mu_e = 1500 \text{cm}^2 / \text{Vs}, \mu_h = 450 \text{cm}^2 / \text{Vs} \]

- The time required for a carrier to traverse the sensitive volume is the collection time.

- The collection time can be reduced by over-biasing the sensor

\[ t(x) = \frac{D^2}{2\mu_p V_d} \ln \left( \frac{V_{bias} - V_{fd}}{V_{bias} - V_{fd} + 2V_{fd} \left(1 - \frac{x}{D}\right)} \right) \]
Historical developments

> NA11 at CERN

First use of a position-sensitive silicon detector in HEP experiment

- Measurement of charm-quark lifetime
- 1200 diode strips on 24 x 36mm$^2$ active area
- 250-500 μm thick bulk material
- 4.5 μm resolution
Historical developments

> LEP and SLAC
  - ASIC’s at end of ladders
  - Minimise the mass inside tracking volume
  - Minimise the mass between interaction point and detectors
  - Minimise the distance between interaction point and the detectors

> Enabled heavy flavour physics i.e. short lived particles

- 2 silicon layers, 40cm long, inner radius 6.3cm, outer radius 11cm
- 300μm Silicon wafers giving thickness of only 0.015X₀
- S/N rΦ = 28:1; z = 17:1
- σ₉₀ = 12μm; σ_z = 14μm
Currently at the LHC

- CMS TIB
- LHCb VELO
- ATLAS SCT
- ATLAS Pixel
- ALICE Pixel
- CMS
Elemental Semiconductor

> **Germanium:**
  - Used in nuclear physics
  - Needs cooling due to small band gap of 0.66 eV (usually done with liquid nitrogen at 77 K)

> **Silicon:**
  - Can be operated at room temperature
  - Synergies with micro electronics industry
  - Standard material for vertex and tracking detectors in high energy physics

> **Diamond (CVD or single crystal):**
  - Allotrope of carbon
  - Large band gap (requires no depletion zone)
  - Very radiation hard
  - Disadvantages: low signal and high cost
Why Silicon

> Semiconductor with moderate bandgap (1.12eV)
> Energy to create e/h pair (signal quanta) = 3.6eV
  
  - (c.f Argon gas = 15eV)
  - High carrier yield
  - Better energy resolution and high signal
    ⇒ no gain stage required

> High density and atomic number
  
  - Higher specific energy loss
    ⇒ Thinner detectors
    ⇒ Reduced range of secondary particles
    ⇒ better spatial resolution

> High carrier mobility ⇒ Fast!
  
  - Less than 30ns to collect entire signal

> Large experience in industry with micro-chip technology

> High intrinsic radiation hardness
**Example – CMS Tracker**

- **Largest silicon tracker**
  - **Micro Strip Tracker:**
    - ~ 214 m² of silicon strip sensors, 11.4 million strips
  - **Pixel:**
    - Inner 3 layers: silicon pixels (~ 1m²)
    - 66 million pixels (100x150μm)
    - Precision: \( \sigma(r\phi) \sim \sigma(z) \sim 15\mu m \)
    - Most challenging operating environments (LHC)
Summary

• More than 100 years of particle physics & discoveries possible thanks to a large variety of instruments and techniques
• Imaging devices are unbeatable in precision but slow & cannot be triggered
• Logic devices still largely in use (Geiger counters, scintillators, Cherenkov detectors)
• Today's particle detectors merge all possible techniques to create “electronic images” of particles

• In order to detect a particle, it has to interact - and deposit energy
  → all means are good = use all types of interaction