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 excitation 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
1. An incident photon or particle ionizes the medium.
2. Ionized electrons slow down causing excitation.
3. Excited states immediately emit light.
4. Emitted photons strike a light-sensitive surface.
5. Electrons from the surface are amplified.
6. A pulse of electric current is measured.

**Scintillation materials:**
- Inorganic crystals
- Organic scintillators
- Polymeres (plastic scintillators)

**Photosensors:**
- Photomultipliers
- Micro-Channel Plates
- Hybrid Photo Diodes
- Visible Light Photo Counter
- Silicon Photomultipliers
Scintillation counters

- **Luminescence**: Emission of photons (visible light, UV, X-ray) after absorption of energy.
- **Scintillation**: Emission of photons following the excitation of atoms and molecules by radiation.
- **Fluorescence**: Emission of light by a substance that has absorbed light or another electromagnetic radiation of a different wave length. In most cases the emitted light has a longer wavelength. The emission follows shortly after \( \sim 10 \text{ ns} \).
- **Phosphorescence**: Similar to Fluorescence, however the re-emission is not immediate. The transition between energy levels and the photon emission is delayed (ms up to hours).

![Diagram](attachment:image.png)

- Singlet states
- Triplet states
- Loss of energy through change in vibrational states
- Fluorescence: \( 10^{-8} \) s
- Phosphorescence: \( 10^{-3} \) s
Inorganic crystals

- **Materials:**
  - Sodium iodide (NaI)
  - Cesium iodide (CsI)
  - Barium fluoride (BaF₂)
  - …

- **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]
Exponential decay of scintillation can be resolved into two components ...

\[ N = A e^{-t/\tau_f} + B e^{-t/\tau_s} \]

\( \tau_f \) : 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 noble gases

Materials:

Helium (He)
Liquid Argon (LAr)
Liquid Xenon (LXe)

Decay time constants:

Helium: $\tau_1 = 0.02\ \mu s$, $\tau_2 = 3\ \mu s$
Argon: $\tau_1 \leq 0.02\ \mu s$

UV
LAr: 130 nm
LKr: 150 nm
LXe: 175 nm

Excitation
A

Ionization
A$^+$

Collision
[with other gas atoms]

Excited molecules
A$^*$$\rightarrow$$A_2^*$

De-excitation and dissociation
A$^*$$\rightarrow$A

Ionized molecules
A$^+$

Recombination
e$^-$
## Inorganic scintillators - properties

<table>
<thead>
<tr>
<th>Scintillator material</th>
<th>Density [g/cm³]</th>
<th>Refractive Index</th>
<th>Wavelength [nm] for max. emission</th>
<th>Decay time constant [μs]</th>
<th>Photons/MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI</td>
<td>3.7</td>
<td>1.78</td>
<td>303</td>
<td>0.06</td>
<td>8·10⁴</td>
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<td>NaI(TI)</td>
<td>3.7</td>
<td>1.85</td>
<td>410</td>
<td>0.25</td>
<td>4·10⁴</td>
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<tr>
<td>CsI(TI)</td>
<td>4.5</td>
<td>1.80</td>
<td>565</td>
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<td>Bi₄Ge₃O₁₂</td>
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<td>2.15</td>
<td>480</td>
<td>0.30</td>
<td>2·10³</td>
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<tr>
<td>CsF</td>
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<td>1.48</td>
<td>390</td>
<td>0.003</td>
<td>2·10³</td>
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<tr>
<td>LSO</td>
<td>7.4</td>
<td>1.82</td>
<td>420</td>
<td>0.04</td>
<td>1.4·10⁴</td>
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<tr>
<td>PbWO₄</td>
<td>8.3</td>
<td>1.82</td>
<td>420</td>
<td>0.006</td>
<td>2·10²</td>
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<tr>
<td>LHe</td>
<td>0.1</td>
<td>1.02</td>
<td>390</td>
<td>0.01/1.6</td>
<td>2·10²</td>
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<tr>
<td>LAr</td>
<td>1.4</td>
<td>1.29*</td>
<td>150</td>
<td>0.005/0.86</td>
<td>4·10⁴</td>
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<tr>
<td>LXe</td>
<td>3.1</td>
<td>1.60*</td>
<td>150</td>
<td>0.003/0.02</td>
<td>4·10⁴</td>
</tr>
</tbody>
</table>

* at 170 nm

The time for 1/e of the atoms to remain excited is the characteristic decay time $\tau$
Inorganic scintillators - properties

Numerical examples:

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

PbWO\(_4\) \( \lambda_{\text{max}} = 420 \text{ nm}; \quad \rightarrow \quad h \cdot \nu = 3 \text{ eV} \)
photon\(s/\text{MeV} = 200 \)
\( \tau = 6 \text{ ns} \)

Scintillator quality:

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

Only a few percent of the deposited energy is transferred into light.
The remaining energy is used up be ionization, etc.
Typical problem

- Gamma rays of 450 keV are absorbed with 12% efficiency. Scintillator photons with average 2.8 eV produce photoelectrons 15% of the time.
- What is the energy to produce a measurable photoelectron?
- How does this compare to a gas detector?
Band structure

- Impurities in the crystal provide energy levels in the band gap.

- Charged particles excites electrons to states below the conduction band.

- Deexcitation causes photon emission.
  - Crystal is transparent at photon frequency.

Impurities improve visible light emission
Aromatic hydrocarbon compounds:

e.g. Naphtalene [C\textsubscript{10}H\textsubscript{8}]
    Antracene [C\textsubscript{14}H\textsubscript{10}]
    Stilbene [C\textsubscript{14}H\textsubscript{12}]
    …

Very fast!
[decay times of 0 ns]

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

Transition of ‘free´ electrons …
Organic scintillators – excited rings

- $\pi$-bonds are most common in aromatic carbon rings.
- Excited states radiate photons in the visible and UV spectra.
  - Fluorescence is the fast component ($S_1 \rightarrow S_0 < 10^{-8}$ s)
  - Phosphorescence is the slow component ($T_0 \rightarrow S_0 > 10^{-4}$ s)

$\pi$-electronic energy levels of an organic molecule.

$S_0$ is the ground state. $S_1, S_2, S_3$ are excited singlet states. $T_1, T_2, T_3$ are excited triplet states. $S_{00}, S_{01}, S_{10}, S_{11}$ etc. are vibrational sublevels.
Plastic scintillators

Organic scintillators can be mixed with polystyrene to form a rigid plastic

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>Liquid scintillators</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>
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<tr>
<td>Plastic scintillators</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>
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</table>

POPOP

Polystyrene

p-Terphenyl
# Organic scintillators - properties

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<th>Photons/MeV</th>
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<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>
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<tr>
<td>Antracene</td>
<td>1.25</td>
<td>1.59</td>
<td>448</td>
<td>30</td>
<td>$4 \cdot 10^4$</td>
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<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>
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<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>
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<td>1.58</td>
<td>405</td>
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<td>$2.4 \cdot 10^4$</td>
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<td>NE110*</td>
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<td>1.58</td>
<td>437</td>
<td>3.3</td>
<td>$2.4 \cdot 10^4$</td>
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<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>
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<td>BC400**</td>
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<td>423</td>
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<tr>
<td>BC428**</td>
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<td>1.58</td>
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<tr>
<td>BC443**</td>
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<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
Wavelength shifting

Principle:

Absorption of primary scintillation light
Re-emission at longer wavelength

Adapts light to spectral sensitivity of photosensor

Requirements:
Good transparency for emitted light
Scintillators - comparison

Inorganic Scintillators

Advantages
- high light yield [typical $\varepsilon_{\text{SC}} \approx 0.13$]
- high density [e.g. PbWO$_4$: 8.3 g/cm$^3$]
- good energy resolution

Disadvantages
- complicated crystal growth
- large temperature dependence

Organic Scintillators

Advantages
- very fast
- easily shaped
- small temperature dependence
- pulse shape discrimination possible

Disadvantages
- lower light yield [typical $\varepsilon_{\text{SC}} \approx 0.03$]
- radiation damage
Oscilloscope traces from scintillation counters

**Plastic scintillator**

- **Vert. scale:** 0.2 V/cm
- **Hor. scale:** 10 ns/cm
- **Source:** $^{207}$Bi, 10 μCi

**Inorganic crystal, NaI**

- **Vert. scale:** 0.2 V/cm
- **Hor. scale:** 5 μs/cm
- **Source:** $^{137}$Cs, 10 μCi

**Longer time scale for fluorescence to occur**
Scintillation counters - setup

Scintillator light to be guided to photosensor

→ light guide [plexiglas, optical fibers]
  light transfer by total internal reflection
  [may be combined with wavelength shifter]

Liouville’s Theorem:

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

Use adiabatic light guide like ‘fish tail’;
→ appreciable energy loss
Consider a phase space element for a photon in a light guide
\( x = \) transverse coordinate
\( p = n \sin \alpha = \) angular divergence

Liouville’s theorem says \( \Delta x_1 \Delta p_1 = \Delta x_2 \Delta p_2 \)
\[ 2 \Delta x_1 \cdot n \cdot \sin \alpha_1 = 2 \Delta x_2 \cdot n \cdot \sin \alpha_2 \]

\[ \sin(\alpha_1) = \frac{\Delta x_2}{\Delta x_1} \sin(\alpha_2) \]

\[ \sin(\alpha_2) = \sin(\varphi + 90^0 - \theta_c) \]

\[ \sin(\alpha_2) = \cos(\varphi - \theta_c) = \sqrt{1 - \sin^2(\varphi - \theta_c)} \]

\[ \sin(\alpha_2) \approx \sqrt{1 - \sin^2(\theta_c)} \quad \text{for small taper angles} \]

\[ \sin(\alpha_2) \approx \sqrt{1 - \frac{1}{n^2}} \]

then \( \sin(\alpha_1) \approx \frac{\Delta x_2}{\Delta x_1} \sqrt{1 - \frac{1}{n^2}} \)

for \( \Delta x_1 = \Delta x_2 \) and \( n=1.5 \)

\[ \sin(\alpha_1) = 0.75 \]

There will be some light losses even in the case of equal dimensions
A photomultiplier tube (phototube, PMT) combines a photocathode and series of dynodes.

**Photocathode:** UV detection (alkali compound, Cs-I, Cs-Te), visible light (bialkali compound, Sb-Rb-Cs, Sb-K-Cs), visible light to IR (semiconductors, GaAsP, InGaAs)

**Dynodes:** Electrons can be multiplied by interaction with surface (emitter: BeO, GaP or metal substrate: Ni, Fe, Cu)

- The high voltage is divided between the dynodes. Dynodes typically operate at around 100 V.
- Output current is measured at the anode.
  - Sometimes at the last dynode
Photomultiplier - Photocathode

\( \gamma \)-conversion via photoeffect …

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

Quantum Efficiency \( Q.E. \approx 10\text{-}30\% \)

\[
\begin{align*}
\text{Photon} & \rightarrow \text{entrance window} \\
\text{Photo cathode} & \rightarrow e^- \\
\text{Electron} & \rightarrow \text{vacuum energy}
\end{align*}
\]

\[
\begin{align*}
\text{valence band} & \quad \text{conduction band} \\
E_G & \quad E_A \\
\psi & \quad h\nu
\end{align*}
\]

Percent of light which passes

Wavelength of light

Indian Institute of Technology Ropar
Hans-Jürgen Wollersheim - 2017
Multiplication process:

Electrons accelerated towards dynode
Further electrons produced $\rightarrow$ avalanche
Secondary emission coefficient: $\delta = \#(e^- \text{ produced}) / \#(e^- \text{ incoming}) = 2 - 10$

#dynodes $n = 8 - 15$
Gain factor: $G = \delta^n = 10^6 - 10^8$
The 9 V battery is “divided” in 3 V and 6 V, now accessible with this circuit.
Photomultiplier – Energy Resolution

Energy resolution influenced by:

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

**Photoelectron statistics:** given by Poisson statistics.

$$P_n(n_e) = \frac{(n_e)^n \cdot e^{-n_e}}{n!}$$

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

**Secondary electron fluctuations:**

$$P_n(\delta) = \frac{\delta^n \cdot e^{-\delta}}{n!}$$

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

$ne$ is given by $dE/dx$ ...

$$ne = \frac{dE}{dx} \times \frac{\text{photons}}{\text{MeV}} \times \eta \times \text{Q.E.}$$

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

$ne = 20000$

$\sigma_n/\langle n \rangle = 0.7\%$
Pulse shape discrimination (PSD) in organic scintillators are used in particularly liquid scintillators (NE213 / BC501A).

PSD is due to long-lived decay of scintillator light caused by high dE/dx particle – neutron scatter interaction events causing proton recoil.