Scintillators revisited

Diagram showing a scintillator device with labels for Thin window, Mu metal Shield, Iron protective Shield, Photomultiplier, and PM Base (Voltage divider network).
Scintillators revisited (cont.)

Outstanding features:

• **Sensitivity to energy**: above certain energy most scintillators behave in a near linear fashion to with respect to the energy deposited

• **Fast time response**: obtain timing information with great precision, can accept higher count rates

• **Pulse shape discrimination**: discriminate between different particle types due to the different shape of the emitted light pulses
Scintillators revisited (cont.)

• Property: luminescence, 2 types
  • **Fluorescence**: reemission occurs immediately after absorption, within $10^{-8}$s
  • **Phosphorescence/Afterglow**: reemission is delayed, because the excited state is metastable
Scintillators revisited (cont.)

Equations describing the reemission process

1) Simple exponential decay:
\[ N = \frac{N_0}{\tau_d} \exp\left(-\frac{t}{\tau_d}\right) \]

- \( N \): no. of photons emitted at a time \( t \)
- \( N_0 \): total no. of photons emitted
- \( \tau_d \): decay constant

2) More complex decay, usually more accurate description:
\[ N = A \exp\left(-\frac{t}{\tau_f}\right) + B \exp\left(-\frac{t}{\tau_s}\right) \]

- \( \tau_f, \tau_s \): decay constant, \( f \): fast, prompt; \( s \): slow, delayed
- \( A, B \): relative magnitudes
Scintillators revisited (cont.)
Scintillators revisited (cont.)

Good detector scintillator

1. High efficiency of conversion of exciting energy to fluorescent radiation
2. Transparency to its fluorescent radiation to allow transmission of light
3. Emission of spectral range consistent with response of existing PMT
4. Short decay time $\tau$
Scintillators revisited (cont.)

Six types

1. Organic crystals
2. Organic liquids
3. Plastics
4. Inorganic crystals
5. Gases
6. Glasses
Organic Scintillators

- organic hydrocarbon compounds
- Very rapid decay time, few ns
- Scintillation light: transition made by free valence electrons of the molecules
- Associated with each electron level is fine structure which corresponds to excited vibrational modes of the molecule
Organic Scintillators (cont.)

![Energy level diagram for organic scintillators showing singlet and triplet states, absorption, internal degradation, and fluorescence.](image)
Organic Scintillators (cont.)

**Singlet Case**

- **Internal degradation**: Singlet excitations decay immediately ($\leq 10$ ps) without emission of radiation ($S^{**} \rightarrow S^*$)
- **Fluorescence**: $S^* \rightarrow S_0$ with radiation, to one of the vibrational states of the ground state $S_0$, few ns $\rightarrow$ prompt exponential component in $\odot$
- **Note**: The fact that $S^*$ decays to excited vibrational states of $S_0$ with emission of radiation energy less than required for the transition $S_0 \rightarrow S^*$ also explains the transparency of the scintillators to their own radiation
Organic Scintillators (cont.)

**Triplet Case**

- $T_0 \rightarrow S_0$ highly forbidden
- Instead: $T_0 + T_0 \rightarrow S^* + S_0 + \text{phonons}$
  (interaction of two excited molecules)
- Than $S^*$ decays as above
- $\rightarrow$ delayed or slow component of scintillation light in ☼
Organic Crystals

- Anthracene (30 ns)
- Trans-stilbene (few ns)
- Naphtalene (few ns)
- Problem: channeling effect → for a constant source the response varies with the orientation of the crystal
- Anthracene: highest light output → light outputs of scintillators are given as percent of anthracene output very often
Organic Liquids

- Liquid solutions of one or more organic scintillators in an organic solvent
- Absorption mechanism is different: in solutions, the ionization energy seems to be absorbed mainly by the solvent and then passed on to the scintillator solute
- Very fast and efficient, 3-4 ns
- Precise details are still not clear
- “loaded”: to increase efficiency (e.g. Boron-11, high neutron cross-section) or to shift wavelength
- Extremely sensitive to impurities (oxygen)
Plastics

• You heard of a lot because it is widely used in nuclear and particle physics
• Solution of organic scintillator in solid plastic solvent
• Extremely fast signal: 2-3 ns
• High light output
• Fast signal, so rise time cannot be ignored → Bengston and Moszynski
• Handling: wear cotton or terylene gloves (body acid can cause cracking of the plastic after some time)
Plastic

Emission spectra
(see page 164 in Leo)
Plastic (cont.)

Fast signal
→ rise time cannot be ignored
→ Bengston & Moszynski:

\[ N(t) = N_0 f(\sigma, t) \exp\left(-\frac{t}{\tau}\right) \]

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>$\sigma$ [ns]</th>
<th>$\tau$ [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE102A</td>
<td>0.7</td>
<td>2.4</td>
</tr>
<tr>
<td>NE111</td>
<td>0.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Naton 136</td>
<td>0.5</td>
<td>1.87</td>
</tr>
</tbody>
</table>

Derived from fits →
Inorganic Crystals

- NaI (Tl), BGO, BaF$_2$
Inorganic Crystals

• Comparison NaI and BGO:
• BGO has higher Z and great efficiency for the photo electric conversion (3-5 times more efficient)
• BGO Non-hygroscopic
• Lower light output
• Relatively expensive
• Both slow response compared to Organic Scintillators ~ 500 ns

BaF2: very fast light component in UV region, 500 ps
Inorganic Crystals

Two processes:
1) Ionization (free electrons and holes)
2) Excitons (in the exciton band, electron and hole are still bound, pair can move freely)

Impurity Atoms: → electron levels in the forbidden energy gap can be locally created
→ migrating free holes or a hole from an exciton pair encountering an impurity center can then ionize the impurity atom
→ subsequent electron arrives and can fall into the opening left by the hole and make a transition from an excited state to the ground state emitting radiation if such a deexcitation is allowed
Trap: if transition is radiation less and the energy is lost to other processes
Gaseous Detectors

- Noble gases: xenon, krypton, argon, and helium + nitrogen
- Atoms individually excited
- Decay time: 1 ns
- UV light
- Used in experiments with heavy charged particles or fission fragments
- Implementation: gas mixtures, e.g. 90% $^3$He, 10% Xe at pressures up to 200 atm to increase the detection efficiency
Glasses

- Cerium activate lithium or boron silicates
- Boron glasses 10 times lower light outputs than lithium
- Glass detectors usually used for neutron detection, also sensitive to beta and gamma radiation
- Resistant to all organic and inorganic reagents (exception hydrofluoric acid)
- High melting points, useful in extreme environmental conditions
- Response time: between plastics and inorganic crystals, few 10$^{th}$ of ns
- Low light output: < 20-30% of anthracene
Pulse shape discrimination

- Fast and slow components depend on dE/dx
- Characteristic for particle type/exciting radiation

Example: CsI(Tl) →

<table>
<thead>
<tr>
<th>tau</th>
<th>Particle ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.425 (\mu)s</td>
<td>(\alpha)</td>
</tr>
<tr>
<td>0.519 (\mu)s</td>
<td>(p)</td>
</tr>
<tr>
<td>0.695 (\mu)s</td>
<td>(e^-)</td>
</tr>
</tbody>
</table>

Explanation:
- **High ionization loss** → higher density of free electrons and holes → favors excitons → excitons captured as a whole by impurity centers → excite impurity centers to radiative states → **fast component**;
- **Low ionization density** → excitons less likely → relatively large number of singly free electrons and holes which are captured successively in metastable states → **slow component**
Pulse shape discrimination

Example: organic scintillator
High dE/dx → high density of excited molecules
  → increased intermolecular interactions
  → hinder normal singlet internal degradation process
  → fast component reduced relative to slow component

Example: Liquid Scintillator
Gamma Ray spectroscopy:
Reminder → Photon-Interaction I
Gamma Ray Spectroscopy:

Detector size matters: