Detection of energetic particles and gamma rays

Scintillation detectors

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A generic scintillation detector

- radioluminescence/fluorescence
  - scintillation (fast)
  - phosphorescence (slow)
- scintillators may be organic and inorganic solids, liquids and gases
weak interactions between molecules

$\rightarrow$ molecular levels are relevant
  - electronic levels ($\Delta E \sim$ few eV)
  - vibrational levels ($\Delta E \sim 0.1$ eV)
  - room temperature ($kT = 0.025$ eV): all in ground state

$\rightarrow$ works as gas, liquid, solid
Organic scintillators: scintillation mechanism

- ionising radiation: excitation & de-excitation to first electronic excited state, lowest vibrational level in a short time (few 100 ps)
- decay to ground-state vibrational levels: few ns decay time (fast !)
- no self-absorption, because:
  - $\lambda$ emission $>$ $\lambda$ absorption (Stokes shift)
  - scintillation final states are not populated
- phosphorescence (up to ms decay time)
Organic scintillators: Stokes shift

Figure 8.1 Energy levels of an organic molecule with π-electron structure. (From J. B. Birks, The Theory and Practice of Scintillation Counting. Copyright 1964 by Pergamon Press, Ltd. Used with permission.)

Figure 8.2 The optical absorption and emission spectra for a typical organic scintillator with the level structure shown in Fig. 8.1.
Types of organic scintillators

• pure organic crystals
  – anthracene (C\textsubscript{14}H\textsubscript{10})
    • highest efficiency amongst organic scintillators
  – stilbene (C\textsubscript{14}H\textsubscript{12})

• liquid organic solutions
  – organic scintillator dissolved in a solvent
  – possible 3\textsuperscript{rd} component as wavelength shifter

• plastic scintillators
  – organic scintillator dissolved in a solvent and polymerized
Pure inorganic scintillators: mechanism

- radiation creates electron-hole pairs
- electron-hole recombination via photon emission
  - inefficient
  - photon energy > visible light
  - emission wavelength = absorption wavelength → self-absorption
Activated inorganic scintillators: mechanism

Figure 8.6 Energy band structure of an activated crystalline scintillator.

- action of radiation:
  - creation of electron-hole pairs
  - holes ionise activation sites
  - electrons migrate until they “drop” into an ionised activated site, leaving the activator in an excited state
  - excited activator state decay time (~50-500 ns) >> electron, hole migration time
- activators act as luminescence centers, recombination centers
- scintillation photons of longer wavelength than pure scintillators
- no self-absorption
- phosphorescence can occur (long-lived excited state)
Types of inorganic scintillators

- unactivated fast
- unactivated slow
- Tl-activated
- Ce-activated
- glass
Unactivated fast inorganic scintillators

- fast component with low light yield
- \( \text{BaF}_2 \)
  - only high-Z scintillator with decay time < 1 ns
    \( \tau = 0.6 \text{ ns at } \lambda \sim 220 \text{ nm}, \text{ 15\% of light yield} \)
  - slow component
    \( \tau = 630 \text{ ns at } \lambda \sim 220 \text{ nm}, \text{ 85\% of light yield} \)
- \( \text{CsI} \)
  - fast component \( \tau \sim 10 \text{ ns} \)
  - slow component \( \tau \) up to several \( \mu \text{s} \)
    • related to impurities

**Figure 8.13** The scintillation emission spectra from \( \text{BaF}_2 \) measured at various temperatures. The fast component (corresponding to the two small peaks at the left) does not display the strong temperature dependence of the slow component. (From Schotanus et al.\textsuperscript{107, 108})
Unactivated slow inorganic scintillators

- BGO (bismuth germanate, $\text{Bi}_4\text{Ge}_3\text{O}_{16}$)
  - very high Z
- CdWO$_4$ (cadmium tungstate)
- PbWO$_4$ (lead tungstate)
  - very high Z
  - very poor light yield (OK if high energy)

- detector PANDA experiment
- electromagnetic calorimeter
- 15 552 PbWO$_4$ crystals
  www-panda.gsi.de
Tl-activated inorganic scintillators

- slow and bright
- NaI(Tl)
  - most widely used scintillator
  - high light yield (38 000 photons/MeV)
  - $\tau = 230$ ns
- CsI(Tl)
  - 65 000 photons/MeV
  - $\tau = 0.68$ (64%), 3.34 (36%) $\mu$s
Ce-activated inorganic scintillators

• relatively fast ($\tau \sim 20-80$ ns) and bright
• examples:
  – GSO(Ce) (gadolinium silicate, $\text{Gd}_2\text{SiO}_5$)
  – LSO(Ce) (lutetium oxyorthosilicate, $\text{Lu}_2\text{SiO}_5$)
  – $\text{LaCl}_3$(Ce), $\text{LaBr}_3$(Ce)
Glass scintillators

- containing Li or B and activated with Ce
- for neutron detection
  - enriched to ~95% $^6$Li:
    - $^6$Li(n,$\alpha$)$^3$H with $\alpha$, $^3$H being detected
    - $Q = 4.78$ MeV $\rightarrow$ detected energy = neutron energy + 4.78 MeV
Scintillators: light yield (output) / efficiency

- mostly: \( \sim 3 \times \) band gap for 1 electron-hole pair
- “quenching”:
  - non-radiative de-excitation modes
    - e.g. lattice vibrations, heat, impurity-related effects
  - phosphorescence (in pulse mode operation)
Scintillation efficiency vs. particle type, energy

- Scintillation efficiency decreases with increasing ionisation density along particle track
  - Scintillation efficiency depends on
    - Particle type
    - Energy → non-linear response
- Typically worse in organic scintillators

Figure 8.3: The scintillation light yield for a common plastic scintillator (NE 102) when excited by electrons and protons. The data are fit by curves from Eq. (8.3) (one parameter) and Eq. (8.9) (two parameter). (From Craun and Smith.36)

Figure 8.8: The relative scintillation response per unit energy deposited for fast electrons plotted as a function of energy for the scintillation materials shown. The curves are normalized to unity at 445 keV. Perfectly linear response would correspond to a horizontal line on this plot. (From Mengesha et al.80)
Scintillators: time response

- normally, decay time ($\tau_D$) is often adequate
- for the fastest scintillators, rise time is important
  - 2 parametrizations of rising edge:
    - exponential (time constant $\tau_R$)
    - gaussian (standard deviation $\sigma_R$)
  - more practical: FWHM

$$I = I_0 e^{-t/\tau_D}$$

$$I = I_0 \left( e^{-t/\tau_D} - e^{-t/\tau_R} \right)$$

$$I = I_0 g(t) \otimes e^{-t/\tau_D}$$

![Graph showing light intensity over time with parameters $\tau_D$, $\tau_R$, $\sigma_R$, and FWHM.]

<table>
<thead>
<tr>
<th>Properties of NE111 (a.k.a. Pilot U)</th>
</tr>
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<tbody>
<tr>
<td>$\tau_D$</td>
</tr>
<tr>
<td>$\tau_R$</td>
</tr>
<tr>
<td>$\sigma_R$</td>
</tr>
<tr>
<td>FWHM</td>
</tr>
</tbody>
</table>
Pulse shape discrimination

- organic scintillators
- fast and slow component
- slow component intensity depends on particle type (for same energy)
- basis for pulse shape discrimination

Figure 8.1 Energy levels of an organic molecule with π-electron structure. (From J. B. Birks, *The Theory and Practice of Scintillation Counting*. Copyright 1964 by Pergamon Press, Ltd. Used with permission.)

Figure 8.5 The time dependence of scintillation pulses in stilbene (equal intensity at time zero) when excited by radiations of different types. (From Bollinger and Thomas.)
Temperature dependence

- many scintillators show temperature dependence of
  - scintillation efficiency (light output)
  - decay constant

Figure 8.12 The dependence of the light output of some common scintillators as a function of temperature. Only the fast (220 nm) component from BaF$_2$ is included (From Melcher.$^{97}$)
# Properties of some organic scintillators

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Light Output % Anthracene*</th>
<th>Wavelength of Max Emission (nm)</th>
<th>Decay Constant (ns)</th>
<th>Attenuation Length (cm)</th>
<th>Refractive Index</th>
<th>H/C Ratio</th>
<th>Density</th>
<th>Loading Element % by weight or dist. feature</th>
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*NaI(Tl) is 230% on this scale
Properties of some inorganic scintillators

<table>
<thead>
<tr>
<th>Alkali Halides</th>
<th>Specific Gravity</th>
<th>Wavelength of Max. Emission</th>
<th>Refractive Index</th>
<th>Decay Time (μs)</th>
<th>Abs. Light Yield in Photons/MeV</th>
<th>Relative Pulse Height Using Bialk. PM tube</th>
<th>References</th>
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<tbody>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>415</td>
<td>1.85</td>
<td>0.23</td>
<td>38 000</td>
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<td>CsI(Tl)</td>
<td>4.51</td>
<td>540</td>
<td>1.80</td>
<td>0.68 (64%), 3.34 (36%)</td>
<td>65 000</td>
<td>0.49</td>
<td>78, 90, 91</td>
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<td>CsI(Na)</td>
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<td>0.46, 4.18</td>
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<td>1.4</td>
<td>11 000</td>
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| Other Slow Inorganics   |                  |                             |                  |                |                               |                                          |            |
|-------------------------|                  |                             |                  |                |                               |                                          |            |
| BGO                     | 7.13             | 480                         | 2.15             | 0.30           | 8200                          | 0.13                                     |            |
| CdWO₄                   | 7.90             | 470                         | 2.3              | 1.1 (40%), 14.5 (60%) | 15 000                        | 0.4                                      | 98–100     |
| ZnS(Ag) (polycrystalline)| 4.09             | 450                         | 2.36             | 0.2            |                               |                                          |            |
| CaF₂ (Eu)               | 3.19             | 435                         | 1.47             | 0.9            | 24 000                        | 0.5                                      |            |

| Unactivated Fast Inorganics |                  |                             |                  |                |                               |                                          |            |
|----------------------------|                  |                             |                  |                |                               |                                          |            |
| BaF₂ (fast component)      | 4.89             | 220                         | 1.56             | 0.0006         | 1400                          | na                                       | 107–109    |
| BaF₂ (slow component)      | 4.89             | 310                         | 1.56             | 0.63           | 9500                          | 0.2                                      | 107–109    |
| CsI (fast component)       | 4.51             | 305                         | 1.80             | 0.002 (35%), 0.02 (65%) | 2000                          | 0.05                                     | 113–115    |
| CsI (slow component)       | 4.51             | 450                         | 1.80             | multiple, up to several μs | varies                        | varies                                    | 114, 115   |
| CeF₃                     | 6.16             | 310, 340                    | 1.68             | 0.005, 0.027   | 4400                          | 0.04 to 0.05                             | 76, 116, 117 |

| Cerium-Activated Fast Inorganics |                  |                             |                  |                |                               |                                          |            |
|---------------------------------|                  |                             |                  |                |                               |                                          |            |
| GSO                             | 6.71             | 440                         | 1.85             | 0.056 (90%), 0.4 (10%) | 9000                          | 0.2                                      | 119–121    |
| YAP                             | 5.37             | 370                         | 1.95             | 0.027          | 18 000                        | 0.45                                     | 78, 125    |
| YAG                             | 4.56             | 550                         | 1.82             | 0.088 (72%), 0.302 (28%) | 17 000                        | 0.5                                      | 78, 127    |
| LSO                             | 7.4              | 420                         | 1.82             | 0.047          | 25 000                        | 0.75                                     | 130, 131   |
| LuAP                           | 8.4              | 365                         | 1.94             | 0.017          | 17 000                        | 0.3                                      | 134, 136, 138 |

| Glass Scintillators            |                  |                             |                  |                |                               |                                          |            |
|--------------------------------|                  |                             |                  |                |                               |                                          |            |
| Ce activated Li glass⁺         | 2.64             | 400                         | 1.59             | 0.05 to 0.1    | 3500                          | 0.09                                     | 77, 145    |
| Tb activated glass⁺           | 3.03             | 550                         | 1.5              | ~3000 to 5000  | ~50 000                       | na                                       | 145        |

| For comparison, a typical organic (plastic) scintillator: |                  |                             |                  |                |                               |                                          |            |
|----------------------------------------------------------|                  |                             |                  |                |                               |                                          |            |
| NE102A                                                   | 1.03             | 423                         | 1.58             | 0.002          | 10 000                        | 0.25                                     |            |

⁺for alpha particles

⁺Properties vary with exact formulation. Also see Table 15.1.
Photosensors

• purpose: transform scintillation light to an electric signal
• two steps:
  1. photon → electron
  2. electron multiplication
• parameters
  – efficiency (wavelength dependent) (step 1.)
  – gain (step 2.)
  – time response (step 2.)
• types
  – photomultiplier tube (PMT)
    • “conventional”
    • MCP-based
  – photodiode (PD)
    • conventional
    • avalanche photodiode (APD)
    • Gieger-mode APD (silicon photomultiplier)
The photomultiplier tube: principle
The photoemission process

1. photon excites an electron to the conduction band
   • photon energy (typically 2-3 eV) > band gap

2. electron migrates to the surface
   • energy loss determines escape depth (up to ~25 nm)
   • semi-transparent to photons

3. electron escapes from the surface
   • electron needs to overcome the electron affinity (surface barrier)
   • suitable semiconductor: 1.5-2 eV
     • high thermoionic noise (‘dark current’)
   • low-energy (long-wavelength) cut-off for incoming photons
     (usually red or near-infrared)

Figure 9.4 Band structure near the surface for conventional semiconductors
(Adapted from Krall et al.6)
The photoemission process

1. photon excites an electron to the conduction band
   • photon energy (typically 2-3 eV) > band gap
2. electron migrates to the surface
   • energy loss determines escape depth (up to ~25 nm)
   • semi-transparent to photons
3. electron escapes from the surface
   • electron needs to overcome the electron affinity (surface barrier)
   • suitable semiconductor: 1.5-2 eV
     • high thermoionic noise (“dark current”)
   • low-energy (long-wavelength) cut-off for incoming photons
     (usually red or near-infrared)
   • negative electron affinity (NEA) materials are superior
sensitivity of photocathodes:
1. (radiant) sensitivity, responsivity
current per unit light flux [Amperes/Watt, Amperes/lumen]
2. quantum efficiency (QE)

\[ QE = \frac{\text{number of photoelectrons emitted}}{\text{number of incident photons}} \]

strong function of wavelength

window transmittance usually included in sensitivity
PMT window transmittance

Figure 4-5: Spectral transmittance of window materials
Photocathodes spectral response

Figure 4-2 (b): Typical spectral response characteristics of transmission mode photocathodes
Secondary electron emission

- similar process to photoemission
- multiple electrons emitted per incident electron
  - secondary emission ratio $\delta$

Figure 9.3 Variation of the secondary emission yield with primary electron energy for standard dynode materials (lower three curves) and an NEA material [GaP(Cs)]. (From Krall et al.\textsuperscript{6})

- multiple (N) dynodes: overall gain = $\delta^N$
- in practice overall gain up to $\sim 10^7$
Figure 4-13: Gain vs. supply voltage
The MCP-PMT

- hollow glass tube
- inner surface is secondary electron emitter
- voltage across tube pushes electrons through microchannel plate (MCP)

- channel diameter: 15-50 μm
- excellent timing: TTS ~100 ps

Figure 9.8 Continuous channel electron multiplier.

Figure 9.9 Elements of a PM tube based on microchannel plate electron multiplication.
PMT pulse timing properties

Figure 9.10 The response of a PM tube to a short pulse of light on the photocathode.

timing performance depends on transit time spread (TTS)
PMTs come in all shapes and sizes

(1) Circular-cage Type
(2) Box-and-grid Type
(3) Linear-focused Type
(4) Venetian Blind Type
(7) Metal Channel Dynode Type
PMTs come in all shapes and sizes
The conventional photodiode

- a.k.a. silicon photodiode
- absorption of photons in Si: window $350 < \lambda < 1000$ nm
- no internal amplification: small signal to noise ratio
  - requires a low-noise amplifier
  - leakage current and noise limit the area to $1$ cm$^2$
  - cooling reduces leakage current exponentially

Figure 9.14 Basic configuration of a conventional photodiode.
Photodiode quantum efficiency

no electron escape needed
(as in conventional photocathode)
• quantum efficiency up to 80%
• broader spectral response than PMT

Figure 9.15 A comparison of the quantum efficiency of a silicon photodiode (labeled #458) with representative bialkali and S-20 photomultiplier quantum efficiencies. The emission spectrum from a BGO scintillator is shown for reference. (From Groom.63)
The avalanche photodiode (APD)

- in the high-field region, additional e-h pairs are created
  - avalanche process leads to a gain of up to few 100
  - gain very sensitive to applied voltage and temperature (few %/K)

Figure 9.17 The reach-through configuration for an avalanche photodiode is sketched at the top of the figure. Below is a plot of the resulting electric field when a bias voltage is applied.
• operation voltage above a threshold: breakdown
  – “Geiger” discharge
• output pulse size is independent of light intensity
  – no energy determination
The Geiger-mode APD (silicon photomultiplier)

- discharge needs to be quickly quenched
- many small pixels (100-1600 /mm²) recovers dynamic range
- high-gain: $10^5$-$10^6$
- excellent timing
- low noise (single photon detection)
The Geiger-mode APD (silicon photomultiplier)
SiPM performance: single photon counting
SiPM performance: timing

coincidence timing resolution for 511 keV gamma’s: 100 ps
## Comparison photosensors

<table>
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<th>PMT</th>
<th>APD</th>
<th>SiPM</th>
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scintillators are versatile but complicated