Scintillation detectors

- incoming radiation (charged particle, $\gamma$-rays) creates excited states in atoms or molecules.
- excited states decay via emission of photons, typically in visible range.
- photons are detected and converted into electrical signals

requirements at scintillation material:
- high light output
- linear conversion: particle energy – number of photons
- transparent medium, no self absorption
- short life time of excited states -> timing properties
- optical quality, light collection at large dimensions
- refraction index (close to glass)
Scintillation detectors

Abb. 5-24. Elektronenverteilung in Butadien. (a) Lokalisierte $\sigma$-Bindungen; (b) unlokalierte $\pi$-Bindungen.

Abb. 5-28. Molekülorbitale für Benzol. (a) Lokalisierte $\sigma$-Bindungen; (b) unlokalierte $\pi$-Bindungen.
Organic scintillator:

- Energy levels of individual molecules, no interactions with neighbour. Material can be solid (powder), fluid, gaseous.

- Radiation populates states in $S_1$ band

- Radiation less decay in $S_1$ band head

- Decay in $S_0$ band light emission

- Decays in triplet state slow decays
Scintillation detectors

important: emitted light should not be re-absorbed!

Raleigh Stokes Anti-Stokes

Absorption or emission intensity

Absorption

Emission

Stokes shift

Wavelength $\lambda$

Photon energy $h\nu$
Loss process: width of absorption- and emission spectrum depends on level density in minimum a and minimum b. Both minima must be sufficiently separated.

With growing temperature the regions increase and cause more overlap.

⇒ reduced light output with increasing temperature
Scintillation detectors

Timing properties
- radiationless decays: 0.2 – 0.4 ns
- fluorescence \( S_1 \rightarrow S_0 \): 1 – 3 ns

rise time: \( I(t) \propto 1 - e^{-t/\tau_{n.r.}} \)
decay time: \( I(t) \propto e^{-t/\tau_f} \)
puls shape: \( I(t) = I_0 (e^{-t/\tau_f} - e^{-t/\tau_{n.r.}}) \)

<table>
<thead>
<tr>
<th>Material</th>
<th>State</th>
<th>( \lambda_{\text{max}} ) [nm]</th>
<th>( \tau_f ) [ns]</th>
<th>( \rho ) [g/cm(^3)]</th>
<th>photons/MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthracene</td>
<td>crystal</td>
<td>447</td>
<td>30</td>
<td>1.25</td>
<td>1.6 \cdot 10^4</td>
</tr>
<tr>
<td>Pilot U</td>
<td>plastic</td>
<td>391</td>
<td>1.4</td>
<td>1.03</td>
<td>1.0 \cdot 10^4</td>
</tr>
<tr>
<td>NE104</td>
<td>plastic</td>
<td>406</td>
<td>1.8</td>
<td>1.03</td>
<td>1.0 \cdot 10^4</td>
</tr>
<tr>
<td>NE102</td>
<td>liquid</td>
<td>425</td>
<td>2.6</td>
<td>1.51</td>
<td>1.2 \cdot 10^4</td>
</tr>
</tbody>
</table>
Scintillation detectors

Light yield and decay time depend on ionisation density.

**Light yield**

**Decay time**

-> effect is used for particle identification!
Anorganic scintillator

- higher $Z$
- higher density
- higher stopping power
- highest light output

**Isolator:**
energy gap $>> kT$, no electrons in conduction band. Radiation excites electrons from valence band into conduction band and creates electron-hole-pairs.

electrons in conduction band and holes in valence band move freely through crystal.
Scintillation detectors

Example: sodium iodid NaJ
- isolator with band gap 7eV
- scintillates in pure state at low temperature
- replace 0.1% of Na atoms by thallium
- moves energy in visible range
- higher light yield
- reduced self absorption
- excitons are created
- excitons move through crystal until absorption by Tl center
- emission of luminiscence photons (3 eV~400 nm)
- material is transparent in this wave length range
## Scintillation detectors

<table>
<thead>
<tr>
<th>Material</th>
<th>Form</th>
<th>$\lambda_{\text{max}}$ (nm)</th>
<th>$\tau_f$ (ns)</th>
<th>$\rho$ (g/cm³)</th>
<th>Photons per MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl) (20°C)</td>
<td>crystal</td>
<td>415</td>
<td>230</td>
<td>3.67</td>
<td>38,000</td>
</tr>
<tr>
<td>pure NaI (-196°C)</td>
<td>crystal</td>
<td>303</td>
<td>60</td>
<td>3.67</td>
<td>76,000</td>
</tr>
<tr>
<td>Bi₄Ge₃O₁₂ (20°C)</td>
<td>crystal</td>
<td>480</td>
<td>300</td>
<td>7.13</td>
<td>8,200</td>
</tr>
<tr>
<td>Bi₄Ge₃O₁₂ (-100°C)</td>
<td>crystal</td>
<td>480</td>
<td>2000</td>
<td>7.13</td>
<td>24,000</td>
</tr>
<tr>
<td>CsI(Na)</td>
<td>crystal</td>
<td>420</td>
<td>630</td>
<td>4.51</td>
<td>39,000</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>crystal</td>
<td>540</td>
<td>800</td>
<td>4.51</td>
<td>60,000</td>
</tr>
<tr>
<td>CsI (pure)</td>
<td>crystal</td>
<td>315</td>
<td>16</td>
<td>4.51</td>
<td>2,300</td>
</tr>
<tr>
<td>CsF</td>
<td>crystal</td>
<td>390</td>
<td>2</td>
<td>4.64</td>
<td>2,500</td>
</tr>
<tr>
<td>BaF₂ (slow)</td>
<td>crystal</td>
<td>310</td>
<td>630</td>
<td>4.9</td>
<td>10,000</td>
</tr>
<tr>
<td>BaF₂ (fast)</td>
<td>crystal</td>
<td>220</td>
<td>0.8</td>
<td>4.9</td>
<td>1,800</td>
</tr>
<tr>
<td>Gd₂SiO₅(Ce)</td>
<td>crystal</td>
<td>440</td>
<td>60</td>
<td>6.71</td>
<td>10,000</td>
</tr>
<tr>
<td>CdWO₄</td>
<td>crystal</td>
<td>530</td>
<td>15000</td>
<td>7.9</td>
<td>7,000</td>
</tr>
<tr>
<td>CaWO₄</td>
<td>crystal</td>
<td>430</td>
<td>6000</td>
<td>6.1</td>
<td>6,000</td>
</tr>
<tr>
<td>CeF₃</td>
<td>crystal</td>
<td>340</td>
<td>27</td>
<td>6.16</td>
<td>4,400</td>
</tr>
<tr>
<td>PbWO₄</td>
<td>crystal</td>
<td>460</td>
<td>2, 10, 38</td>
<td>8.2</td>
<td>500</td>
</tr>
</tbody>
</table>
Scintillation detectors

temperature dependence of light yield

Scintillators require:
- careful calibration and inspection
- temperature stabilisation
Scintillation detectors

Photo multiplier:
conversion of scintillation light
=> electron signal
quantum efficiency Q.E.

\[
Q.E. = \frac{\text{# emitted photo electrons}}{\text{# incoming photons}}
\]

<table>
<thead>
<tr>
<th>photo cathode</th>
<th>Q.E.</th>
<th>( \lambda_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgOCs</td>
<td>0.4%</td>
<td>800 nm</td>
</tr>
<tr>
<td>BiAgOCs</td>
<td>7%</td>
<td>420 nm</td>
</tr>
<tr>
<td>Cs(_3)SbO</td>
<td>21%</td>
<td>390 nm</td>
</tr>
<tr>
<td>Na(_2)Ksbc</td>
<td>22%</td>
<td>380 nm</td>
</tr>
<tr>
<td>K(_2)CsSb</td>
<td>27%</td>
<td>380 nm</td>
</tr>
<tr>
<td>Na(_2)Ksb</td>
<td>21%</td>
<td>360 nm</td>
</tr>
<tr>
<td>KCsRbSb</td>
<td>24%</td>
<td>440 nm</td>
</tr>
<tr>
<td>RbCsSb</td>
<td>25%</td>
<td>450 nm</td>
</tr>
<tr>
<td>CeTe</td>
<td>18%</td>
<td>200 nm</td>
</tr>
<tr>
<td>CsI</td>
<td>15%</td>
<td>135 nm</td>
</tr>
</tbody>
</table>
Scintillation detectors

photo multiplier tube
conversion scintillation light
-> electrical signal

- match to detector
- photo cathode
- focusing electrode
- accelerating field
- dynode structure
- anode
Scintillation detectors

Spectral distribution of different scintillator materials and spectral sensitivity of photo cathodes
Photo cathode:  
- low work function for electrons
- thin layers of semiconductor, antimony alkali compounds
(1) excitation from incoming photon
(2) deexcitation via lattice, phonons (~1ps)
(3) recombination

Electrons can move to surface and (2') electrons above $E_A$ are emitted
Photo cathode: - thin surface of electro positive material (Cs) onto doped semiconductor (GaP + acceptor) -> negative electron affinity material
- (1) photon excitation
- (2) deexcitation via phonons (~1ps)
- (3) vacuum emission, Q.E. ~ 80% !!!

- used also for dynode material
Scintillation detectors

Equipotential line and electron trajectory in photo multiplier
Scintillation detectors

- Secondary multiplication by dynodes

- Similar process like at photo cathode, incoming particle is electron

- Typical materials: BeO(Cs), Cs$_3$Sb, MgO
Magnetic fields affect amplification of Photo Multiplier Tube, Properties depend on orientation of B-field.
-> protection, shielding with μ-metall

Timing properties depend on dynode configuration.
- typical time from photo cathode to anode ~30 ns
- typical rise time ~1.5 – 2.0 ns
- two coincident PMTs with ~1500 photo electrons allow a timing resolution of ~200 - 250 ps.
- Special dynode structure to minimize broadening.
Scintillation detectors

Continuous multiplier structure: Micro channel plates

Two staged micro channel plate detector

⇒ position sensitive detection of photons
Signal yield is determined by:
- *Light collection (isotropic emission of light) in crystal affected by reflection and total reflection at surfaces* ➞ *reflecting material around crystal*
  ➞ *no difference in diffraction index*
  (matter between crystal and entrance window of PMT)

- *High transmission through entrance glass window of PMT*

- *High photon absorption in photo cathode material* ➞ *adapt the wave length \( \lambda \):*

- *High transmission of photo electrons through cathode*

- *Electron focus at first dynode*
Scintillation detectors

Signal development
1. $E$ absorption in scintillator

2. Population of excited states
time constant

3. Decay of states -> photons
time constant, absorption, reflection in crystal

4. Absorption in photo cathode
   -> Photo electrons
   transmission in glass, absorption in cathode, quantum efficiency

5. Multiplication of photo electrons

example:
511 keV in NaI

determines error!

25000 photons @ crystal

15000 photons @

3000 electrons @ first dynode

$3 \times 10^9$ electrons @ anode ($\sim 2 mA$)
**Light guide**

*Photo multiplier are often coupled by light guide to scintillator.*

**basic principal:** total reflection at surface of light guide

**efficiency of light guide is limited by:**

- **angle of total reflection**

\[
F = \frac{\Omega}{4\pi} = \frac{1}{4\pi} \int_0^{\phi_c} 2\pi \sin \phi \, d\phi =
\]

\[
\frac{1}{2} (1 - \cos \phi_c) = \frac{1}{2} (1 - \sin \theta_c) =
\]

\[
\frac{1}{2} \left( 1 - \frac{n_1}{n_0} \right)
\]

*air* \(n_1 \sim 1\) and \(n_0 \sim 1.5\)

\[\Rightarrow \quad F = 0.167\]
Scintillation detectors

Improved timing resolution is achieved when the light path is constant for all light guides.
Applications of scintillators in nuclear and high energy physics

- high efficiency, low resolution $\gamma$-spectroscopy

- time of flight TOF measurements

- particle calorimetry, kinetic energy

- electromagnetic shower detector

- hadron spectroscopy
PRESPEC fast beam set-up at GSI

$^{36}\text{Ar}$ 450 MeV/u
~ $2\times10^{10}$ pps

$^9\text{Be}$ 4 g/cm$^2$
production target

$^{197}\text{Au}$ 0.4 g/cm$^2$
secondary target

MUSIC
ionization chamber

HECTOR
BaF$_2$ detectors

LYCCA
Scint, Si, CsI
Z, A, (X, Y), TOF

EB-Cluster
Ge detector
LYCCA – detection principle

**Secondary target**

- Plastic Scintillator
- DSSD
- Diamond

- CsI scintillator

**Time of Flight**

- \((x, y)\)
- \((\Delta E, x, y)\)
- \((E)\)
TOF

Intrinsic timing resolution: 12.5 ps FWHM

Exp. TOF resolution: 27 ps FWHM

2 mm BC 420 - 32 PMT
**ΔE - Detector**

DSSD, 58 × 58 mm², 310 μm, 32 Strips per side

**E - Detector**

9 CsI-Scintillators, 19 × 19 mm², 10 oder 33 mm APD-readout
Avalanche photo diode APD

$p^+$-doped side and intrinsic Si is used for light absorption, electron hole generation.

A absorption and collection region

At pn junction the reverse voltage cause acceleration in high $E$ field of electron into

$M$ multiplication region

High electric field strength cause secondary charge carriers by ionisation and secondary amplification.

Operation voltage of several 100V close to break through.

$M = 100...500$ multiplication factor
### Scintillation crystals for calorimetry

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Density g/cm$^3$</th>
<th>Refractive index</th>
<th>Radiation Length cm</th>
<th>Moliere Radius cm</th>
<th>$\lambda_{\text{max}}$ nm</th>
<th>Light yield %NaI(Tl)</th>
<th>Decay time ns</th>
<th>dLY/dT %/°C</th>
<th>Melting point °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>1.85</td>
<td>2.59</td>
<td>4.13</td>
<td>410</td>
<td>100</td>
<td>230</td>
<td>~0</td>
<td>651</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>4.51</td>
<td>1.79</td>
<td>1.86</td>
<td>3.57</td>
<td>560</td>
<td>165</td>
<td>1250</td>
<td>0.3</td>
<td>621</td>
</tr>
<tr>
<td>CsI</td>
<td>4.51</td>
<td>1.95</td>
<td>1.86</td>
<td>3.57</td>
<td>420 310</td>
<td>3.6 1.1</td>
<td>30 6</td>
<td>-0.6</td>
<td>621</td>
</tr>
<tr>
<td>BaF$_2$</td>
<td>4.89</td>
<td>1.50</td>
<td>2.03</td>
<td>3.10</td>
<td>300 220</td>
<td>36 3.4</td>
<td>630 0.9</td>
<td>~2</td>
<td>~0</td>
</tr>
<tr>
<td>CeF$_3$</td>
<td>6.26</td>
<td>1.62</td>
<td>1.70</td>
<td>2.41</td>
<td>300</td>
<td>7.3</td>
<td>30</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>BGO (Bi$_3$Ge$<em>3$O$</em>{12}$)</td>
<td>7.13</td>
<td>2.15</td>
<td>1.12</td>
<td>2.23</td>
<td>480</td>
<td>21</td>
<td>300</td>
<td>-1.6</td>
<td>1050</td>
</tr>
<tr>
<td>PWO (PbWO$_4$)</td>
<td>8.3</td>
<td>2.20</td>
<td>0.89</td>
<td>2.00</td>
<td>425 420</td>
<td>0.29 0.083</td>
<td>30 6</td>
<td>-1.9</td>
<td>1123</td>
</tr>
<tr>
<td>LSO (Lu$_2$SiO$_5$:Ce)</td>
<td>7.40</td>
<td>1.82</td>
<td>1.14</td>
<td>2.07</td>
<td>420</td>
<td>84</td>
<td>42</td>
<td>~0</td>
<td>2050</td>
</tr>
<tr>
<td>GSO (Gd$_2$SiO$_5$:Ce)</td>
<td>6.71</td>
<td>1.85</td>
<td>1.38</td>
<td>2.23</td>
<td>440</td>
<td>30</td>
<td>60</td>
<td>-0.1</td>
<td>1950</td>
</tr>
</tbody>
</table>
# High Energy Physics Crystal Calorimeters

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Crystal Ball, SPEAR, BINP Novosibirsk</th>
<th>SND, LEP, CERN</th>
<th>L3, Tevatron, Fermilab</th>
<th>KTeV, SLAC</th>
<th>CLEO c, CESR, Cornell</th>
<th>BABAR, PEP II</th>
<th>BELLE, KEK B</th>
<th>BELLE, KEK B</th>
<th>CMS, LHC, CERN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>75–85</td>
<td>90–15</td>
<td>80–00</td>
<td>96–00</td>
<td>80–08</td>
<td>94–08</td>
<td>94–18</td>
<td>95–20</td>
<td></td>
</tr>
<tr>
<td>Crystal</td>
<td>NaI(Tl)</td>
<td>NaI(Tl)</td>
<td>BGO</td>
<td>CsI(Tl)</td>
<td>CsI(Tl)</td>
<td>CsI(Tl)</td>
<td>PbWO₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N crystals</td>
<td>672</td>
<td>1640</td>
<td>11400</td>
<td>3260</td>
<td>7800</td>
<td>6580</td>
<td>8800</td>
<td>76000</td>
<td></td>
</tr>
<tr>
<td>Inner radius (m)</td>
<td>0.254</td>
<td>0.25</td>
<td>0.55</td>
<td>-</td>
<td>1.0</td>
<td>0.9</td>
<td>1.25</td>
<td>1.29</td>
<td></td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
<td>7</td>
<td>5.9</td>
<td>9.5</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Thickness (X₀)</td>
<td>16</td>
<td>13.4</td>
<td>22</td>
<td>27</td>
<td>16</td>
<td>16–17.5</td>
<td>16.2</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Photo sensor</td>
<td>PMT</td>
<td>VPT</td>
<td>Si PD</td>
<td>PMT</td>
<td>Si PD</td>
<td>Si PD</td>
<td>Si PD</td>
<td>APD, VPT</td>
<td></td>
</tr>
<tr>
<td>Noise (MeV)</td>
<td>0.05</td>
<td>0.2</td>
<td>0.8</td>
<td>-</td>
<td>0.5</td>
<td>0.15</td>
<td>0.2</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Dynamic range</td>
<td>10⁴</td>
<td>10³</td>
<td>10⁵</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁵</td>
<td></td>
</tr>
</tbody>
</table>
Crystal Ball Detector

first large-scale crystal calorimeter in high energy physics
NaI(Tl) calorimeter Crystal Ball detector
Crystal Ball NaI(Tl) Calorimeter

Number of crystals 672
Inner radius 25.4 cm
Outer radius 66.0 cm
Thickness 16 $X_0$
Solid angle coverage 93%
Photodetector PMT
Noise 0.05 MeV
Dynamic range $10^4$

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt[4]{E(\text{GeV})}}$$

Inclusive photon spectrum at $\psi(2S)$ resonance
SND detector
1 – Be vacuum chamber
2 – tracking system
3 – aerogel Cherenkov counters
4 – NaI(Tl) scintillation counters
5 – vacuum phototriodes
6 – iron absorber
7,8 – muon system.
SND NaI(Tl) calorimeter

SND calorimeter geometry

SND calorimeter segment

Number of crystals - 1632, thickness – 13.5 $X_0$, mass – 3.5 tons
Photodetectors – vacuum phototriodes with photocathode quantum efficiency of ~15% and gain ~10.
L3 BGO calorimeter

Number of crystals:
- Barrel – 7680
- Endcaps – 2×1527

Thickness – 22X₀

Photo detector – Si PD

L3 detector at LEP 1980-2000
CLEO-c CsI(Tl) calorimeter

- Number of crystals 7784:
  - Barrel – 6144
  - Endcaps – 2 × 820
- Crystal size – 5 × 5 × 30 cm³
- Thickness – 16.2 X₀
- Inner radius – 1.02 m
- Barrel length – 3.26 m
- Total CsI(Tl) mass – 27000 kg
- Solid angle coverage – 95%
- Photodetector Si photodiode (4 per crystal)
- Material in front of the barrel part – 0.18 X₀

- installed 1990
- **Improved endcap**
- photon det.
- electron ID
- Trigger
- Luminosity
- π⁰, η
- missing E
Spectroscopy of $\gamma$-decays from $\psi(2S)$

- $\pi^0 \rightarrow \gamma \gamma$
- $\eta \rightarrow \gamma \gamma$
- $\mu^+ \mu^- \gamma$
- $\psi(2S) \rightarrow \gamma \chi_{cJ}$

Fit huge combinatoric background & subtract
Number of crystals: 6580
Thickness: 16 - 17.5 \( X_0 \)
Inner radius: 0.92 m
Length: 2.9 m
Solid angle coverage: 90%
Construction Overview

Submodule
10 crystals

Module

Dee

Barrel
61,200 PbWO$_4$ crystals
Readout with 122,400 APD’s

Endcap
14684 crystals readout with VPT’s.
CMS detector
Outlook

NaI detector (scintillator)

Ge detector (semiconductor) for $\gamma$-ray spectroscopy