Topics of this lecture

- Inorganic scintillators
- Organic scintillators
- Geometries and readout
- Fiber tracking
- Photo detectors
Scintillation

Energy deposition by ionizing particle
→ production of scintillation light (luminescence)

Scintillators are multi purpose detectors

- calorimetry
- time of flight measurement
- tracking detector (fibers)
- trigger counter
- veto counter
  .....

Two material types: Inorganic and organic scintillators

- high light output but slow
- lower light output but fast
Three different scintillation mechanisms:

1a. Inorganic crystalline scintillators (NaI, CsI, BaF$_2$...)

Often $\geq 2$ time constants:
- Fast recombination (ns-$\mu$s) from activation centre
- Delayed recombination due to trapping ($\approx 100$ ms)

Due to the high density and high Z inorganic scintillator are well suited for detection of charged particles, but also of $\gamma$. 
Light output of inorganic crystals shows strong temperature dependence

![Graph showing relative light output percent against crystal temperature in degrees centigrade.](From Harshaw catalog)

1b. Liquid noble gases (LAr, LXe, LKr)

- **Excitation**: \( A^+ \)
- **Collision with g.s. atoms**: \( A_2^{*} \)
- **Ionization**: \( A^- \)
- **Excited molecule**: \( A_2^{*} \)
- **De-excitation and dissociation**: \( A \)
- **Ionized molecule**: \( A_2^- \)
- **Recombination**: \( e^- \)

Also here one finds 2 time constants: few ns and 100-1000 ns, but same wavelength.
**Properties of some inorganic scintillators**

<table>
<thead>
<tr>
<th>scintillator composition</th>
<th>density (g/cm$^3$)</th>
<th>index of refraction</th>
<th>wavelength of maximum emission (nm)</th>
<th>decay time constant (µs)</th>
<th>scintillation pulse height$^1$ ($\times 10^4$)</th>
<th>notes</th>
<th>Photons/MeV</th>
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<tbody>
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<td>3.67</td>
<td>1.78</td>
<td>303</td>
<td>0.06</td>
<td>190</td>
<td>2)</td>
<td>4 x 10^4</td>
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<td>NaI(Tl)</td>
<td>3.67</td>
<td>1.85</td>
<td>410</td>
<td>0.25</td>
<td>100</td>
<td>3)</td>
<td>1.1 x 10^4</td>
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<tr>
<td>CsI</td>
<td>4.51</td>
<td>1.80</td>
<td>310</td>
<td>0.01</td>
<td>6</td>
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<td>1.4 x 10^4</td>
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<td>4.51</td>
<td>1.80</td>
<td>565</td>
<td>1.0</td>
<td>45</td>
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<td>1.4 x 10^4</td>
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<td>4.51</td>
<td>1.84</td>
<td>420</td>
<td>0.63</td>
<td>85</td>
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<tr>
<td>KI(Tl)</td>
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<td>1.71</td>
<td>410</td>
<td>0.24/2.5</td>
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<td>$^{6}$Li(Eu)</td>
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<td>1.96</td>
<td>470-485</td>
<td>1.4</td>
<td>35</td>
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<td>CaF$_2$(Eu)</td>
<td>3.19</td>
<td>1.44</td>
<td>435</td>
<td>0.9</td>
<td>50</td>
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<tr>
<td>BaF$_2$</td>
<td>4.88</td>
<td>1.49</td>
<td>190/220 310</td>
<td>0.0006</td>
<td>5</td>
<td>5</td>
<td>6.5 x 10^3</td>
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<tr>
<td>Bi$_4$Ge$<em>3$O$</em>{12}$</td>
<td>7.13</td>
<td>2.15</td>
<td>480</td>
<td>0.30</td>
<td>10</td>
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<td>2 x 10^3</td>
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<td>CaWO$_4$</td>
<td>6.12</td>
<td>1.92</td>
<td>430</td>
<td>0.5/20</td>
<td>50</td>
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<td>2.8 x 10^3</td>
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<tr>
<td>ZnWO$_4$</td>
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<td>CdWO$_4$</td>
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<td>540</td>
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<tr>
<td>CsF</td>
<td>4.65</td>
<td>1.48</td>
<td>390</td>
<td>0.005</td>
<td>5</td>
<td>3)</td>
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<td>CeF$_3$</td>
<td>6.16</td>
<td>1.68</td>
<td>300/340</td>
<td>0.005/0.020</td>
<td>5</td>
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<tr>
<td>ZnS(Ag)</td>
<td>4.09</td>
<td>2.35</td>
<td>450</td>
<td>0.2</td>
<td>150</td>
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<td>GSO</td>
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<td>440</td>
<td>0.060</td>
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<tr>
<td>ZnO(Ga)</td>
<td>5.61</td>
<td>2.02</td>
<td>385</td>
<td>0.0004</td>
<td>40</td>
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<td>420</td>
<td>0.035</td>
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<tr>
<td>YAP</td>
<td>5.50</td>
<td>1.9</td>
<td>370</td>
<td>0.030</td>
<td>40</td>
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1) relative to NaI(Tl)  2) at 80 K  3) hygroscopic  4) polycrystalline

PbWO$_4$ 8.28 1.82 440; 530 0.01 100

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>LAr</td>
<td>1.4</td>
<td>1.29$^5$</td>
<td>120-170</td>
<td>0.005 / 0.860</td>
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<tr>
<td>LKr</td>
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<td>1.40$^5$</td>
<td>120-170</td>
<td>0.002 / 0.085</td>
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<tr>
<td>LXe</td>
<td>3.06</td>
<td>1.60$^5$</td>
<td>120-170</td>
<td>0.003 / 0.022</td>
<td>4 x 10^4</td>
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</tbody>
</table>

$^5$ at 170 nm
Organic scintillators

2. Organic scintillators: Monocrystals or liquids or plastic solutions

Monocrystals: naphtalene, anthracene, p-terphenyl….

Liquid and plastic scintillators
They consist normally of a solvent + secondary (and tertiary) fluors as wavelength shifters.

Fast energy transfer via non-radiative dipole-dipole interactions (Förster transfer).
→ shift emission to longer wavelengths
→ longer absorption length and efficient read-out device

Scintillation is based on the 2 π electrons of the C-C bonds.

Emitted light is in the UV range.

Molecular states

Singlet states

<table>
<thead>
<tr>
<th>S_3</th>
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<tbody>
<tr>
<td>S_2</td>
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</tr>
<tr>
<td>S_1</td>
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</tr>
<tr>
<td>S_0</td>
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</table>

Triplet states

<table>
<thead>
<tr>
<th>T_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_1</td>
</tr>
</tbody>
</table>

Non-radiative transitions

Fluorescence
10^{-8} - 10^{-9} s

Phosphorescence
10^{-4} s

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<td>S_0</td>
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Some widely used solvents and solutes

<table>
<thead>
<tr>
<th></th>
<th>solvent</th>
<th>secondary fluor</th>
<th>tertiary fluor</th>
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<tr>
<td>Liquid scintillators</td>
<td>Benzene</td>
<td>p-terphenyl</td>
<td>POPOP</td>
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<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>Plastic scintillators</td>
<td>Polyvinylbenzene</td>
<td>p-terphenyl</td>
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<td></td>
<td>Polyvinyltoluene</td>
<td>DPO</td>
<td>TBP</td>
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<td></td>
<td>Polystyrene</td>
<td>PBD</td>
<td>BBO</td>
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<td></td>
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<td>DPS</td>
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After mixing the components together plastic scintillators are produced by a complex polymerization method.

Some inorganic scintillators are dissolved in PMMA and polymerized (plexiglas).
Organic scintillators have low Z (H,C). Low $\gamma$ detection efficiency (practically only Compton effect). But high neutron detection efficiency via (n,p) reactions.

### Table A6.3 Properties of some organic scintillators

<table>
<thead>
<tr>
<th>scintillator</th>
<th>density (g/cm$^3$)</th>
<th>index of refraction</th>
<th>wavelength of maximum emission (nm)</th>
<th>decay time constant (ns)</th>
<th>scintillation pulse height 1)</th>
<th>H/C ratio 2)</th>
<th>yield/NaI</th>
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<td>naphthalene</td>
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<td>348</td>
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<td>11</td>
<td>0.800</td>
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<td>anthracene</td>
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<td>448</td>
<td>30-32</td>
<td>100</td>
<td>0.714</td>
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<td>trans-stilbene</td>
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<td>384</td>
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<td>46</td>
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<td>p-terphenyl</td>
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<td>391</td>
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<td>30</td>
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<td>1.105</td>
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<td>0.995</td>
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1) relative to anthracene  
2) ratio of hydrogen to carbon atoms  
3) Nuclear Enterprises Ltd. Sighthill, Edinburgh, U.K.  
4) Bicron Corporation, Newbury, Ohio, USA
Scintillator readout

Readout has to be adapted to geometry and emission spectrum of scintillator.

**Geometrical adaptation:**

- Light guides: transfer by total internal reflection (+outer reflector)

**Diagram:**

- "fish tail" adiabatic
- Wavelength shifter (WLS) bars
Scintillator readout

- **Optical fibers**

  typ. 25 µm  
  typically <1 mm  

  ![Diagram of optical fibers](image)

  $\theta \geq \arcsin \frac{n_2}{n_1} \approx 69.6^\circ$  
  $\frac{d\Omega}{4\pi} = 3.1\%$  
  in one direction

  minimize $n_{\text{cladding}}$

  Ideal: air ($n=1$), but impossible due to surface imperfections

  **multi-clad fibres**

  for improved aperture

  $\frac{d\Omega}{4\pi} = 5.3\%$

  and absorption

  length: $\lambda > 10$ m for visible light
Scintillator readout

readout of a scintillator with a fiber (schematically)

ATLAS Hadron Calorimeter:
Scintillating tile readout via fibers and photomultipliers

Periodical arrangement of scintillator tiles (3 mm thick) in a steel absorber structure
Scintillating fiber tracking

- Scintillating plastic fibers
- Capillary fibers, filled with liquid scintillator

Planar geometries
(end cap)

Circular geometries
(barrel)

a) axial
b) circumferential
c) helical


- High geometrical flexibility
- Fine granularity
- Low mass
- Fast response (ns) (if fast read out) \(\rightarrow\) first level trigger
Charged particle passing through a stack of scintillating fibers (diam. 1mm)

Hexagonal fibers with double cladding.

Only central fiber illuminated.

Low cross talk!

(H. Leutz, NIM A 364 (1995) 422)
Photo Detectors

Purpose: Convert light into detectable electronics signal
In HEP we are usually interested in visible and UV spectrum

Threshold of some photosensitive material

standard requirement
- high sensitivity, usually expressed as quantum efficiency \( Q.E. = \frac{N_{p.e.}}{N_{photons}} \)

Main types
- gas based devices (see RICH detectors)
- vacuum based devices
- solid state detectors
Photo Multiplier Tube (PMT)

main phenomena:
• photo emission from photo cathode.
• secondary emission from dynodes.
  dynode gain $g=3-50 \ (f(E))$
  total gain $M = \prod_{i=1}^{N} g_i$

10 dynodes with $g=4$
$M = 4^{10} \approx 10^6$

PM’s are in general very sensitive to B-fields, even to earth field (30-60 $\mu$T). $\mu$-metal shielding required.
Quantum efficiencies of typical photo cathodes

- Bialkali: SbK$_2$Cs, SbRbCs
- Multialkali: SbNa$_2$KCs
- Solar blind: CsTe (cut by quartz window)

\[
Q.E.(\%) \approx 124 \cdot \frac{sk_e (mA/W)}{\lambda (nm)}
\]

Transmission of various PM windows
**Energy resolution of PMT’s**

The energy resolution is determined mainly by the fluctuation of the number of secondary electrons emitted from the dynodes.

Poisson distribution: \( P(\bar{n}, m) = \frac{\bar{n}^m e^{-m}}{m!} \)

Relative fluctuation: \( \frac{\sigma_n}{\bar{n}} = \frac{\sqrt{\bar{n}}}{\bar{n}} = \frac{1}{\sqrt{n}} \)

Fluctuations biggest, when \( \bar{n} \) small! → First dynode!

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**Photo detectors**

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Dynode configurations

Dynode configurations: (a) venetian blind, (b) box, (c) linear focusing, (d) circular cage, (e) mesh and (f) foil

Multi Anode PM
example: Hamamatsu R5900 series.

Up to 8x8 channels.
Size: 28x28 mm².
Active area 18x18 mm² (41%).
Bialkali PC: Q.E. = 20% at $\lambda_{\text{max}} = 400$ nm. Gain $\approx 10^6$.

Gain uniformity and cross-talk used to be problematic, but recently much improved.
Hybrid photo diodes (HPD)

Photo cathode like in PMT, $\Delta V$ 10-20 kV

$$G = \frac{e\Delta V}{W_{Si}} = \frac{20 \text{ keV}}{3.6 \text{ eV}} \approx 5 \cdot 10^3 \quad \text{(for } \Delta V = 20 \text{ kV)}$$

Single photon detection with high resolution

Poisson statistics with $\bar{n} = 5000$!

Background from electron backscattering from silicon surface
Cherenkov ring imaging with HPD’s

Pad HPD, Ø127 mm, fountain focused

Pixel-HPD, 80mm Ø cross-focused

2048 pads

3 x 61 pixels
- **Photo diodes**

  P(I)N type

  High Q.E. (≈80% at \( \lambda \approx 700\text{nm} \)), gain \( G = 1 \).

- **Avalanche Photo diodes (APD)**

  High reverse bias voltage ≈ 100-200V. High internal field → avalanche multiplication. \( G \approx 100(0) \)

- **Photo triodes = single stage PMT (no Silicon !)**

  \( G \approx 10 \).
  work in axial B-fields of 1T
  OPAL, DELPHI: readout of lead glass in endcap calorimeter
  \( G \) at 1T ≈ 7-10
Visible Light Photo Counter VLPC

- Operation at low bias voltage (7V)
- High IR sensitivity → Device requires cooling to LHe temperature.
- Q.E. ≈ 70% around 500 nm.
- Gain up to 50,000!

Hole drifts towards highly doped drift region and ionizes a donor atom → free electron. Multiplication by ionization of further neutral donor atoms.

Si:As impurity band conduction avalanche diode

<table>
<thead>
<tr>
<th>Q.E.</th>
<th>λ (nm)</th>
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<tr>
<td>0.0</td>
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<tr>
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<tr>
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<tr>
<td>0.0</td>
<td>900</td>
</tr>
<tr>
<td>0.2</td>
<td>1000</td>
</tr>
</tbody>
</table>

VLPC
- bialkali (ST)
- GaAs (opaque)
- Multialkali (ST)
High gain → real photon counting as in HPD

Fermilab: D0 (D zero) fiber tracker (72,000 channels)

8 pixels per chip
(vapour phase epitaxial growth)