The Basics of Particle Detection

Christian Joram / CERN
Outline

- Lecture 1 – Interaction of charged particles
- Lecture 2 – Gaseous and solid state tracking detectors
- Lecture 3 – Calorimetry, scintillation and photodetection
  - Calorimetry
    - electromagnetic cascades
    - hadronic interactions
    - neutrons and neutrinos
    - hadronic cascades
  - Scintillation
  - Photodetection
Summary: basic electromagnetic interactions

**e^+ / e^-**
- Ionisation
  - Graph: $dE/dx$ vs. $E$
  - $\beta_\gamma$

**$\gamma$**
- Photoelectric effect
  - Graph: $\sigma$ vs. $E$
- Compton effect
  - Graph: $\sigma$ vs. $E$
- Pair production
  - Graph: $\sigma$ vs. $E$
Electromagnetic cascades (showers)

Electron shower in a cloud chamber with lead absorbers

• Consider only Bremsstrahlung and (symmetric) pair production.

• Assume: $X_0 \sim \lambda_{\text{pair}}$

$$N(t) = 2^t \quad E(t)/\text{particle} = E_0 \cdot 2^{-t}$$

Process continues until $E(t) < E_c$

$$N^{\text{total}} = \sum_{t=0}^{t_{\text{max}}} 2^t = 2^{(t_{\text{max}}+1)} - 1 \approx 2 \cdot 2^{t_{\text{max}}} = 2 \frac{E_0}{E_c}$$

$$t_{\text{max}} = \frac{\ln E_0 / E_c}{\ln 2}$$

After $t = t_{\text{max}}$ the dominating processes are ionization, Compton effect and photo effect $\rightarrow$ absorption of energy.

Simple qualitative model

Shower can be initiated by photon OR by electron.
Electromagnetic calorimeters

- A detector, which measures the energy of a $e^+/-$ or a high energy $\gamma$ by fully absorbing it → destructive method!

Longitudinal profile

$$\frac{dE}{dt} \propto t^\alpha e^{-t}$$

Shower maximum at

$$t_{\text{max}} = \ln \frac{E_0}{E_c} \frac{1}{\ln 2}$$

95% containment

$$t_{95\%} \approx t_{\text{max}} + 0.08Z + 9.6$$

Size of a calorimeter grows only logarithmically with $E_0$

- Transverse shower development: 95% of the shower cone is located in a cylinder with radius $2 \, R_M$

$$R_M = \frac{21 \, \text{MeV}}{E_c} \, X_0 \, [g/cm^2]$$

Molière radius

Example: $E_0 = 100$ GeV in lead glass

$E_c = 11.8$ MeV $\Rightarrow t_{\text{max}} \approx 13, \; t_{95\%} \approx 23$

$X_0 \approx 2 \, \text{cm}, \; R_M = 1.8 \cdot X_0 \approx 3.6 \, \text{cm}$
Energy resolution of a calorimeter

General expression

\[ \frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \]

- **stochastic term**
  - inhomogenities
  - bad cell inter-calibration
  - non-linearities
  - Quality factor!

- **‘constant term’**

- **‘noise term’**
  - Electronic noise
  - radioactivity
  - pile up

Homogeneous calorimeter
Absorber = active material.

- High E-resolution, no longitudinal shower information. High cost.

Sampling calorimeter
Absorber and active detector layers.

- Extra sampling fluctuations

\[ \frac{\sigma(E)}{E} \propto \sqrt{\frac{d}{E}} \]

- Shower ‘image’
  - Lower cost.

Also true for hadron showers (see below)

Simulation!
The interaction of energetic hadrons (charged or neutral) with matter is dominated by inelastic nuclear processes. 

Excitation and finally break-up of nuclei → nuclear fragments (radioactive) + production of secondary particles.

For high energies (>1 GeV) the cross-sections depend only little on the energy and on the type of the incident particle (π, p, K...).

\[ \sigma_{inel} \approx \sigma_0 A^{0.7} \quad \sigma_0 \approx 35 \text{ mb} \]

In analogy to \( X_0 \) a hadronic absorption length can be defined

\[ \lambda_a = \frac{A}{N_A \sigma_{inel}} \propto A^{\frac{1}{4}} \quad \text{because} \quad \sigma_{inel} \approx \sigma_0 A^{0.7} \]

similarly a hadronic interaction length

\[ \lambda_I = \frac{A}{N_A \sigma_{total}} \propto A^{\frac{1}{3}} \quad \lambda_I < \lambda_a \]
## Interaction of charged particles

### Table: Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Z</th>
<th>A</th>
<th>$\rho$ [g/cm$^3$]</th>
<th>$X_0$ [g/cm$^2$]</th>
<th>$\lambda_I$ [g/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (gas)</td>
<td>1</td>
<td>1.01</td>
<td>0.0899 (g/l)</td>
<td>63</td>
<td>50.8</td>
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<td>Helium (gas)</td>
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<td>4.00</td>
<td>0.1786 (g/l)</td>
<td>94</td>
<td>65.1</td>
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<td>Beryllium</td>
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<td>9.01</td>
<td>1.848</td>
<td>65.19</td>
<td>75.2</td>
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<td>Carbon</td>
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<td>12.01</td>
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<td>43</td>
<td>86.3</td>
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<td>Nitrogen (gas)</td>
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<td>1.25 (g/l)</td>
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<td>87.8</td>
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<td>Oxygen (gas)</td>
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<td>16.00</td>
<td>1.428 (g/l)</td>
<td>34</td>
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<td>Aluminium</td>
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<td>Iron</td>
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<td>8.96</td>
<td>12.9</td>
<td>134.9</td>
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<td>Tungsten</td>
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<td>183.85</td>
<td>19.3</td>
<td>6.8</td>
<td>185.0</td>
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<tr>
<td>Lead</td>
<td>82</td>
<td>207.19</td>
<td>11.35</td>
<td>6.4</td>
<td>194.0</td>
</tr>
<tr>
<td>Uranium</td>
<td>92</td>
<td>238.03</td>
<td>18.95</td>
<td>6.0</td>
<td>199.0</td>
</tr>
</tbody>
</table>

For $Z > 6$: $\lambda_I > X_0$
Interaction of neutrons and neutrinos

Interaction of neutrons

Neutrons have no charge, i.e. their interaction is based only on strong (and weak) nuclear force. To detect neutrons, we have to create charged particles. Use neutron conversion and elastic reactions …

\[
\begin{align*}
  n + {^6}\text{Li} & \rightarrow \alpha + {^3}\text{H} & E_n < 20 \text{ MeV} \\
  n + {^{10}}\text{B} & \rightarrow \alpha + {^7}\text{Li} & E_n < 1 \text{ GeV} \\
  n + {^3}\text{He} & \rightarrow p + {^3}\text{H} \\
  n + p & \rightarrow n + p
\end{align*}
\]

In addition there are …

- neutron induced fission \( E_n \approx E_{th} \approx 1/40 \text{ eV} \)
- inelastic reactions \( E_n > 1 \text{ GeV} \)
Interaction of neutrons and neutrinos

Interaction of neutrinos

Neutrinos interact only weakly → tiny cross-sections. For their detection we need again first a charged particle. Possible detection reactions:

\[ \nu_\ell + n \rightarrow \ell^- + p \quad \ell = e, \mu, \tau \]

\[ \nu_\ell + p \rightarrow \ell^+ + n \quad \ell = e, \mu, \tau \]

The cross-section for the reaction \( \nu_e + n \rightarrow e^- + p \) is of the order of \( 10^{-43} \text{ cm}^2 \) (per nucleon, \( E_\nu \approx \text{few MeV} \)).

\[ \varepsilon_{\text{det}} = \sigma \cdot N_a = \sigma \cdot \rho \cdot \frac{N_A}{A} d \quad (N_a : \text{area density} \neq N_A : \text{Avogadro’s number}) \]

- 1 m Iron: \( \varepsilon_{\text{det}} \approx 5 \cdot 10^{-17} \)
- 1 km water: \( \varepsilon_{\text{det}} \approx 6 \cdot 10^{-15} \)

Neutrino detection requires big and massive detectors (ktons - Mtons) and very high neutrino fluxes (e.g. \( 10^{20} \nu / \text{yr} \)).

In collider experiments fully hermetic detectors allow to detect neutrinos indirectly:
- sum up all visible energy and momentum.
- attribute missing energy and momentum to neutrino.
Interaction of neutrons and neutrinos

Direct neutrino detection

Super-Kamiokande is a 50,000 ton water Cherenkov detector, able to observe a couple of thousands of neutrinos per year.

Indirect neutrino detection

e^+e^-(\sqrt{s}=181 \text{ GeV}) \rightarrow W^+W^- \rightarrow q\bar{q}\mu\nu_{\mu}

\rightarrow 2 \text{ hadronic jets} + \mu + \text{missing momentum}

Super-Kamiokande is a 50,000 ton water Cherenkov detector, able to observe a couple of thousands of neutrinos per year.

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The Basics of Particle Detection  L3-11
Hadronic cascades

Lots of processes involved:
Strong, e.m. and weak interactions.

Much more complex and larger than electromagnetic cascades. ($\lambda_1 > X_0$)

A hadronic shower has two components:

**hadronic** + **electromagnetic**

\[ \downarrow \]

- charged hadrons $p, \pi^{\pm}, K^{\pm}$
- nuclear fragments ....
- breaking up of nuclei (binding energy)
- neutrons, neutrinos, soft $\gamma$'s, muons

\[ \Rightarrow \text{ invisible energy} \rightarrow \text{large fluctuations of visible energy} \]

\[ \Rightarrow \text{Modest energy resolution of hadronic calorimeters.} \]

neutral pions $\pi^0 \rightarrow 2\gamma$

$\Rightarrow \text{electromagnetic cascades}$

\[ n(\pi^0) \approx \ln(E\text{GeV}) - 4.6 \]

example $E = 100 \text{ GeV}$: $n(\pi^0) \approx 18$
Introduction to Scintillators

**Two categories**

**Organic scintillators**  
(crystals, plastics or liquid solutions)

- Up to 10000 photons per MeV
- Low Z (not good for photoeffect)
- Low density $\rho \sim 1 \text{g/cm}^3$
- Doped, large choice of emission wavelength
- ns decay times
- Relatively inexpensive
- Medium Rad. Hard (10 kGy/year)
- Used in hadr./e.m. calorimetry, as trigger counters, for lab tests

**Inorganic**  
(crystalline structure)

- More light (up to 70000 ph/MeV)
- High Z, high density
- Rel. expensive
- Used in e.m. calorimetry

Don’t confuse scintillators with lead glass!

The light generation in lead glass is actually based on the Cherenkov effect. Lead glass is the poor man's crystal. High density, but little light output.

Energy deposition by an ionizing particle or photon ($\gamma$)

$\rightarrow$ generation  
$\rightarrow$ transmission  
$\rightarrow$ detection
The organic scintillation mechanism is based on the pi-electrons (molecular orbitals) of the benzene ring \((C_6H_6)\).
Organic scintillators exist as

- **crystals** (very rarely used in HEP)
  - naphthalene $\text{C}_{10}\text{H}_8$ m.p. 81$^\circ$ C
  - anthracene $\text{C}_{14}\text{H}_{10}$ m.p. 217$^\circ$ C

- **liquids** (solutions) (rarely used in HEP)
  - e.g. toluene

- **plastics** (polymerized solutions) (much used in HEP)
  - e.g. polyvinlyltoluene (a) or polystyrene (b)
  - a) $\text{H}_2\text{C} = \text{CH} - \text{X}$
  - b) $\text{CH}_2\text{CH}_2\text{CH} = \text{CH}$

- **solvent** + **activator**
  - e.g. p-terphenyl
  - e.g. Butyl-PBD

E.g. $p$-terphenyl

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The Basics of Particle Detection  L3-15
Plastic scintillators

Often they consist of a solvent + activator and a secondary fluor as wavelength shifter.

- **Solvent**
  \[ \Delta E = \frac{dE}{dx} \cdot \Delta x \]
  - fast and local energy transfer via non-radiative dipole-dipole interactions (Förster transfer).

- **Activator**
  - fluorescence light
  - radiative transfer

- **Wavelength shifter (‘fluor’)**
  - UV (~300 nm)
  - Visible (≥400 nm)
  - A fluor has shifted absorption and emission spectra. The difference of the two peaks is called Stokes shift.
Two dopant scheme for plastic scintillators

Abs. and emission spectra

- Förster (non-radiative)
- Radiative, UV
- Emission, blue
Some examples of commercial plastic scintillators. There are just two main suppliers: (Saint Gobain, FR/US) or ELJEN (US) which deliver rather comparable products.

Approximately 8000 photons / MeV

### Physical Constants of SGC Plastic Scintillators

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Light Output % Anthracene</th>
<th>Wavelength of Maximum Emission, nm</th>
<th>Decay Constant, Main Component, ns</th>
<th>Bulk Light Attenuation Length, cm</th>
<th>Refractive Index</th>
<th>H/C Ratio</th>
<th>Loading Element % by weight</th>
<th>Density</th>
<th>Softening Point °C</th>
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<tr>
<td>BC-400</td>
<td>65</td>
<td>423</td>
<td>2.4</td>
<td>250</td>
<td>1.58</td>
<td>1.103</td>
<td></td>
<td>1.032</td>
<td>70</td>
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<tr>
<td>BC-404</td>
<td>68</td>
<td>408</td>
<td>1.8</td>
<td>160</td>
<td>1.58</td>
<td>1.107</td>
<td></td>
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<td>70</td>
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<tr>
<td>BC-408</td>
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<td>425</td>
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<td>380</td>
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<td>1.104</td>
<td></td>
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<tr>
<td>BC-412</td>
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<td>400</td>
<td>1.58</td>
<td>1.104</td>
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<td>BC-414</td>
<td>68</td>
<td>392</td>
<td>1.8</td>
<td>100</td>
<td>1.58</td>
<td>1.110</td>
<td></td>
<td>1.032</td>
<td>70</td>
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<tr>
<td>BC-416</td>
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<td>434</td>
<td>4.0</td>
<td>400</td>
<td>1.58</td>
<td>1.110</td>
<td></td>
<td>1.032</td>
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<tr>
<td>BC-418</td>
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<td>391</td>
<td>1.4</td>
<td>100</td>
<td>1.58</td>
<td>1.100</td>
<td></td>
<td>1.032</td>
<td>70</td>
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<tr>
<td>BC-420</td>
<td>64</td>
<td>391</td>
<td>1.5</td>
<td>110</td>
<td>1.58</td>
<td>1.102</td>
<td></td>
<td>1.032</td>
<td>70</td>
</tr>
<tr>
<td>BC-422</td>
<td>55</td>
<td>370</td>
<td>1.6</td>
<td>8</td>
<td>1.58</td>
<td>1.102</td>
<td><strong>Benzenophenone, 0.5%</strong></td>
<td>1.032</td>
<td>70</td>
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<tr>
<td>BC-422Q</td>
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<td>370</td>
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<td>&lt;8</td>
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<td>BC-428</td>
<td>36</td>
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<td>1.58</td>
<td>1.103</td>
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<td>1.032</td>
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<tr>
<td>BC-430</td>
<td>45</td>
<td>580</td>
<td>16.8</td>
<td>NA</td>
<td>1.58</td>
<td>1.108</td>
<td></td>
<td>1.032</td>
<td>70</td>
</tr>
</tbody>
</table>
Readout has to be adapted to geometry, granularity and emission spectrum of scintillator.

Geometrical adaptation:

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

- **Wavelength shifter (WLS) bars / fibres**

**Watch out: it’s very hard to beat Liouville!**
Most common applications of organic scintillators

• Large volume liquid or solid detectors
• neutron detection
• underground experiments
• sampling calorimeters (HCAL in CMS or ATLAS, etc.),
• trigger counters,
• TOF counters,
• Fibre tracking  
  (see below)

Plastic scintillators in various shapes (Saint Gobain)


Scintillating tiles of CMS HCAL.
Working principle of scintillating plastic fibres:

- Scintillating fibres light transport by total internal reflection.

\[
\theta \leq \arccos \left( \frac{n_2}{n_1} \right) \approx 20.4^\circ
\]

Typical core:
- Polystyrene: \( n = 1.59 \)
- Cladding (PMMA): \( n = 1.49 \)
- Fluorinated outer cladding: \( n = 1.42 \)
- Core diameter: typ. 25 \( \mu m \), typically <1 mm

Trapping fraction:

\[
\frac{d\Omega}{4\pi} = 0.5 \left( 1 - \cos \theta \right) \approx 3\%
\]

Double cladding system (developed by CERN RD7):
- Core: Polystyrene, \( n = 1.59 \)
- Cladding (PMMA): \( n = 1.49 \)
- Fluorinated outer cladding: \( n = 1.42 \)
- Core diameter: typ. 25 \( \mu m \)

There are also square fibres. Their trapping fraction is slightly higher (additional angular phase space), but corners are problematic for light transport.
Inorganic scintillation mechanism

- Based on band structure of a crystal. Does not work for liquids or gases.

![Diagram showing the band structure of a crystal with excitons, electrons, holes, and traps.](image)

**Warning**: sometimes ≥ 2 time constants:
- fast recombination (ns-μs) from activation centers
- delayed recombination due to trapping (μs-ms)

Band gap $E_g$ should be large (>3 eV) to ensure that crystal is transparent.

Exception: Liquefied noble gases scintillate, too. Different process. Not treated here.
Inorganic scintillators

~75000 $\text{PbWO}_4$ crystals in the CMS electromagnetic calorimeter
Please wake up

New topic: Photodetection

(Detection of light in the optical domain)
The classical domains of application

- **Calorimetry**
  - Readout of organic and inorganic scintillators, lead glass, scint. or quartz fibres → Blue/VIS, usually 10s – 10000s of photons

- **Particle Identification**
  - Detection of Cherenkov light → UV/blue, single photons
  - Time Of Flight → Usually readout of organic scintillators (not competitive at high momenta) or Cherenkov radiators

- **Tracking**
  - Readout of scintillating fibres → blue/VIS, few photons
Purpose:
Convert light into detectable electronic signal
(we are not covering photographic emulsions!)

Principle:
Use photoelectric effect to ‘convert’ photons (\(\gamma\)) to photoelectrons (\(pe\))

Details depend on the type of the photosensitive material (see below).
Photon detection involves often materials like K, Na, Rb, Cs (alkali metals). They have the smallest electronegativity \(\rightarrow\) highest tendency to release electrons.
Many photosensitive materials are semiconductors, but photoeffect can also be observed from gases and liquids.

Internal photoeffect: \( E_\gamma > E_g \)

External photoeffect: \( E_\gamma > E_g + E_A \)
Basics of photon detection

Requirements on photodetectors

- **High sensitivity**, usually expressed as: **quantum efficiency**

\[
QE(\%) = \frac{N_{pe}}{N_\gamma}
\]

or **radiant sensitivity** \( S \) (mA/W), with \( QE(\%) \approx 124 \cdot \frac{S(mA/W)}{\lambda(nm)} \)

QE can be >100% (for high energetic photons)!

- **Good Linearity**: Output signal \( \sim \) light intensity, over a large dynamic range (critical e.g. in calorimetry (energy measurement)).

- **Fast Time response**: Signal is produced instantaneously (within ns), low jitter (<ns), no afterpulses

- **Low intrinsic noise**. A noise-free detector doesn’t exist. Thermally created photoelectrons represent the lower limit for the noise rate \( \sim A_0T^2\exp(-eW_{ph}/kT) \). In many detector types, noise is dominated by other sources.

- + many more (size, fill factor, radiation hardness, cost, tolerance/immunity to B-fields...)

\[
N_{pe} \approx \left( \frac{V}{e} \right) N_\gamma
\]
Frequently used photosensitive materials / photocathodes

Remember: $E_{[eV]} \approx \frac{1239}{\lambda_{[nm]}}$

Almost all photosensitive materials are very reactive (alkali metals). Operation only in vacuum or extremely clean gas. Exception: Silicon, CsI.
Latest generation of high performance photocathodes

The Basics of Particle Detection

QE Comparison of semitransparent bialkali QE

Example Data for
UBA : R7600-200
SBA : R7600-100
STD : R7600

Ultra Bialkali available only for small metal channel dynode tubes

Super Bialkali available for a couple of standard tubes up to 5”.

Quantum Efficiency [%]

Wavelength [nm]

UBA:43% x1.6
SBA:35% x1.3
STD:26%

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The Basics of Particle Detection

L3-30
**Photo-multiplier tubes (PMT’s)**

**Basic principle:**

**Photo-emission** from photo-cathode

**Secondary emission** from \( N \) dynodes:

- dynode gain \( g \approx 3-50 \) (function of incoming electron energy \( E \));
- total gain \( M \):

\[
M = \prod_{i=1}^{N} g_i
\]

Example:

- 10 dynodes with \( g = 4 \)
- \( M = 4^{10} \approx 10^6 \)

Very sensitive to magnetic fields, even to earth magnetic field (30-60 \( \mu \)T = 0.3-0.6 Gauss).

\( \rightarrow \) Shielding required (mu-metal).
Gain fluctuations of PMT’s

- Mainly determined by the fluctuations of the number of secondary electrons $m_i$ emitted from the dynodes;

- Poisson distribution:
  \[ P(n, m_i) = \frac{m_i^n e^{-m_i}}{n!} \]

- Standard deviation:
  \[ \frac{\sigma_n}{m_i} = \sqrt{\frac{m_i}{m_i}} = \frac{1}{\sqrt{m_i}} \]

⇒ fluctuations dominated by 1\textsuperscript{st} dynode gain $m_1 = \delta_1$

- Pulse height Counts
  - SE coefficient $\delta$
    - CuBe dynodes $E_A > 0$
    - GaP(Cs) dynodes $E_A < 0$

Electron energy

Counts

Pedestal noise

Pulse height

Counts

(H. Houtermanns, NIM 112 (1973) 121)
Multi-anode and flat-panel PMT’s

Multi-anode PMT (Hamamatsu)
- Up to $8 \times 8$ channels ($2 \times 2$ mm$^2$ each);
- Size: $28 \times 28$ mm$^2$;
- Bialkali PC: QE $\approx 25 - 45\%$ @ $\lambda_{\text{max}} = 400$ nm;
- Gain $\approx 3 \times 10^5$;
- Gain uniformity typ. 1 : 2.5;
- Cross-talk typ. 2%

Flat-panel (Hamamatsu H8500):
- $8 \times 8$ channels ($5.8 \times 5.8$ mm$^2$ each)
- Excellent surface coverage (89%)

Cherenkov rings from 3 GeV/c $\pi^-$ through aerogel

(T. Matsumoto et al., NIMA 521 (2004) 367)
Micro Channel Plate (MCP) based PMTs

MCPs are usually based on glass disks, with lots of aligned pores. The surface of the pores are metal coated.

Gain stage and detection are decoupled \( \rightarrow \) lots of potential and freedom for MA-PMTs: Anode can be easily segmented in application specific way.

- Typical secondary yield is 2
- For 40:1 L:D there are typically 10 strikes \( (2^{10} \sim 10^3 \text{ gain per single plate}) \)
- Pore sizes range from <10 to 25 \( \mu \text{m} \).
- Small distances \( \rightarrow \) small TTS and good immunity to B-field.

Available with up to 1024 (32 x 32) channels (1.6 x 1.6 mm\(^2\)).
Light absorption in Silicon

At large $\lambda$, temperature effects become important.

Surface effects dominate.

Transparency, interference are issues.

Atmospheric cutoff.

$E_g \approx 1.147$ eV

$\lambda_g \approx 1081$ nm

(silicon bandgap at 150 K)

[http://pdg.ge.infn.it/~deg/ccd.html](http://pdg.ge.infn.it/~deg/ccd.html)
(Si) – Photodiodes (PIN diode)

- P(I)N type
- p layer very thin (<1 μm), as visible light is rapidly absorbed by silicon
- High QE (80% @ λ ≈ 700nm)
- Gain = 1

Avalanche photodiode (APD)

- High reverse bias voltage: typ. few 100 V
- Special doping profile → high internal field (>10^5 V/cm) → e and h avalanche multiplication
- Avalanche must stop due to statistical fluctuations.
- Gain: typ. O(100)
- Rel. high gain fluctuations (excess noise from the avalanche). CMS ECAL APD: ENF = 2 @G=50.
- Very high sensitivity on temp. and bias voltage ΔG = 3.1%/V and -2.4 %/K

Hamamatsu S8148.
(140,000 pieces used in CMS barrel ECAL).
Solid-state ... Geiger mode Avalanche Photodiode (G-APD)

How to obtain higher gain (= single photon detection) without suffering from excessive noise?

Operate APD cell in Geiger mode (= full discharge), however with (passive) quenching.

Photon conversion + avalanche short-circuits the diode.
Solid-state ... Geiger mode Avalanche Photodiode (G-APD)

\[ \tau = R_S C_D \] (sub – ns)

\[ I_D \]

\[ I_{\text{max}} \sim (V_{\text{BIAS}} - V_{\text{BD}}) / R_Q \]

\[ \tau = R_Q C_D \]

10s of ns

Gain = \( Q / e \)

\[ = I_{\text{max}} \cdot \tau / e \]

\[ = (V_{\text{BIAS}} - V_{\text{BD}}) C_D / e \]

\[ = \Delta V C_D / e \]

\[ G \sim 10^5 - 10^6 \text{ at reasonable bias voltage} \]<100 V

Sample of 3 G-APDs

HPK311-53-1A-002-1

J. Haba, RICH2007

Sample of 3 G-APDs

J. Haba, RICH2007
Multi pixel G-APD, called G-APD, MPPC, SiPM, ...

Sizes up to 6×6 mm² now standard.

Quantiﬁcation detector allows photon counting with a clearly quantized signal

- Quench resistor
- GM-APD
- Bias bus

100 – several 1000 pix / mm²

Only part of surface is photosensitive!

Quantiﬁcation detector allows photon counting with a clearly quantized signal
You cannot get "something for nothing"

- G-APD show dark noise rate in the O(100 kHz – MHz / mm²) range.
- The gain is temperature dependent O(<5% /°K)
- The signal linearity is limited
- The price is (still too) high

\[ N_{\text{fired}} = N_0 \times \left(1 - \exp \left( \frac{x}{N_0} \right) \right) \]
**SiPM designs (just examples)**

**Hamamatsu HPK** (http://jp.hamamatsu.com/)
- 25x25\(\mu\)m\(^2\), 50x50\(\mu\)m\(^2\), 100x100\(\mu\)m\(^2\) pixel size

**Arrays**
- 1x1mm\(^2\)
  - 1x1mm\(^2\) 1x4 channels
  - 3x3mm\(^2\)
  - 1x4mm\(^2\) 1x4 channels
  - 6x6 mm\(^2\) 2x2 channels

**FBK-IRST**
- 50x50\(\mu\)m\(^2\) pixel size
- 4x4mm\(^2\)
  - 3x3mm\(^2\)
  - 2x2mm\(^2\)
  - 1x1mm\(^2\)
  - 2x2 channels
  - 2x2 channels

**SensL** (http://sensl.com/)
- 20x20\(\mu\)m\(^2\), 35x35\(\mu\)m\(^2\), 50x50\(\mu\)m\(^2\), 100x100\(\mu\)m\(^2\) pixel size
- 3.16x3.16mm\(^2\)
  - 4x4 channels
  - 4x4 channels
- 6 x 6 cm\(^2\)
  - 16x16 channels
Gaseous photodetectors: A few implementations...

**Proven technology:**
Cherenkov detectors in ALICE, HADES, COMPASS, J-LAB.... Many m² of CsI photocathodes

**Micro Pattern Structures (GEM) + CsI**
HBD (RICH) of PHENIX.

**R&D:**
Thick GEM structures
Visible PC (bialkali)
Sealed gaseous devices

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CsI on multi-GEM structure
Dark counts due to ... 

- **Thermal/tunneling**: thermal/tunneling carrier generation in the bulk or in the surface depleted region around the junction.
- **After-pulses**: carriers trapped during the avalanche discharging and then released triggering a new avalanche during a period of several 100 ns after the breakdown.
- **Optical cross-talk**: $10^5$ carriers in an avalanche plasma emit on average 3 photons with an energy higher than 1.14 eV (A. Lacaita et al. IEEE TED 1993). These photons can trigger an avalanche in an adjacent μcell.

→ Limit gain, increase threshold
→ add trenches btw μcells
Different from analog SiPMs: Upon the detection of a photon, the avalanche is actively quenched using a dedicated transistor, and a different transistor is used to quickly recharge the diode back to its sensitive state.

1 digital cell (area depends on type, e.g. 30 x 50 µm)

- Cell electronics area: 120µm²
- 25 transistors including 6T SRAM
- ~6% of total cell area
- Modified 0.18µm 5M CMOS
- Foundry: NXP Nijmegen

Implementation of SiPMs in a CMOS process allows adding lots of functionality…
Digital SiPM

Compared to the analog technology, the digital one (offered by Philips) has a number of advantages:

+ Integration of bias supply, amp, TDC, counter…
+ Fast active quenching $\rightarrow$ no afterpulses
+ Possibility to de-activate noisy cells $\rightarrow$ potentially lower dark noise
+ Reduced sensitivity to voltage and temperature variations
+ Compactness
+ Possibility to add local intelligence

… problems shared with analog

- High dark noise (a discharging cell doesn’t know whether it is digital or analog)
- Signal saturation (limited number of cells)

… and also has some drawbacks

- The local electronics is a source of heat $\rightarrow$ cooling advisable
- The readout functionality is designed into the sensor. In case of mismatch with the needs, relatively expensive modifications of the sensor/FPGA may be required.
Hybrid Photon Detectors (HPD’s)

Basic principle:

- Combination of vacuum photon detectors and solid-state technology;
- Optical window, (semitransparent) photo-cathode;
- Electron optics (optional: demagnification);
- Charge Gain: achieved in one step by energy dissipation of keV pe’s in solid-state detector anode; this results in low gain fluctuations;
- Encapsulation of Si-sensor in the tube implies:
  - compatibility with high vacuum technology (low outgassing, high $T^\circ$ bake-out cycles);
  - internal (for speed and fine segmentation) or external connectivity to read-out electronics;
  - heat dissipation issues;

\[ W_{Si} = 3.6 \text{ eV} \]

\[ \Delta V = 20 \text{ kV} \]
\[ M \approx 5000 \]

\[ \sigma_M = \sqrt{F \times M} \]
\[ F = \text{Fano factor} \]
\[ F_{Si} \approx 0.1 \]
Hybrid Photon Detectors (HPD’s)

10-inch prototype HPD (CERN) for Air Shower Telescope CLUE.

Photon counting. Continuum due to electron back scattering.

HV_{HPD} = 26 kV

p.e.

脉冲高度信号

1 p.e. 2 p.e. 3 p.e. 4 p.e. 5 p.e.

脉冲高度 (ADC 计数)

Pedestal cut
Pixel-HPD’s for LHCb RICH detectors

- Cross-focused electron optics
- Pixel array sensor bump-bonded to binary electronic chip, developed at CERN
- 8192 pixels of 50 × 400 μm.
- Specially developed high T° bump-bonding;
- Flip-chip assembly, tube encapsulation (multi-alkali PC) performed in industry (VTT, Photonis/DEP)


During commissioning: illumination of 144 tubes by beamer. In total: 484 tubes.
Gaseous Photodetectors

Principle: (A) Ionize photosensitive molecules, admixed to the counter gas (TMAE, TEA); or (B) release photoelectron from a solid photocathode (CsI, bialkali...); Then use free photoelectron to trigger a Townsend avalanche $\rightarrow$ Gain

- TEA, TMAE, CsI work only in deep UV region.
- Bialkali works in visible domain, however requires VERY clean gases.
- Long term operation in a real detector not yet demonstrated.

Usual issues: How to achieve high gain ($10^5$)? How to control ion feedback and light emission from avalanche? How to purify gas and keep it clean? How to control aging?
Bremsstrahlung plays an important role in accelerators, but essentially only in circular $e^\pm$ machines. Here it is called ‘Synchrotron radiation’

Magnetic field forces particles on a circle $\rightarrow$ permanent acceleration towards the centre of the circle.

Negative aspect: The radiated energy per turn can eat up the gained energy by acceleration and so limit the achievable energy. Famous example: LEP ($e^+e^-$ collider).

Positive aspect: The radiated energy is extremely forward peaked (Lorentz transformed) and can be used as very bright and intense photon source, e.g. for material studies. See e.g. ESRF (www.esrf.eu)
A few more words on muons (at very high energies)

Muons interact electromagnetically (like the $e^+, e^-$, but due to its high mass, direct Bremsstrahlung ($\sim E/m^2$) is strongly suppressed.

There are other radiative processes

- Photo-nuclear interactions

- Pair production

Like for Bremsstrahlung, they scale with $E$

$$\frac{dE}{dx} = b(Z, A, E_{\mu}) \cdot E_{\mu}$$
Total energy loss of muons (in different materials)

\[
\frac{dE}{dx} = a + b \cdot E_\mu
\]

ionization  radiative
Basics of photon detection

Opaque photocathode

\[ \gamma \]

\[ e^- \]

\[ \text{PC} \]

\[ \text{substrate} \]

Semitransparent photocathode

\[ \gamma \]

\[ e^- \]

\[ \text{Detector window} \]

\[ \text{PC} \]

Light absorption in photocathode

\[ \lambda_A = \frac{1}{\alpha} \]

Red light (\( \lambda \approx 600 \text{ nm} \))
\[ \alpha \approx 1.5 \cdot 10^5 \text{ cm}^{-1} \]
\[ \lambda_A \approx 60 \text{ nm} \]

Blue light (\( \lambda \approx 400 \text{ nm} \))
\[ \alpha \approx 4 \cdot 10^5 \text{ cm}^{-1} \]
\[ \lambda_A \approx 25 \text{ nm} \]

Blue light is stronger absorbed than red light!

→ Make semitransparent photocathode just as thick as necessary!