Photon Detectors

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EURIZON detector school

eurizon
European network
for developing new horizons for RIs

Introduction: why photon detection?

- detection of particles requires an interaction with matter
- the interaction leads to ionisation or excitation of matter
- most detection interactions are of electromagnetic nature

- the choice of the material employed to build a detector is the key point: what particle are we looking for? what interaction with matter is the particle having? what is the signature of the interaction?

- some interactions of particles with matter produce photons as a signature:
  - Scintillation
  - Cherenkov

These two lectures on photon detectors will cover:

- interaction of particles with matter leading to the production of photons
- basic principles of photon detection
- the photon detectors zoo
- applications of photon detection

Principle of scintillation

Certain materials, when struck by a particle or radiation, emit scintillation light

principle:

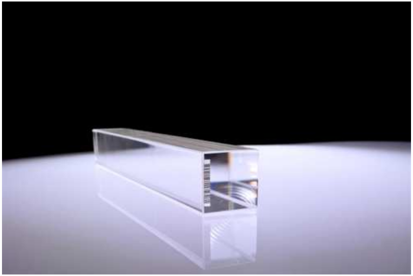
- energy deposit dE/dx converted into light detectable with photon detector
- light emission when hit by ionising radiation
- the scintillator is transparent to the scintillation light

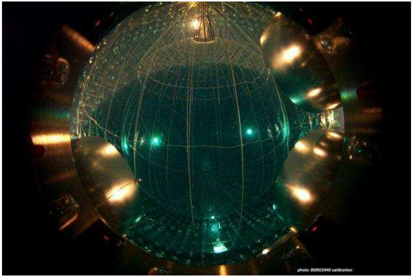
main features:

- detection sensitive to amount of energy deposited: scintillators emits light linearly proportional to deposed energy (calorimetry, spectroscopy)
- fast time response: high rate (time-of-flight, triggering)
- the response of some scintillators depends on the particle (particle identification)

materials: organic solid (plastic), organic liquid (hydrocarbon), inorganic (crystals), noble gas, glasses

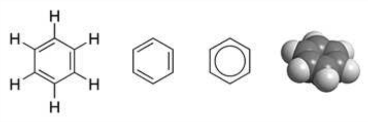
large variety of materials employed in various types of detectors!

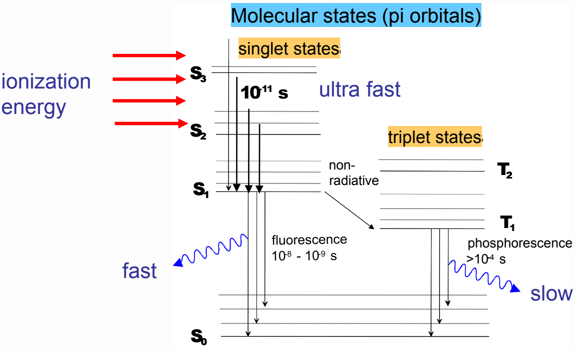




Organic scintillation mechanism

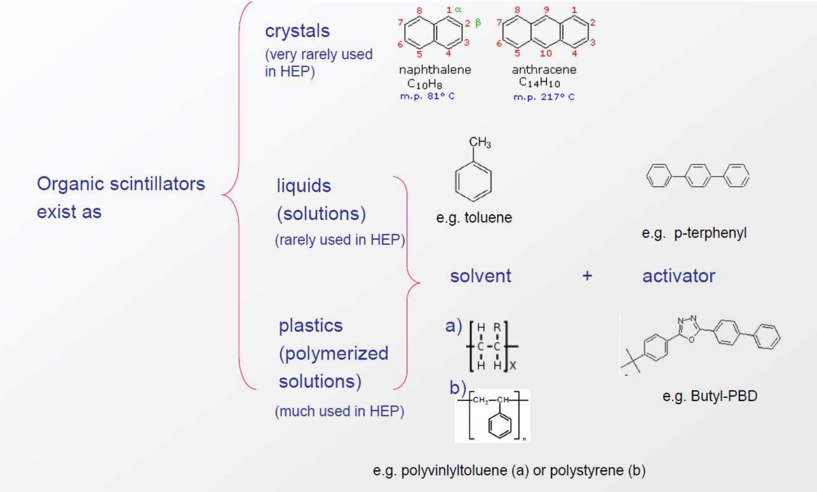
- aromatic hydrocarbon compounds (benzene ring)
- scintillation light is due to delocalised molecular electrons in π-orbitals
- the two components are related two different de-excitation mechanisms





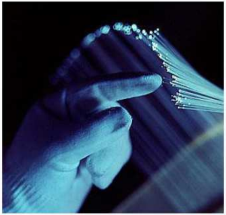
- fast: ground to excited state decaying to an intermediate molecular state (~ps) and subsequent decay to ground (ns)
- slow: de-excitation of levels interacting with the lattice (>100ns)
- an intermediate state is necessary to make the material transparent to the de-excitation light
- A small amount of a second fluorescent compound (wavelength shifter) is added to increase the overall visible light collection

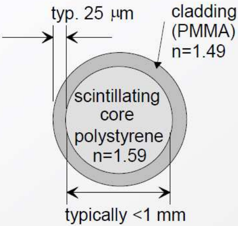
Organic scintillation mechanism



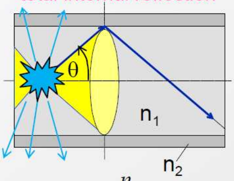
Scintillating fibres

Working principle of scintillating plastic fibres :





light transport by
total internal reflection



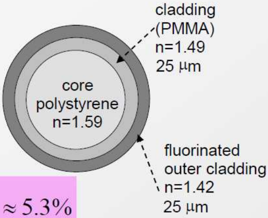
$$\theta \leq \arccos \frac{n_2}{n_1} \approx 20.4°$$

Trapping fraction

$$\frac{d\Omega}{4\pi} = 0.5\,(1-\cos\theta) \approx 3\%$$

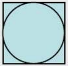
(per side)

Double cladding system
(developed by CERN RD7)



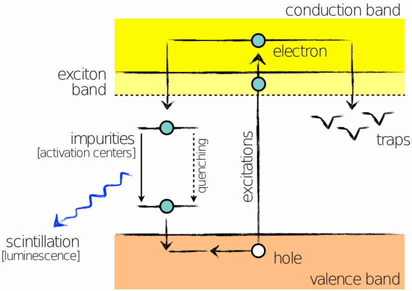
$$\frac{d\Omega}{4\pi} = 0.5\,(1-\cos\theta) \approx 5.3\%$$

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



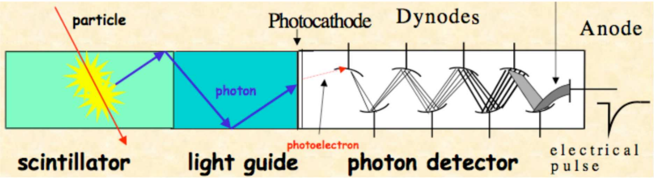
Inorganic scintillation mechanism

- typically alkaline non-conductive crystals with a small amount of fluorescent dopant: Sodium Iodide (NaI), Cesium Iodide (CsI), ...
- non-alkaline species: Barium fluoride (BaF_2),...
- scintillation mechanism related to the crystal lattice bands:
  - energy deposition by ionisation
  - energy transfer to impurities
  - radiation of scintillation photons
- fast: recombination from activation centres [ns ... μs]
- slow: recombination due to trapping [ms ... s]



Energy bands in impurity activated crystal
showing excitation, luminescence, quenching and trapping

Scintillators



Organic scintillators (crystals, plastics or liquid solutions)

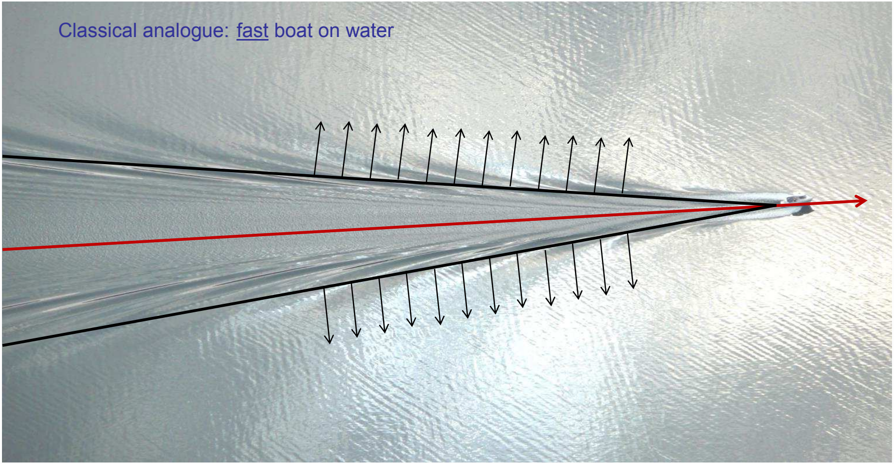
- up to 10000 photons per MeV
- low Z, low density
- doped, large choice of emission wavelength
- ns decay times
- relatively inexpensive
- used in hadronic/electromagnetic calorimetry, as trigger counters, for lab tests

Inorganic scintillators (crystalline structure)

- higher light yields (up to 70000 ph/MeV)
- high Z, high density
- relatively expensive
- used in electromagnetic calorimetry

Cherenkov radiation

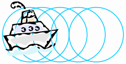
A charged particle, moving though a medium at a speed which is greater than the speed of light in the medium, produces Cherenkov light



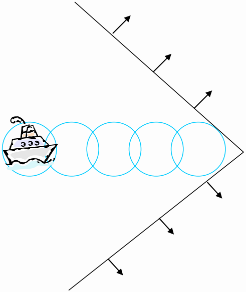
from propagating waves...

a stationary boat bobbing up and down
on a lake, producing waves

the boat starts to move, but slower than the waves:
No coherent wavefront is formed

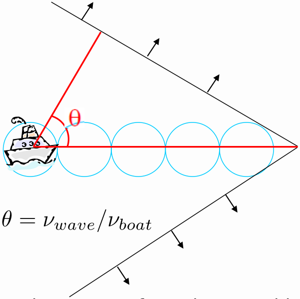


the boat moves faster than the waves



a coherent wavefront is formed

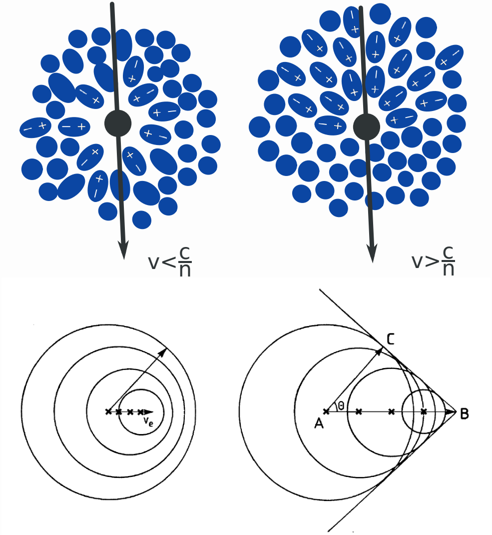
Finally the boat moves even faster



$$\cos\theta = \nu_{wave}/\nu_{boat}$$

The angle of the coherent wavefront changes with the speed

... to Cherenkov radiation

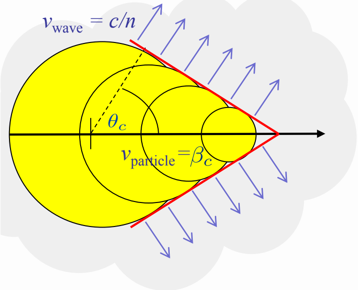


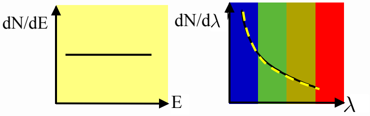
charged particle traversing medium

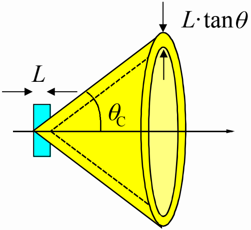
- atoms in the medium are polarised along track: emission of electromagnetic pulse
- particle slower than local the speed of light: symmetric polarised field and destructive interference
- particle faster than local the speed of light: asymmetric polarisation and coherent wavefront produced
- Huygen's principle: coherent wavefront only at a specific angle θ with respect to the particle trajectory

P. A. Cerenkov. "Visible Radiation Produced by Electrons Moving in a Medium with Velocities Exceeding that of Light", Phys. Rev. 52 (4 Aug. 1937), pp. 37 8-379. DOI: 10.1103/PhysRev.52.378. (Nobel prize in 1958 Cherenkov, Frank, Tamm)

Cherenkov radiation: properties







threshold

$$\beta_{threshold} = \frac{v_{threshold}}{c} = \frac{1}{n(\lambda)}$$

angle

$$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$

photons

$$N_{photons} = L\frac{\alpha^2 z^2}{r_e m_e c^2}\int \sin^2\theta_c(E)dE$$

$$N_{photons} \propto \frac{1}{\lambda^2}$$

number of Cherenkov photons per unit path length and per unit energy interval of the photons:

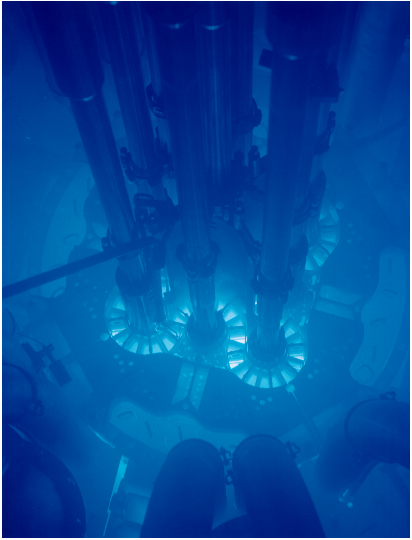
$$d^2N/dEdx \approx 370\sin^2\theta_C(E)\ [\mathrm{eV}^{-1}][\mathrm{cm}^{-1}]$$

low number of Cherenkov photons ⇒ negligible energy loss of the charged particle under identification

Cherenkov radiation

- radiation first observed as faint blue light around radioactive preparation
- typical emission observed around open pool reactors: beta particles emitted as fission products

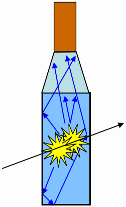
- natural employment in particle physics to identify charged particles
- choice of dielectric (radiator) $\Rightarrow n$ known
- measurement of Cherenkov photons allows to obtain $\theta \Rightarrow$ speed of the particle v
- need for a tracking detector to obtain momentum p
- mass of the particle known $m = \frac{p}{v}$ $\Rightarrow$ particle identity known!



Photon detectors in High Energy Physics

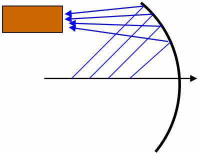
Calorimetry

- readout of organic and inorganic scintillators, scintillating or quartz fibres → blue/visible wavelength, 10s-10000s photons



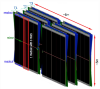
Particle Identification

- detection of Cherenkov light → UV/blue wavelength, single photons
- time of flight detectors → usually readout of organic scintillators or Cherenkov radiators



Tracking

- readout of scintillating fibres → blue/visible wavelength, few photons



Photon Detectors

From light to a detectable electric signal
Use Photoelectric effect to convert photons to electrons

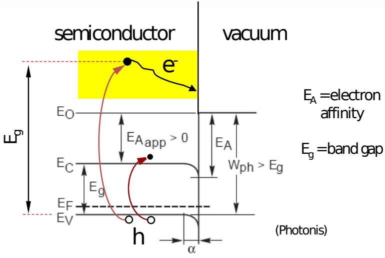
many types of photon detectors developed over the years!

Principle of photon detection

Multistep process

- Photo-ionisation: electrons lifted from valence to conduction band (internal photoelectric effect)
- electrons drift in photocathode: energised electrons diffuse through the material, losing part of their energy (random walk) due to electron-phonon scattering
- escape into vacuum: only electrons with sufficient excess energy escape from the photocathode (external photoelectric effect)

$$E_{ph} = h\nu > W_{ph} = E_g + E_A$$
$$E_e = h\nu - W_{ph}$$



E_g =band gap, energy to lift electron from valence to conduction band

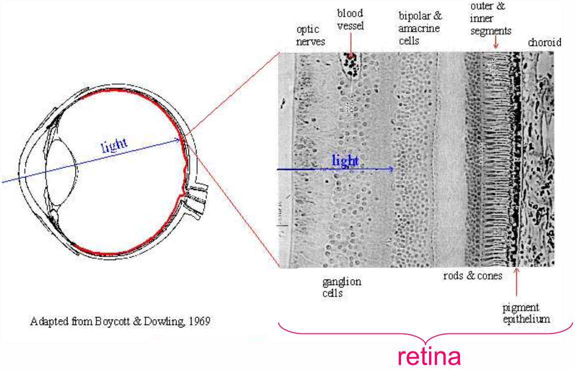
E_A =electron affinity, energy needed to free electron from potential of crystal

W_{ph} =work function, total energy needed to free an electron

terminology: photons hit the cathode and are converted to electrons; electrical signal is collected at the anode

Human eye

The oldest photon detector, build many billion times!



- good spatial resolution
- very large dynamic range (1-10^6)+ automatic threshold adaptation
- energy (wavelength) discrimination
- modest sensitivity: 500 to 900 photons must arrive at the eye every second for our brain to register a conscious signal
- modest speed: data taking rate ~10Hz (including processing)

What are the parameters to classify photon detectors?

Requirements on photon detectors

- sensitivity
- linearity
- signal fluctuation
- time response
- rate capability/ageing
- dark count rate
- operation in magnetic field
- radiation tolerance

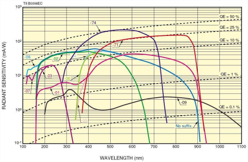
Sensitivity

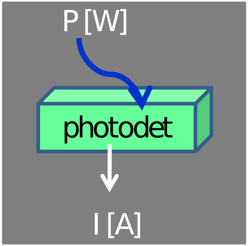
the sensitivity is usually expressed as Quantum Efficiency:

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

or as radiant sensitivity:

$$S[mA/W] \approx \frac{QE[\%] \cdot \lambda[nm] \cdot e}{hc} = \frac{QE[\%] \cdot \lambda[nm]}{124}$$





Quantum Efficiency is extremely difficult to measure

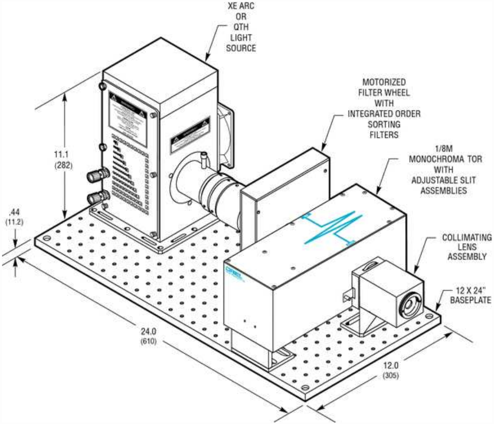
Photo detection efficiency (PDE): combined probability to produce a photo-electron and to detect it

$$PDE = \epsilon_{geom} \cdot QE \cdot \epsilon_{photondetection}$$

High sensitivity required in:

- UV/blue: water Cherenkov telescope, Imaging Atmospheric Cherenkov Telescopes, Ring Imaging Cherenkov detectors
- blue/green: HEP calorimeters

Example of setup to measure the QE



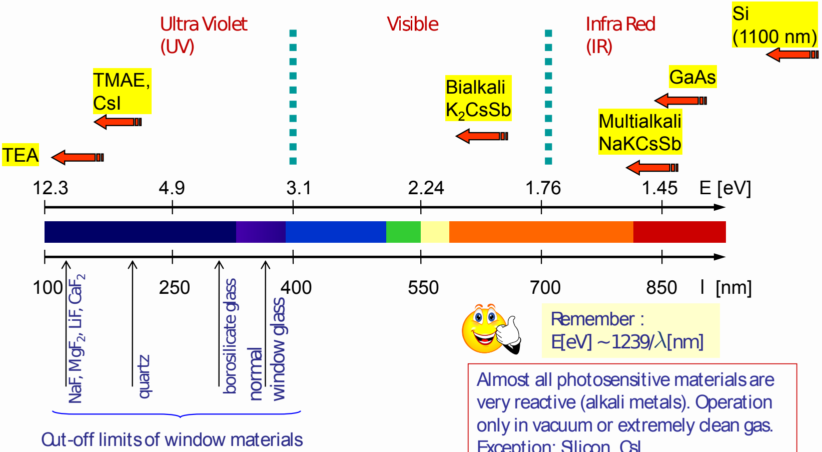
Tunable light source:

- xenon lamp
- motorized filter wheel (minimize second order effects)
- monocromator (2 slits to adjust bandwidth)
- collimating system

- calibrated photodiode
- power meter to readout photodiode

- power supply to bias cathode
- picoammeter to readout photocurrent

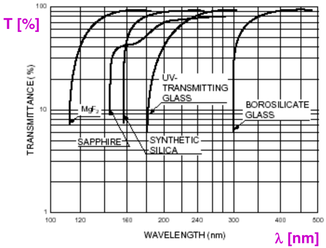
Frequently used photosensitive materials / photocathodes

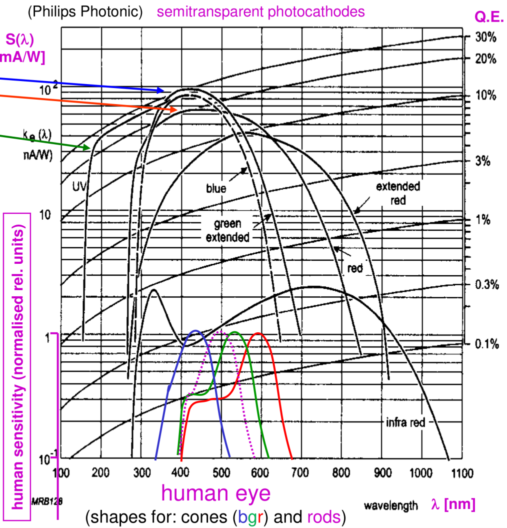


choice of photon detector starts from wavelength of interest

Examples of photo-cathode materials: Alkali

- Photo cathode types:
  - Bialkali : SbK_2Cs, SbRbCs
  - Multialkali : $SbNa_2KCs$
  - Solar blind : CsTe
- Human eye sensitivity:
  - approx. shapes
  - relative units
- Window transmissions:

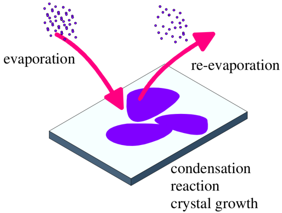




human eye
(shapes for: cones (bgr) and rods)

Examples of photo-cathode production: Alkali

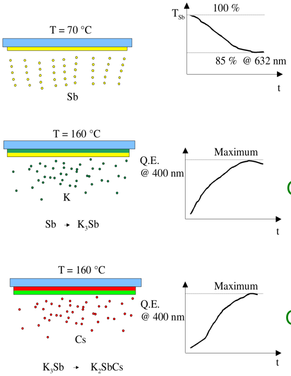
- Evaporation of metals in high vacuum:
  - $< 10^{-7}$ mbar
  - $< 10^{-9}$ mbar H_2O partial pressure
  - no other contaminants (CO, C_xH_y...)
  - ➔ bakeout of process chamber (>150°C) and substrate (>300°C)
- Condensation of vapour and chemical reaction on entrance window:



- Relatively simple technique
  - but exact recipes are trade secrets…

- Example: SbK_2Cs

simplified sequential bialkali process



$d_{Sb} \approx 5$ nm

Q.E. ≈ 3 - 5 %

Q.E. ≈ 15 - 20 %

Photocathode thickness

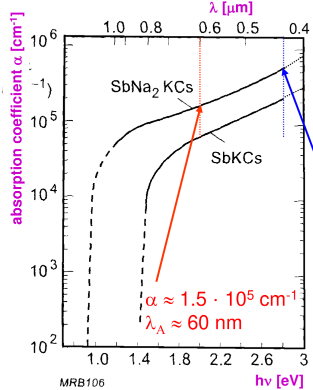
- Semi-transparent cathodes:
  - best compromise for the thickness of the PC:
  - ↗ photon absorption length $\lambda_A(E_{ph})$
  - ↘ electron escape length $\lambda_E(E_e)$

Blue light is stronger absorbed than red light!

- Q.E. of thin cathode:
  - blue response ↗
  - red response ↘

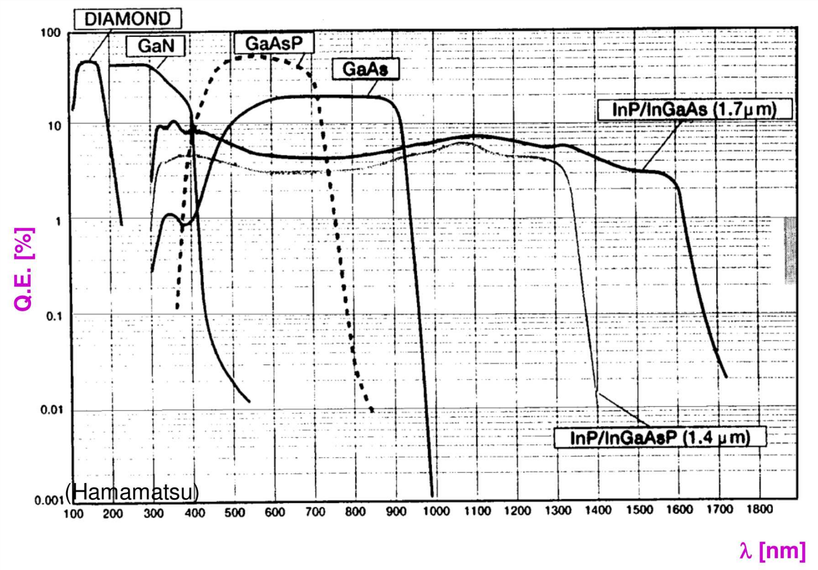
- Q.E. of thick cathode:
  - red response ↗
  - blue response ↘

$\lambda_A = 1/\alpha$



$\alpha \approx 4 \cdot 10^5$ cm^{-1}
$\lambda_A \approx 25$ nm

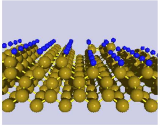
QE of semiconductor photo-cathodes



QE of semiconductor photo-cathodes

- Disadvantage:
  - complex production

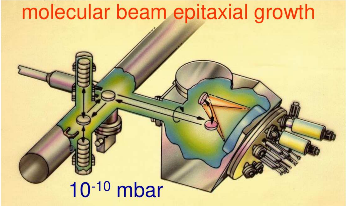
    a) grow PC on crystalline substrate

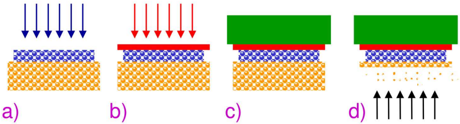


    b) create interface layer

    c) fuse to entrance window

    d) etch substrate away

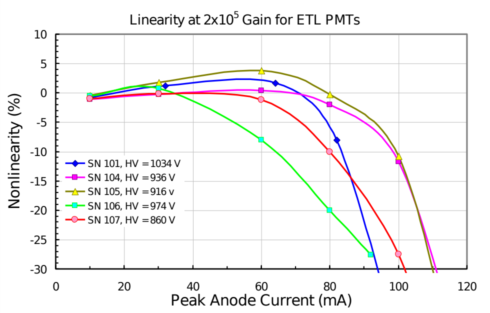




Linearity

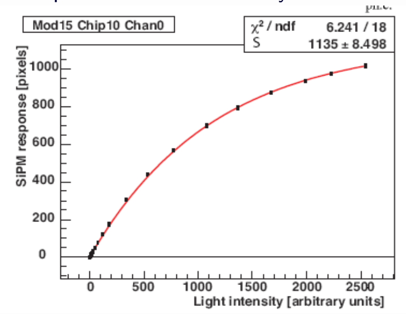
Requirement: Photocurrent response of the photo-detector is linear with incident radiation over a wide range. Any variation in response with incident radiation represents a variation in the linearity of the detector

Example of PMT non linearity curve:



at UCLA PMT Test Facility

Example of SiPM non linearity curve:



arXiv:0902.2848v1 [physics.ins det] 17 Feb 200

Example of dynamic range: HCAL of ILC Min 20 photons/mm^2 (μ for calibration)
Max: 5.10^{2}photons/mm^2 (high-energy jet)

Signal fluctuation

various categories of photon detectors are characterised by an internal gain: one photo-electron produced is multiplied to obtain $\sim 10^6$Me

statistical fluctuations of the avalanche multiplication widen the response of a photon detector to a given photon signal beyond what would be expected from simple photo-electron statistics (Poissonian distribution)

variable to quantify fluctuations: excess noise factor (ENF):

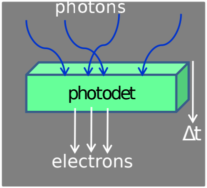
$$ENF = \frac{\sigma^2_{out}}{\sigma^2_{in}},$$ general definition

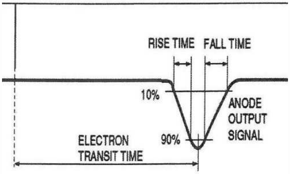
$$ENF = 1 + \frac{\sigma^2_M}{M^2},$$ M=gain

detector	ENF
PMT	1-1.5
APD	~ 2
HPD	~ 1
SiPM	1-1.5
MCP=PMT	~ 1

- impacts the photon counting capability for low light measurements
- deteriorates the stochastic term in the energy resolution of a calorimeter

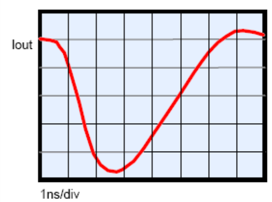
Time response





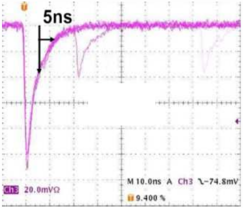
- rise time, fall time (or decay time)
- duration
- Transit time (Δt): time between the arrival of the photon and the electrical signal
- Transit time spread (TTS): transit time variation between different events ⇒ timing resolution

standard PMT



MCP-PMT

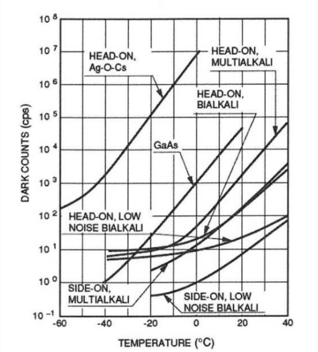
SiPM



Good time resolution required for example in particle identification at LHCb upgrade 2 ⇒ ∼30 ps

Dark count rate

Dark noise: the electrical signal emitted by a photocathode when there is no photon hitting the photon detector



PMTs

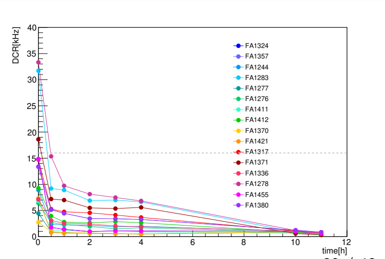
- it depends on the photocathode material, the cathode area and the temperature
- is highest for cathodes with high sensitivity at long wavelengths
- increases considerably if exposed to daylight: when a PMT is exposed to ambient light before operations it will have a higher DCR that will decrease in time; exposure to direct sunlight can permanently damage the photocathode

SiPM

- depends on the pixel size, the bias voltage, the temperature
- can reach hundreds of kHz at room temperature

DCR depends a lot on the signal to be detected:

- not a big issue when we want to detect hundreds or thousands of photons
- key parameter in single photon detectors



Rate capability/ageing

Rate capability: inversely proportional to the time needed, after the arrival of one photon, to get ready to receive the next

requirements for HEP experiments can reach the order of tens of MHz

Ageing (long-term operation at high counting rates): how is the photon detector behaviour changed when operated at high counting rate during several years? Parameters affected generally in a negative way:

- gain
- quantum efficiency
- dark count rate

ageing can be caused by operations over the year as well as by radiation

Radiation tolerance

Electromagnetic calorimeter: very hostile environment for photon detectors

Damages caused by:

- ionising radiation: energy deposited by particles in the detector material (the unit of absorbed dose is Gray (Gy) $\Rightarrow$ 1 Gy = 1 J/kg) and by photons from electromagnetic showers
- neutrons created in hadronic showers, also in the forward shielding of the detectors and in beam collimators

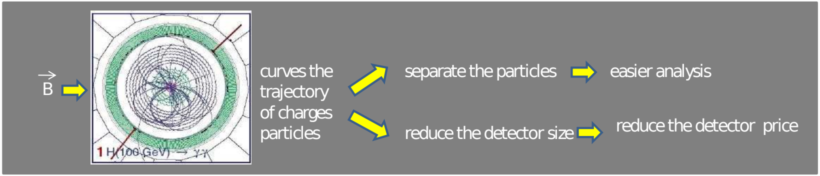
$\Rightarrow$ degradation of the dark current, gain, quantum efficiency

Example of orders of magnitude:

- at LHC, the ionising dose is $\sim 2 \times 10^6$ Gy/r_T^2/year (r_T= transverse distance to the beam)
- calorimeters in LHC experiments operating for $\sim$ 10 years...

Operation in magnetic field

HEP experiments often operated in high magnetic field:



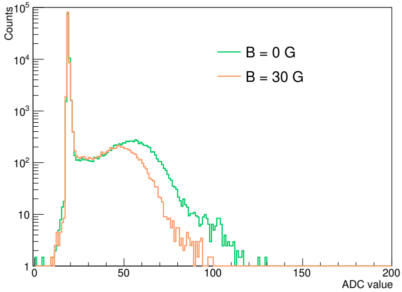
Principle of photon detection is to convert photons into electrons ⇒ photon detectors can be sensitive to magnetic field!

typical fields can be:

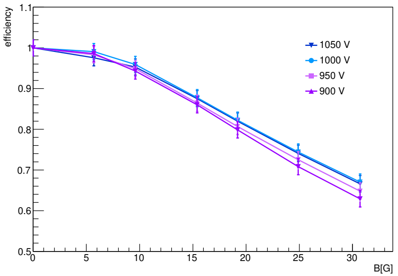
- Earth: 30-60 μT
- LHCb: 5 mT
- PANDA: 2T
- CMS: 4T

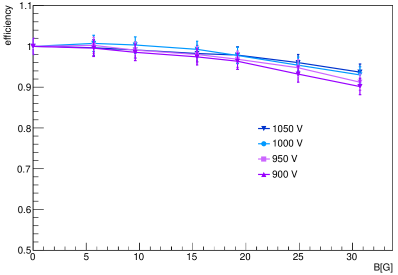
Photon detectors can be equipped with magnetic shield (using high permeability materials) to reduce the fringe field

Example of performance in magnetic field

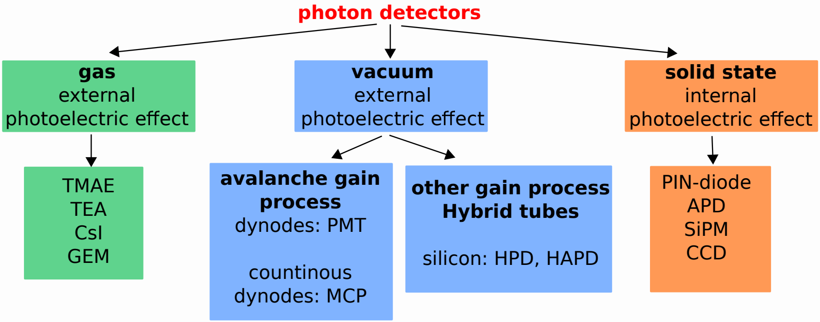


- example of magnetic field effect on MaPMTs
- electrons deviated by field $\Rightarrow$ reduction of gain and efficiency
- possible effects also on cross-talk between adjacent pixels
- in this case the performance is recovered by means of magnetic shield in mu-metal ($\sim$ 0.5 mm thickness)





Family tree



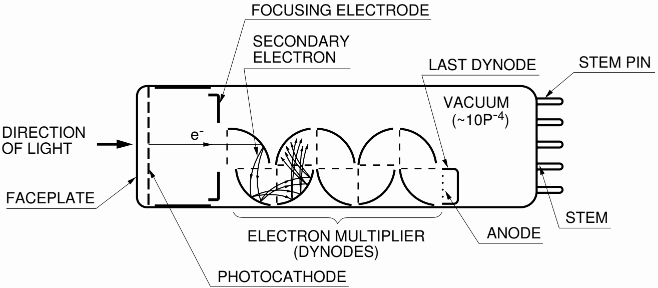
just the main (most used) types of photon detectors in this table

Photo-multiplier tubes (PMT)

photo-emission from photocathode
secondary emission from N dynodes (dynode gain ≈3-50 depending on incoming electron energy)

$$G = \prod_{i=1}^{N} g_i$$

for example: 10 dynodes with gain=4 ⇒ $G \approx 10^6$



- Input: few photons
- Output: sizeable current (100uA - 100mA)
- high photon detection efficiency
- very sensitive to magnetic field, even to Earth field ⇒ magnetic shield required

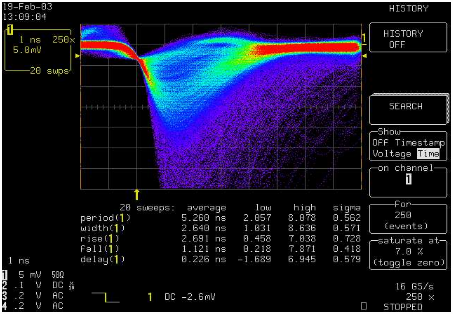
Photomultiplier tubes: brief history

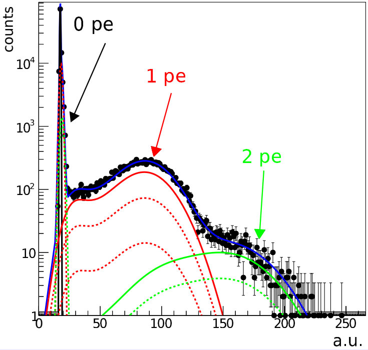
- 1887: photoelectric effect discovered by Hertz
- 1902: first report on a secondary emissive surface by Austin et al.
- 1905: Einstein: "Photoemission is a process in which photons are converted into free electrons."
- 1913: Elster and Geiter produced a photoelectric tube
- 1929: Koller and Campbell discovered compound photocathode (Ag-O-Cs; so-called S-1)
- 1935: Iams et al. produced a triode photomultiplier tube (a photocathode combined with a single-stage dynode)
- 1936: Zworykin et al. developed a photomultiplier tube having multiple dynode stages using an electric and a magnetic field
- 1939: Zworykin and Rajchman developed an electrostatic-focusing type photomultiplier tube
- 1949 & 1956: Morton improved photomultiplier tube structure

$\Rightarrow$ commercial phase, but still many improvements to come

Gain fluctuation

- mainly determined by the fluctuations of the number $m(\delta)$ of secondary electrons emitted from the dynodes
- secondary emission ratio δ is a function of the interstate voltage V: $\delta = \alpha V^k$ where k depends on structure and type of dynodes
- secondary emission at the first dynode is given by: $\delta_1 = \frac{I_{d1}}{I_k}$
- secondary emission at the n-th stage is: $\delta_n = \frac{I_{dn}}{I_{d(n-1)}}$
- anode current: $I_a = I_k \cdot \alpha\delta_1 \cdot \delta_2 \cdots \delta_n$
- fluctuations dominated by gain of first dynode
- if all the dynodes have the same interstate voltages: $G = A \cdot V^{kn}$



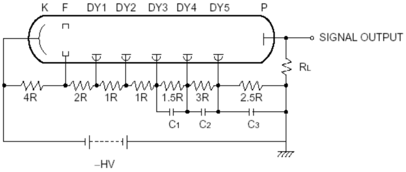


Linearity

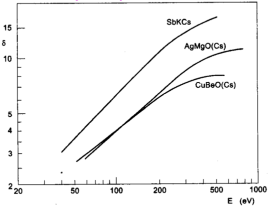
- "Bleeder chain":
  - typically: 8 … 14 dynode stages

    external circuit to define
    for dynode potentials
    & to recharge dynodes

  - bleeder current >> photo current



linearity on photo cathodes



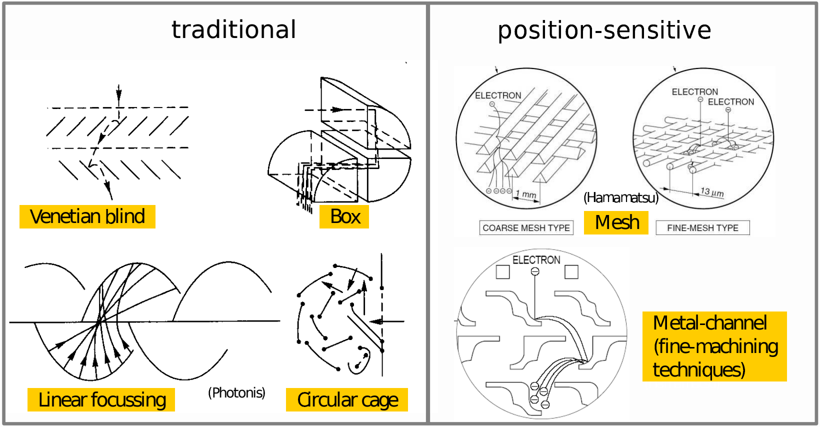
- Linearity limits from too large signals:
  - saturation effects for single pulses:
    - a) lack of local charge to replenish late dynodes

      → stabilise by capacities
  - saturation effects for "DC" illumination:
    - photo current ~ bleeder current
    - b) space charge between dynodes reduces eff. ΔV

      → reduce gain
    - c) current limit in PC and dynode materials spoils potentials

      → reduce gain

Dynode configuration

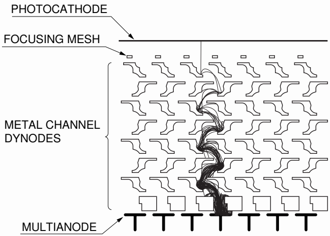


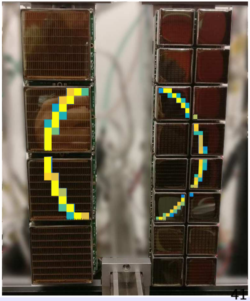
The design of a dynode structure is a compromise between:

- collection efficiency (input optics: from cathode to first dynode)
- gain (minimise losses of electrons during passage through structure)
- transit time and transit time spread (minimise length of path and deviations)
- immunity to magnetic field

Multi-anode Photomultiplier Tubes

position sensitive PMTs: up to 64 dynodes packed in a single tube 1inch side (pixel size 2x2mm^2)



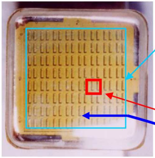


- active area ~80%
- low cross-talk (<2%)
- low dark count rate
- $G \sim 10^6$
- QE up to 45%
- TTS $\sim$ 150ps
- metallic packaging (kovar): resilient to magnetic field

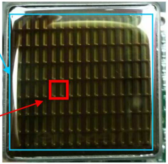
MaPMTs evolution

- Position sensitive PMT:
  - 8x8 metal channel dynode chains in one vacuum envelope (26x26 mm^2)
  - segmented anode:
    2x2 mm^2 $\rightarrow$ 2.3x2.3 mm^2
  - active area fraction:
    48% $\rightarrow$ 83%
  - low cross-talk
- Gain:
  - G = 1x10^6 at 900 V
- UV glass window
  - transparent down to ~200nm
- Bialkali photo cathode:
  - QE = ~25% at λ = 380 nm
  - super bialkali: $\rightarrow$ 34%
  - ultra bialkali: $\rightarrow$ 41%

1st generation



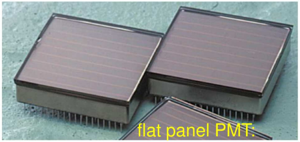
2nd generation



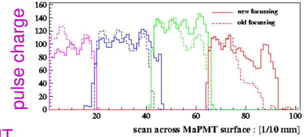
active area

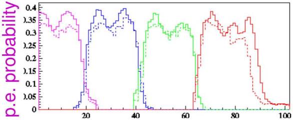
pixel

MaPMT window & electron focusing



variant 2nd generation MaPMT





Relative distance [0.1 mm]

End of part one