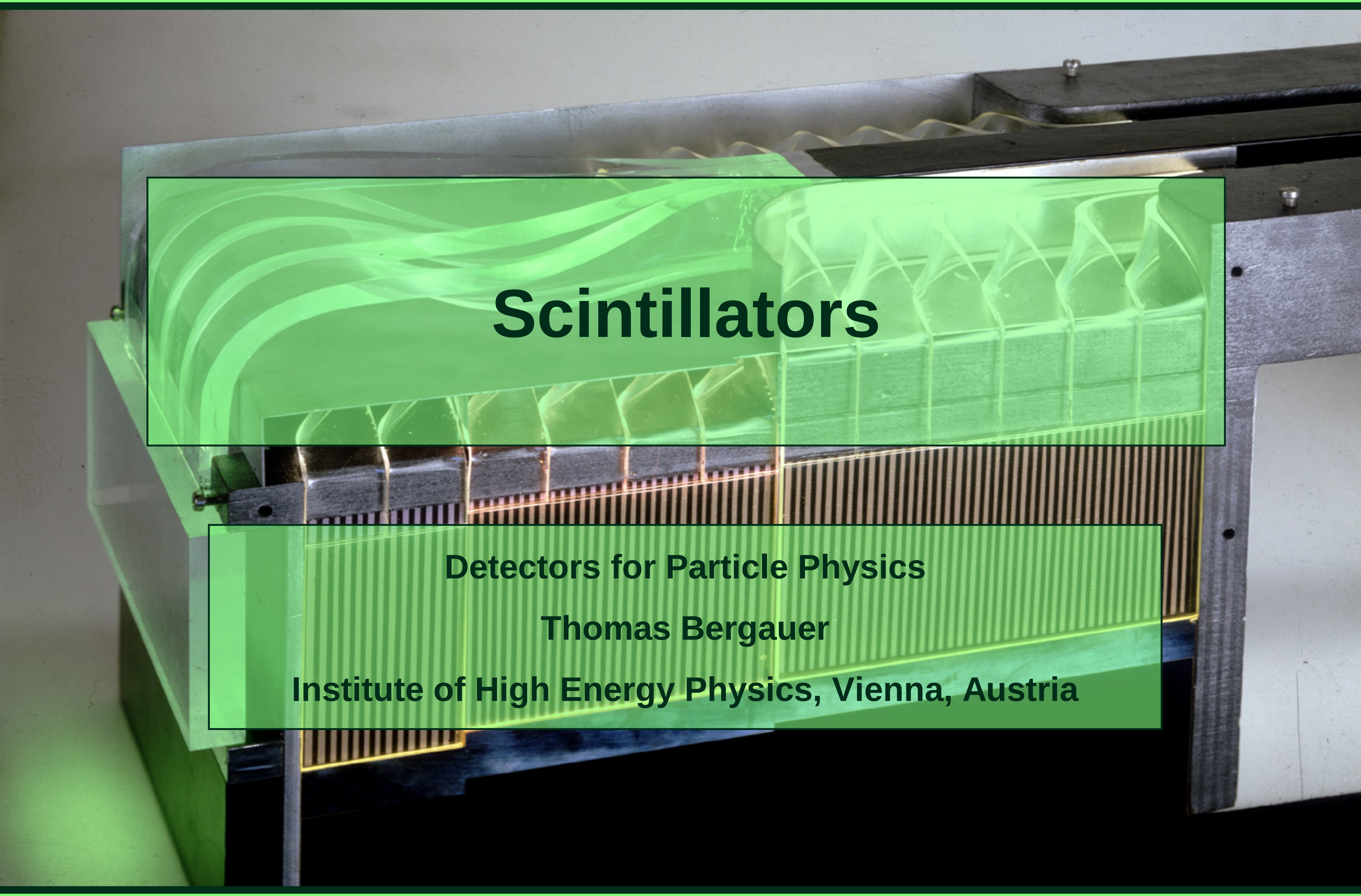


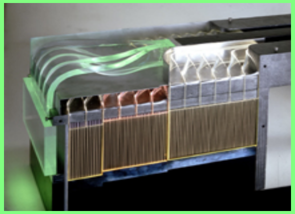
Scintillators

Detectors for Particle Physics

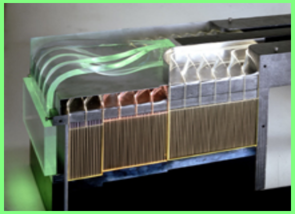
Thomas Bergauer

Institute of High Energy Physics, Vienna, Austria

5 Scintillators
Content

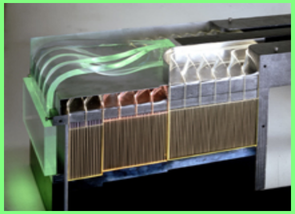


5.1 Definitions – 1



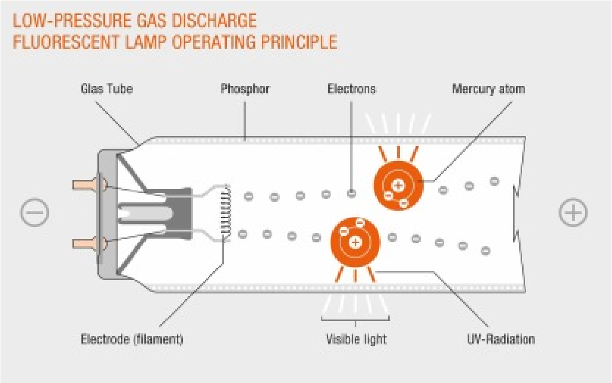
- Luminescence: Emission of photons (visible light, UV, X ray) after absorption of energy. Energy deposition in the material by
  - Light → Photoluminescence
  - Heat → Thermoluminescence
  - Sound → Sonoluminescence
  - Electric energy → Elektrolumineszence
  - Mechanical deformation → Triboluminescence
  - Chemical reactions → Chemoluminescence
  - Living organism → Bioluminescence
  - **Ionizing radiation → Scintillation**

- Scintillation: Emission of photons following the excitation of atoms and molecules by radiation (γ or particle radiation).



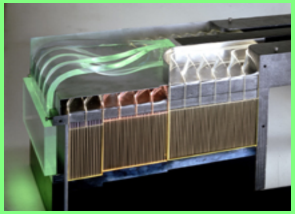
5.1 Definitions – 2

- Fluorescence: emission of light by a substance that has absorbed light or another electromagnetic radiation of a different wave length. In most cases the emitted light has a longer wavelength. The emission follows shortly after (appr. 10 ns).



- Phosphorescence: Similar to Fluorescence, however the re-emission is not immediate. The transition between energy levels and the photon emission is delayed (ms up to hours).

5.1 Parts of a Detector based on Scintillators

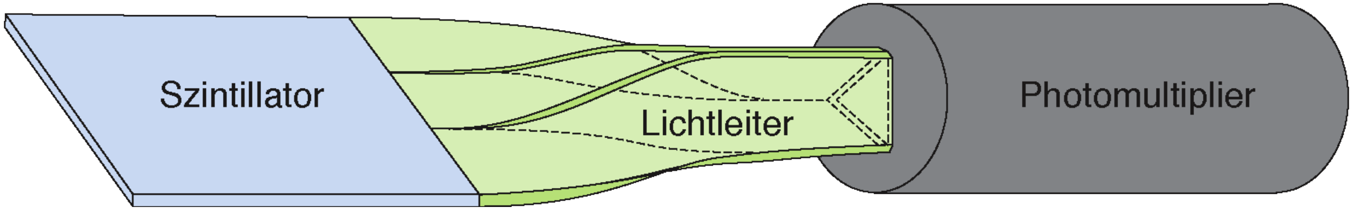


A scintillation detector consists of a scintillating material, often coupled to a light guide, and a photo detector.

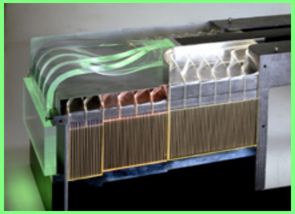
•The scintillating material converts γ- and particle-radiation into light (visible, UV, sometimes X-rays). Often a wavelength shifter is mixed to the primary scintillator.

•The light guide leads the light to the photo detector. Again a wavelength shifter is often used to match the wave length to the response characteristics of the photo cathode and hence improves the signal.

•The photo detector converts the light into an electric signal. Various photo detectors are applied, e.g. photo multipliers, SiPMs, gaseous detectors.

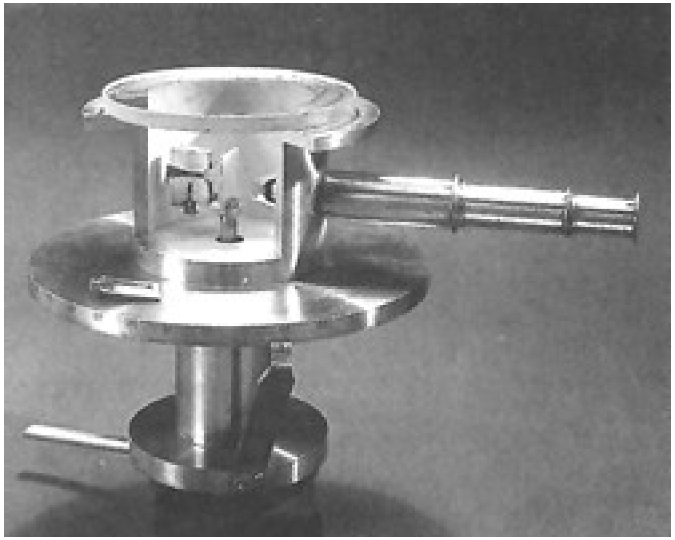


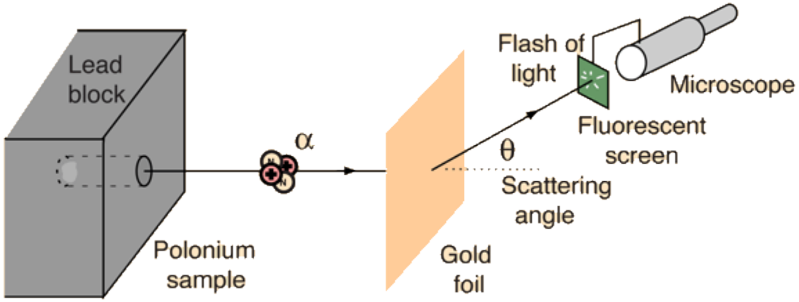
History



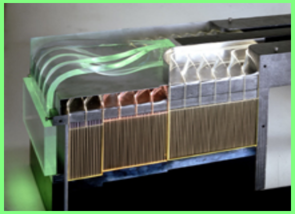
Rutherford's scattering experiment:

- Discovery of atomic nucleus with positive charge which holds most of its mass (1908-1913)
- Experiment:
  - Scattering of Alpha particles on thin metal (gold) foils)
  - Using microscope to count light flashes on ZnS (scintillation)

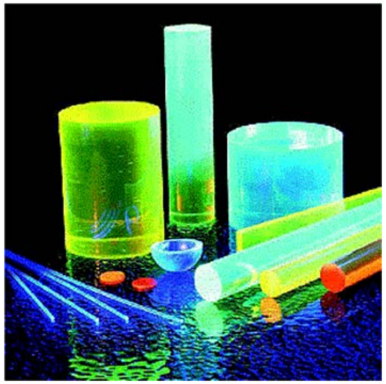




5.1 Scintillating Materials and Applications

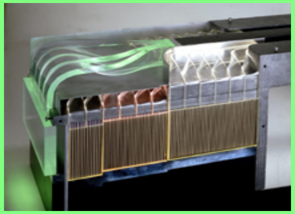


Various scintillators:



- Scintillating materials:
  - Inorganic crystals
  - Organic crystals
  - Organic liquids
  - Plastic scintillators
  - Nobel gases (gaseous and liquid)
  - Scintillating glasses
- Applications in nuclear- and particle physics:
  - Trigger detectors for slow detectors (e.g. drift chambers)
  - Time of flight counters (TOF-Counter)
  - Calorimeters
  - Position detectors (scintillating fibres)
  - Detection and spectroscopy of thermal and fast neutrons
  - Neutrino detectors (liquid scintillators)

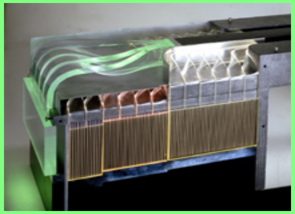
5.1 Basic Propoerties



- Advantages:
  - Fast response time (especially organic scintillators, ~ ns)
  - Sensitive to deposited energy
  - Construction and operation simple → cheap and reliable

- Disadvantages:
  - Aging (especially plastic scintillators)
  - Radiation damage (especially plastic scintillators)
  - Hygroscopic (especially inorganic crystals)
  - Low light output (especially gaseous scintillators)
  - In combination with the optical readout sensitive to magnetic fields (e.g. when using photo multipliers)

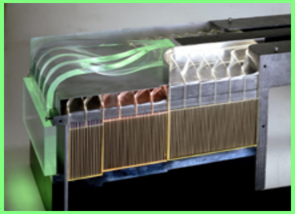
5.1 Requirements



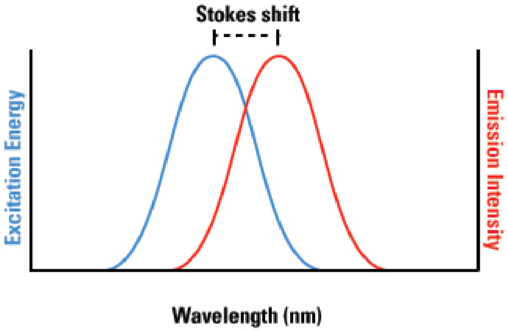
Many materials show luminescence. However, a useful scintillation detector has to fulfil the following requirements:

- High light yield Y_L, i.e. high efficiency to convert the excitation energy into fluorescence: $Y_L = \langle N_{photons} \rangle / E$
- Transparency with respect to the own fluorescence light. Otherwise the light is absorbed within the material itself.
- An emission spectra matched to the spectral sensitivity of the photo detector. Matching can also be achieved by introducing a wave length shifter.
- Refractive index of scintillator close to readout (glass in case of PMT)
- Short decay constant.

5.1 Light Output



- Only a few per cent of the deposited energy is transferred into light. The remaining energy is used up by ionisation, etc.
  - Emitted light usually of lower energy than deposited energy.
    → light shifted to longer wavelengths (Stokes shift)
  - In addition photons are lost in the scintillator itself (re-absorption) and in the light guide.



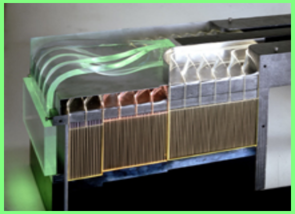
- Mean energy required to create a photon:
  - o Anthracen ($C_{14}H_{10}$): ~ 60 eV
  - o NaI:Tl:* ~ 25 eV
  - o BGO ($Bi_4Ge_3O_{12}$): ~ 300 eV

* Sodiom iodide doped with Thallium

- Anthracen or NaI are often used as reference material, i.e. the light yield is given in percentage of the yield of Anthracen or NaI.

5.1 Scintillators

Material properties of some important scintillators



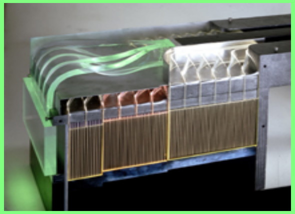
Material	Typ	Density [g/cm³]]	max. emission λ [nm]	Light output [% Anthracen]	Decay time* [ns]
NaI:Tl	Inorgan. Cristal	3.67	413	230	230
CsI	Inorgan. Cristal	4.51	400‡	500‡	600‡
BGO (= $Bi_4Ge_3O_{12}$)	Inorgan. Cristal	7.13	480	35–45	350
$PbWO_4$	Inorgan. Cristal	8.28	440–500	≈2.5	5–15
Anthracen	Organ. Cristal	1.25	440	100	30
trans-Stilben	Organ. Cristal	1.16	410	50	4.5
p-Terphenyl	In liquid solution, plastic	–	440	≈58	5
t-PBD	In liquid solution, plastic	–	360	–	1.2
PPO	In liquid solution, plastic	–	355	–	?

*main component

‡ at T = 77 K

http://www.mkt-intl.com/crystals/scintcrystal.htm; C. Grupen, *Teilchendetektoren*, B.I. Wissenschaftsverlag, 1993; W.R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer 1987

5.2 Inorganic Scintillators
Overview

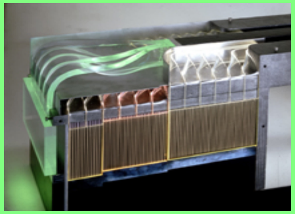


- Different types of inorganic scintillators:
  - Inorganic crystals
  - Glasses
  - Noble gases (gaseous or liquid)
- Scintillation mechanism is different for inorganic crystals, glasses and noble gases. The consequence are very different response times.

  → inorganic crystals, glasses: rather slow (compared to organic crystals)

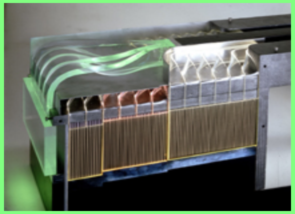
  → noble gases: fast
- Inorganic scintillators are relative radiation resistant.

5.2.1 Inorganic Crystals
Properties



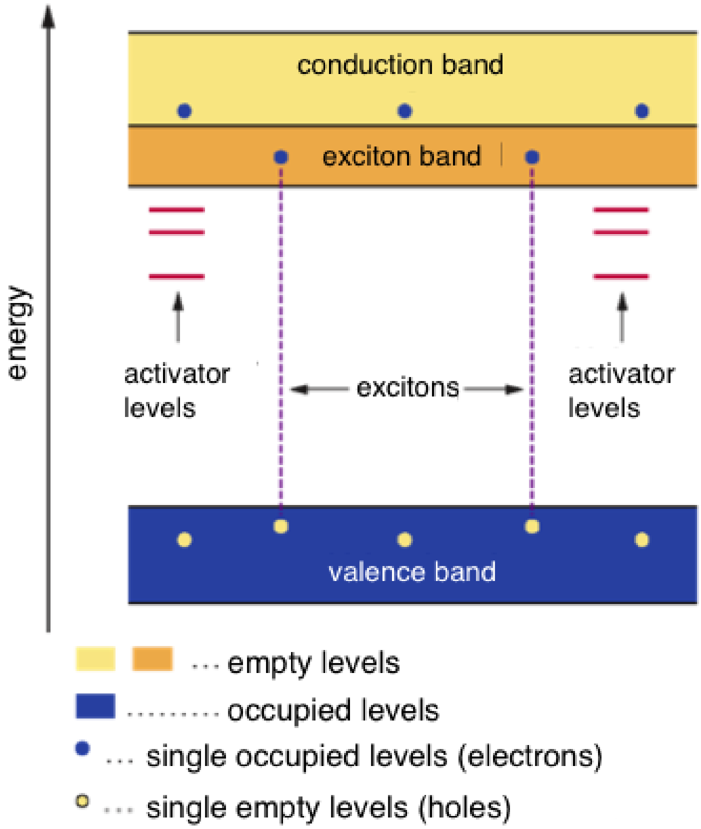
- Important inorganic crystals are:
  - NaI,CsI: as pure crystal or doped with Thallium ((NaI:Tl),(CsI:Tl))
  - BGO: $Bi_4Ge_3O_{12}$
  - GSO: Gadolinium silicate (Gd_2SiO_5), usually doped with Cer
  - BaF_2, CeF_3, $PbWO_4$
- Emitted light usuall at 400–500 nm. (NaI: 303 nm, CsI:Tl : 580 nm)
- Advantages:
  - High density, short radiation length X_0
  - High light output : ≈100%–400% of Anthracen
  - relative radiation resistant: especially: CeF_3, GSO, $PbWO_4$, (bad: BGO)
- Disadvantages:
  - Usually slower than organic Szintillatoren: Decay times a few hundred ns, Phosporescence.
    Exception: CsF_2 ~ 5 ns and $PbWO_4$ ~ 5–15 ns.
  - Some are hygroscopic: especially: NaI.
    BGO, $PbWO_4$,CeF3 are not hygroscopic.

5.2.1 Inorganic Crystals
Scintillation mechanism



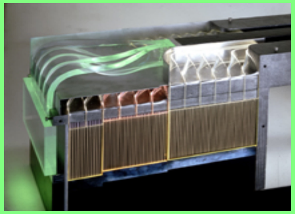
Inorganic crystals feature a band structure. The band gap between valance and conduction band is about 5-10 eV (Isolator).

- Absorbed energy excites electrons to the conduction band.
- Recombination causes the emission of a photon.
- The transition probability is in increased by activator centres (add. discrete energy levels). → doping is essential

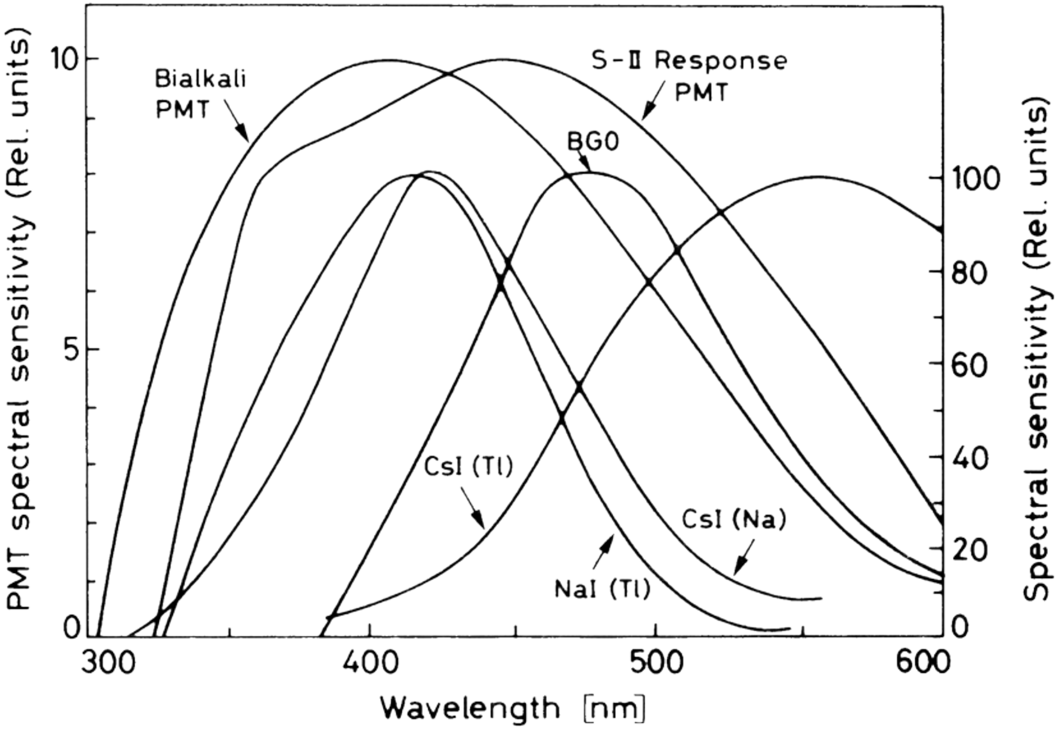


- Electrons could also be bound as excitons (coupled e-hole pairs). De-excitation causes also the emission of photons.

5.2.1 Inorganic Crystals
Emission spectra

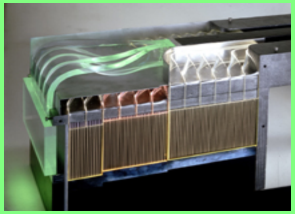


Emission spectra of various inorganic crystals (right axis) and spectral sensitivity of two typical photo multipliers (left axis):



W.R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer, 1987

5.2.1 Inorganic Crystals
Application

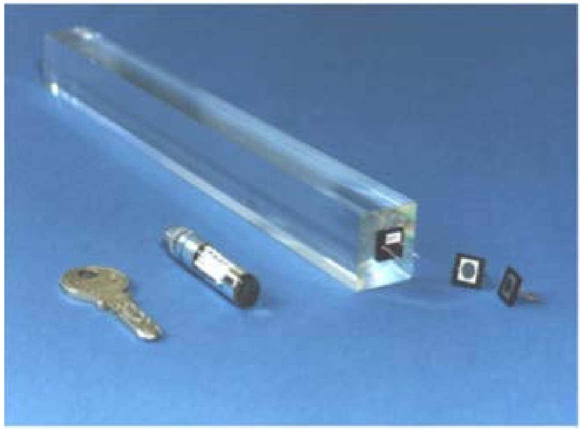


- The light output of inorganic crystals is in good approximation linear to the energy deposited by high energy particles.
- Inorganic crystals are perfect devices for homogeneous calorimeters (see chapter calorimeter).

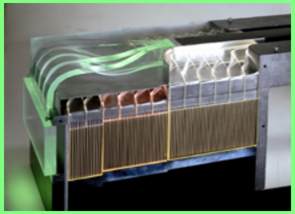
Examples:

Electromagnetic calorimeter of L3: BGO crystals, short radiation length (1.11 cm), very sensitive to temperate (-1,5% variation per ° C)

Electromagnetic calorimeter of CMS: PbWO4 crystals, also short radiation length, fast and very radiation hard.

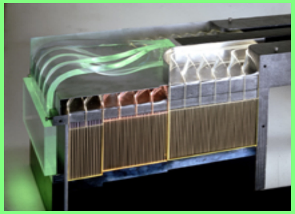


5.2.2 Scintillating Glasses



- A typical scintillating glass is Cer ($_{58}Ce$) doped with Lithium- or Boron-silicate.
- High melting point and high resistance against organic and inorganic substances (except hydrofluoric acid) → Application under extreme conditions.
- Light yield is relatively low, ~25–30% of Anthracen.
- Application of scintillating glasses predominantly as neutron detector (detectors also sensitive to β and γ radiation). Sensitivity to slow neutrons is increased by enrichment of Lithium component with ^6Li.

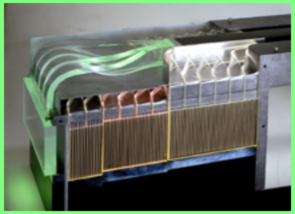
5.2.3 Scintillating Noble Gases



- Scintillating gases used: Helium, Xenon, Krypton and Argon (partially also
  - Nitrogen)
- The fluorescence mechanism in noble gases is a purely atomic process and the life time of the excited states is therefore short.
- Scintillating noble gas detectors are very fast, response time ≤ 1 ns.

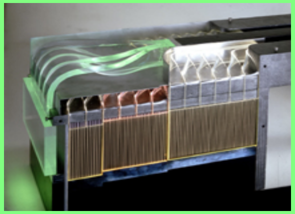
- The emitted light is in the UV range. In this range classic photomultipliers are not sensitive. The use of wave length shifters is mandatory (e.g. as coatings on the walls)
- Due to the relative low density the light yield of gaseous scintillators is low. Can be compensated by high pressure operation (up to 200 atm).
- Liquid noble gas scintillators used in experiments searching for dark matter: e.g. XENON100 at LNGS, Italy, 161 kg LXe, 242 PMTs (see picture)

5.3 Organic Scintillators
Overview

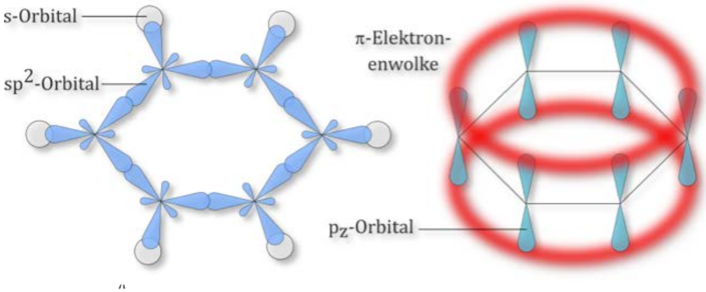


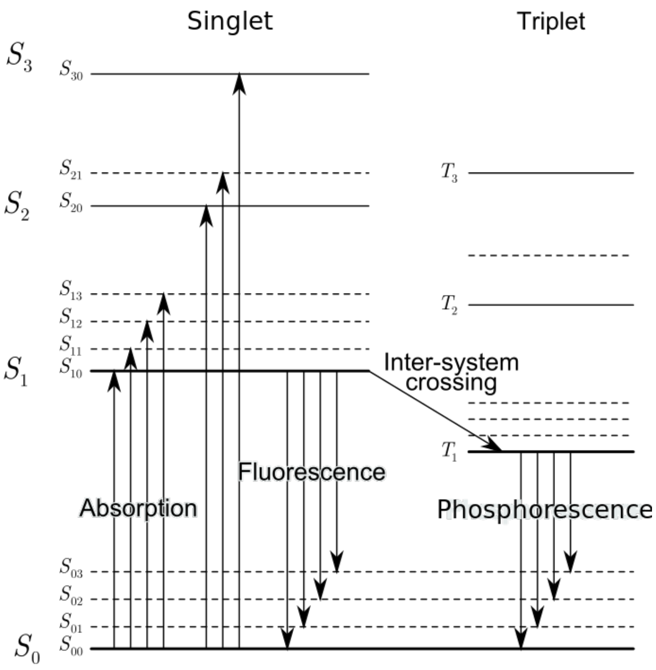
- Different types of organic scintillators:
  - Organic crystals
  - Organic liquids
  - Plastic scintillators
- Organic scintillators are aromatic hydrocarbon compounds (containing benzene ring compounds)
- The scintillation mechanism is due to the transition of electrons between molecular orbitals → organic scintillators are fast ~ few ns.
- Organic crystals consist of only one component
- Liquid- und Plastic scintillators are usually composed of 2–3 components:
  - Primary scintillator
  - Secondary scintillator as wave length shifting component (optional)
  - Supporting material

5.3 Organic Scintillators
Work Principle

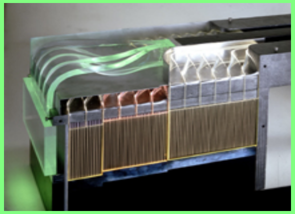


- defined by electron configuration of carbon
  - Organic = carbon atoms
- Benzol (C_6H_6): p-orbital contains weakly bound π-electrons
- Scintillation principle:
  - Excitation to $S_{1,i}$ $S_{2,i}$ $S_{3,i}$ levels
  - radation-less drop to S1(~ ps)
  - Fluresence at S_1 -> S_0 ~ 3-4eV (400-300nm) in ns



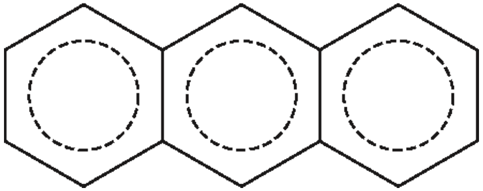


5.3.1 Organic Crystals

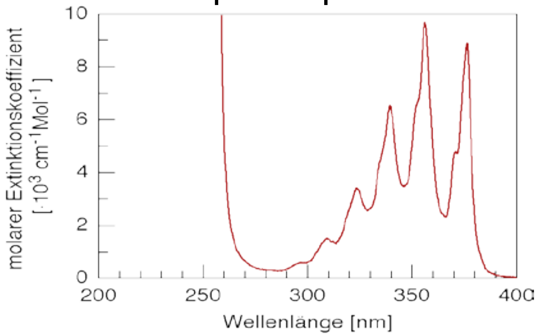


- Important organic scintillating crystals:
  - Naphtalen ($C_{10}H_8$)
  - Anthracen ($C_{14}H_{10}$)
  - trans-Stilben ($C_{14}H_{12}$)
- Advantages: Fast fluorescence: few ns (exception: Anthracen ~ 30 ns)
  Mechanically strong (exception: Stilben brittle)
- Disadvantages: Anisotropic light output: "channeling" effect in crystals
  Mechanically difficult to process (fragile)

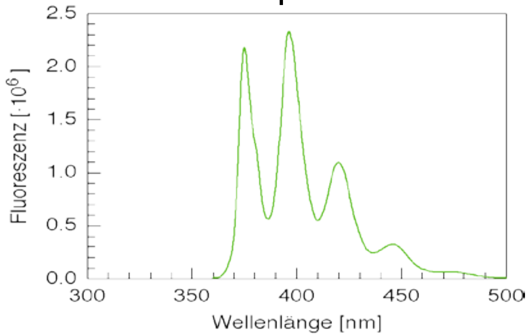
e.g. Anthracen:



Absorption spectrum:

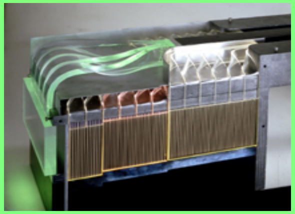


Emission spectrum:



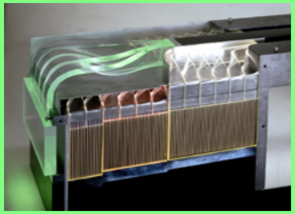
http://omlc.ogi.edu/spectra/PhotochemCAD/html; generated with PhotoChemCAD
(H. Du, R. A. Fuh, J. Li, A. Corkan, J. S. Lindsey, *Photochemistry and Photobiology*,**68**, 141-142, (1998)).

5.3.2 Organic Liquid Scintillators

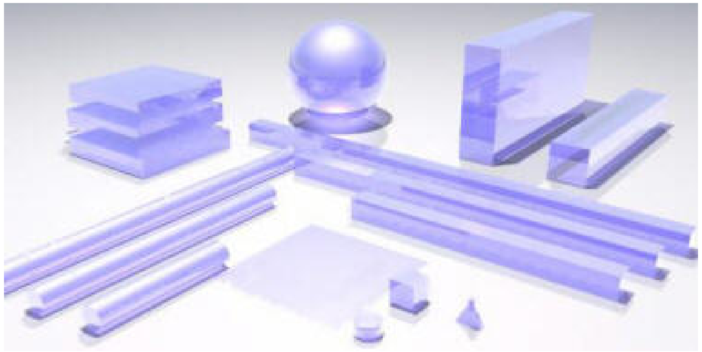


- Important liquid scintillators:
  - p-Terphenyl ($C_{18}H_{14}$)
  - PPO (2,5-Diphenyloxazol; $C_{15}H_{11}NO$)
  - PBD (2-Phenyl,5-(4-Biphenylyl)-1,3,4-Oxadiazol; $C_{20}H_{14}N_2O$)
- Mixture of one or several organic scintillators in an organic solvent (typ. 3 g per liter solvent).
- Important solvents (itself scintillators, but low efficient)
  - Benzol (C_6H_6)
  - Toluol (C_7H_8)
  - Xylol (C_8H_{10})
  - Phenylcyclohexan ($C_{12}H_{16}$)
  - Triethylbenzol
  - Decalin ($C_{10}H_{18}$)
- Properties:
  - Fast fluorescence: ca. 3–4 ns
  - Any possible detector shape
  - Easy use of additives (wave length shifter, additive to increase neutron cross section, etc.)
  - Very sensitive to impurities (especially Oxygen)

5.3.3 Plastic Scintillators

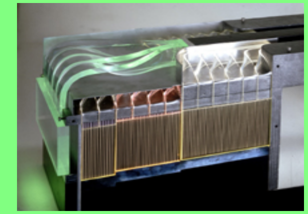


- Polymerisation of liquid scintillators
  - Almost any shape (perfect for HEP application)
- Advantages:
  – Fast fluorescence: ≤ 3 ns
  – Easy to machine, cheap
- Disadvantage:
  – Not very radiation resistant



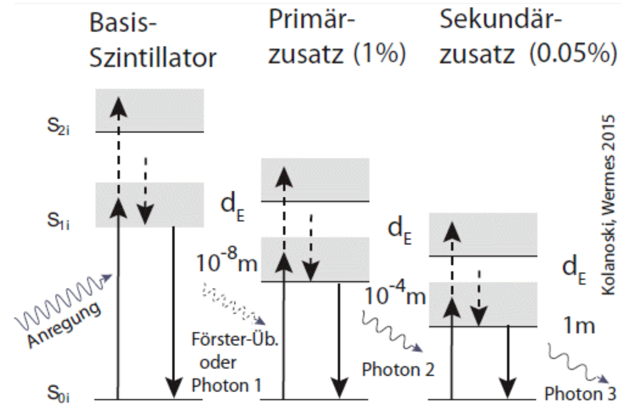
- The support structure is a polymere matrix containing a primary scintillator
  – matrix materials: Polyvinyltoluol, Polyphenylbenzol, Polystyrol, PMMA
  – Primary scintillators: p-Terphenyl, PPO, t-PBD,…
  – Wave length shifter: POPOP, BBQ,…
- Plastic scintillators used in numerous applications in particle and nuclear physics.

5.4 Wave Length Shifter



Wave length shifter absorb photons of a certain wave length and re-emit photons at a different wave length (usually larger) to better match the scintillator light to the read out device (Stokes shift)

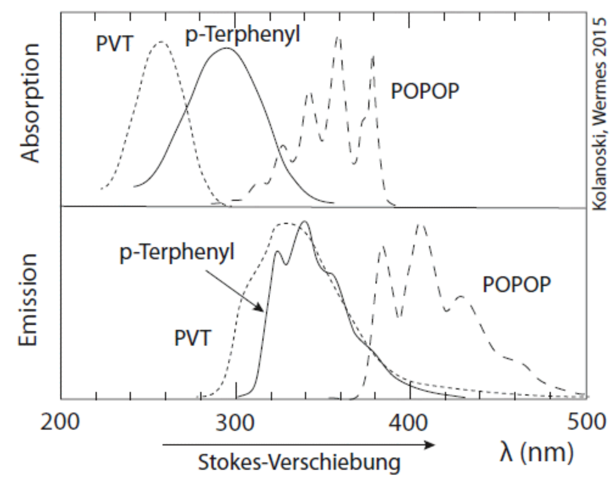
- Necessary to make scintillator transparent (reduce self-absoption)



(a) Wellenlängenschiebung: Prinzip

Important wave length shifter materials:

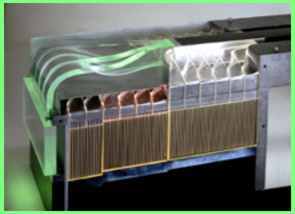
- POPOP (1,4-bis-[2-(5-Phenyloxazolyl)]-Benzen; $C_{24}H_{16}N_2O_2$)
- bis-MSB (1,4-bis(2-Methylstyryl)-Benzen; $C_{24}H_{22}$)
- BBQ (Benzimidazo-Benzisochinolin-7-on)



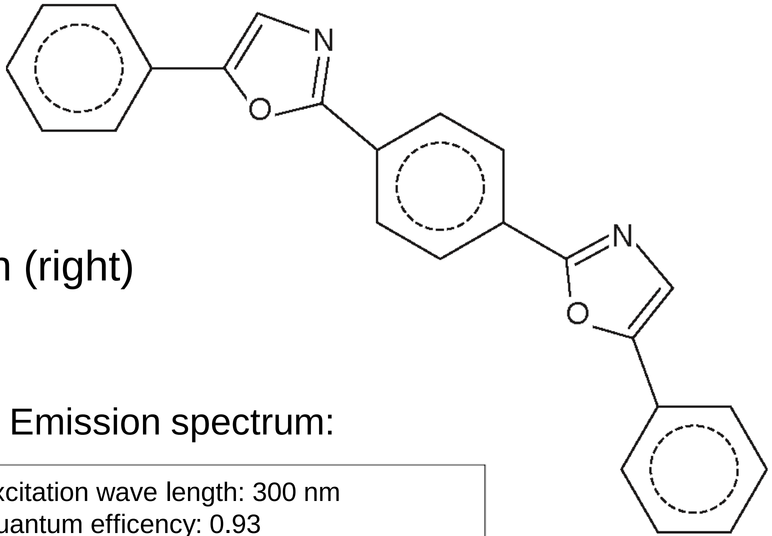
Wave length shifter can be mixed into the scintillator or integrated into the light guide.

5.4 Wave Length Shifter

Example POPOP – Structure und Spectra

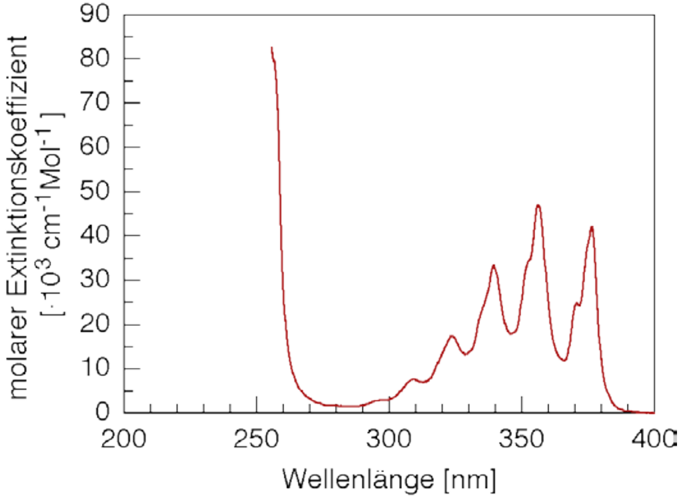


Chemical formula and structure of POPOP
(1,4-bis-[2-(5-Phenyloxazolyl)]-
Benzen; $C_{24}H_{16}N_2O_2$)

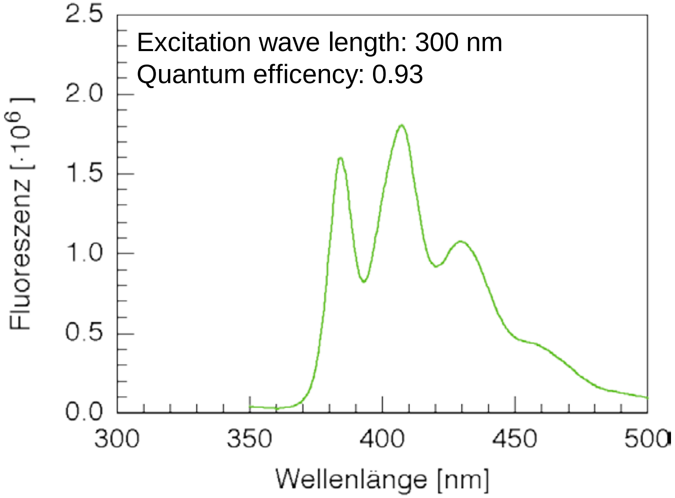


Spectra for absorbtion (left) and fluorescence emision (right)
POPOP (disolved in Cyclohexan).

Absorption spectrum:

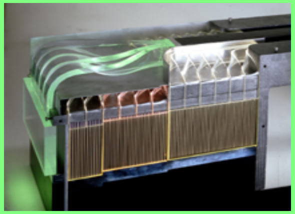


Emission spectrum:



http://omlc.ogi.edu/spectra/PhotochemCAD/html; generated with PhotoChemCAD
(H. Du, R. A. Fuh, J. Li, A. Corkan, J. S. Lindsey, *Photochemistry and Photobiology*,**68**, 141-142, (1998)).

5.3 Organic Scintillators
Light output



The dependence of light output from energy deposition is usually not linear in organic scintillators.

A high density of excited molecules along the particle track causes de-excitation without photon emission (quenching effect).

→ Light output becomes saturated

Light output described by Birks law:

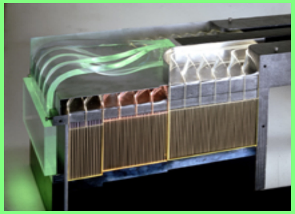
$$\frac{dL}{dx} = \frac{S\,\frac{dE}{dx}}{1 + K_B\,\frac{dE}{dx}}$$

dL/dx … Light output per path length
dE/dx … Energy loss per path length
S …… scintillation efficiency
K_B …… Birks constant

K_B needs to be determined experimentally. Typical numbers 10^{-2} g/(cm^2 MeV)

Plastic scintillators of 1cm thickness: 20.000 photons/mip

5.1 Signal Shape



- Many scintillators show a simple exponential signal decay. In case of several signal components overlap has to be considered.
- The rise time of the signal is usually very fast.

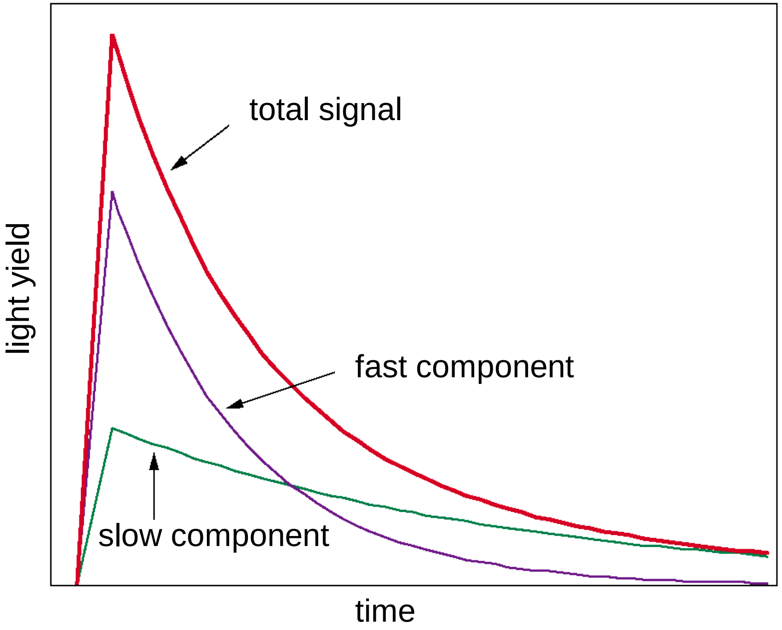
Signal of a scintillator with a short and slow signal:

$$N(t) = A \cdot \exp\left(\frac{-t}{\tau_f}\right) + B \cdot \exp\left(\frac{-t}{\tau_s}\right)$$

t … time; A, B … proportional factors

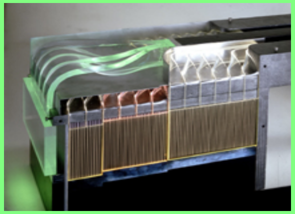
$N(t)$… number of emitted photons at time t

τ_f, τ_s … decay constants for fast and slow component



Signal vs. time of a scintillator with fast and slow component.

5.5 Light Guides



Often scintillators cannot be directly coupled to the read out device for space constraints or magnetic fields. The shape of the scintillator also rarely matches the shape of the photo detector → use light guides for coupling!

Light is guided by total reflexion (surfaces polished and with reflective coating)

However, density of photons cannot be compressed (Liouville Theorem)
The maximum light transferred is proportional to the ratio of surface cross sections of light guide output to input.

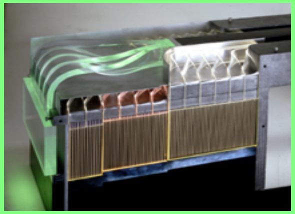
$$\frac{I_{out}}{I_{in}} \le \frac{A_{out}}{A_{in}} \qquad (A_{out} \le A_{in})$$

A … Surface cross section
I_{in} … total light intensity

The shape of the light guide is irrelevant. Sharp kinks have to be avoided.

Commonly used material PMMA (Polymethylmethacrylat), often with wave length shifter material added.

5.5 Light Guides
Example



Light guide: flat top couples to scintillator, round bottom to photo detector.

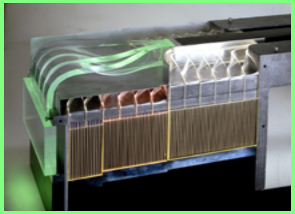
http://www.brantacan.co.uk/LightGuide1.jpg

Adiabatic light guide:

CERN Microcosm Ausstellung, Photo: M. Krammer

5.5 Scintillator detector System

Example

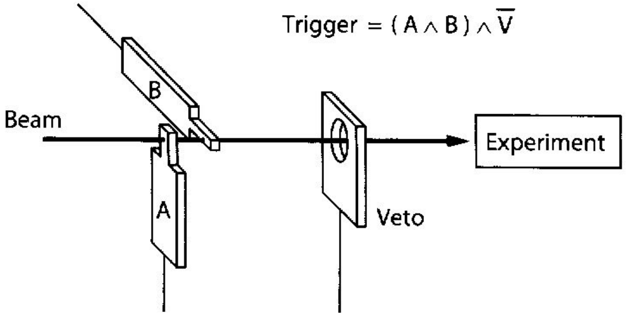


- Full System consists of:
  - Scintillator, light-tight packed
  - Light guide
  - Photomultiplier (+ base + shielding)

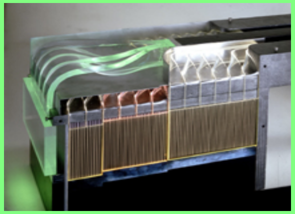
- Typical application:

  Trigger generator for beam tests

  - Coincidence of two scintillators
  - Third one for Veto



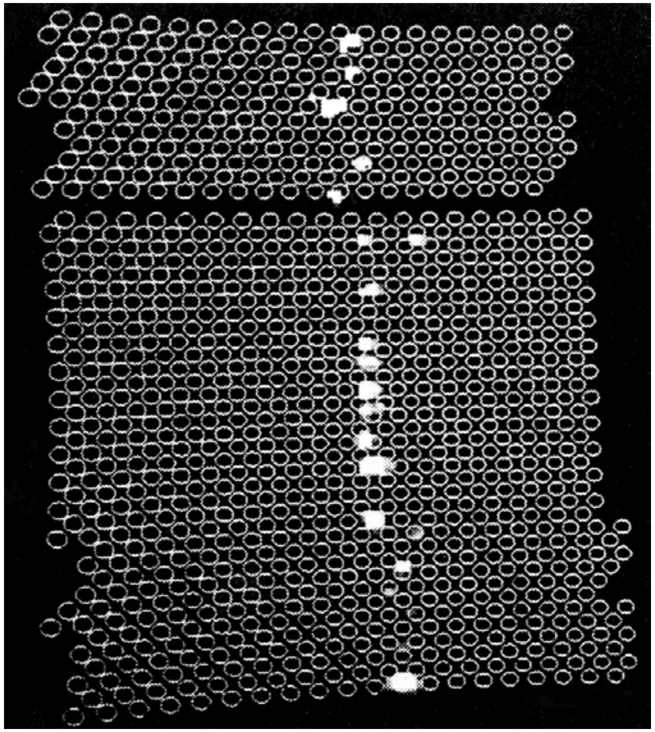
5.6 Scintillating Fibers



- Different fiber technologies:
  - Plastic fibers
  - Glass fibers
  - Capillaries, filled with scintillating liquid

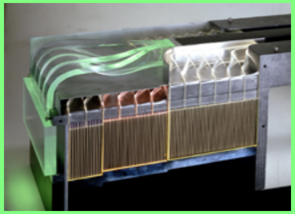
- Scintillating fibers are used in:
  - Calorimeters
  - Pre-shower detectors
  - Position sensitive detectors

Particle track in a stack of scintillating fibers.
Fiber diameter 1 mm.

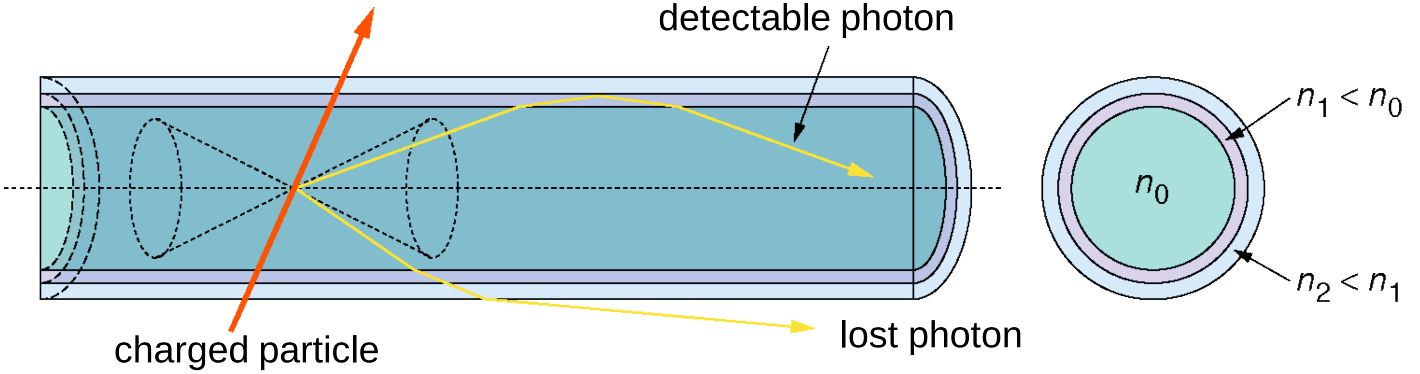


C. Grupen, *Teilchendetektoren*,
B.I. Wissenschaftsverlag, 1993

5.6 Scintillating Fibers
Plastic fibers

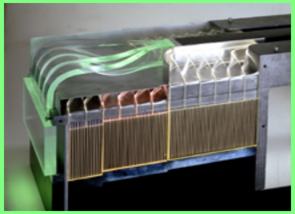


- Core made of Polystyrol or Polyvinyltoluol (refraction index n_0). Inserted is a primary scintillator and often a wave length shifter additive.
- The core is surrounded by at least one thin sheet of a material with refraction index $n_1 < n_0$ ➔total reflection at the boundary.
- Only a small fraction of the emitted light remains in the fiber and is forwarded by total reflection.



Longitudinal and cross section of a scintillating fiber with two sheets. Shown is a through going charged particle with 2 emitted photons and the allowed opening angle for total reflection.

5.6 Scintillating Fibers
Examples



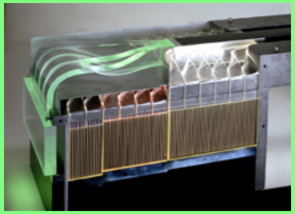
Scintillating fibers for the electromagnetic calorimeter of the CHORUS experiment (SPS, CERN)

CERN Photodatabase, Photo number: CERN-EX-9201043, http://cdsweb.cern.ch/

Scintillating fibers for the MINOS detector (Fermilab), fiber diameter 1 mm.

Leon Mualem, Presentation at the 2nd NuMI Off-Axis Experiment Detector Workshop, Argonne National Laboratory, April 2003

5.7 Photo Detectors



Different photo detectors used to read light from scintillators and transform it into electric signals:

•“Classical” Photomultipliers

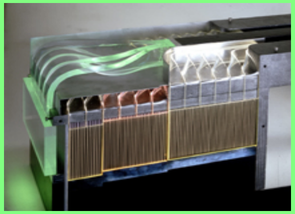
•“New” silicon devices: APD, SiPM

•Hybrid Photon Detectors HPD

•Gaseous Detectors

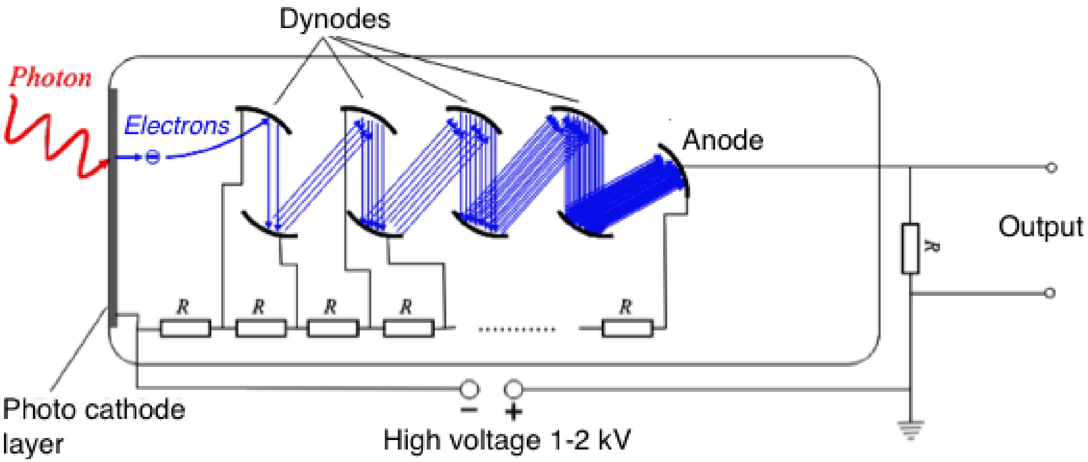
This subchapter gives only an overview of the most commonly used photo detectors. Photo detectors exist in huge variety!

5.7.1 Photomultipliers



Photons hitting the photo cathode release electrons (photoelectric effect). The electrons are accelerated towards the 1st dynode and produce secondary emission. This process is repeated at each dynode and finally the largely amplified electrons reach the anode.

Quantum efficiency 10 – 30% depending on wave length, entry window material, photo cathode.

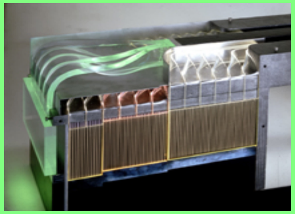


(Hamamatsu)

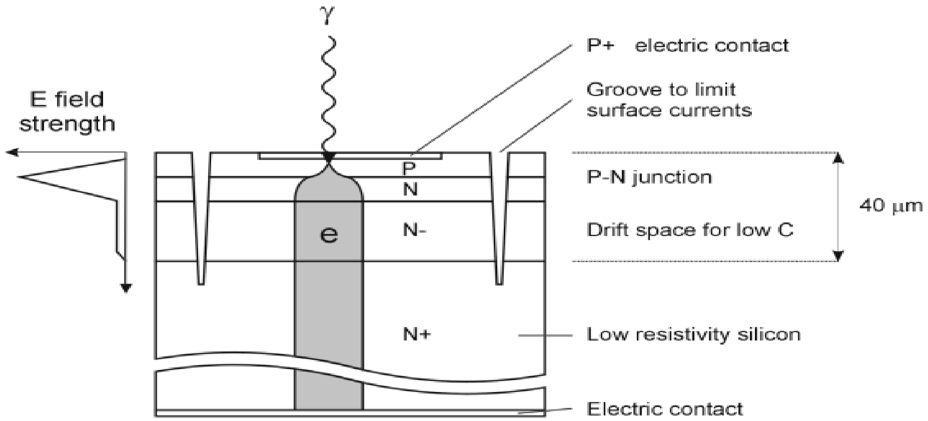
Advantages: high amplification gains $10^4 – 10^7$
Disadvantage: sensitive to magnetic fields

Other similar devices: Multi-anode and flat PMT's, Micro Channel Plate (MCP) PMT's

5.7.2 APD, SiPM

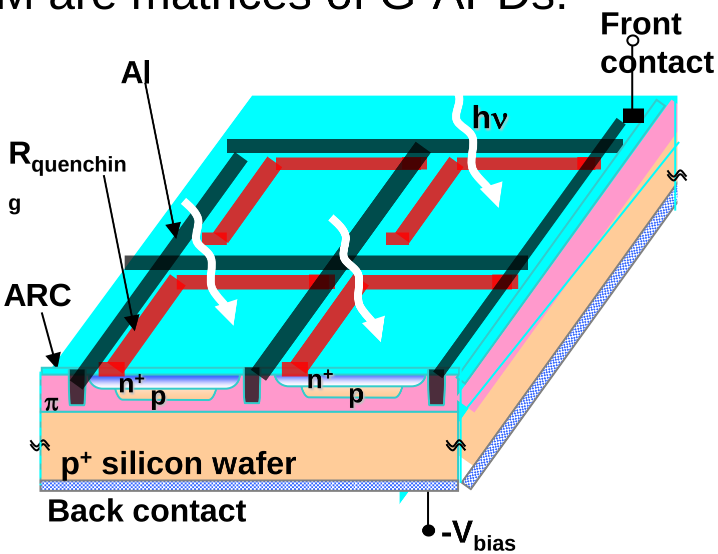


Avalanche Photo Diodes (APDs) are silicon devices operated in reverse bias mode in the breakdown regime. Geiger mode APDs (G-APD) operate in full breakdown, current limited by quenching resistor



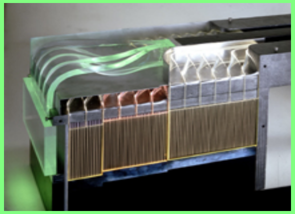
D. Renker, Nucl. Instr. Methods A 571 (2007) 1-6

SiPM are matrices of G-APDs:



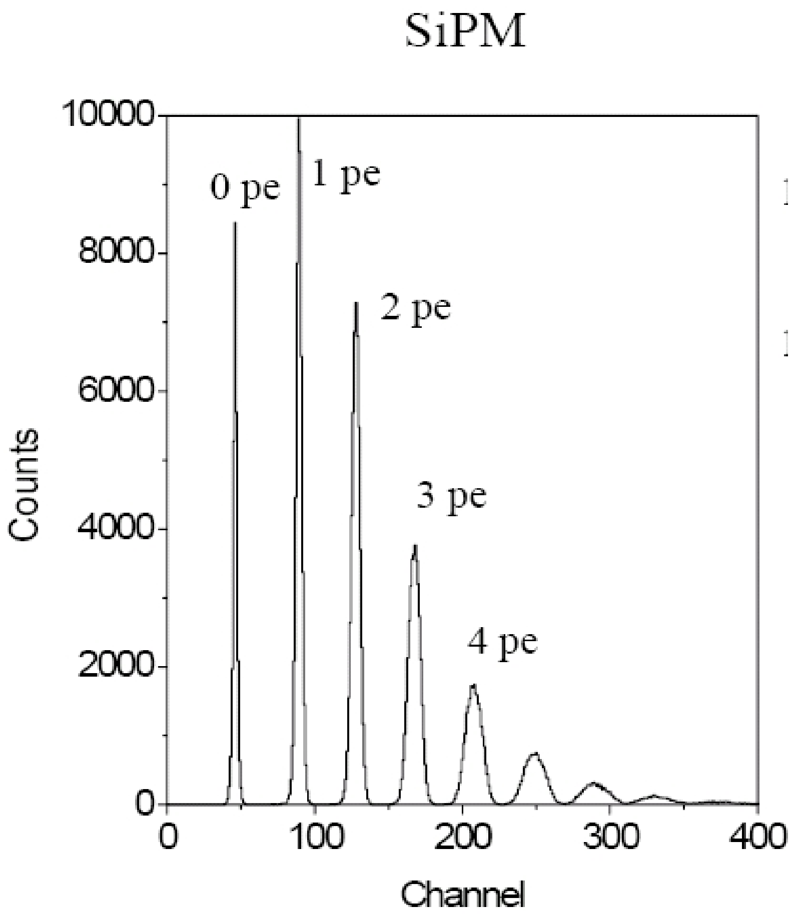
SiPM become more and more popular as replacement for standard photo multipliers.

5.7.2 SiPM
Properties



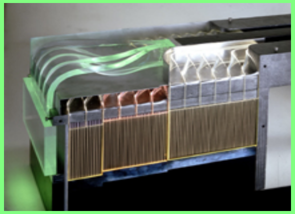
- APDs (operated in Geiger mode) can detect single photons!
- High gain in the range of 10^5 to 10^7
- Work at low bias voltage ~50 V
- Low power consumption
- Insensitive to magnetic fields
- Radiation hard
- Tolerant against accidental illumination
- Cheap

But high dark counts!

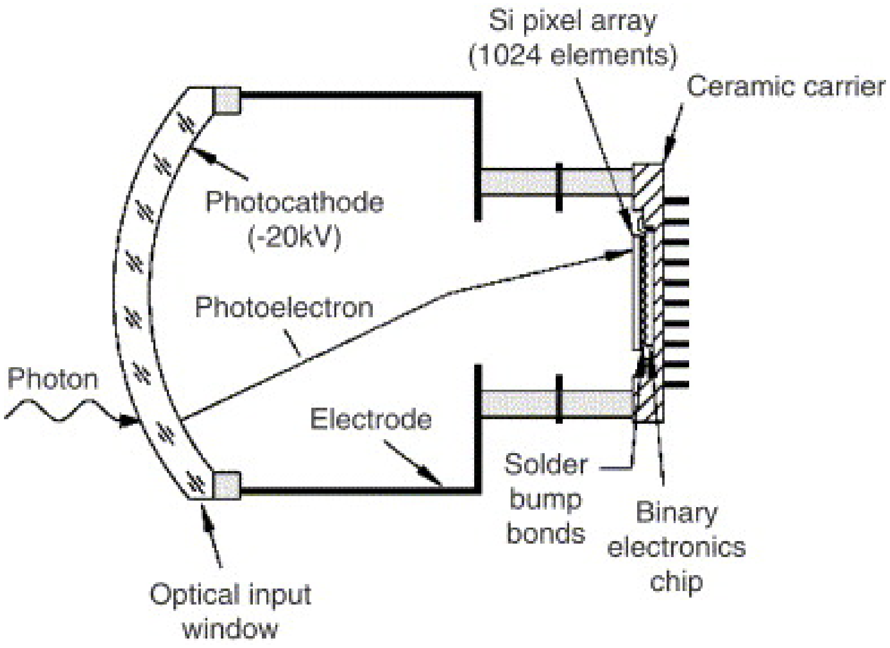


P. Buzhan et al., Nucl. Instr. Methods A 504 (2003) 48

5.7.3 Hybrid Photon Detectors (HPD)

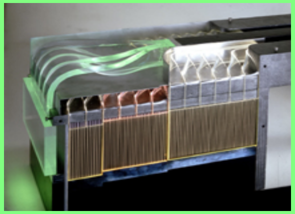


Photoelectrons are accelerated in vacuum (20 kV) and detected with a silicon hybrid pixel detector.



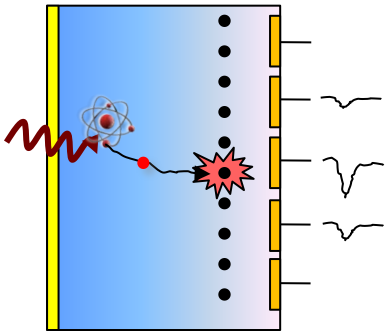
S. Eisenhardt, Nucl. Instr. Methods A 565 (2006) 234

5.7.4 Gaseous Photo Detectors



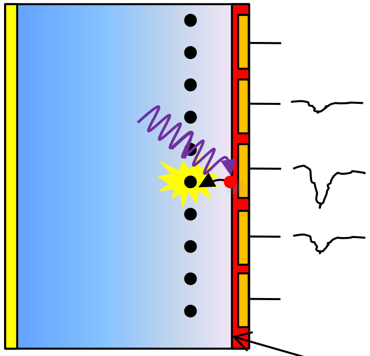
Two techniques:

•Photo sensitive additive (TMAE, TEA) mixed to counter gas:



or

•Solid photo cathode deposited:



The photoelectrons trigger an avalanche ➔ gas amplification.