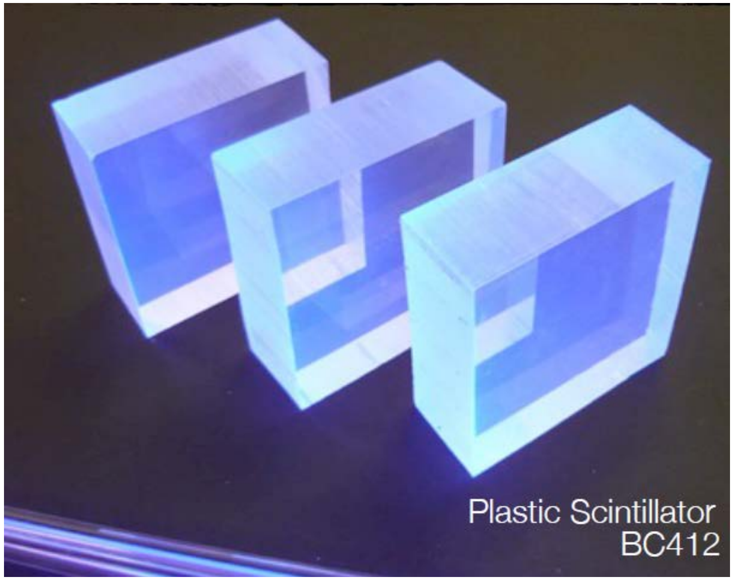
Scintillators – General Characteristics



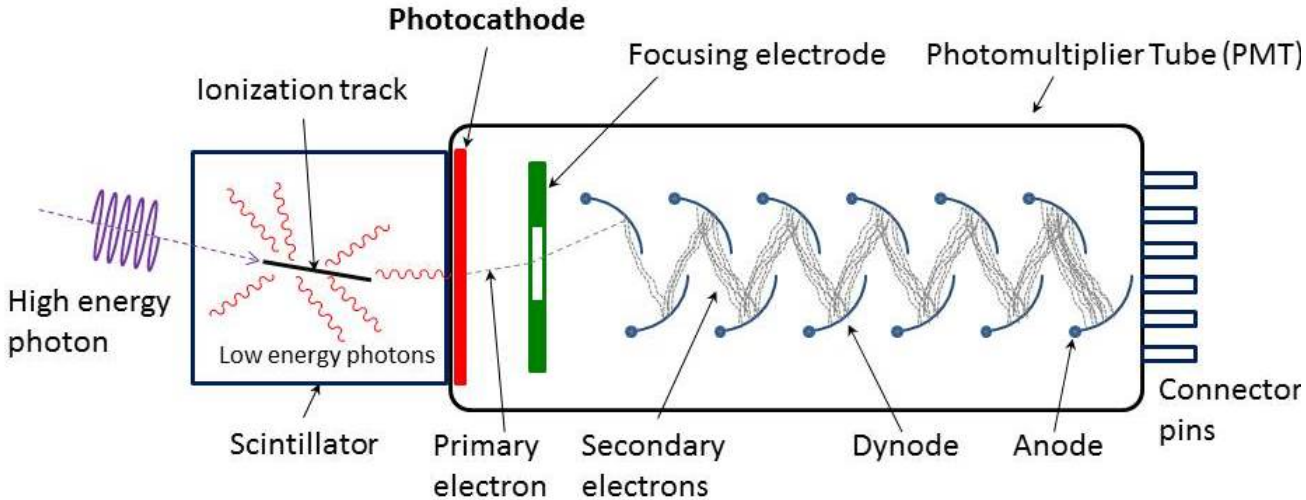
Principle:
dE/dx converted into visible light
Detection via photosensor
[e.g. photomultiplier, human eye …]

Main Features:
Sensitivity to energy
Fast time response
Pulse shape discrimination

Requirements
High efficiency for conversion of excitation energy to fluorescent radiation
Transparency to its fluorescent radiation to allow transmission of light
Emission of light in a spectral range detectable for photosensors
Short decay time to allow fast response

Scintillators – basic counter setup

1. An incident photon or particle ionizes the medium.
2. Ionized electrons slow down causing excitation.
3. Excited states immediately emit light.
4. Emitted photons strike a light-sensitive surface.
5. Electrons from the surface are amplified.
6. A pulse of electric current is measured.



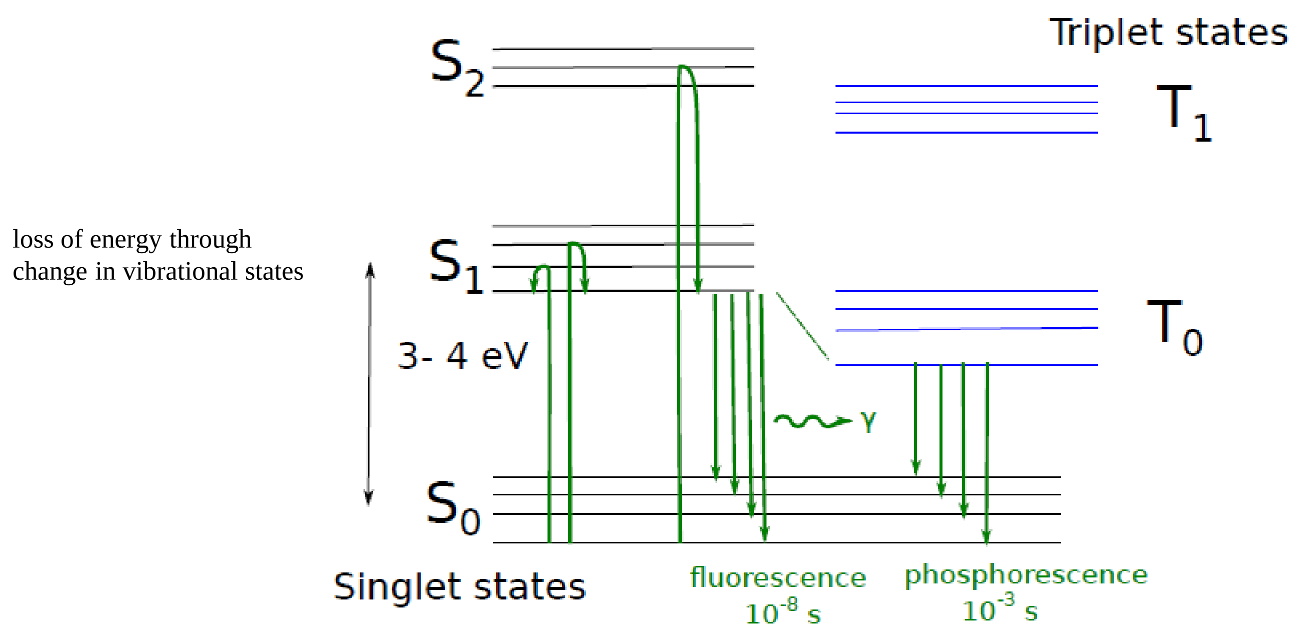
Scintillation materials:

- Inorganic crystals
- Organic scintillators
- Polymeres (plastic scintillators)

Photosensors:

- Photomultipliers
- Micro-Channel Plates
- Hybrid Photo Diodes
- Visible Light Photo Counter
- Silicon Photomultipliers

Scintillation counters



- Luminescence: Emission of photons (visible light, UV, X-ray) after absorption of energy.
- Scintillation: Emission of photons following the excitation of atoms and molecules by radiation.
- 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 ~ 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)

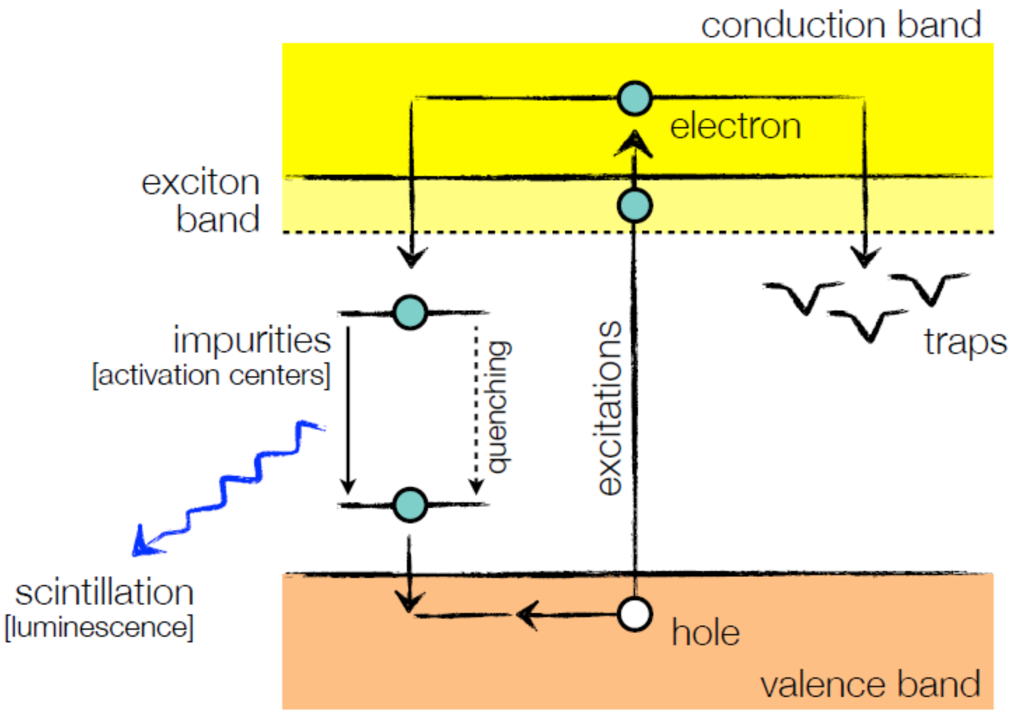
Inorganic crystals

❖ **Materials:**

Sodium iodide (NaI)
Cesium iodide (CsI)
Barium fluoride (BaF_2)
…

❖ **Mechanism:**

Energy deposition by ionization
Energy transfer to impurities
Radiation of scintillation photons



Energy bands
in impurity activated crystals

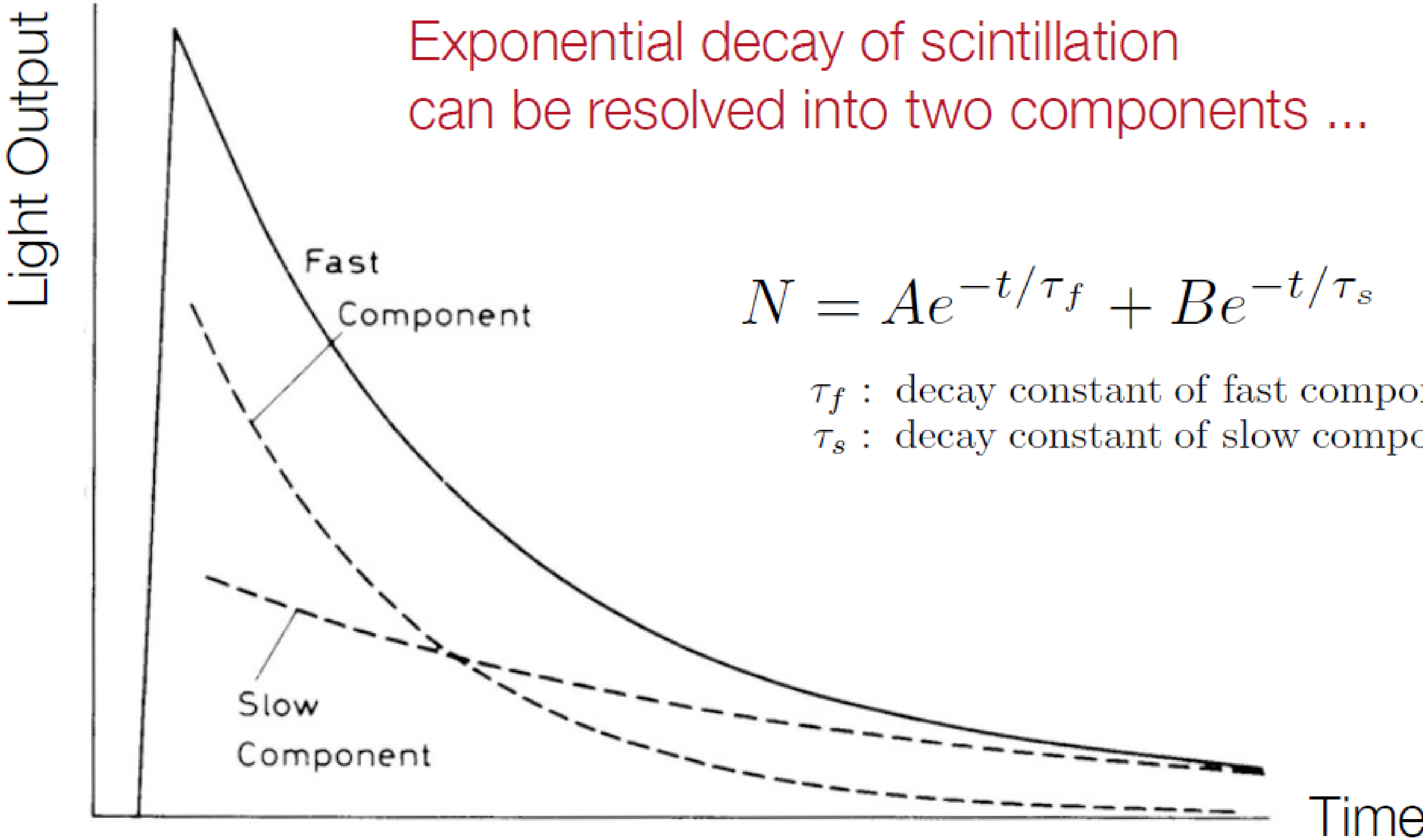
showing excitation, luminescence, quenching and trapping

❖ **Time constants:**

Fast: recombination from activation centers [ns … µs]
Slow: recombination due to trapping [ms … s]

Inorganic crystals – time constants

Exponential decay of scintillation
can be resolved into two components ...

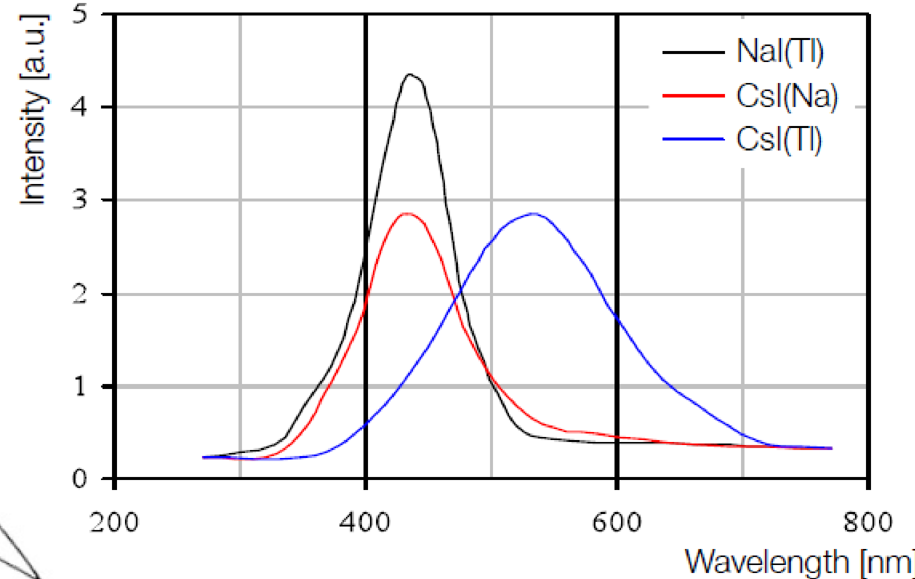


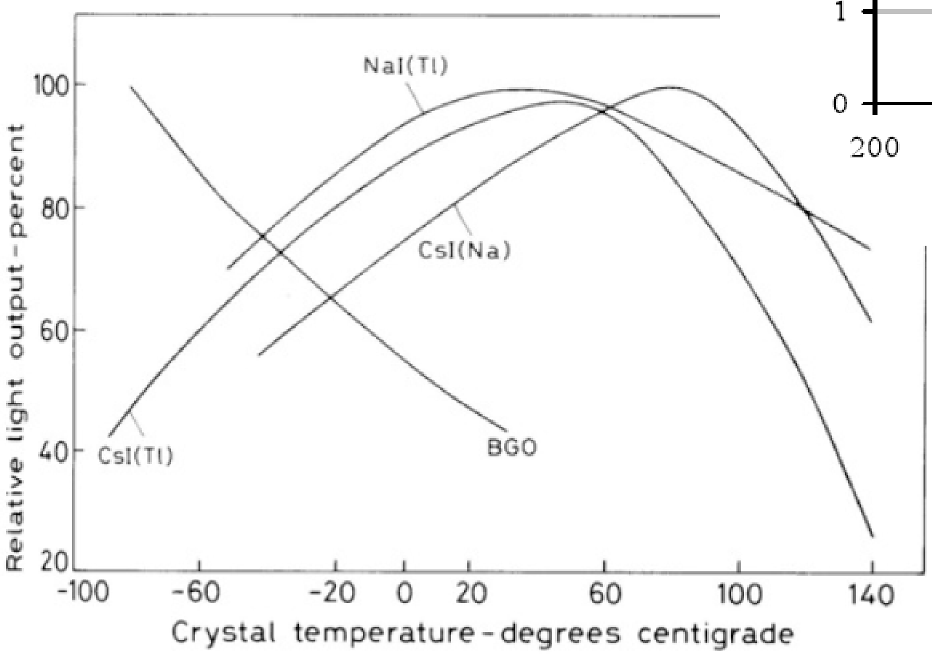
$$N = Ae^{-t/\tau_f} + Be^{-t/\tau_s}$$

τ_f : decay constant of fast component
τ_s : decay constant of slow component

Inorganic crystals – light output

scintillation spectrum
for NaI and CsI





strong temperature dependence
[in contrast to organic scintillators]

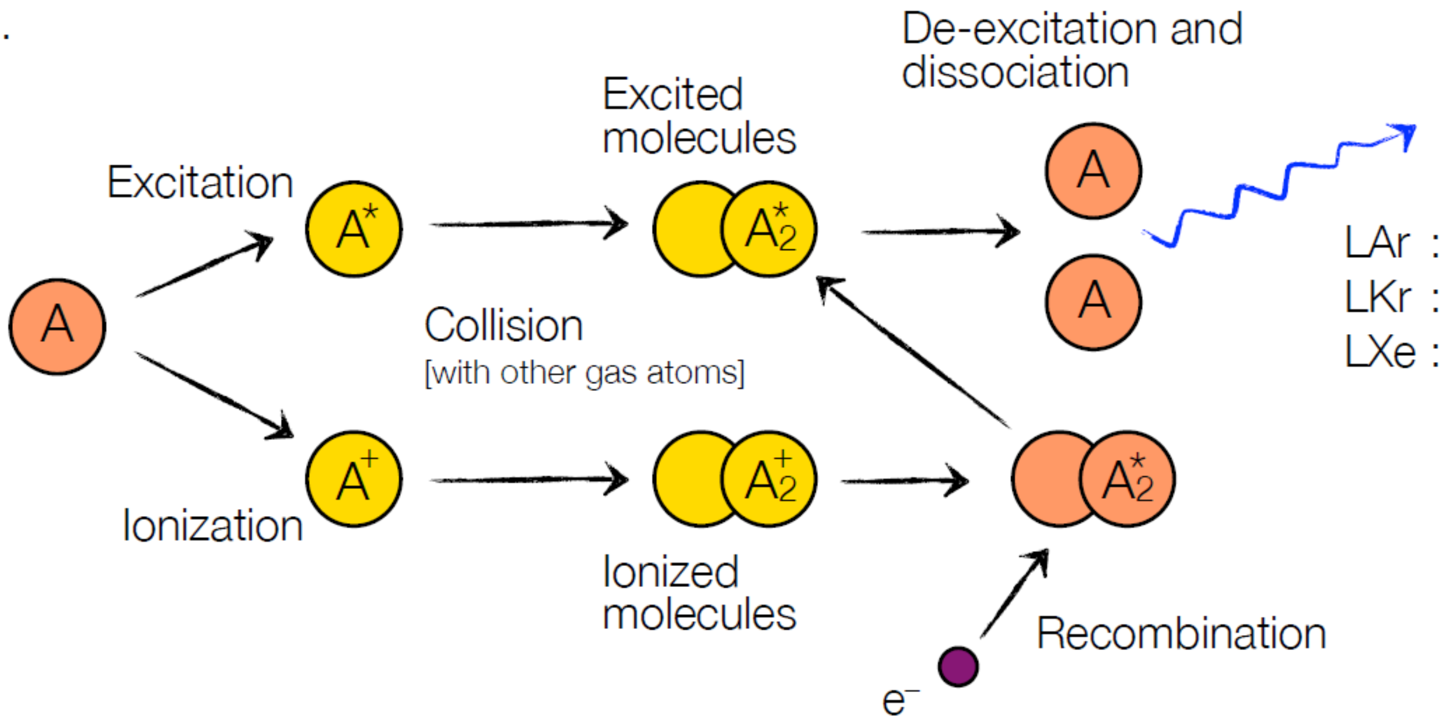
Scintillation in liquid noble gases

Materials:

Helium (He)
Liquid Argon (LAr)
Liquid Xenon (LXe)
...

Decay time constants:

Helium : τ_1 = .02 μs, τ_2 = 3 μs
Argon : $\tau_1 \leq$ .02 μs



LAr : 130 nm
LKr : 150 nm
LXe : 175 nm

Inorganic scintillators - properties

Scintillator material	Density [g/cm³]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29 *	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60 *	150	0.003/0.02	$4 \cdot 10^4$

* at 170 nm

The time for 1/e of the atoms to remain excited is the characteristic decay time τ

Inorganic scintillators - properties

Numerical examples:

NaI(Tl)

λ_{max} = 410 nm; → $h \cdot \nu$ = 3 eV
photons/MeV = 40000
τ = 250 ns

$PbWO_4$

λ_{max} = 420 nm; → $h \cdot \nu$ = 3 eV
photons/MeV = 200
τ = 6 ns

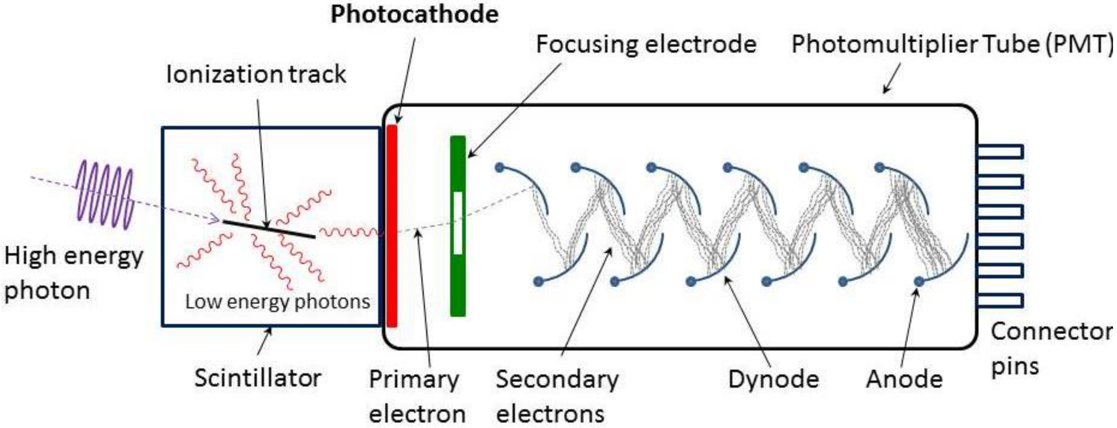
Scintillator quality:

Light yield ε_{SC} ≡ fraction of energy loss going into photons

Only a few percent of the deposited energy is transferred into light.
The remaining energy is used up be ionization, etc.

$h = 0.41 \cdot 10^{-14}$ [eV/Hz]

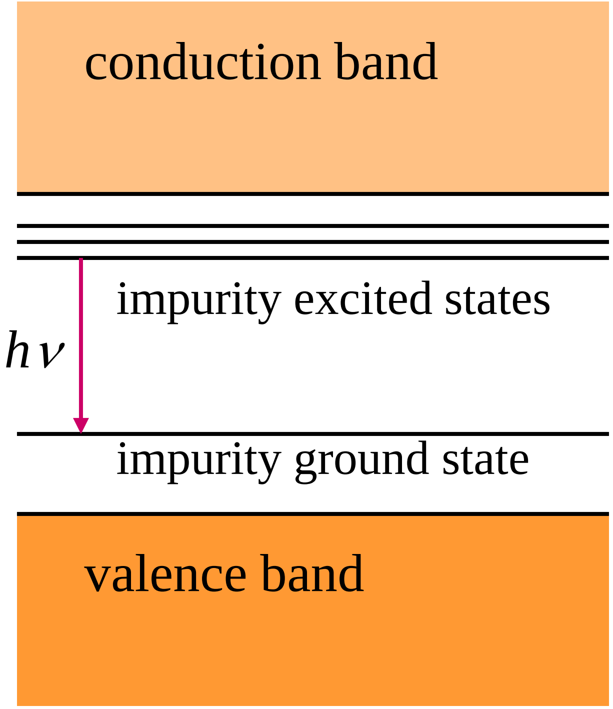
Photon statistics



Typical problem

- Gamma rays of 450 keV are absorbed with 12% efficiency. Scintillator photons with average 2.8 eV produce photoelectrons 15% of the time.
- What is the energy to produce a measurable photoelectron?
- How does this compare to a gas detector?

Band structure



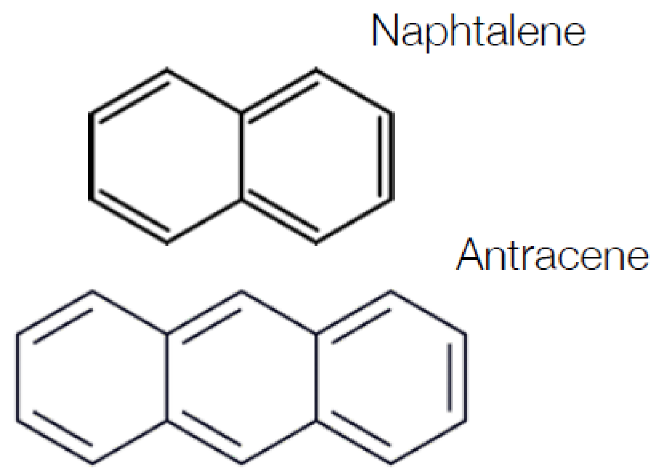
- Impurities in the crystal provide energy levels in the band gap.
- Charged particles excites electrons to states below the conduction band.
- Deexcitation causes photon emission.
  - Crystal is transparent at photon frequency.

Impurities improve visible light emission

Organic scintillators

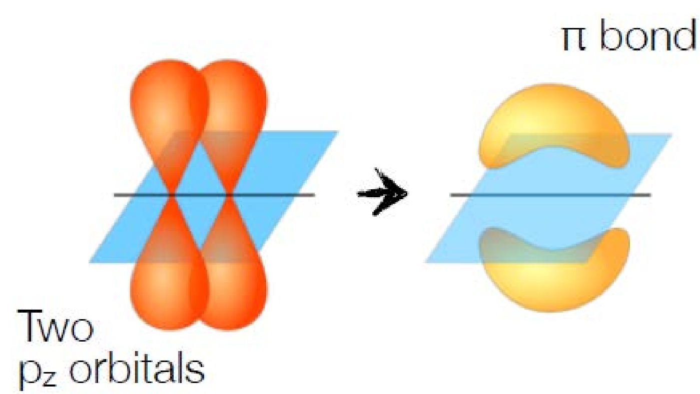
Aromatic hydrocarbon compounds:

e.g. Naphtalene [$C_{10}H_8$]
Antracene [$C_{14}H_{10}$]
Stilbene [$C_{14}H_{12}$]
…



Very fast!
[decay times of 0 ns]

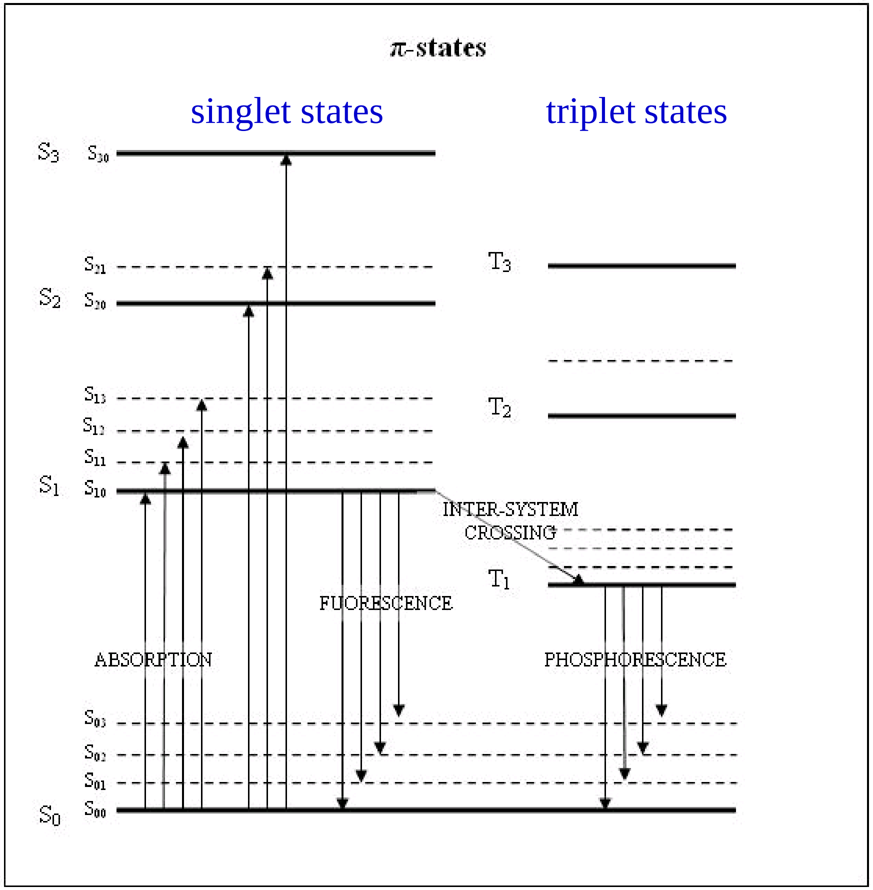
Scintillation is based on electrons of the C=C bond …



Scintillation light arises from
delocalized electrons in π-orbitals

Transition of ´free´ electrons …

Organic scintillators – excited rings



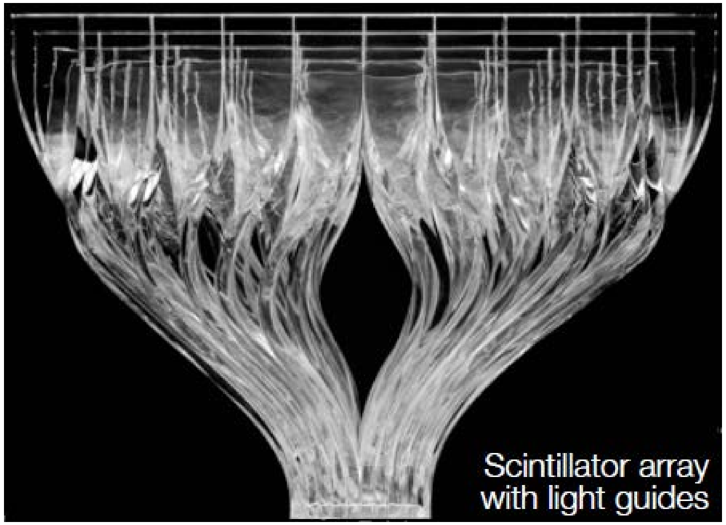
π-electronic energy levels of an organic molecule.

S_0 is the ground state. S_1, S_2, S_3 are excited singlet states. T_1, T_2, T_3 are excited triplet states. S_{00}, S_{01}, S_{10}, S_{11} etc. are vibrational sublevels.

- π-bonds are most common in aromatic carbon rings.
- Excited states radiate photons in the visible and UV spectra.
  - Fluorescence is the fast component ($S_1 \rightarrow S_0 < 10^{-8}$ s)
  - Phosphorescence is the slow component ($T_0 \rightarrow S_0 > 10^{-4}$ s)

Plastic scintillators

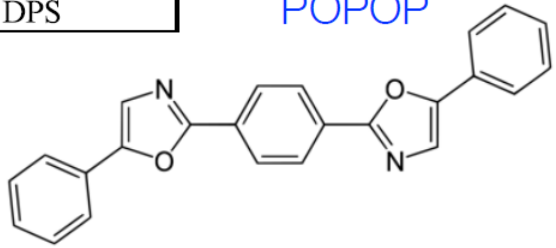
Organic scintillators can be mixed with polystyrene to form a rigid plastic



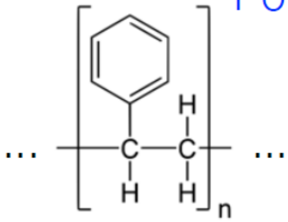
Some widely used solvents and solutes

	solvent	secondary fluor	tertiary fluor
Liquid scintillators	Benzene Toluene Xylene	p-terphenyl DPO PBD	POPOP BBO BPO
Plastic scintillators	Polyvinylbenzene Polyvinyltoluene Polystyrene	p-terphenyl DPO PBD	POPOP TBP BBO DPS

POPOP



Polystyrene



p-Terphenyl

Organic scintillators - properties

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

Wavelength shifting

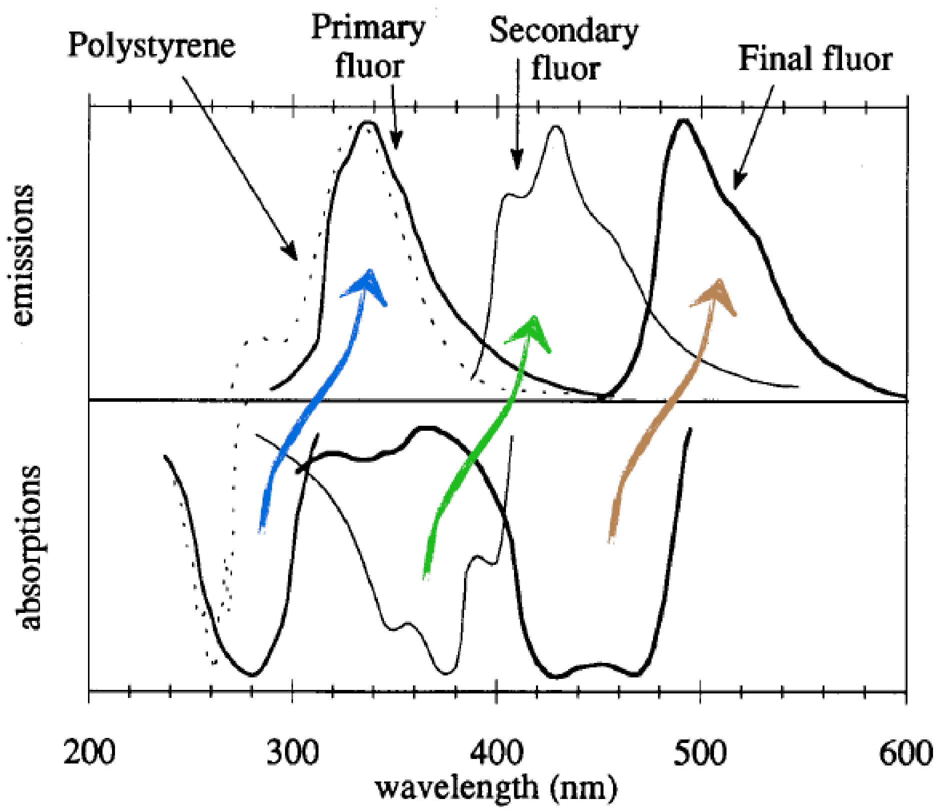
Principle:

Absorption of primary scintillation light
Re-emission at longer wavelength

Adapts light to spectral sensitivity of photosensor

Requirements:
Good transparency for emitted light

Schematics of wavelength shifting principle



Scintillators - comparison

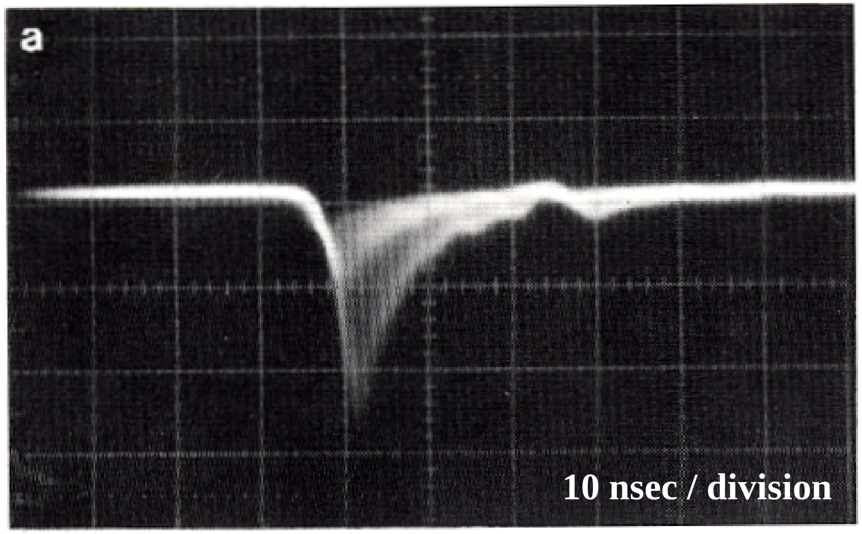
Inorganic Scintillators

Advantages	high light yield [typical $\varepsilon_{SC} \approx 0.13$]
	high density [e.g. $PbWO_4$: 8.3 g/cm^3]
	good energy resolution
Disadvantages	complicated crystal growth
	large temperature dependence

Organic Scintillators

Advantages	very fast
	easily shaped
	small temperature dependence
	pulse shape discrimination possible
Disadvantages	lower light yield [typical $\varepsilon_{SC} \approx 0.03$]
	radiation damage

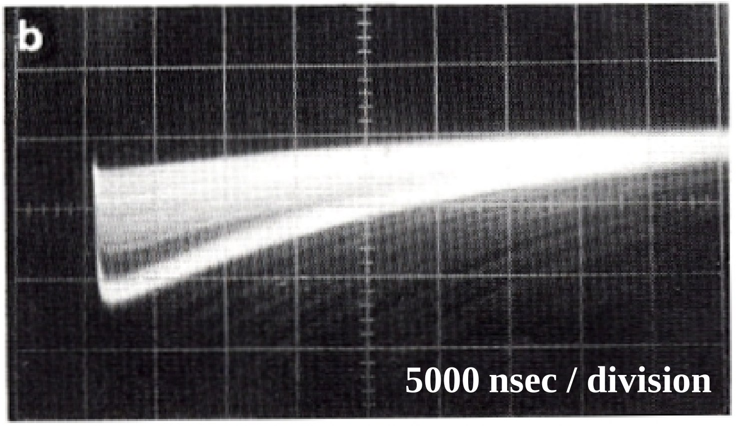
Oscilloscope traces from scintillation counters



Plastic scintillator

Plastic

Vert. scale : 0.2 V/cm
Hor. scale : 10 ns/cm
Source : ^{207}Bi 10μCi



Inorganic crystal, NaI

NaI

Vert. scale : 0.2 V/cm
Hor. scale : 5μs/cm
Source : ^{137}Cs 10μCi

Longer time scale for fluorescence to occur

Scintillation counters - setup

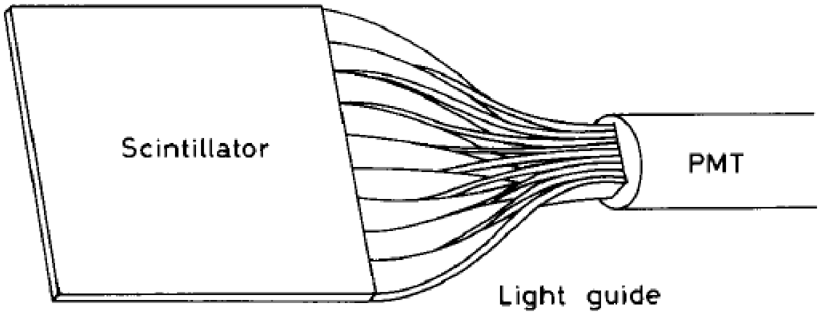
Scintillator light to be guided to photosensor

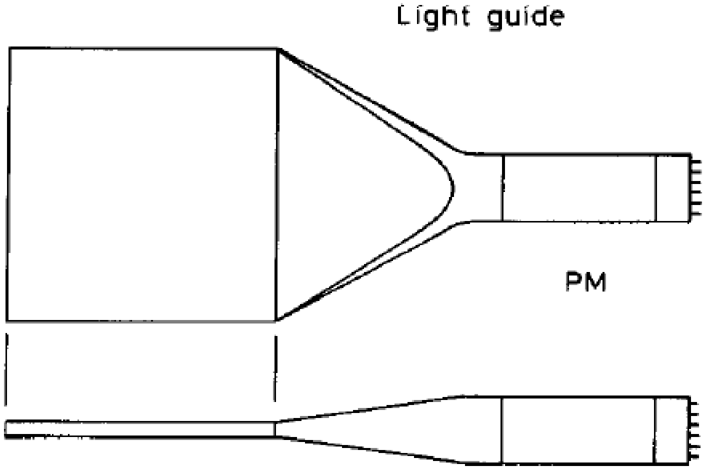
→ light guide [plexiglas, optical fibers]
light transfer by total internal reflection
[may be combined with wavelength shifter]

Liouville´s Theorem:

Complete light transfer
impossible as $\Delta x \cdot \Delta\theta = \text{const.}$
[limits acceptance angle]

Use adiabatic light guide like ´fish tail´;
→ appreciable energy loss





'fish tail'

Liouville´s Theorem

Consider a phase space element for a photon in a light guide
x = transverse coordinate
p = n sin α = angular divergence

Liouville´s theorem says $\Delta x_1 \Delta p_1 = \Delta x_2 \Delta p_2$

$$2\,\Delta x_1 \cdot n \cdot \sin\alpha_1 = 2\,\Delta x_2 \cdot n \cdot \sin\alpha_2$$

$$sin(\alpha_1) = \frac{\Delta x_2}{\Delta x_1} sin(\alpha_2)$$

$$sin(\alpha_2) = sin(\varphi + 90^0 - \theta_c)$$

$$sin(\alpha_2) = cos(\varphi - \theta_c) = \sqrt{1 - sin^2(\varphi - \theta_c)}$$

$$sin(\alpha_2) \approx \sqrt{1 - sin^2(\theta_c)}$$ for small taper angles

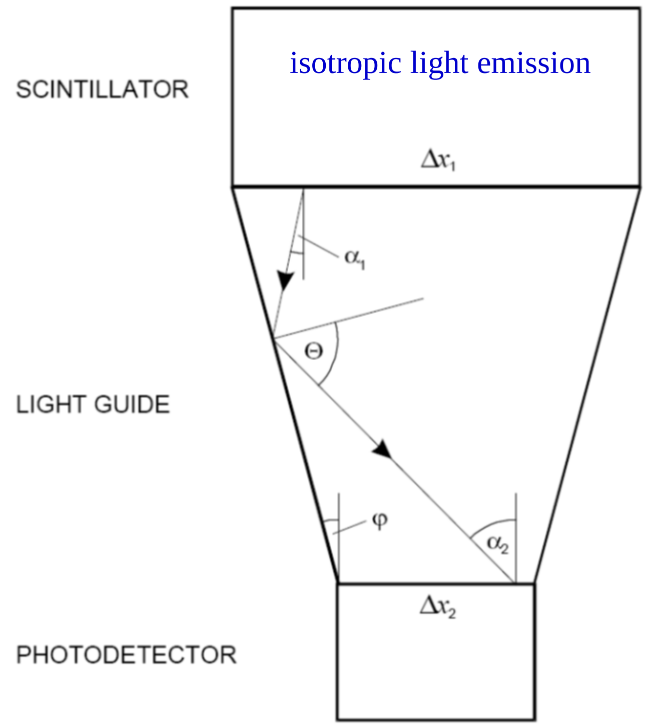
$$sin(\alpha_2) \approx \sqrt{1 - \frac{1}{n^2}}$$

then $$sin(\alpha_1) \approx \frac{\Delta x_2}{\Delta x_1}\sqrt{1 - \frac{1}{n^2}}$$

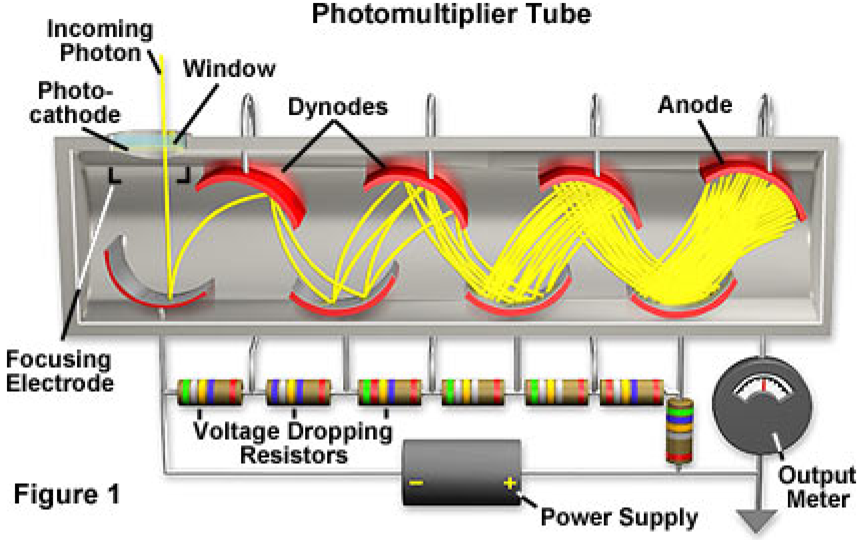
for $\Delta x_1 = \Delta x_2$ and n=1.5

$$sin(\alpha_1) = 0.75$$

There will be some light losses even in the case of equal dimensions



Photomultiplier tube



- A photomultiplier tube (phototube, PMT) combines a photocathode and series of dynodes.

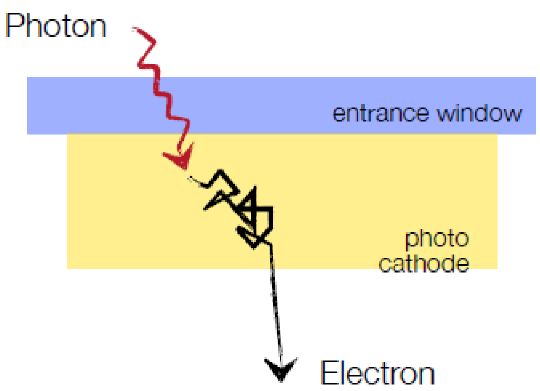
  Photocathode: UV detection (alkali compound, Cs-I, Cs-Te), visible light (bialkali compound, Sb-Rb-Cs, Sb-K-Cs), visible light to IR (semiconductors, GaAsP, InGaAs)

  Dynodes: Electrons can be multiplied by interaction with surface (emitter: BeO, GaP or metal substrate: Ni, Fe, Cu)

- The high voltage is divided between the dynodes. Dynodes typically operate at around 100 V.

- Output current is measured at the anode.
  - Sometimes at the last dynode

Photomultiplier - Photocathode

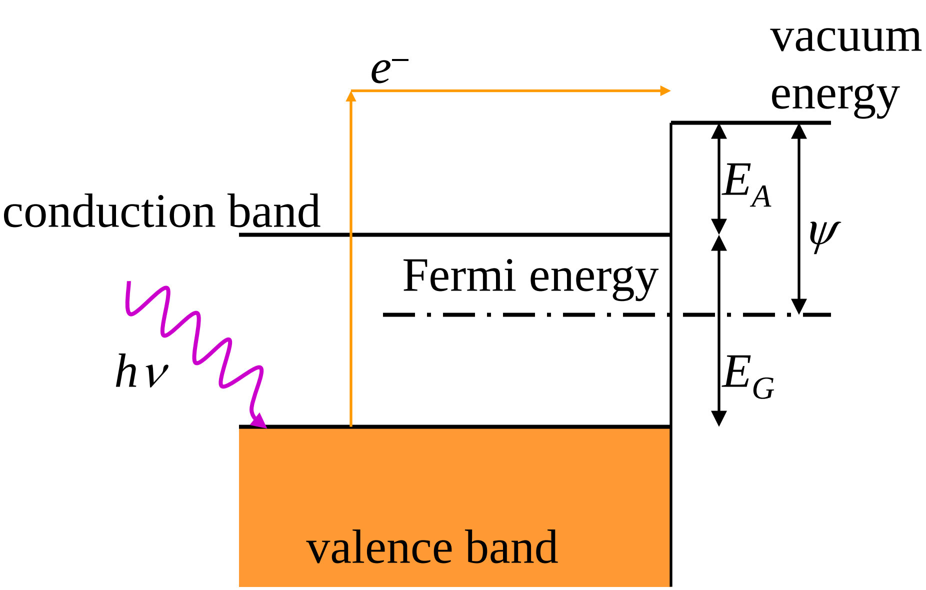


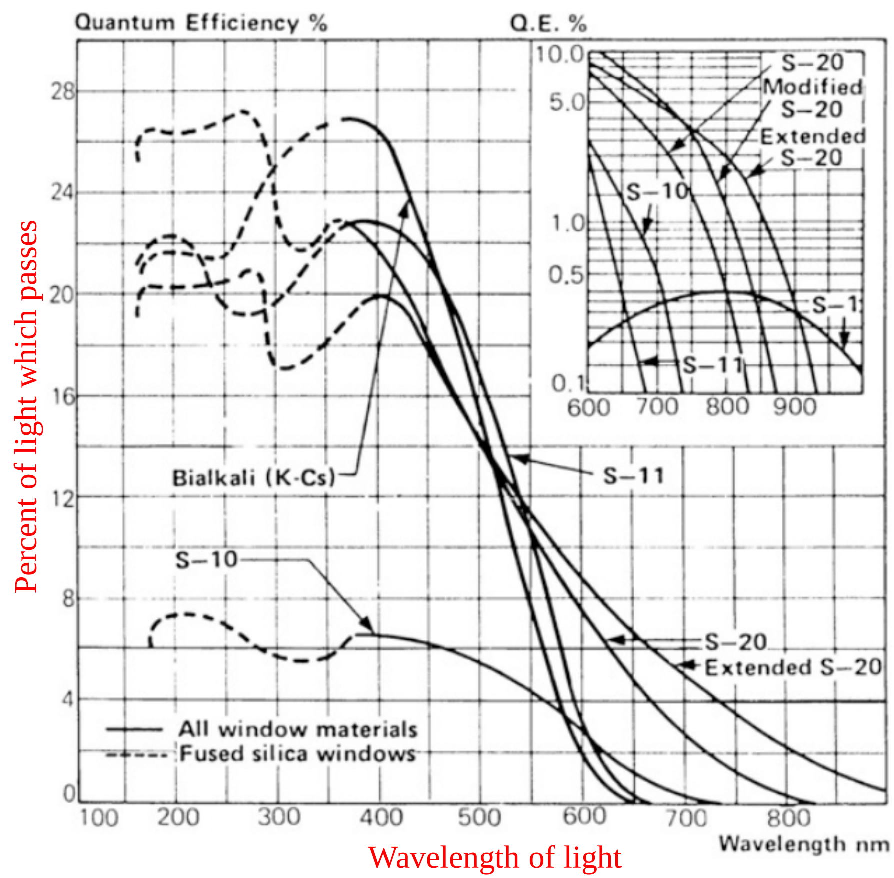
γ-conversion via photoeffect …

3-step process:

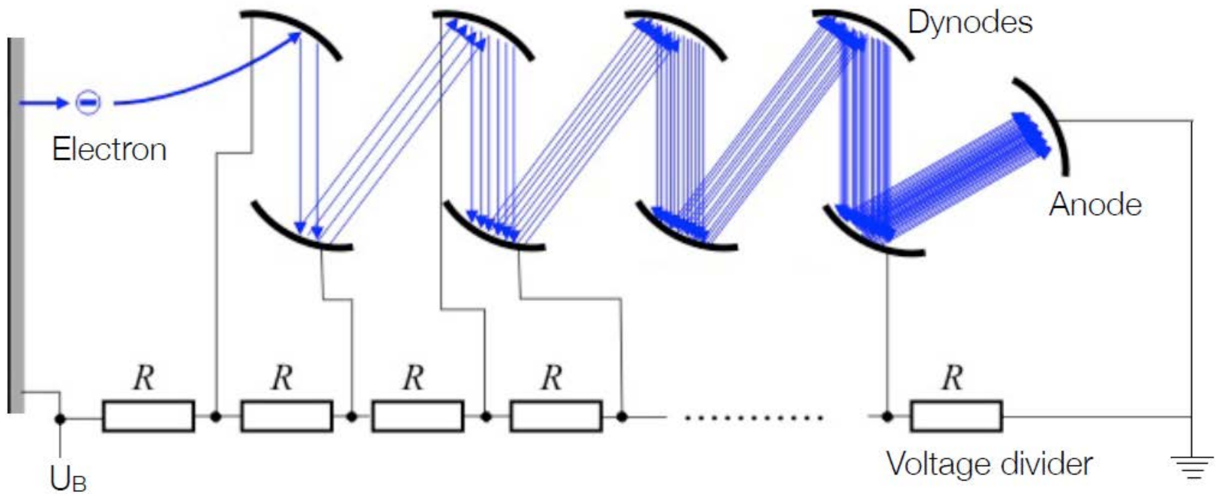
Electron generation via ionization
Propagation through cathode
Escape of electron into vacuum

Quantum Efficiency Q.E. ≈ 10-30%





Photomultiplier – Dynode Chain

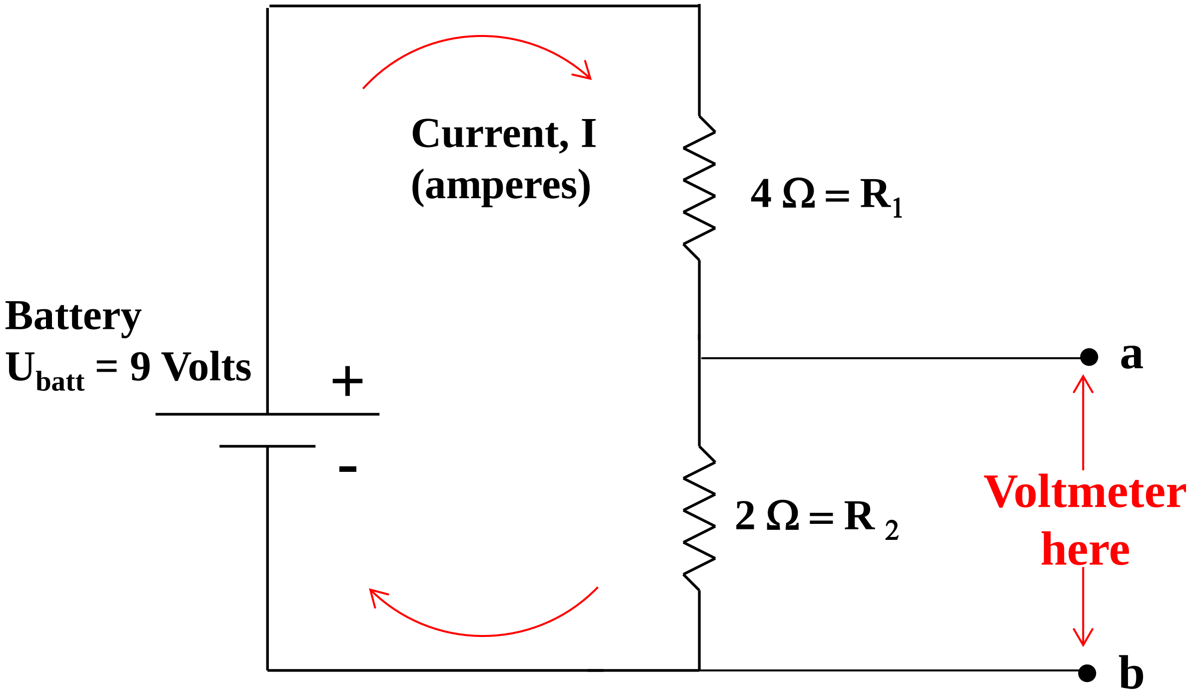


Multiplication process:

Electrons accelerated towards dynode
Further electrons produced → avalanche
Secondary emission coefficient: **δ** = #(e^- produced) / #(e^- incoming) = **2 – 10**

#dynodes **n = 8 – 15**
Gain factor: **$G = \delta^n = 10^6 - 10^8$**

Voltage divider



Ohm´s law: $U = R \cdot I$ or $I = \frac{U}{R}$

current in circuit: $I = \frac{U_{batt}}{R_1 + R_2} = \frac{9\ V}{6\ \Omega} = 1.5\ A$

$$U_{across\ R_2} = I \cdot R_2 = 1.5\ A \cdot 2\ \Omega = 3\ V$$

The 9 V battery is "divided" in 3 V and 6 V, now accessible with this circuit.

Photomultiplier – Energy Resolution

Energy resolution influenced by:

Linearity of PMT: at high dynode current possible saturation by space charge effects;
$I_A \approx n\gamma$ for 3 orders of magnitude possible …

Photoelectron statistics: given by Poisson statistics.

$$P_n(n_e) = \frac{(n_e)^n \cdot e^{-n_e}}{n!}$$

$$\sigma_n/\langle n\rangle = 1/\sqrt{n_e}$$

n_e is given by dE/dx …

$$n_e = \frac{dE}{dx} \times \frac{photons}{MeV} \times \eta \times Q.E.$$

For NaI(Tl) and 10 MeV photon
photons/MeV = 40000
light collection efficiency η = 0.2
quantum efficiency Q.E. = 0.25

$n_e = 20000$
$\sigma_n/\langle n\rangle = 0.7\%$

Secondary electron fluctuations:

$$P_n(\delta) = \frac{\delta^n \cdot e^{-\delta}}{n!}$$

$$\sigma_n/\langle n\rangle = 1/\sqrt{\delta}$$

Pulse shape discrimination

- Pulse shape discrimination (PSD) in organic scintillators are used in particularly liquid scintillators (NE213 / BC501A)
- PSD is due to long-lived decay of scintillator light caused by high dE/dx particle – neutron scatter interaction events causing proton recoil