Scintillation Detectors

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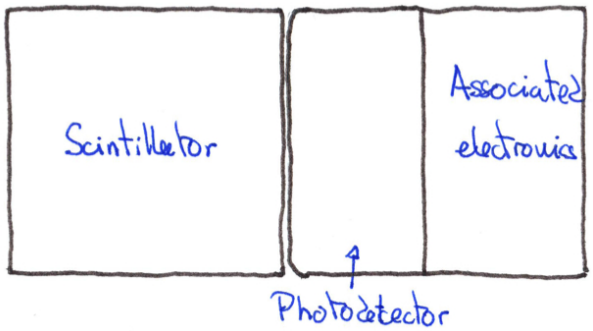
Section 1

Scintillation Properties

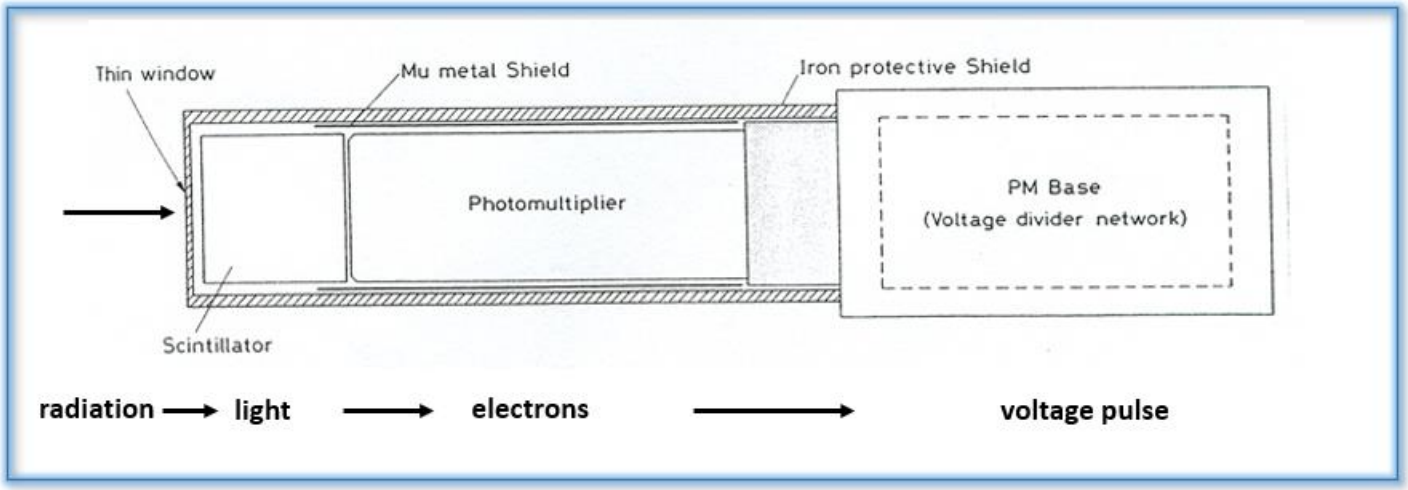
Scintillation Detectors

- The basic elements of an scintillation detector are



  - Scintillating material.
  - A Photon detector optically coupled to the scintillator
  - Associated electronics (PM base, etc)
- We have seen that passage of radiation with matter can produce:
  - Ionization of atoms of the matter
  - Excitation of the same atoms
- De-excitation of these atoms with the emission of a photon.
- The process of emission of photons is called luminescence
- Scintillation detectors use luminescence for radiation detection
- It's probably the most widely used particle detector

Scintillation Detectors



Inorganic

High light output but slow

High Z -> good for γ-detection

Example: NaI, CsI

Organic

Low light output but fast

Low Z -> good for β-detection

Example: plastics

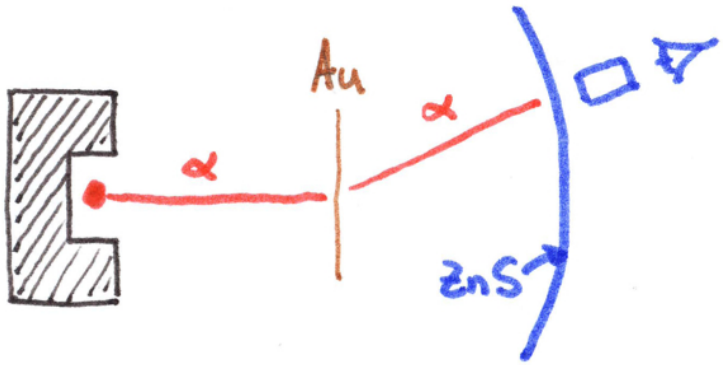
Luminescence

- Luminescence is the property exhibited by scintillators that
  - when exposed to certain form of energy: light, heat, radiation, ...
  - Absorbs and reemit the energy in form of visible light
- Is a two step process:
  - Absorption of the energy: from radiation, (or heat, ...)
  - Re-emission of the energy absorbed in form of light after a time τ_l

- Two types of transitions
  - $\tau_l < 10^{-8}$s $\rightarrow$ Fluorescence
    Typical time for atomic transitions
  - $\tau_l > 10^{-8}$s $\rightarrow$ Phosphorescence or Afterglow
    Excited electron trapped in a metastable state
    τ_l typically $\sim 10^{-3}$ s-hours

Scintillation Detectors: History

- Invented in 1903 by Crookes
  - Spinthariscope: ZnS screen
  - Scintillation produced when struck by α particles.
  - Weak light output: needed a microscope and patience
  - Tedious and not so reliable



  - Technique used by Geiger and Marsden to perform the famous Rutherford experiment

- Reinvented in 1944 by Curran and Baker:
  - Substitute human eye by a photomultiplier
  - Electronic dispositive to convert light into electrical pulse
  - Amplification $\sim 10^6$
  - Scintillation could now be counted reliably and efficiently

General properties of the scintillators

- Linear response $\rightarrow$ Light yield $\propto \frac{dE}{dx}$
- High scintillation efficiency
- Medium should be transparent to emitted light
- n $\sim$ 1.5 to allow an efficient optical coupling
- Fast response to radiation passage
- Easy manufacture: polish, large volume.

- No material meets simultaneously all these characteristics.
- Choice of an scintillator is a compromise

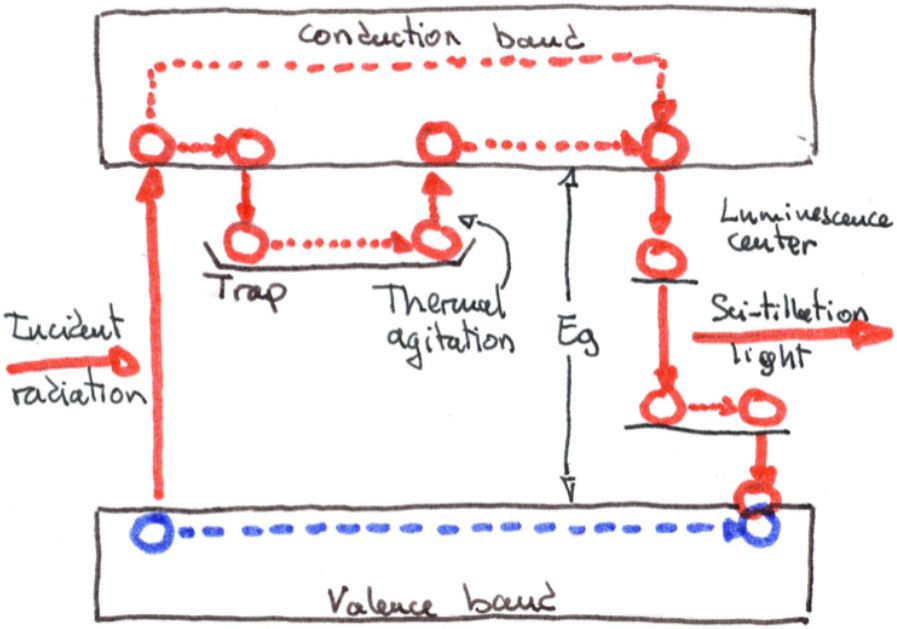
Scintillators Families

- Organic scintillators:
  - Plastics and organic liquids: $C_nH_m \rightarrow Z <<$
  - Fast response
  - Low light yield
  - Suitable for charged particles and fast n

- Inorganic scintillators
  - Alcalines-Halides (NaI, CsI, ...) : $Z >>$
  - Hight ligth yield
  - Good linearity
  - Slow response
  - Suitable for photon detection and spectroscopy

Scintillation Mechanism

- Scintillators are insulators with a wide band gap.
- Within this gap scintillators are present also the luminescence centers:



  - Composed by two energies
  - If an electron is trapped into higher level it decays into lower level
  - An scintillation photon is emitted
- Processes that can remove electrons from luminescence center are called generically quenching processes
- A typical type of quenching processes are electron traps:
  - Metastable states
  - An electron can remain for a period of time before it's released
  - Luminescence can be delayed

Light yield (L)

- Probably the most important parameter of any scintillator
- If L is low $\rightarrow$ S/N ratio in the photodetector cannot be acceptable
- Light yield is measured as
  - # of photons per MeV (common values: 20000-30000 γ per MeV)
  - # of photo-e$^-$ per MIP (common values 5-10 photo-e$^-$ per MIP)
- Light output depends on:
  - Scintillation material
  - Incident particles (type and energy)
  - Temperature

- We define the scintillation efficiency as:

$$S = \frac{\text{Energy converted into light}}{\text{Energy delivered}} = \frac{E_l}{E_d}$$

Scintillation Efficiency

- Scintillation is a relatively inefficient process:

$$L = 20000\,\gamma/\mathrm{MeV} \quad \rightarrow \quad E_\gamma = \frac{hc}{\lambda} = \frac{1.239}{\lambda(\mu\mathrm{m})} = \begin{cases} 2.63\,\mathrm{eV} & \text{for } \lambda = 470\,\mathrm{nm} \\ 1.65\,\mathrm{eV} & \text{for } \lambda = 750\,\mathrm{nm} \end{cases}$$

$$S = \frac{E_l}{E_d} = \frac{20000 \times E_\gamma}{1\,\mathrm{MeV}} = \begin{cases} 5.26\% & \text{for } \lambda = 470\,\mathrm{nm} \\ 3.30\% & \text{for } \lambda = 750\,\mathrm{nm} \end{cases}$$

- This low efficiency can also be expressed in the average energy (ε) needed to create a photon

Material	ε [eV/photon]
Anthracene	60
NaI	25
Plastic	100
BGO	300

- Special attention should be paid in all alternative de-excitation modes that can decrease luminescence (=quenching)

Quenching

Quenching in scintillation is any effect that decrease light output;

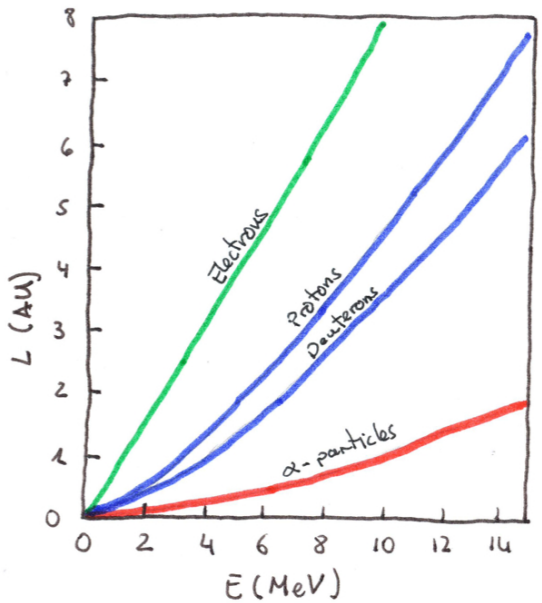
- Self Quenching.
  - Scintillation materials are usually a mixture of two of more materials.
  - L increases with concentration of primary fluor,
  - Usually this primary fluor has bad optical properties.
- Impurity Quenching.
  - Impurities decrease L because they create traps and can modify optical properties.
  - It can become problematic $\rightarrow$ use highly purified materials
- Thermal Quenching.
  - Trapping is dependent on temperature
- Energy Quenching.
  - Delivering more energy to the scintillator does not provides more light output.
  - Light output saturates after a certain $\frac{dE}{dx}$.
  - More pronounced in organic scintillators.

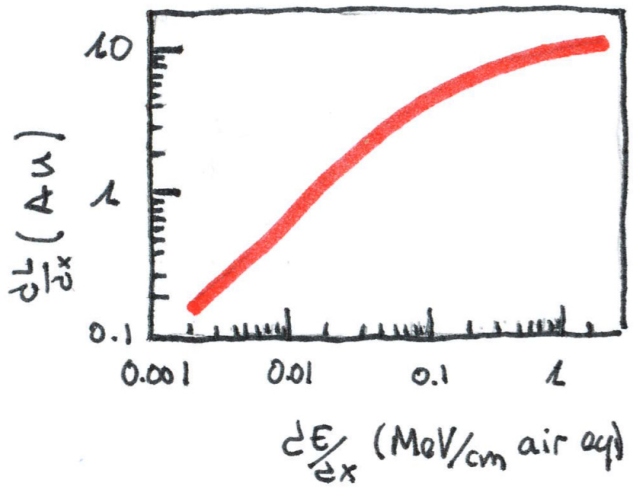
Energy quenching. Birks Formula

- From the scintillation efficiency relation:

$$S = \frac{E_l}{E_d} \quad \rightarrow \quad \frac{dL}{dx} = S\frac{dE}{dx}$$

- This linear relation is valid for $\frac{dE}{dx}$ small
- There exists deviations from linearity for large values of $\frac{dE}{dx}$
- For very large values of $\frac{dE}{dx}$ light output saturates





Energy quenching. Birks Formula

- This effect was first explained by Birks in the 1950's
  - When high ionization occurs, it produces a local concentration of damaged or ionized molecules

    $$\text{Number of ionized/damaged molecules} = B\frac{dE}{dx}$$
  - These molecules may cause quenching with a probability k

    $$\text{Number of molecules producing quenching} = kB\frac{dE}{dx}$$
- The specific light output is then

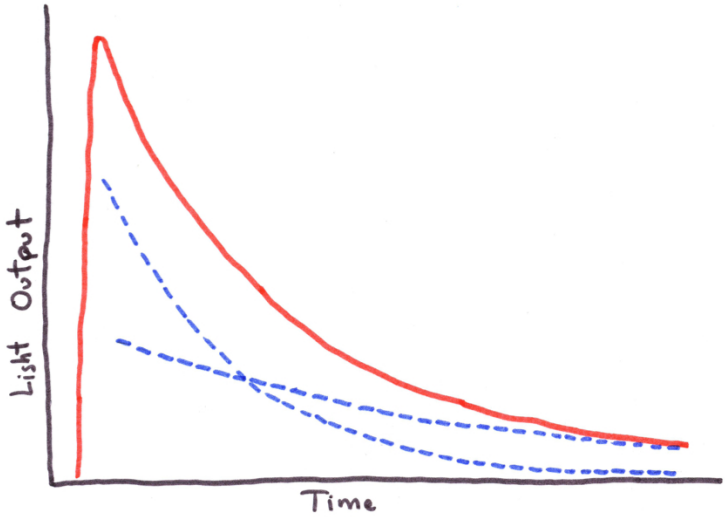
$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx}} \qquad \text{Birk's formula}$$

- It explains both non linearities and saturation
- Factor kB is difficult to compute. Determined experimentally.
- Other formulas proposed to fit experimental data

$$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + B\frac{dE}{dx} + C\left(\frac{dE}{dx}\right)^2} \qquad \frac{dL}{dx} = \frac{A}{2B}\ln\left(1 + 2B\frac{dE}{dx}\right)$$

Time Response

- Typical scintillation light pulse has the following characteristics:



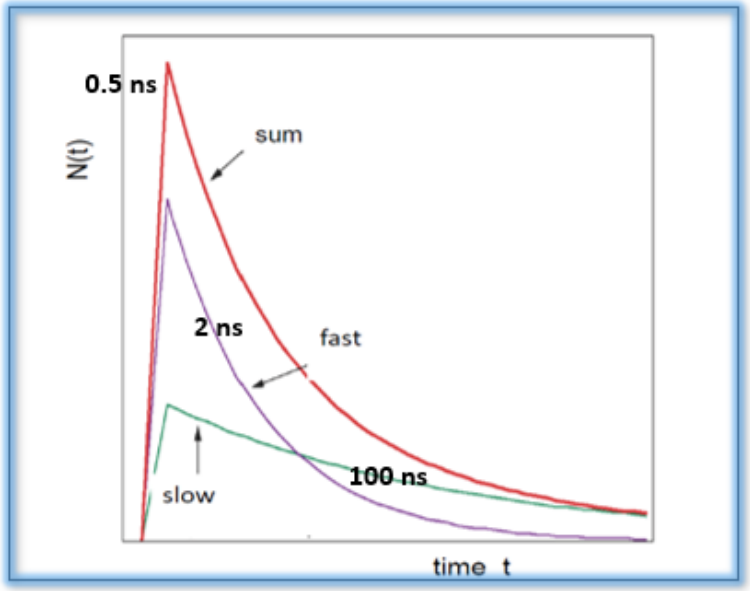
- Rise time:

$$L = L_0(1 - e^{-t/\tau_r})$$

  - τ_r: time required to populate luminescent states
  - $\tau_r \lesssim 0.5\,\text{ns}$
  - Quite similar in all scintillators

Time Response

- Typical scintillation light pulse has the following characteristics:



- Decay time:

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

  - τ_f is a fast component (∼few ns)
  - τ_s is a slow component (∼few ns-ms)
  - A, B, τ_f, τ_s depends on the material but also on radiation type
  - Base of Pulse shape discrimination

Time Response

- If we neglect the slow component, the overall shape of light pulse is

$$L = L_0(e^{-t/\tau_f} - e^{-t/\tau_r})$$

- Rise time can also be modeled by a gaussian (characterized by σ)

$$L = L_0 f(t;\sigma) e^{-t/\tau_f}$$

- Experimentally the rise and fall of the light output can be characterized by the FWHM

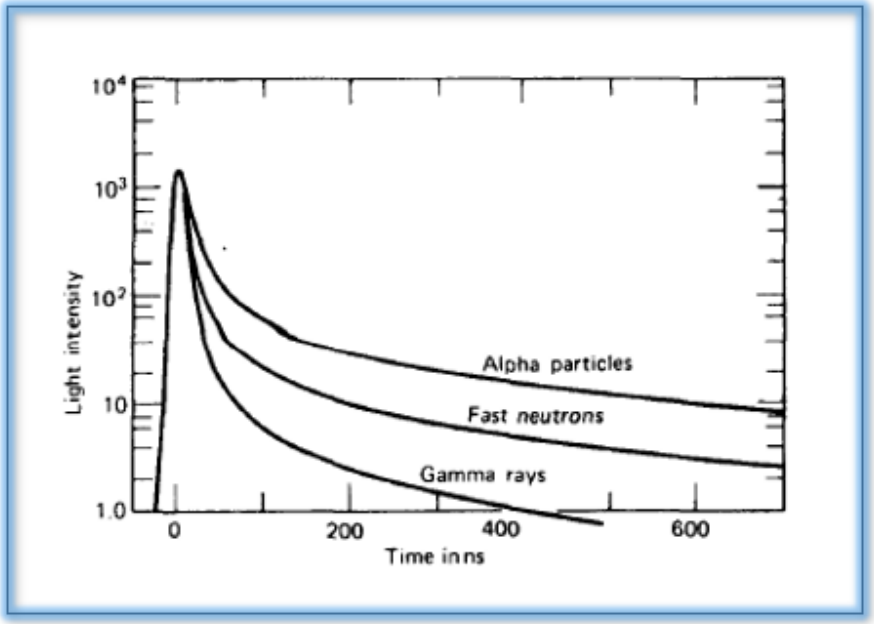
	Exponential parameters		Gaussian parameters		Measured FWHM
	τ_r	τ_f	σ_{ET}	τ_f	
NE111	0.2 ns	1.7 ns	0.2 ns	1.7 ns	1.54 ns
Naton 136	0.4 ns	1.6 ns	0.5 ns	1.87 ns	2.3 ns
NE102A	0.6 ns	2.4 ns	0.7 ns	2.4 ns	3.3 ns

Pulse shape discrimination

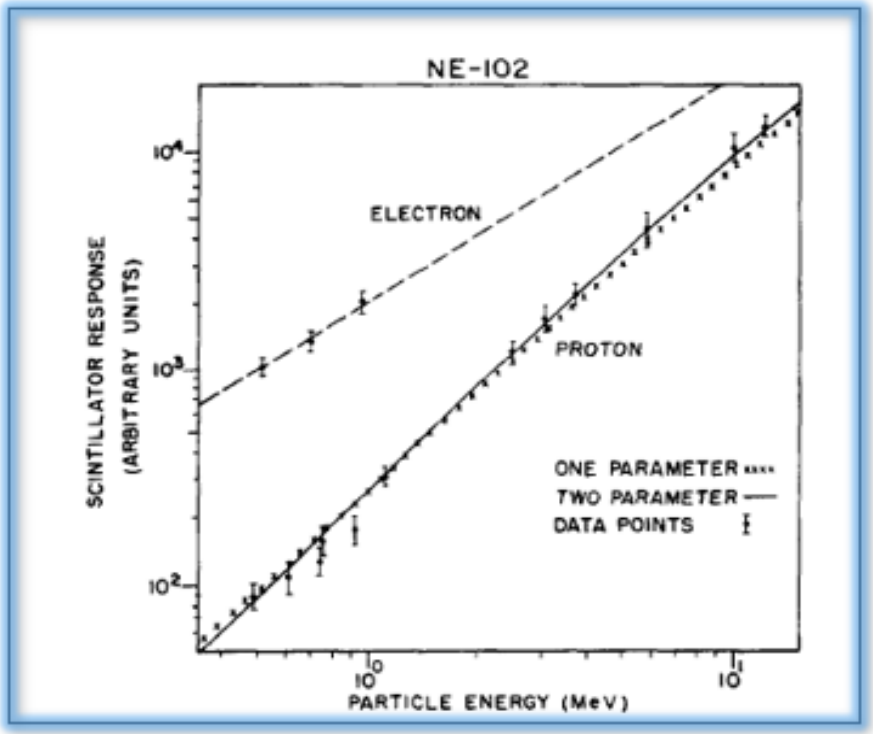
- If the slow part cannot be neglected:

$$L = L_0(Ae^{-t/\tau_f} + Be^{-t/\tau_s} - e^{-t/\tau_r})$$

- Fast and slow components arise from de-excitation of different states
- Depending on $\frac{dE}{dx}$ states are populated differently:
  - Relative intensity between fast and slow depends on $\frac{dE}{dx}$
  - Different particles will provide different $\frac{dE}{dx}$
- This behavior can be used to distinguish particles.



Light output



- rather linear above ≅ 100 keV
- larger for β particles than heavy charged particles

high ionization efficiency along path → recombination

Section 2

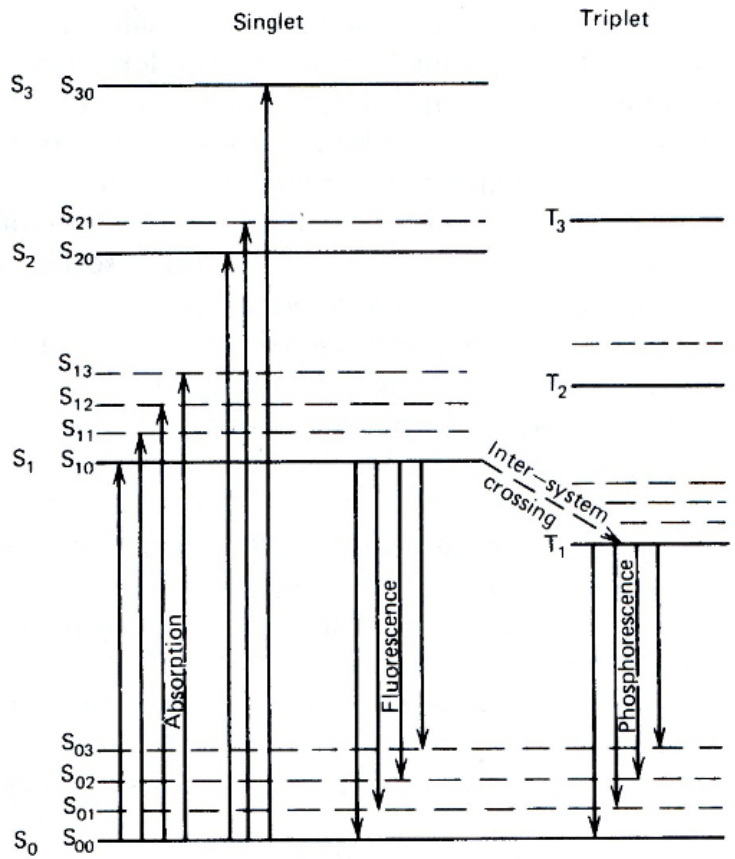
Organic Scintillators

Organic Scintillators

- Organic scintillators are aromatic hydrocarbon compounds
- Fluorescence processes arises from transitions in the energy levels of single molecules
  - Does not need a crystalline structure like inorganic scintillators
  - They are found in solid, liquid and gaseous states
- Usually organic scintillators are presented in a dissolution:
  - Small fraction of highly efficient organic scintillation (solute)
  - Bulk of solvent with good optical properties
  - Most of energy is released in the solvent
  - Excitation is transferred to solute that emits luminescence
  - Any impurity or quenching process can low luminescence process
- Most organic scintillation molecules are based on covalent bindings
  - π-electron structure
  - Atomic states can be: S=0 $\rightarrow$ Singlets S_n
    S=1 $\rightarrow$ Triplets T_n

Scintillation Mechanism

- $S_0 - S_1 \rightarrow 3 - 4\,\text{eV}$
- Further states can be present due to vibrational states
  - $S_{0n} - S_{0m} \sim 0.15\,\text{eV}$
- As thermal energy is $\sim$0.025 eV, at room temperature all molecules are in state S_{00}



Fluorescence

Absorption mechanism

- Energy from radiation is used to excite electrons:
  - From S_{00} to S_{nm} $(n \geq 1,\ m \geq 0)$
  - In $\sim 10^{-12}$ s $\quad S_n(n \geq 2) \rightarrow S_1$ (non radiative)
    $S_{1n}(n \geq 1) \rightarrow S_{10}$ (non radiative)
- Excitation can be originated by
  - Incoming radiation
  - Another photon ($E \sim 4 - 5$ eV) coming from another de-excitation.

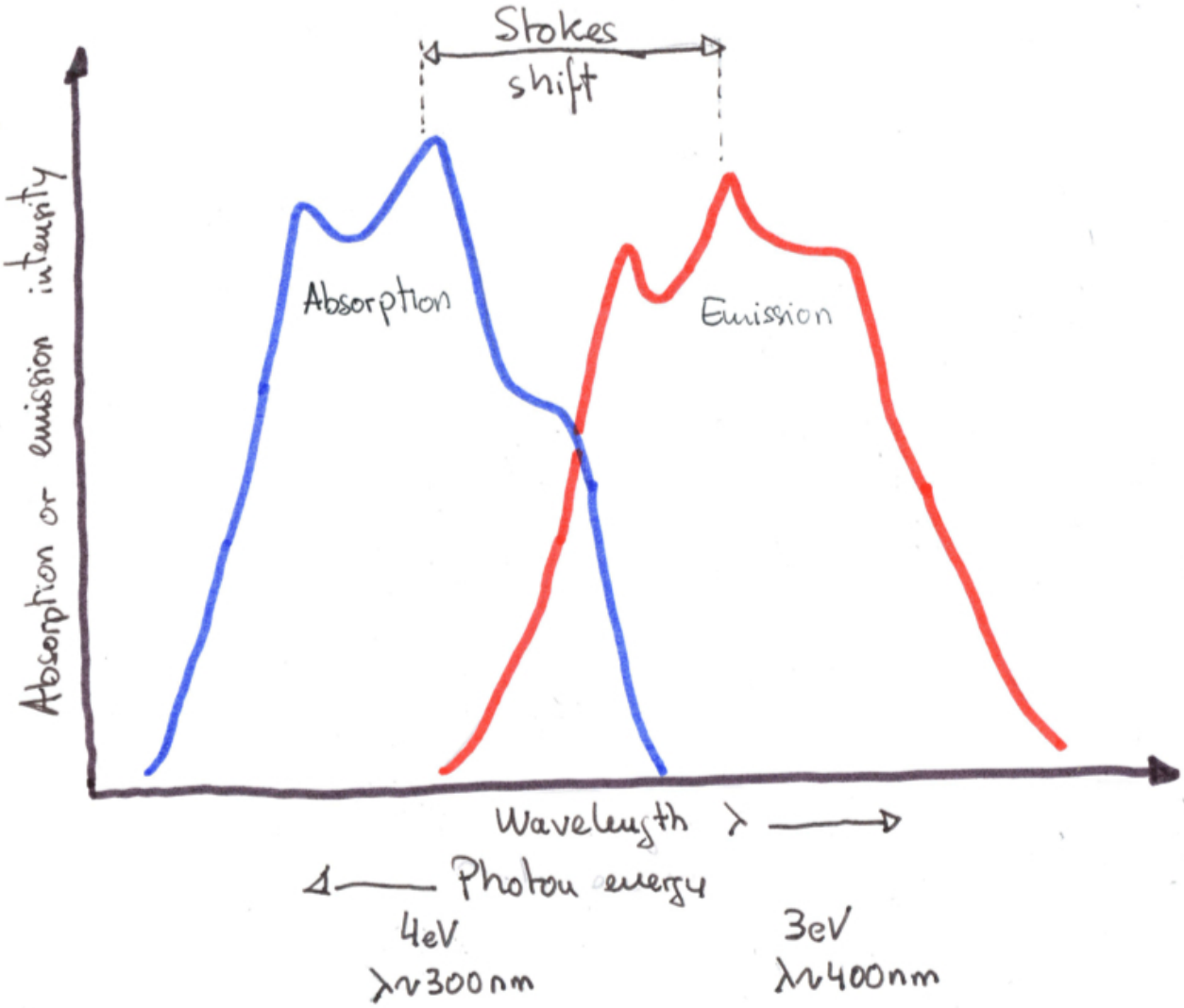
Emission mechanism

- S_{10} luminescence state
  - In $\tau_f \sim 10^{-9}$ s $\quad S_{10} \rightarrow S_0$ (radiative)
    $S_{0n}(n \geq 1) \rightarrow S_{00}$ (non radiative)

Wavelength shifter

- In case the excitation is produced by a photon, the net effect is:
  - Absorbs photons from primary radiation
  - Emits a photon of larger wavelength

Fluorescence



Phosphorescence

- Some excited singlet states can decay into triplet state T_1
  - Process called "intersystem crossing"
  - Spin of excited electron should change. Spin-Orbital interaction
- By non-radiative processes electron arrives to T_{00}
- $T_0 \rightarrow S_0$ is not allowed.
- Electrons are trapped.
- De-excitation possible as:
  - Return to S_1 by thermal excitation (same E as fluorescence)
  - $T_0 + T_0 \rightarrow S_1 + S_0 +$ phonons (E smaller than fluorescence)

Organic Crystal Scintillators

- Organic crystals have been found advantageous
  - Non-hygroscopicity, contrary to inorganic crystals
  - Small back-scattering because the big amount of H
- Drawbacks
  - Fragile $\rightarrow$ difficult cutting
  - Present anysotropies. Light output varies up to 30% with orientation
- Anthracene (C_4H_{10})
  - Highest light output of all organic scintillators
  - Absolute efficiency $\sim$5%
  - Absorption peak on UV ($\sim$420 nm). It can be shifted to $\sim$500 nm
    - ★ Naphtalene impurities or with a wavelength shifter
- P-Therphenyl ($C_{18}H_{14}$)
  - Very short decay time
  - Poor light output. Doping with impurities can increase L up to 5 times
- Stilbene ($C_{14}H_{12}$)
  - Light output not as good as anthracene

Liquid Scintillators

- Organic scintillators disolved in a solvent
- In general composed by three organic components
  - Primary scintillator or primary fluor
    High scintillation efficiency. Emission in the UV region
  - Wavelenght shifter or secondary fluor
    UV photons have short attenuation lengths in solvants
    Shifts UV light into visible light
  - Base liquid or solvant
    Where both fluor are homogeneously mixed.
    Good optical properties

P-terphenyl	$C_{14}H_{12}$
PBD	$C_{20}H_{14}N_2O$
PPO	$C_{15}H_{11}NO$
POPOP	$C_{24}H_{16}N_2O_2$

Benzene	C_6H_6
Toluene	$C_6H_5CH_3$

Liquid Scintillators

- Energy absorption is different form rest of organic scintillators
  - Energy absorption mainly in the solvent
  - Absorbed energy passed to solute (within 3-4 ns)
- Sensitive to impurities. Great attention during manipulation
- Useful if large volumes are needed
- Useful if sample to be analyzed is inside the liquid
- It can be doped with:
  - Boron. Sensitive to neutrons
  - Wavelength shifter.
- If doped it present few drawbacks
  - Less light yield
  - Decay time larger
  - Shorter absorption lengths

Plastic Scintillators

- Same idea as liquid scintillators
  - Scintillator dissolved in a solvent
  - Solvent is a monomer that can be polymerized
  - Obtained a solid scintillator
- Same solutes as the liquid scintillators
- Usual solvents:
  - Styrene monomer $C_6H_5C_2H_3 \rightarrow$ polystyrene
  - Vinyltholuene monomer $C_6H_4CH_3C_2H_3 \rightarrow$ poly-vinyltholuene
- Plastic scintillators are fast
- They can be easily machined to almost any shape
- They can be doped (loaded) as liquid scintillators

Organic scintillators: examples

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

Plastic Scintillators

Table 8.1 Properties of Some Commercially Available Organic Scintillators

Eljen	Bicron	Light Output %Anthracene*	Wavelength of Max Emission (nm)	Decay Constant (ns)	Attenuation Length (cm)	Refractive Index	H/C Ratio	Density	Loading Element % by weight or dist. feature	Softening or Flash Point (°C)	Uses
Crystal											
Anthracene		100	447	30		1.62	0.715	1.25		217	
Stilbene		50	410	4.5		1.626	0.858	1.16		125	
Plastic											
EJ-212	BC-400	65	423	2.4	250	1.581	1.103	1.032		70	General purpose
EJ-204	BC-404	68	408	1.8	160	1.58	1.107	1.032	1.8 ns time constant	70	Fast counting
EJ-200	BC-408	64	425	2.1	380	1.58	1.104	1.032		70	TOF counters, large area
EJ-208	BC-412	60	434	3.3	400	1.58	1.104	1.032	Longest attn. length	70	General purpose, large area, long strips
	BC-420	64	391	1.5	110	1.58	1.100	1.032	1.5 ns time constant	70	Ultrafast timing, sheet areas
EJ-232	BC-422	55	370	1.4	8	1.58	1.102	1.032	1.4 ns time constant	70	Very fast timing, small sizes
	BC-422Q	11	370	0.7	< 8	1.58	1.102	1.032	Benzephenone, 1%	70	Ultrafast timing, ultrafast counting
	BC-428	36	480	12.5	150	1.58	1.103	1.032	Green emitter	70	Photodiodes and CCDs; phoswich detectors
	BC-430	45	580	16.8	NA	1.58	1.108	1.032	Red emitter	70	Silicon photodiodes and red-enhanced PMTs
EJ-248	BC-434	60	425	2.2	350	1.59	0.995	1.049	High temp	100	General purpose
	BC-436	52	425	2.2	NA	1.61	0.960 D:C	1.130	Deuterium, 13.8%	90	Thin disks
EJ-240	BC-444	41	428	285	180	1.58	1.109	1.032		70	Phoswich detectors for dE/dx studies
EJ-256	BC-452	32	424	2.1	150	1.58	1.134	1.080	Lead, 5%	60	X-ray dosimetry (< 100 keV)
	BC-454	48	425	2.2	120	1.58	1.169	1.026	Boron, 5%	60	Neutron spectrometry, thermal neutrons
EJ-252	BC-470	46	423	2.4	200	1.58	1.098	1.037	Air equivalent	65	Dosimetry
	BC-490	55	425	2.3		1.58	1.107	1.030	Casting resin	70	General purpose
	BC-498	65	423	2.4		1.58	1.103	1.032	Applied like paint	70	β, γ detection
Liquid											
EJ-301	BC-501A	78	425	3.2			1.212	0.874	Pulse shape discrim.	26	γ > 100 keV, fast n spectroscopy
EJ-305	BC-505	80	425	2.5			1.331	0.877	High light output	47	γ, fast n, large volume
EJ-313	BC-509	20	425	3.1			0.0035	1.61	F	10	γ, fast n
EJ-321H	BC-517H	52	425	2.0			1.89	0.86	Mineral oil-based	81	γ fast n, cosmic, charged particles
	BC-517P	28	425	2.2			2.05	0.85	Mineral oil-based	115	γ, fast n, cosmic, charged particles
EJ-325	BC-519	60	425	4.0			1.73	0.875	Pulse shape discrim.	74	γ, fast n, n-γ discrimination
EJ-331	BC-521	60	425	4.0			1.31	0.89	Gd (to 1%)	44	Neutron spectroscopy, neutrino research
EJ-339	BC-523A	65	425	3.7			1.67	0.93	Enriched ^{10}B	1	Total absorption neutron spectrometry
EJ-335	BC-525	56	425	3.8			1.57	0.88	Gd (to 1%)	64	Neutron spectrometry, neutrino research
	BC-533	51	425	3.0			1.96	0.8	Low temp operation	65	γ, fast n, cosmic
	BC-537	61	425	2.8			.99 (D:C)	0.954	^{2}H	−11	Fast n, pulse shape discrimination
	BC-551	40	425	2.2			1.31	0.902	Pb (5% w/w)	44	γ, X-rays < 200 keV
	BC-553	34	425	3.8			1.47	0.951	Sn (10% w/w)	42	γ, X-rays

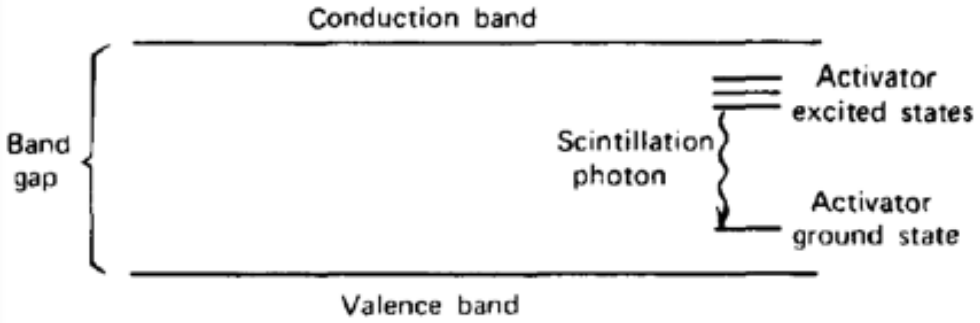
*NaI(Tl) is 230% on this scale

Section 3

Inorganic Scintillators

Inorganic Scintillators

- Scintillators that have an crystalline structure.
- They are denser than organic scintillators and with higher Z
- In average it's light output is larger than organic scintillators
- Decay times are larger ($\sim \mu$s)
- As they have crystalline structure, when radiation passes through an inorganic crystal it produces electron-hole pairs

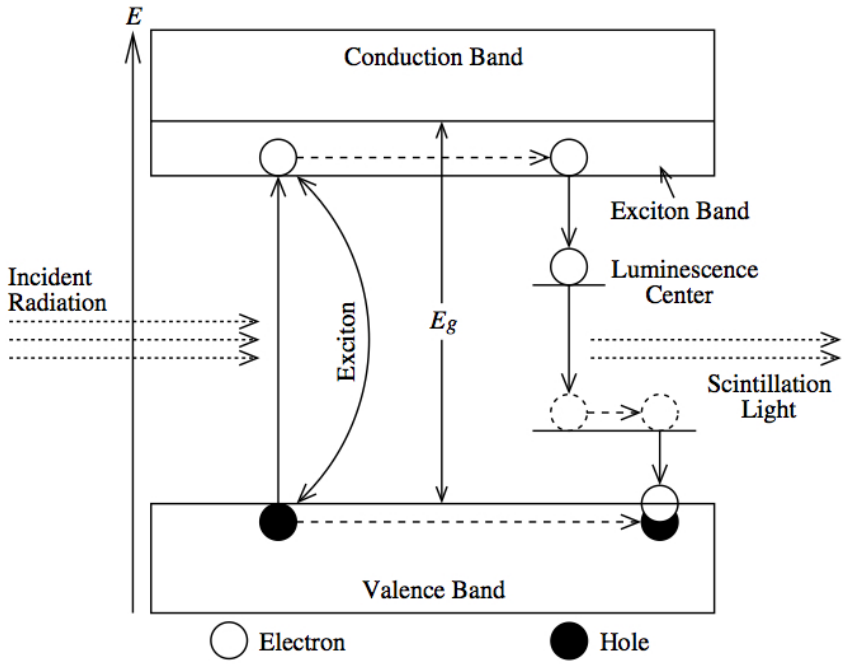


Energy band structure of an activated crystalline scintillator

e.g. NaI with Tl as activator: NaI(Tl)

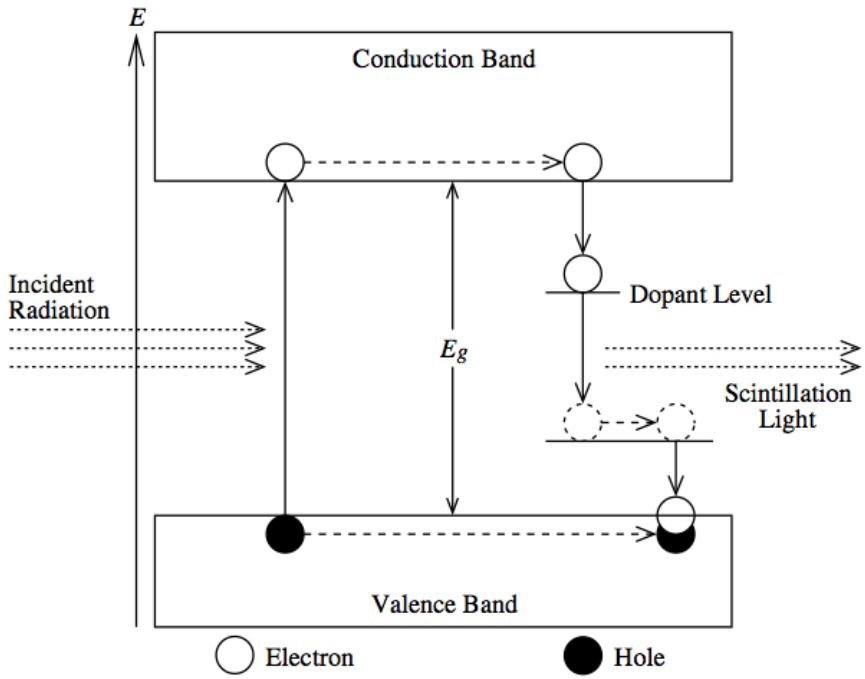
Exciton Luminescence

- For not so high energy deposed: e-h system quasi bound (exciton)
- Electron stays below conduction band: exciton band
- Exciton can move freely and can get trapped by luminescence center



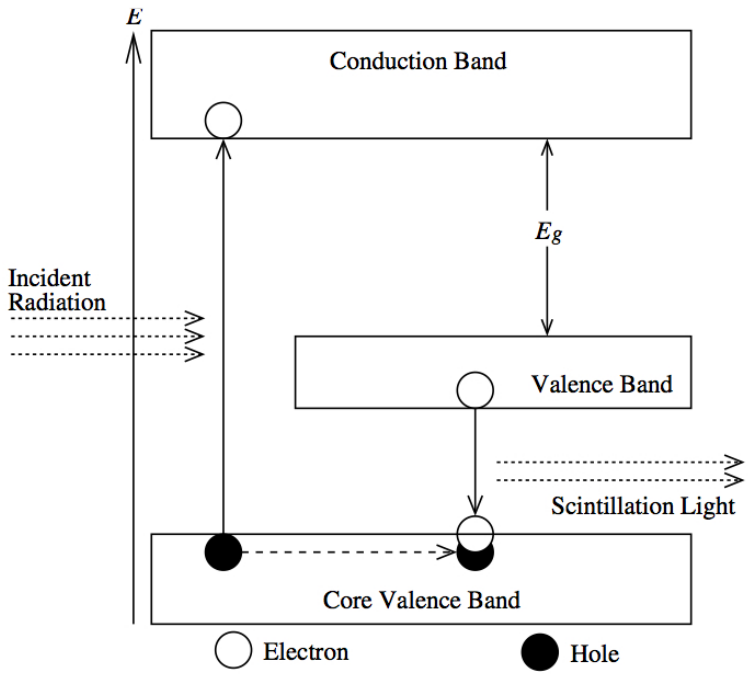
Dopant Luminescence

- Holes goes immediately to impurities called activators
- Electrons moves freely in conduction band till found an activator
  De-excitation $\sim 10^{-7}$ s
- Some scintillators are loaded with an impurity to enhance its scintillation properties



Core Valence Luminescence

- If incident radiation deposit enough energy it can elevate electrons from core band to conduction band
- Electron leaves a hole in the core valence band
- Most likely a valence band electron quickly fill the vacancy
- It can result in the emission of scintillation light



Inorganic Scintillators

- Thallium doped Sodium Iodide (NaI:Tl)
  - high light yield (41000 γ/MeV)
  - blue light (accordance with most PMs)
  - very low self absoprtion
  - good spectroscopic performance
  - easy production, possibility to produce large crystals
  - vulnerability to moisture (hygroscopicity)
- Sodium doped Cesium Iodide (CsI:Na)
  - High light yield (41000 γ/MeV)
  - blue light (accordance with most PMs)
  - less hygroscopic than NaI:Tl

Inorganic Scintillators

- Bismuth Germanate (BGO)
  - BGO: $Bi_{14}Ge_3O_{12}$
  - High absorption efficiency
  - High energy resolution
  - Short decay time
  - Mechanically stable and strong.
  - Large crystals can be produced
- Lead Tungstate (PWO_4)
  - Fast response
  - Very low radiation length
  - Resistant to radiation

http://scintillator.lbl.gov

Inorganic Scintillators

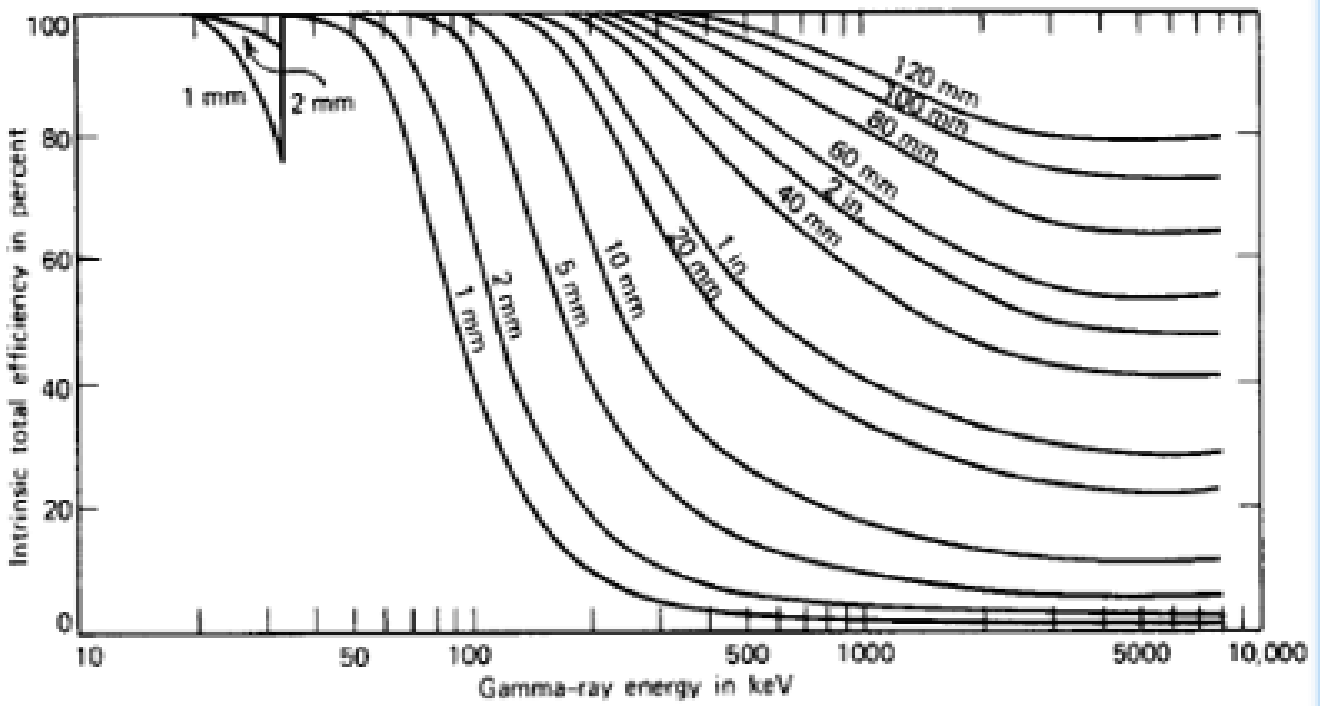


Figure 10.24 The intrinsic total efficiency of various thicknesses of NaI(Tl) for gamma rays perpendicular to its surface.

Inorganic scintillators: general characteristics

Scintillator composition	Density (g/cm^3)	Index of refraction	Wavelength of max.Em. (nm)	Decay time Constant (μs)	Scinti Pulse height[1)]	Notes
NaI(Tl)	3.67	1.9	410	0.25	100	2)
CsI	4.51	1.8	310	0.01	6	3)
CsI(Tl)	4.51	1.8	565	1.0	45	3)
CaF_2(Eu)	3.19	1.4	435	0.9	50	
BaF_2	4.88	1.5	190/220 310	0,0006 0.63	5 15	
BGO	7.13	2.2	480	0.30	10	
$CdW0_4$	7.90	2.3	540	5.0	40	
$PbWO_4$	8.28	2.1	440	0.020	0.1	
CeF_3	6.16	1.7	300 340	0.005 0.020	5	
GSO	6.71	1.9	430	0.060	40	
LSO	7	1.8	420	0.040	75	
YAP	5.50	1.9	370	0.030	70	

1) Relative to NaI(Tl) in %; 2) Hygroscopic; 3) Water soluble

Inorganic Scintillators

Table 8.3 Properties of Common Inorganic Scintillators

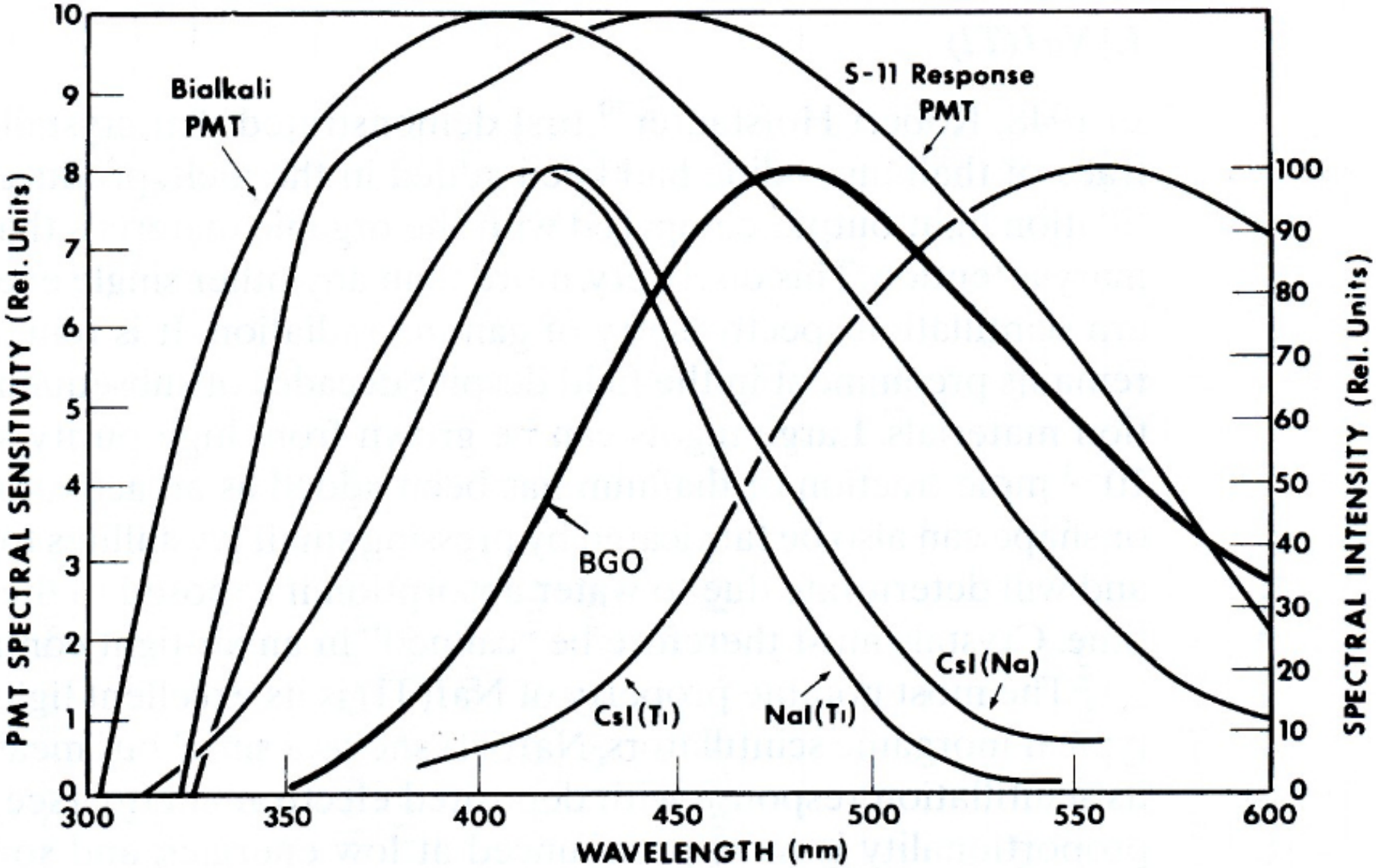
	Specific Gravity	Wavelength of Max. Emission	Refractive Index	Decay Time (μs)	Abs. Light Yield in Photons/MeV	Relative Pulse Height Using Bialk. PM tube	References
Alkali Halides							
NaI(Tl)	3.67	415	1.85	0.23	38 000	1.00	
CsI(Tl)	4.51	540	1.80	0.68 (64%), 3.34 (36%)	65 000	0.49	78, 90, 91
CsI(Na)	4.51	420	1.84	0.46, 4.18	39 000	1.10	92
LiI(Eu)	4.08	470	1.96	1.4	11 000	0.23	
Other Slow Inorganics							
BGO	7.13	480	2.15	0.30	8200	0.13	
$CdWO_4$	7.90	470	2.3	1.1 (40%), 14.5 (60%)	15 000	0.4	98–100
ZnS(Ag) (polycrystalline)	4.09	450	2.36	0.2		1.3[a]	
CaF_2 (Eu)	3.19	435	1.47	0.9	24 000	0.5	
Unactivated Fast Inorganics							
BaF_2 (fast component)	4.89	220		0.0006	1400	na	107–109
BaF_2 (slow component)	4.89	310	1.56	0.63	9500	0.2	107–109
CsI (fast component)	4.51	305		0.002 (35%), 0.02 (65%)	2000	0.05	113–115
CsI (slow component)	4.51	450	1.80	multiple, up to several μs	varies	varies	114, 115
CeF_3	6.16	310, 340	1.68	0.005, 0.027	4400	0.04 to 0.05	76, 116, 117
Cerium-Activated Fast Inorganics							
GSO	6.71	440	1.85	0.056 (90%), 0.4 (10%)	9000	0.2	119–121
YAP	5.37	370	1.95	0.027	18 000	0.45	78, 125
YAG	4.56	550	1.82	0.088 (72%), 0.302 (28%)	17 000	0.5	78, 127
LSO	7.4	420	1.82	0.047	25 000	0.75	130, 131
LuAP	8.4	365	1.94	0.017	17 000	0.3	134, 136, 138
Glass Scintillators							
Ce activated Li glass[b]	2.64	400	1.59	0.05 to 0.1	3500	0.09	77, 145
Tb activated glass[b]	3.03	550	1.5	~3000 to 5000	~50 000	na	145
For comparison, a typical organic (plastic) scintillator:							
NE102A	1.03	423	1.58	0.002	10 000	0.25	

[a]for alpha particles

[b]Properties vary with exact formulation. Also see Table 15.1.

Source: Data primarily from Refs. 74 and 75, except where noted.

Inorganic Scintillators



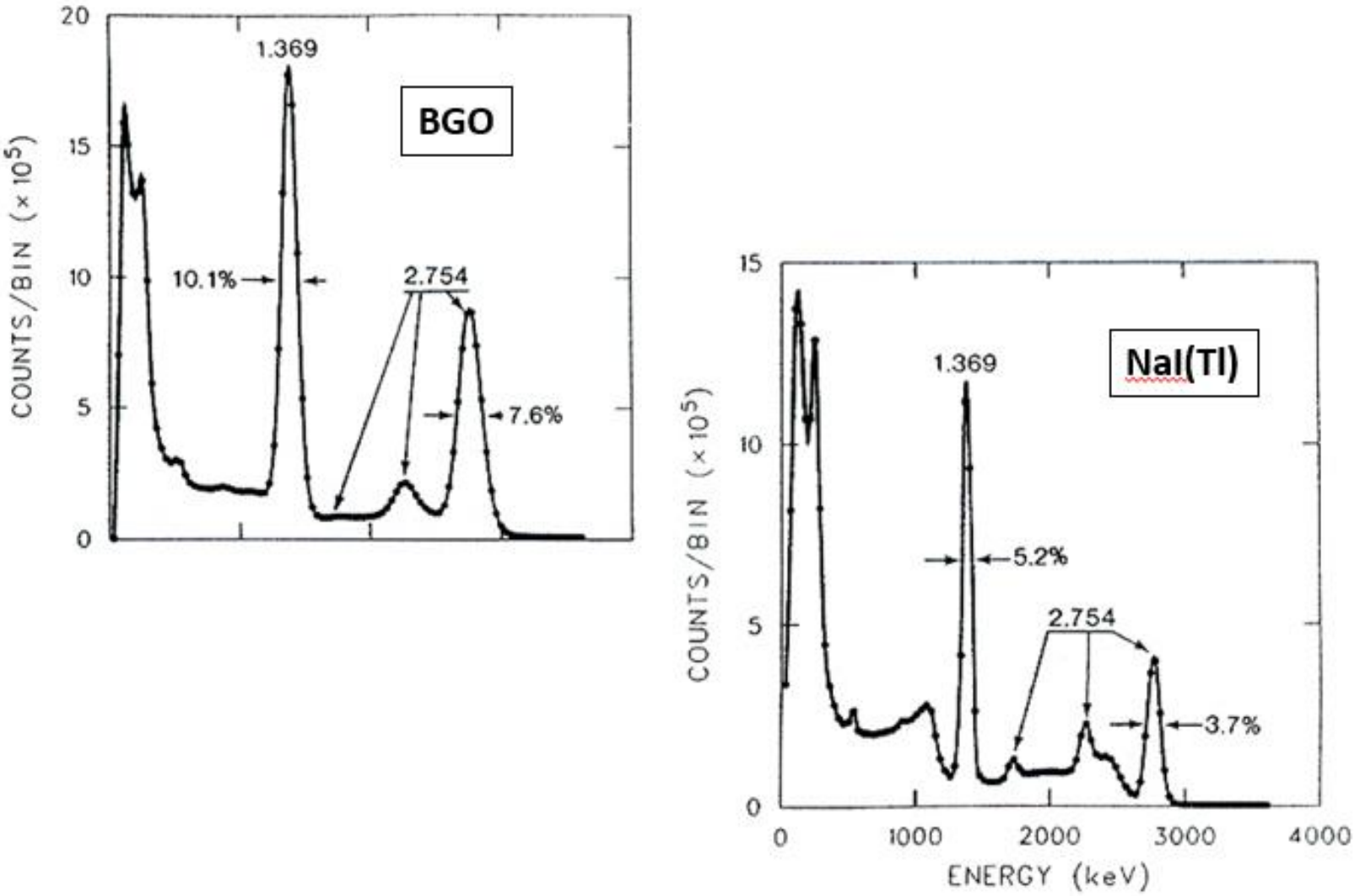


Figure 10-14 Comparative pulse height spectra measured for BGO (top) and NaI(Tl) (bottom) scintillators of equal 7.62 cm × 7.62 cm size for gamma rays from ^{24}Na. (From Moss et al.[14])

Beta-spectrometry

Tail at low-energy side of "full-energy" peak due to:

- **backscattering of electrons**
- **bremsstrahlung that escapes from detector**

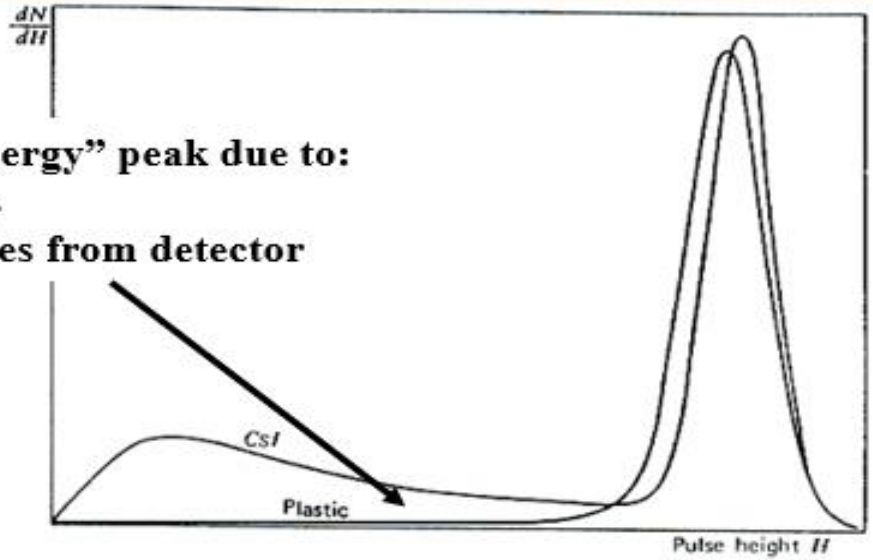


Figure 10-28 Experimental pulse height spectra from CsI(Tl) and plastic scintillators for 1.0 MeV electrons at normal incidence. The spectra are normalized to the same maximum pulse height. (From Titus.[41])

TABLE 10-1 Fraction of Normally Incident Electrons Backscattered from Various Detector Surfaces

	Electron Energy (MeV)				
Scintillator	0.25	0.50	0.75	1.0	1.25
Plastic	0.08 ± 0.02	0.053 ± 0.010	0.040 ± 0.007	0.032 ± 0.003	0.030 ± 0.005
Anthracene	0.09 ± 0.02	0.051 ± 0.010	0.038 ± 0.004	0.029 ± 0.003	0.026 ± 0.004
NaI(Tl)	0.450 ± 0.045	0.410 ± 0.010	0.391 ± 0.014	0.375 ± 0.008	0.364 ± 0.007
CsI(Tl)	0.49 ± 0.06	0.455 ± 0.023	0.430 ± 0.013	0.419 ± 0.018	0.404 ± 0.016

Source: Titus.[41]

Summary: organic vs. inorganic

	Material	Light Output (photons/Mev)	Wavelength of Max. Emission (nm)	Decay Constant (nsec)	Density gms/cc	Index of Refraction
inorganic	NaI(Tl)	38,000	415	230	3.67	1.85
	BGO	9,000	480	300	7.13	2.15
	CsI(Tl)	59,000	560	1000	4.51	1.84
	$CdWO_4$	15,000	480	1100/14500	8.00	2.20
	CaF_2(Eu)	19,000	435	940	3.19	1.44
	GOS*		510	3000	7.34	2.20
	LSO**	30,000	420	40	7.40	1.82
organic	Plastics	~10,000	420	2-17	1.03	1.58

* Gd_2O_2S with dopants; properties vary with dopant types and levels.[2]

** $Lu_2(SiO_4)O$:Ce

Summary: organic vs. inorganic

Inorganic (crystalline structure)
Up to 40000 photons per MeV
High Z
Large variety of Z and ρ
Un-doped and doped
ns to μs decay times
Expensive

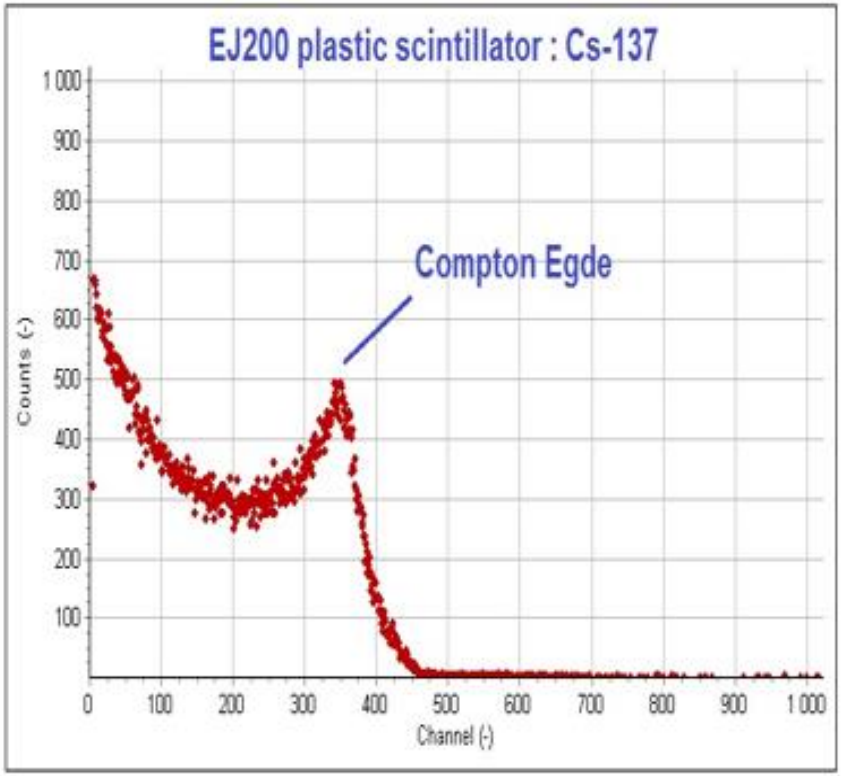
E.m. calorimetry (e, γ)
medical imaging
radiation hard (100 kGy/year)

Organic (plastics or liquid solutions)
Up to 10000 photons per MeV
Low Z
$\rho \sim 1 g/cm^3$
Doped, choice of emission wavelength
ns decay times
Relatively inexpensive

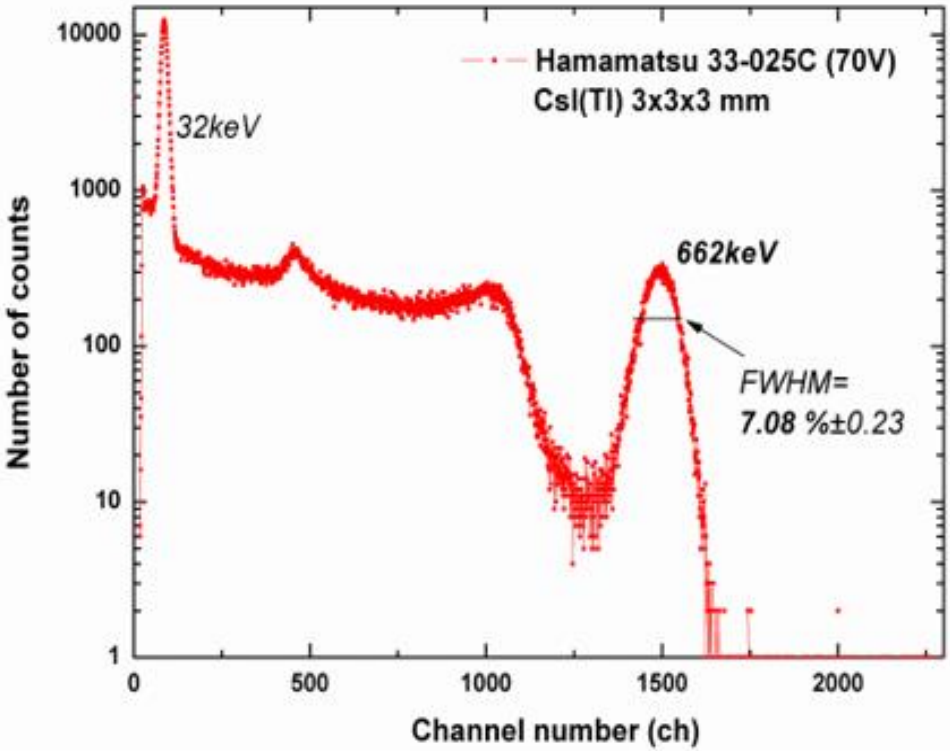
Tracking, TOF, trigger, veto counters,
sampling calorimeters.
medium rad. hard (10 kGy/year)

Spectrometry: organic vs. inorganic

organic



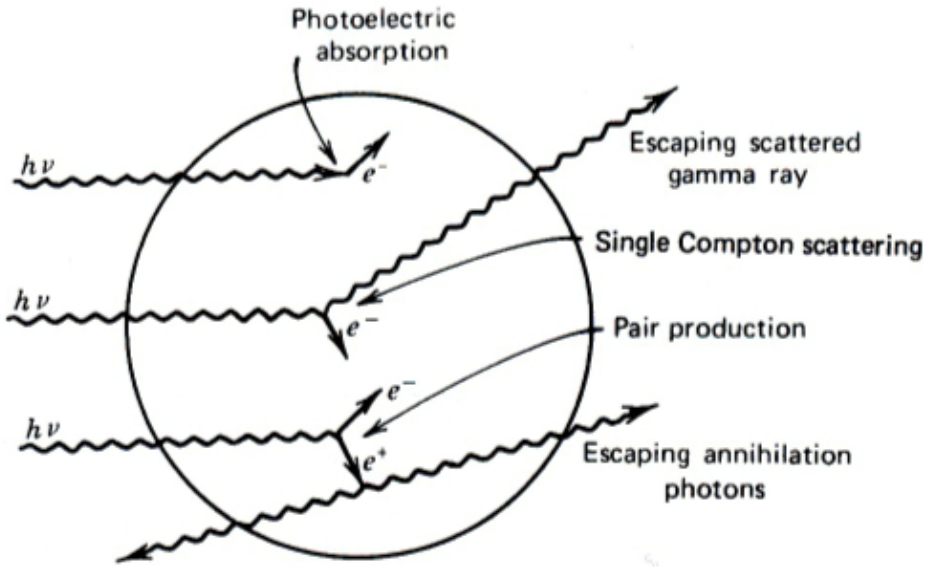
inorganic

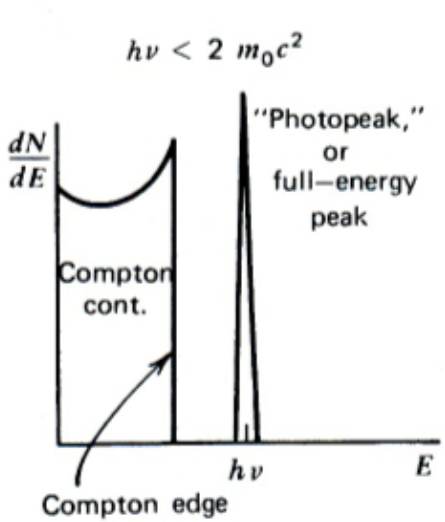


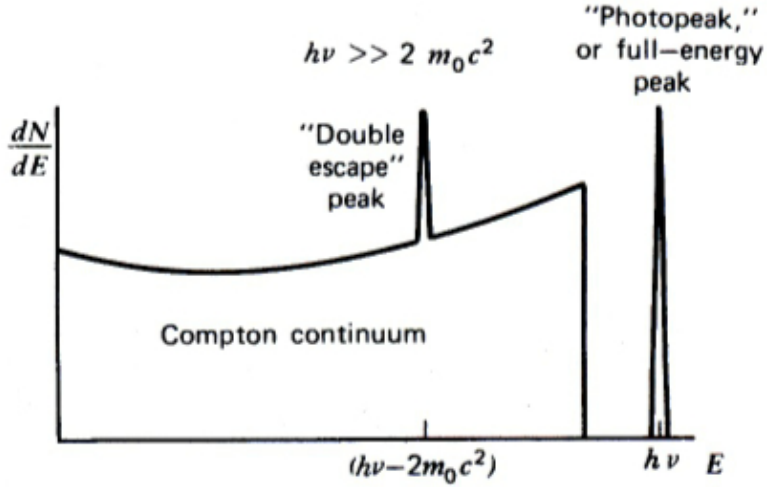
Section 4

Photon Spectroscopy with scintillators

Small size detector



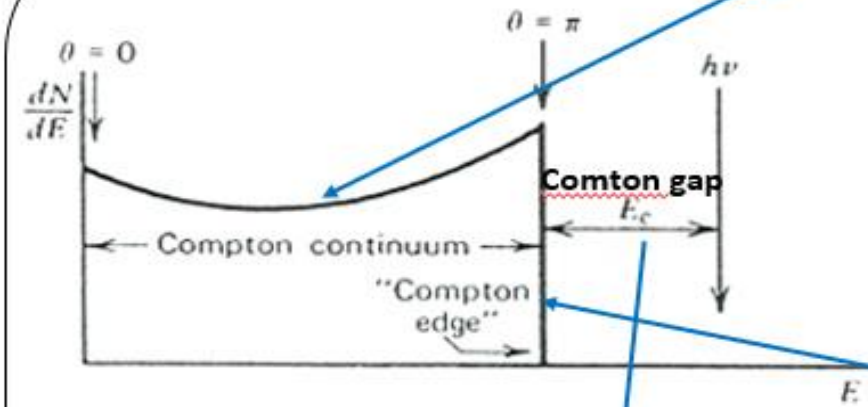




Compton continuum – some details

$$h\nu' = \frac{h\nu}{1 + (h\nu/m_0c^2)(1 - \cos\theta)}$$

→ $E_{e^-} = h\nu - h\nu' = h\nu\left(\frac{(h\nu/m_0c^2)(1 - \cos\theta)}{1 + (h\nu/m_0c^2)(1 - \cos\theta)}\right)$



$$E_C \equiv h\nu - E_{e^-}|_{\theta=\pi} = \frac{h\nu}{1 + 2h\nu/m_0c^2}$$

$\cong$ ½ m_0c^2 indien $h\nu >>$ ½ m_0c^2

Two extreme cases:

a) $\theta \cong 0$ → $h\nu' \cong h\nu$, $E_{e^-} \cong 0$

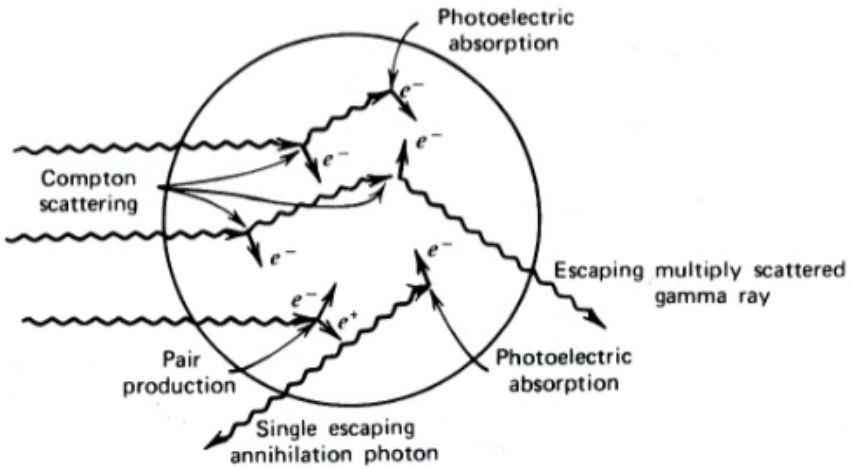
b) $\theta \cong \pi$ → $h\nu'|_{\theta=\pi} = \frac{h\nu}{1 + 2h\nu/m_0c^2}$

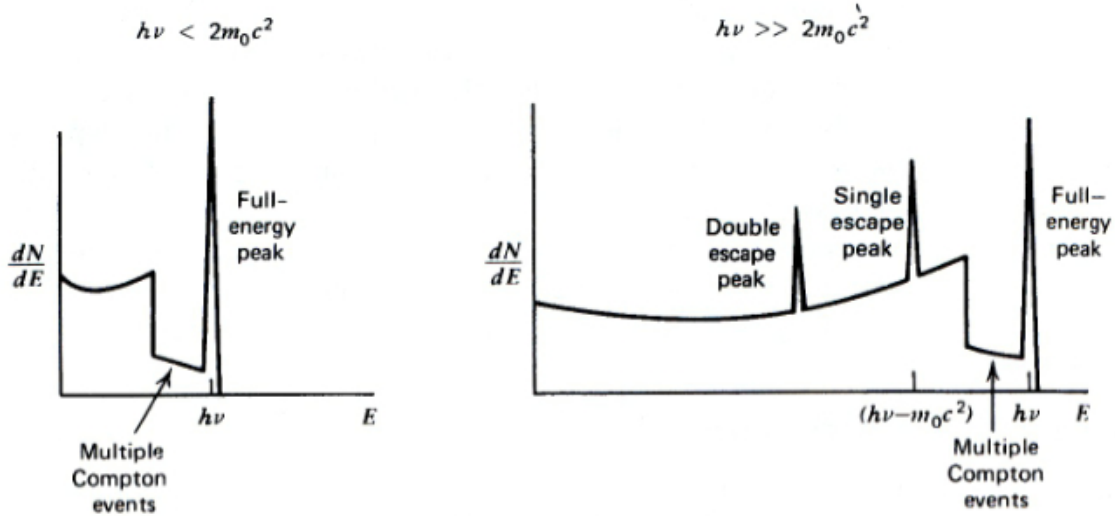
and

$$E_{e^-}|_{\theta=\pi} = h\nu\left(\frac{2h\nu/m_0c^2}{1 + 2h\nu/m_0c^2}\right)$$

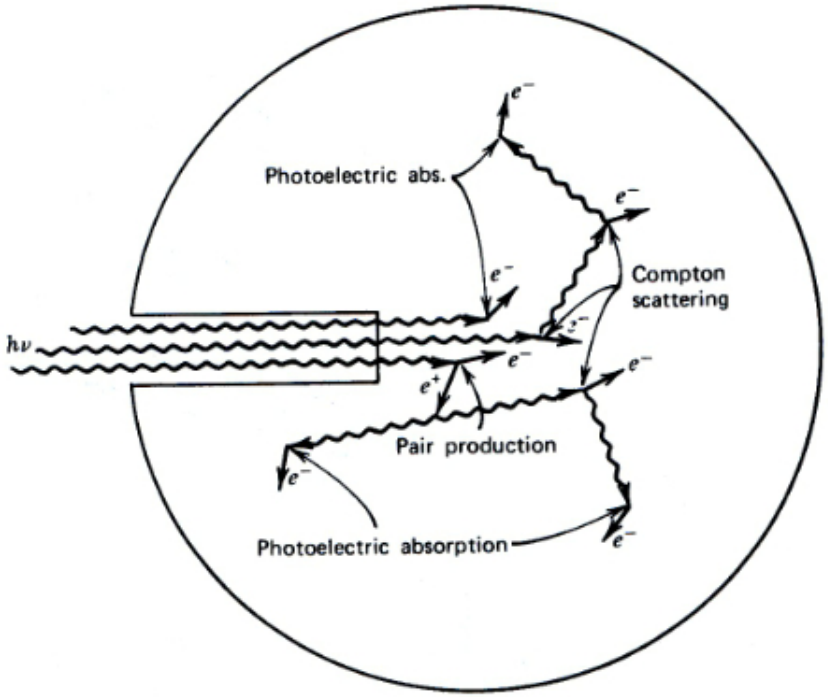
(Compton edge)

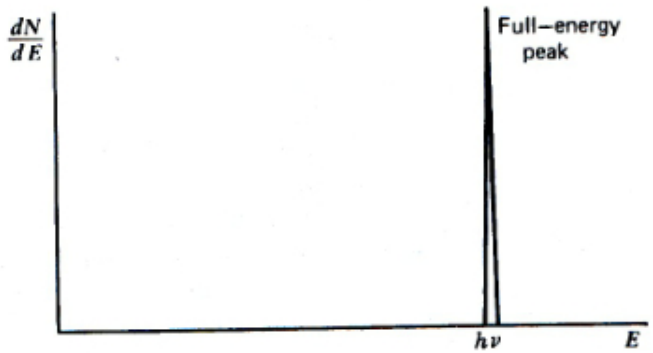
Medium size detector



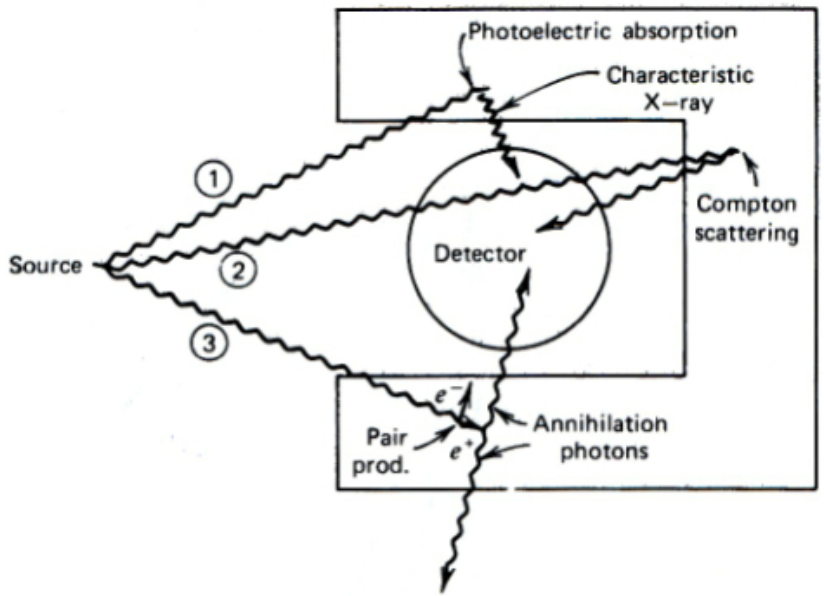


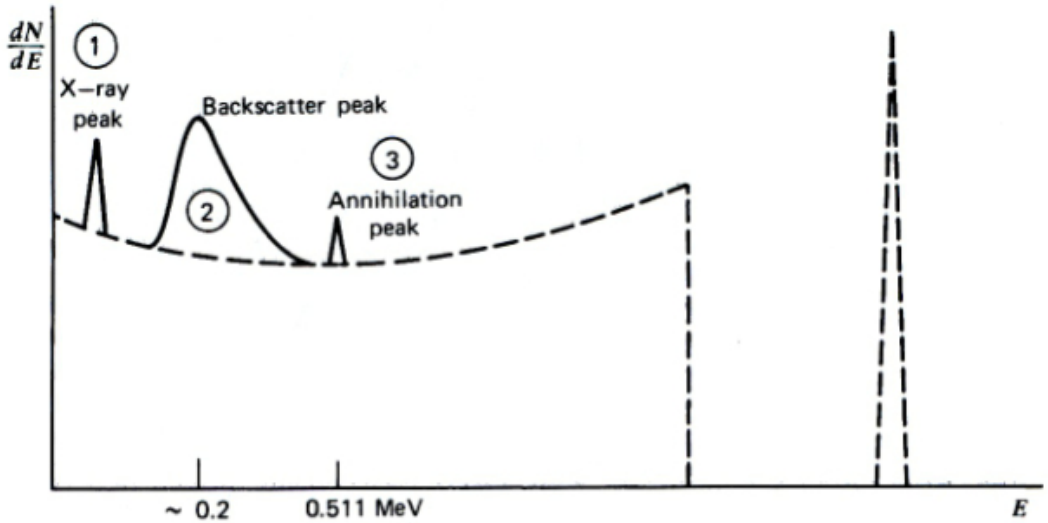
Large size detector





Effects of surrounding materials





Effects of surrounding materials

(Compton) backscatter peak

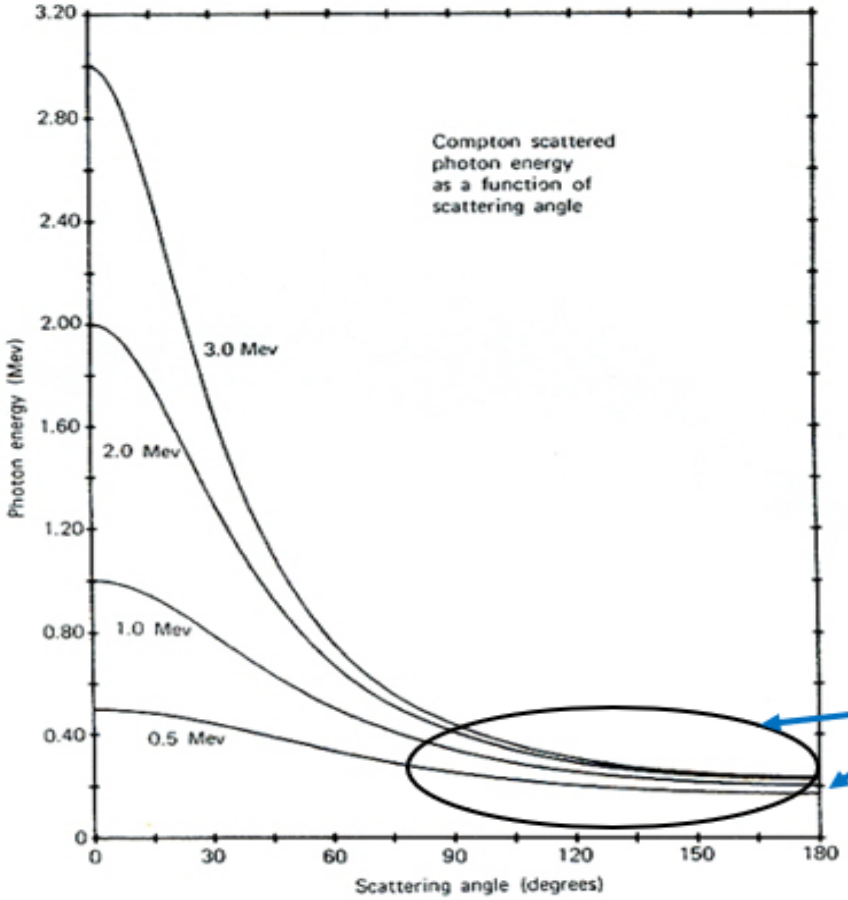


Figure 10-7 Variation of scattered gamma-ray energy with scattering angle.

photon energy after 180° backscattering

$$h\nu'|_{\theta=\pi} = \frac{h\nu}{1 + 2h\nu/m_0c^2}$$

$$\cong \frac{m_0c^2}{2} \cong 250\ \text{keV}, \quad \text{voor } h\nu >> \frac{m_0c^2}{2}$$

photon energy after scattering over angle between 90° and 180° is in 250 to 400 keV range

Section 5

Photodetectors

Photodetectors

- Photodetectors are devices able to convert the extremely weak light output of a scintillator into an measurable electrical signal.
- The electrical signal expected from conversion of photons to electrons is quite weak. Let's see an example
  - How many photons do we expect by the passage of a MIP in 1 cm of scintillator?

$$\frac{dE}{dx}\Big|_{MIP} = 2\,MeV\,cm^2/g$$

Light yield =	Anthracene	2 photons/100 eV	w=50 eV
	Plastic	1 photons/100 eV	w=100 eV
	NaI	4 photons/100 eV	w=25 eV

  - In case of plastic ($\rho \sim 1$ g/cm^3) $\rightarrow$ $\Delta E = 2$ MeV
  - # scintillation photons = 2 MeV/100 eV = 20000 photons
  - If 1 photon = 1 electron, as the timing is $\sim$10 ns

$$Q = 2\,10^4 \times 1.6\,10^{-19}\,C \simeq 3, \text{fC}$$

$$I = \frac{Q}{t} = \frac{2\,10^4 \times 1.6\,10^{-19}\,C}{10\,10^{-9}\,s} \simeq 0.3\,\mu A$$

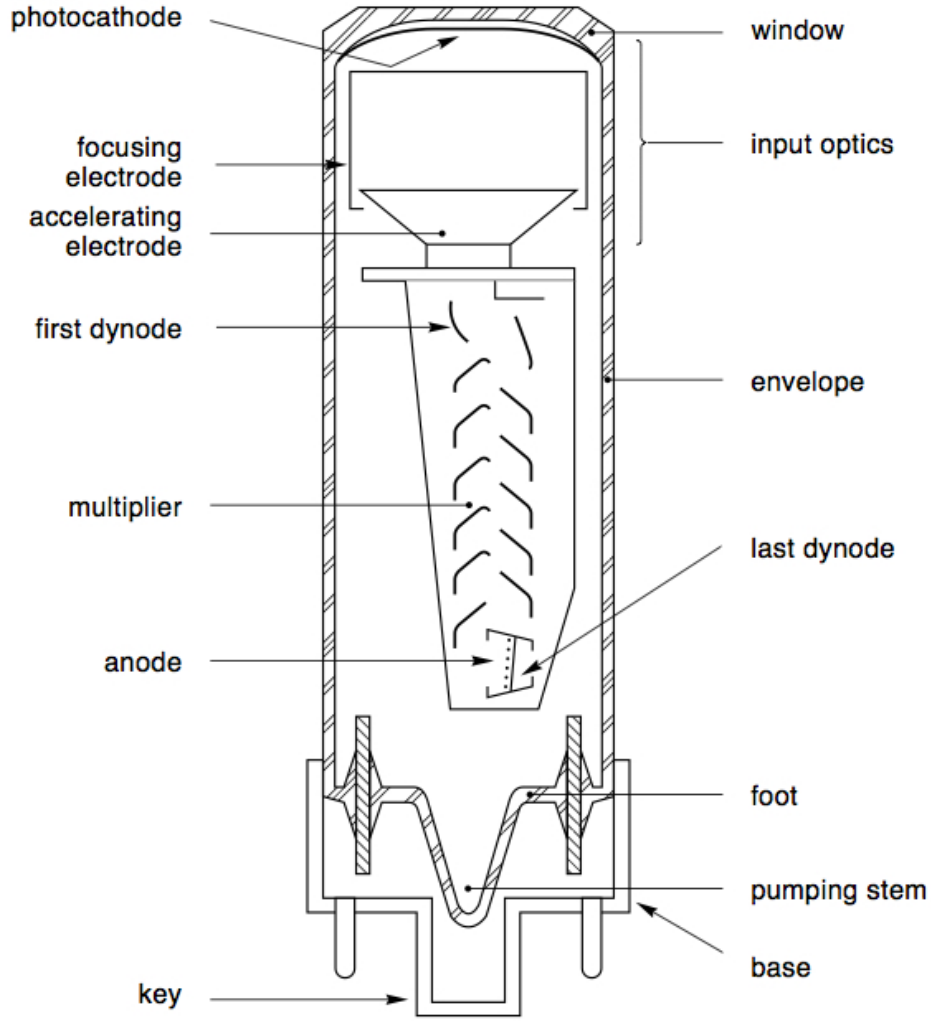
Pulse of 0.3 μA during 10 ns!!!

Photodetectors types

- Vacuum and photocatode based + electron multipliers
  - Photomultipliers (PM)
  - Microchannel plates (MCP)
- Solid state based:
  - Photodiode
  - Avalanche photodiode (APD)
  - Silicon Photomultiplier (SiPM)
  - Charge Coupling Device (CCD)
- Hybrid technology
  - Hybrid Photodetectors

Photomultiplier

- A photomultiplier tube is a vacuum tube consisting of
  - an input window,
  - a photocathode,
  - focusing electrodes,
  - an electron multiplier and
  - an anode



Photomultiplier

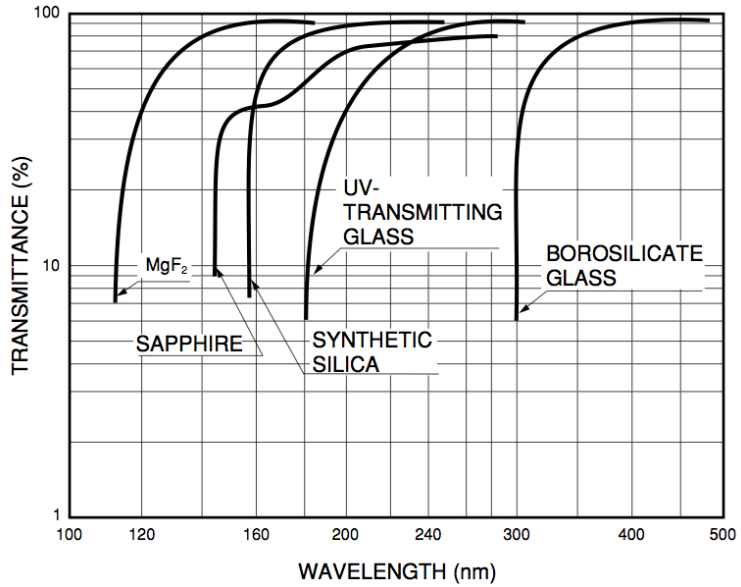
Light which enters a photomultiplier tube is detected and produces an output signal through the following processes:

- Light passes through the input window
- Light excites the electrons in the photocathode $\rightarrow$ photoelectrons are emitted into the vacuum (external photoelectric effect).
- Photoelectrons are accelerated
  - focused by the focusing electrode onto the first dynode
  - Multiplied in dynode by means of secondary electron emission.
  - This secondary emission is repeated at each of the successive dynodes.
- The multiplied secondary electrons emitted from the last dynode are finally collected by the anode.

Input window

Main characteristic to control in the input window is the absorption of short wave lengths.

- MgF_2 crystal. Alkali-halides are the best in transmitting UV. Main drawback is their high deliquescence
- Sapphire. Al_2O_3 crystal
- Synthetic silica. Less absorption than shappire for $\lambda > 160$ nm. Main drawback its thermal expansion coefficient, quite different form Kovar

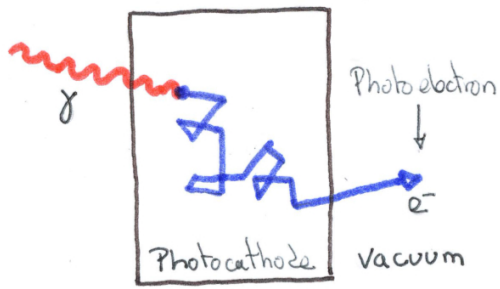


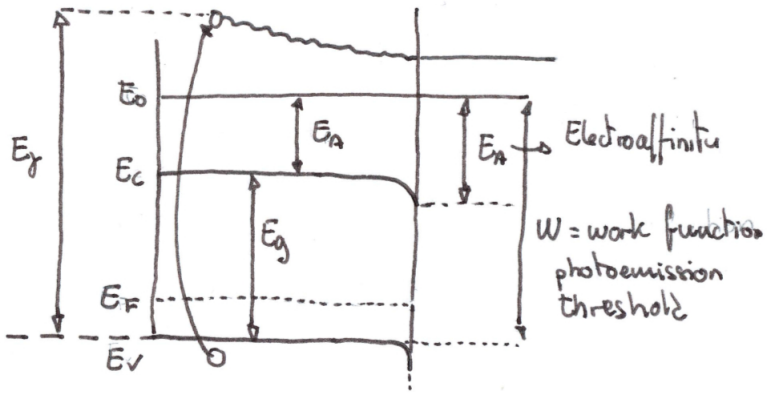
- UV-Transmitting glass
- Borosilicate glass. Most commonly used window material. Thermal expansion coefficient close to Kovar. May contain ^{40}K, although "K-free" glass can be obtained

Photocathode

- Material that converts light into electrons
- It's a three step process
  - Absorbed γ's impart energy to electrons
  - electrons diffuse through the material losing part of its energy
  - electrons reaching the surface with enough energy to escape
- Not all photons are able to generate a photoelectron
- We define the quantum efficiency as:

$$\text{QE} = \frac{\#\text{ emitted electrons}}{\#\text{ incident photons}} = \frac{n_k}{n_\gamma} \simeq 25\%$$





Photocathode: Spectral response characteristics

- Radiant sensitivity: Defined as the ratio of the cathode current (I_k) to the incident flux (ϕ_e). It depends on λ

$$S_{k,\lambda}(A/W) = \frac{I_k(A)}{\phi_{e,\lambda}(W)} \quad \rightarrow \quad \text{cathode radiant sensitivity}$$

$$S_{k,\lambda}(A/lm) = \frac{I_k(A)}{\phi_{e,\lambda}(lm)} \quad \rightarrow \quad \text{cathode luminous sensitivity}$$

  - Cathode radiant sensitivity is usually specified for a wavelentgth λ

$$S_{k,\lambda} = \lim_{d\lambda \to 0} \frac{dI_k}{d\phi_e}$$

    This is called monochormatic or absolute spectral sensitivity
  - Relative spectral sensitivity is the ration between the sensitivity at a given wavelength and at a reference wavelength.

Photocathode: Spectral response characteristics

- Quantum efficiency: Is another way of expressing cathode sensitivity

$$\rho_\lambda = \frac{n_k}{n_\gamma}$$

- Both quantities are related

$$S_{k,\lambda} = \frac{I_k}{\phi} = \frac{\frac{n_k e}{t}}{\frac{n_\gamma h\nu}{t}} = \frac{n_k}{n_\gamma}\frac{\lambda e}{hc}$$

$$S_{k,\lambda}(mA/W) = \frac{\lambda(nm)}{124}\rho_\lambda$$

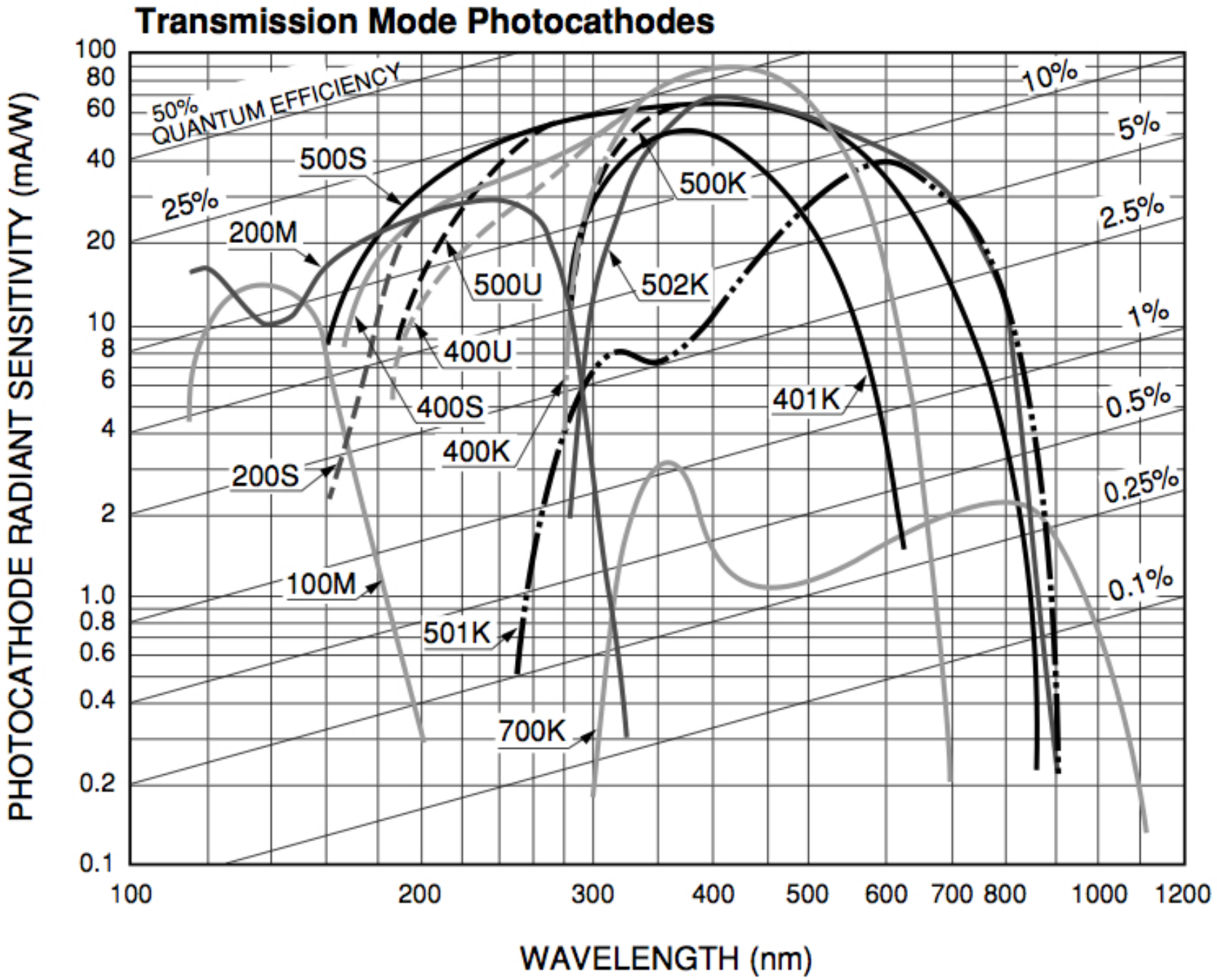
Photocatode materials

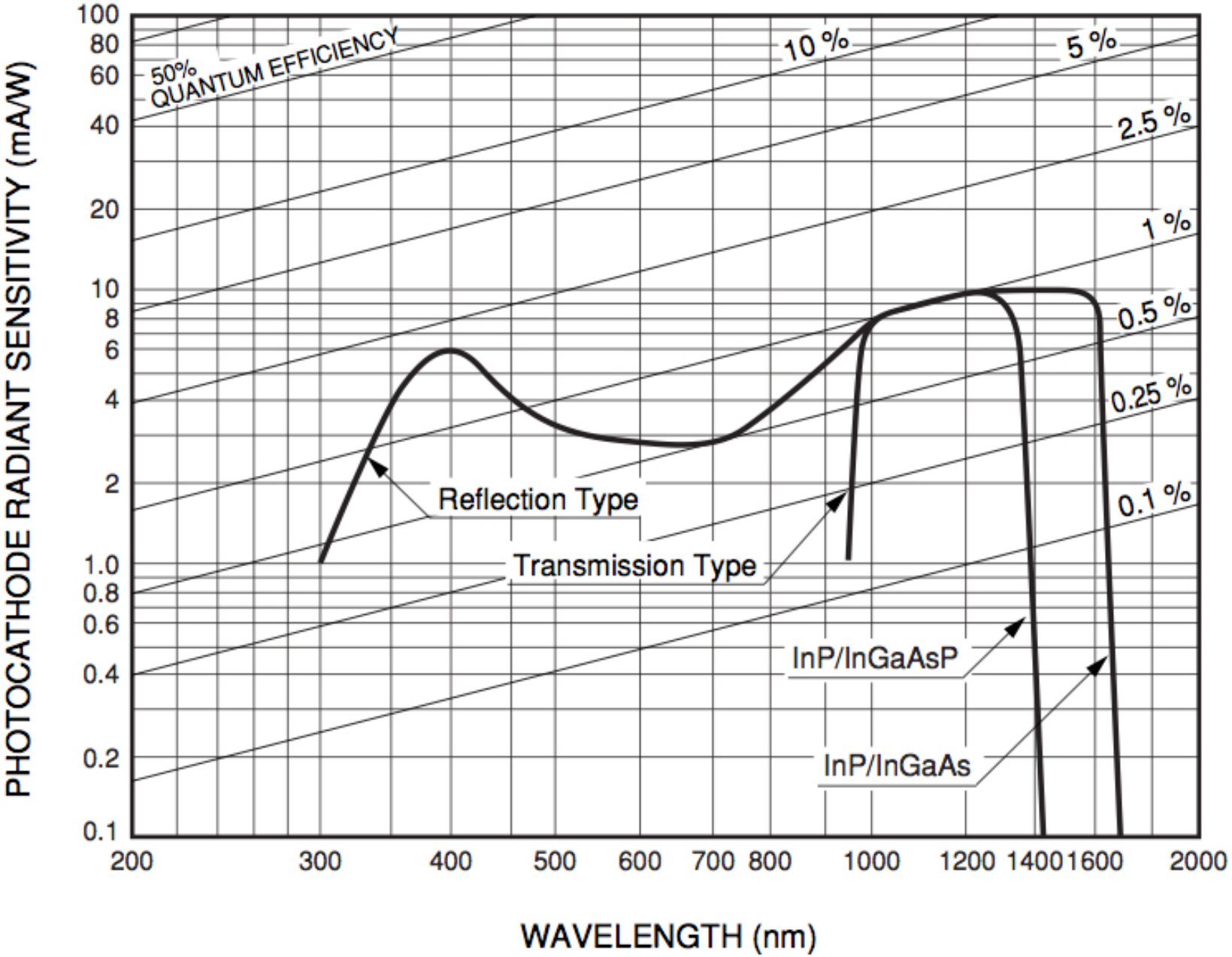
- Semiconductors consisting of alkali metals with a low work function
- There are $\sim$10 materials of practical use
  - Cs-I: Insensitive to $\lambda >$200 nm. Solar blind
  - CS-Te: Insensitive to $\lambda >$300 nm. Solar blind
  - Sb-Cs: UV$\rightarrow$visible. Low cathode resistance. Adapted for high fluxes
  - Bialkali (Sb-Rb-Cs, Sb-K-Cs): UV$\rightarrow$visible but higher sensitivity and lower dark current. Matches with NaI(TI) scintillator
  - High temp Bialkali (Sb-Na-K): Same spectral response as bialkali, but it can operate up to 175^{o}C (rest $\sim$ 50^{o}C).
  - Multialkali (Sb-Na-K-Cs): Wide spectral response up to 850 nm.
  - Ag-O-Cs: Large spectral response 300-1200 nm. Poor sensitivity in the visible compared with bialkaly. Used for mainly for infrared
  - GaAs(Cs): Flat sensitivity between 300-850 nm. When exposed to high intensity suffers degradation
  - InGa(Cs): Best S/N in 900-1000 nm
  - InP/InGaAsP(Cs), InP/InGaAs(Cs): Sensitive in 1.4-1.7 μm. It should be polarized to be used. Because of the high noise it should be operated at -70^{o}C.

Photocathode types

Photocathodes can be broadly classified as

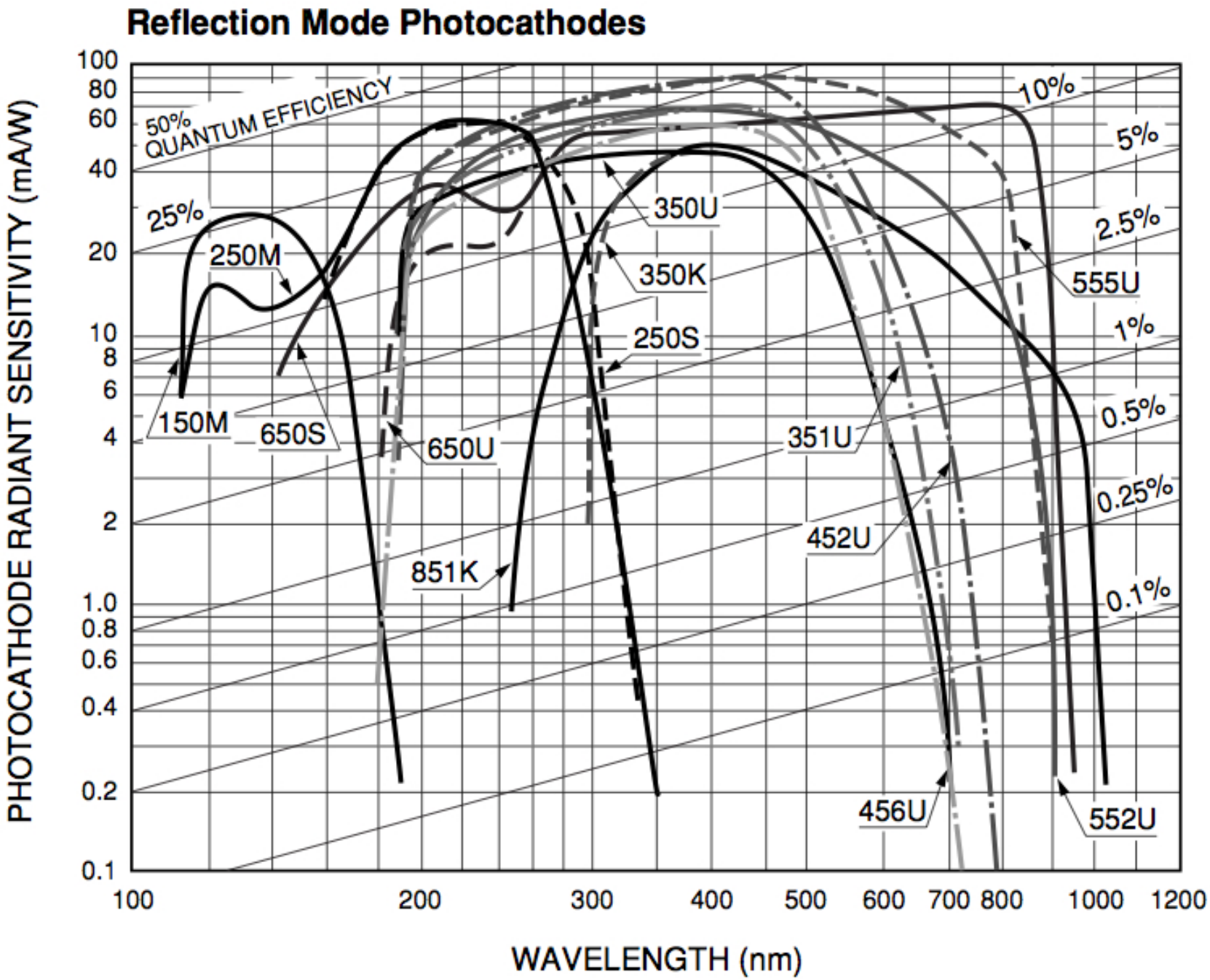
- Transmission (Semitransparent) photocathodes:
  - Photocathodes deposited on a thin film or glass optically transparent
  - Photoelectrons emitted in the same direction of ligth
- Reflection (Opaque) photocathodes:
  - Photocathodes formed on a metal plate
  - Photoelectrons emitted in the opposite direction of incident light


Transmission Mode Photocathodes
PHOTOCATHODE RADIANT SENSITIVITY (mA/W)
WAVELENGTH (nm)
100
80
60
40
20
10
8
6
4
2
1.0
0.8
0.6
0.4
0.2
0.1
100
200
300
400
500
600
700
800
1000
1200
50% QUANTUM EFFICIENCY
25%
10%
5%
2.5%
1%
0.5%
0.25%
0.1%
500S
500K
200M
500U
502K
400U
400S
401K
400K
200S
100M
501K
700K


PHOTOCATHODE RADIANT SENSITIVITY (mA/W)
100
80
60
40
20
10
8
6
4
2
1.0
0.8
0.6
0.4
0.2
0.1
50% QUANTUM EFFICIENCY
10 %
5 %
2.5 %
1 %
0.5 %
0.25 %
0.1 %
Reflection Type
Transmission Type
InP/InGaAsP
InP/InGaAs
200
300
400
500
600
700
800
1000
1200
1400
1600
2000
WAVELENGTH (nm)

Transmission mode photocathodes

Curve Code (S number)	Photocathode Material	Window Material	Luminous Sensitivity (Typ.)	Spectral Response				
				Spectral Range	Peak Wavelength			
					Radiant Sensitivity		Quantum Efficiency	
			(μA/lm)	(nm)	(mA/W)	(nm)	(%)	(nm)
150M	Cs-I	MgF_2	—	115 to 200	25.5	135	26	125
250S	Cs-Te	Quartz	—	160 to 320	62	240	37	210
250M	Cs-Te	MgF_2	—	115 to 320	63	220	35	220
350K (S-4)	Sb-Cs	Borosilicate	40	300 to 650	48	400	15	350
350U (S-5)	Sb-Cs	UV	40	185 to 650	48	340	20	280
351U (Extd S-5)	Sb-Cs	UV	70	185 to 750	70	410	25	280
452U	Bialkali	UV	120	185 to 750	90	420	30	260
456U	Low dark bialkali	UV	60	185 to 680	60	400	19	300
552U	Multialkali	UV	200	185 to 900	68	400	26	260
555U	Multialkali	UV	525	185 to 900	90	450	30	260
650U	GaAs(Cs)	UV	550	185 to 930	62	300 to 800	23	300
650S	GaAs(Cs)	Quartz	550	160 to 930	62	300 to 800	23	300
851K	InGaAs(Cs)	Borosilicate	150	300 to 1040	50	400	16	370
—	InP/InGaAsP(Cs)	Borosilicate	—	300 to 1400	10	1250	1.0	1000 to 1200
—	InP/InGaAs(Cs)	Borosilicate	—	300 to 1700	10	1550	1.0	1000 to 1200

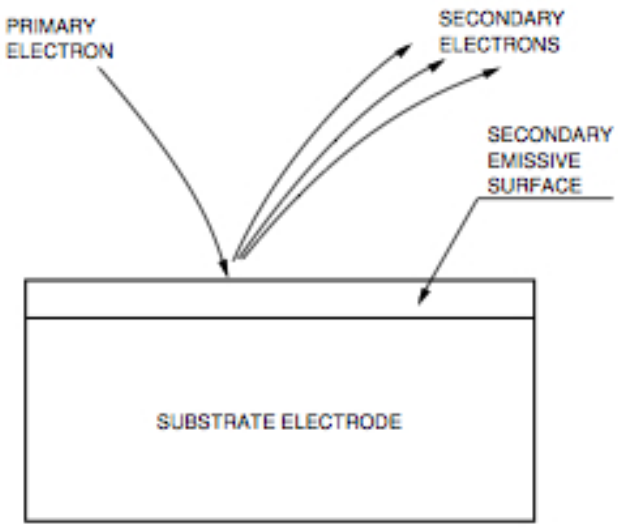

Reflection Mode Photocathodes
PHOTOCATHODE RADIANT SENSITIVITY (mA/W)
WAVELENGTH (nm)
50% QUANTUM EFFICIENCY
25%
10%
5%
2.5%
1%
0.5%
0.25%
0.1%
150M
250M
650S
650U
350U
350K
250S
851K
351U
452U
456U
555U
552U
100
80
60
40
20
10
8
6
4
2
1.0
0.8
0.6
0.4
0.2
0.1
100
200
300
400
500
600
700
800
1000
1200

Reflection mode photocathodes

Curve Code (S number)	Photocathode Material	Window Material	Luminous Sensitivity (Typ.) (μA/lm)	Spectral Response				
				Spectral Range (nm)	Peak Wavelength			
					Radiant Sensitivity		Quantum Efficiency	
					(mA/W)	(nm)	(%)	(nm)
100M	Cs-I	MgF_2	—	115 to 200	14	140	13	130
200S	Cs-Te	Quartz	—	160 to 320	29	240	14	210
200M	Cs-Te	MgF_2	—	115 to 320	29	240	14	200
400K	Bialkali	Borosilicate	95	300 to 650	88	420	27	390
400U	Bialkali	UV	95	185 to 650	88	420	27	390
400S	Bialkali	Quartz	95	160 to 650	88	420	27	390
401K	High temp. bialkali	Borosilicate	40	300 to 650	51	375	17	375
500K(S-20)	Multialkali	Borosilicate	150	300 to 850	64	420	20	375
500U	Multialkali	UV	150	185 to 850	64	420	25	280
500S	Multialkali	Quartz	150	160 to 850	64	420	25	280
501K(S-25)	Multialkali	Borosilicate	200	300 to 900	40	600	8	580
502K	Multialkali	Borosilicate (prism)	230	300 to 900	69	420	20	390
700K(S-1)	Ag-O-Cs	Borosilicate	20	400 to 1200	2.2	800	0.36	740
—	InP/InGaAsP(Cs)	—	—	950 to 1400	10	1250	1.0	1000 to 1200
—	InP/InGaAs(Cs)	—	—	950 to 1700	10	1550	1.0	1000 to 1200

Electron multipliers

- Structures that amplify the weak primary photocurrent.
- In the PM jargon electron multipliers are called dynodes
- Besides electron multiplication, dynodes also focus electron trajectories



- Basic principle: When an electron strikes dynode surface with an energy larger then E_P, δ secondary rays are emitted
- Positioning n dynodes in cascade with a ΔV assuring that $E_e > E_p$, the total gain is:

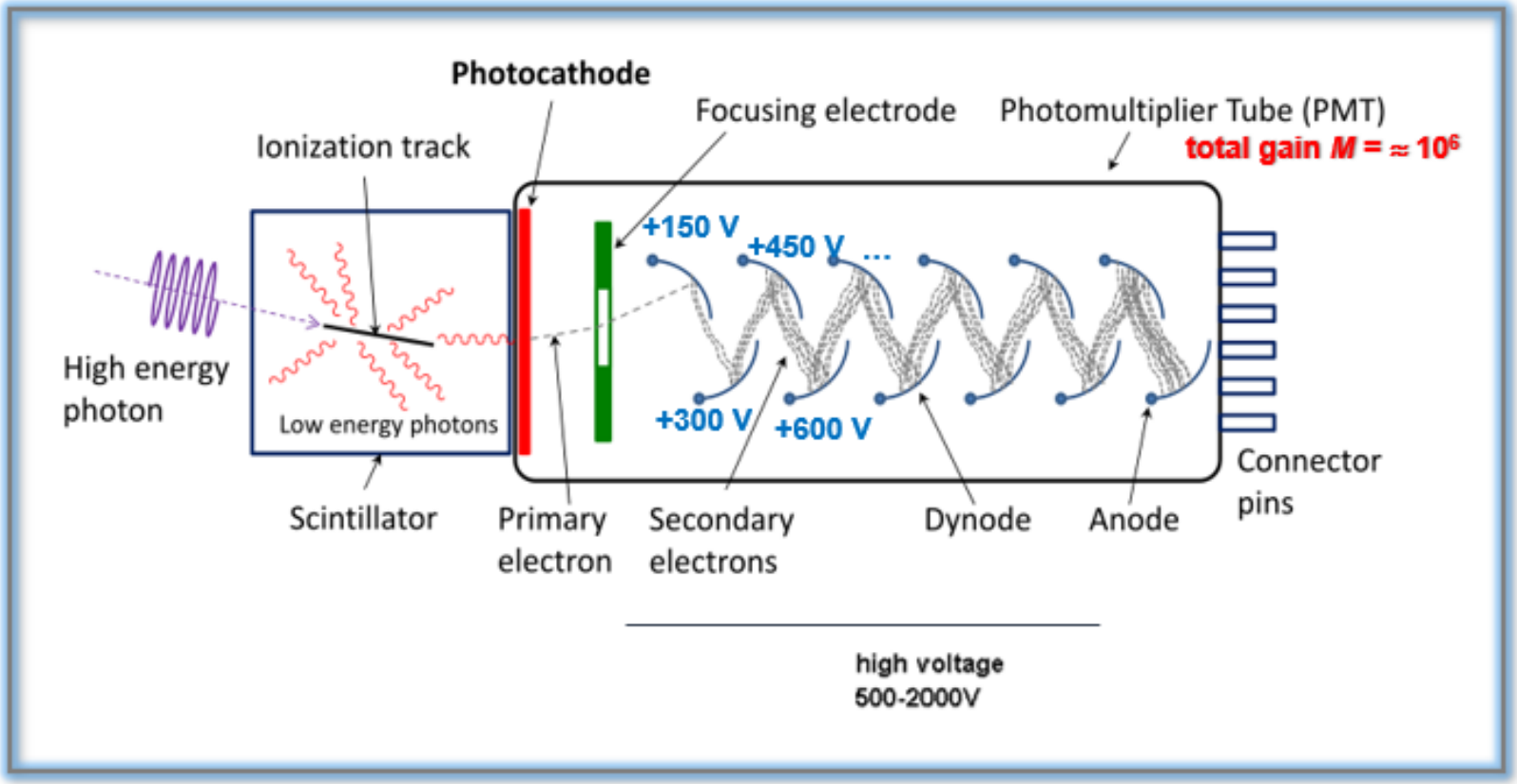
$$G = \delta^n$$

if $\delta = 4$ and $n = 10 \rightarrow G = 4^{10} \sim 10^6$

Electron multipliers

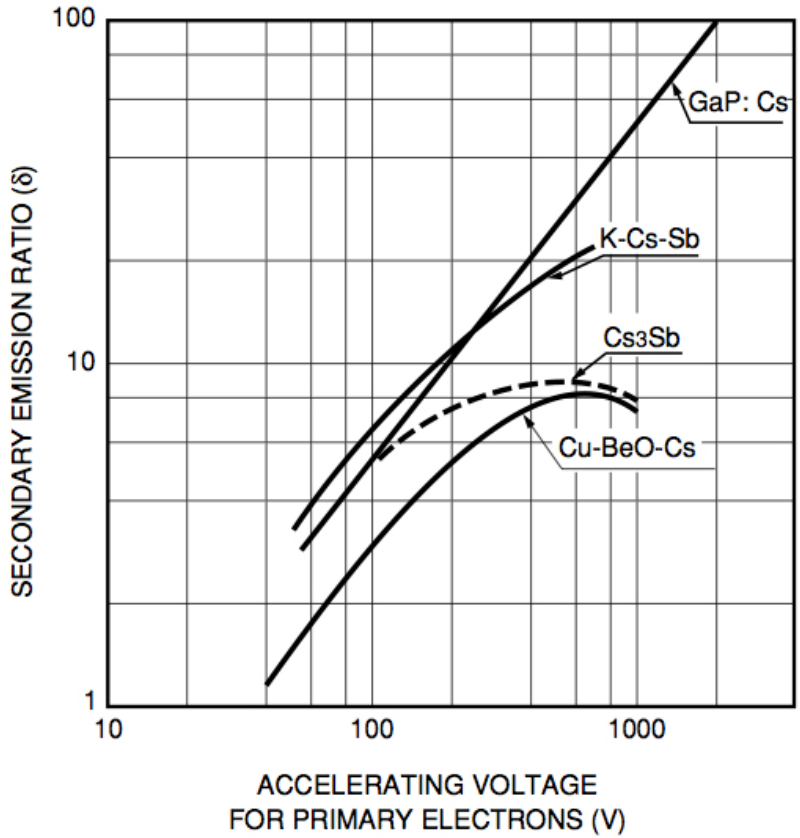
Main phenomena:

- photo emission from photo cathode
- secondary emission from dynodes



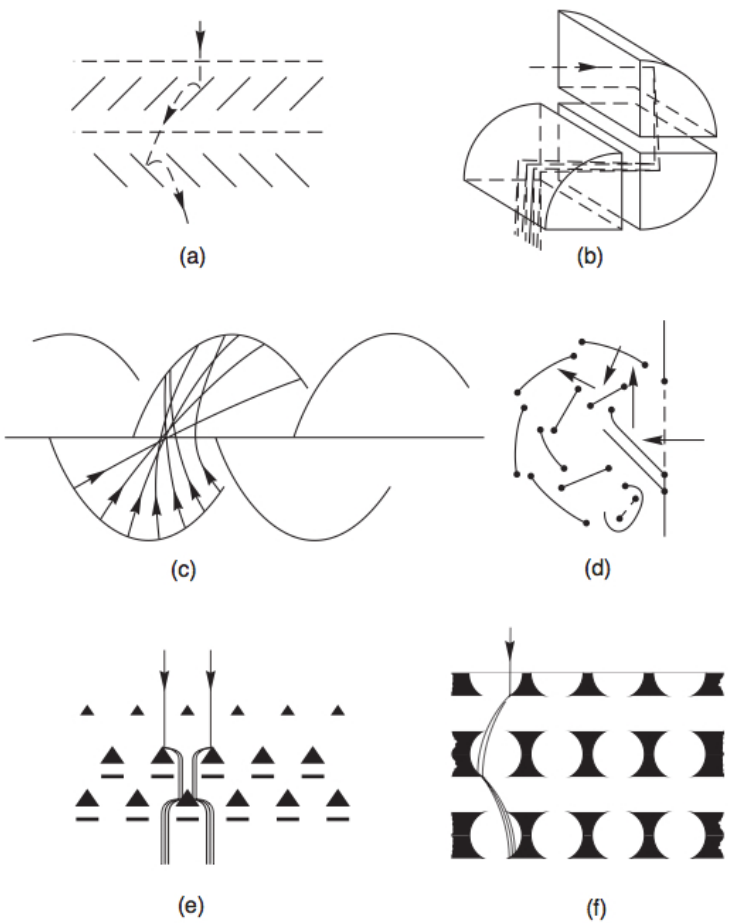
Electron multipliers: materials

- Dynodes are composed by:
  - Materials with high secondary electron emission on the surface: Alkali antimonide (Sb), Beryllium Oxide (BeO), Magnesium Oxide (MgO), Gallium Phosphide (GaP)
  - Substrate electrode made of Ni, Stainless-steel of Cu-Be alloy.



Dynode configuration

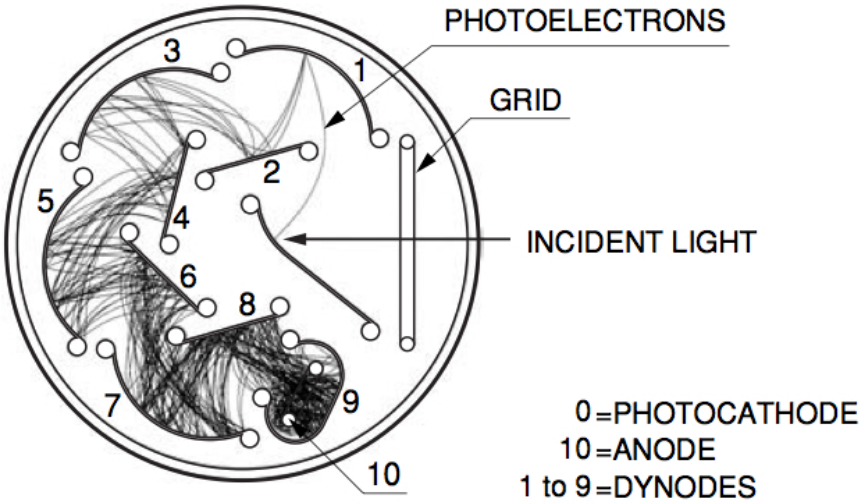
- In order to collect electrons generated by secondary emission dynodes are disposed in various arrangements and with characteristic shapes

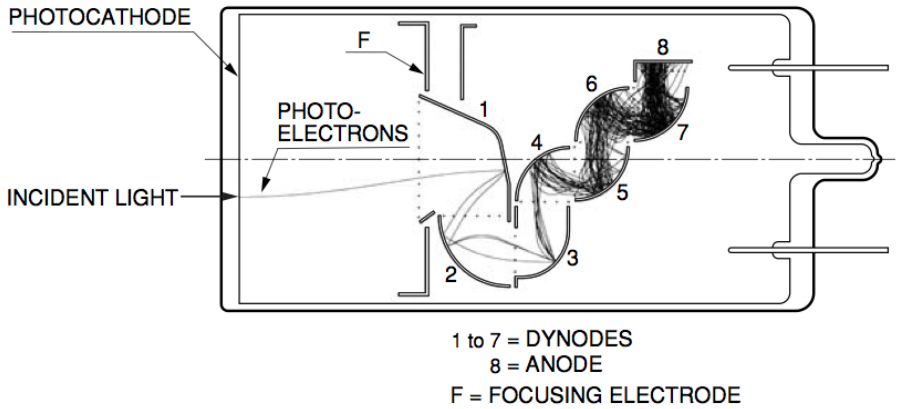


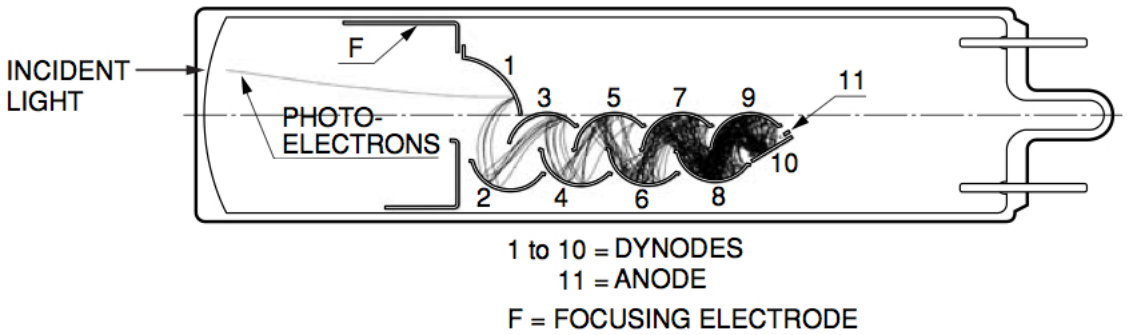
  - Venetian-blind
  - Box dynodes
  - Linear focusing
  - Circular cage
  - Mesh dynodes
  - Foil dynodes

- Electron trajectories depends mainly of the electric field between dynodes
- External magnetic fields can modify greatly these trajectories
- Screen material: μ-metal $\rightarrow \mu_r \sim 1000$

Electron trajectories







Anode

- Final dynode that collects secondary electrons acts as an anode
- Anodes are also carefully designed in order to optimize electron trajectories
- Usually designed in the form of rod, plate or mesh electrode
- Potential difference between last dynode and anode should be high enough:
  - Avoid space charge effects
  - Obtain large output current: induced current $\propto$ velocity

Photomultipler characteristics

- Gain

$$\left.\begin{array}{l}\delta = kV_d \\ G = \delta^n\end{array}\right\} \rightarrow \quad G = (kV_d)^n \quad \rightarrow \quad \begin{array}{c} G = aV^n \\ V_d = \dfrac{G^{1/n}}{k}\end{array}$$

  - Voltage stability to minimize variation in gain

$$\frac{dG}{G} = \frac{n\,dV_d}{V_d} \sim n\frac{dV}{V} \quad \Rightarrow \quad \left.\begin{array}{c} n{=}10 \\ dG{=}10\%\end{array}\right\} \rightarrow dV{=}1\%$$

  - Minimum number of dynodes: $V = nV_d = \frac{n}{k}G^{1/n}$

$$\frac{dV}{dn} = \frac{1}{k}G^{1/n} - \frac{n}{k}\frac{1}{n^2}G^{1/n}\ln G = 0$$

$$n = \ln G \quad \rightarrow \quad \begin{array}{l} G \sim 10^5 \rightarrow n \sim 11 \\ G \sim 10^6 \rightarrow n \sim 13\end{array}$$

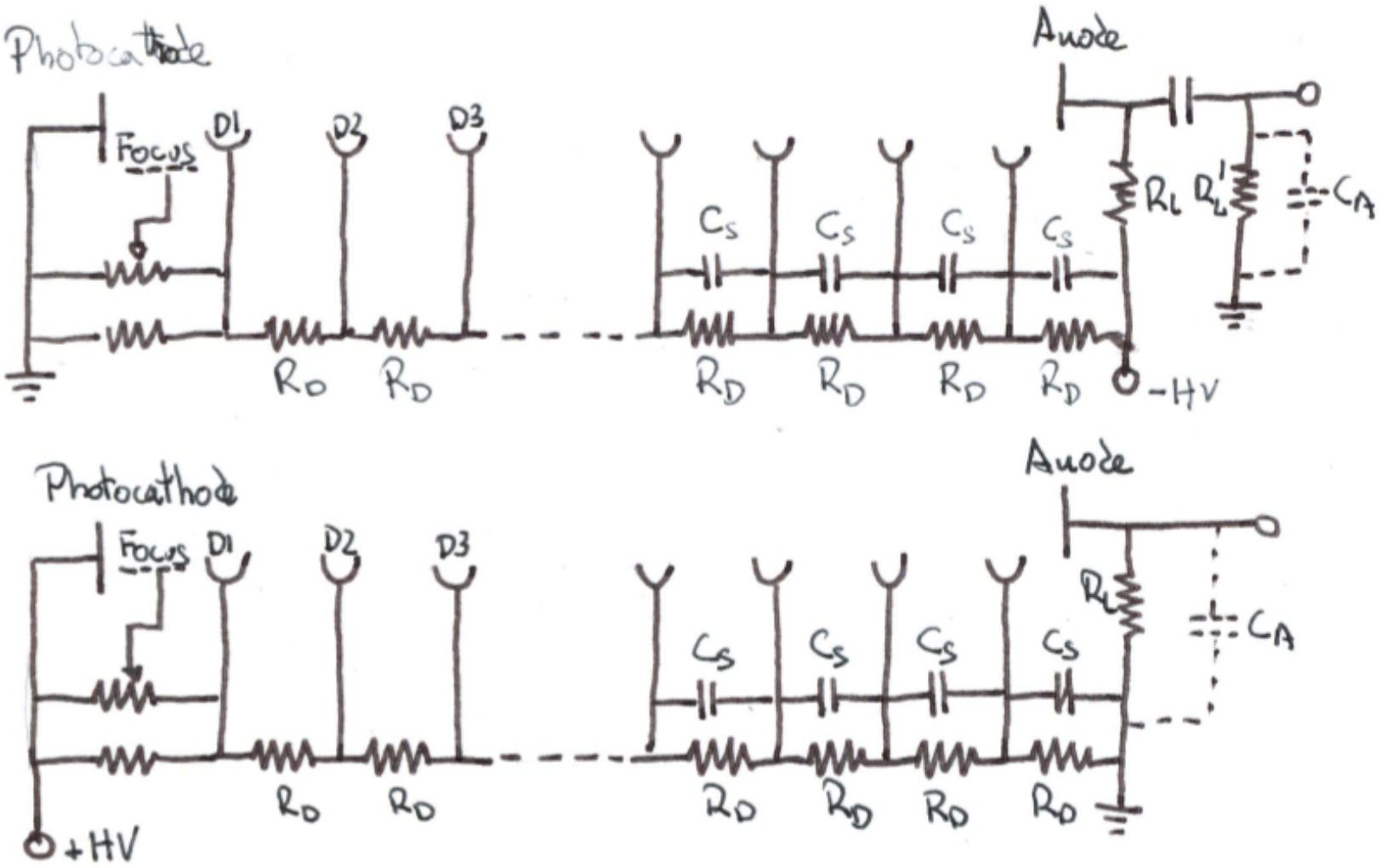
Voltage dividers

- Stable voltage between dynodes is crucial in PM operation
- Most common method to provide this voltage is:
  - Stabilized high voltage power supply
  - Voltage divider: chain of resistance chosen to provide the desired voltage to each dynode
- Current passing through voltage divider (bleeder current) may affect the gain

$$\frac{\Delta G}{G} = \frac{I_{an}}{I_{bl}} \frac{n(1-\delta)+1}{(n+1)(1-\delta)}$$

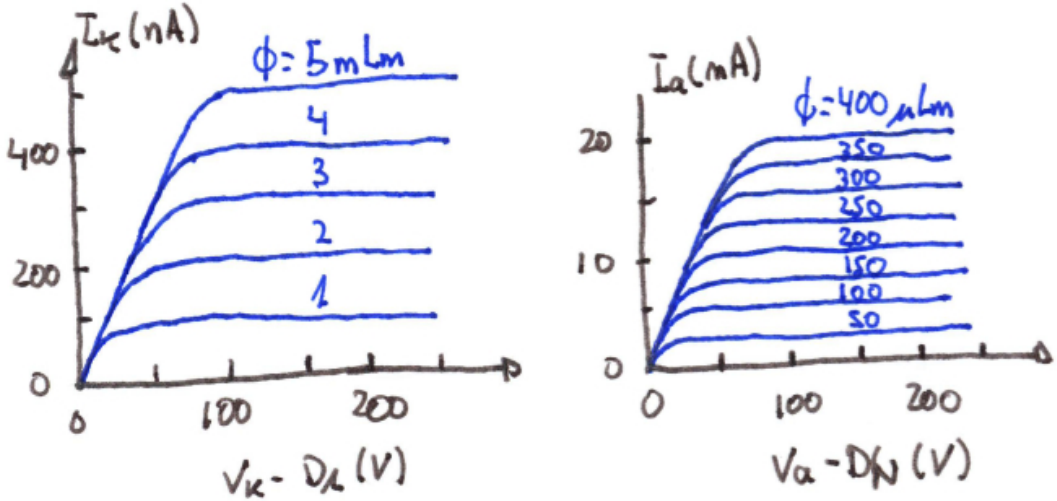
- To maintain 1% linearity $\rightarrow I_{bl} \sim 100 I_{an}$
- In case of large anode currents, potential may drop momentarily
- To avoid this, ΔV in the last stages can be fixed adding capacitors
- Different voltage divider profiles are used for different uses.

Voltage dividers



Photomultiplier characteristics

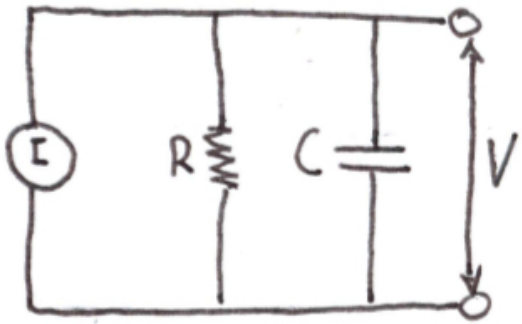
- Linearity
  - Linearity depends strongly on dynode configuration and the current
  - Linearity requires that current is fully collected at each stage
  - Collection of photoelectrons in first dynode is essential
  - Dependence of the cathode and anode current on applied voltages



  - Initial dependence on voltage is due to the formation of a space charge around emitting electrode
  - This cloud tends to cancel electric field and prevents electrons arriving to the receiving electrode

Photomultiplier characteristics

- Pulse Shape
  - Pulse shape depends on scintillator pulse shape and number of photoelectrons
  - Assuming the input scintillator light output is described by an exponential



$$I(t) = \frac{GNe}{\tau_s} e^{-t/\tau_s}$$

$$I(t) = \frac{V(t)}{R} + C\frac{dV(t)}{dt}$$

$$V(t) = \begin{cases} -\frac{GNeR}{\tau - \tau_s}\left[e^{-t/\tau_s} - e^{-t/\tau}\right] & \tau \neq \tau_s \quad \text{current mode} \\ -\frac{GNeR}{\tau_s^2} t e^{-t/\tau_s} & \tau = \tau_s \quad \text{voltage mode} \end{cases}$$

where $\tau = RC$

Shape of scintillation pulses

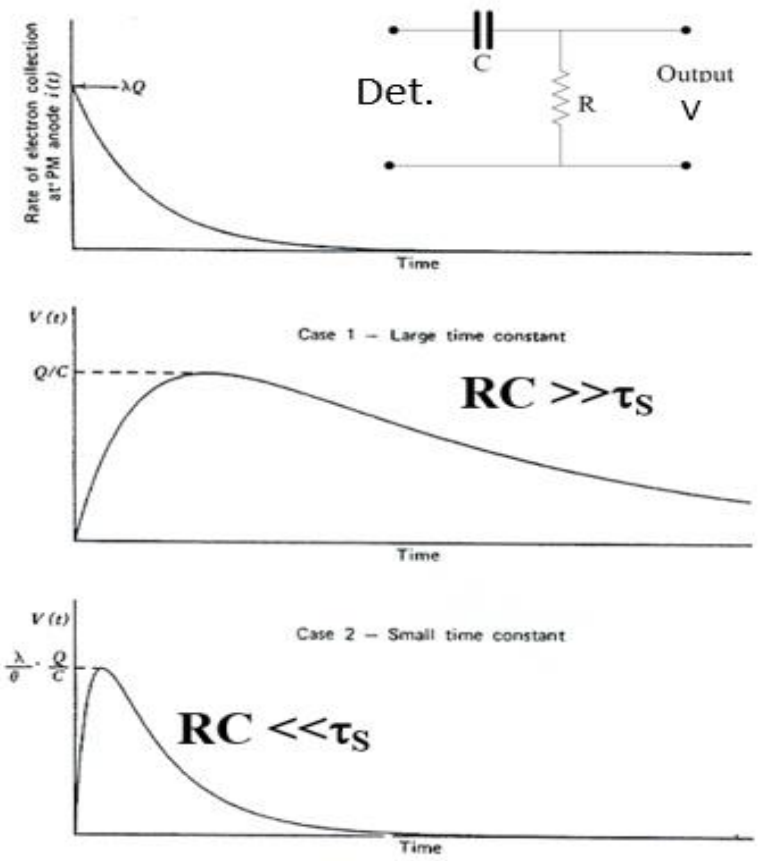


Figure 9-17 For the assumed exponential light pulse shown at the top, plots are given of the anode pulse $V(t)$ for the two extremes of large and small anode time constant. The duration of the pulse is shorter for Case 2, but the maximum amplitude is much smaller.

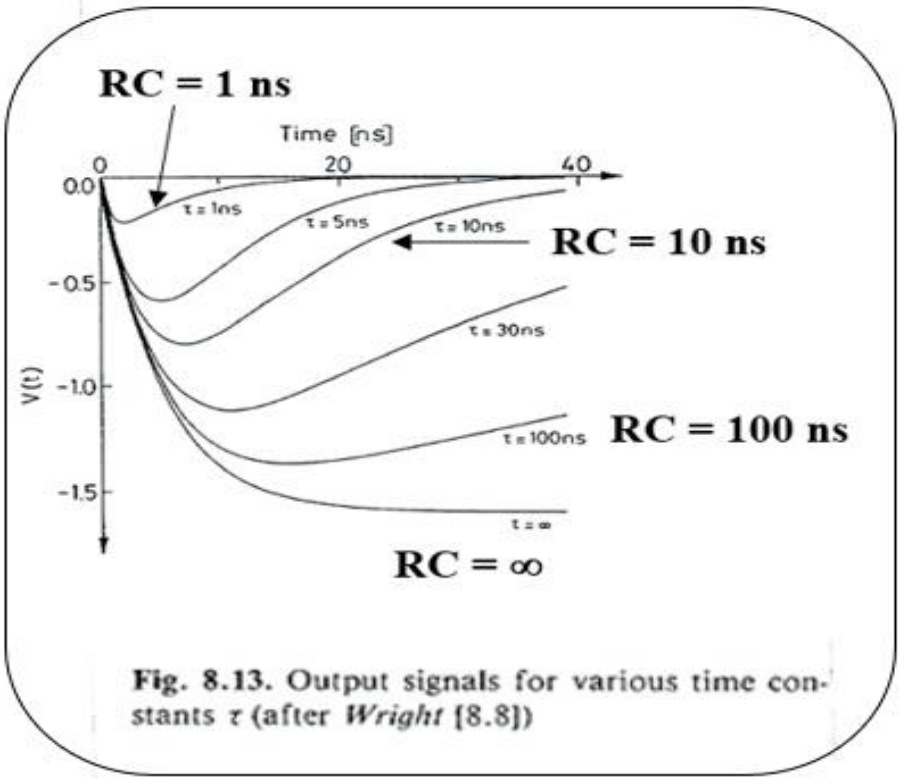


Fig. 8.13. Output signals for various time constants τ (after *Wright* [8.8])

τ_S = scintillation time $\cong$ few ns

- If counting rates $> \frac{1}{\tau}$ pile-up ocurs

Dark current

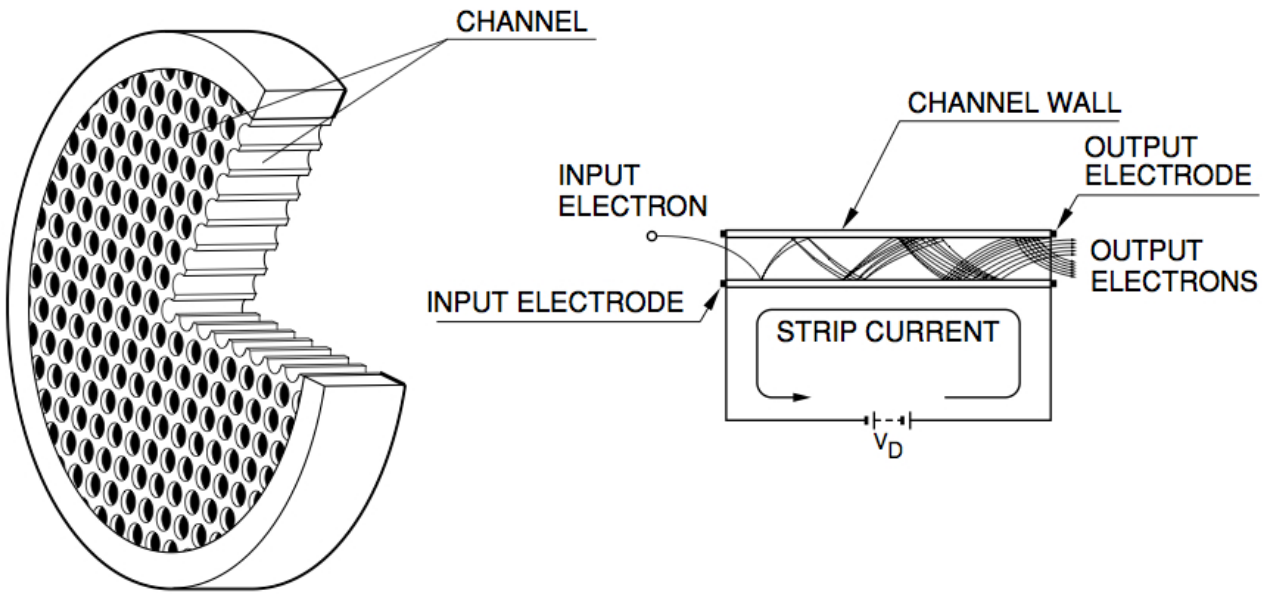
- Even if PM is not illuminated, a small current still flows.
- This current is called dark current.
- Origin of dark current is multiple:
  - Thermoionic emission from the cathode and dynodes
    This is the main contribution and can be parametrized as

$$I = AT^2 \exp\left(\frac{-e\phi}{kT}\right)$$

    where ϕ=work function
  - Leakage currents, mainly in between connection pins. Difficult to avoid
  - Radioactive contamination in the materials composing the PM
  - Ionization phenomena in residual gases inside the (see afterpulsing)
  - Light phenomena. PMs have high sensitivity
  - Cosmic rays and environmental gamma rays
- Normal dark currents are small, not more than few nA

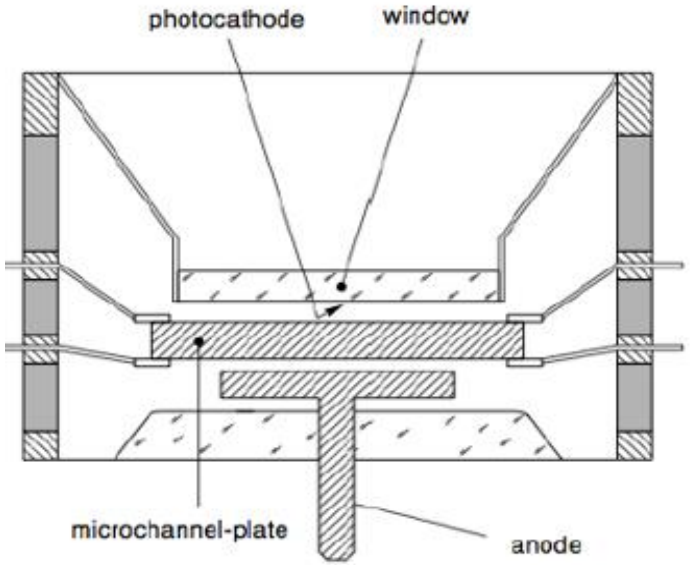
Microchannel plates

- Special type of PM with a special electron multiplier stage
- Two dimensional array of glass capillaries (microchannels)
  - Inner diameter $\sim$6-10 μm
  - Inner wall with secondary emission properties
  - Each channel acs as an independent electron multiplier with high gain



Microchannel plates

- Main features
  - Compact size
  - Two dimensional detection (spatial resolution)
  - Fast time response (10's ps!!!)
  - Stable operation even in presence of high magnetic fields
  - Low power consumption



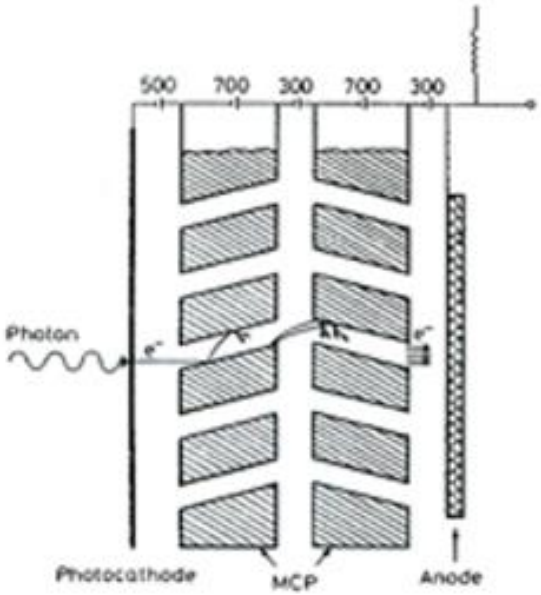


Fig. 8.7. Chevron configuration in a microchannel plate photomultiplier (after *Dhawan* [8.4]). A further increase in gain may be obtained by adding a third plate to form a "Z" configuration (picture © 1975 IEEE)

Photodiodes

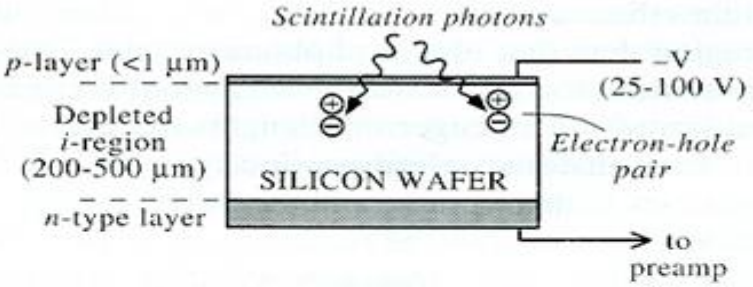


Figure 9.14 Basic configuration of a conventional photodiode.

Normal photodiode :

V = several 10's of V

Shower photodiode:

several 100's of V

→ electrons are accelerated sufficiently so that they can themselves also create electron-ion pairs

→ charge multiplication

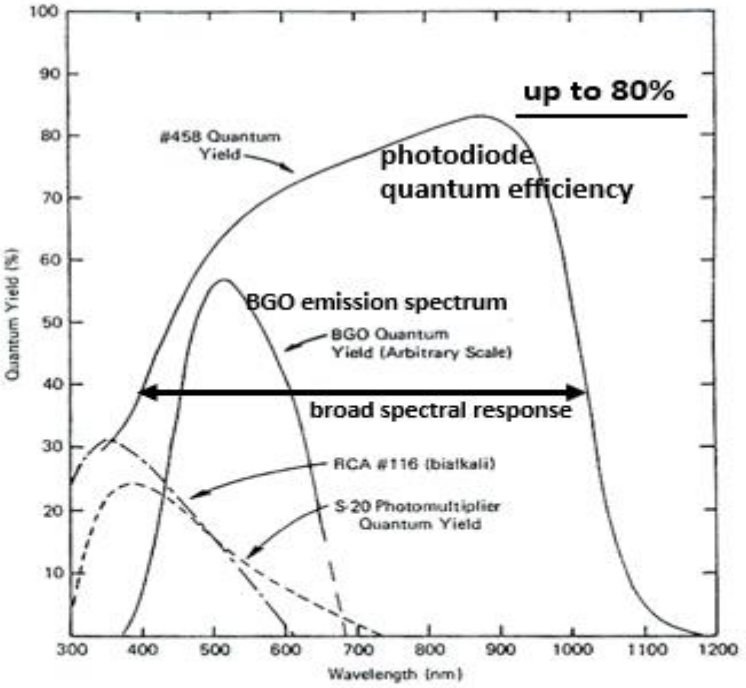


Figure 9-14 A comparison of the quantum efficiency of a silicon photodiode (labeled #458) with representative bialkali and S-20 photocathode quantum efficiencies. The emission spectrum from a BGO scintillator is shown for reference. (From Groom.[53])

Section 6

Light collection

Photon transportation

- Scintillation photons are emitted isotropically
- These photons should be transported to photodetectors
- Light collection can affect detector performances
  - # scintillation photons arriving to photodetector is reduced:
    - ★ Worse energy resolution
    - ★ Pulse height cannot overpass the threshold in photon counting
  - Non-uiformity in the light collection:
    - ★ Can change pulse shape
    - ★ Some places can be more efficient than others
- The easiest way is to "attach" directly photodetector to scintillator
- Sometimes this is not possible
  - Shapes of scintillator and photodetector are different
  - Scintillator have a larger area than the photodetector
  - Photodetector cannot be close to scintillator (i.e. presence magnetic field)

Light guides

- Photons can be lost by:
  - Self-absorption $L(x) = L_0 e^{-x/l}$
  - Escape at the surfaces
- Light should be guided from scintillator to photodetectors
- A light guide is then a structure that directs scintillation photons to photodetectors
  - Scintillator itself can be considered a light guide
  - External pieces can accomplish also this task (i.e. adapting scintillator and photdetector shape)
- Light guides are made with materials with good optical properties
  - Lucite (plexiglass)
  - n=1.5

Light guides

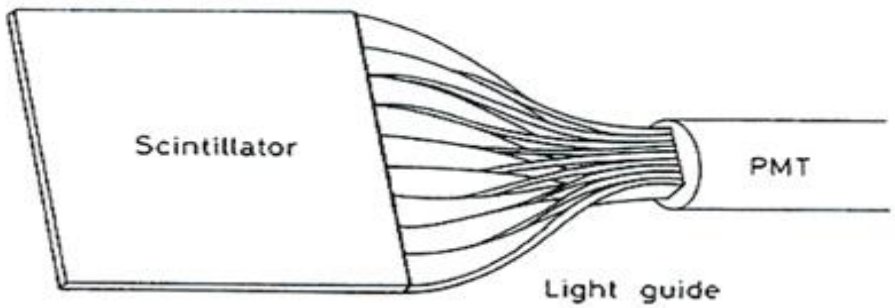


Fig. 9.7. The *twisted* light guide. Many strips of light guide material are glued on to the edge of the scintillator and then twisted 90° so as to fit onto the PM face

Different ways to couple light guides and PMTs to a scintillator crystal

For good light transmission between scintillator, light guide and PMT **optical grease** can be used.

Refractive index of scintillator, light guide and optical grease **much match**!

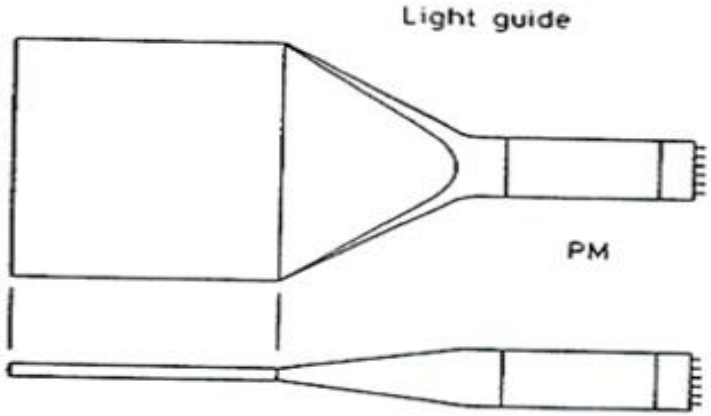


Fig. 9.6. Adapting a flat scintillator sheet to the circular face of a PM with a light guide

Fig. 9.4. A large scintillator viewed by multiple PM's for better light collection efficiency

Light collection

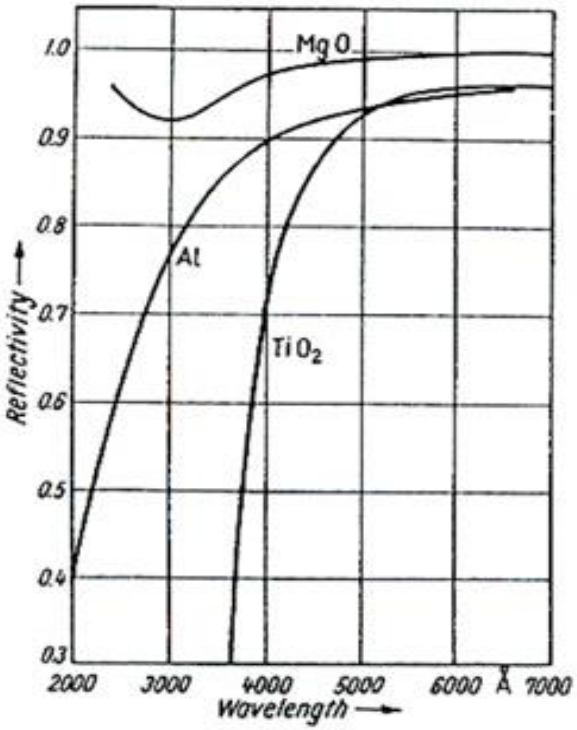


Fig. 9.3. Reflectivity of various materials (from *Mott* and *Sutton* [9.1])

Cover scintillator with light-reflecting material (this also keeps external light out !)

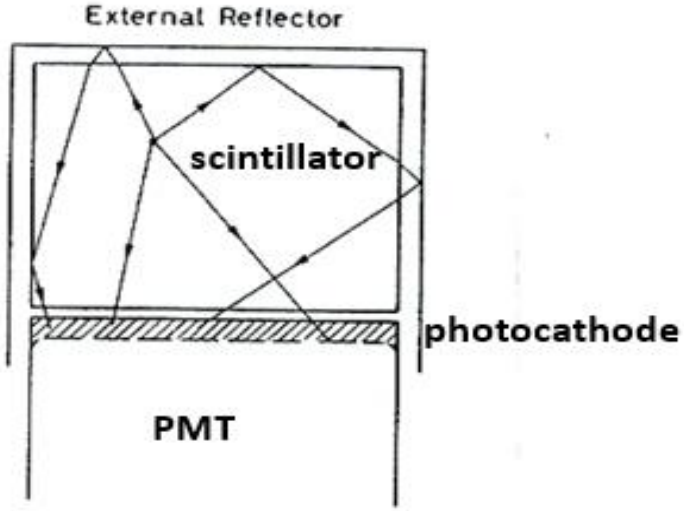
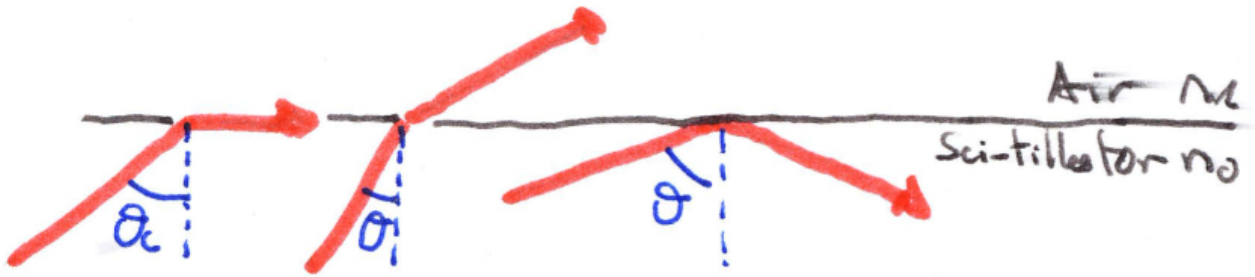


Fig. 9.2. Scintillator with an external reflector for improved light collection

Light guides

- Light guides works in total reflection mode to recover photons escaping by the surfaces non-equiped with photodetectors
- In order to have total reflection $n_{light\ guide} > n_{medium}$



$$\sin\theta_c = \frac{n_1}{n_0}$$

  - If incidence angle of the photon is greater than critical angle total reflection occurs
  - If incidence angle of the photon is smaller than critical angle photon can be:
    - ★ reflected with a probability r=reflectivity
    - ★ refracted (photon escapes)

Light guides

- In order to recover some of the photons refracted, reflectors can be placed covering the surface:
- There are two kind of reflectors:
  - Specular reflectors (i.e. polished metallic surfaces) $\theta_r = \theta_i$
  - Diffuse reflectors (i.e. Magnesium oxide, tyvek). Reflected angle is independent of the incidence angle.

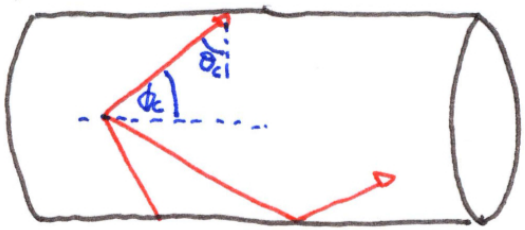
$$\frac{d\theta_r}{dI_0} = \cos\theta_r \qquad \text{Lambert's law}$$

- Total reflection is interesting in all surfaces excepting in the side where photodetectors will be placed
- To avoid reflection in these interfaces:

$$n_{scint} = n_{light\ guide} = n_{photocathode}$$

Light guide: cylindrical geometry

- Photodetectors placed at one end (or both) of a cylindrical rod
- As scintillation light is emitted isotropically, the fraction of photons arriving to the photodetector is simply the solid angle of two cones defined by critical angle.

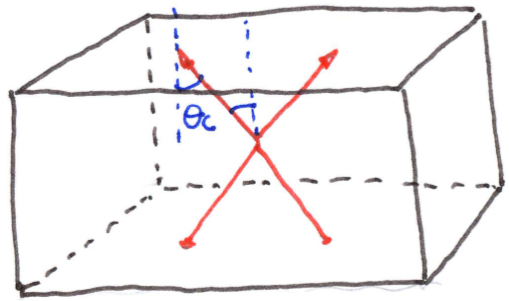


$$F = \frac{\Omega}{4\pi} = \frac{1}{4\pi}\int_{\phi=0}^{\phi=\phi_c} d\Omega = \int_0^{\phi_c} 2\pi \sin\phi d\phi$$
$$= \frac{1}{2}(1-\cos\phi_c) = \frac{1}{2}(1-\sin\theta_c) = \frac{1}{2}\left(1-\frac{n_1}{n_0}\right)$$

- If $n_1 = 1$ and $n_0 = 1.5$ then $F = 0.167$ (=0.334 if both ends are equipped)

Ligth guide: Slab geometry

- In the case of slab geometry is easier to count the number of photons that escape



$$E = 2\frac{\Omega}{4\pi} = \frac{1}{2\pi}\int_{\theta=0}^{\theta=\theta_c} d\Omega = \int_0^{\theta_c} 2\pi \sin\theta d\theta$$

$$= 1 - \cos\theta_c = 1 - \sqrt{1 - \left(\frac{n_1}{n_0}\right)^2}$$

- The fraction of light trapped in the slab is then

$$F = 1 - E = \sqrt{1 - \left(\frac{n_1}{n_0}\right)^2}$$

- If $n_1 = 1$ and $n_0 = 1.5$ then $F = 0.75$

Ligth guide: features

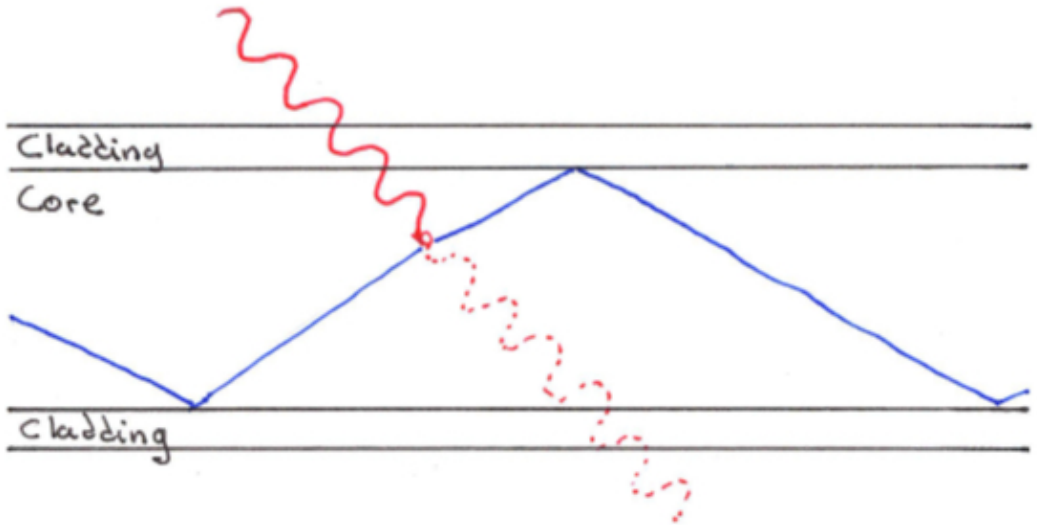
- No matter how complicated is the shape of the light guides we can use the expressions above. Locally, any smooth shape can be decomposed in slabs and cylinder
- The flux of photons per unit are and per unit solid angle can never be larger at any point inside the light guide than it its input
- If there is a reduction on the cross section, only a fraction of photons equal to the ratio of areas will stay trapped in the light guide
- In case cross sectional area is constant, the light guide is called adiabatic

Section 7

Scintillating Fibers

Scintillating Fibers: General Properties

- Some scintillation materials can also be manufactured as small fibers
  - Scintillation light is conducted by total internal reflection
- Common configuration consist of:
  - A core: in which scintillation light is generated
  - One or more layers of cladding material
- Both core and cladding are transparent to light
- $n_{core} > n_{cladding}$
- Typical sizes: core=0.1-10 mm, cladding=few % core diameter



Cladding

- Cladding: Material added to protect the core from abrasion or contamination
- Thickness of just few % of core diameter
- No cladding: $n_{core} > n_{air}$ (1.58,1.0)
  - About 1/3 of the scintillation light is "piped"
  - Scratch and contamination may reduce light yield
- Single cladding: $n_{core} > n_{cladding}$ (1.58, 1.48)
  - Just 5-10% of scintillation light is "piped"
  - Some light can be recovered in the cladding
  - Minor contribution due to inferior optical quality
- Multiple cladding: $n_{core} > n_{cladding1} > ncladding2$
  - Two protected reflection surface
  - $\sim$40% more light than single-clad fibers

Core materials

- Plastic core
  - Core of polystyrene with few percent of organic fluor (n=1.59)
  - A third component (wavelength shifter) may be added → reduce self-absorption
  - Usual cladding material: polymethylmethacrylate (n=1.49)
  - Fast decay times:2-4 ns
- Liquid cores
  - Glass capillary tube filled with liquid organic scintillator
  - Excellent scintillator-glass interface: almost no light loss
  - Good light yield (because of liquid scintillator)
  - Fast decay times
- Glass cores
  - Cerium-activated glass scintillators (n=1.59)
  - Cladding: glass with lower refraction index
  - Lower light yield and slow decay times (50-60 ns)
  - Glass can be doped with ^{6}Li → sensitive to neutrons

Light capture

- Two extreme cases:
  - Meridional rays: always pass by the center of fiber axis
  - Skew rays: originated near the
- Meridional rays.Fraction of photons captured by total reflection:

$$F = \frac{1}{2}\left(1 - \frac{n_1}{n_0}\right)$$

  - Few reflexion till the end of the fiber
  - In case both ends are readout, double the previous expression
- Skew rays.
  - Higher capture fraction
  - Suffer more reflections $\rightarrow$ higher attenuation
- Net effect is that light capture is higher by 10-30% than that given by the expression for meridional rays.

Light yield and propagation

- Factors affecting scintillation light yields of scintillation fibers are the same as any other scintillator

Core material	Photons/keV	λ_{peak}(nm)
Glass scintillator	3-5	400
Plastic scintillator	8-10	420
Liquid scintillator	11-13	420
NaI(Tl)	38	415

- We have to add the fact that a fraction of photons piped to the ends
- Effects that affect attenuation length (L: typically few meters): $I = I_0 e^{-x/L}$
  - Imperfections at the core-cladding interface
  - Overlap of emission and absorption bands
  - Rayleigh scattering $\rightarrow$ not anymore internal reflection conditions
- Attenuation observed in scintillating fibers not well described with a single exponential
  - Short wavelengths more attenuated than long wavelength
- Overall scintillation light reduced to few photons!!!