Scintillation Detectors

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ARDENT
Advanced Radiation Dosimetry European Network Training

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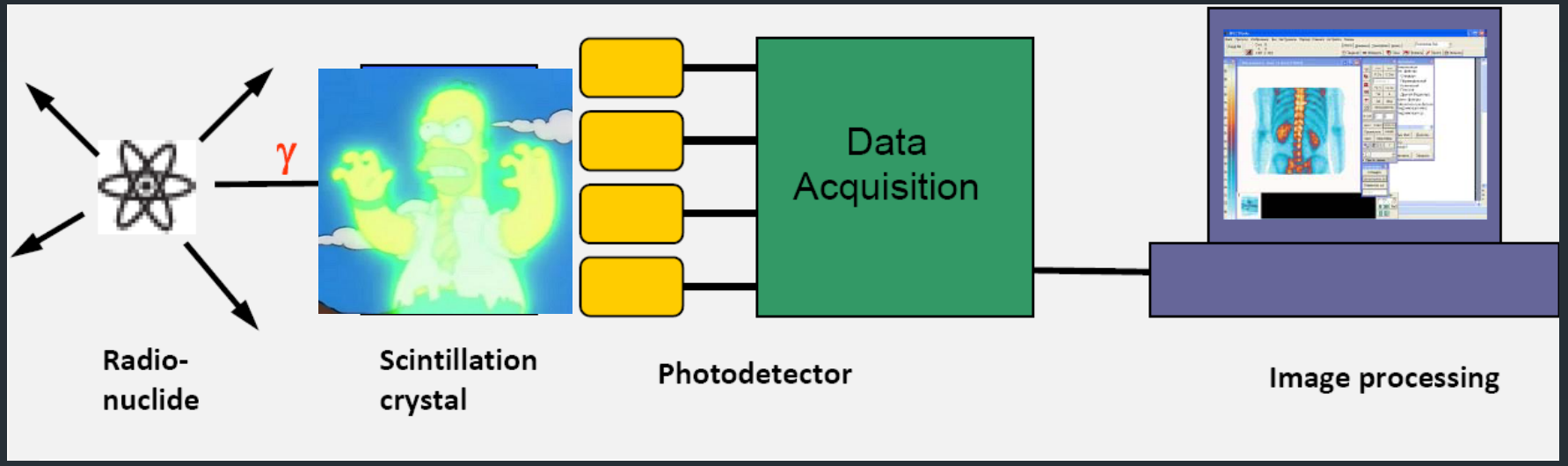
Outline


γ
Data Acquisition
Radio-nuclide
Scintillation crystal
Photodetector
Image processing

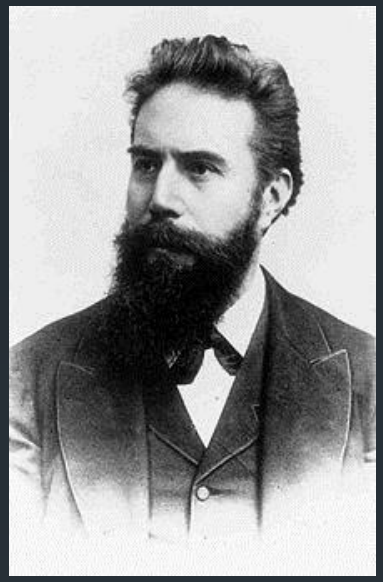
Scintillating History

- Early history
  - 10th century Japan and China
  - 17th century Sir Isaac Newton – Thermoluminescence from diamond
  - 17th century Vincentinus Casciarolo (Bologna) coined the term phosphor Phosphor – "gk. Light bearer"– "Bolognian Stone" (BaSO4)
  - 19th century -Eilhardt Wiedemann (German Physicist) – coined word luminescence in 1888.

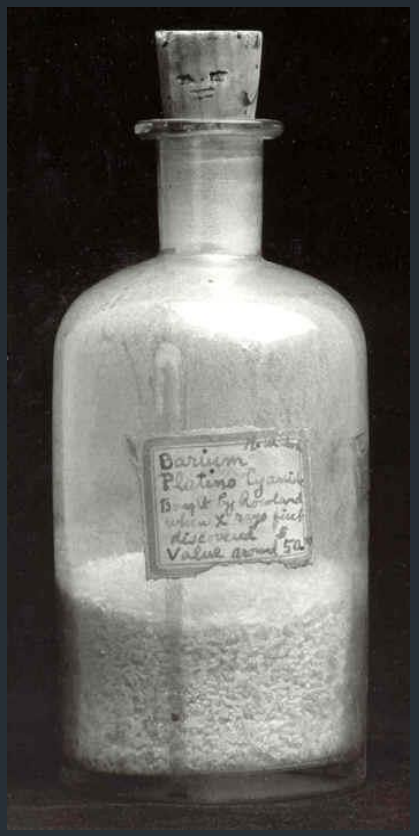
Glenn Tyrrell – IWORID 2004

- Recent history
  - Lenard (1862-1947) – alkaline earth sulfides
  - Pohl (1920s and 1930s) Tl activated alkali halides
  - Humboldt Leverenz (1940s and 1950s) - ZnS
  - Ginther (1960s) – neutron detection glasses
  - Van Loef (2001) – LaBr3
  - Yan (2014) – BaCl2:Eu

Scintillating History



Wilhelm Conrad Röntgen



Barium Platinocyanide purchased in the late 1800's by Sidney Rowland, King's College, London

Barium platinocyanide is considered to be the first radiation detector. The scintillation from a screen of platinocyanide alerted Wilhelm Röntgen to the presence of some strange radiation emanating from a gas discharge tube he was using to study cathode rays. Since Röntgen did not know what these "rays" were, he named them x-rays.

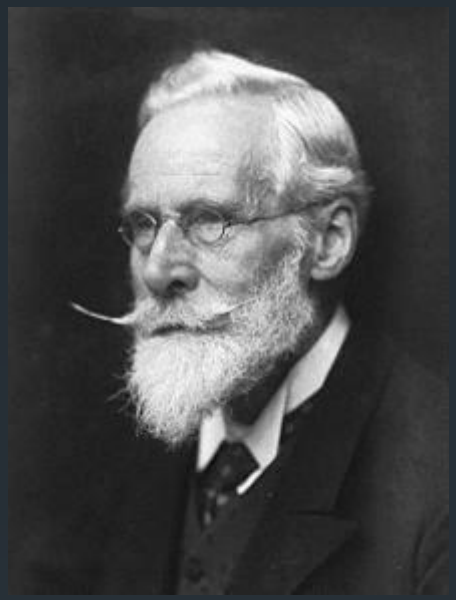
Scintillating History

This radiographic image was formed by placing the barium platinocyanide on a photographic film. The reason for this effect is that the state of separations chemistry in the 1800's was poor and the barium platinocyanide was contaminated by radium.

Georg Brandes found that sufficiently energetic x-rays produced a uniform blue-grey glow that seemed to originate within the eye itself.

Friedrich Giesel (Curie) "saw" radiation from radium "to obtain this effect, one places the box containing the radium in front of the closed eye or against the temple" and "one can attribute this phenomenon to a phosphorescence in the middle of the eye under the action of the invisible rays of radium" (Curie 1900, 1903). In the United States, the Colorado physician George Stover was among the first investigate radiation phosphenes (the proper name for visual sensations induced by radiation within the eye): "Sitting in a perfectly dark room and closing the eyes, if the tube of radium is brought close to the eyelids a sensation of light is distinctly perceived, which disappears on removal of the tube..."

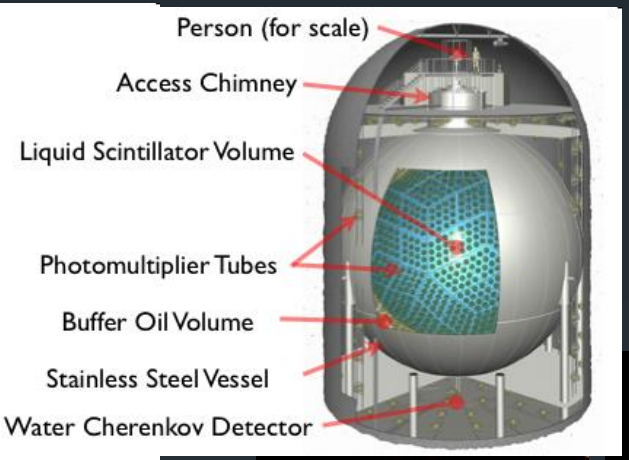
1st Scintillation Device



Sir William Crookes in 1906

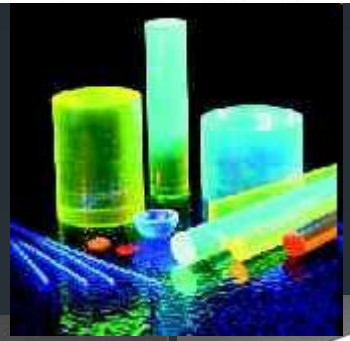
http://www.theodoregray.com/PeriodicTable/Elements/095/index.html#sample4

Scintillation Detector



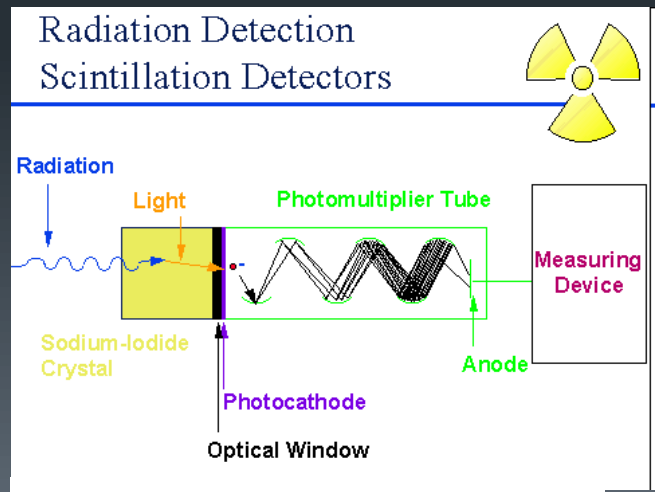
KamLAND-det.png

www.drct.com/Model_700_MCA.htm



Amcrys-h.com

http://www.directindustry.com



www.physics.isu.edu/radinf/naidetector.htm

Scintillator Types

Organic Crystal Scintillators – Organic crystal scintillators are aromatic hydrocarbon compounds which contain benzene ring structures interlinked in various ways. Their luminescence typically decays within a few nanoseconds. They are very durable, but their response is anisotropic (which spoils energy resolution when the source is not collimated), and they cannot be easily machined, nor can they be grown in large sizes; hence they are not very often used.

Organic Liquid Scintillators – Organic liquid scintillators are liquid solutions of one or more organic scintillators in an organic solvent. The typical solutes are fluors and wavelength shifter scintillators. For many liquids, dissolved oxygen can act as a quenching agent and lead to reduced light output, hence the necessity to seal the solution in an oxygen-free, air-tight enclosure.

Plastic Scintillators – The term plastic scintillator typically refers to a scintillating material in which the primary fluorescent emitter, is suspended in a solid polymer matrix. The advantages of plastic scintillators include fairly high light output and a relatively quick signal, with a decay time between 2-4 nanoseconds, but perhaps the biggest advantage of plastic scintillators is their ability to be shaped, through the use of molds or other means, into almost any desired form with what is often a high degree of durability.

Inorganic Crystal Scintillators –are usually crystals often with a small amount of activator impurity. Inorganic crystals have superior performance for the detection of high-energy gamma rays.

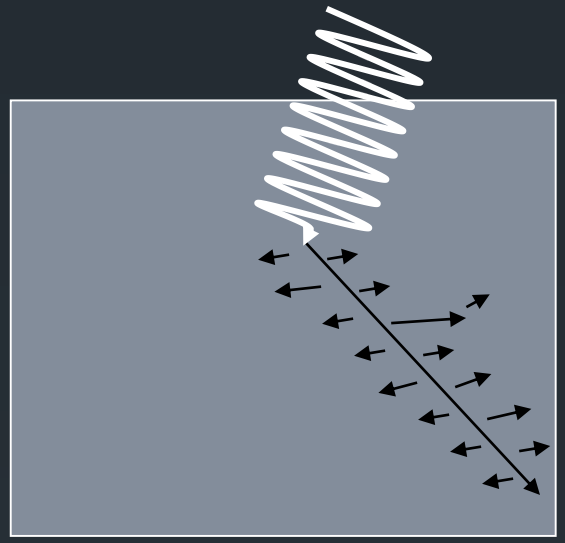
Gaseous Scintillators – Gaseous scintillators consist of nitrogen and the noble gases helium, argon, krypton, and xenon, with helium and xenon receiving the most attention. The scintillation process is due to the de-excitation of single atoms excited by the passage of an incoming particle.

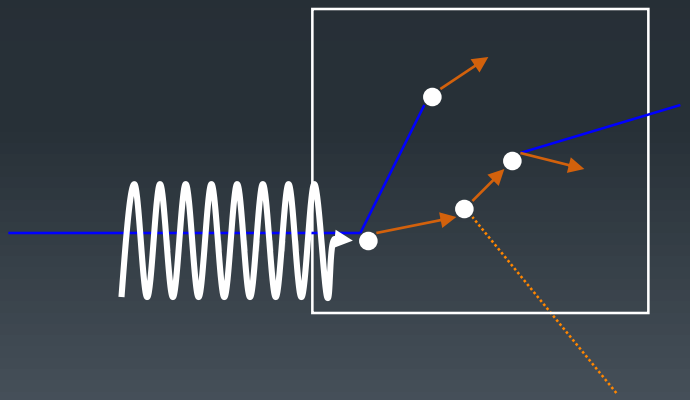
Glass Scintillators – Glass scintillators are sensitive to electrons and γ rays as well (pulse height discrimination can be used for particle identification). Being very robust, they are also well-suited to harsh environmental conditions. Glasses and glass fibers are often used for neutron detection.

Ceramic Scintillators are commonly used for X-ray imaging, and nanophase-powders allow the synthesis of special compositions that, if successfully developed, may become improved alternatives to single crystal scintillators.

Scintillation Detector

- Scintillation detectors are made up of two primary components; (a) Scintillator and (b) Light detector.
- The scintillator converts the kinetic energy of the incident particle or radiation into detectable light.
- The light detector converts the light into electrical pulse or signal to register the event, and analyse it.

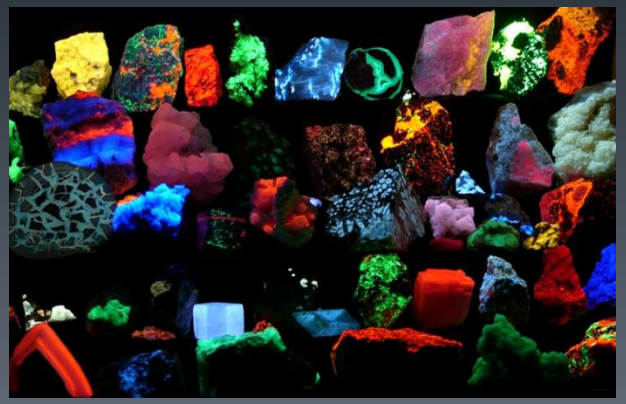




Scintillation Detector

Ideal Scintillator

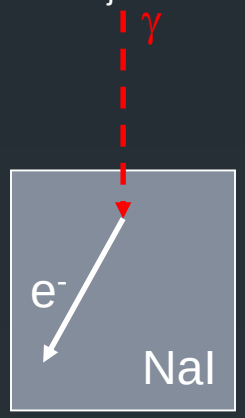
1. High scintillation efficiency
2. Linear – light yield proportional deposited energy
3. Transparent – own emission light should not be reabsorbed
4. Short decay time – light emission should occur very quickly
5. Mechanically rugged – good practical scintillator
6. Radiation Hard
7. Suitable refractive index – should match the light detector's refractive index.



Basic Physical Processes

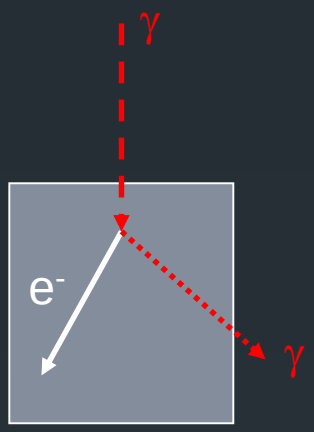
Idealy light given off is proportional to energy absorbed.
E.g. light yield ~ 1 photon/25 eV deposited in NaI, decay time ~250nsec

Photoelectric Effect
γ absorbed by material, electron ejected



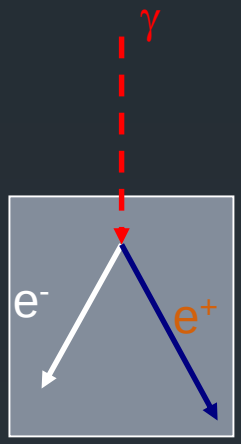
hv < 0.05 MeV

Compton Scattering
$\gamma e^- \rightarrow \gamma e^-$ "elastic scattering"

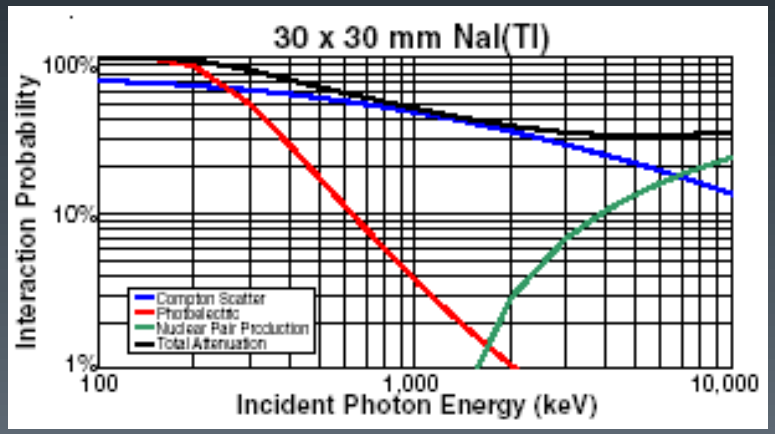


0.05 < hv < 10 MeV

Pair Production
$\gamma \rightarrow e^+e^-$ creates anti-matter



hv > 10 MeV γ-ray must have $E>2m_e$



Attenuation of the gamma rays is energy dependent

radiation length of NaI ~2.5 cm
but only useful for E > few MeV

Cerenkov Light

The Cerenkov effect occurs when the velocity of a charged particle traveling through a dielectric medium exceeds the speed of light in the medium.

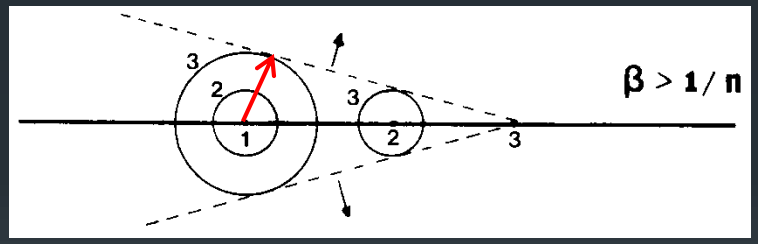
Index of refraction (n) = (speed of light in vacuum)/(speed of light in medium)

Will get Cerenkov light when:

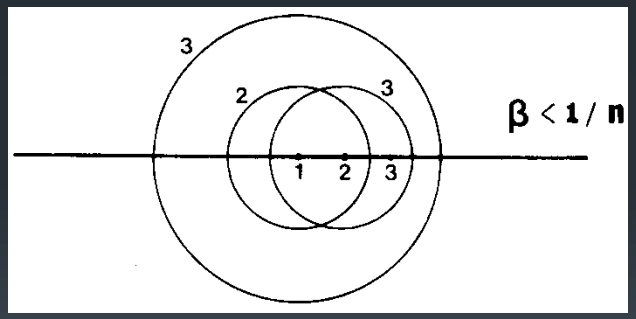
speed of particle > speed of light in medium $\frac{v}{c} = \beta > \frac{1}{n}$

For water n=1.33, will get Cerenkov light if v > 2.25×10^{10} cm/s

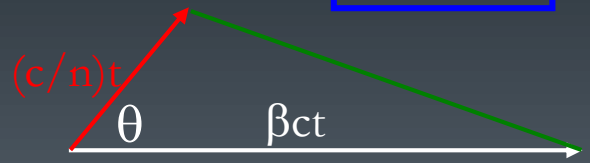
Huyghen's wavefronts



Radiation



No radiation



Angle of Cerenkov Radiation: $\cos\theta = \frac{1}{n\beta}$

In a time *t* wavefront moves (c/n)t but particle moves βct.

Number of photons from Cerenkov Radiation

Classical electrodynamics (Frank&Tamm 1937, Nobel Prize 1958)
energy loss per wavelength (λ) per *dx* for charge=1, $\beta n>1$:

$$\frac{dE}{dxd\lambda}=\frac{2\pi\alpha E}{\lambda^2}[1-\frac{1}{\beta^2 n(\lambda)^2}]$$

α=fine structure constant, $n(\lambda)$ index of refraction.
Re-write in terms of the number of photons (N) using: $dN=dE/E$

$$\frac{dE}{dxd\lambda}=\frac{2\pi\alpha E}{\lambda^2}[1-\frac{1}{\beta^2 n(\lambda)^2}]\Rightarrow\frac{dN}{dxd\lambda}=\frac{2\pi\alpha}{\lambda^2}[1-\frac{1}{\beta^2 n(\lambda)^2}]$$

Simplify the above by considering a region were $n(\lambda)$ is a constant=n:

$$1-\frac{1}{\beta^2 n(\lambda)^2}=1-\cos^2\theta=\sin^2\theta \quad\Rightarrow\quad \frac{dN}{dxd\lambda}=\frac{2\pi\alpha}{\lambda^2}[1-\frac{1}{\beta^2 n(\lambda)^2}]=\frac{dN}{dxd\lambda}=\frac{2\pi\alpha}{\lambda^2}\sin^2\theta$$

Calculate the number of photons/*dx* by integrating over the wavelengths that can be detected by our photodetector (λ_1, λ_2):

$$\frac{dN}{dx}=2\pi\alpha\sin^2\theta\int_{\lambda_1}^{\lambda_2}\frac{d\lambda}{\lambda^2}=2\pi\alpha\sin^2\theta[\frac{1}{\lambda_1}-\frac{1}{\lambda_2}]$$

Note: if using a phototube with a photocathode efficiency that varies as a function of λ then we have:

$$\frac{dN}{dx}=2\pi\alpha\sin^2\theta\int_{\lambda_1}^{\lambda_2}\frac{f(\lambda)d\lambda}{\lambda^2}$$

Number of photons from Cerenkov Radiation

For a typical phototube the range of wavelengths (λ_1, λ_2) is (350nm, 500nm).

$$\frac{dN}{dx} = 2\pi\alpha \sin^2\theta\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right] = 2\pi\alpha \sin^2\theta\left[\frac{1}{3.5} - \frac{1}{5}\right]\frac{10^5}{cm} = 390\sin^2\theta \,\text{photons/cm}$$

We can simplify using:

$$\sin^2\theta = 1 - \cos^2\theta = 1 - \frac{1}{\beta^2 n^2} = \frac{(\beta n+1)(\beta n-1)}{\beta^2 n^2} \underset{\beta\to 1}{\Rightarrow} \frac{(n+1)(n-1)}{n^2}$$

For a highly relativistic particle going through a gas the above reduces to:

$$\sin^2\theta = \frac{(\beta n+1)(\beta n-1)}{\beta^2 n^2} \underset{\beta\to 1}{\Rightarrow} \frac{(n+1)(n-1)}{n^2} \underset{\beta\to 1,\,\text{gas}}{\Rightarrow} 2(n-1)$$

$$\frac{dN}{dx} = 780(n-1)\,\text{photons/cm}$$

GAS

For He we find: 2-3 photons/meter (not a lot!)
For CO_2 we find: ~33 photons/meter
For H_2O we find: ~34000 photons/meter

Photons are preferentially emitted at small λ's (blue)

For most Cerenkov counters the photon yield is limited (small) due to space limitations, the index of refraction of the medium, and the phototube quantum efficiency.

Organic Scintillators

Organic Scintillator

- Not necessarily regular crystalline lattice.
- The light or “fluorescence” process in organics arises from transitions in the energy level structure of a single molecule (independent of its state).
- Transparent to own fluorescence.
- The intensity of the fluorescence is given by

$$I = I_0 e^{\frac{-t}{\tau}}$$

t = time follow excitation

τ = fluorescent decay time

$\langle\tau\rangle$ ~ns for most organic scintillators

Organic Scintillators

Types of organic scintillators:

1. Pure organic crystals – Anthracene and Stilbene (20-30% direction dep)
2. Liquid organic solutions – large volume detectors, radiation hard, (quenching due to presence of O_2)
3. Plastic Scintillator – ie polymerized, easily shaped, fast, (low Z)
4. Thin Film – down to 10 μm, fast (ns), low Z
5. Loaded – increased Z by adding Pb, Sn, B, Li, Gd (lower light output)

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 detector
	BC-430	45	580	16.8	NA	1.58	1.108	1.032	Red emitter	70	Silicon photodiodes and red-enhanced PM
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

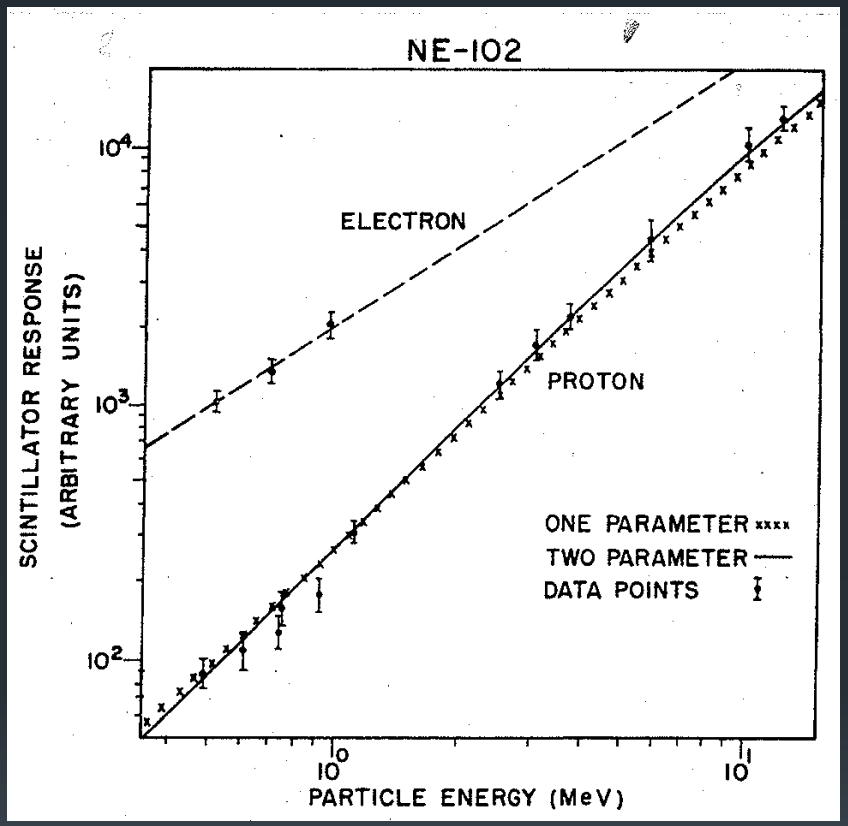
*NaI(Tl) is 230% on this scale.

Organic Scintillator - Response

- Small fraction of kinetic energy lost by charged particles in a scintillator is converted into fluorescent energy.
- Rest is lost non radiatively (lattice vibrations or heat)
- In some cases the response to electrons is linear above ~130 keV
- Much higher for protons or α's
- Response is described by the relation between $\frac{dL}{dx}$

fluorescent energy emitted per unit path length and $\frac{dE}{dx}$

energy loss of the charged particle per unit path length



Knoll, G, "Radiation Detection and Measurement" 4th Ed., Wiley

- Significant energy deposition → damage of molecules from high density of track → quenching of the scintillator efficiency

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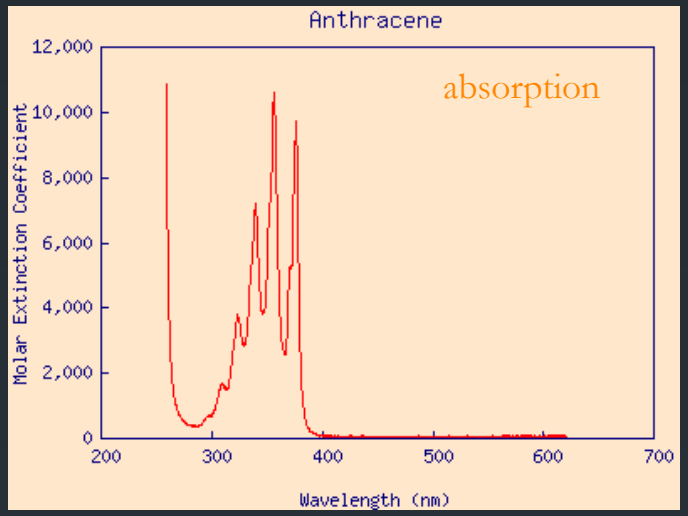
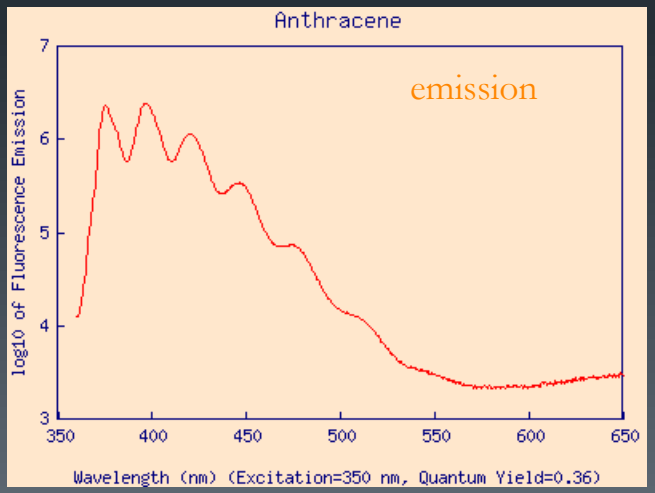
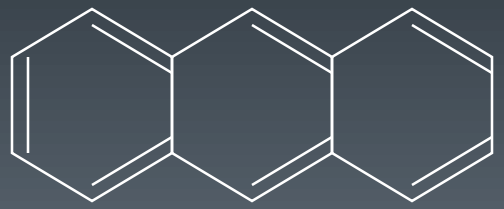
Organic Scintillators





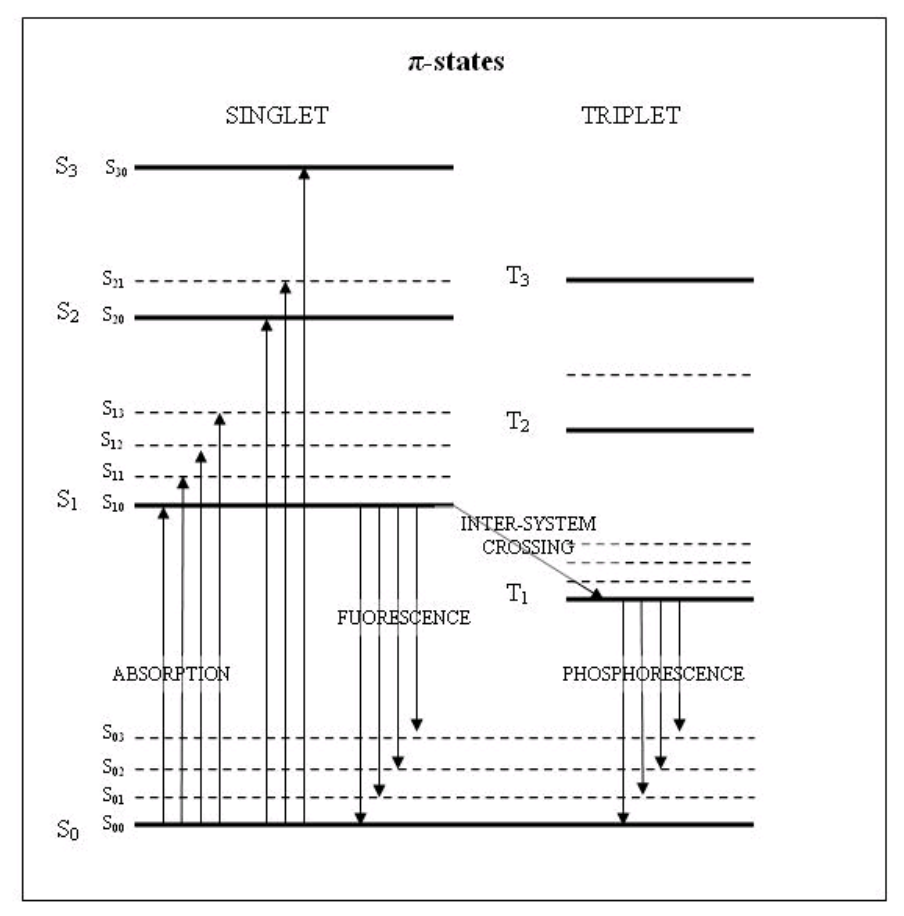
- A number of organic compounds fluoresce when molecules are excited.
- The benchmark molecule is anthracene.
  - Compounds are measured in % anthracene to compare light output



R. A. Fuh 1995

Organic Scintillator

Excited Rings



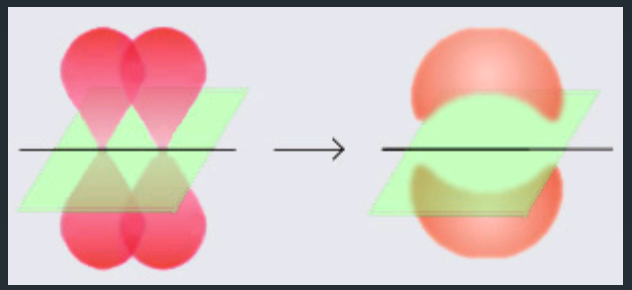
- π-bonds are most common in aromatic carbon rings.
- Excited states radiate photons in the visible and UV spectra.
  - Fluorescence is the fast component
  - Phosphorescence is the slow component

At left: 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.

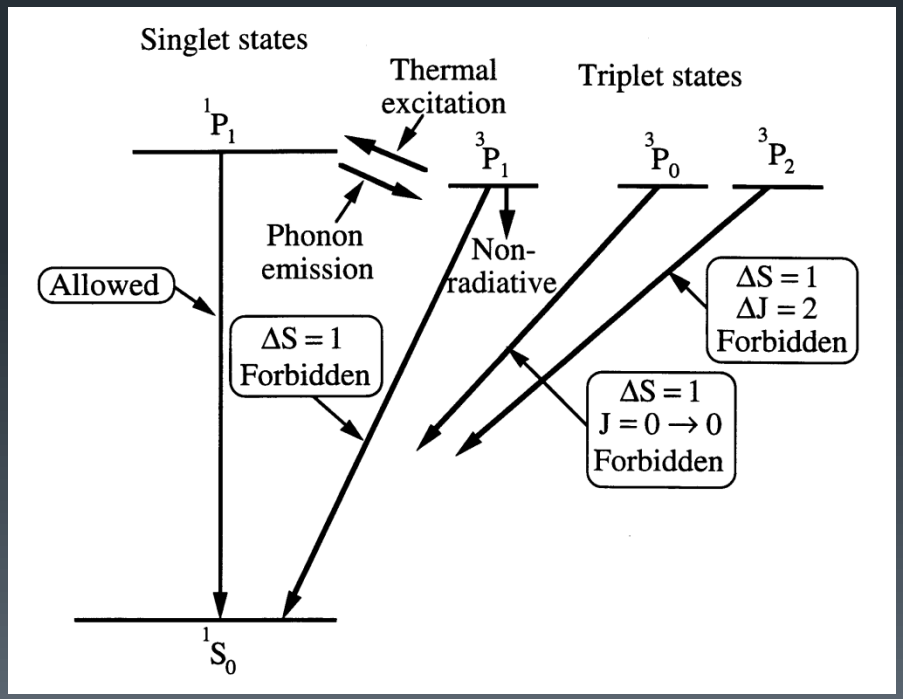
Knoll, G, "Radiation Detection and Measurement" 4th Ed., Wiley

Pi-Bonds

- Carbon in molecules has one excited electron.
  - Ground state $1s^2 2s^2 2p^2$
  - Molecular $1s^2 2s^1 2p^3$



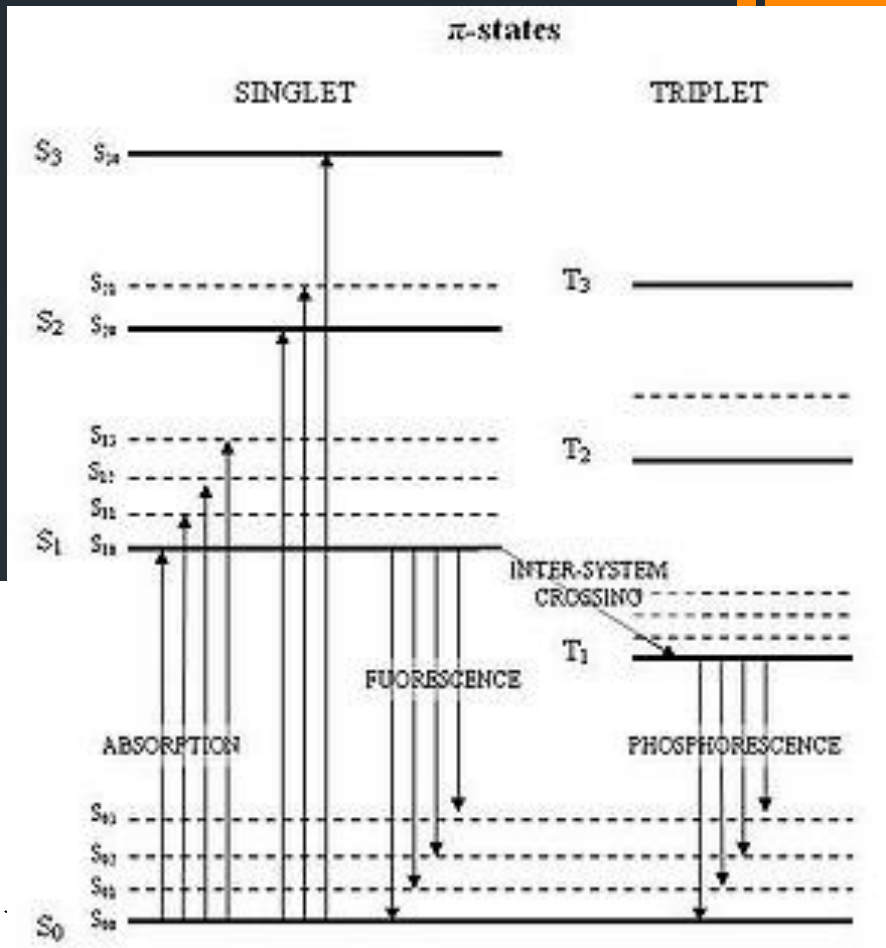
- Hybrid p-orbitals are π-orbitals.
  - Overlapping π-orbitals form bonds
  - Appears in double bonds

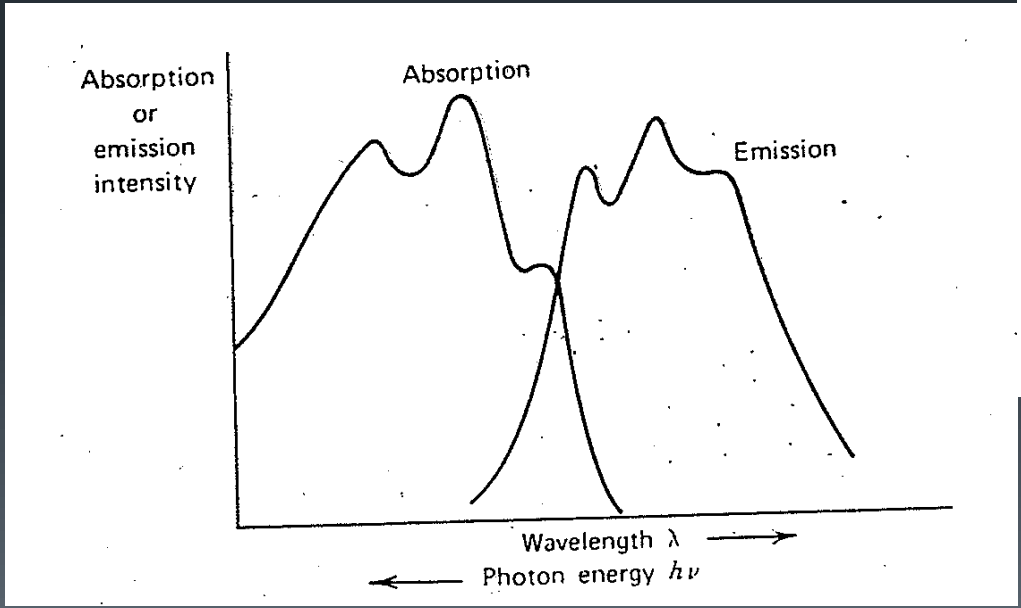


Scintillation Detector

Organic Scintillator

- Waveshifter – added impurity to “shift” the scintillation light to longer wavelength.

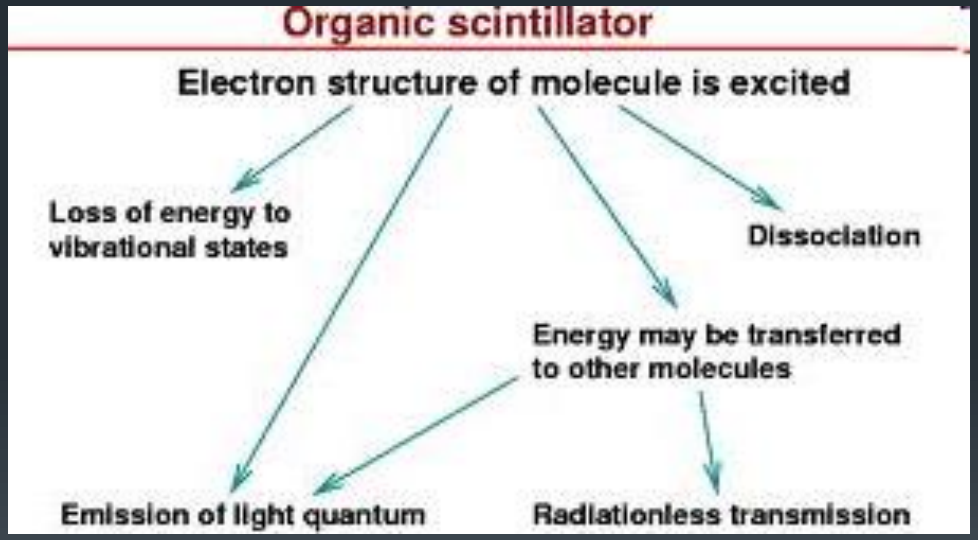


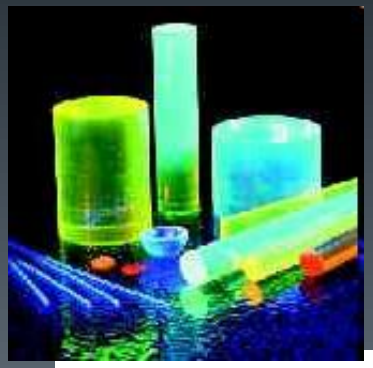


Knoll, G, “Radiation Detection and Measurement” 4th Ed., Wiley

Organic Scintillator

- Scintillation efficiency = fraction of all incident particle energy converted into light
- Quenching – refers to any mechanism (de-excitation process) that does not lead to detectable light





www.pha.jhu.edu

Organic Scintillator - Response

- Density of damaged molecules is assumed (Birk's Formulation) to be B(dE/dx), B = constant
- Some fraction, k, of these molecules lead to quenching.
- In the absence of quenching, assume the light yield is proportional to the energy loss:

$$\frac{dL}{dx} = S\frac{dE}{dx}; \mathrm{S} \equiv \mathrm{scint.effic.}$$

- To account for the probability of quenching

$$\frac{dL}{dx} = \frac{S\dfrac{dE}{dx}}{1 + kB\dfrac{dE}{dx}}; \mathrm{kB\ adj.\ param\ to\ fit\ exp\ data}$$

Organic Scintillator - Response

$$\frac{dL}{dx} = \frac{S\dfrac{dE}{dx}}{1 + kB\dfrac{dE}{dx}}\ ;\ \text{kB adj. param to fit exp data}$$

- For fast electrons (directly or via γ - irradiation)

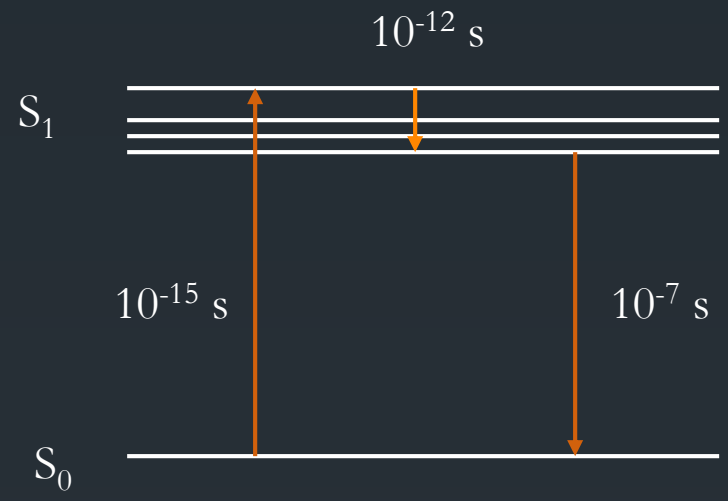
$$\frac{dE}{dx} << 1 \Rightarrow \left.\frac{dL}{dx}\right|_e = S\frac{dE}{dx} \Rightarrow \left.\frac{dL}{dE}\right|_e = S$$

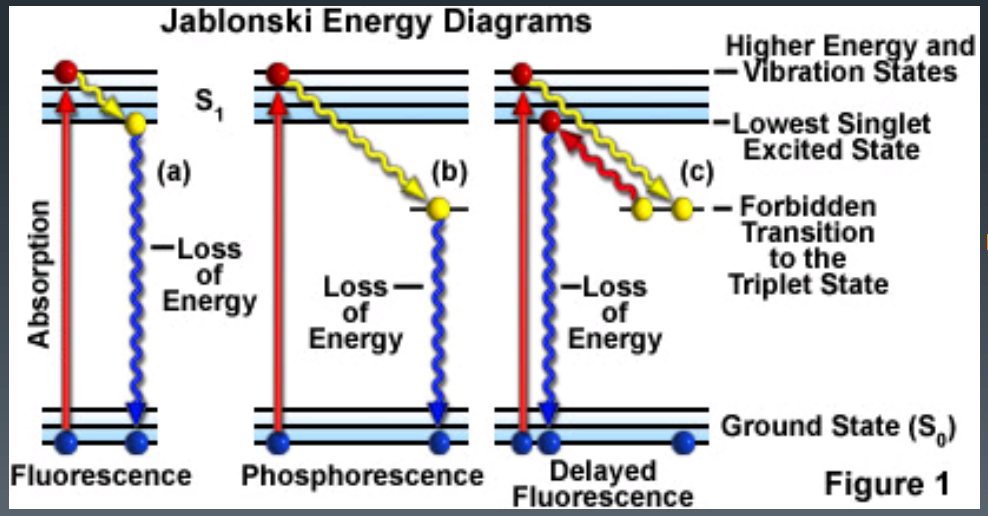
$$\Rightarrow L_e = \int_0^E \frac{dL}{dE}\,dE = SE$$

- For α-particles

$$\frac{dE}{dx} >> 1 \Rightarrow \left.\frac{dL}{dx}\right|_\alpha = \frac{S}{kB} \Rightarrow kB = \frac{\left.\dfrac{dL}{dx}\right|_e}{\left.\dfrac{dL}{dx}\right|_\alpha}$$

Timing Related Processes





- Fluorescence typically involves three steps.
  - Excitation to higher energy state.
  - Loss of energy through change in vibrational state
  - Emission of fluorescent photon.
- The time for 1/*e* of the atoms to remain excited is the characteristic time τ.

Organic Scintillator – Pulse Shape Discrimination

- The decay time depends on the type of particle we can discriminate between different particle events using timing pulse discrimination techniques.
- Light intensity curves differ for different radiation types:

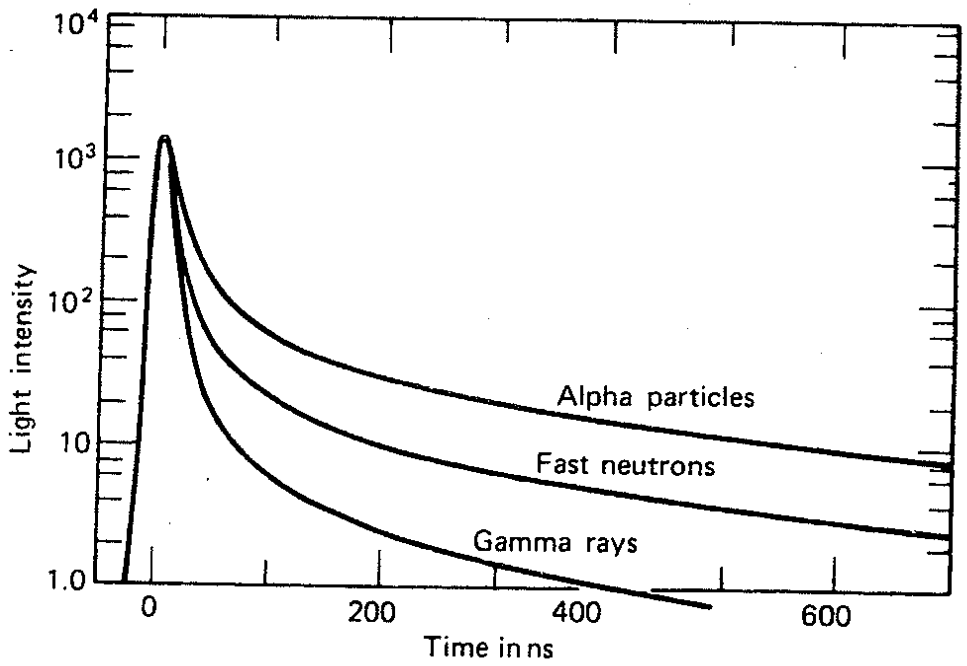
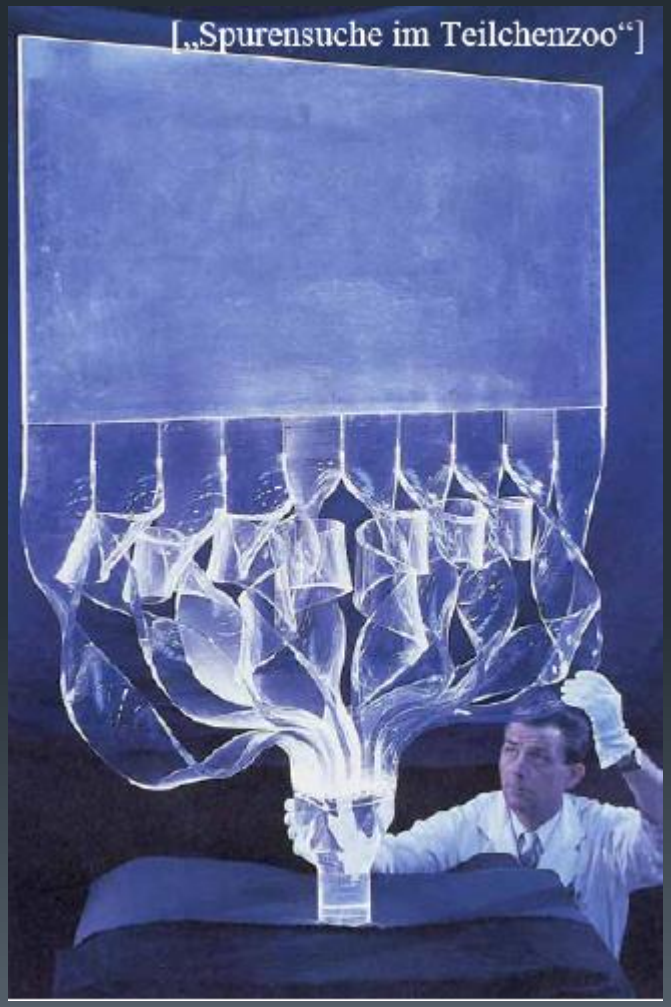


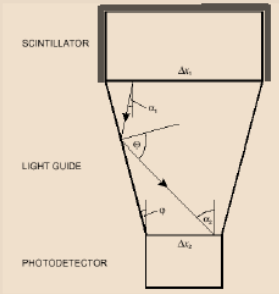
Figure 8.5 The time dependence of scintillation pulses in stilbene (equal intensity at time zero) when excited by radiations of different types. (From Bollinger and Thomas.[60])

Plastic Scintillation Detectors

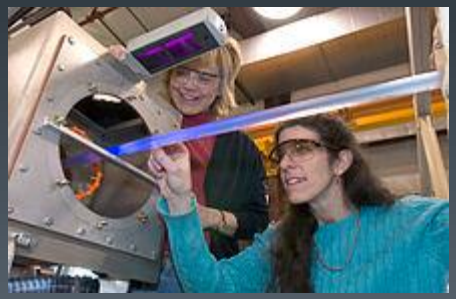


Light transmission

- Total reflection
  sin θ> n_{ext}/n,
  sin θ> 1/n, n_{ext} = air
- Light guide
- Optical grease (optical cement)
- Light reflector
  Teflon, Al, white paint



Scintillator
Has also to
Be put in external
REFLECTOR
(Teflon, Alu..)
to Improve light
collection



Inorganic Scintillators

- Fluorescence is known in many natural crystals.
  - UV light absorbed
  - Visible light emitted
- Artificial scintillators can be made from many crystals.
  - Doping impurities added
  - Improve visible light emission

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
Li(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	

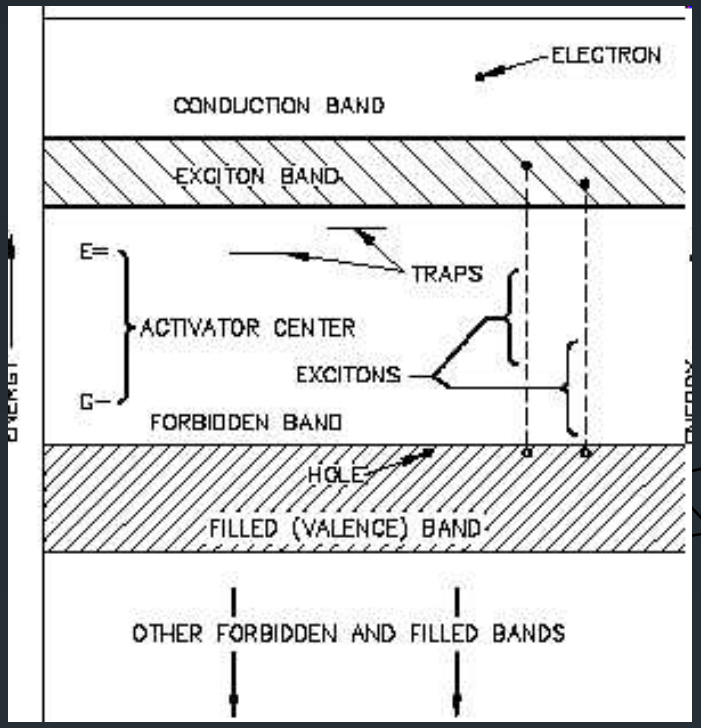
[a]for alpha particles

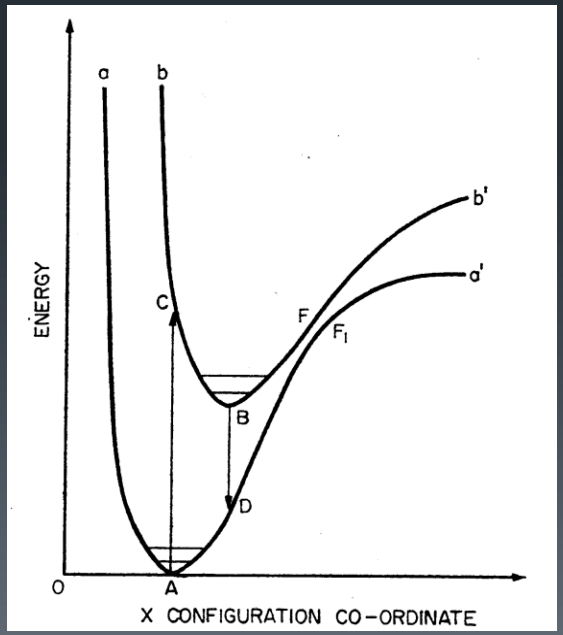
[b]Properties vary with exact formulation. Also see Table 15.1.

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

Inorganic Scintillators

- Scintillator is a single crystal with a regular crystalline lattice.
- Scintillation mechanism depends on the energy states determined by the crystal lattice of the material.
- Electrons, excited by the incident particle or radiation have only discrete bands of energy available for them to exist.
- Valence band:- electrons essentially bound at lattice sites
- Conduction band: electrons have sufficient energy to be free to migrate throughout the crystal.
- Forbidden band: no energy state exists for electrons in the pure crystal





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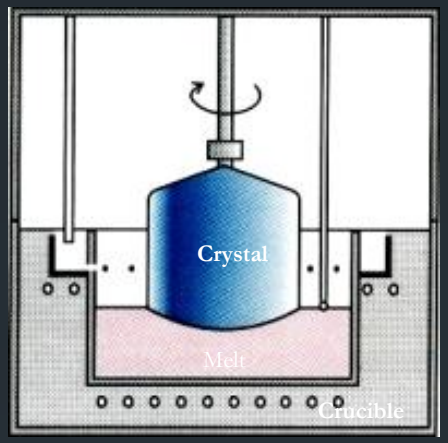
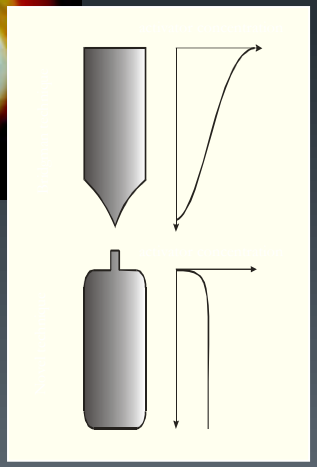
NOVEL TECHNOLOGIES FOR CRYSTAL GROWTH



Advantages:

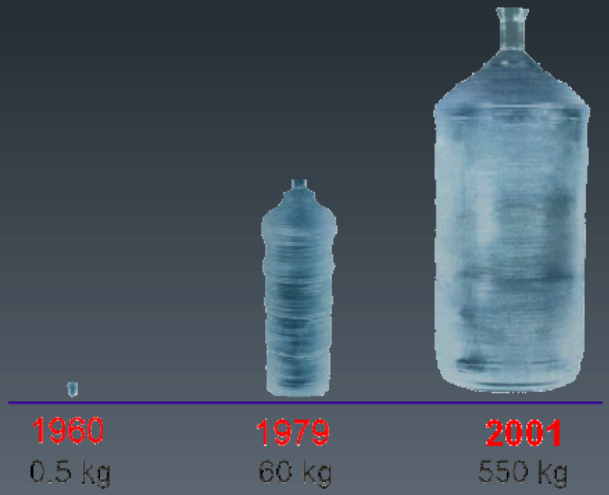
- •. Continuous growth process (large size of crystal)
- •. Fixed “crystal-melt” interface
- •. Feeding by raw material and activator
- •. Simple melt level control

GROWTH PROCESS



Uniform activator distribution

HALIDES GROWTH TECHNOLOGY MILESTONES



AMCRYS-H

Inorganic Scintillators

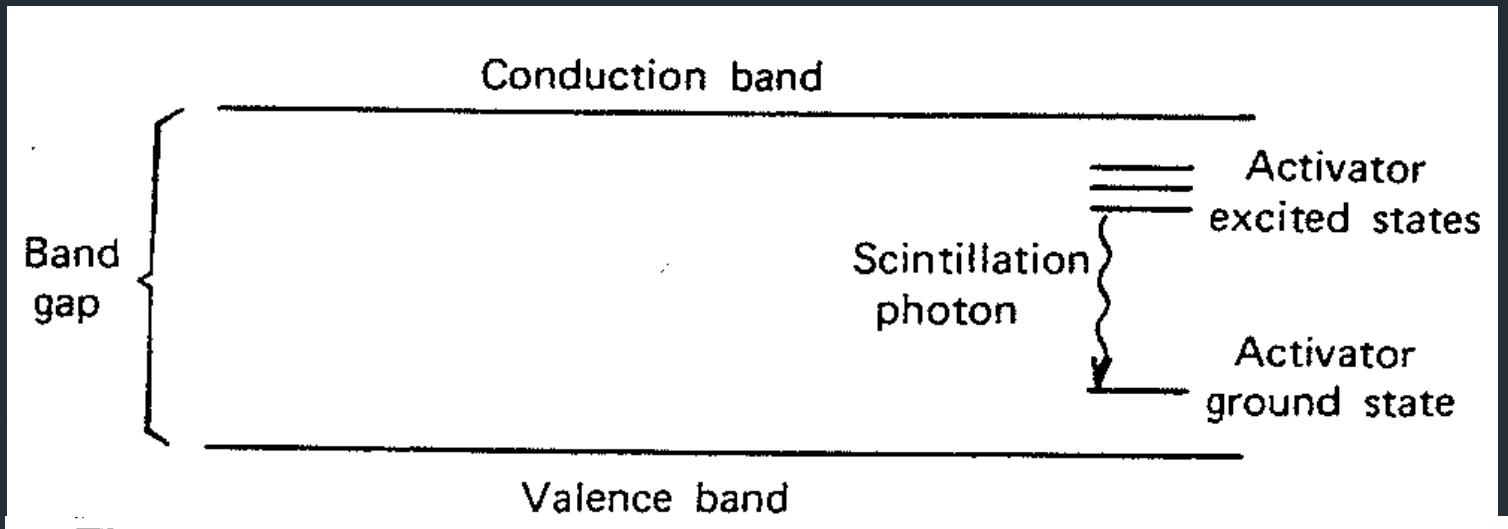
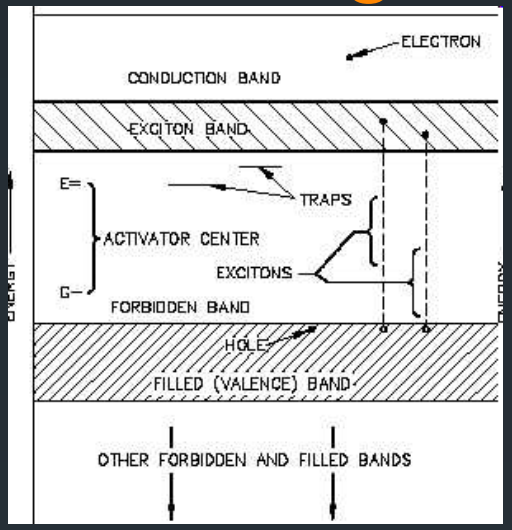


Figure 8.6 Energy band structure of an activated crystalline scintillator.

- To change the wavelength of the scintillation light (to be detected) impurities (activators) are purposely introduced to create levels within the forbidden band gap. ($E = hf = hc/\lambda$)

Inorganic Scintillators



charged particle or γ/X-ray → *e* - *h* pairs

migrate to trap → de-excited without any emission "quenching"

migrate to trap (recombination forbidden)→ re- excited out of trap

migrate to activator site

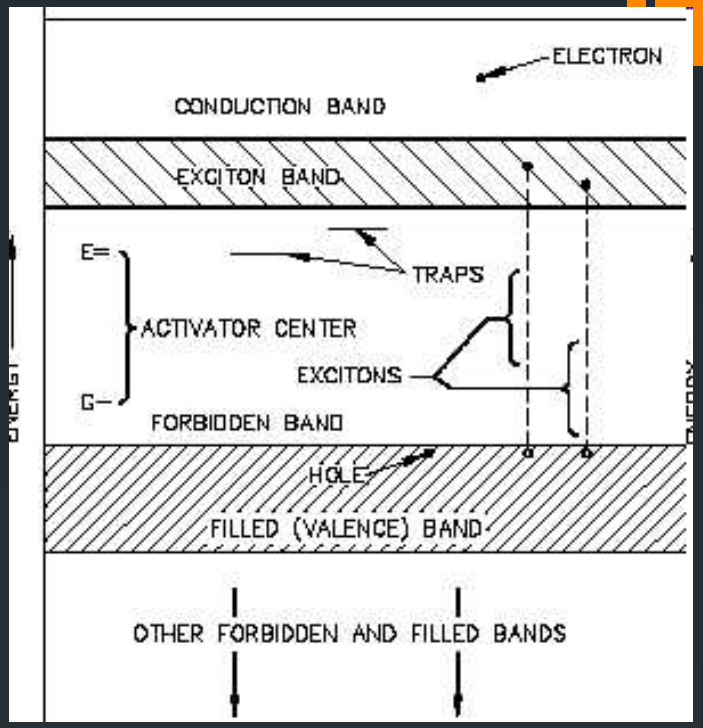
drift to activator site & ionize it

recombine via emission of a scintillation light (50-500 ns)

recombines with hole "phosphorescence" (>1-5 μs)

Inorganic Scintillators

- Example : Thallium – activated (doped) Sodium Iodide NaI(Tl)
- W = 20 eV (~3 E_g) ∴1 MeV particle -→ 5 x 10^4 *e-h* pairs
- Experimentally: scintillation efficiency shown to be ~12%
- ∴ 1 MeV particle → 1.2x 10^5 eV in total light energy.
- Scintillation photon energy = 3eV
  ∴ 4 x 10^4 photons are emitted.
- Shows that energy transfer to activator sites is extremely efficient.
- NaI(Tl) – "standard" inorganic scintillator (see table 8.3).
- NaI(Tl) – very hygroscopic and long scintillation light decay time (~230ns).



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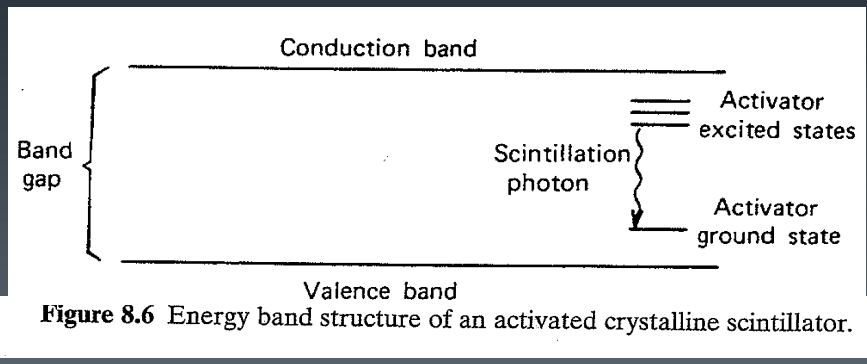
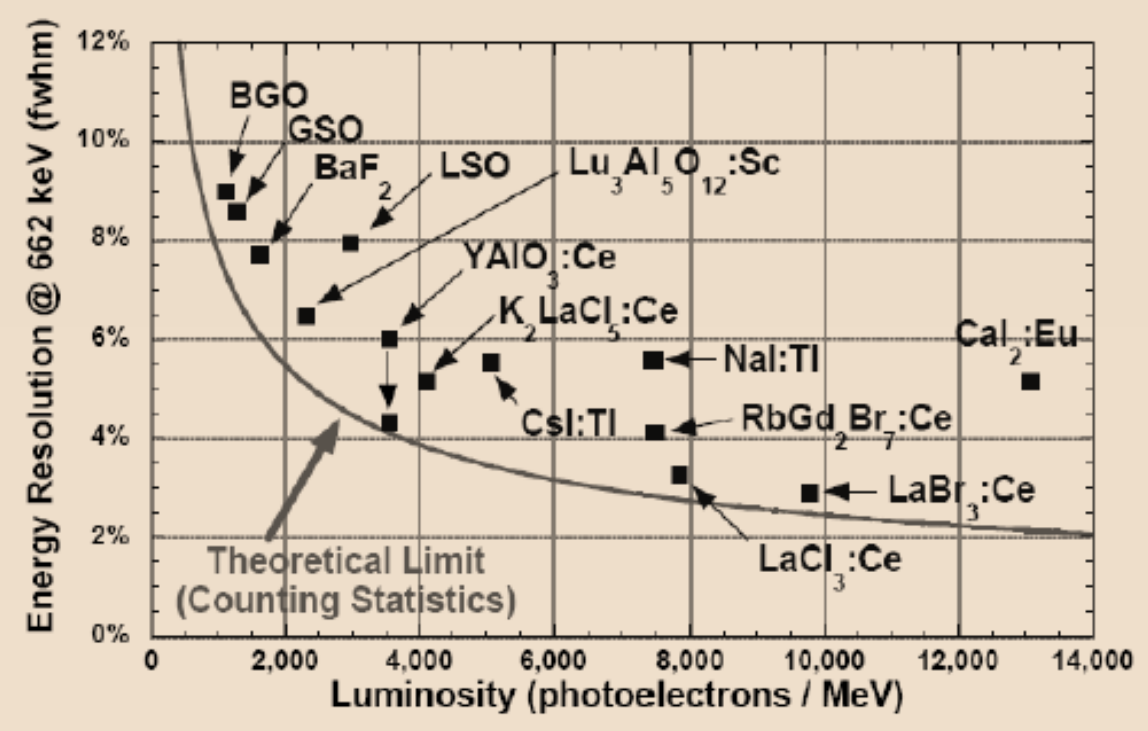


Figure 8.6 Energy band structure of an activated crystalline scintillator.

Energy Resolution

Lots of different Materials on the market, but everytime compromise between, resolution, efficiency, timing, cost



Inorganic Scintillators

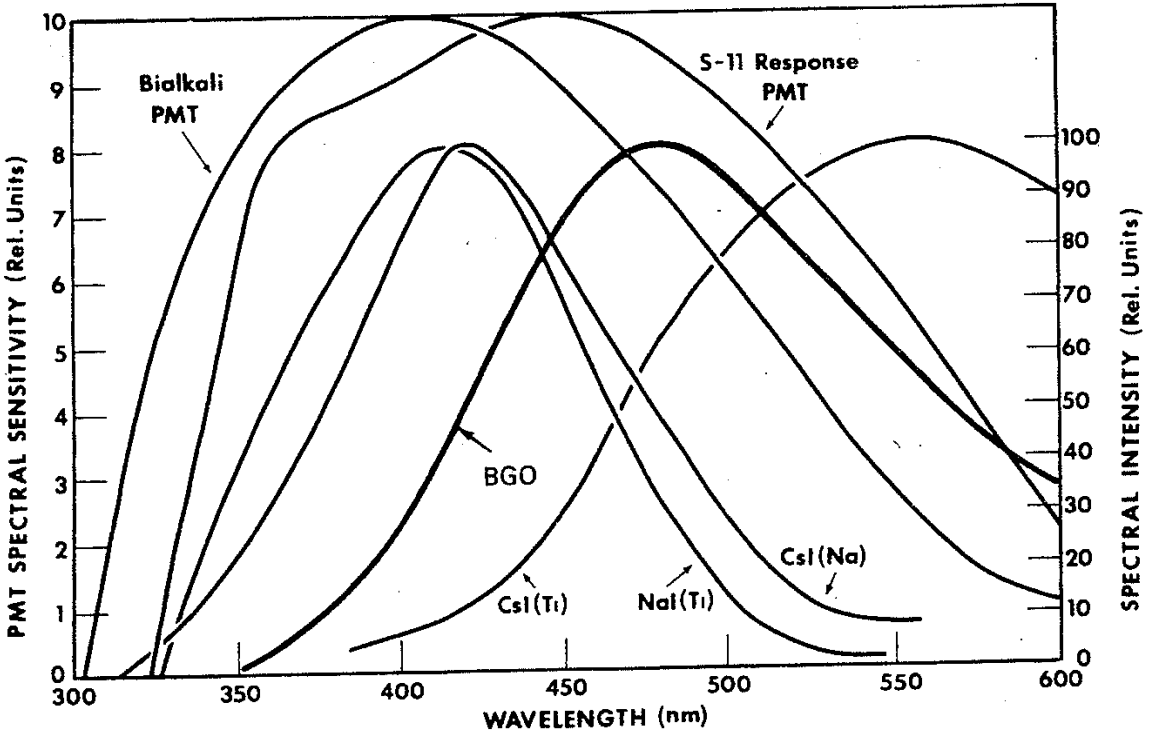
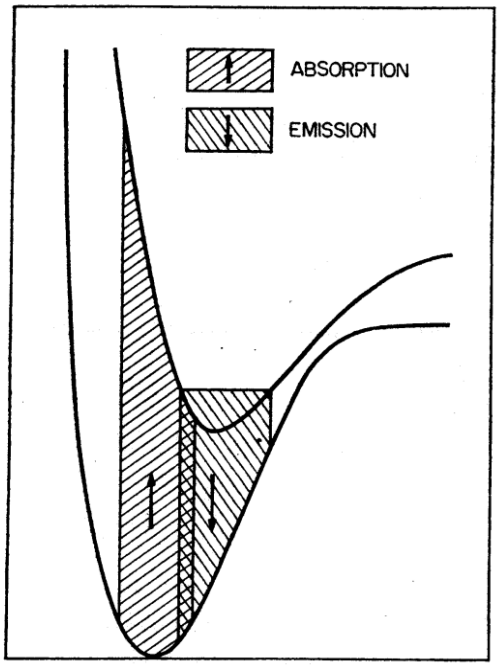
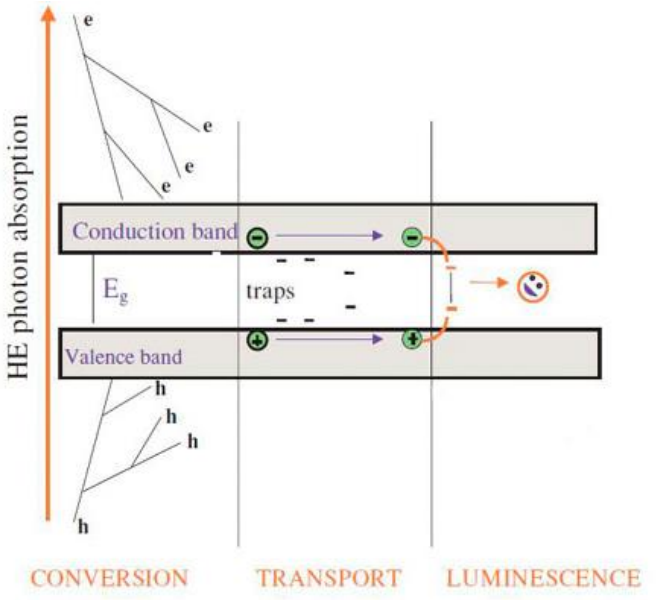


Figure 8.7 The emission spectra of several common inorganic scintillators. Also shown are the response curves for two widely used photocathodes. (Primarily from *Scintillation Phosphor Catalog*, The Harshaw Chemical Company. The emission spectrum for BGO is from Ref. 72.)





www.stanford.edu/group/ceramics/scintillators.htm

State of the Art Scintillators

Material	Light Yield (photons/MeV)	Resolution @ 662keV (%)
NaI(Tl)	38,000	5.5
BGO	8,200	9.0
$LaBr_3(Ce)$	70,000	2.8
LSO(Ce)	39,000	7.9
BC-408 Plastic	10,600	-
GS-20 Li Glass ($2930 for 1-inch round, 2mm thick/ $4,739 for 6.2-inch square, 2mm thick plate)	4,100	17

Scintillator Light Detectors

- Device that converts the extremely weak light pulse (scintillation pulse) into a corresponding electrical signal.
- Two types of detectors:
  - 1) Photo multiplier tube (PMT)
  - 2)Semiconductor photodetectors

PMT'S

- Represents "golden" standard in scintillation detectors.
- Extremely high gain 1 photon (photoelectron) → 10^6e's
- Very fast → picosecond timing resolution is possible
- good linearity
- customized wavelength sensitivity
- position sensitive designs for spatial information are available
- requires high voltage (1 – 2 kV)
- very sensitive to magnetic fields
- bulky in design → low packing fraction
- not very rugged or robust
- large area can lead to long dead times
- low quantum efficiency

Scintillator Light Detectors - PMTs

- Outer (glass) envelope (maintain vacuum conditions) low energy electrons accelerated efficiently by internal electric fields.
- Two major components:
  - Photocathode converts scintillation photons to photoelectrons.
  - Electron multiplier collects the photoelectrons and amplifies them by ~ 10^6 for every initial photoelectron created.

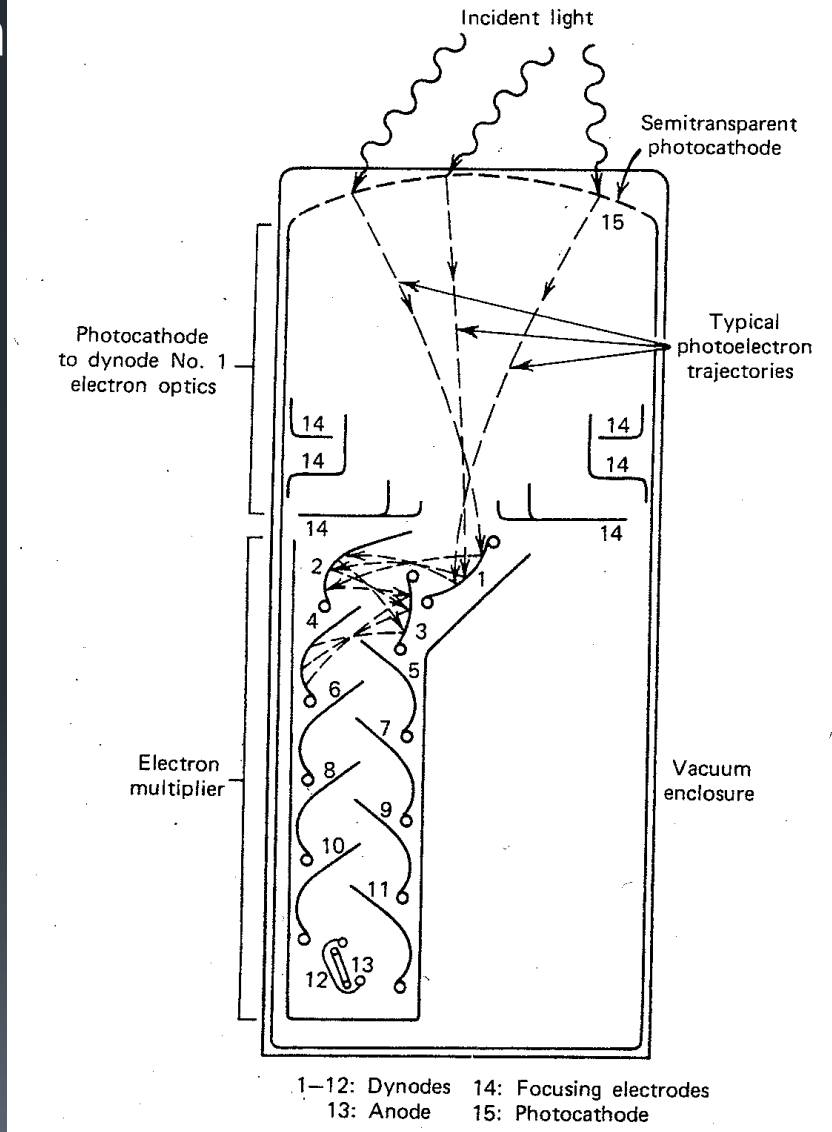


Figure 9.1 Basic elements of a PM tube. (From Ref. 1.)

Scintillator Light Detectors - PMTs

- Charge amplification is very linear. Output pulse at the anode is proportional to the number of original photoelectrons over a wide amplitude.
- Much of the timing information of the original scintillation light pulse is retained. A short light pulse → electron pulse (width ~ ns) after a time delay of 20 – 80 ns.

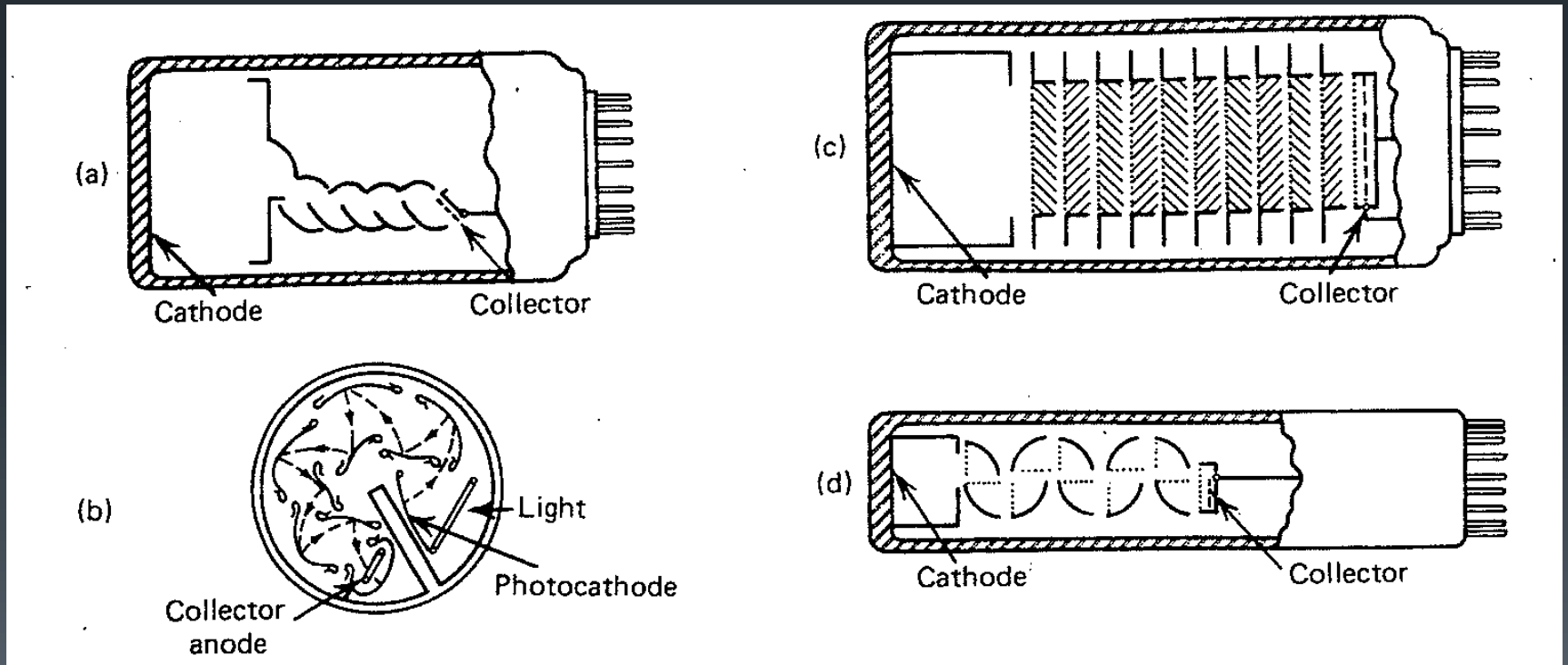


Figure 9.7 Configurations of some common types of PM tubes. (*a*) Focused linear structure. (*b*) Circular grid. (*c*) Venetian blind. (*d*) Box-and-grid. (Courtesy of EMI

Scintillator Light Detectors - PMTs

PMT Photocathode

- (1) Scinitillation photon absorption & energy transfer to an electron within photoemissive material (depends on incident photon energy, *hf*)
- (2) Migration of the electron to the surface (some energy loss via e-e collisions)
- (3) Escape of the electron from the surface of the photocathode. Must overcome potential barrier at the material-vacuum interface ie work function

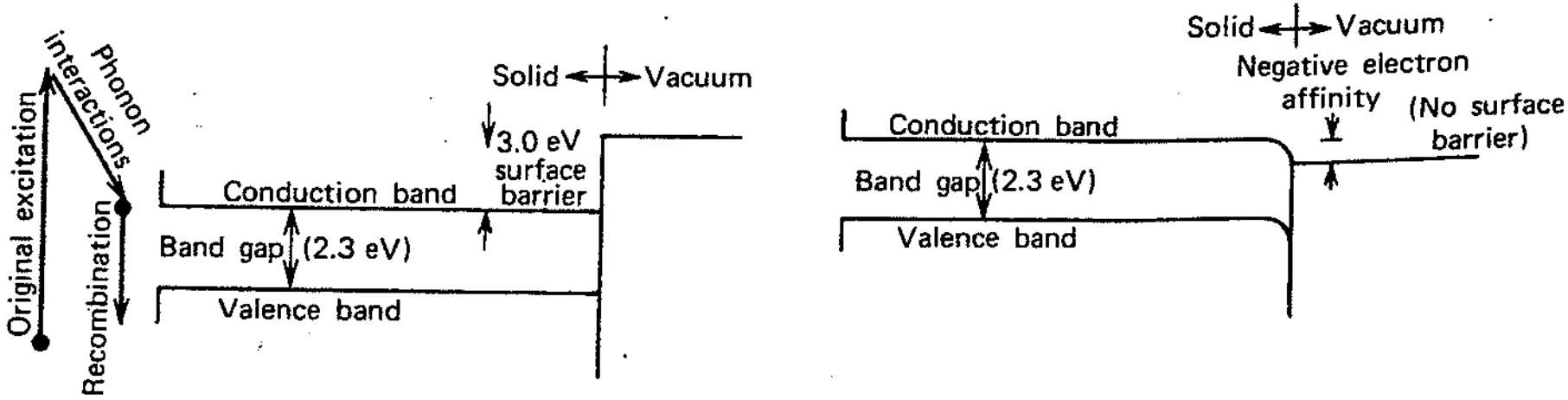


Figure 9.4 Band structure near the surface for conventional semiconductors (left) and NEA materials (right). (Adapted from Krall et al.[6])

Scintillator Light Detectors - PMTs

PMT Quantum Efficiency

- Q.E.$_{DC}$(amps/lumen) = current output per unit light flux on surface
- Q.E. = # of photoelectrons emitted / # of incident photons = 20 – 30 % typically
- long λ - limit due to low energy photo electron not having enough energy to escape photocathode surface → Fig. 9.4
- short λ - limit due to absorption in the glass before reaching to photoemissive layer → fused silica or quartz extends to ~ 160 nm.

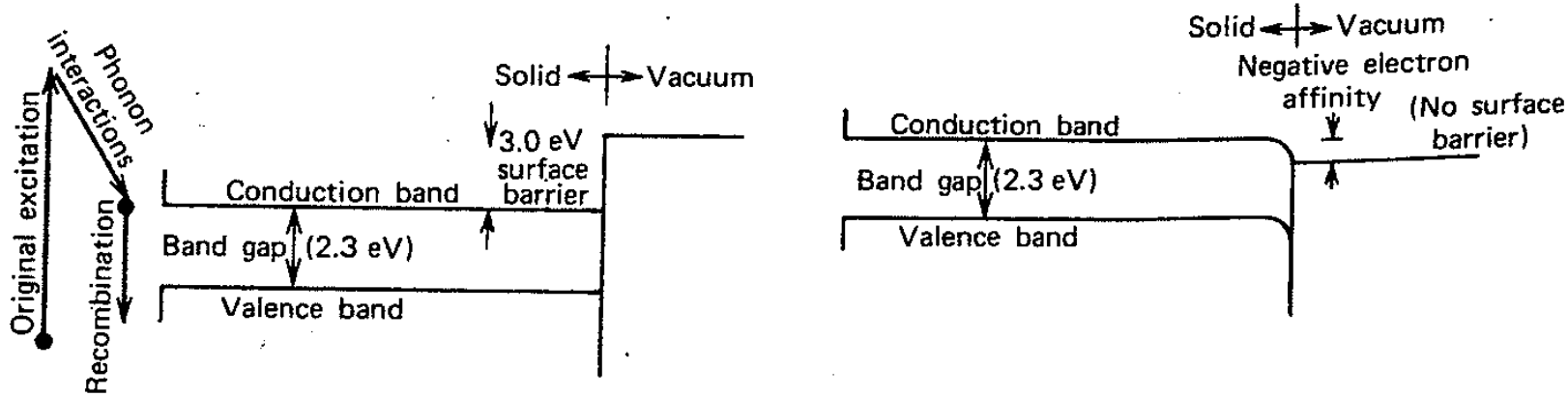


Figure 9.4 Band structure near the surface for conventional semiconductors (left) and NEA materials (right). (Adapted from Krall et al.[6])

Scintillator Light Detectors - PMTs

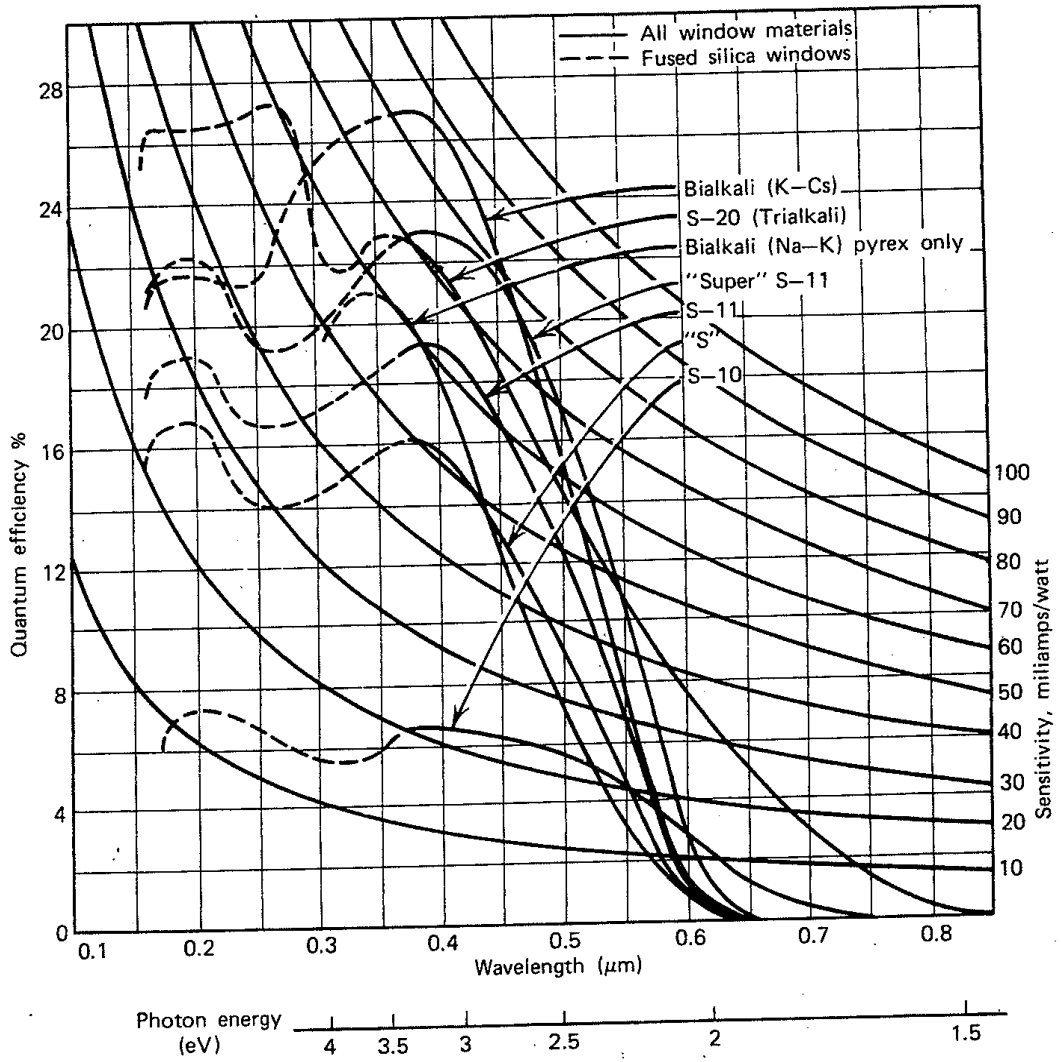
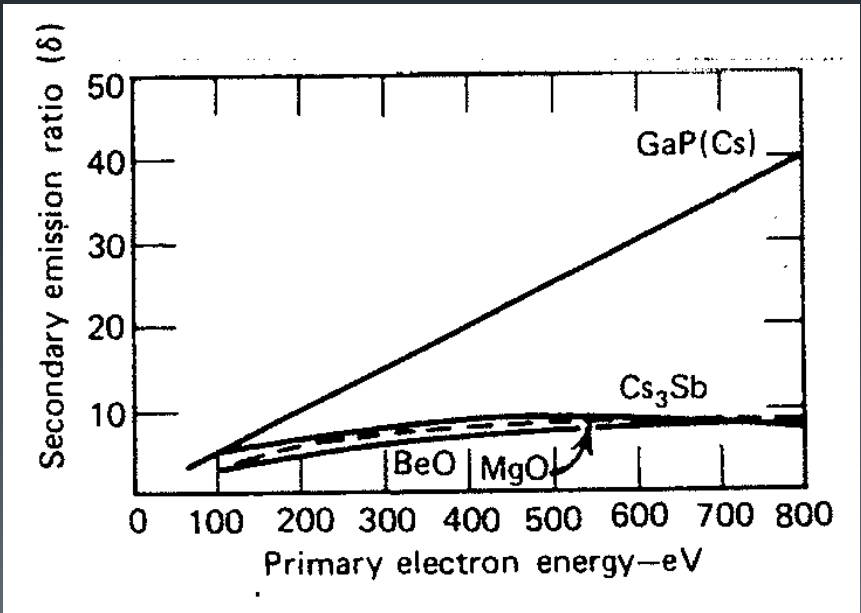


Figure 9.2 The spectral sensitivity of a number of photocathode materials of interest in PM tubes. The use of silica or quartz windows is necessary to extend the response into the ultraviolet region. (Courtesy of EMI GENCOM Inc., Plainview, NY.)

Scintillator Light Detectors - PMTs

PMT Electron Multiplication

- Based on the phenomena of secondary electron emission.
- *e*'s from the photocathode are accelerated and caused to strike the surface of an electrode, called a dynode → re-emission of more than one electron.
- dynode surface materials are specially chosen to maximize the secondary electrons
- Multiplication factor for a single dynode, δ = # 2ndry electrons emitted / primary incident electrons

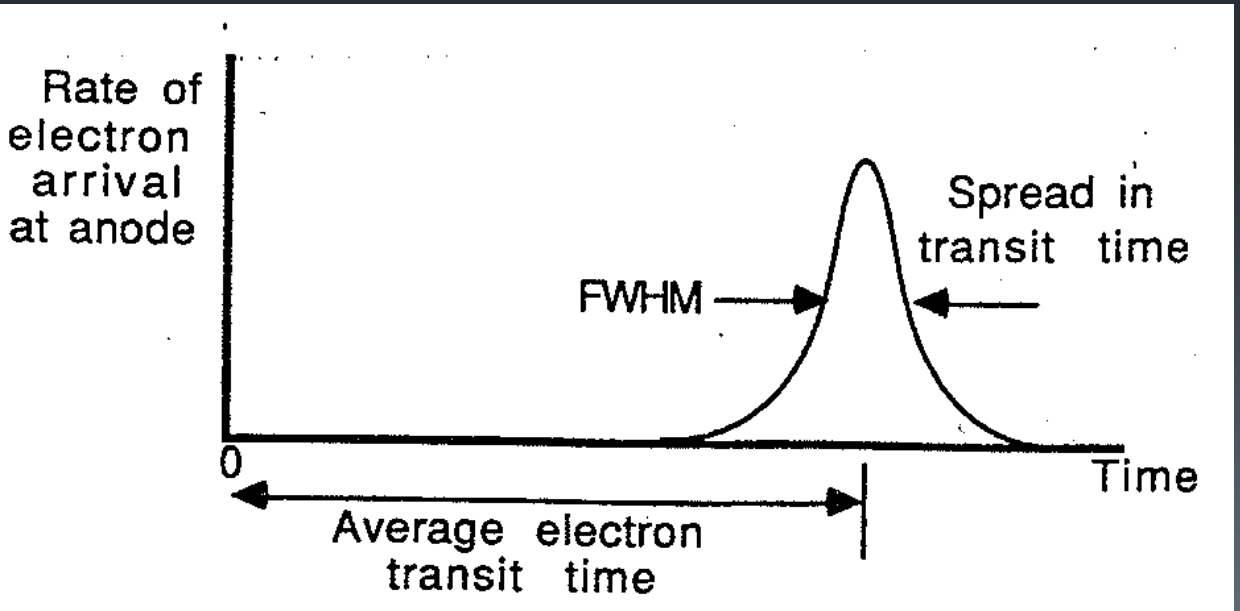


Variation of the secondary emission yield with primary electron energy for standard dynode materials and an NEA material [GaP(Cs)]

Scintillator Light Detectors - PMTs

PMT Pulse Timing Properties

- Time characteristics are dominated by the electron “transit time” since photoemission time in the photocathode is very fast (< 0.1 ns).
- Electron transit time – average time difference in photon arrival at the photocathode and the collection of the electron burst at the anode.
- Typically 20 – 80 ns → delay only.
- For timing applications the spread in the transit time is most important (see figures 9.10, 9.11 & 9.12)



Response of a PM tube to a short pulse of light on the photocathode

Scintillator Light Detectors

Semiconductor PD's

- High quantum efficiency (improve energy resolution)
- low power operation & consumption (10 – 300 V)
- extremely good linearity possible
- very compact (high packing fraction) → good spatial info.
- robust & rugged
- insensitive to magnetic fields
- intrinsically very fast
- more complicated electronics required
- complicated geometries → rapidly increases production cost.

Scintillator Light Detectors – Semiconductor Phototdetectors

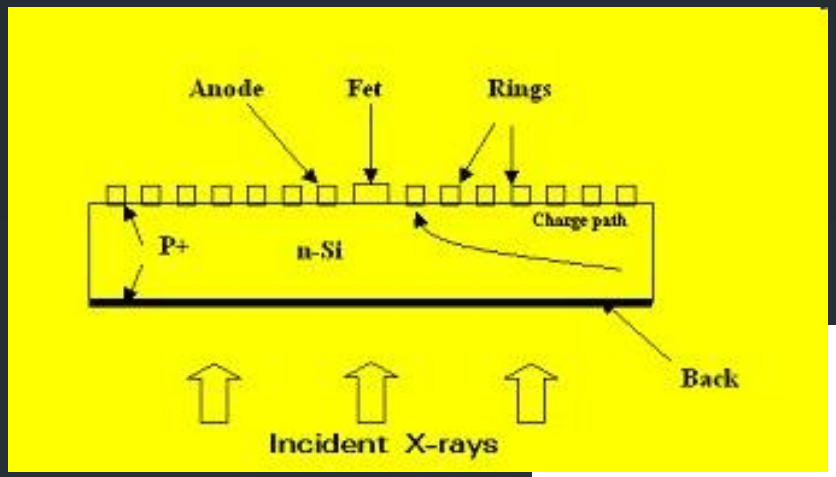
- Generally three types of such photodetectors can be considered as replacements for PMTs in certain applications;
- Conventional photodiodes, avalanche photodiodes and SiPMs.
- Scintillator is mounted optically to the PD by optically transparent glue or grease.

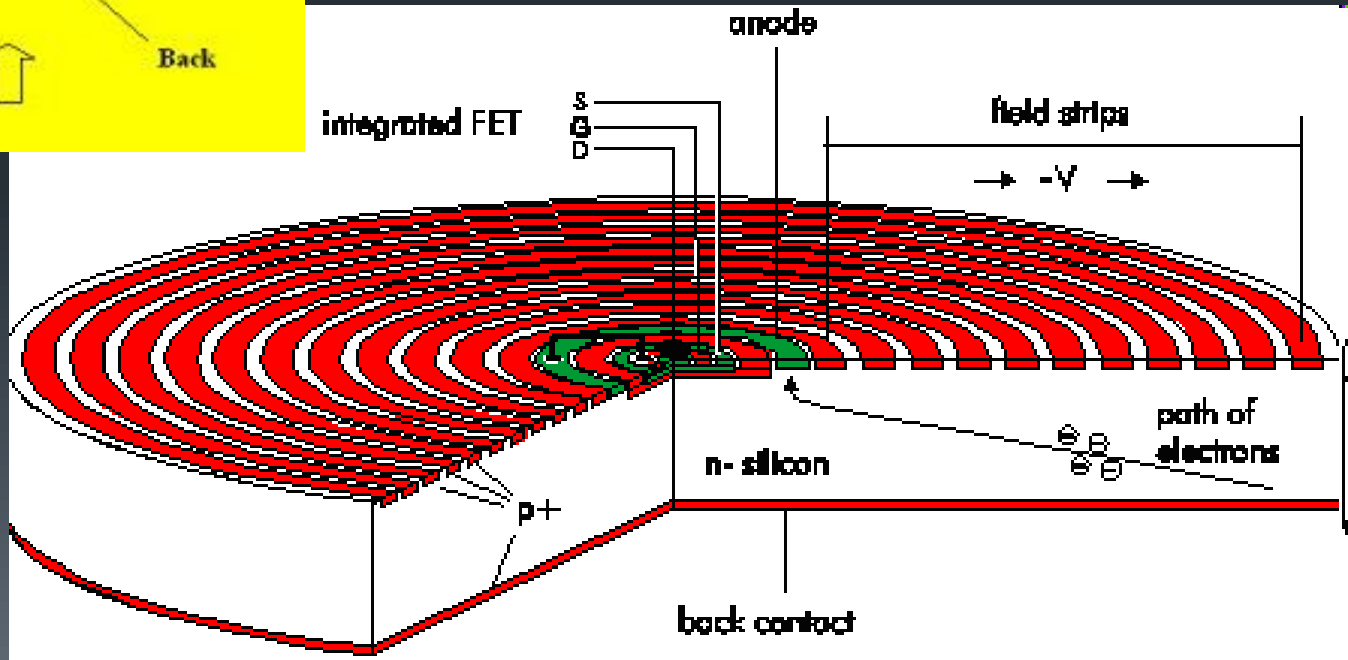
http://jp.hamamatsu.com/products/sensor-ssd/index_en.html

Scintillator Light Detectors – Semiconductor PDs

Noise in PDs

- Also can reduce noise by using a semiconductor material with a large bandgap, eg. HgI (Mercuric Iodide) cf Si (silicon)
- Finally we could also reduce the capacitance. Silicon drift detectors or by using sapphire substrates.

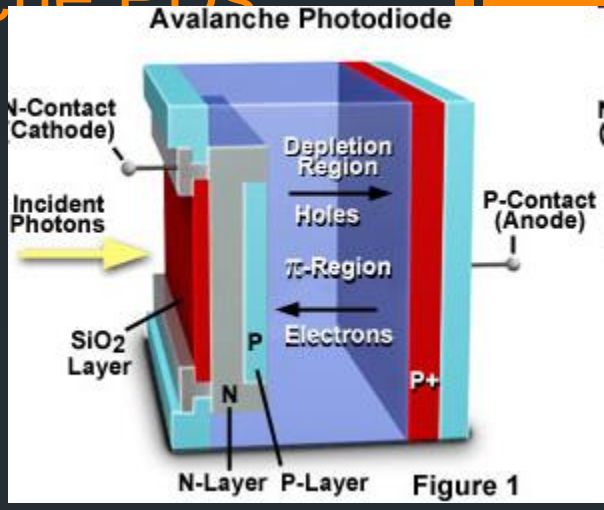




Scintillator Light Detectors – Avalanche PDs

Avalanche Photodetectors

- The small amount of charge produced in a conventional photodiode by a typical scintillation event can be increased through an avalanche process in a semiconductor.
- High values of applied voltage are required → charge acceleration between collisions → additional e-h pair creation along the collection path → internal gain → better S/N ratio
- Solid-state analogue of the gas proportional counter.
- Figure 9.17 – "Reach-through configuration" of an avalanche photodiode.



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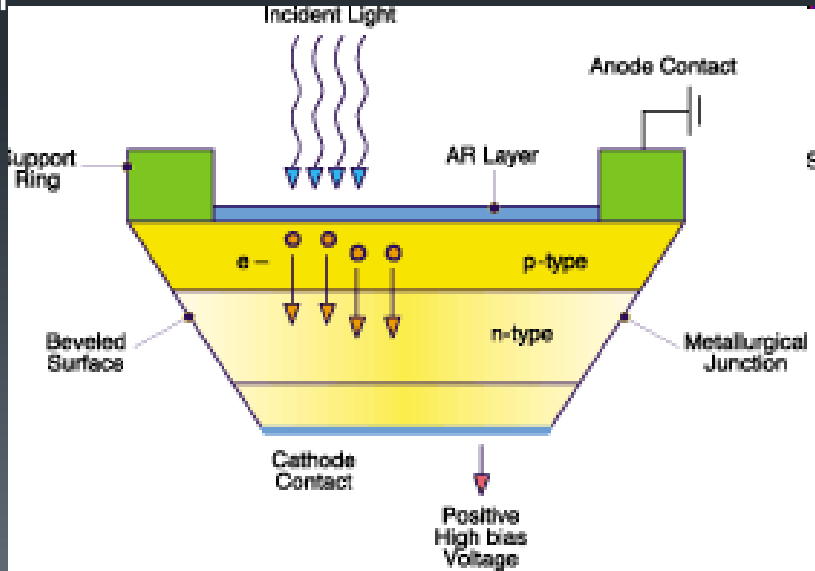
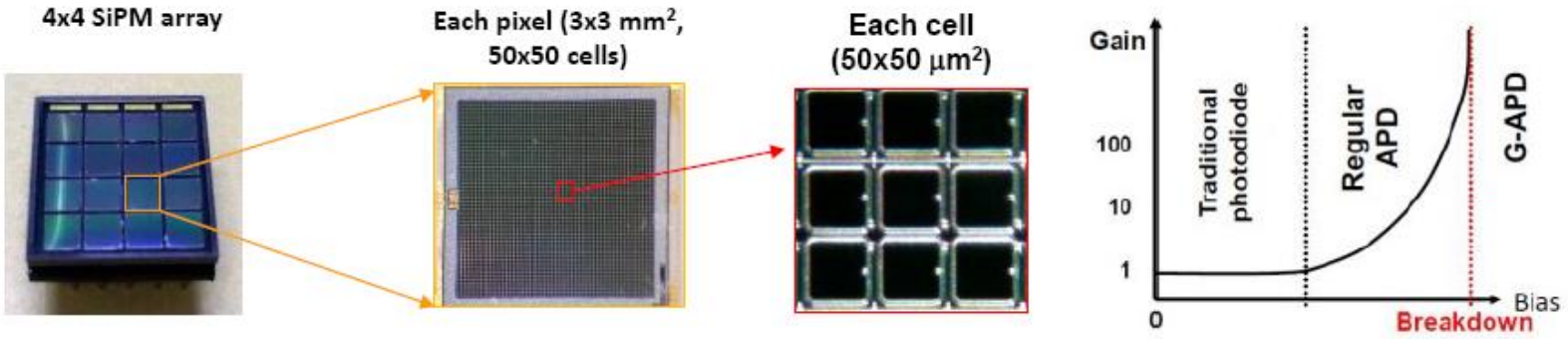
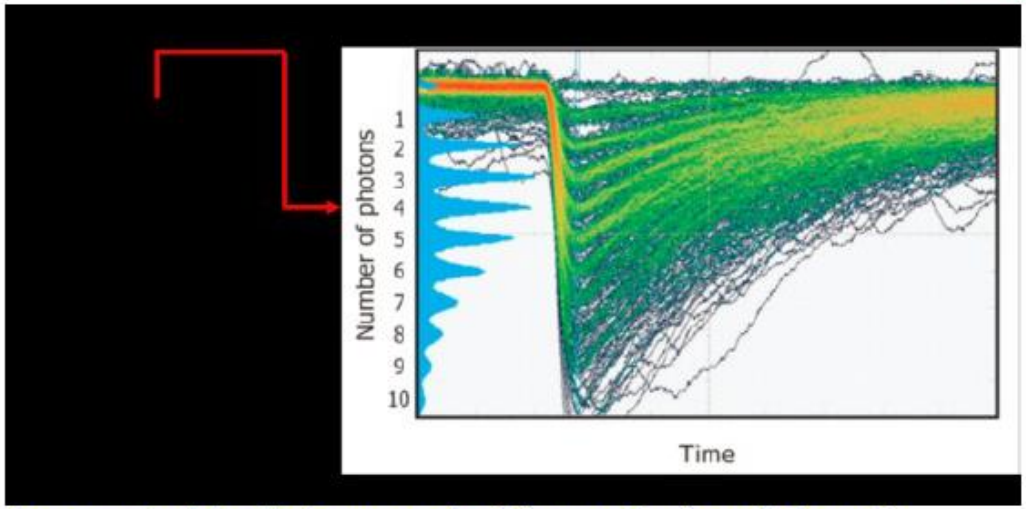


Silicon Photomultipliers



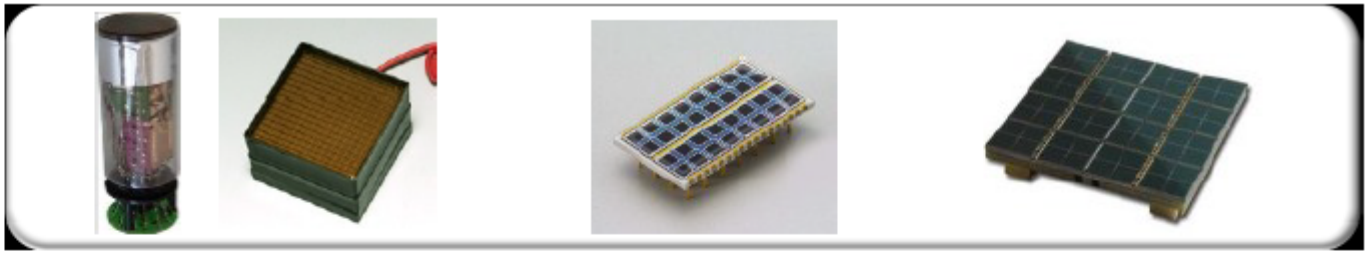
Work principle of SiPM

(Geiger mode - APD)



- ✓ Each cell (APD) is operated in Geiger mode (above the breakdown)
- ✓ Counting individual light photons
- ✓ Output signal is sum of all cells
- ✓ Each cell provides maximum-gain signal on photon interaction

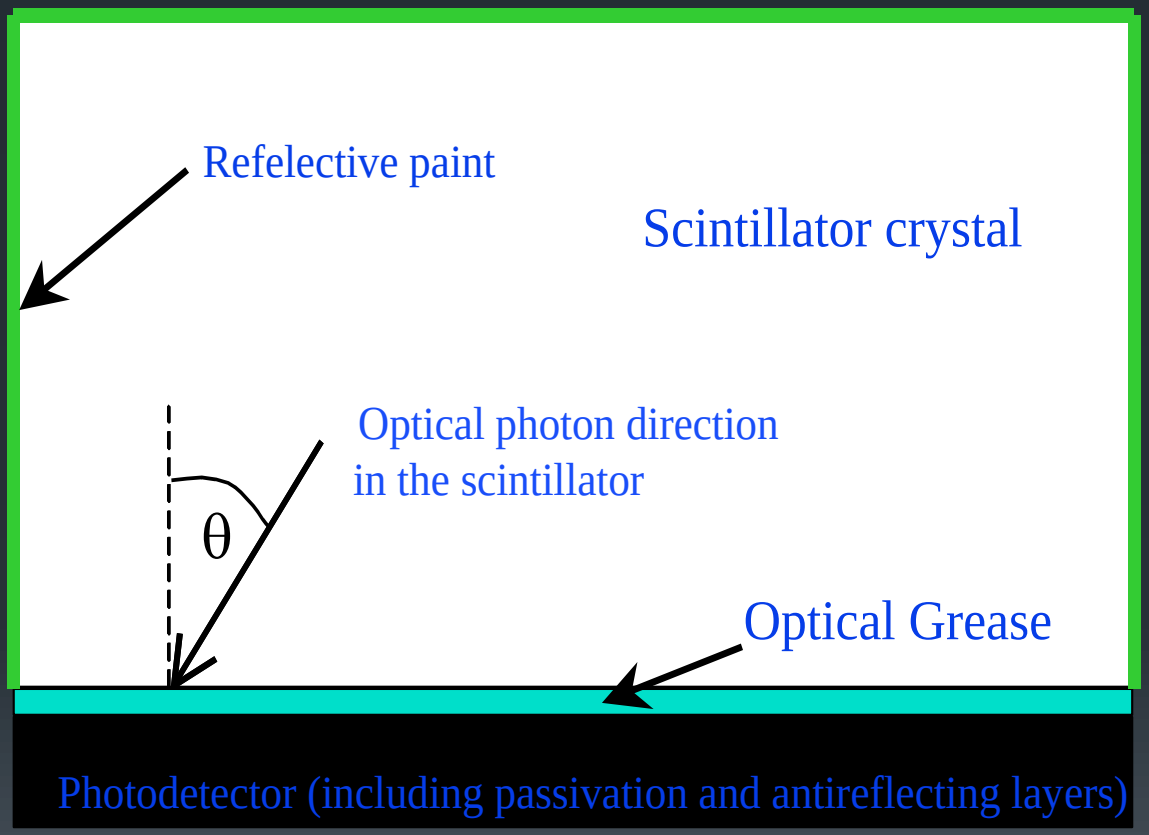
Silicon Photomultipliers



Type	PMT	APD	SiPM
Amplification	High (10^6)	Low (~10^2)	High (10^6)
Magnetic field	Sensitive	Not sensitive	Not sensitive
Compactness	bulky	compact	compact
Bias (V)	HV (600~1200)	HV (300-1500)	20-70
S/N ratio	High	Low	High
Time resolution	~1 ns	> 1 ns (2-4 ns)	<1 ns (~200ps)
Electronic readout	Voltage amplifier	Charge sensitive preamplifier	Voltage amplifier

SiPM has very appealing properties for next generation of PET and SPECT with MR-compatible

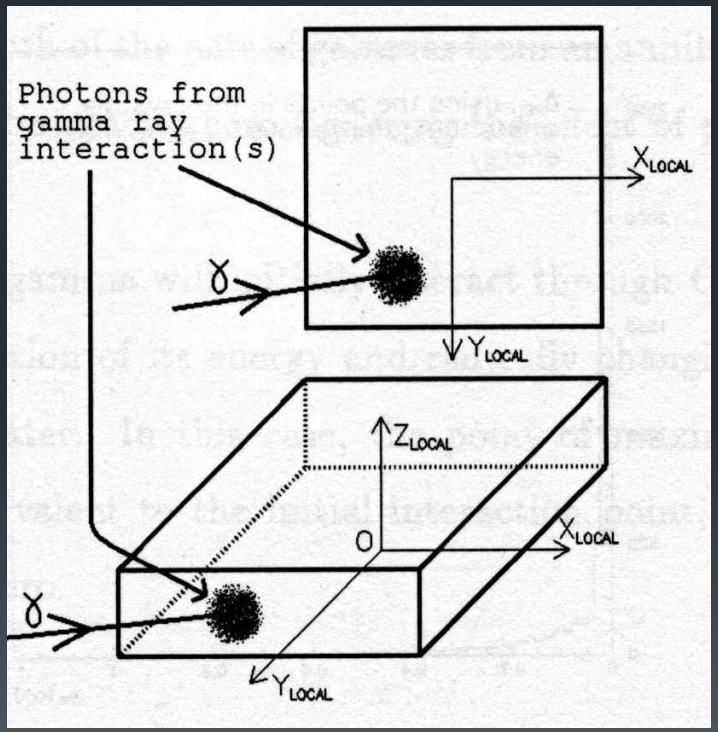
Scintillation Detector Modelling

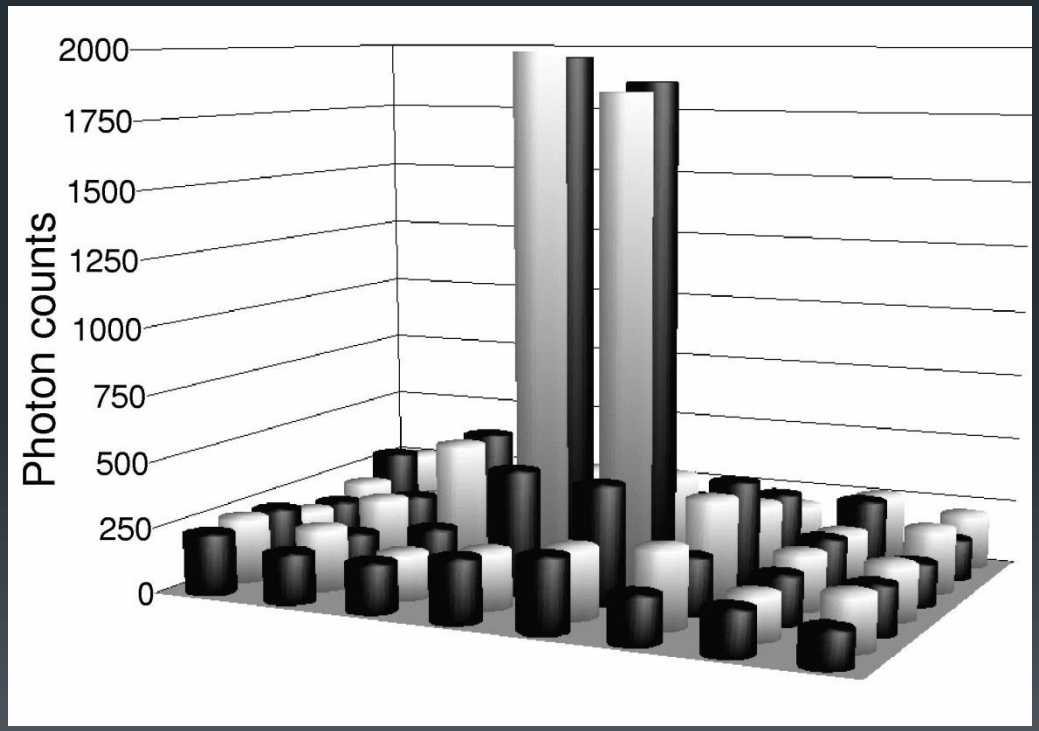


- Schematic picture of the experimental layout modelled

Light Collection Simulations

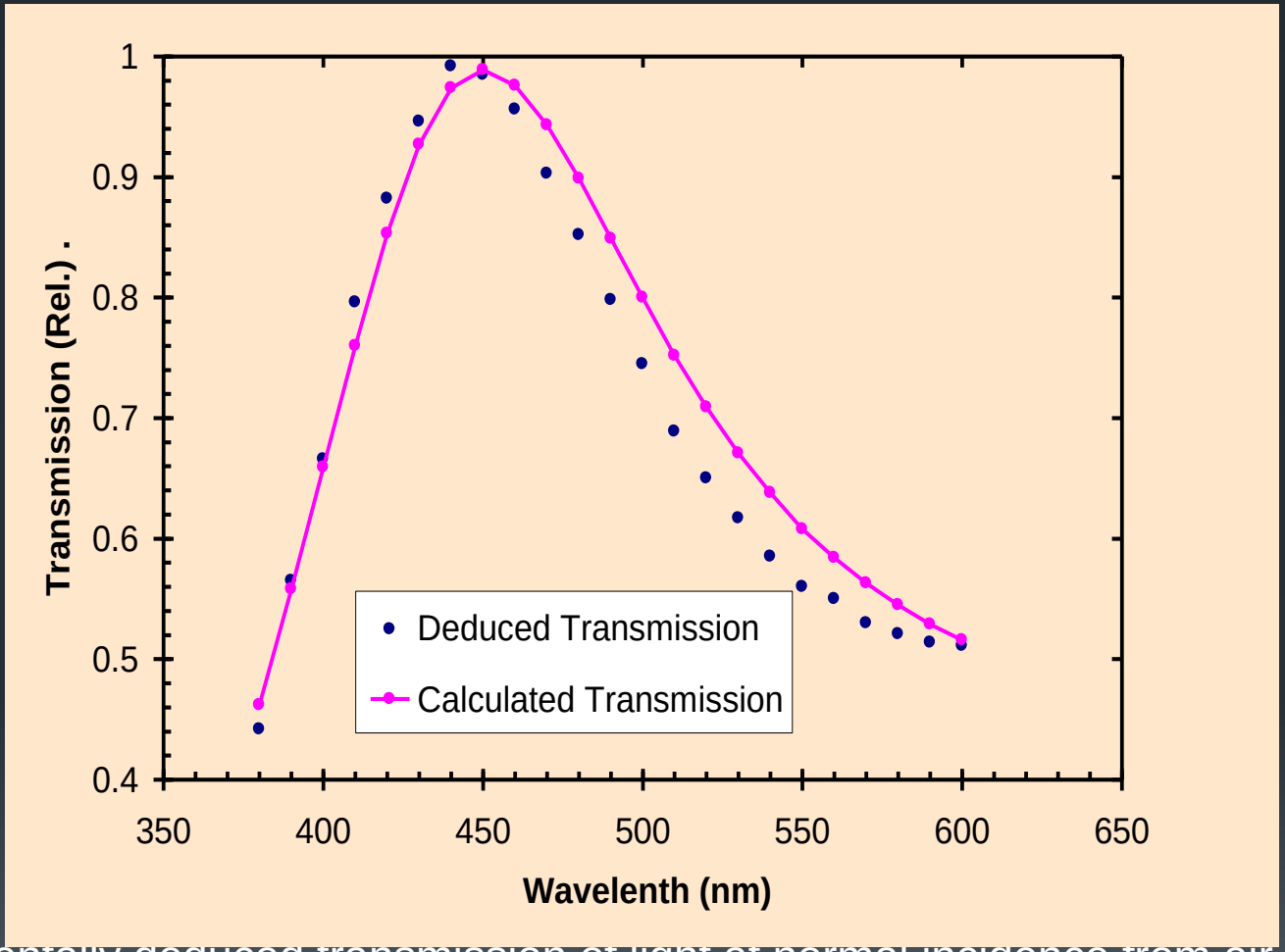
- Monte Carlo Simulations were performed by G. Takacs to:
  - determine the ideal crystal geometry so as to maximise the light output
  - optimise detector pixel size to improve the DOI measurements.





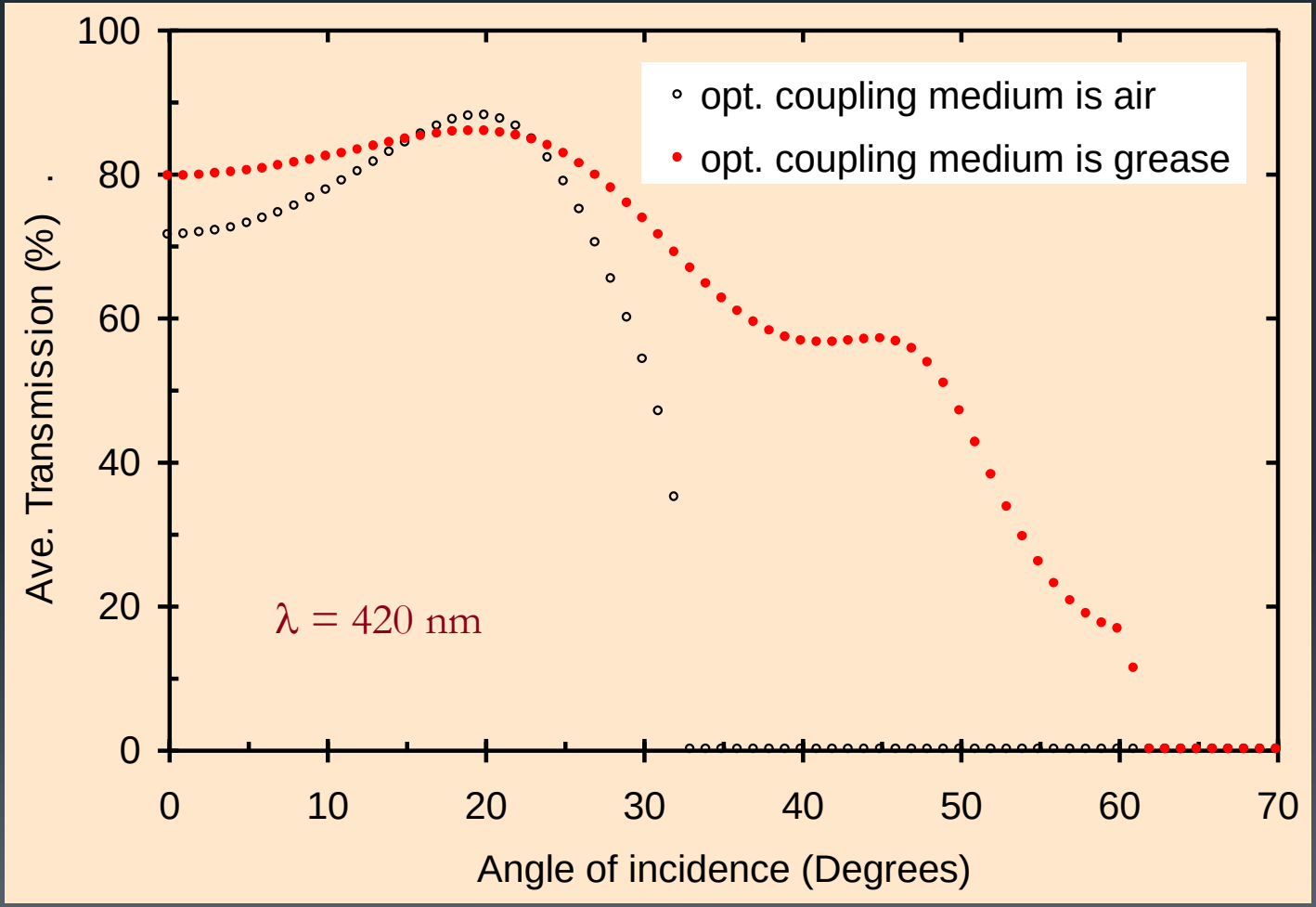
Interaction point above the corner of four pixels

Photodetector Model

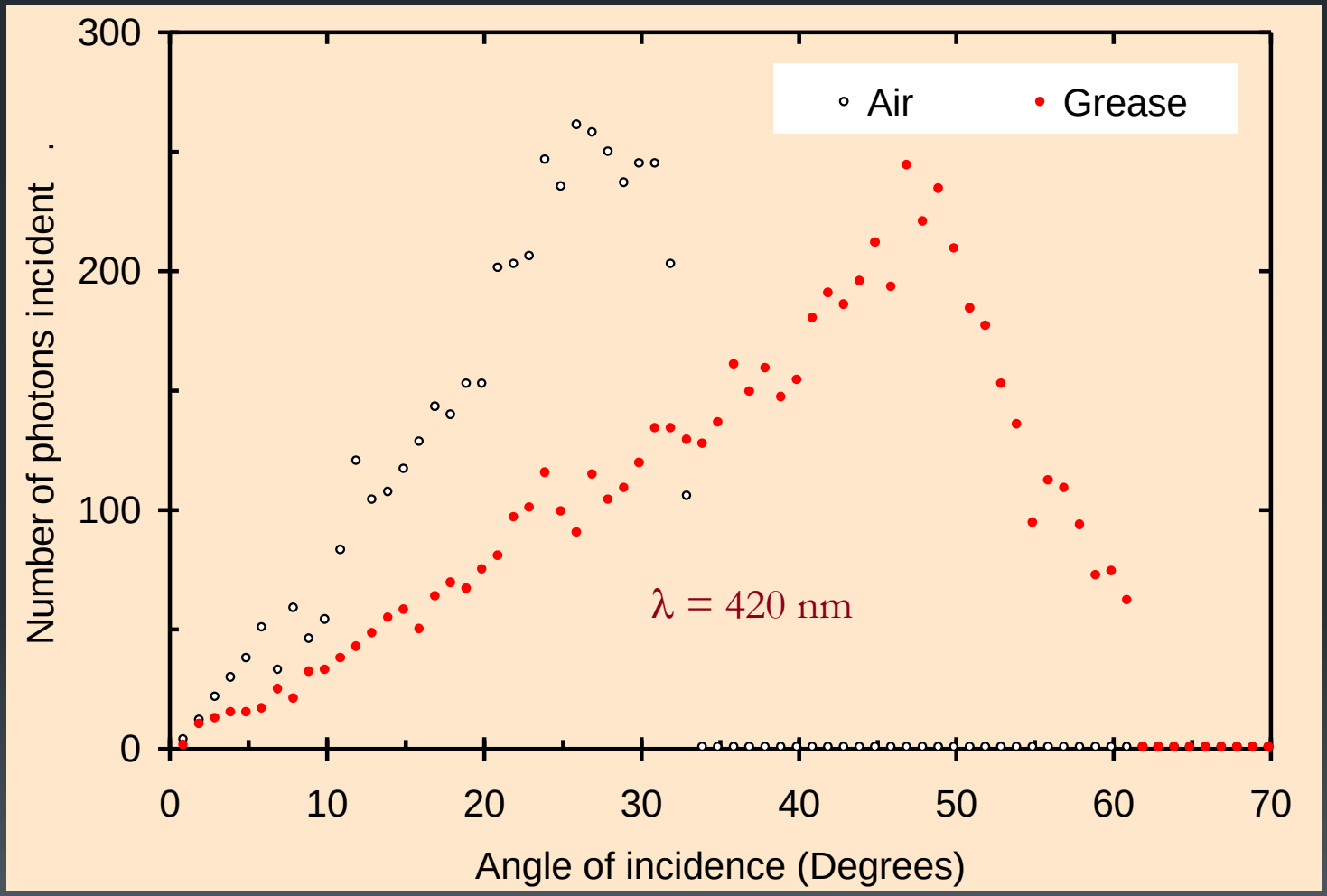


Experimentally deduced transmission of light at normal incidence from air through the overlayers that make up the optical entrance window of the photodetector. Overlayed is the calculated transmission data from the growth parameters of the photodetector.

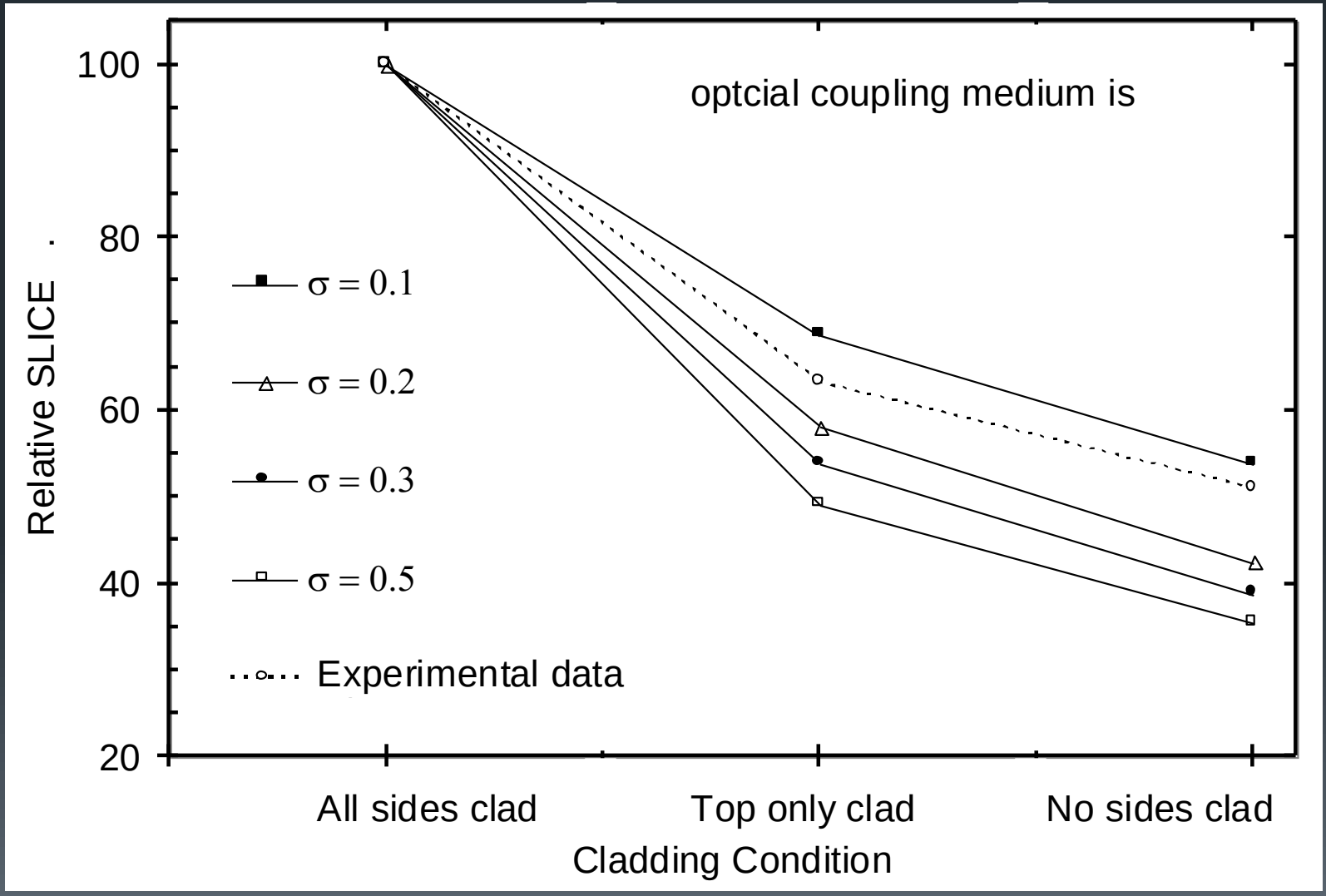
Transmission into the PD from LYSO



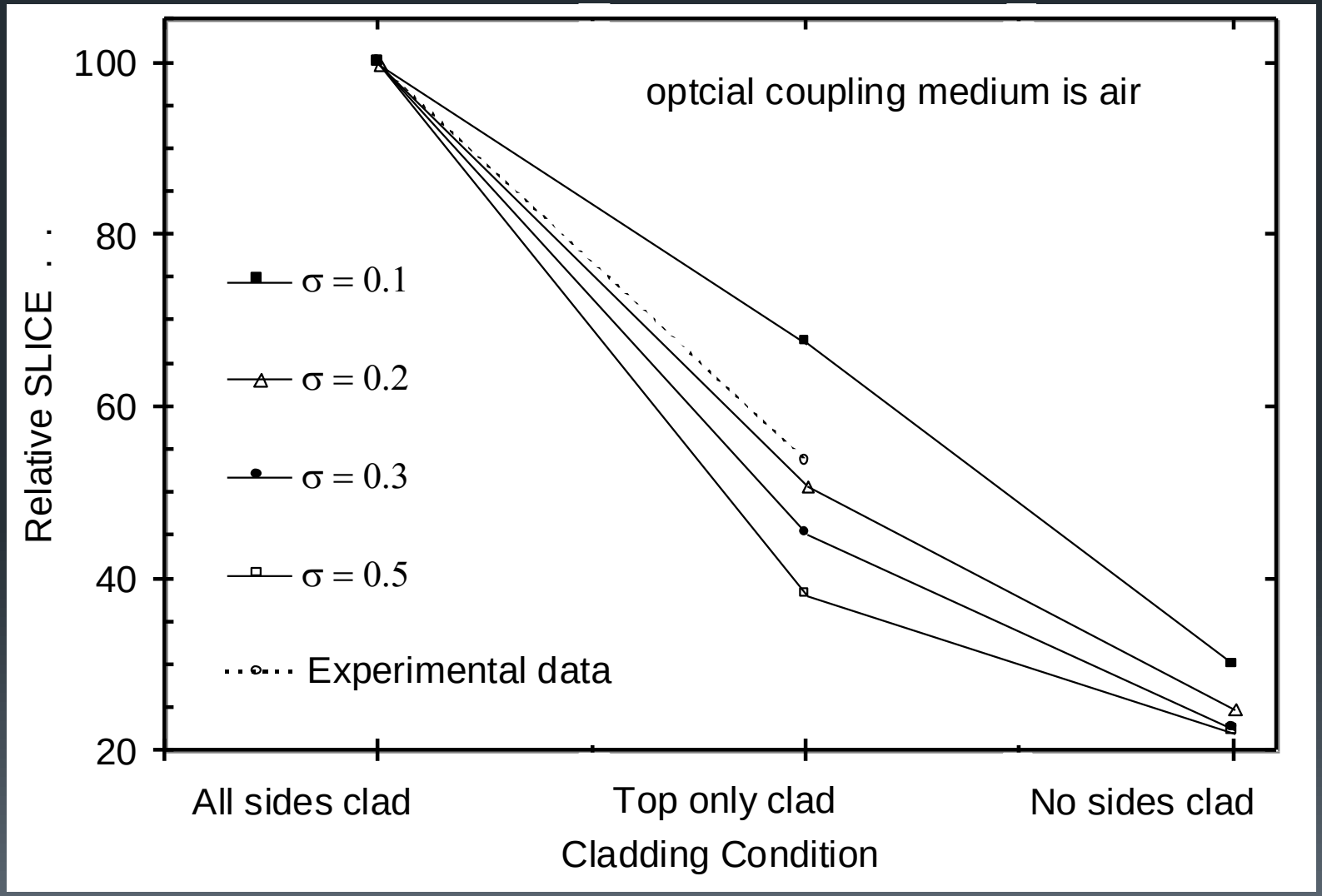
Scintillator photon distribution



Relative light collection



Relative light collection



Absolute Light Collection

Scint. Clad Cond.	Model Data						Experimental Data		
	Grease σ=0.1	Air σ=0.1	% reduc.	Grease σ=0.2	Air σ=0.2	% reduc.	Grease	Air	% reduc.
All clad	49.1	33.7	31.4	54.1	42.9	20.8	58.1	42.7	26.6
top clad	33.7	22.7	32.7	31.5	21.8	30.6	36.8	22.9	37.8
unclad	26.4	10.1	61.9	23.0	10.7	53.3	29.6		

13,300 scintillation photons per 511 keV event in LYSO