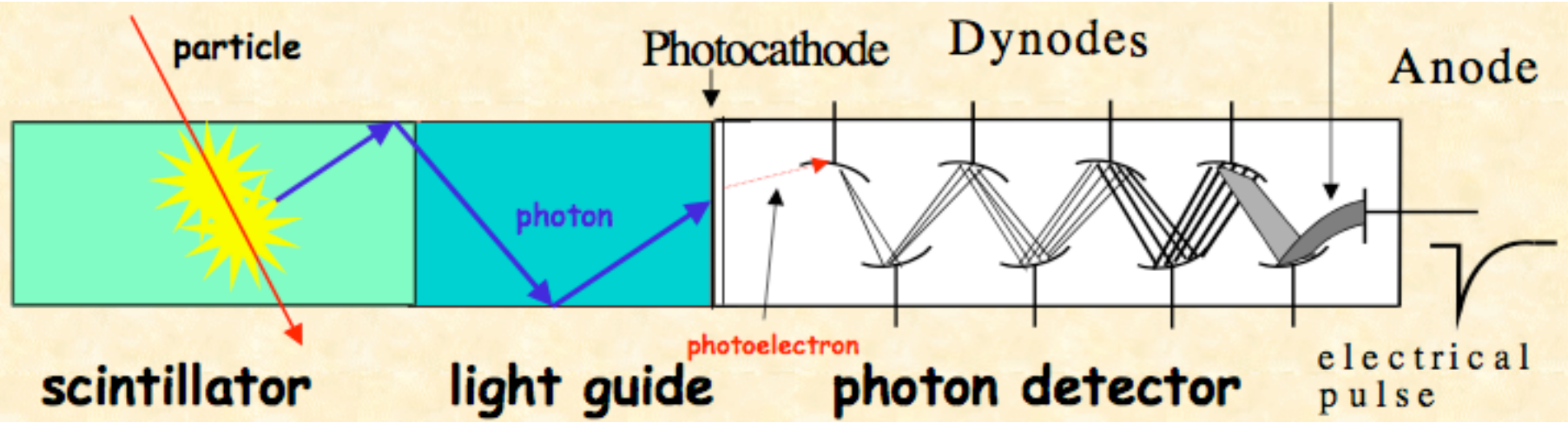
Scintillation detectors

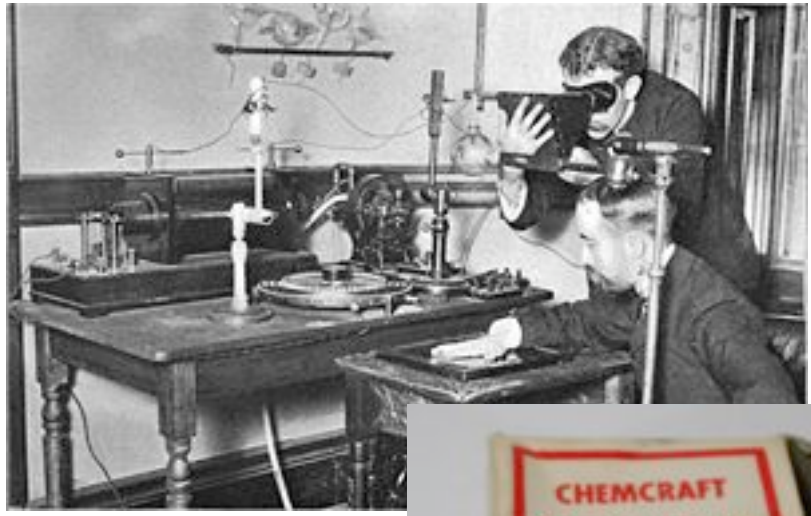
(Dan Green, page 31-49 , W.Leo , page 150 onwards)

Scintillation Detectors



Certain materials, when struck by radiation, emit a small flash of light, a scintillation.
Coupled to a amplifing device such as a photomultiplier, this light is transformed into electrical pulses, which can be analized and provide us with precise information about the time of passage of that particle

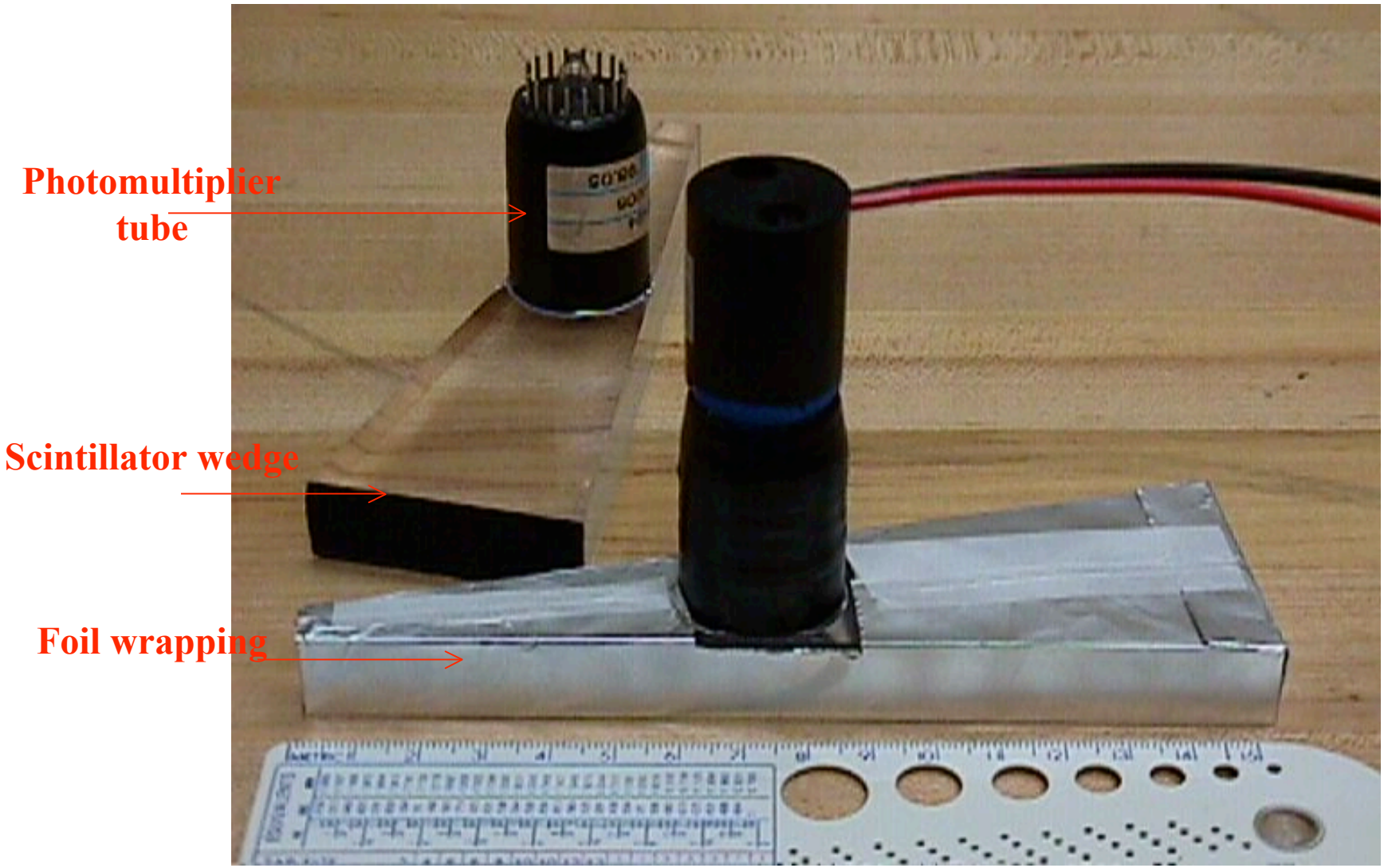
In 1903 Sir William Crookes invented the first inorganic scintillator detector,
a Zinc sulfide screen
which produced weak scintillations when struck by
α particles



These scintillations could be viewed by the naked eye in a dark room.
It was used by Geiger and Marsden in their experiments with alpha particles

Not so practical, fell In disuse with the arrival of gaseous ionization instruments.

Then in 1944 Curran and Baker replaced the naked eye with the photomultiplier tube and revived the use of scintillators.
still nowadays scintillator detectors are widely used and highly reliable and conveniently available


Photomultiplier tube
Scintillator wedge
Foil wrapping

Scintillation signal provides:

1. Sensitivity to energy of the particle striking the scintillator :

Most scintillators have linear response to energy deposited

light output $\propto$ exciting energy

If photomultiplier is also operated linearly, then scintillator detector can be used as energy spectrometer

2. Fast signal response :

Response and recovery time is short wrt other detectors.
Time between two events can be determined very precisely (~100 ps)
AND they can also accept very fast counting rates

3. Pulse shape discrimination :

shape of emitted light pulses is different for different particles, in some scintillators. Due to excitation of different fluorescence mechanisms by articles with different ionizing power.

Scintillator materials show property called luminescence.

When hit by radiation, an ionizing particle,
they absorbe and re-emit energy in form of **visible light**

If re-emission is fast ($<10^{-8}$ sec) the phenomenon is called fluorescence
If re-emission is slower ($>10^{-6}$ sec) the phenomenon is called Phosphorescence

$$N=N_0\, e^{-t/\tau}\ \ 1/\tau$$

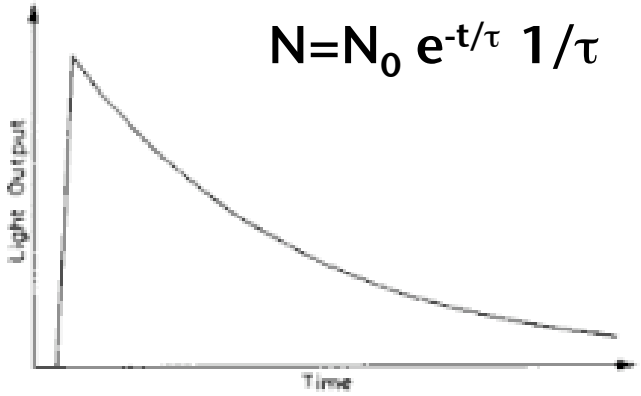


Fig. 7.2. Simple exponential decay of fluorescent radiation. The rise time is usually much faster than the decay time

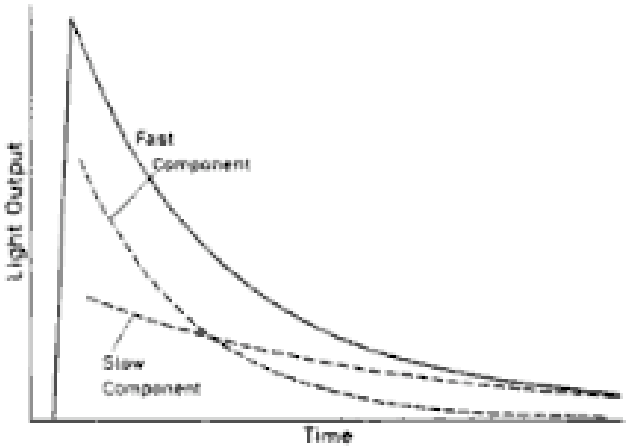


Fig. 7.3. Resolving scintillation light into *fast* (prompt) and *slow* (delayed) components. The *solid line* represents the total light decay curve

Fast component usually dominates

Not all scintillating materials will do a good detector.

Requirements are:

1. High efficiency for conversion of exciting energy of incident particle to fluorescent radiation

2. Transparency of detector to its own fluorescent radiation, so light can be propagated

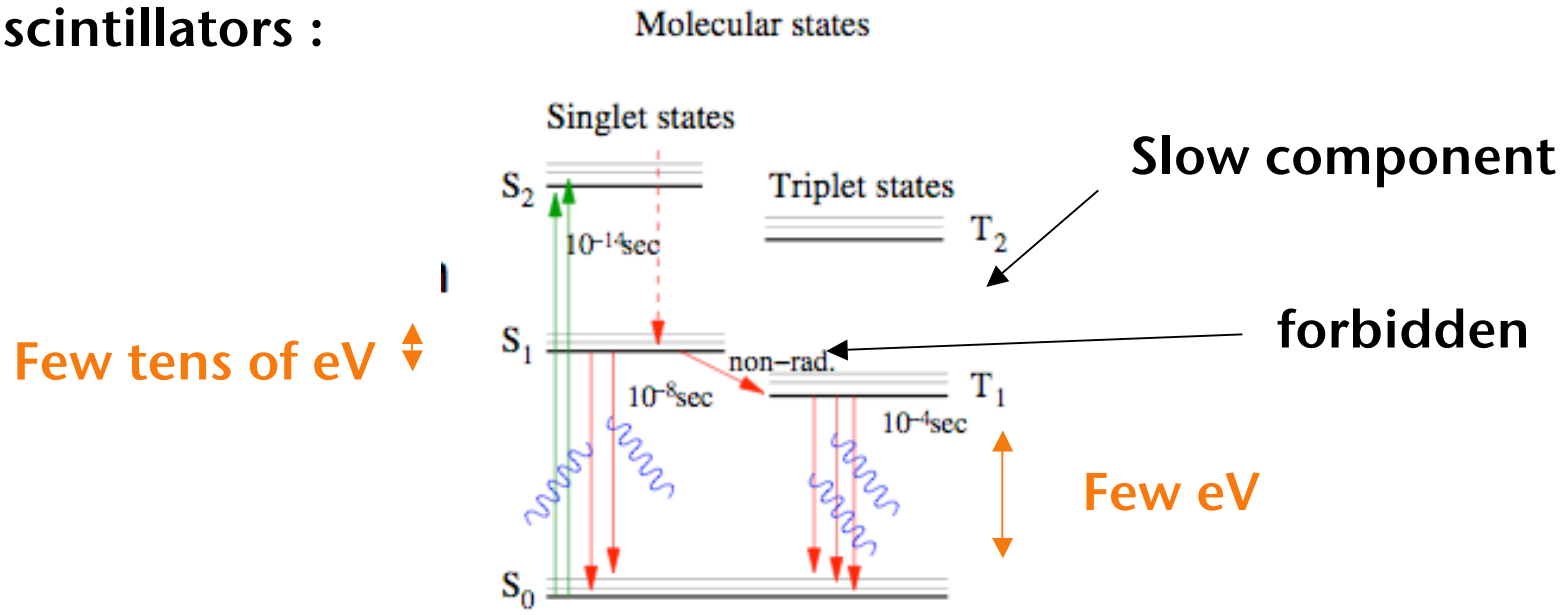
3. Light emission in spectral range that matches photomulitplier

4. Short decay constant τ

6 types of scintillator materials are used:

Organic crystals, organic liquids, plastics, inorganic crystals, gases, glasses

Organic scintillators :



Hydrocarbon compounds with benzene structures

Fast response : decay time of few nanoseconds

Fluorescent light is emission from transitions of free valence electrons of the molecules. Delocalized, they occupy the “π molecular orbitals”. Associated with each electron level is a fine structure which corresponds to excited vibrational modes of the molecule.

Incident particle excites electrons and vibrational levels

Energy S1 → S0 < S0 → S2 => transparent to emitted light

Can be used as detector in form of

crystals (e.g. anthracene $C_{14}H_{10}$, slowest one : decay time 30 ns)

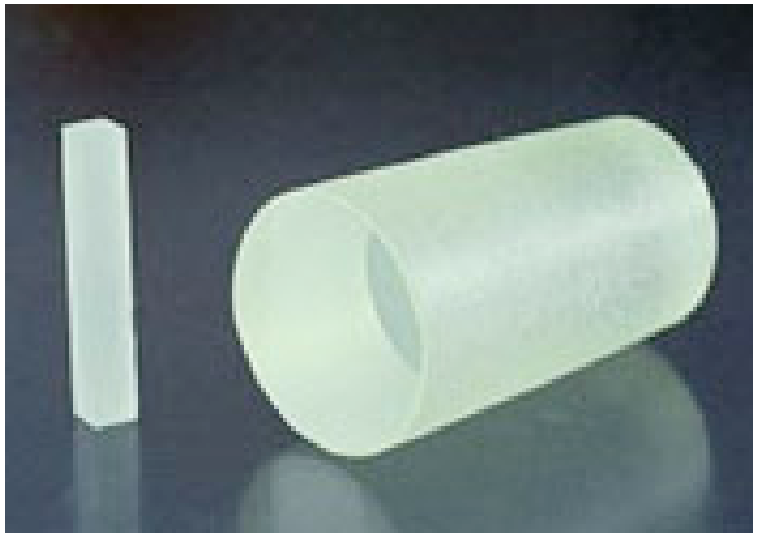
- Fast, few ns response
- anysotropic : response varies with orientation of the crystal.
- Hard, so cutting in desired shape is often difficult.
- Anthracene has the highest light output of all the organic scintillators

Liquids : crystal solved in organic solvent.

- Ionizing energy of incident particle goes to solvent first, and then passed to scintillation solute.
- Most common solvents: benzene, xylene, etc…
- Fast, 3 ns response.
- advantage: the can easily be loaded with other materials to improve performance. Eg. Wavelength shifter material, absorbes emitted light and re-emits in frequency suiting better the photomultiplier . Decay time increases, though.

Plastics :

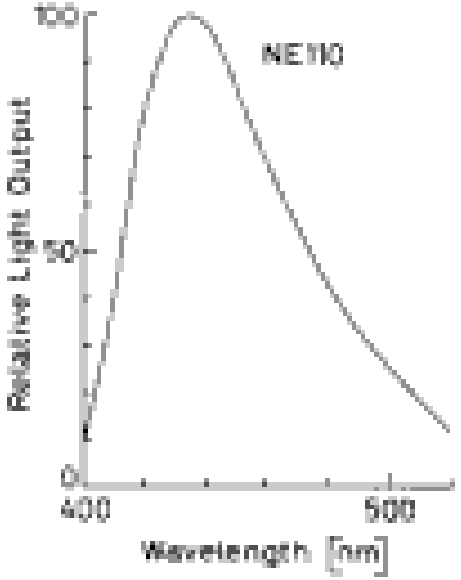
Most widely used in particle and nuclear physics



e.g. polystyrene

Fast , 2-3 ns. Finite rise time cannot be ignored.
High light output.
Very flexible, easily shaped to need.

Produced commercially, in various forms and sizes.



Light emission spectrum for typical plastic scintillator

Blue-UV light

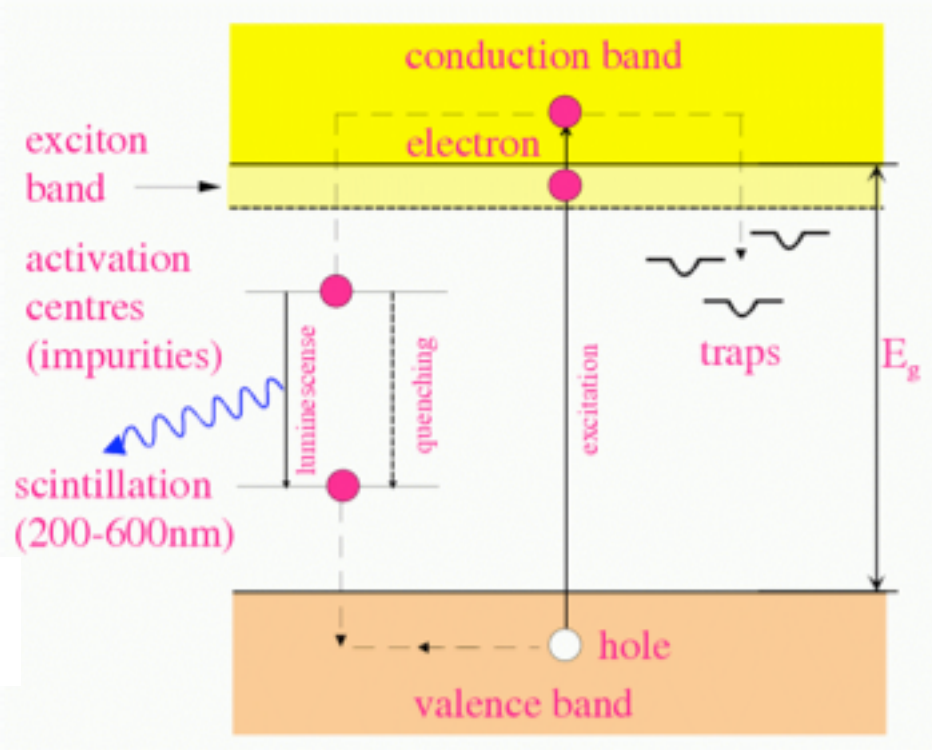
Should be handled with cotton gloves as the body acid can cause the cracking of the plastic.
They are easily attacked by organic solvents like acetone

This is the material of the big and small scintillator plates we use down in the lab for almost all our experiments

Inorganic crystals

Crystals of alkali halides with small activator impurity

NaI, CsI most common



Scintillation mechanism is characteristic of the electronic band structure found in crystals.
Incident particle comes through. What can happen is:

1. Ionize crystal, eject electrons from valence to conducting band, creating free electron and free hole

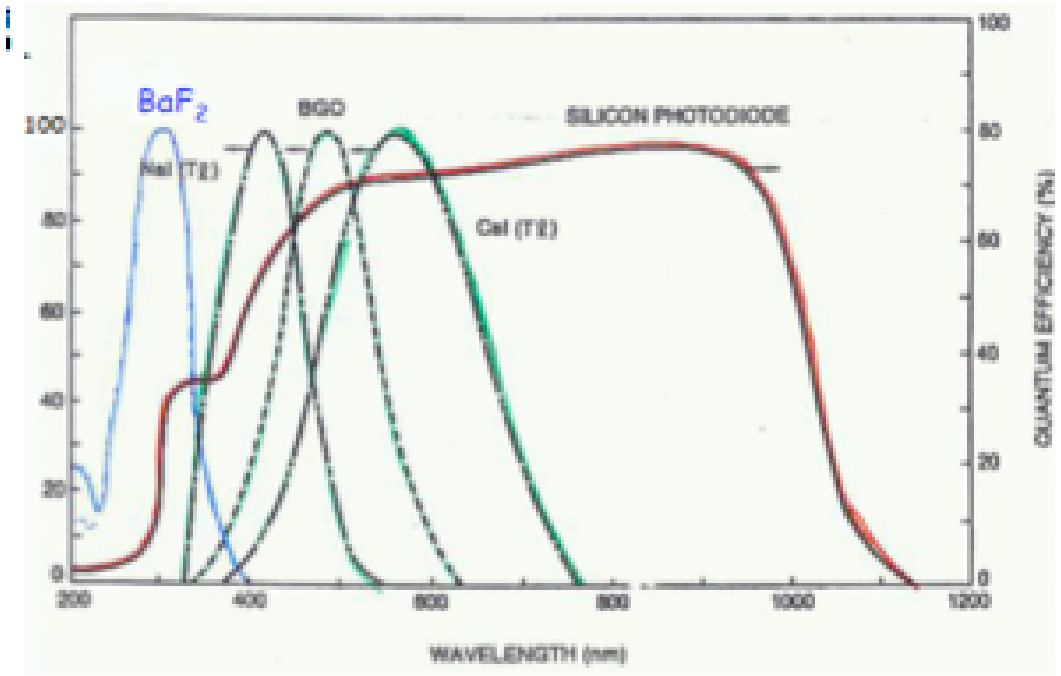
2. Create an exciton by exciting electron to a band located just below the conducting band

In case 2., hole-electron remain bound together as a pair, but are free to move. If there are impurity atoms, then electronic levels in the forbidden energy gap are created.
The free hole or electron can ionize the impurity atom

$h+A \rightarrow A^+$

$A^+ + e^- \rightarrow A + photon$

If the transition is radiationless, the impurity center is a trap and the Energy is lost in other processes



• Time response is bigger than for plastics
~500 ns

• inorganic crystals are hygroscopic, must be housed very tight to avoid contact with humid air
Disadvantage

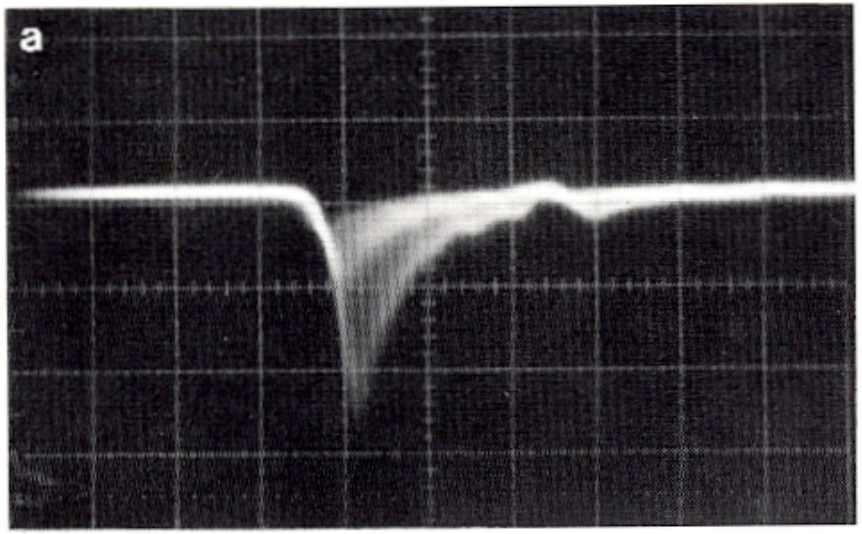
• major advantage of inorganic scintillators is their higher Z and density, hence the greater stopping power.
They also have the highest light output, which results in better energy resolution
This makes them very suited for detection of X and gamma ray and high energy electron and positrons

This is what we use in the radiation lab downstairs

Comparison of scintillators

Material	Plastik	NaI(Tl)	CsI	CsI(Tl)	BGO	$PbWO_4$
Density [g/cm³]	1.03	3.7	4.5	4.5	7.1	8.3
n. photons/MeV	10000	40000	2000	20000	4000	400
Decay time[ns]	2-5	230	35^s	1300	300	50^s, 10^f
Emission wl [cm]		2.6	1.9	1.9	1.1	0.9
Moliere Radius[cm]		4.8	3.5	3.5	2.3	2.0
Remarks	'easy'	hygrosk.		sensitiv		rad.hard

Oscilloscope traces from scintillation counters

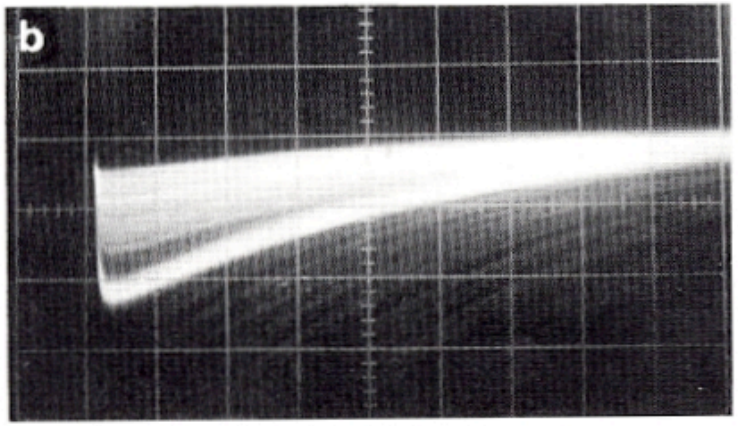


Plastic scintillator

Plastic

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

10 nsec / division



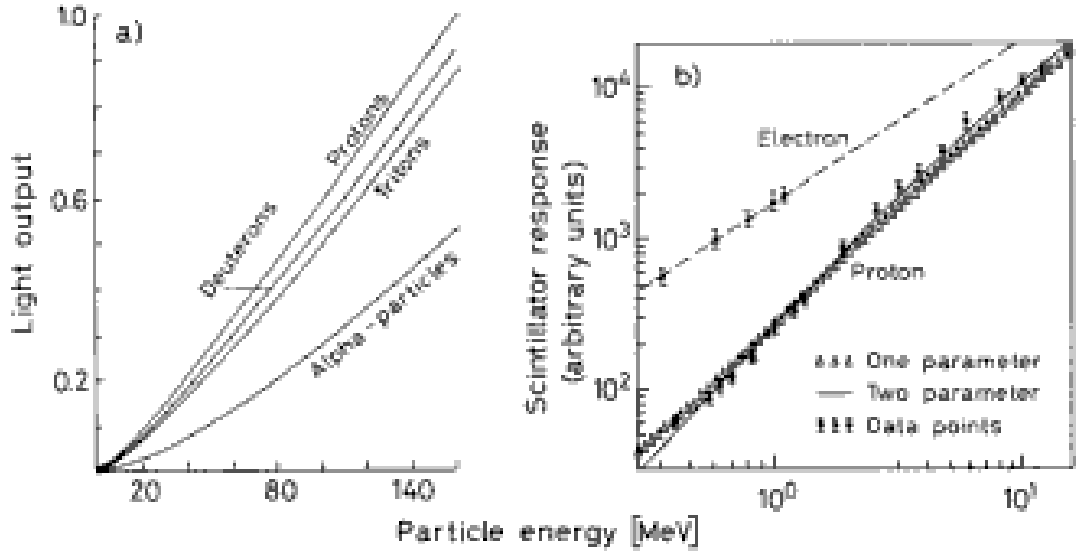
Inorganic crystal, NaI

NaI

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

5000 nsec / division (Longer time scale for fluorescence to occur)

Light output response



Plastic scintillator

Conversion of ionizing energy into light depends on particle type

Usually, the heavier the particle, the less the light output

This can be explained as :
Higher ionizing power, higher density of excited molecules, more quenching interactions or better said, interactions that drain energy which would otherwise go in luminescence

For an electron

material	Energy loss (eV/scintillator photon)
anthracene	60
NaI	25
Plastic	100
BGO	300

Linearity of light output with energy

$$\frac{dL}{dx} = \frac{A\,\frac{dE}{dx}}{1 + kB\,\frac{dE}{dx}}$$

Light output per unit length

Table 7.4. Measured values of kB for NE102 plastic scintillator (from *Badhwar* et al. [7.8])

Particle	Energy [MeV/nucl.]	dE/dx [MeV/g cm^2]	kB [mg/(cm^2 MeV)]
Compton electrons and recoil protons	<4	>97	9.1±0.6
Compton electrons and alpha particles	<1.3	>272	9.8±0.8
Compton electrons and protons	1.2–14	>34	10±1
Recoil protons	<2.3	>150	10
Recoil protons	<8.4	>50	2
			3±1
Protons	<100	>7	3.7–7.5
Protons	28–148	5.5–20	13.2±2.5
Deuterons	23–60	10–23	
Nitrogen ions	3–9.5	$(1-2)\times10^3$	<10
Protons to oxygen ions	Rigidity 1.5–1.6 GV	2.0–120	10
Oxygen-iron nuclei	Rigidity 1.5–1.6 GV	120–1300	10 $C = -5\times10^{-6}$
Protons	36–220	4.2–12.3	12.6±2.0
^{4}He	38–220	17–49	7.2±1.0
Carbon nuclei	95	265	7.8
Oxygen nuclei	105	550	$C = -7\times10^{-6}$

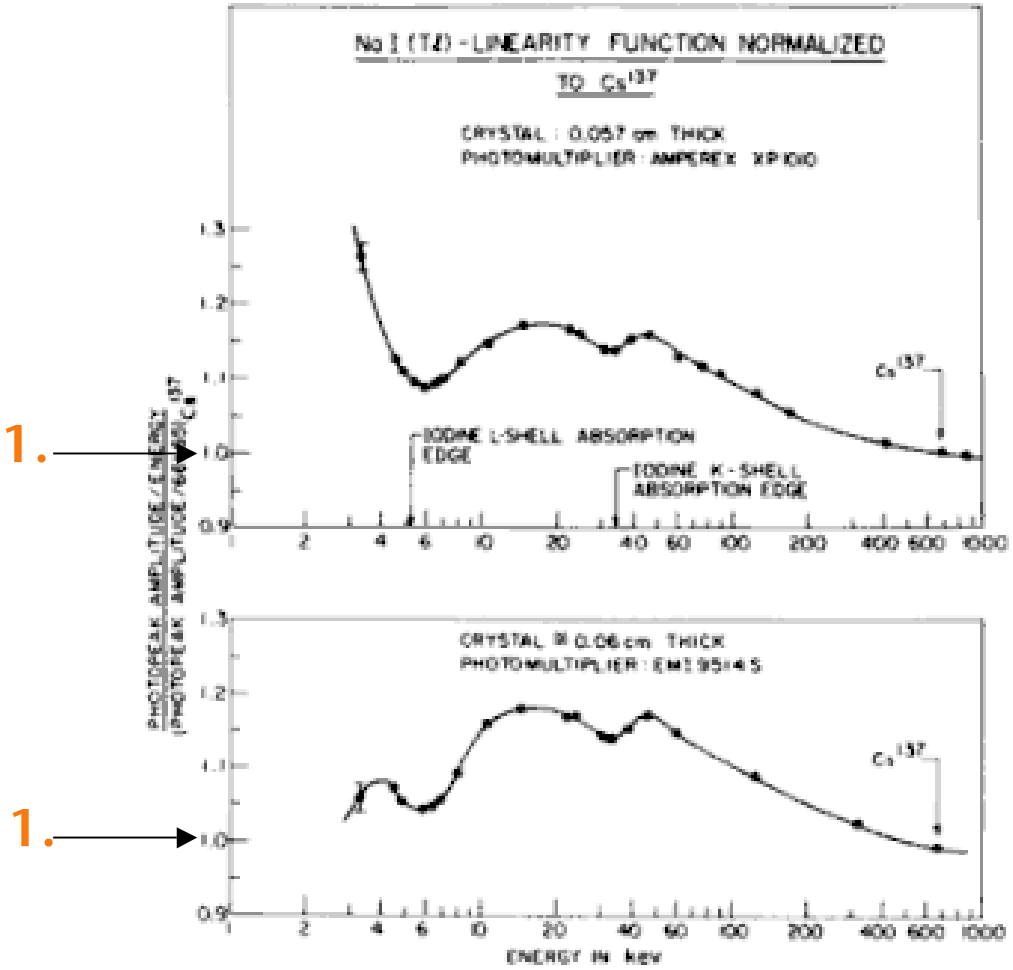
with A: absolute scintillation efficiency; kB: parameter relating the density of ionization centers to dE/dx.

In organic material, non linearities for electrons
are observed at 150 KeV and lower.
For heavier particles, deviations are more pronounced and become very noticeable at lower energies, with the higher ionizing particles showing the largest deviations

In inorganic crystals
linearity is mantained down to
400 KeV and also for energies
lower than that, deviations are
small

-> inorganic scintillators provide
very good energy resolution

See our radiactive source
detector downstairs



Intrinsic detection efficiency for various incident particles

For a given radiation and scintillator, not always usable light signal is produced efficiently. One should consider

1. Mechanism of interaction of radiation with molecules of scintillator material
2. probability for these interactions to happen in the scintillator volume
3. response in light output

2. Is given by the mean free path of the radiation in the scintillator material

Heavy ions

Scintillators are not good for detecting heavy ions, due to the reduced light output due to quenching effects, stronger for these higher ionizing particles

An alpha particle in plastic scintillator has 1/10 light output than an electron of the same energy

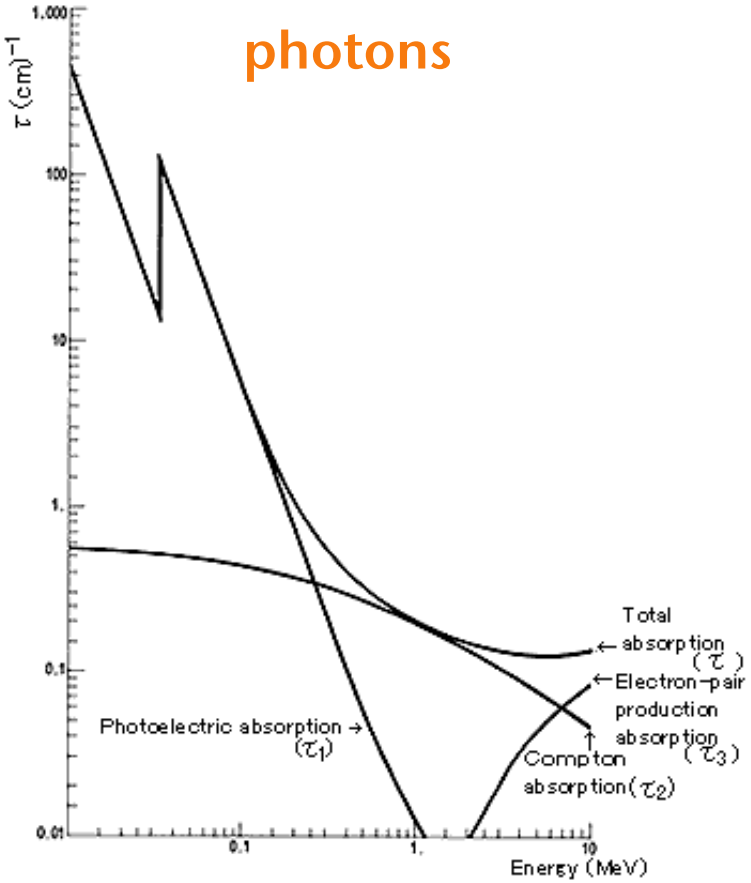
Inorganic scintillators are better, but still light output is 50-70% of that of electrons

Electrons

Efficiency is almost always 100%.
But, with increasing Z, backscattering prob. increases and electron will not manage to go through the scintillator
In NaI backscattering is 80%, while in plastic is 8%

At high E, inorganic crystals are much better, due to the stopping power. provide also very good energy resolution.

photons



The γ ray is the energy of an excited atomic nucleus emitted as photons. Its energy range, although it differs according to the state of excitement of the nucleus, covers from several keV to several MeV.
It is created by high-speed electron radiation, and reactions with materials can be divided into three basic effects: photoelectric effect, compton effect, and electron-pair production.
Number I after I0 γ ray has passed over d cm can be given as $I=I_0e^{-\tau.d}$ and transmission T is given as $T=e^{-\tau.d}$.
Here, τ is called the linear absorption coefficient, and is expressed as $\tau=\tau_1+\tau_2+\tau_3$.
It indicates absorption coefficient for the photoelectric effect, compton effect, and electron-pair production.
The chart indicates the absorption coefficient of the NaI(Tl).

Compton scatt.
~ Z

PE and pair prod.
~ Z^5 and Z^2

By choosing a material with high Z one is sure to stop and detect photons (via the electrons/positrons produced in PE or pair production)

Inorganic scintillators are very good

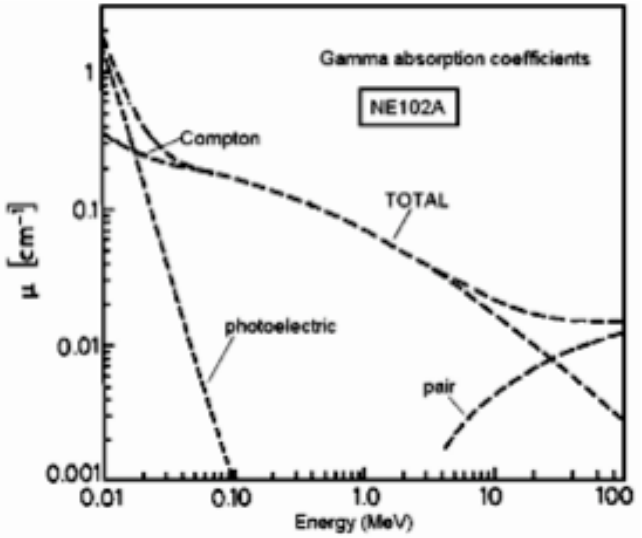


Fig. 1. Gamma ray absorption coefficients in NE102A plastic scintillator.

Exercise 1

Electrons with an energy $E = 3\,\mathrm{GeV}$ enter a CsI(Tl) calorimeter. In the following use the simplified model of an electromagnetic cascade introduced in the lecture.

a) How large is the critical energy E_c of CsI(Tl)?

b) What is the number of charged particles in the shower at a depth of 4 cm.

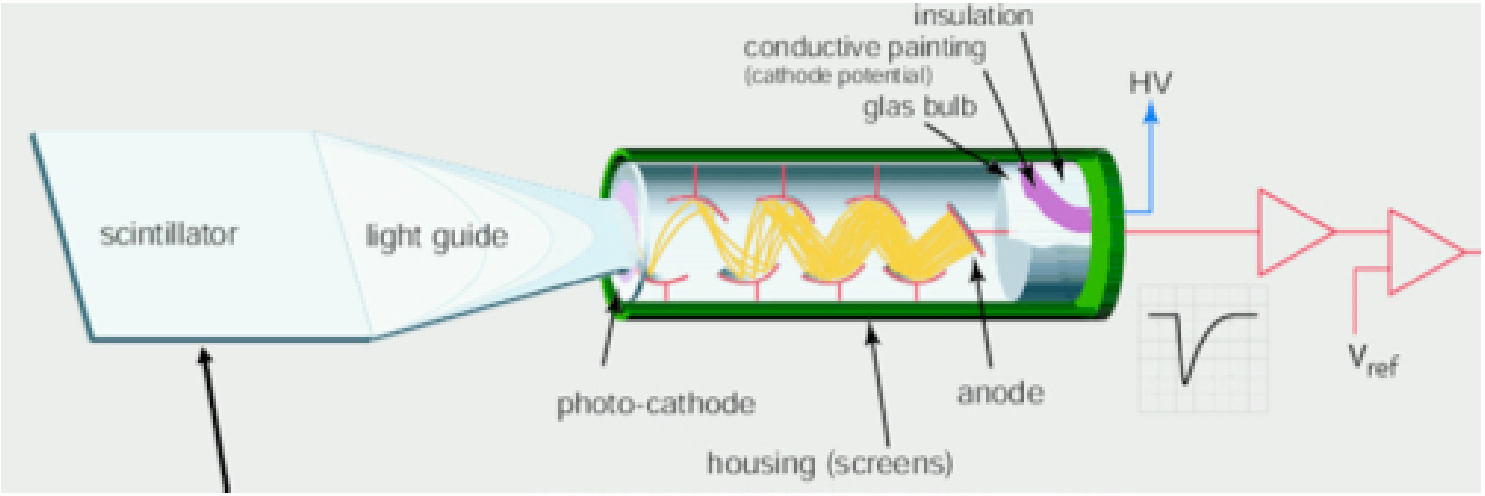
c) How large is the average particle energy at that depth?

d) How large is the maximum number of particles present in the shower?

e) Where does the shower reach its maximum?

Photomultipliers

(W.Leo, page 169-192, D.Green pages 44-50)



Cathode of photosensitive material. Light guided into PhotoMultiplier Tube (PMT) cathode and by photoelectric effect will produce electrons.

An electron multiplier system, made of dynodes, follows. Avalanche is created.

The final signal of electrons is collected on the anode.

Evacuated glass tube

Photocatode: semiconducting alloy containing Na, K or Cs.

Quantum Efficiency (QE)= number of photoelectrons released

$$\frac{\text{number of photoelectrons released}}{\text{number of incident photons on cathod}(\lambda)}$$

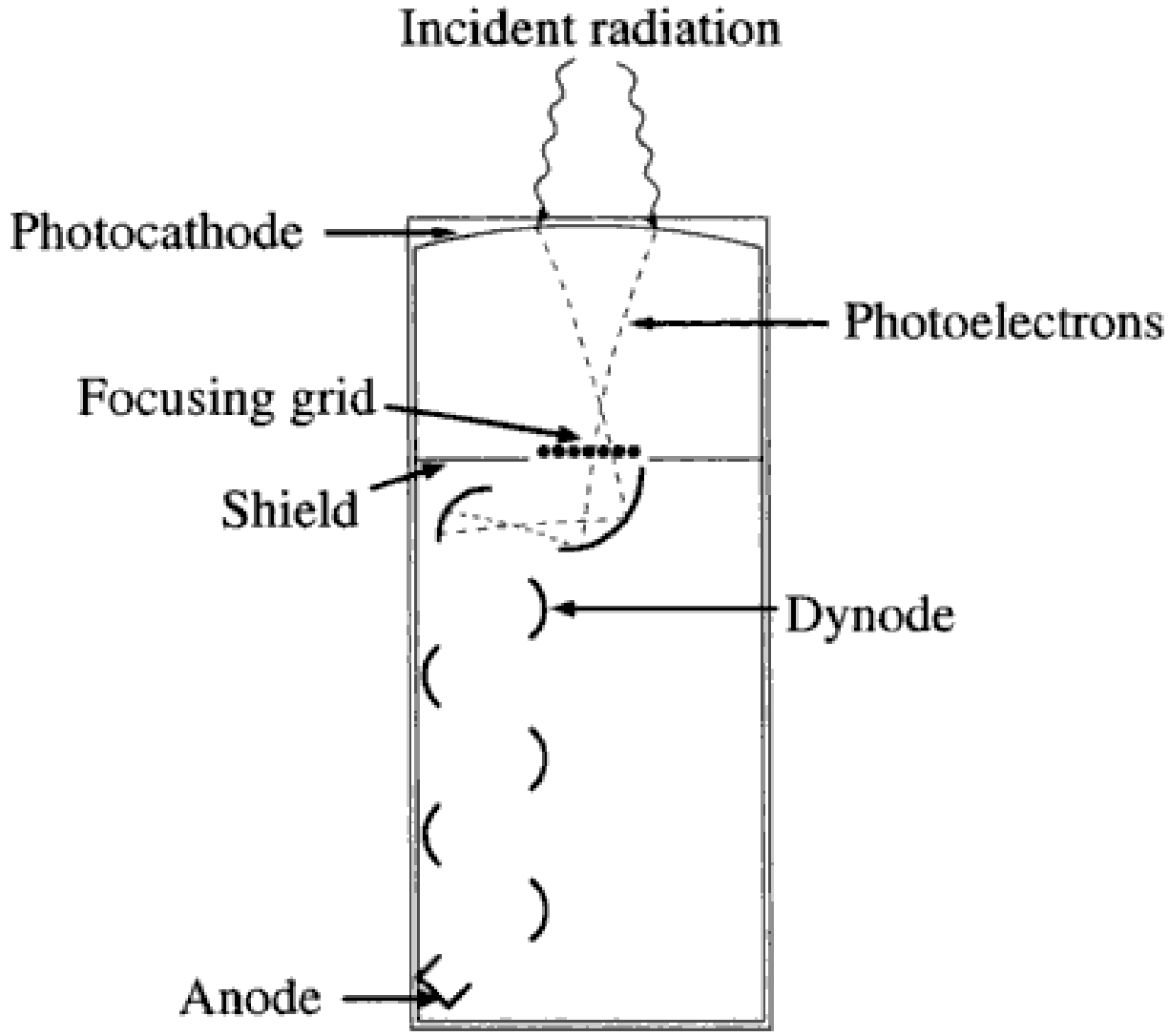
λ= wavelength of incident light

E=hv - W, W=work function

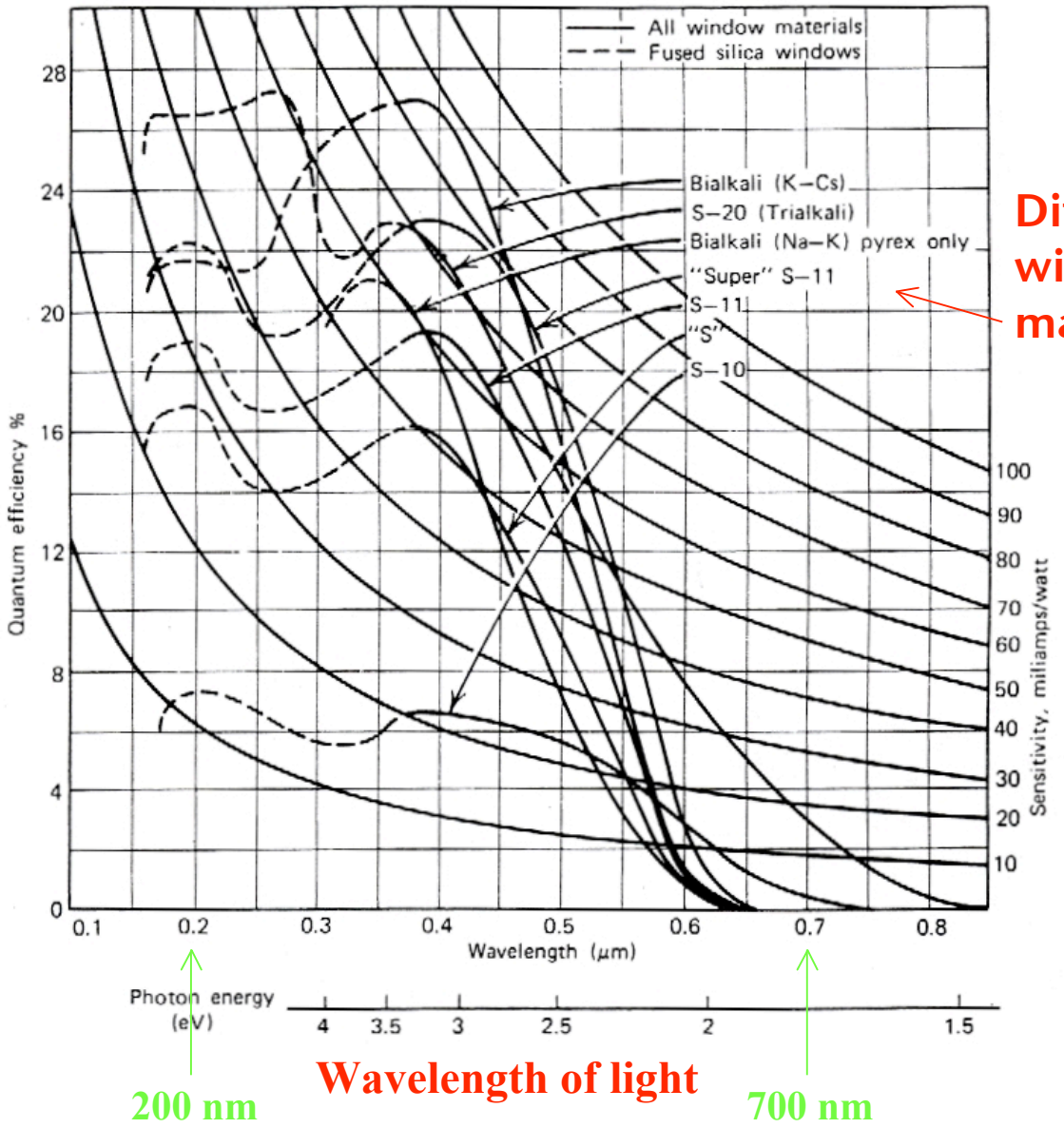
e.g. for photocathodes of bialkali, at λ=380 nm , QE = 27% , tipical

Photoelectrons are then accelerated onto an electrode made of material of high cofficient of secondary emission, eg. BeO
3-5 secondary electrons per incident electron of 100 eV can be Achieved

PMT with 14 dynodes mantained at 150-200V potential difference between stages, the multiplication is roughly 10^8
Charge of 10^{-11} C in 5 ns arrives at anode, and (50 Ohm resistor)
Voltage pulse is 200 mV, rise time 2 ns. Total cathode-anode = 40 ns


Incident radiation
Photocathode
Photoelectrons
Focusing grid
Shield
Dynode
Anode

Light transmission through entrance window



- Observe:
  - 20% transmission typical for 400 nm light
  - Fused silica extends transmission into lower wavelengths
  - Less than 400 nm is ultraviolet light

Spread in transit time in the photomultiplier = time jitter

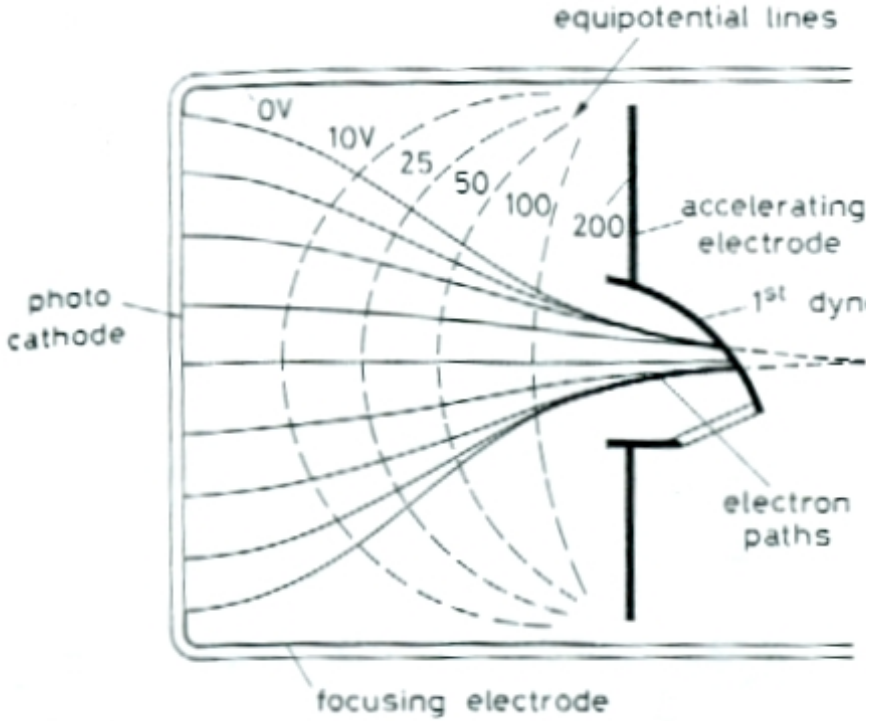
Varying time spent by the photoelectrons on their way
from cathode to first dynode. Two effects :

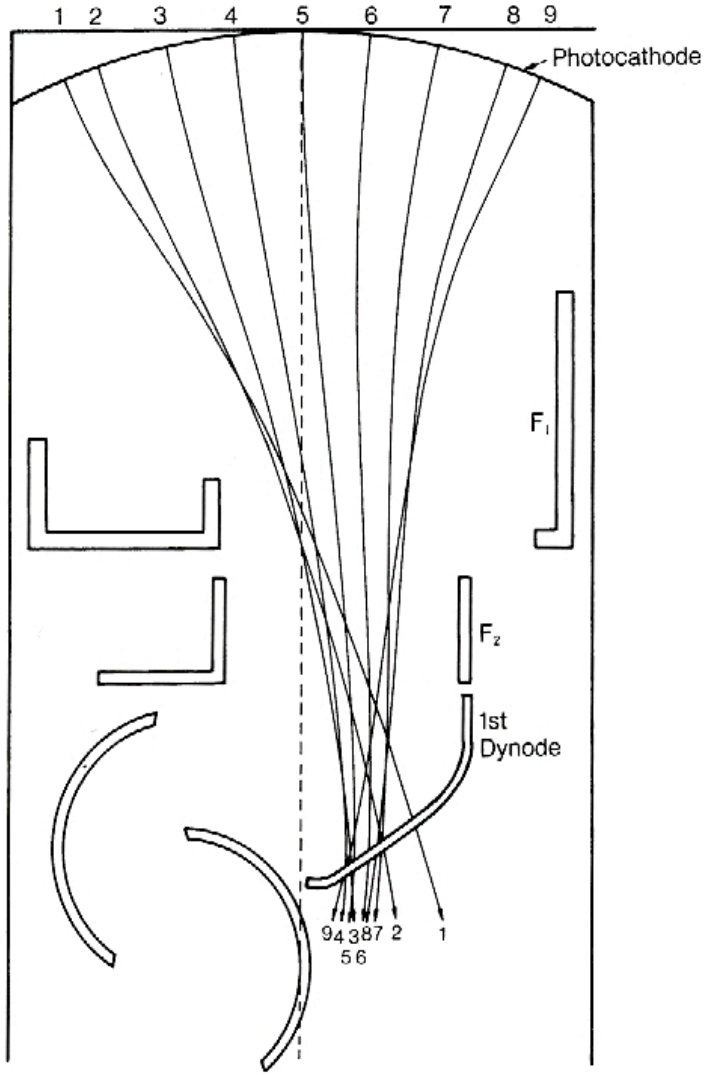
1. distribution in velocity in the electrons coming out of the cathode
2. distribution in path length from cathode to first dynode

More in details:
1. For a bialkali cathode (sensitive to light in 400-430 nm) spread in kinetic energy for photoelectrons is between 0 and 1.8 eV, peak at 1.2 eV

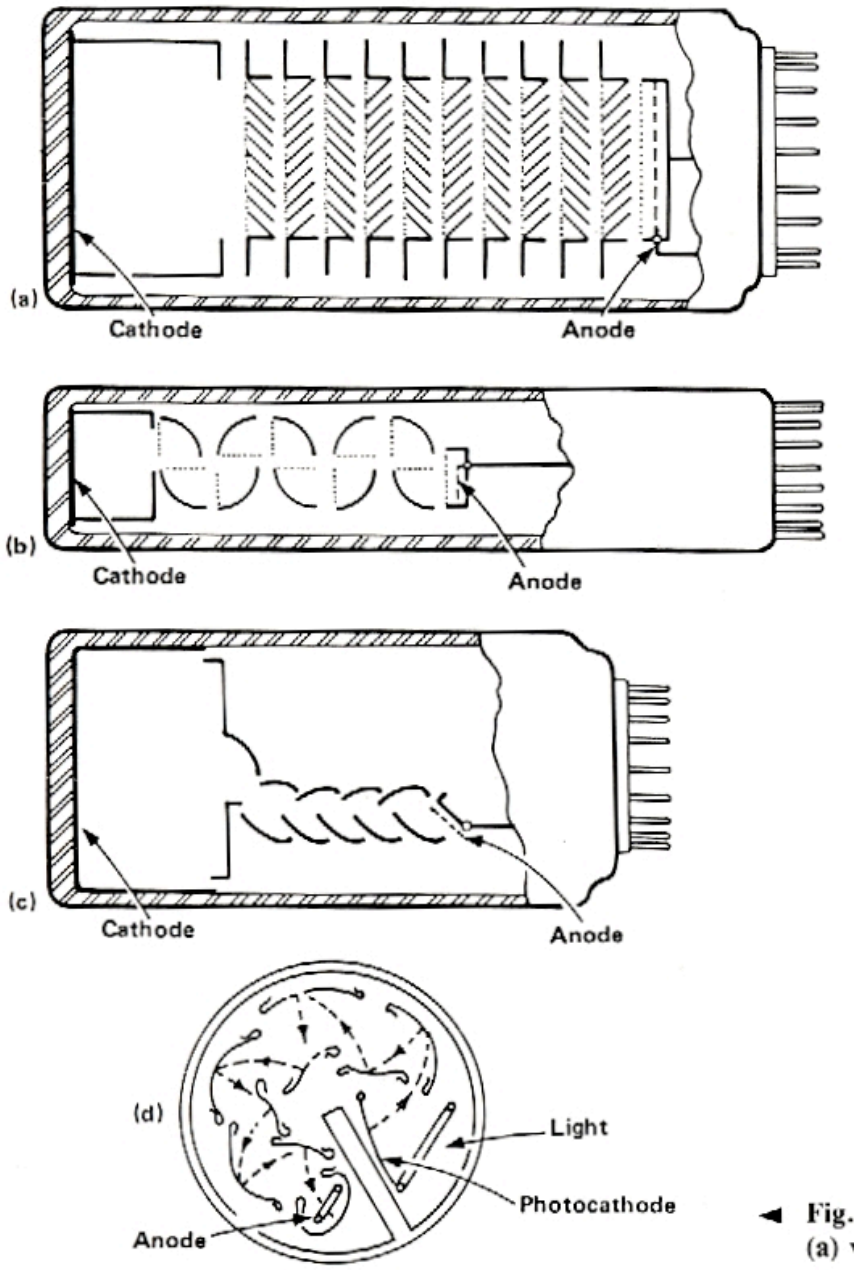
2. For an electric field of 150V/cm between cathode and first dynode,
t(kinetic energy=0) - t(kinetic energy=1.2eV) = 0.2 ns
Transit time difference
Geometry also can contribute , roughly same order of magnitude spread

Close-up of photoelectron trajectories to first dynode





Different types of dynode chain geometries



◄ Fig.
(a)

Usually PMT and scintillator slab are connected via a light guide

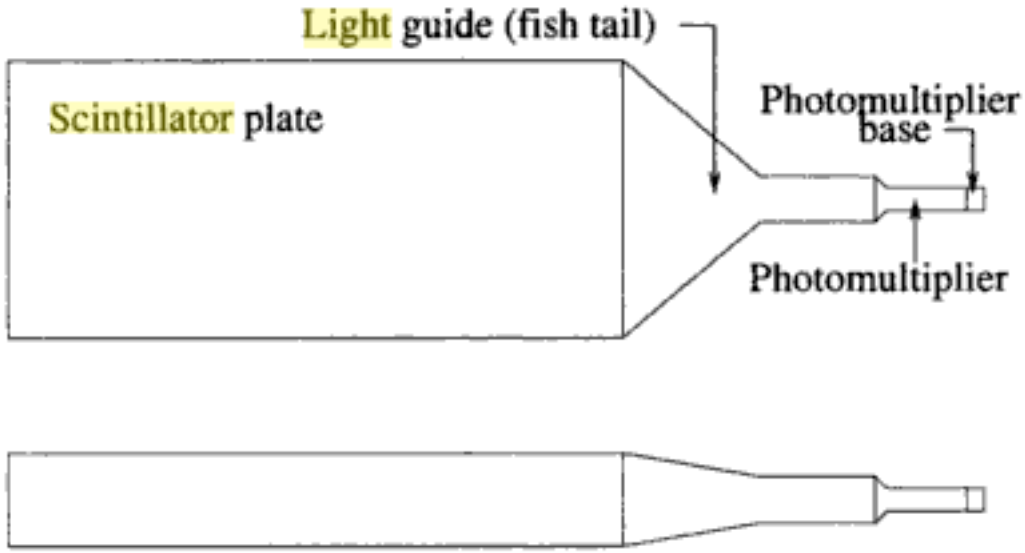
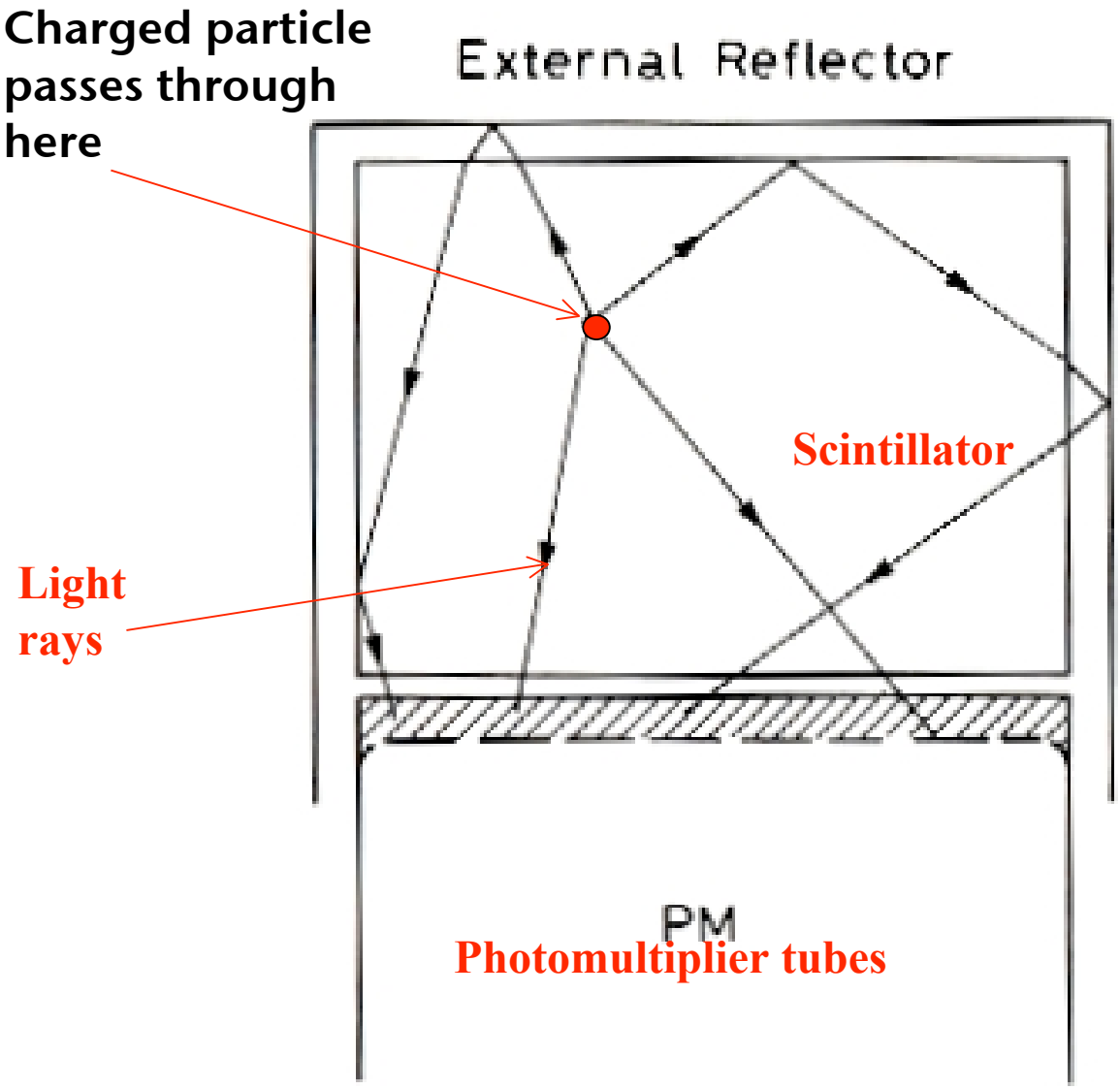


Fig. 4.9 Schematic view of a scintillator coupled to a photomultiplier via a *fish tail* light guide.

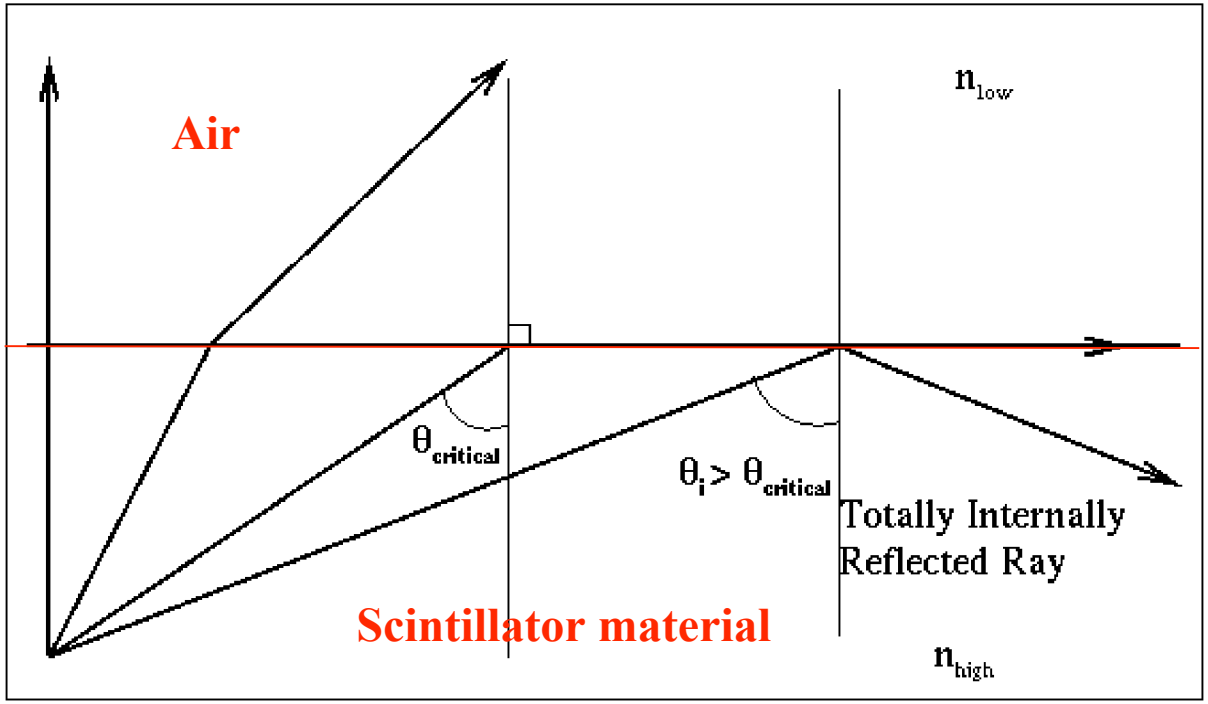
It allows the coupling of the photocathode (small area) to a scintillator with large cross section. Light goes from scintillator to PMT via total internal reflection.

Light emitted in scintillator gets reflected totally on surface if incident angle $\theta_c > \sin^{-1} 1/n$ (n= refractive index in scintillator)

Light transmission within scintillator



Reflection and transmission at surfaces



Light totally internally reflected for incident angle greater than $\Theta_{critical}$ which depends on optical properties of scintillator and air

If n=1.58 (typical for scintillator) then θ_c = 39 degrees

Then the fraction of light trapped is :

$f=1/2\ (1- 1/n) = 0.18$

Both scintillator and light guide are typically coated with aluminium foil to prevent leak of light, and then also by black tape to prevent outside light to leak in the detector

Geometrical constraints force bending of the light guide (which sometimes is just a bunch of fibers) to allow coupling to PMT.
Maximum bending before important loss of light occurs (liouville law) :

$n^2 -1 >= (d/2r + 1)^2$ should be satifisfied for having total internal reflection.

Basically the light pipe must have an area which does not diminish.
d =diamater of light guide window, r =bending radius, n=rifr. index

Wavelength shifting:

Alternative solution to light guide.

Using a fiber that takes scintillation light and shifts it to longer wavelengths, and by total internal reflection pipes it into the PMT

One can reduce area also by factor 10^4

This does not violate Liouville Law because the light has been shifted to longer wavelengths, less energetic light.
It has been “cooled down”, and therefore can be forced to occupy a smaller area

Exercise 2

The passage of charged particles through organic scintillators creates about 10^4 photons per MeV of deposited energy. A light guide routes these photons to a photocathode connected to a photomultiplier. Assume that 1% of all photons reach the photocathode and that its quantum efficiency in the relevant wavelength region is 25%.

What is the required thickness of the scintillator that a minimally ionizing particle is registered with a probability of $> 95\%$?

Typical dE/dX in organic scintillator is 2 MeV/cm

I also know in organic scintillator typical photon emission due to scintillation is 10^4 photons / MeV

So in *x* cm I expect ($2\ 10^4\ x$) photons produced. Now 1% loss in light guide and 25% loss in cathode gives ($50\ x$) electrons produced at the photocathode on average.

Counts (electrons detected) are distributed according to Poisson probability . Average is $(50\ x)$, P(n counts) = $(50x)^n e^{-(50x)} / n!$

I want to find *x* such that
P (n counts>0) = probability of at least 1 electron detected when average is $(50\ x)$ = 1 - P(n counts=0) = $1- e^{-(50x)} > 0.95$

This gives $(50\ x) >= 3$, so $x >= 3/50 = 0.06$ cm