Detector Physics

Scintillation Detectors

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Outline

- Scintillation Detectors
  - Organic v. inorganic crystals
  - Detection efficiency
  - Light output response
- Photomultiplier Tubes
  - Photocathodes
  - Electron optics
  - Charge multiplication/dynodes

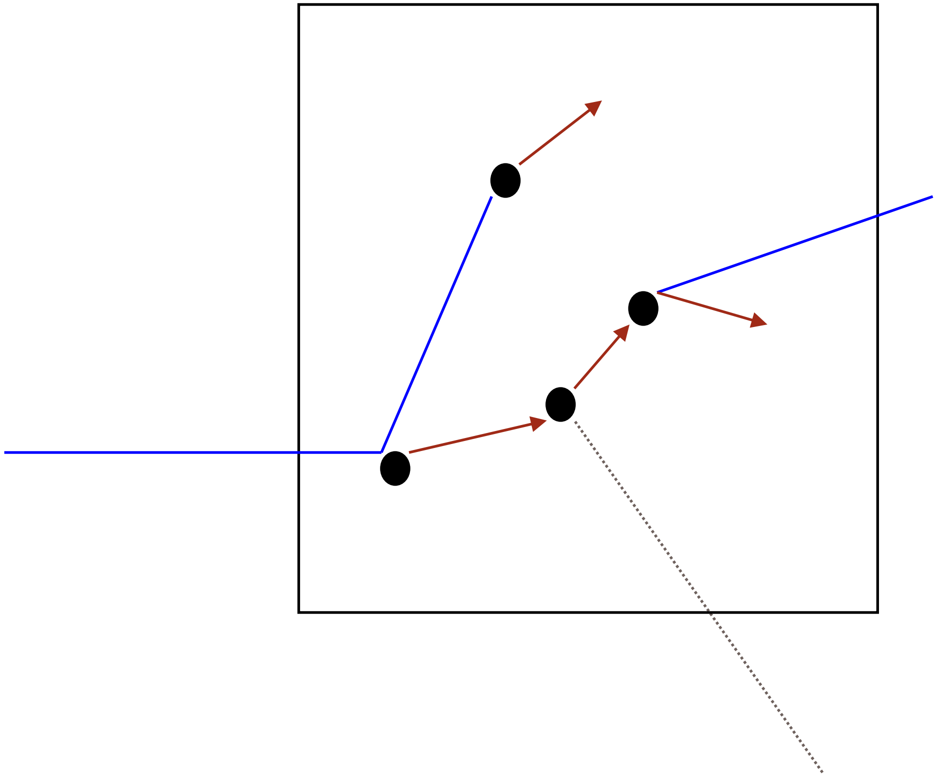
From semiconductors to scintillators

- Similarities:
  - Takes advantage of the increased density of crystal lattices
  - Makes use of band gap energies
  - Doping lowers the energy required for a measureable interaction
- Differences:
  - Whereas scintillators re-radiate the energy absorbed as photons, semiconductors “move” electrons.

Scintillators

- Ionizing radiation ionizes and/or excites the matter it passes through.
- When the excited matter returns to g.s. in some materials γ's are in the visible range.
  - Radioluminesence
- The most efficient materials for visible γ generation are called *scintillators*.
- If light emission continues for > 1 ms
  - Phosphor

Energy Collection



- Counters need only note that some energy was collected.
- For calorimetery the goal is to convert the incident energy to a proportional amount of light.
  - Losses from shower photons
  - Losses from fluorescence x-rays

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Photon Statistics

Typical Problem

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

Answer

- The total energy of scintillation is 450 x 0.12 = 54 keV.
  - $5.4 \times 10^4 / 2.8 = 1.93 \times 10^4$ photons produced
  - $1.93 \times 10^4 \times 0.15 = 2900$ photoelectrons produced
- The equivalent W-value for the scintillator is:
  - 450 keV/2900 = 155 eV/pe
  - W-value in gas = 30 eV/ip

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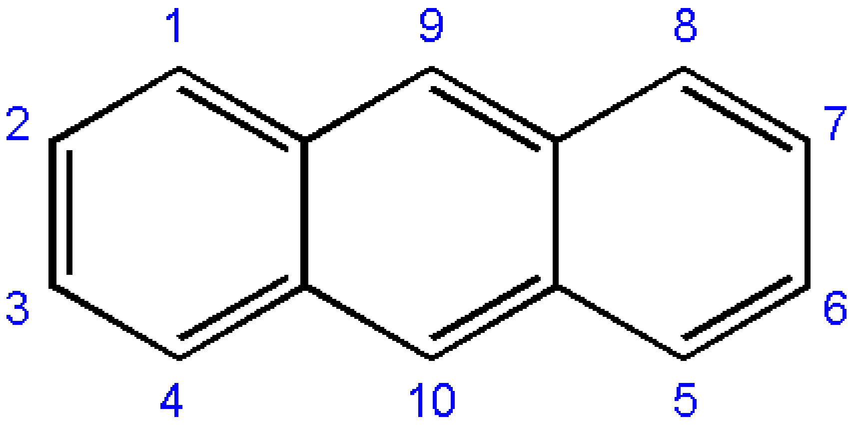
Good Scintillator Requirements

- High efficiency γ production.
- Transparent to the λ of the emitted γ.
  - $n \sim 1.5$
- τ should decay quickly and with minimal delay.
- $N_\gamma \propto E$
- Pulse shape discrimination
- Cheap would be nice

Organic Scintillators

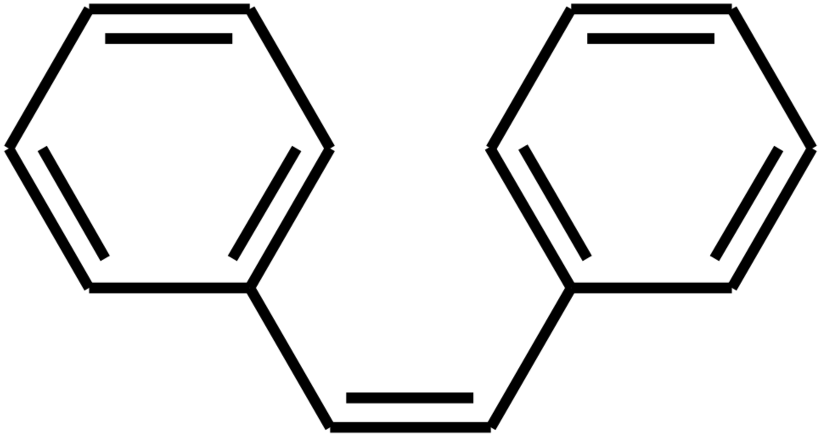
- Made of linked or condensed benzene structures.
    - Tend to be expensive.
- Liquid scintillator made by dissolving material in solvent
- Plastic scintillators radiate UV
    - Cheaper
    - Wavelength shifters (flour) required

Anthracene



https://en.wikipedia.org/wiki/Anthracene

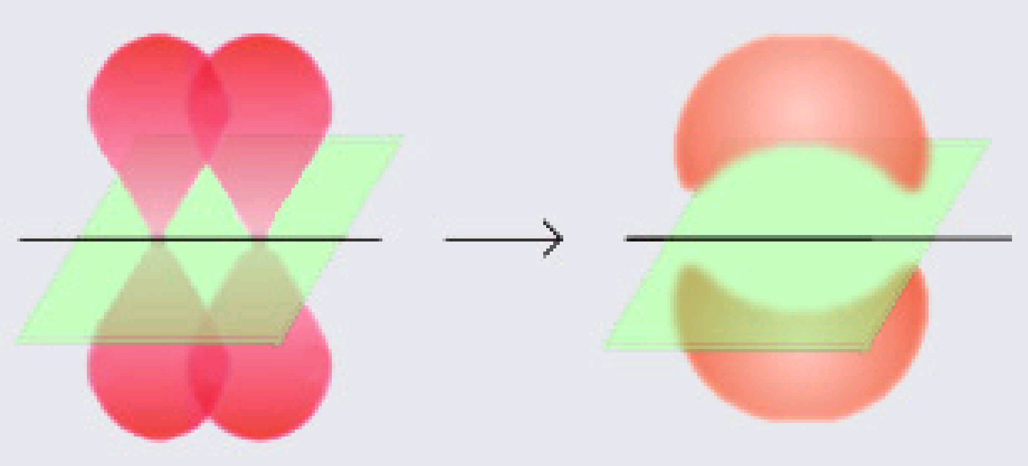
Stilbene



https://en.wikipedia.org/wiki/(Z)-Stilbene

Pi-Bonds

- Carbon in molecules has one excited electron.
  - G.S. $1s^2 2s^2 2p^2$
  - Excited $1s^2 2s^1 2p^3$
- Hybrid p-orbitals are π-orbitals.
  - Overlapping π-orbitals form bonds
  - Appears in double bonds



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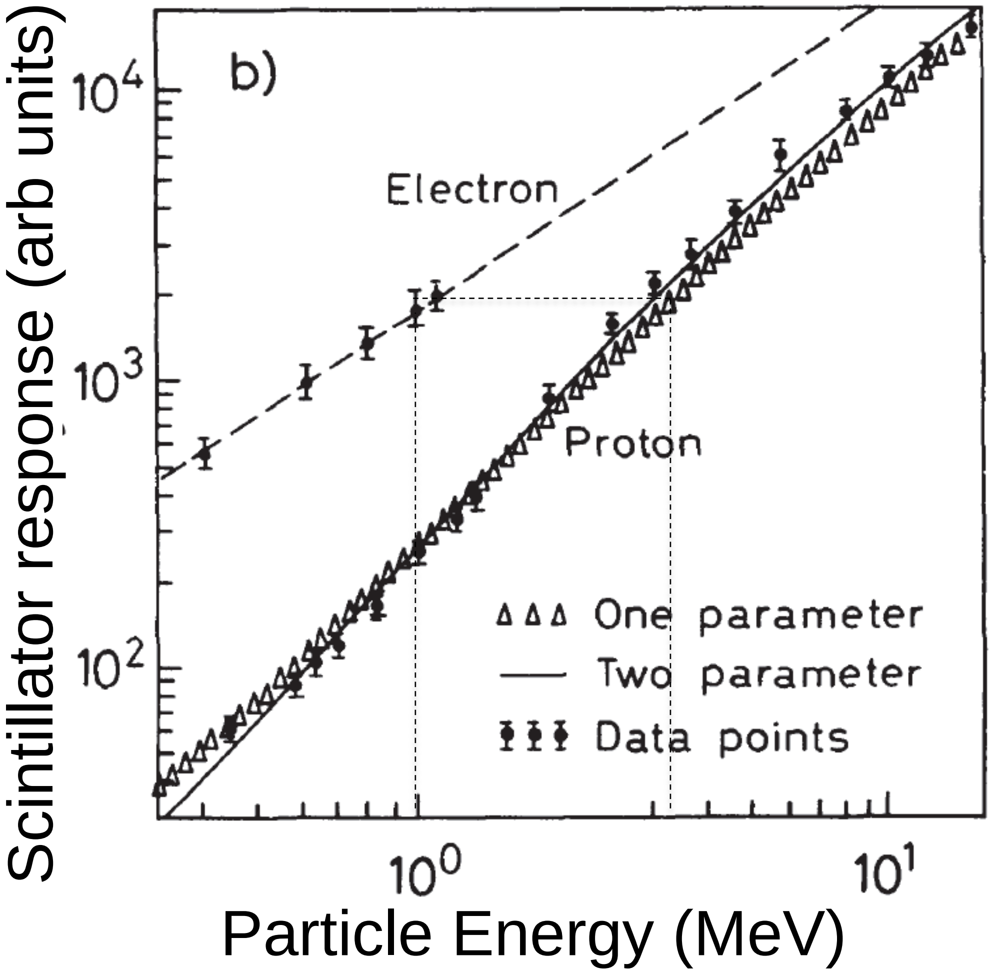
Organic scintillator response

- Above 125 keV e^- response is linear
- Proton/heavy particle always has a lower response
- MeV electrons equivalent (MeVee)
    - 1 MeV e^- → 1 MeVee
    - >2 MeV p → 1 MeVee

NE-102



Organic scintillator response

$$\frac{dL}{dx} = S\,\frac{dE}{dx}$$

Flourescent energy/unit path length

Normal scintillation efficiency

Energy loss/unit path length

Organic scintillator response

$$\frac{dL}{dx} = S\frac{dE}{dx}$$

To account for the probability of quenching:

Normalization parameter

$$\frac{dL}{dx} = \frac{S\dfrac{dE}{dx}}{1 + \underbrace{kB}\dfrac{dE}{dx}}$$

Birk's formula

Experimentally derived

Organic scintillator response - electrons

$$\frac{dL}{dx} = S\frac{dE}{dx}$$

To account for the probability of quenching:

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

For high-E e$^-$, dE/dx is small

$$\left.\frac{dL}{dx}\right|_e = S\frac{dE}{dx} \text{ or } \left.\frac{dL}{dE}\right|_e = S$$

The light output is linearly related to E

$$L \equiv \int_0^E \frac{dL}{dE}\,dE = SE$$

Organic scintillator response – α's

$$\frac{dL}{dx} = S\frac{dE}{dx}$$

To account for the probability of quenching:

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

For α's, $dE/dx \gg 1$

$$\left.\frac{dL}{dx}\right|_{\alpha} = \frac{S}{kB}$$

$$kB = \frac{\left.\frac{dL}{dE}\right|_{e}}{\left.\frac{dL}{dx}\right|_{\alpha}}$$

Organic Scintillators

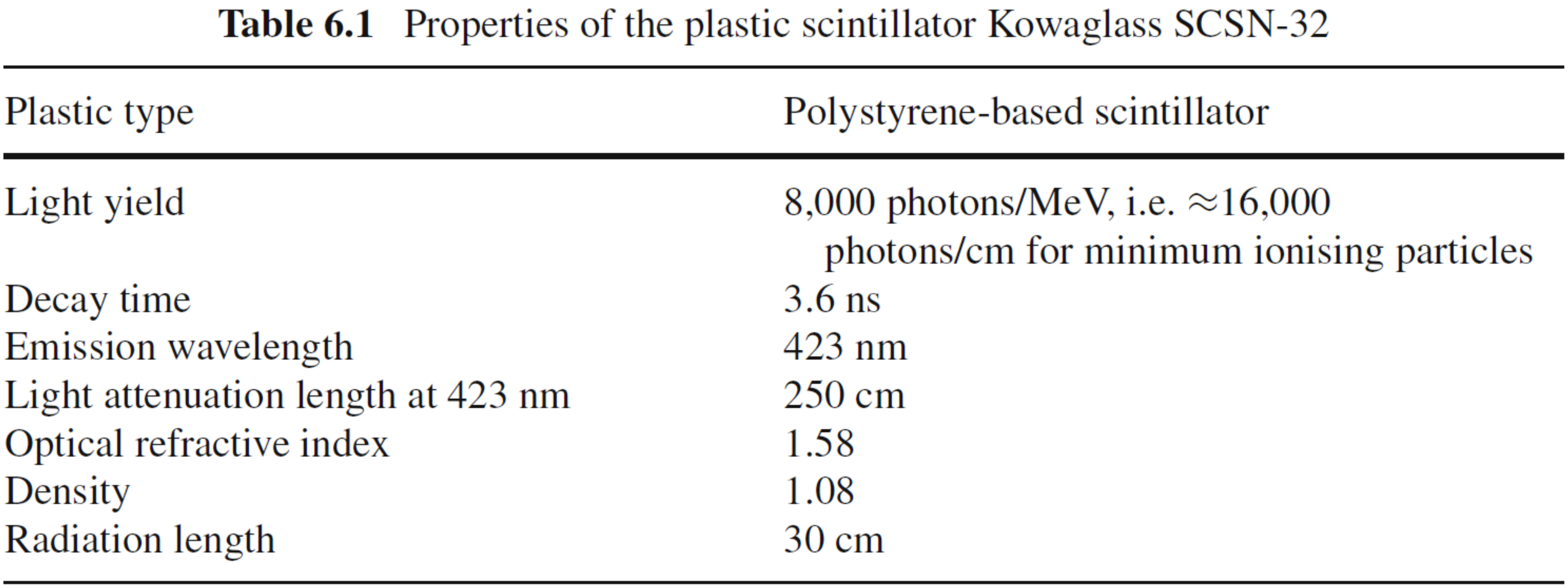
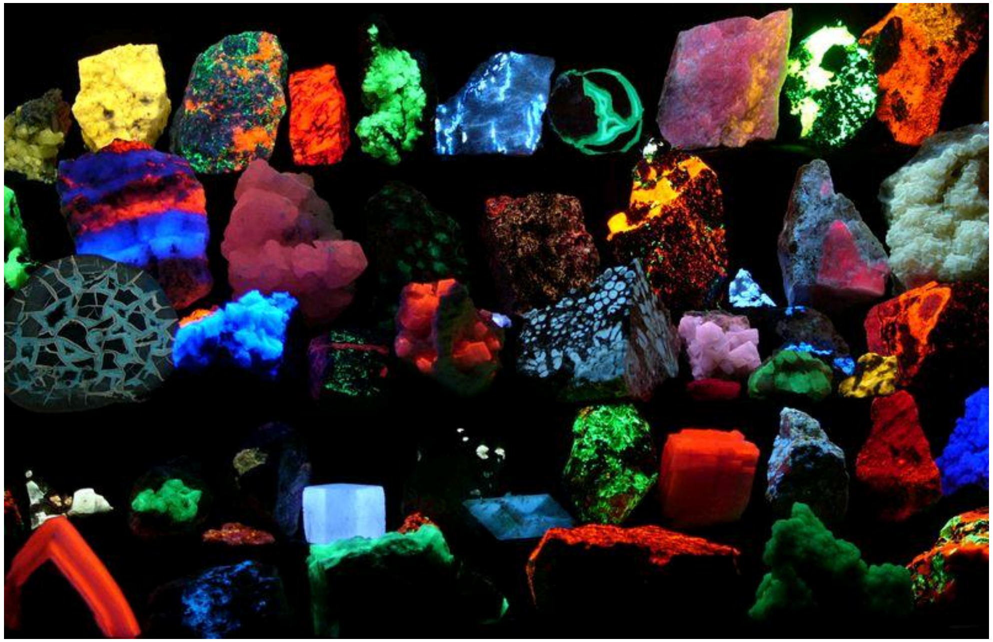


Table 6.1 Properties of the plastic scintillator Kowaglass SCSN-32

Plastic type	Polystyrene-based scintillator
Light yield	8,000 photons/MeV, i.e. ≈16,000 photons/cm for minimum ionising particles
Decay time	3.6 ns
Emission wavelength	423 nm
Light attenuation length at 423 nm	250 cm
Optical refractive index	1.58
Density	1.08
Radiation length	30 cm

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



- Higher density = More interaction = More efficient

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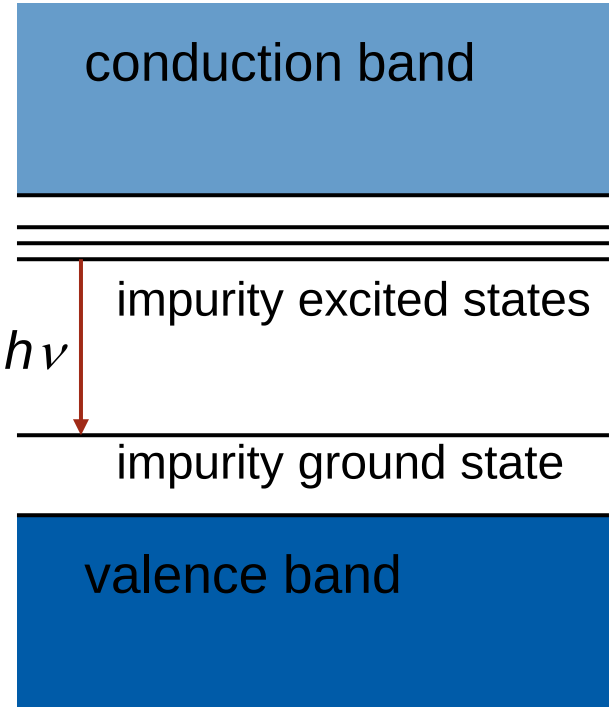
Band Structure



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

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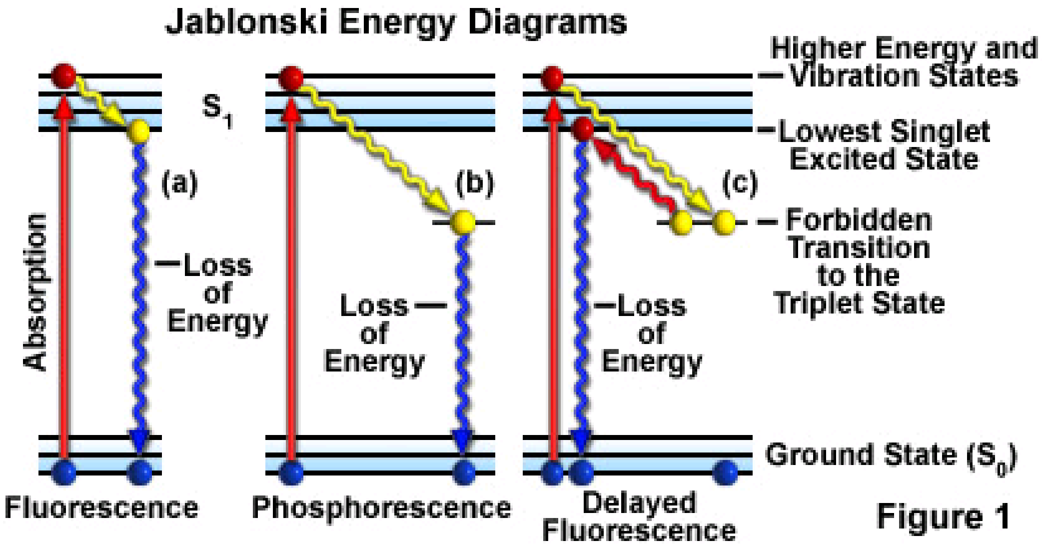
Jablonski Diagram

- Jablonski diagrams characterize the energy levels of the excited states.
  - Vibrational transitions are low frequency
  - Fluorescence and phosphorescence are visible and UV
- Transitions are characterized by a peak wavelength λ_{max}.



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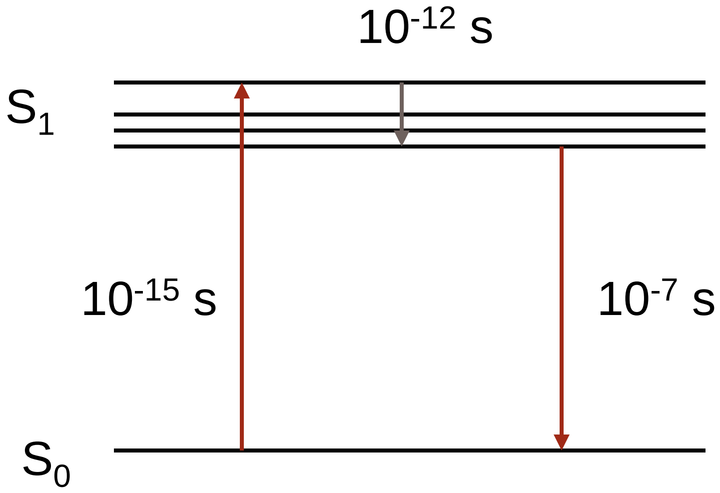
Time Lag



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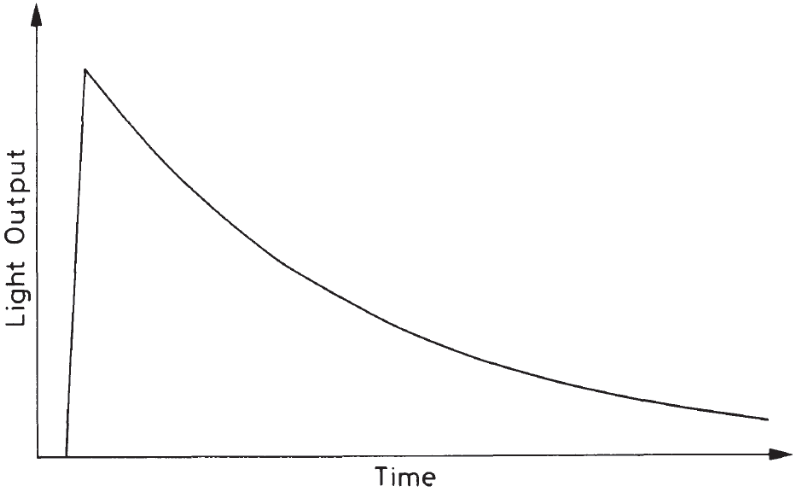
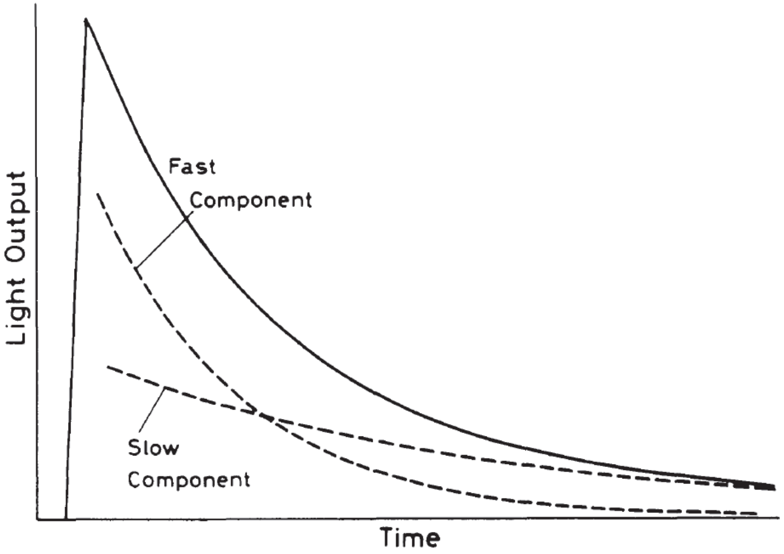
- Fluorescence typically involves three steps.
  - Excitation to higher energy state.
  - E loss through change in vibrational state
  - Emission of fluorescent photon.
- The time for 1/*e* of the atoms to remain excited is the characteristic time τ.

Decay Constant (τ_d)

$$N = \frac{N_0}{\tau_d} e^{-t/\tau_d}$$



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



Crystal Specs

- Common crystals are based on alkali halides
  - Thallium or sodium impurities
- Fluorite (CaF_2) is a natural mineral scintillator.
- (BGO, $Bi_4Ge_3O_{12}$) is popular in physics detectors.

Crystal	τ (ns)	λ_{max} (nm)	Output (nm)
Na(Tl)	250	415	100
CsI(Tl)	1000	550	45
CsI	16	315	5
ZnS(Ag)	130	110	450
CaF_2(Eu)	930	435	50
BGO	300	480	20

www.detectors.saint-gobain.com

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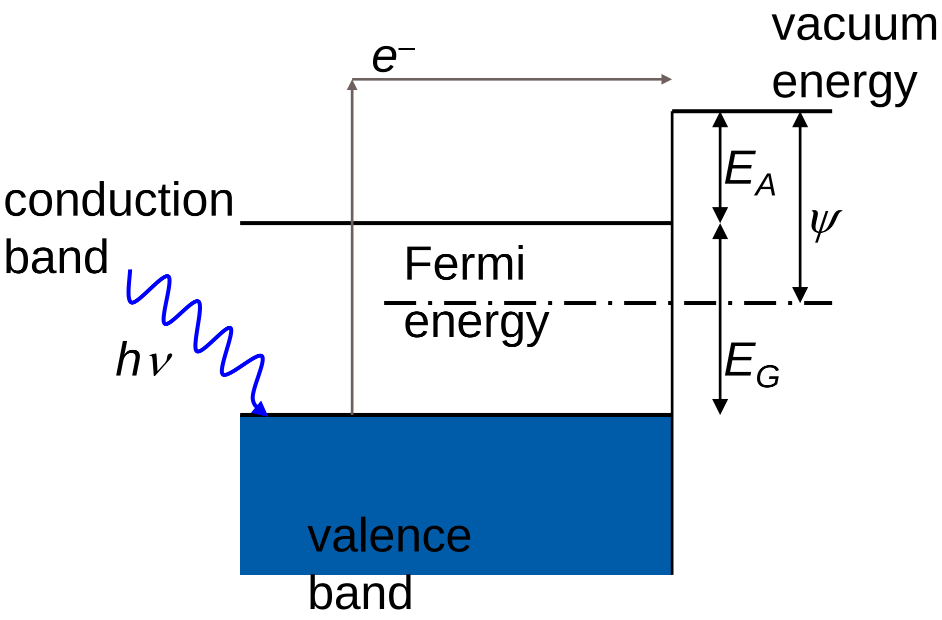
What can we do with photons

- The radiation that interacts with the scintillator generates photons.
- We can't count photons.
- We can manipulate them.
    - Light guides can reflect and transmit photons at near 100% efficiency.
- We can send them into materials to generate predictable behavior.

Photocathodes

Photoelectron Emission



- Counting photons requires conversion to electrons.
- The photoelectric effect can eject electrons from a material into a vacuum.
  - Exceed gap energy E_g and electron affinity energy E_A
  - Compare to work function ψ

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Quantum Efficiency

- There is a probability that a photon will produce a free electron.
  - Depends on bulk material properties & atomic properties
- This is expressed as the quantum efficiency $\eta(\nu)$.

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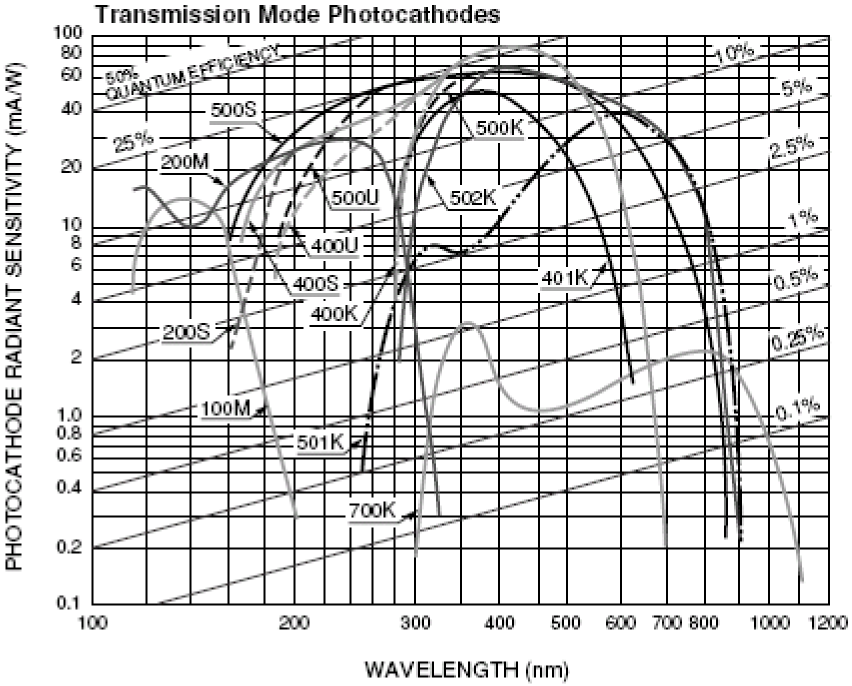
- Reflection coefficient R
- Photon absorption k
- Mean e escape length L
- Probability to eject from surface P_s
- Probability to reach vacuum energy P_V

$$\eta(\nu) = (1 - R)\frac{P_s P_V}{k + \frac{1}{L}}$$

Commercial Photocathodes

- Different photocathodes vary in response to ν and $\eta(\nu)$.
  - Alkali for UV detection (Cs-I, Cs-Te)
  - Bialkali for visible light (Sb-Rb-Cs, Sb-K-Cs)
  - Semiconductors for visible to IR (GaAsP, InGaAs)



Hamamatsu.com

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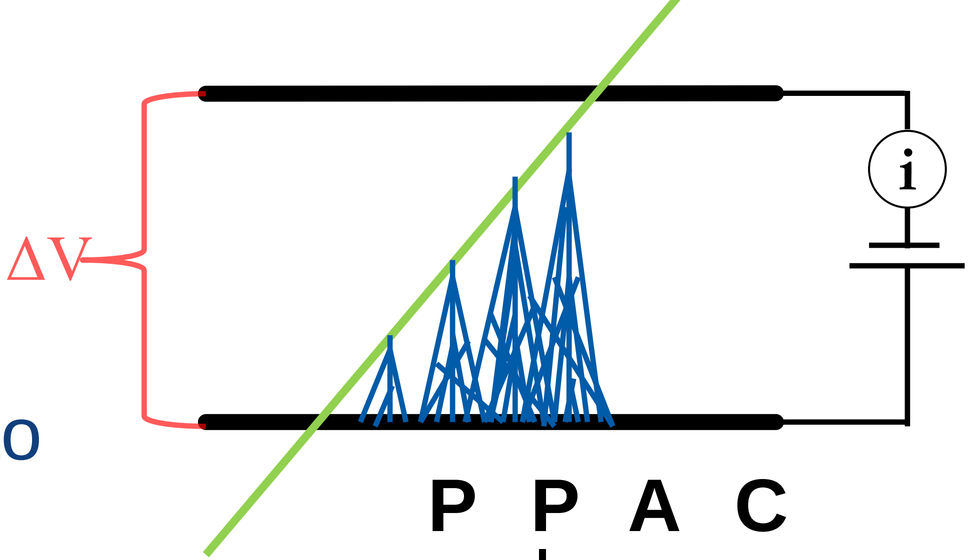
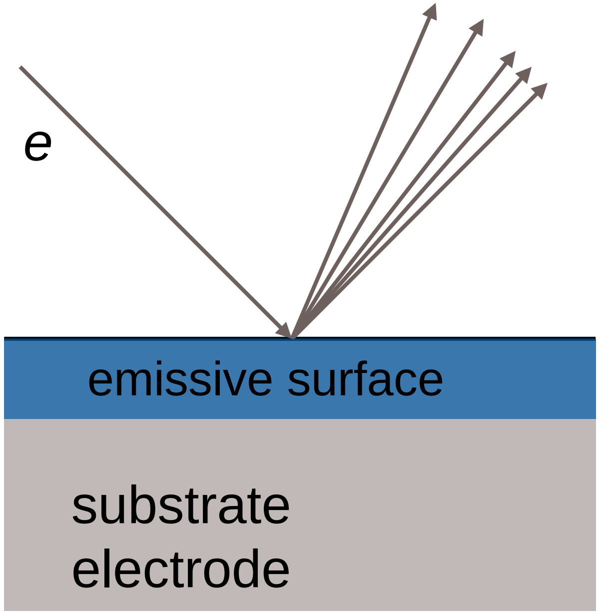
Challenge:

- Single electrons are hard to detect. What to do?
- Stronger Field
  - Gives electrons more energy
  - If the electrons have enough energy to ionize along their path
- Constant E-field so avalanche everywhere



Parallel **P**late **A**valanche **C**ounter

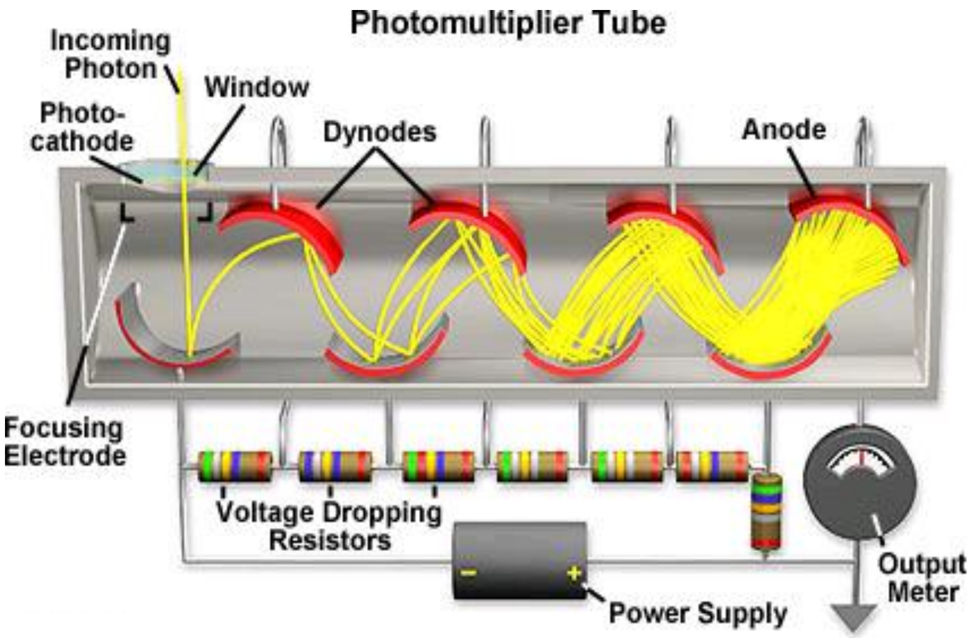
Electron Multiplier



- Electrons can be multiplied by interaction with a surface.
  - Emitter: BeO, GaP
  - Metal substrate: Ni, Fe, Cu
- This electrode is called a **dynode**.

Photomultiplier Tube (PMT)

- PMTs combines a photocathode and series of dynodes.
- High voltage is divided between the dynodes.
- Output current is measured at the anode.
    - Sometimes at the last dynode



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Gain (δ)

- δ depends on the material and V.
  - k typically 0.7-0.8
- Multiple dynodes are staged to increase gain.
  - Photocathode current I_{d0}
  - Input stage current I_{dn}
- Total gain is a product of stage gain.
  - Collection efficiency α

$$\delta = aE^k$$

$$I_{dn} = \delta_n I_{d(n-1)}$$

$$I_{out} = I_{d0}\alpha\delta_1\delta_2 \dots \delta_n$$

$$\mu = \frac{I_{out}}{I_{do}} = \alpha\delta_1\delta_2 \dots \delta_n$$

$$\mu \cong \alpha\left[a\left(\frac{V}{n+1}\right)^k\right]^n = AV^{kn}$$

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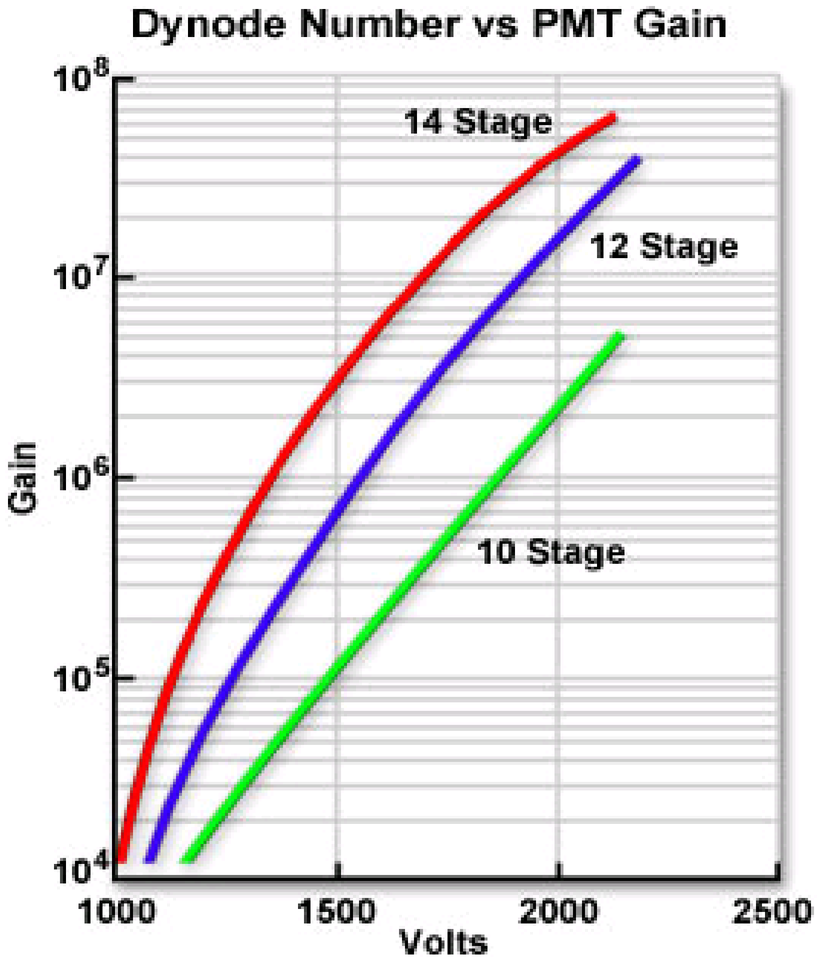
Amplifier



- Photomultiplier tubes often have 10-14 stages.
  - Gain in excess of 10^7
- A single photon can produce a measurable charge.
  - Single photoelectron
  - $Q_{\mathrm{pe}} \sim 10^{-12}$ C
- Fast response in about 1 ns.
  - $I_{\mathrm{pe}} \sim 1$ mA

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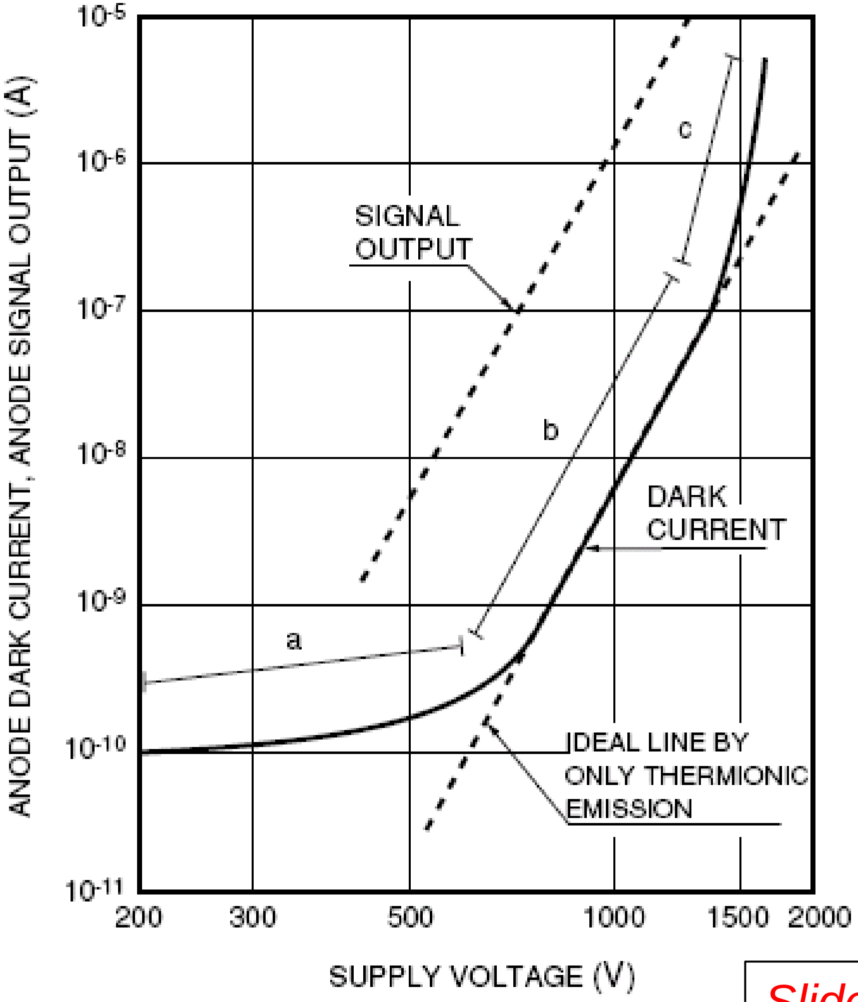
Dark Current



- Phototubes have “dark” current even with no incident light.
  - Thermionic emission
  - Anode leakage
  - Case scintillation
  - Gas ionization
- This increases with applied voltage.

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Thank you!
Merci

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