Radiation Detection and Measurement

Lecture 16

Chapter 7: Scintillation Detection Principles

Properties of the ideal scintillation material

- High efficiency of converting the kinetic energy of charged particles into light (detectable)

- the conversion of KE to light should be linear

- the medium should be transparent to the wavelength of its own emission for good light collection

- the decay time of the induced luminescence should be shoot so fast signal processing can be generated

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Properties of the ideal scintillation material

- the material should be of good optical quality and subject to manufacture in sizes large enough to make practical detectors

- its index of refraction should be near that of glass (~1.5) to allow efficient coupling to a photomultiplier tube (or other light sensor)

- no material meets all these qualifications and in comparing organics to inorganics, the inorganics tend to have the best light output and linearity but slow in their response time

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# Properties of the ideal scintillation material

- Fluorescence : the prompt emission of visible radiation from a substance following its excitation by some means

- Phosphorescence: the emission of a longer wavelength than fluorescence with a characteristic time that is much slower

- Delayed Fluorescence: same spectrum as fluorescence but with a longer emission time following excitation.

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Organic scintillators

Scintillation Mechanism in Organics:

- Fluorescence stems from the transition in energy level structure of a single molecule

- Fig 8.1 shows the energy levels of an organic molecule with a π electronic structure, S_i foe i^{th} singlet state, T_i for i^{th} triplet state, 2nd subscript is notation for a vibrational state

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Organic scintillators
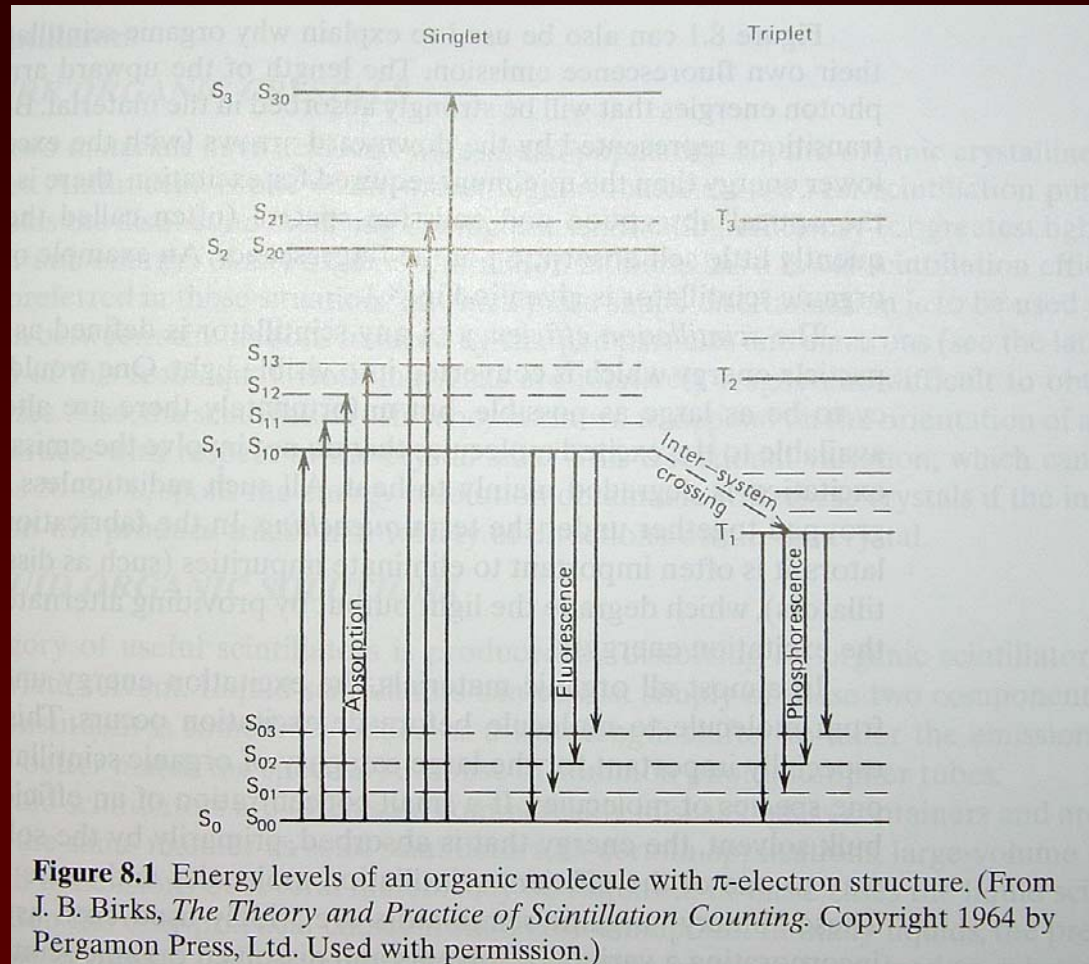
Figure 8.1 Energy levels of an organic molecule with π-electron structure. (From J. B. Birks, *The Theory and Practice of Scintillation Counting.* Copyright 1964 by Pergamon Press, Ltd. Used with permission.)

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- The energy difference , ΔE, between the S_0 and S_1 state is ~ 3-4 eV while the energy between vibrational modes ~ 0.15 eV

- General excitation above S_1 are internally converted (without radiation) and thus excited states tend to decay to S_1 quickly (~ pico second)

- The vibrational excitations quickly lose energy to surrounding molecules and the overall effect is an excitation to the S_{10} state

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Organic scintillators

- Light intensity from prompt fluorescence decays with time as , for organics $\tau \sim 10^{-9}$ s

- Phosphorescence occurs when inter- system crossing converts molecules in the singlet state to a triplet state where lifetimes are on the order of 10^{-3} sec

- Delayed fluorescence occurs when energy is absorbed in the triplet state and crosses to a singlet state where it de excites by fluorescence

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Organic scintillators

- Scintillation Efficiency : the fraction of all incident particle energy which is converted to visible light

- Quenching are any other radiation-less de excitations in the material, the majority of quenching is through heat

- Generally an efficient scintillation molecule is dissolved into a solvent making a binary organic scintillator. Here the energy is absorbed by the bulk of the solvent, where it then makes its way to the scintillator molecule

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Organic scintillators

- One can also add a tertiary component to absorb the light from the primary scintillator and emit light at a longer wavelength, these are called " wave shifters"

- Fig 8.2 shows a common absorption emission spectrum where there is little overlap between the two (stokes shift)

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Organic scintillators
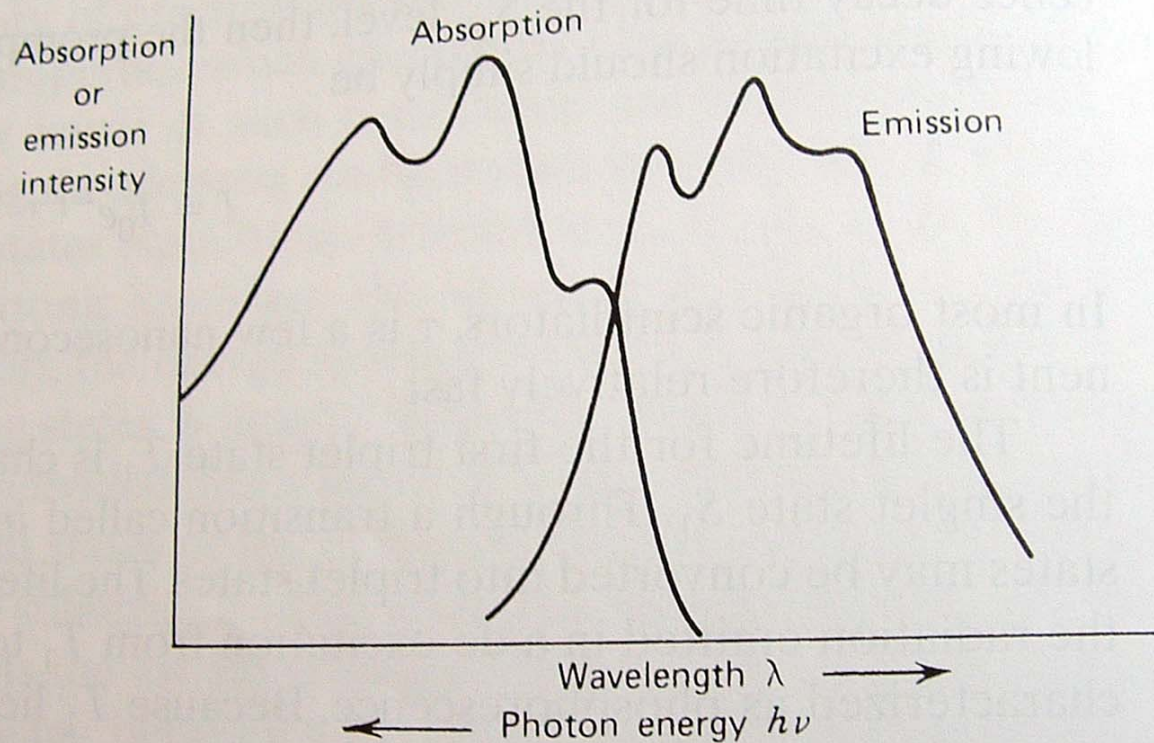
Figure 8.2 The optical absorption and emission spectra for a typical organic scintillator with the level structure shown in Fig. 8.1.

Types of organic scintillators

Pure organic crystals:

- Anthracene : lightest scintillation efficiency

- Stilbene : lower scintillation efficiency, but shorter time decay constant

- Both have a directional anisotropy or 20-30% and are relatively fragile to manufacture (especially in large crystals)

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Types of organic scintillators

Liquid organic solutions:

- Tend to be more resistant to radiation effects (deteuoration) due to the liquid nature, so useful for high dose measurements ~ 105 Gy

- Can also be used for radiation sources that can be dissolved as part of the scintillator solution (useful for low level β detection)

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Types of organic scintillators

Plastic scintillators:

- Formed by dissolving the scintillation in solution and then polymerizing the compound

- Relatively cheap and reasonable way to do large volume solid scintillaors

- Are subject to radiation damage and with high levels (10^3-10^4 Gy) show losses inefficiency due to damage to the fluorescent component and ?or formation of optical absorption centers

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Types of organic scintillators

Thin Film Scintillators:

- Can be made as thin as 20 μg/cm^2, less than the range of weakly penetrating particles (like heavy ions)

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Types of organic scintillators

Loaded Organic Scintillators:

- Adding high Z materials to the scintillator to increase the photon cross section (Pb, Sn, etc.)

- For neutron detection one can add element with high neutron cross section (B, Li, or Gd)

- These additions also decrease the light output and scintillator efficiency.

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Response of organic scintillators

Light output:

- A small fraction of the kinetic energy lost by a charged particle in a scintillator is converted to fluorescent energy. The remainder is dissipated non radiatively, primarily in the form of lattice vibration or heat.

- MeV electron equivalent (MeVeq): the particle energy required to generate 1 MeVeq of light by definition is 1 MeV for fast electrons, but is several MeV for heavy charged particles because of their reduced light yield per unit energy.

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Response of organic scintillators

- The response of organic scintillators to charged particles is best described by the relation dL/dx (light per unit length) and dE/dx or the specific energy loss of each particle.

- We first assume: the density of damaged molecules along the wake of the incident charged particle equals B(dE/dx); a fraction k of those lead to quenching; in absence of quenching the light yield is proportional to the energy loss; and S is the normal scintillation efficiency.

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Response of organic scintillators

- Then
$$dL/dx = S\ dE/dx$$

- and to account for quenching Birk's formula:

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

  – where *kB* is treated as a variable parameter to fit experimental data for a specific scintillator.

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Response of organic scintillators

- For fast electron (either from direct or gamma ray irradiation), *kB*=0

$$dL/dx = S\ dE/dx$$

- which means the incremental light output per unit energy loss is a constant:

$$dL/dE = S$$

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Response of organic scintillators

- For an electron that stops in the scintillator with initial energy E, the total light output is:

$$L = \int_0^E dL\big/dE \, dE = SE$$

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Response of organic scintillators

- For an α-particle, dE/dx is quite large and the fluorescent energy emitted per unit path becomes:

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

  - where the parameter *kB* is found by:

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

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Response of organic scintillators

- Through further analysis of data, Birks formula has been extended to:

$$\frac{dL}{dx} = \frac{S\,dE/dx}{1 + kB\,dE/dx + C\left(\dfrac{dE}{dx}\right)^2}$$

  – where C is empirically fit parameter.

- The alpha to beta ratio is the ratio of light outputs from the alpha and beta particle of the same energy.

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Response of organic scintillators

Time response:

- Three factors affect time response: the finite time required to populate the luminescent, the slower components of the scintillation corresponding to the delayed fluorescence and phosphorescence and the time decay of the prompt fluorescent state decay

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Response of organic scintillators

- A model of the shape of the light pulse

$$I = I_0 \left(e^{-t/\tau} - e^{-t/\tau_1} \right)$$

  where τ_1 is the time constant describing the population of the optical levels and т is the time constant describing their decay.

- Or one might use a Gaussian function : f(t) characterized by a standard deviation σ_{ET}, where the overall light versus time profile is given by :

$$\frac{I}{I_0} = f(t)e^{-t/\tau}$$

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Response of organic scintillators

Pulse Shape Discrimination:

- Shown in fig 8.5 is the time dependence of scintillation pulses in stillbene (which have equal intensity at t=0) when excited by radiations of different types.

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Response of organic scintillators

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])

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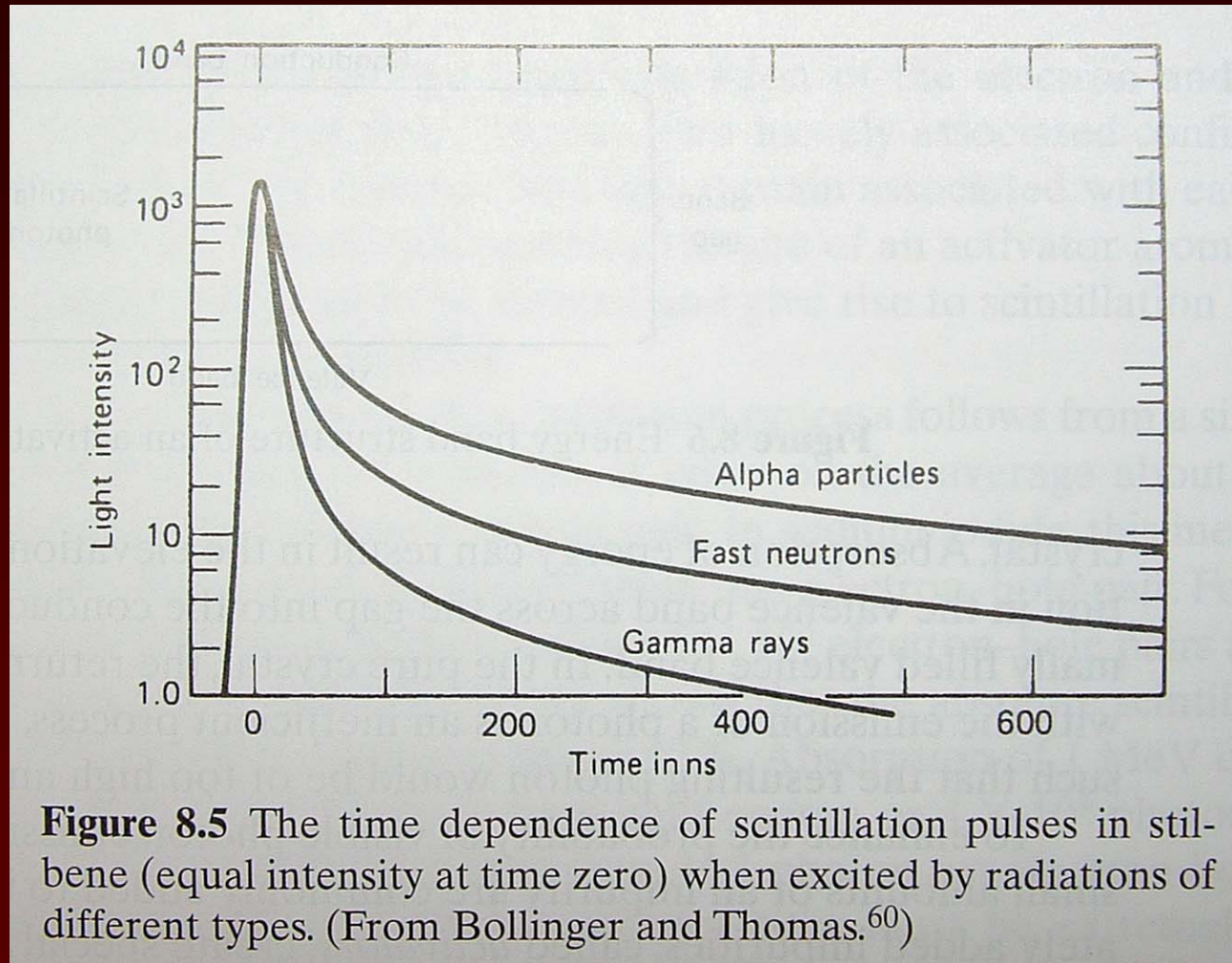
Response of organic scintillators

- The fraction of light that appears in the slow component often depends on the nature of the exciting particle

- One can then use this difference as discrimination between particles of different kinds that deposit the same energy.

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