

LECTURE 16

Scintillation Detection Principles

Properties of the ideal Scintillation Material

1. High efficiency of converting the kinetic energy of charged particles into light (detectable)
2. the conversion of KE to light should be linear
3. the medium should be transparent to the wavelength of its own emission for good light collection
4. the decay time of the induced luminescence should be short so fast signal processing can be generated
5. the material should be of good optical quality and subject to manufacture in sizes large enough to make practical detectors
6. 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
 - 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.

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 for i^{th} singlet state, T_i for i^{th} triplet state, 2^{nd} subscript is notation for a vibrational state
- The energy difference, ΔE , between the S_0 and S_1 state is $\sim 3\text{-}4$ 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 (\sim pico second)
- The vibrational excitations quickly lose energy to surrounding molecules and the overall effect is an excitation to the S_{10} state
- Light intensity from prompt fluorescence decays with time as $I = I_0 e^{-t/\tau}$, 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
- 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
- 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)

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 of 20-30% and are relatively fragile to manufacture (especially in large crystals)

Liquid organic solutions:

- Tend to be more resistant to radiation effects (deterioration) due to the liquid nature, so useful for high dose measurements $\sim 10^5$ Gy
- Can also be used for radiation sources that can be dissolved as part of the scintillator solution (useful for low level β detection)

Plastic scintillators:

- Formed by dissolving the scintillation in solution and then polymerizing the compound
- Relatively cheap and reasonable way to do large volume solid scintillators
- Are subject to radiation damage and with high levels (10^3 - 10^4 Gy) show losses in efficiency due to damage to the fluorescent component and/or formation of optical absorption centers

Thin Film Scintillators:

- Can be made as thin as $20 \mu\text{g}/\text{cm}^2$, less than the range of weakly penetrating particles (like heavy ions)

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.

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.
- 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
- Then $\frac{dL}{dx} = S \frac{dE}{dx}$ and to account for quenching

Birk's formula: $\frac{dL}{dx} = \frac{S \frac{dE}{dx}}{1 + kB \frac{dE}{dx}}$, where kB is treated as a variable parameter to

fit experimental data for a specific scintillator.

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

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

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

$$dL/dE = S$$

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

output is: $L = \int_0^E \frac{dL}{dE} dE = SE$

- 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:

$$kB = \frac{dL/dx|_e}{dL/dx|_\alpha}$$

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

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

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.

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

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.
- 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.