

35.3 Organic scintillators

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Organic scintillators produce light when transversed by a charged particle. They can be broadly categorized into four types: single crystal, liquid, plastic, and a recently emerged glass [35]. The most useful scintillators produce photons with wavelengths between 370-750 nm (blue to red), typically peaking at 425 nm [36] via a series of processes that are initialized when charged particles interact with the material via both excitation and ionization/recombination (see Sec. 34.2 of this Review). Typical photon yields are about 1 photon per 100 eV of energy deposit [37], although the collected and transduced signal can be much lower. Methods to guide the light towards the photon-electron converter, such as diffusive paint, reflectors, photonic crystals, or light guides, may be required to optimize light yield. Organic scintillators have found use in a wide variety of detectors [38]. Plastics are mostly used in collider detectors, and liquids in neutrino experiments. Ease of fabrication into desired shapes and low cost has made plastic scintillator ideal for large detectors. In the form of scintillating fiber, it has found widespread use in tracking and calorimetry. Demand for large volume detectors (e.g. neutrino detectors: MiniBooNE, NOvA) has led to increased use of liquid scintillator, which can be very low cost.

35.3.1 Scintillation mechanism

Plastic and liquid scintillators are based on an aromatic “matrix” such as benzene. The p electrons form both “pi” and “sigma” bonds between the atoms; the pi bonds are responsible for scintillation. Scintillation is produced via standard photophysical interactions, shown schematically in Fig. 35.1.

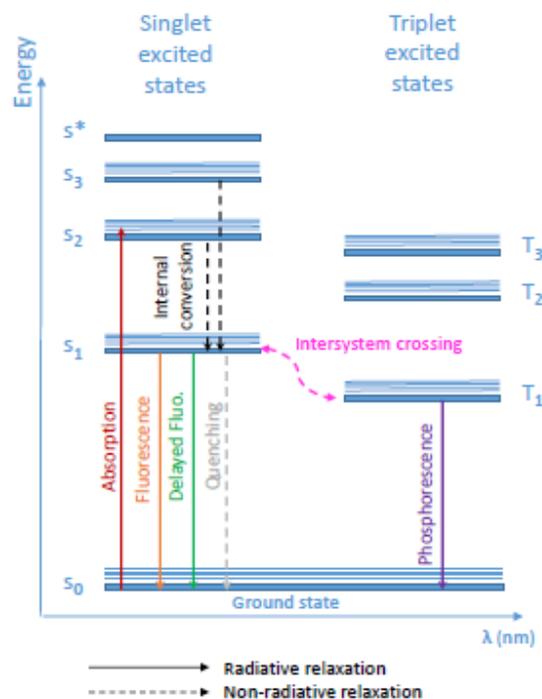


Figure 35.1: Schematic of scintillation mechanism. Schematic of typical excitation and de-excitation of matrix modules.

While there have been claims of delayed light production on long time scales (labeled “phosphorescence” in the figure), this is still a subject of active debate in the community. As aromatic molecules scintillate in the ultraviolet (UV), useful scintillators have one or several fluorophores dissolved into the matrix as dopants. Common fluorophores include 2,5-diphenyloxazole, p-terphenyl, 9,10-diphenylanthracene (9,10-DPA), 1,4-bis(2-methylstyryl)benzene (bis-MSB) and 1,4-bis(5-phenyl-2-oxazolyl)benzene (POPOP). Each molecule has its own role: the matrix (whether liquid or plastic) is where most of the radiation/matter interaction occurs. After radiation interaction, ions may recombine giving birth to excited molecules (excitons). Excitons in the matrix are transferred to a “primary fluorophore”, whose concentration is typically 1-3 weight % in commercial plastic and liquid scintillators. This concentration is large enough to ensure exciton transfer is primarily via the Förster mechanism, a resonant dipole-dipole interaction which decreases at sixth the power of the distance between molecules. The concentration, however, can be up to the solubility limit. Transfer via the Förster mechanism increases both speed and light output of the organic scintillator. To reduce reabsorption of the emitted light by the matrix or the primary fluorophore, and the resulting shortened attenuation length, a “secondary fluorophore” is also used to shift the light to longer wavelengths. Transfer from the primary to the secondary is generally radiative. Typical secondary concentrations in plastic and liquids are 0.01-0.2 weight %. The chain of emission and absorption from the matrix to the subsequent fluorophores is shown in Fig. 35.2. Scintillators with two fluorophores typically have absorption lengths of several meters.

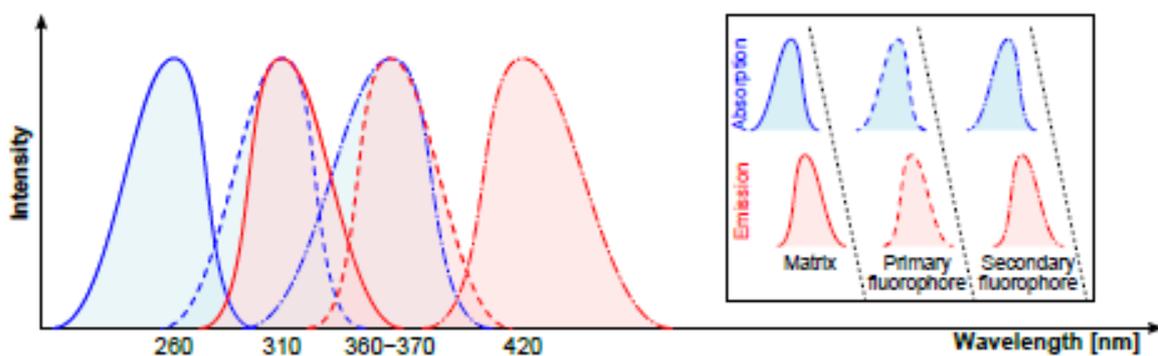


Figure 35.2: Schematic of scintillation mechanism. Typical emission and absorption spectra for the matrix, the primary, and the secondary fluorophore

The longest attenuation lengths require a third fluorophore: when the matrix is transparent up to 1 cm, adding a primary fluorophore increases the light transmission up to ≈ 10 cm, whereas the ternary cocktail is transparent up to 2 m and longer [39].

For most scintillators, decay times are in the ns range; rise times are much faster. Sub-ns timing resolutions have been achieved [40]. Organic scintillators do not respond linearly to the ionization density. Very dense ionization tracks, with large dE/dx , emit less light than expected compared to minimum-ionizing particles. A widely used semi-empirical model by Birks posits that recombination and quenching effects between the excited molecules reduce the light yield [41]. These effects are more pronounced the greater the density of the excited molecules. Birks’ formula is

$$\frac{dL}{dx} = L_0 \frac{dE/dx}{1 + kB dE/dx'}$$

Where L is the luminescence, L_0 is the luminescence at low specific ionization density, and the product kB is known as Birks’ constant, which must be determined for each scintillator by

measurement. The value of kB for polystyrene is 0.126 mm/MeV, which is large enough to play an important role in compensation in scintillator-based calorimetry. The high hydrogen content of plastic, which enhances the neutron interaction cross section, as well as its large mass stopping power, also contributes to calorimetry compensation. In the case of large dE/dx values (e.g. with alpha particles), ion recombination may lead to the creation of triplet excited states instead of singlet excited states. If two triplet states are close enough (typically in the order of 10\AA), then triplet-triplet annihilation may occur following the Dexter process [42], leading to delayed fluorescence. This phenomenon is useful for α/β or neutron/ γ discrimination.

Extensive research searching for new efficient molecules that can act as matrix, primary, or secondary fluorophores, is ongoing [43]. Other chemical modifications can affect the scintillator emission wavelength and decay time, or be used e.g. as stabilizers or to enhance thermal neutron sensitivity. Other parameters that can be modified are the density and the effective atomic number.

35.3.2 Plastic scintillator practicalities

Most commercial plastic scintillators use either polystyrene (PS) or poly(vinyltoluene) (PVT) as matrix. A variety of manufacturing techniques [43] are used in the production of plastic scintillator. Cast plastic has the highest light yield, while extruded scintillator is less expensive and allows creation of the scintillator and coating with a diffusive reflector in a single process. 3D printing of plastic scintillator is being actively pursued [44]. Plastic scintillator is also used to produce scintillating, wavelength-shifting, and clear fibers. These fibers can be useful to guide light to photodetectors, and as the active element in the type of calorimeter pioneered by the RD52/DREAM collaboration [45]. They have even been used in the construction of trackers [46, 47].

Plastic scintillators are reliable, robust, and convenient. However, exposure to solvent vapors, high temperatures, mechanical flexing, irradiation, or rough handling will cause degradation. The surface is a particularly fragile region and can “craze” – develop microcracks which degrade transmission of light by total internal reflection. crazing is particularly likely where oils, solvents, or fingerprints have contacted the surface or when mechanical stresses are present. The light yield is influenced by several environmental factors: it decreases with the partial pressure of oxygen [48] and increases with increasing magnetic field. Water vapour can also diffuse into plastic and cause clouding.

Plastics are susceptible to radiation damage [49]. At high enough dose, the visible color of the plastic can change to yellow or (at high enough dose) even brown. During irradiation, broken molecular bonds (“radicals”) absorb light, generally strongly in the UV, with tails to longer wavelengths. Because of this, shifting the light to longer wavelengths reduces the decrease in light output and in attenuation length due to radiation effects. Radicals produce mostly temporary damage that “anneals” when the irradiation ends, as the bonds can reform. Radicals can also polymerize via cross linking, and this leads to a permanent reduction in light yield [50]. In an inert atmosphere at room temperature, the bond reformation timescale is on the order of a month. Oxygen, which diffuses into the plastic during radiation to a depth that scales as the inverse square root of dose rate, can quickly bind to the radicals, reducing but not eliminating temporary damage at the price of a small increased permanent damage [51–53]. After irradiation, oxygen, if present, will diffuse through the entire sample, leading to oxide formation and speeding the annealing process. The decrease in light output due to permanent damage depends on the dose rate. Lower dose rates show large light losses for the same dose. The ratio of the light output to the unirradiated light output can roughly be parameterized as an exponential. For dose rates typical of current collider detectors at the Large Hadron Collider (from a few 10^{-3} to 10 Gy/hr), an exponential dose constant of tens of kGy is observed.

35.3.3 Liquid scintillator practicalities

Liquid scintillators have been used in large scale neutrino experiments 36.3.1.1 due to their low cost. They can hermetically fill any vessel shape. Liquid scintillators are also, due to the mobility of the molecules, much less susceptible to radiation damage. Care must be taken to avoid dissolved water, solvents such as isopropyl alcohol, and oxygen, which reduce light yield. As they can dissolve many materials (e.g. plastics, adhesives, paints..) care must be taken in their handling. Flammability concerns limit their use in practical experiments in intense radiation fields.

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