Radiation Detector 2018/19 (SPA6309)

Scintillator

General characteristics (Leo, 7.1)

The **scintillator** is my favourite material. The general classification is

1. organic scintillator (doping in plastic or oil)
2. inorganic scintillator (crystal)
3. gas scintillator (noble gas, often a cryogenic liquid)

Scintillation process is the emission of light from materials (scintillators) when radiation passes through (either charged particles or photons). And this light is detected by a photon detector, such as **photo-multiplier tube (PMT)**, so scintillator and PMT are often combined to make a detector or any **transducers**.

Luminescence is the light emitted by materials by absorption of energy. Thus, scintillation light is a type of luminescence.

Fluorescence and **phosphorescence** are words often used for fast and slow emission of luminescence, but their processes are different depending on the type of scintillators.

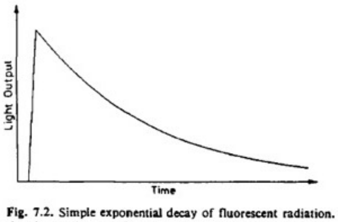


Fig. 7.2. Simple exponential decay of fluorescent radiation. The rise time is usually much faster than the decay time

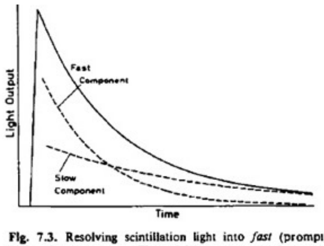


Fig. 7.3. Resolving scintillation light into *fast* (prompt) and *slow* (delayed) components. The *solid line* represents the total light decay curve

Organic scintillators (Leo, 7.2)

Organic scintillator is probably the most inexpensive particle detector and very popular with neutrino experiments which often require very large detector. The main process is the excitation of the **valence electrons** of aromatic hydrocarbon compound (or a benzene ring, all organic scintillators have "ring" structure at somewhere). De-excitation of them emits luminescence.

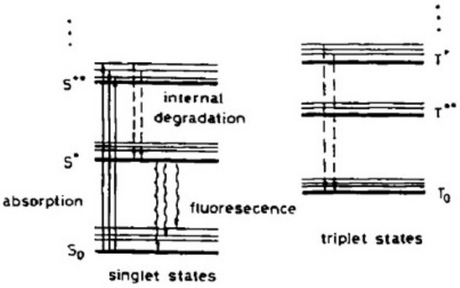


Fig. 7.4. Energy level diagram of an organic scintillator molecule. For clarity, the singlet states (denoted by S) are separated from the triplet states (denoted by T)

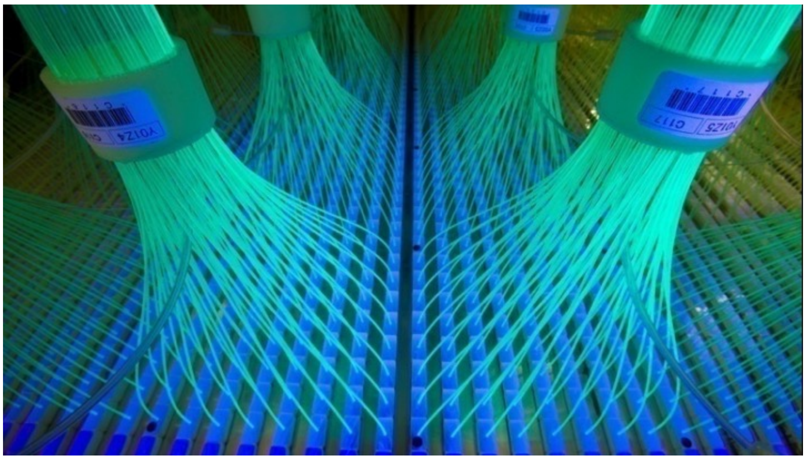
Importantly, molecules also have excitation of vibration states. However, their separations are smaller and they decay quickly to the vibration ground state. Now, an electron in S_0 orbit is excited to S_1 orbit by the propagation of a charged particle, and the transition $S_1 \rightarrow S_0$ emit fluorescence (this is fast, order $\sim ns$). If you look the detail, an electron is sitting in the ground state of vibration state, however, when it was excited to S_1, it may be located at the vibration excited state. Electron vibration state decays to the ground vibration state of S_1, then it decays to S_0. Notice, the separation of the lowest vibration state of S_1 to any vibration state of S_0 is shorter than the separation of the lowest vibration state of S_0 to the excited vibration state of S_1. This means, the absorbed energy is always a bit higher than emitted photon energy, and an emitted photon cannot be re-absorbed by the same scintillator. This is called **Stokes shift**, and absence of self-absorption is an important feature of scintillator as a detector.

Absorption and emission spectrum can be anything, but they are located in a narrow region for a practical reason. Since emitted light is weak and it has to be detected by a photo-multiplier tube (PMT), scintillators are designed to emit light so that it's easy for PMT to detect. Since PMT window is made by glass, emission spectrum must be long enough (say 350nm or longer) because UV light would be absorbed by glass material. On the other hand, long wavelength means low energy photon and not easy to produce photo-electron by the photo-electric effect, ao the wavelength should not be too long (say 700nm or shorter). Thus, most of the scintillator are designed to emit **blue to green** light (400-500nm). The energy of photon and wavelength is related by

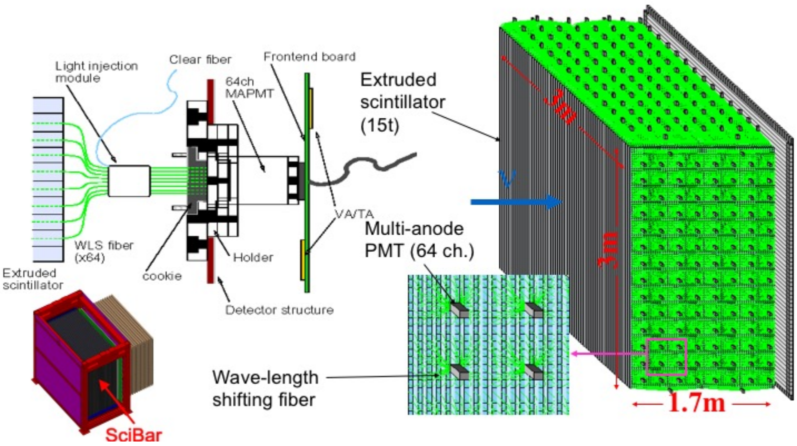
$$E(eV) = \frac{1240}{\lambda(nm)}$$

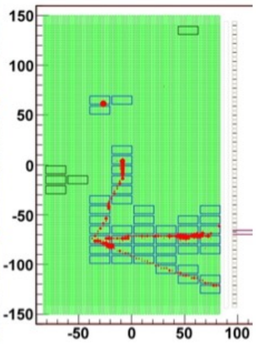
Organic scintillators can be liquid or plastic. Either way, scintillation materials are mixed with a polymer (plastic) or mineral oil (liquid). Scintillation materials are often radical and higher concentration may damage container material, and sometimes scintillators are even flammable.

e.g) SciBar detector



SciBar detector is a combination of plastic scintillators, **wavelength shifting (WLS) fibres**, and PMTs. First, propagation of charged particles in scintillators emit **blue** light, then this blue light is absorbed by WLS fibres, and **green** light is sent to PMTs. Notice, every transition, the wavelength is getting longer (=lower energy). In this way, we can see the trace of a particle in a scintillator. By making an array of them, covering X and Y direction, now you can see the track of particles in 2-dimension. This is an example of **tracker** detectors. These scintillators are made at a factory in Fermilab, USA.





Inorganic scintillator (Leo, 7.3)

In general, **inorganic scintillators** are crystal and more expensive. Light output is usually higher than organic scintillators, and these are favoured for other applications. Light is emitted by the transition of electrons between excited band and valence band.

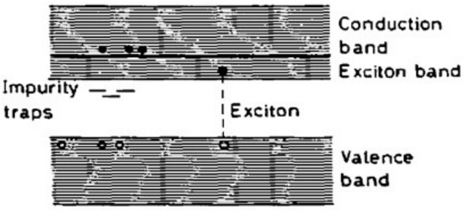
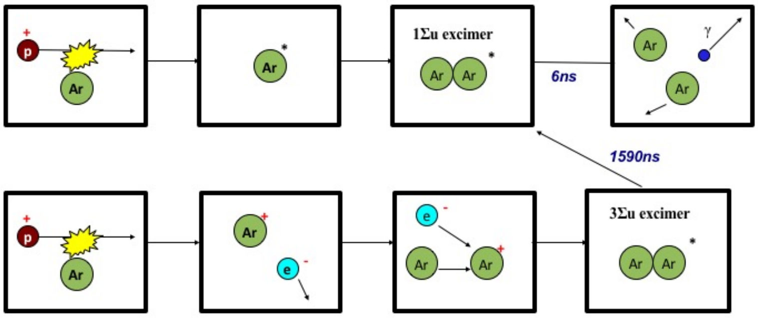


Fig. 7.7. Electronic band structure of inorganic crystals. Besides the formation of free electrons and holes, loosely coupled electron-hole pairs known as excitons are formed. Excitons can migrate through the crystal and be captured by impurity centers

Gaseous scintillator (Leo, 7.4)

The **gas scintillator** uses mainly noble gas. The excited atom makes excimer, and decay of excimer produce photons. This process is used by many dark matter detectors, namely, those experiments try to detect scintillation light coming from collisions of dark matter particles with nuclei (such as argon or xenon).



The problem is, most of the noble gas has very short (=UV) emission spectrum. To detect scintillation light, we need a photon detector, but scintillation light from noble gas cannot penetrate the glass window of photo-multiplier tubes. To overcome this problem, scintillation light is absorbed by **wave-length shifter**, and re-emitted to a longer wavelength. For example, argon scintillation light is 125nm (so-called vacuum UV, since such light cannot propagate even in the air!), this is absorbed by TPB (a type of wavelength shifter), and re-emitted to ~450nm. The emission peak overlaps with absorption peak (peak of quantum efficiency, QE) of PMTs.

e.g.) MicroBooNE photon detection system

The MicroBooNE detector is a cryogenic tank filled with liquid argon. in its wall, an array of cryogenic PMTs is equipped to monitor scintillation light from argon atoms. Since typical PMTs are not sensitive to scintillation light from argon, wavelength shifters are placed in front of the PMTs, so that 128 nm light is converted to ~450nm, which is visible by PMTs. PMTs are designed for a cryogenic application, and I tested all of them in a liquid nitrogen bath (77K).