Physics 736

Experimental Methods in Nuclear-, Particle-, and Astrophysics

- Detectors and Detector Properties -

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# Class Schedule & Course Website

Course website

http://neutrino.physics.wisc.edu/teaching/PHYS736/

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Scintillation Detector
The First Scintillation Detector

1903 Crookes

spinthariscope
Scintillation

- Luminescence
  - absorption
  - re-emission

Figure 8.1 can also be used to explain why organic scintillators can be transparent to their own fluorescence emission. The length of the upward arrows corresponds to the photon energies that will be strongly absorbed in the material. Because all the fluorescent transitions represented by the downward arrows (with the exception of 516 - S6s) have lower energy than the minimum required for excitation, there is very little overlap between the optical absorption and emission spectra (often called the Stokes shift), and consequently little self-absorption of the fluorescence. An example of these spectra for a typical organic scintillator is given in Fig. 8.2.

The scintillation efficiency of any scintillator is defined as the fraction of all incident particle energy which is converted into visible light. One would always prefer this efficiency to be as large as possible, but unfortunately there are alternate de-excitation mechanisms available to the excited molecules that do not involve the emission of light and in which excitation is degraded mainly to heat. All such radiationless de-excitation processes are grouped together under the term quenching. In the fabrication and use of organic scintillators, it is often important to eliminate impurities (such as dissolved oxygen in liquid scintillators), which degrade the light output by providing alternate quenching mechanisms for the excitation energy.

In almost all organic materials, the excitation energy undergoes substantial transfer from molecule to molecule before de-excitation occurs. This energy transfer process is especially important for the large category of organic scintillators that involves more than one species of molecules. If a small concentration of an efficient scintillator is added to the bulk solvent, the energy that is absorbed, primarily by the solvent, can eventually find its way to one of the efficient scintillation molecules and cause light emission at that point. These "binary" organic scintillators are widely used both as liquid and plastic solutions incorporating a variety of solvents and dissolved organic scintillants.

A third component is sometimes added to these mixtures to serve as a "wavelength shifting" light. Its function is to absorb the light produced by the primary scintillant and re-radiate it at longer wavelength. This shift in the emission spectrum can be useful for closer matching of the spectral sensitivity of a photomultiplier tube or to minimize bulk self-absorption in large liquid or plastic scintillators. Birks and Pringle3 have reviewed the energy transfer mechanisms in binary and tertiary organic mixtures together with their influence on scintillation efficiency and pulse timing characteristics.

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

wavelength shifting
Some scintillation materials can also be fabricated as small diameter fibers in which a fraction of the scintillation light is conducted over substantial distance by total internal reflection. General reviews of scintillating fibers of this type are given in Refs. 180-182. As shown in Fig. 8.17, a common configuration consists of a core, in which the scintillation light is generated through interaction of the incident radiation, surrounded by a thin layer of cladding material. Both the core and the cladding are transparent materials, and the index of refraction of the core is higher than that of the cladding. Light rays that arrive at the core-cladding interface with an angle of incidence that is greater than the critical angle for total internal reflection are "piped" down the length of the fiber. In some cases, a light absorbing "extramural absorber" may be applied to the outer surface of the cladding to provide optical isolation.

For a typical core material with index of refraction of 1.58 surrounded by air, the index change would be large enough to pipe over a third of the light toward one end or the other. However, when a cladding material is added to protect the core surface from abrasion or accumulation of foreign material that would inhibit the light piping effect, then the index of refraction change is less pronounced and only 5 to 10% of the light is trapped. Some of...
Scintillation Detectors

Puons

- Photomultiplier Tubes
- Scintillator
- Lead Shield
- Scintillator

Image of a scintillation detector with labeled components.
The scintillation detector is undoubtedly one of the most often and widely used particle detection devices in nuclear and particle physics today. It makes use of the fact that certain materials when struck by a nuclear particle or radiation, emit a small flash of light, i.e., a scintillation. When coupled to an amplifying device such as a photomultiplier, these scintillations can be converted into electrical pulses which can then be analyzed and counted electronically to give information concerning the incident radiation.

Probably the earliest example of the use of scintillators for particle detection was the spinthariscope invented by Crookes in 1903. This instrument consisted of a ZnS screen which produced weak scintillations when struck by α-particles. When viewed by microscope in a darkened room, they could be discerned with the naked eye, although practice was necessary. It was tedious to use, therefore, and thus never very popular, even though it was spectacularly employed by Geiger and Marsden in their famous scattering experiments. Indeed, with the invention of the gaseous ionization instruments, the optical scintillation counter fell into quick disuse.

In 1944, not quite a half century later, Curran and Baker resuscitated the instrument by replacing the human eye with the then newly developed photomultiplier tube. The weak scintillations could now be counted with an efficiency and reliability equal to that of the gaseous ionization instruments. Thus was born the modern electronic scintillation detector. New developments and improvements followed rapidly so that by the mid-1950's scintillation detectors were among the most reliable and convenient available. This is still true today. In this chapter, we will survey the existing materials and current techniques in use as well as describe their basic underlying principles.

### 7.1 General Characteristics

The basic elements of a scintillation detector are sketched below in Fig. 7.1. Generally, it consists of a scintillating material which is optically coupled to a photomultiplier directly or via a light guide. As radiation passes through the scintillator, it excites the atoms and molecules making up the scintillator causing light to be emitted.
Scintillation Detectors

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

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

There are two decay constants, and . For most scintillators, one component is generally much faster than the other so that it has become customary to refer to them as the fast and slow components (hence the subscripts f and s), or the prompt and delayed components. Their relative magnitudes, and , vary from material to material, although it is the fast component which generally dominates. Figure 7.3 shows the relation between these components. As will be seen in a later section, the existence of these components forms the basis for the technique of pulse shape discrimination.

While many scintillating materials exist, not all are suitable as detectors. In general, a good detector scintillator should satisfy the following requirements:

- High efficiency for conversion of exciting energy to fluorescent radiation
Organic Scintillator

With each electron level is a fine structure which corresponds to the modes of the molecule. The energy spacing between electron levels is a few eV whereas that between vibrational levels is of the order of a few cm$^{-1}$. Ionization energy from penetrating radiation excites both the electronic levels as shown by the solid arrows. The singlet excitations go immediately (<10 ps) to the $S_{1}$ state without the emission of radiation, a process known as internal degradation. From $S_{1}$, there is generally a high probability of proceeding to one of the vibrational states of the ground state within a few nanoseconds time. This is the normal process of fluorescence described by the prompt exponential component in (7.2). The fact that $S_{1}$ has several vibrational states of $S_{0}$, with emission of radiation energy less than the ionization energy of the incoming particle. The dissipation of the energy to the surroundings is the mechanism by which this takes place.
light emission spectra
Inorganic Crystals

light emission spectra

electronic band structure

excitons are captured by impurity centers
Light Output Response & Radiation Type

Up until now, we have assumed that scintillators respond in a linear fashion to the exciting energy, that is, the fluorescent light emitted is directly proportional to the energy, $E$, deposited by the ionizing particle.

Strictly speaking, this linear relation is not true, although for many materials, it can be considered as a good approximation. In reality, the response is a complex function of not only energy but the type of particle and its specific properties.

In organic materials, non-linearities are readily observed for energies below 125 keV, although they are small [7.4]. For heavier particles, these deviations are more pronounced and become very noticeable at lower ionizing particle energies, showing the larger deviations.

The response of NE102 plastic scintillator to different particles is shown in Fig. 7.6.1, with the particle energy in MeV.

**NE-102** = common plastic scintillator

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- **Light output** vs. **particle energy [MeV]**

**Figure E.3** The scintillation light yield for a common plastic scintillator (NE 102) when excited by electrons and protons. The data are fit by curves from Eq. (8.3) (one parameter) and Eq. (8.9) (two parameter). (From Croun and Smith.)
Birk Model

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

\begin{center}
\begin{tikzpicture}
\node at (0,0) {NaI(Tl) Scintillator};
\node at (4,0) {Target LS};
\node at (2.5,1) {backward-scattered $\gamma$-ray (184.4 keV)};
\node at (1,0.5) {$^{137}$Cs source};
\end{tikzpicture}
\end{center}

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    xlabel={$E_{\text{recoil}}$ (keV)},
    ylabel={Quenching Factor (%)}
]
\addplot[red, only marks] table [col sep=comma] {data1.csv};
\addlegendentry{Park et al (0.07%)}
\addplot[blue, only marks] table [col sep=comma] {data2.csv};
\addlegendentry{Park et al (0.43%)}
\addplot[black, only marks] table [col sep=comma] {data3.csv};
\addlegendentry{Pecourt et al}
\addplot[green, only marks] table [col sep=comma] {data4.csv};
\addlegendentry{Kudryavtsev et al}
\addplot[black, only marks] table [col sep=comma] {data5.csv};
\addlegendentry{Wang et al}
\end{axis}
\end{tikzpicture}
\end{center}
Temperature Dependence of Light Output

7.6 Light Output Response

This behavior should be taken into account. A similar behavior is also observed in CsI. While Birk's formula is only applicable to organic scintillators, some portions of the NaI response seem also to be well described by this expression.

7.6.2 Temperature Dependence

The light output of most scintillators is also a function of the temperature. This dependence is generally weak at room temperatures, but should be considered if operation at temperatures very different from normal is desired.

In organic scintillators, the light output is practically independent of temperature between -60°C and +20°C and only drops to 95% of this value at +60°C. Inorganic crystals, on the other hand, are more sensitive as shown in Fig. 7.10. Both CsI(Tl) and CsI(Na), for example, show relatively strong variations in the normal range of temperatures, while NaI appears much less sensitive. BGO light output has also been found to exhibit a strong temperature dependence, increasing by about 1% per degree Celsius as the temperature decreases. As the temperature decreases, the decay time for BGO also increases, however.

Fig. 7.10. Temperature dependence of light output from inorganic crystals (from Hanhaw Catalog).

Pulse Shape Discrimination (PSD)

Although the light emission of most scintillators is dominated by a single fast decay component, some materials, as we have mentioned, exhibit a substantial slow component. In general, both of these components depend on dE/dx to some degree or another. In scintillators where this dependence is strong, the overall decay time of the emitted light will, therefore, vary with the type of exciting radiation. Such scintillators are thus capable of pulse shape discrimination, i.e., they are capable of distinguishing between different types of incident particles by the shape of the emitted light pulse. Figure 7.11 illustrates the different decay times and hence different pulse shapes exhibited by different crystals when excited by different particles. Similar differences were also observed in other materials.
Scintillation Detectors

BGO - Temperature Dependence of Light Output

![Graph showing light output vs temperature for BGO at 295 K, 77 K, and 6 K.](image)


Fig. 2. Scintillation decay curves of BGO measured at $T = 6$ (a), 77 (b) and 295 K (c) using $\alpha$ excitations. The solid line shows the best fit to the experimental data using one (a) and two exponentials (b, c). The parameters of the fit are listed in Table 1.
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.)

Particle. Bimolecular interactions between two such excited molecules can lead to product molecules one in the lowest singlet state (S1) and the other in the ground state. The singlet state molecule can then de-excite in the normal way, leading to delayed fluorescence. The variation in the yield of the slow component can then be partially explained by the differences expected in the density of triplet states along the track of the particle, because the bimolecular reaction yield should depend on the square of the triplet concentration. Therefore, the slow component fraction should depend primarily on the rate of energy loss dE/dx of the exciting particle and should be greatest for particles with large dE/dx. These predictions are generally confirmed by measurements of the scintillation pulse shape from a wide variety of organics.

Certain organic scintillators, including stilbene crystals and a number of commercial liquid scintillators, are particularly favored for pulse shape discrimination because of the large differences in the relative slow component induced by different radiations. Figure 8.5 shows the differences observed in stilbene for alpha particles, fast neutrons (recoil protons), and gamma rays (fast electrons). In such scintillators, it is not only possible to differentiate radiations with large dE/dx differences (such as neutrons and gamma rays) but also to separate events arising from various species of heavy charged particles as well. Reviews of the pulse shape discrimination properties of different types of organic scintillators and examples of applications are given in Refs. 61-69. Electronic circuits designed to carry out this pulse shape discrimination are described in Chapter 17.
Pulse Shape Discrimination

Inorganic Crystrals with Activators

Mechanism in Organics and with Activators

Figure 8.5 shows the differences observed in stilbene for alpha particles, fast neutrons (recoil protons, protons and o-particles respectively). A strong difference is also observed for the slow component of the pulse shape when excited by different radiations. The time integral of the light pulses is also shown. A discrimination between these radiations may be obtained by measuring the time it takes for the integrated pulse to reach a certain fixed level (from Lynch [7.171; picture Fig. 7.12). In stilbene, for example, the slow component (used to distinguish pulse shapes) is thus reduced. In stilbene, for example, the slow component not accessible to excitons. At low ionization density, exciton formation is less likely so that the proportion of excitons relative to free electrons and holes is lower. The proportion of radiative to metastable excited states will be different, the former and hence the pulse shape.

In alkali halides such as CsI, for example, a high ionization loss produces a high density of excited molecules which are then captured as a whole by impurity centers, exciting the latter to certain threshold states (fast component). The singly free electrons and holes, on the other hand, are able to recombine into localized bound systems known as excitons. These excitons then wander through the crystal until they are captured as a whole by impurity centers, exciting the latter to certain threshold states (fast component).

Certain organic scintillators, including stilbene crystals and a number of commercial products, show large differences in the relative slow component induced by different radiations. Figure 8.5 illustrates the differences expected in the density of triplet states along the track of the particle, because the singlet excited state molecule can then de-excite in the normal way, leading to delayed fluorescence. The singlet state is thus reduced.

In organic scintillators, a high ionization loss produces a high density of excited molecules which are then captured as a whole by impurity centers, exciting the latter to certain threshold states (fast component). The singly free electrons and holes, on the other hand, are able to recombine into localized bound systems known as excitons. These excitons then wander through the crystal until they are captured as a whole by impurity centers, exciting the latter to certain threshold states (fast component).
Detection Efficiency & Radiation Type

7.7 Intrinsic Detection Efficiency for Various Radiations

Gamma-ray absorption coefficients for NaI and NE102A plastic scintillator. Note the difference in the relative magnitudes of the photoelectric and Compton cross sections.

For neutrons, the detection of neutrons requires a transfer of all or part of its energy to a particle capable of ionizing and exciting the scintillator material. For fast and higher energy neutrons, detection relies mainly on detecting the recoil proton in (n, p) scattering processes. Plastic and other organics are particularly convenient here, since they contain large amounts of hydrogenous material. The standard scintillator in neutron spectroscopy is liquid organic scintillator (e.g. NE213). This material offers excellent pulse shape discrimination properties and allows a rejection of gamma ray background which usually accompanies neutron reactions. As well it is easily adapted and can be adapted to a wide variety of geometries.

For thermal neutrons, detection is most efficiently done using the (n, γ) or (n, c) reactions. Scintillators which contain elements with high cross sections for these reactions, e.g. Ti or Tb, or are capable of being loaded with these elements are therefore the most convenient. LiI(Eu), for example, is a particularly good thermal neutron detector. Indeed, a 2 cm thick crystal is almost 90% efficient for thermal neutrons. It, unfortunately, is also sensitive to γ radiation, which is a major source of background. The advantages of LiI(Eu) are therefore somewhat diminished. More effective are the glass scintillators which are particularly well suited since they can be doped with either enriched Ti or Tb. They are also sensitive to P and γ radiation, although some glasses offer the possibility of pulse shape discrimination. Liquid scintillator is again, however, the most effective here since it can also be loaded with elements such as Ti or Tb, in addition to offering pulse shape discrimination.