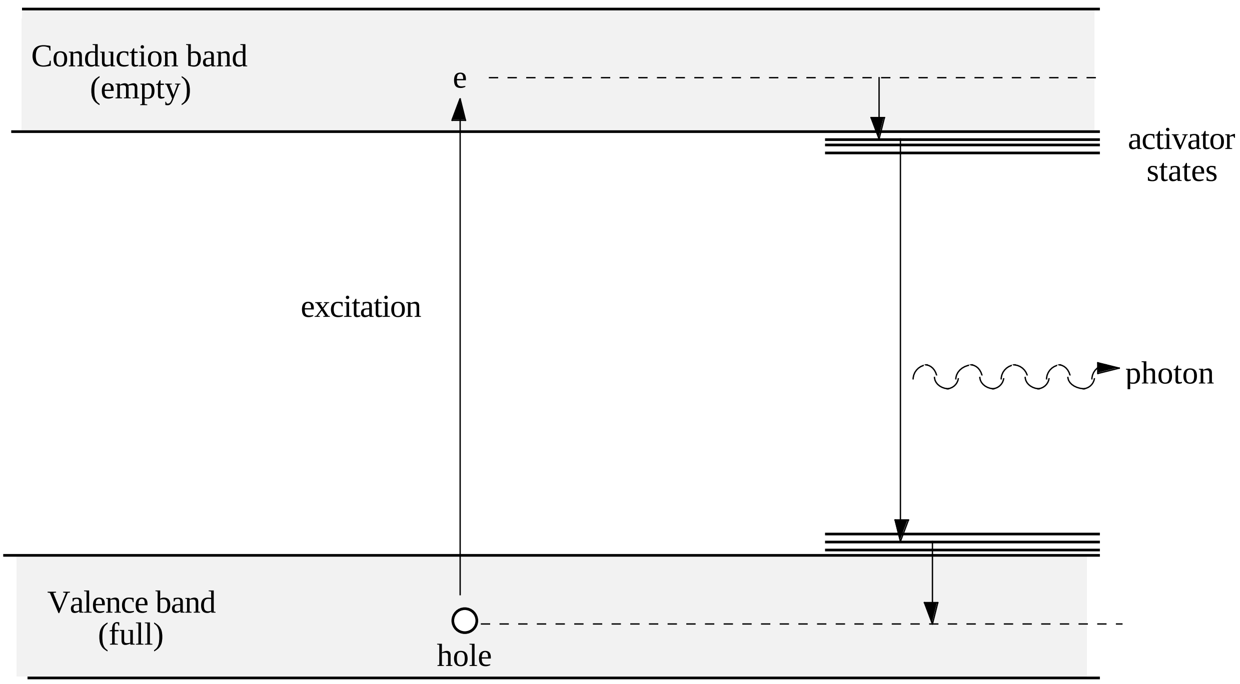
Scintillation Counters

Unlike many other particle detectors, which exploit the ionisation produced by the passage of a charged particle, scintillation counters rely on the atomic or molecular **excitation** produced. De-excitation then results in the emission of light, a process known as **fluorescence**. This light then acts as a detectable signal. However, the material detecting the particle must be transparent to its own signal, which is not naturally the case, as is shown below.

There are two main types of scintillator:

1) Inorganic, such as sodium iodide (NaI).

Single crystals of NaI, doped with an activator such as Thallium to modify the energy levels, are used to form detectors.



(Energy gap about 4 eV)

The passage of the charged particle excites electrons from the valence band to the conduction band. Without any activator states, each electron would subsequently fall back to its unexcited level, emitting a photon of exactly the correct energy to cause further excitation – the photon would thus be rapidly reabsorbed. In the presence of an activator, the excited electron rapidly makes non-radiative transitions down into additional states at the top end of the band gap. When it falls from here, the photon emitted does not have sufficient energy to re-excite ground state electrons, and so is not absorbed.

2) Organic, plastic such as polystyrene or Plexiglas $(C_5H_8O_2)_n$.

The principle of operation of an organic scintillator is broadly the same as in the inorganic case, but in this case excitation occurs between molecular bound states (corresponding to ultra-violet wavelengths). The plastic is doped with a low concentration of wavelength shifter (WLS), which converts the u.v. photons to longer wavelength (lower energy) light in the visible, where absorption is greatly reduced.

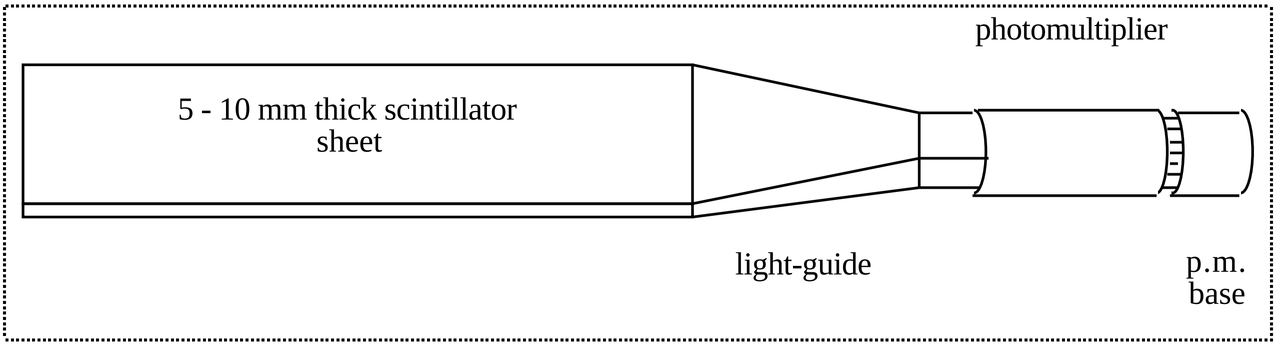
(Wavelength shifters are generally known by abbreviated chemical or commercial names, examples including POPOP, BBQ, PBD, K27, ...)

Typical responses from a 1 cm thickness of scintillator:

	No. of photons	λ_{peak}	Decay time
Plastic	~10^4	(~420 nm)	3 – 4 ns
NaI (Tl)	~3×10^4	410 nm	250 ns

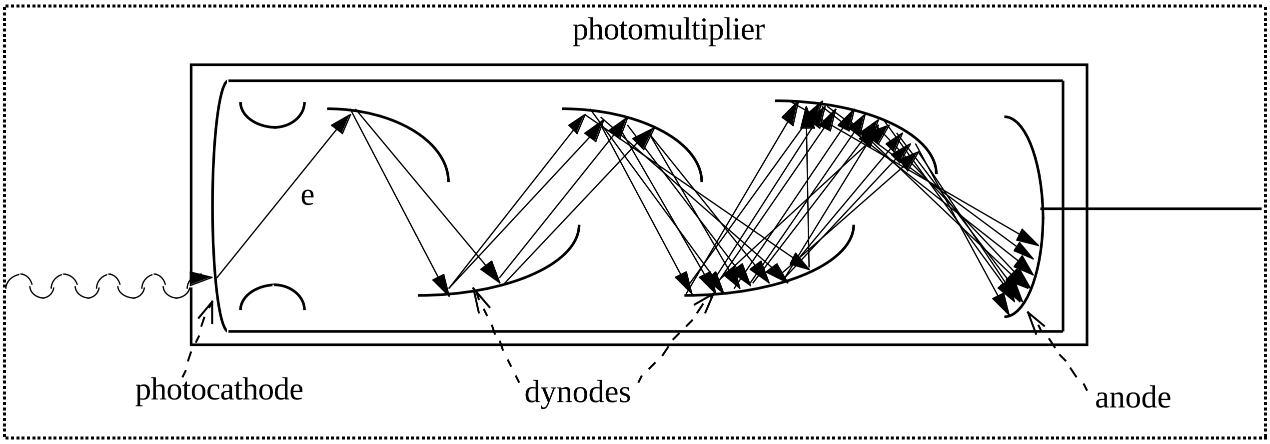
(The rise time for plastic scintillator is ~100 ps)

Simple Scintillation Counter



The scintillator may have an area of a few cm^2 to ~1 m^2, depending on the application. Light travels along the thin sheet undergoing many total internal reflections. Most light travels close to the critical angle, and the surfaces must be highly polished to avoid losses.

The light is converted to an electrical signal and amplified by a **photomultiplier** (p.m.).



A photon passes through the transparent glass window, and liberates an electron from the alkali metal cathode (such as a Caesium-Rubidium mixture) deposited on the inner surface of the glass. The quantum efficiency of this process (the probability of liberating an electron per photon) is typically 20 to 25%.

The cathode is normally at about –1500 to –2200 V and the anode at 0 V. Dynodes are connected at intermediate voltages, typically about 150 V per step. The photoelectron liberated at the cathode is accelerated towards the first dynode, liberating about 4 secondary electrons when it strikes it. These are then accelerated to the next dynode, and the process continues. A 12-stage tube can thus provide a gain of the order of 10^7.

The voltages for the dynodes are supplied by a potential divider chain mounted in the p.m. base. The output from the anode normally drives a 50Ω load, and a pulse of a few mV is produced for a single detected photon.

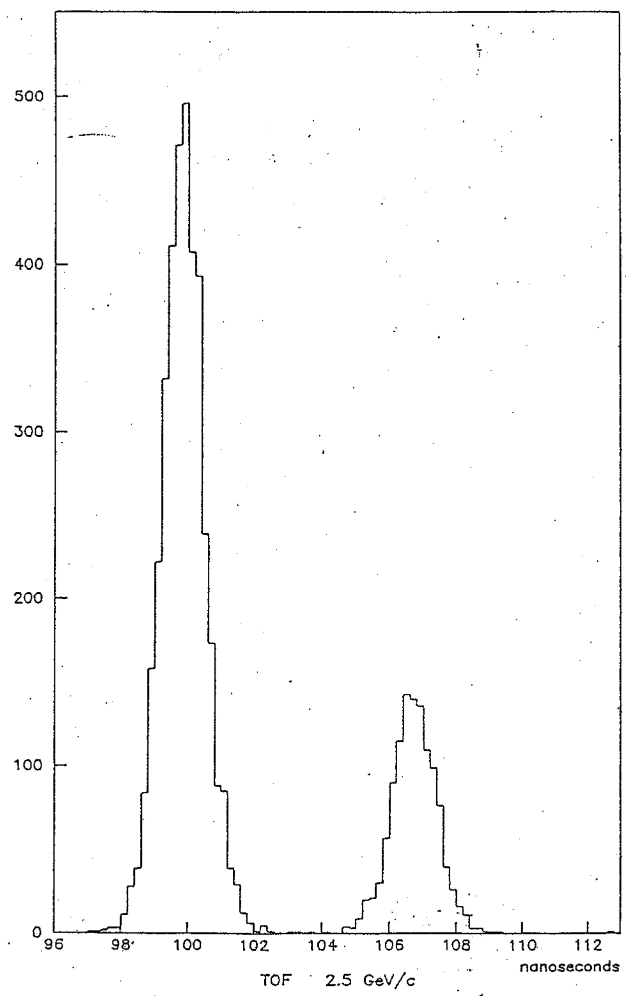
The photomultiplier may be optimised for the specific application. For example, the photocathode can be chosen to match the wavelength produced by the scintillator, and a tube with an appropriate time response can be selected. Photomultipliers produce a certain amount of noise pulses, typically 10 to 1000 Hz, depending on voltage and temperature.

A **light guide** couples the scintillator to the photomultiplier. For a simple counter, this may be in the shape of a "fish tail", but more contorted shapes may be adopted, e.g. to couple many scintillator sheets to the same photomultiplier. It can be shown (using Liouville's theorem) that the light transfer efficiency is always smaller than the output area divided by the input area of the light guide. It is thus not possible <u>efficiently</u> to couple a large scintillator edge area to a small photomultiplier (of typical diameter 44 mm). The very best counters have about 10% photon collection efficiency.

Typical scintillation counters have poor spatial resolution (simply indicating a particle passed somewhere through their area) but good time resolution (~0.5 ns for small counters). The good time resolution means that two (planes of) counters can be used to measure a particle's velocity using time-of-flight measurements.

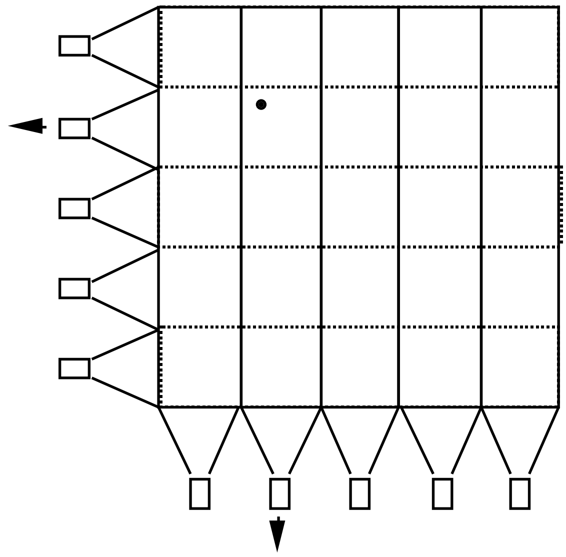
The figure shows the time of flight measured over 30 m for a mixed beam of pions and protons of momentum 2.5 GeV/c.

Fig. 4 Time of flight



Improved spatial localisation can be achieved by a number of means. If a long counter is equipped with a light guide and p.m. at each end, the relative arrival time of the pulse at each end gives a measure of the position along the counter where the particle traversed.

Alternatively, two layers of crossed scintillators can be used to form a **hodoscope**. A coincidence between signals from two counters then greatly restricts the area through which the particle may have passed. However, such an application is normally restricted to cases where the density of particles is rather small, as if two or more particles give signals together there are ambiguities in deciding which pairs of hits should be associated.



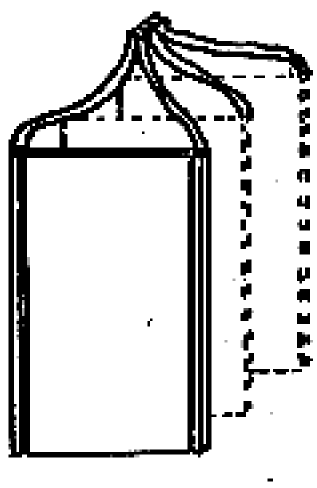
Scintillator Hodoscope

Further points:

- When a coincidence between counters is demanded, the noise due to the photomultipliers (and other sources) is normally negligible.
- Because scintillation counters are continuously sensitive and have a fast response, they are ideal **triggers** for other detectors.

Alternative geometries

i) Where many scintillators are to be connected to a single photomultiplier, a normal light guide is not practical. One solution to this is to use wavelength shifter bars or sheets (doped with BBQ for example) along the edges of the scintillators.



The scintillator contains a primary wavelength shifter emitting in the violet.

WLS bars are placed in adjacent to the edges of the scintillator sheets (not in good optical contact).

Light escaping from the scintillator into the bars is wavelength shifted and re-emitted isotropically.

Light from one end of the bars is led by clear perspex bars to a common photomultiplier.

(An example of such a geometry will be shown when we look at calorimeters.)

There are a number of advantages to such a solution:

- A large scintillator area can be matched to a single photomultiplier.
- Light can be fed out of compact detectors with little dead space for light guides.
- Better uniformity of response for different particle positions can be obtained than with a fish-tail light guide at one end.

However, there is also a disadvantage:

- The light collection efficiency is less than for a simple geometry and fish-tail light guide.

ii) Scintillating Optical Fibres

Plastic optical fibres can be made out of scintillator material. If these have a diameter of 0.5 to 1 mm, they can form a detector with very good spatial resolution. Because of the small diameter, light has to make very many reflections before reaching the end of the fibre. For this reason, the fibre is coated with a thin layer of lower refractive index material (known as cladding) to ensure total internal reflection with a very high efficiency.

The small size of each independent scintillator means that very many readout channels are required (60,000 in one application). For this reason, photomultipliers are clearly not practical, and a more sophisticated readout scheme is required. One solution to this is to use image intensifiers (optical amplifiers) connected to optical CCDs, viewing a bundle of scintillating fibres.

Scintillating glass fibres are also being tested. These can be produced with diameters down to 20 µm, giving extremely good spatial resolution. However, at present these have a low light yield and have a poor attenuation length of a few cm (or are very slow).