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DSE2T (Nuclear and Particle Physics)

Topic – Detector for Nuclear Radiations (Part – 2)

We have already discussed part 1 of this e-report.

Now let us continue part 2 of it.

Scintillation Detectors:

A disadvantage of gas-filled counters is their low efficiency for many radiations of interest in nuclear Physics. The range in air of 1 MeV gamma ray is of the order of ~100 m. Solid detectors have the higher densities that give reasonable absorption probabilities for detectors of reasonable size. To make a workable solid detector, however, we must satisfy two contradictory criteria, namely

(1) The material must be able to support a large electric field, so that the electrons and ions can be collected and formed into an electronic pulse, and little or no current must flow in the absence of radiation, so that the background noise is low.

(2) Electrons must be easily removed from atoms in large numbers by the radiation, and the electrons and ionized atoms must be able to travel easily through the material. Actually, the ions themselves do not move in a solid, instead, the electronic vacancy or hole is filled by successive electron transfers from one atom to the next, so that the hole appears to travel.

The first condition supports the choice of an insulating material, while the second suggests using a conductor. The obvious compromise is a semiconductor and we consider such devices in the upcoming section. Bulk semiconducting materials in sizes large enough to make useful radiation detectors (tens of cm^3) did not become available until the late 1960s and to fill the need for nuclear spectroscopic devices of high efficiency and reasonable resolution, *Scintillation detectors* or *scintillators* were developed during the 1950s. These are kinds of

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materials that provide detectable photons in the visible part of the light spectrum, following the passage of a charged particle.

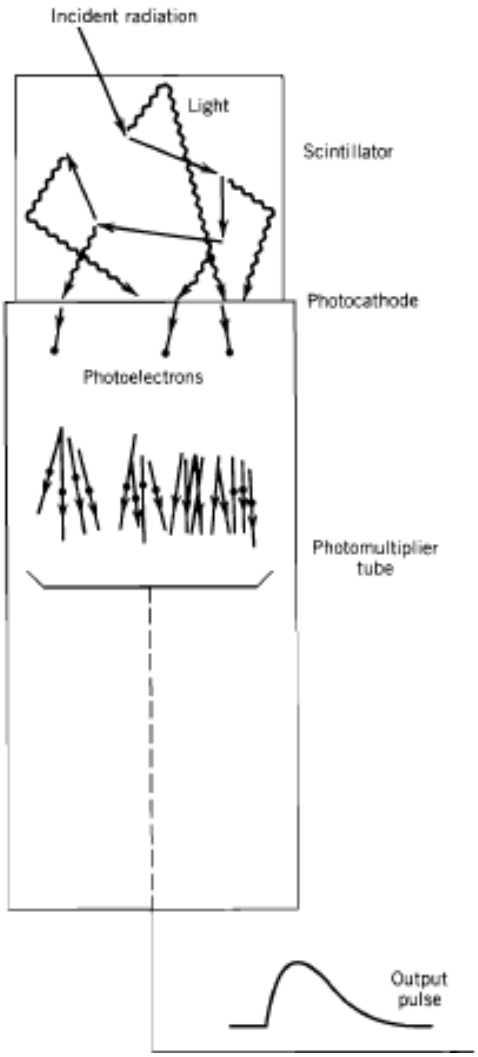

Fig. 1

Basic Principles. The complete process of scintillators can be understood as follows, as shown in Fig. 1.

(1) The incident radiation enters the detector and suffers a large number of interactions, which result in the raising of the atoms to excited states.

(2) The excited states rapidly emit visible (or near-visible) light. The material is said to fluoresce.

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(3) The light strikes a photosensitive surface, releasing at most one photoelectron per photon.

(4) These secondary electrons are then multiplied, accelerated and formed into the output pulse in a tube, called the *photomultiplier tube* (or *PMT*).

Many different varieties of scintillators and PMTs are available, depending on the application in which they will be used. Properties that are usually considered in making the choice of a material include light output (the fraction of the incident energy that appears as light), efficiency (the probability for the radiation to be absorbed), timing and energy resolution. Other criteria may have to do with ease of working with the material. One common scintillator, crystalline NaI, is hygroscopic. Exposure to water vapour causes a transparent crystal to become an opaque powder and NaI must be kept sealed. On the other hand, many plastic scintillators can be cut with an ordinary saw and formed into any desired size and shape.

Types of Scintillators:

There are primarily two types of scintillators in common use in nuclear and particle Physics, namely organic or plastic scintillators and inorganic or crystalline scintillators.

Organic Scintillators. In organic scintillators (which can be liquid or solid), the interactions between the molecules are relatively weak and we can discuss their properties in terms of the discrete excited states of the molecules. There are two ways in which a molecule can absorb energy, e.g. the electrons can be excited to higher excited states and the atoms in the molecule can vibrate against one another. Typical spacing of vibrational energies is about 0.1 eV, while the electronic excitation energies are of the order of a few eV. The resulting structure may look something like that of Fig. 2. The excited electrons are generally those not strongly involved in the bonding of the material. In aromatic hydrocarbons, such as those typified by the ring structure of benzene, three of the four valence electrons of carbon are in the hybridized orbitals, called $\sigma -$ orbitals. These are strongly localized between each carbon, its two carbon neighbours and single hydrogen. The fourth electron, which is in the so-called

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$\pi -$ orbital, is not as well localized and does not participate in the bonding process as strongly as the $\sigma -$ electrons. It is this $\pi -$ electron that is most responsible for the scintillation process. The incoming radiation interacts with many molecules, losing a few eV at each interaction as it excites the molecule. Many possible vibrational states can be excited and also many possible electronic excited states. For simplicity only the lowest electronic excited state is shown. These decay quickly (≈ 1 ps) to the lowest vibrational state of the electronic excited state, which then decays (in a time of order ~ 10 ns) to one of the vibrational states of the electronic ground state. These in turn decay quickly to the vibrational ground state.

Under normal circumstances, at room temperature all of the molecules of the scintillator are in the lowest vibrational state of the electronic ground state. The thermal energy $k_B T$ at room temperature is ~ 0.025 eV, and thus according to the Boltzmann population distribution $e^{-\frac{E}{k_B T}}$, it is unlikely to find any population of the vibrational states above the electronic ground state. Thus only one of the many emitted photon transitions has any probability to be absorbed. This represents an important property of a scintillator that it must be transparent to its own radiation.

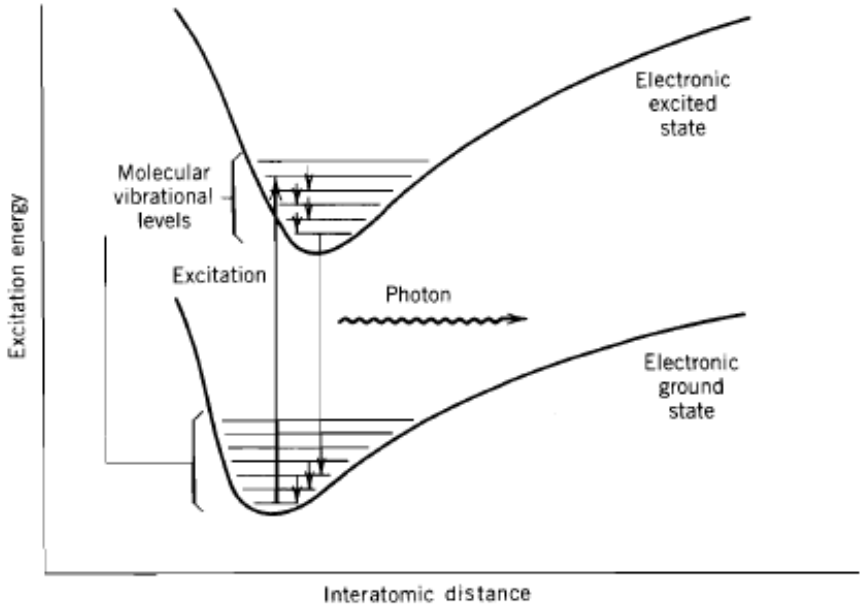

Fig. 2

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Inorganic Scintillators. Of the inorganic scintillators, the most common variety is the single crystal of an alkali halide, NaI is the most frequently used. A single crystal is needed to obtain transparency. Reflections and absorption at the crystal faces would make a polycrystalline scintillator useless. The cooperative interactions of the atoms in a crystal cause the discrete energy levels to smear out into a series of energy bands. The two highest bands are the valence band and the conduction band (shown in Fig. 3). In an insulating material such as NaI, the valence band states are generally full and the conduction band states are empty. An incoming radiation can excite an electron across the energy gap (about 4 eV) and into the conduction band. Eventually, it loses energy by emission of a photon and drops back into the valence band.

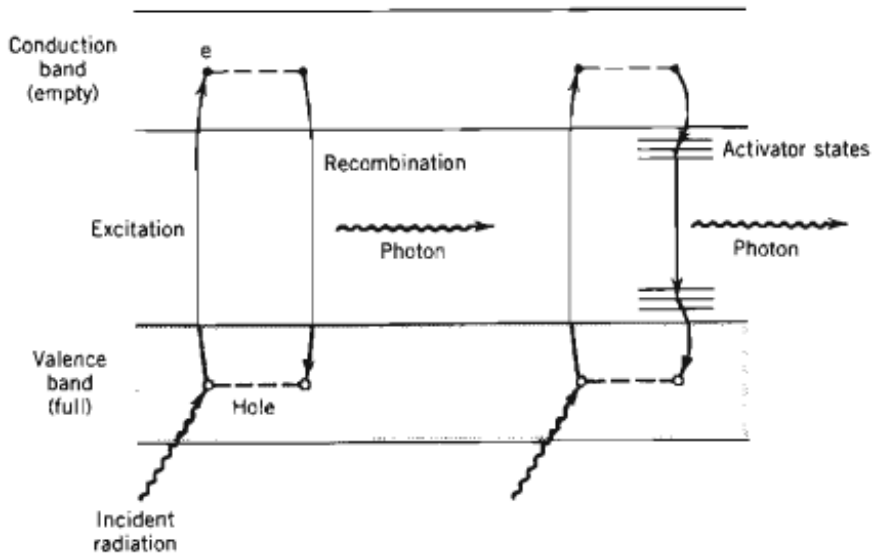

Fig. 3

To increase the probability for photon emission and to reduce self-absorption of the light, small amounts of impurities called *activators* are added to the crystal. A commonly used activator is thallium and so these detectors are indicated as, for instance, NaI(Tl). The activator provides states in the energy gap and the light emission takes place between the activator states. In the case of NaI, the wavelength of maximum emission is shifted from 303 nm in pure NaI to 410 nm in NaI(Tl). Absorption at this energy cannot occur in NaI(Tl), because the activator ground states are not populated and the change in wavelength from the

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ultraviolet to the visible gives a better overlap with the maximum sensitivity of most photomultiplier tubes.

Coupling and Design of a Photomultiplier Tube:

The coupling of a scintillator to a photomultiplier tube (PMT) can be done in a variety of ways. Some detector-tube combinations are purchased as a sealed unit. NaI(Tl) detectors can be placed into direct contact with the glass of the PMT using transparent *optical grease* to provide a relatively uniform change in index of refraction and minimize internal reflection. Sometimes the photomultiplier geometry is very different from the scintillator geometry or it must be located far away from the scintillator (to eliminate the effects of magnetic fields, for instance). In this case a light pipe is used. Light pipes can be cut to any size or shape out of any ordinary transparent material such as Lucite. Both the scintillator and the light pipe must be wrapped with reflective material to improve the efficiency of light collection

A schematic diagram of a PMT is shown in Fig. 4. A small number of electrons (smaller than the number of incident photons) is released at the photocathode, then multiplied and focused by a series of electrodes called *dynodes*. The dynodes are connected to a voltage chain produced by a high-voltage supply and a series of voltage dividers. The typical potential difference between adjacent dynodes is about 100 V, and thus electrons strike the dynodes with about 100 eV of energy. The dynodes are constructed of materials with a high probability of secondary electron emission. It may take $2-3$ eV to release an electron and thus a gain in the number of electrons of factors of $30-50$ is possible. However, because the electrons are released in random directions in the material, relatively few will actually be released at the surface and a gain of 5 at each dynode is more typical. Even so, with a 10-dynode tube, the overall gain would be 5^{10} (about $\sim 10^7$). For energy spectrometers, two important characteristics are *linearity* and *stability*. Linearity means that the amplitude of the eventual output pulse must be directly proportional to the original number of scintillation events and thus in turn to the energy deposited in the detector by the radiation. Because the gain of each dynode stage depends on the voltage

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difference, any change in the high voltage will cause a variation in the output pulse. Thus it is often necessary to stabilize the high-voltage supply.

A wide variety of photomultiplier tubes is available. Choices may be determined by such parameters as physical size, response of photocathode to different incident wavelengths, sensitivity of photocathode, gain, noise level, and timing characteristics.

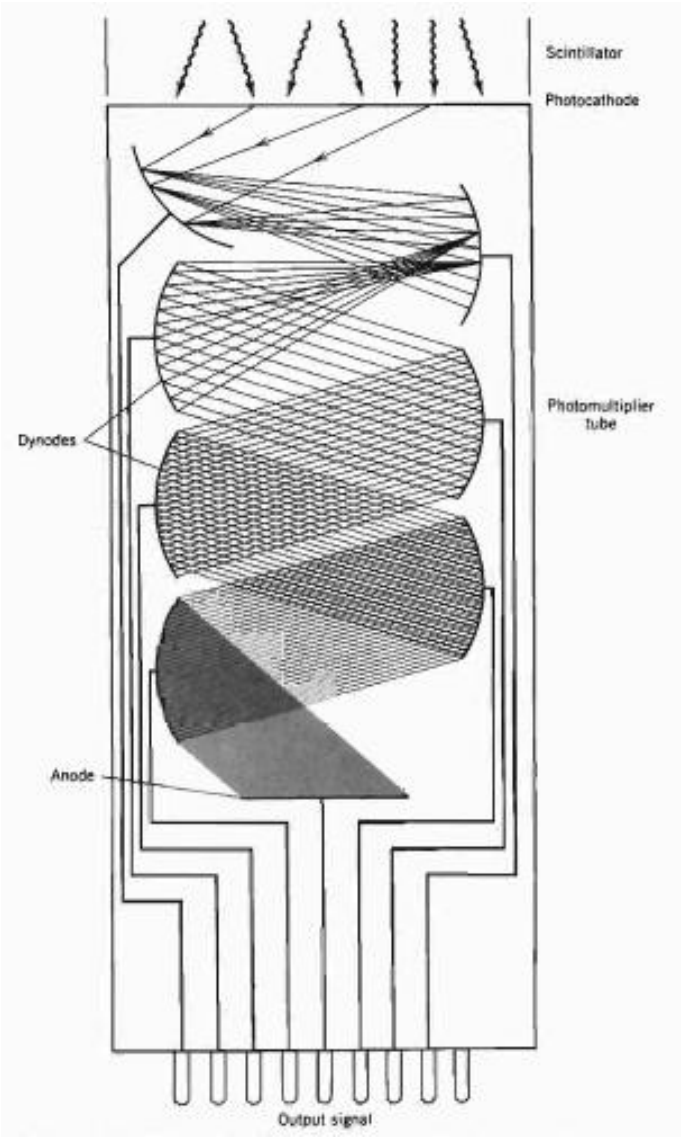

Fig. 4

A scintillator used in conjunction with a photomultiplier is consequently an excellent detector of charged particles, and of any photons or neutrons that

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interact within the scintillator material. As an example, let us consider the beta decay of ^{60}Co (shown in Fig. 5)

$$^{60}\text{Co}^{27} \rightarrow {}^{60}\text{Ni}^{28} + e^{-} + \bar{\nu}_e$$

The ^{60}Ni nucleus in this decay is, in fact, left in an excited state and decays to the ground level through two successive photon emissions, one of 1.17 MeV to the first excited level, which is followed by a 1.33 MeV photon to the ground level. Let us suppose that the ^{60}Co sample is mounted on the front face of a NaI(Tl) crystal and a PMT is attached to the opposite side of the crystal. Because the anticipated signals are small, the crystal and PMT must be properly wrapped to prevent external light from leaking into the detector. Also, because crystals such as NaI are often hygroscopic, they must be well sealed to prevent deterioration through absorption of moisture. Plastic scintillators do not have this disadvantage.

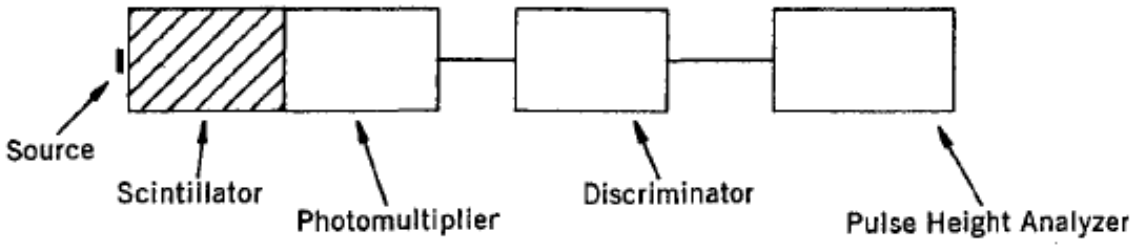

Fig. 5

When photons from the de-excitation of ^{60}Ni enter the scintillator, they can interact through the photoelectric effect, through Compton scattering or through e^+ e^- pair production. Any photon that is converted to a photoelectron through the photoelectric effect generally deposits all of its energy within the scintillator in the form of ionization produced by the emitted electron. The intensity of the subsequently produced scintillation light is therefore proportional to the energy of the original photon. On the other hand, photons that undergo Compton scattering usually do not deposit all their energy within the scintillator, unless that scintillator block is exceedingly large. That is, although the scattered electrons often deposit their entire energy, the scattered photons tend to escape from the scintillator. The radiation length of NaI is about 2.6 cm, while that of

plastic scintillator is about 40 cm. It is therefore not surprising that, for detectors several cm on a side, only a fraction of the energy of the incident photon is converted into ionization, and some leaves the detector. Pair production is exceedingly unlikely for low-energy photons, but, when it occurs, the produced electron and positron deposit their kinetic energy in the scintillator and eventually the positron annihilates with an atomic electron, yielding two 0.511 MeV photons.

This concludes part 2 of this e-report.

The discussion will be continuing in the part 3 of this e-report.

Reference(s):

Introduction to Nuclear and Particle Physics, A. Das & T. Ferbel, World Scientific

Introductory Nuclear Physics, Kenneth S. Krane, John Wiley & Sons

(All the figures have been collected from the above mentioned references)