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An Overviews of Gamma Ray Detector - A Review

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ABSTRACT

In order for a gamma ray to be detected, it must interact with matter that interaction must be recorded. Fortunately, the electromagnetic nature of gamma-ray photons allows them to interact strongly with the charged electrons in the atoms of all matter. The key process by which a gamma ray is detected is ionization, where it gives up part or all of its energy to an electron. The ionized electrons collide with other atoms and liberate many more electrons. The liberated charge is collected, either directly (as with a proportional counter or a solid-state semiconductor detector) or indirectly (as with a scintillation detector), in order to register the presence of the gamma ray and measure its energy. The final result is an electrical pulse whose voltage is proportional to the energy deposited in the detecting medium. In this paper, we will present some general information on types of gamma-ray detectors that are used in non-destructive assay (NDA) of nuclear materials.
Keywords : Gamma Ray, Electromagnetic, Scintillation Detector, Ionizations, Photomultiplier

I. INTRODUCTION

Gamma rays are the highest-energy form of electromagnetic radiation, being physically the same as all other forms (e.g., x-rays, visible light, infrared, radio) but having (in general) higher photon energy due to their shorter wavelength. Because of this, the energy of gamma-ray photons can be resolved individually, and a gamma-ray spectrometer can measure and display the energies of the gamma-ray photons detected. The boundary between gamma rays and X rays is somewhat blurred, as X rays typically refer to the high energy electronic emission of atoms, which may extend to over 100 Kev, whereas the lowest energy emissions of nuclei are typically termed gamma rays, even though their energies may be below 20 Kev. Gamma-ray detectors can be placed in two broad classes. The first class includes what would typically be called spectrometers or photometers in optical astronomy. These instruments are "light buckets" that focus on a region of the sky containing the target and collect as many photons as possible. These types of detectors typically use scintillators or solid-state detectors to transform the gamma-ray into optical or electronic signals, which are then recorded. The second class includes detectors that perform the difficult task of gamma-ray imaging. Detectors of this type either rely on the nature of the gamma-ray interaction process such as pair production or Compton scattering to calculate the arrival direction of the incoming photon, or use a device such as a coded-mask to allow an image to be reconstructed. The operation of scintillation and solid state detectors for gamma-ray astronomy is the same as it is for X-ray astronomy. Below we describe three types of detectors used uniquely for gamma-ray astronomy.

II. Detector Overview

The kinds of detectors commonly used can be categorized as:
(1) Gas-filled Detectors (2) Scintillation Detectors (3) Semiconductor Detectors

The choice of a particular detector type for an application depends upon the X-ray or gamma energy range of interest and the application's resolution and efficiency requirements. Additional considerations include count rate performance, the suitability of the detector for timing experiments, and of course, price.

III. Gas-Filled Detectors

Gas counters consist of a sensitive volume of gas between two electrodes. (See Fig.1) In most designs the outer electrode is the cylindrical wall of the gas pressure vessel, and the inner (positive) electrode is a thin wire positioned at the center of the cylinder. In some designs (especially of ionization chambers) both electrodes can be positioned in the gas separate from the gas pressure vessel.

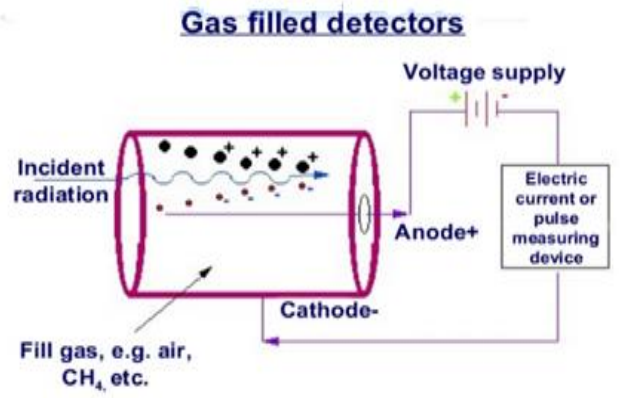

Fig.1 Gas filled detectors

An ionization chamber is a gas-filled counter for which the voltage between the electrodes is low enough that only the primary ionization charge is collected. The electrical output signal is proportional to the energy deposited in the gas volume. If the voltage between the electrodes is increased, the ionized electrons attain enough kinetic energy to cause further ionizations. One then has a proportional counter that can be tailored for specific applications by varying the gas pressure and/or the operating voltage. The output signal is still proportional to the energy deposited in the gas by the incident gamma-ray photon, and the energy resolution is intermediate between NaI scintillation counters and germanium (Ge) solid-state detectors. Proportional counters have been used for spectroscopy of gamma rays and x rays whose energies are low enough (a few tens of Kev) to interact with reasonable efficiency in the counter gas. If the operating voltage is increased further, charge multiplication in the gas volume increases until the space charge produced by the residual ions inhibits further ionization. As a result, the amount of ionization saturates and becomes independent of the initial energy deposited in the gas. This type of detector is known as the Geiger-Mueller (GM) detector. A GM tube gas counter does not differentiate among the kinds of particles it detects or their energies, it counts only the numbers of particles entering the detector. Gas counters do not have much use in gamma-ray NDA of nuclear materials. The scintillation and solid-state detectors are much more desirable for obtaining the spectroscopic detail needed in the energy range typical of uranium and plutonium radiation (approximately 100-1000 Kev

IV. The Scintillation Detectors

The sensitive volume of a scintillation detector is a luminescent material (a solid, liquid, or gas) that is viewed by a device that detects the gamma-ray-induced light emissions [usually a Photomultiplier tube (PMT)]. The scintillation material may be organic or inorganic; the latter is more common. Examples of organic scintillators are anthracene, plastics, and liquids. The latter two are less efficient than anthracene (the standard against which other scintillators are compared). Some common inorganic scintillation materials are sodium iodide (NaI), cesium iodide (CSI), zinc sulfide (ZnS), and lithium iodide (LiI). The most common scintillation detectors are solid, and the most popular are the inorganic crystals NaI and CSI. A new scintillation material, bismuth germanate ($BiqGesO_{12}$), When gamma rays interact in scintillator material, ionized (excited) atoms in the scintillator material A "relax" to a lower-energy state and emit photons of light. In a pure inorganic scintillator crystal, the return of the atom to lower-energy states with the emission of a photon is an inefficient process. Furthermore, the emitted photons are usually too high in energy to lie in the range of

wavelengths to which the PMT is sensitive. Small amounts of impurities (called activators) are added to all scintillators to enhance the emission of visible photons. Crystal de-excitations channeled through these impurities give rise to photon that can activate the PMT. One important consequence of luminescence through impurities is that the bulk scintillator crystal is transparent to the scintillation light. A common example of scintillator activation encountered in gamma-ray measurements is thallium-doped sodium iodide [NaI(Tl)]. The scintillation light is emitted isotopically; so the scintillator is typically surrounded with reflective material to minimize the loss of light and then is optically coupled to the photocathode of a PMT.

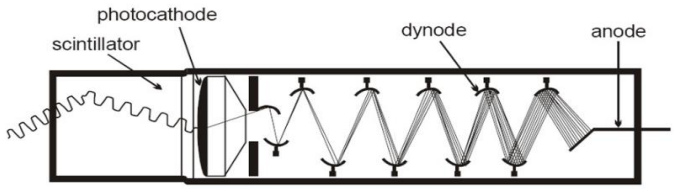

Fig.2 Scintillation Detector

Scintillation photons incident on the photocathode liberate electrons through the photoelectric effect, and these photoelectrons are then accelerated by a strong electric field in the PMT. As these photoelectrons are accelerated, they collide with electrodes in the tube (known as dynodes) releasing additional electrons. This increased electron flux is then further accelerated to collide with succeeding electrodes, causing a large multiplication (by a factor of 10^4 or more) of the electron flux from its initial value at the photocathode surface. Finally, the amplified charge burst arrives at the output electrodes (anode) of the tube. The magnitude of this charge ,surge is proportionality to the initial amount of charge liberated at the photocathode of the PMT, the constant of proportionality is the gain of the PMT. Furthermore, by virtue of the physics of the photoelectric effect, the initial number of photoelectrons liberated at the photocathode, is proportional to the amount of light incident on the phototube, which, in turn, is proportional to the amount of energy deposited in the scintillator by the gamma ray (assuming no light loss from the scintillator volume). Thus, an output signal is produced that is proportional to the energy deposited by the gamma ray in the scintillation medium. As discussed above, however, the spectrum of deposited energies (even for a monoenergetic photon flux) is quite varied, because of the occurrence of the photoelectric effect, Compton effect, and various scattering phenomena in the scintillation medium and statistical fluctuations associated with all of these processes.

V. Solid State Detectors

In solid-state detectors, the charge produced by the photon interactions is collected directly. The gamma-ray energy resolution of these detectors is dramatically better than that of scintillation detectors; so greater spectral detail can be measured and used for SNM evaluations. A generic representation of the solid-state detector is shown in Fig.3. The sensitive volume is an electronically conditioned region (known as the depleted region) in a semiconductor material in which liberated electrons and holes move freely. Germanium possesses the most ideal electronic characteristics in this regard and is the most widely used semiconductor material in solid-state detectors. The detector functions as a solid-state proportional counter, with the ionization charge swept directly to the electrodes by the high electric field in the semiconductor, produced by the bias voltage. The collected charge is converted to a voltage pulse by a preamplifier. The most popular early designs used lithium-drifted germanium [Ge (Li)] as the detection medium. The lithium served to inhibit trapping of charge at impurity sites in the crystal lattice during the charge collection process. In recent years, manufacturers have produced hyper pure germanium (HPGe) crystals, essentially eliminating the need for the lithium doping and simplifying operation of the detector.

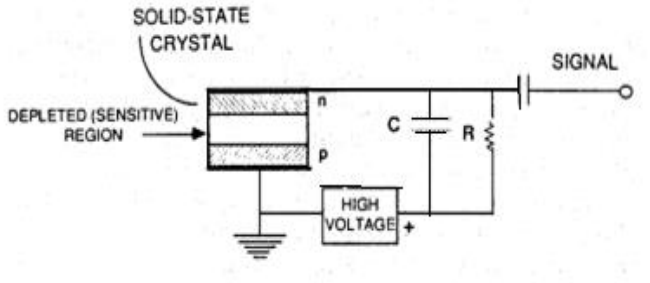

Fig.3 Solid State Detectors

VI. Detector Efficiency

The efficiency of a detector is a measure of how many pulses occur for a given number of gamma rays. Various kinds of efficiency definitions are in common use for gamma ray detectors:

(a) Absolute Efficiency: The ratio of the number of counts produced by the detector to the number of gamma rays emitted by the source (in all directions).

(b) Intrinsic Efficiency: The ratio of the number of pulses produced by the detector to the number of gamma rays striking the detector.

(c) Relative Efficiency: Efficiency of one detector relative to another; commonly that of a germanium detector relative to a 3 in. diameter by 3 in. long NaI crystal, each at 25 cm from a point source, and specified at 1.33 MeV only.

(d) Full-Energy Peak (or Photo peak) Efficiency: The efficiency for producing full-energy peak pulses only, rather than a pulse of any size for the gamma ray

VII. Conclusion

Gamma-ray assay applications have varied objectives that can dictate the use of a variety of detectors. Discussion of the choice of detectors from the standpoint of energy resolution. An additional consideration is the gamma- ray (or x-ray) energy range of interest in a particular application. In general, the photon energies of major interest in the NDA of nuclear material range from below the x-ray region (85- 100 Kev) to approximately 400 Kev. As was illustrated in the discussion above, detectors that are thick in the axial dimension are more efficient for the high-energy applications, and for low-energy gamma and x-ray measurements, axially thin detectors are better suited because of their optimum detection efficiency at low to medium energies and relative insensitivity to higher-energy radiation. Other factors, such as cost and portability may the use of less expensive and more portable NaI (scintillation) detectors, with the attendant sacrifice of good energy resolution. In recent years, high-resolution detectors have become available with small liquid-nitrogen dewars that render the detector assembly every bit as portable as a NaI detector. However, cost considerations still favor the scintillation detector over the high-resolution detector

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