Chapter Seven (Nuclear Detectors)

Ali Abdulwahab Ridha
Al-Mustansiriya University

Chapter Seven
(Nuclear Detectors)

Ionizing radiation is rarely detected directly. Instead, detectors usually measure the secondary products arising from the interactions of the radiation with the detector material. For example, as an alpha or beta particle traverses a detector's sensitive volume, electron-ion pairs or electron-hole pairs are created and the subsequent movement and collection of charges gives rise to an electrical pulse or current. Indirectly ionizing radiation such as gamma photons and neutrons must first undergo interactions in the detector material that produce secondary charged particles, recoil atoms or electrons that, in turn, produce charge pairs as they slow down.

The collection of the ionization created by radiation in a detector volume can be used simply to detect the passage of a radiation particle. The rate of generation of radiation-induced pulses can then be used to measure the rate at which radiation particles traverse the detector. Such detectors are termed radiation counters. In some detectors, the magnitude of the radiation induced pulse is related to the type of radiation particle and its energy. By measuring both the number of pulses and the distribution of pulse sizes produced by a given type of radiation, both the number and energy distribution of the incident radiation can be determined. These detectors can then be used as energy spectrometers. In some detectors the average current can be used as a measure of the amount of ionization or energy deposition, per unit mass of detector material, caused by incident radiation. These detectors can then be calibrated to measure radiation absorbed doses and are thus called dosimeters. In this chapter, the properties of some of the most common radiation detectors are reviewed.

An important aspect of radiation detection is an assessment of the uncertainties associated with ionization measurements. Both the release of radiation by radioactive decay and the interactions of radiation with matter are stochastic in nature. Thus, repeated measurements of radiation emitted by a source of constant activity, in a given detector volume in a given time interval, exhibit random statistical fluctuations. The quantification of such statistical fluctuations is a necessity in radiation measurements.

(7-1) Gas-Filled Radiation Detectors

The idea of measuring the radiation induced ionization in a gas volume dates to the nineteenth-century. These early gas-filled detectors became known as ionization chambers. As ionizing radiation passes through a chamber, the motion within an electric field of the ion pairs formed inside the chamber produces an electrical current. The magnitude of the current is measured and correlated (calibrated) to the intensity of the radiation field. A very common geometry is a coaxial detector that consists of a thin, positively charged, center wire anode (held in place by insulators) surrounded by an outer, negatively-charged, cathode tube. The outer tube contains the gas and defines the active volume of the chamber. Air filled chambers may or may not be sealed from the ambient environment. A gas-filled chamber is illustrated in Fig. (7-1).

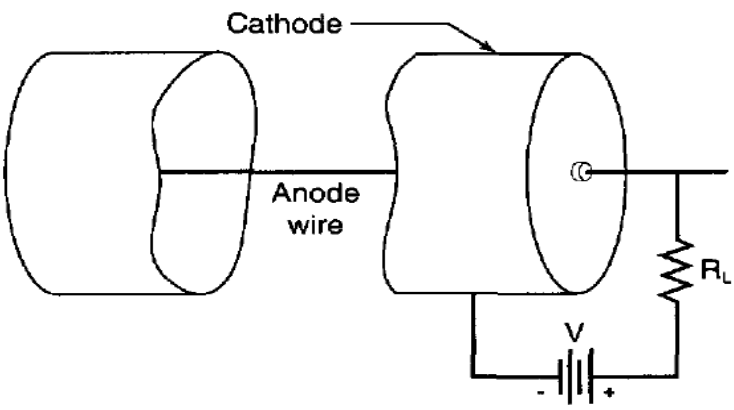

Figure (7-1) Basic elements of a gas-filled radiation-detector tube. The cathode is often used to seal the gas cavity from the ambient environment. The output voltage pulse is produced across the load resistor.

Radiation either interacts in the wall of the chamber or directly in the filling-gas. For incident electromagnetic radiation the dominant interactions, photoelectric effect, Compton scatter, and pair production, occur primarily in the chamber wall material. If the electrons released from the atoms in the wall material escape from the wall and enter the active gas volume of the chamber, then these charged particles (secondary radiation) produce ionization as they pass through the gas. The potential difference between the anode wire and the cathode establishes an electric field that causes positive and negative charges to move in opposite directions. Electrons rapidly drift toward the anode and positive ions migrate more slowly toward the cathode. The motion of these ion pairs causes a flow of current in the external circuit and establishes a voltage across the load resistance. If the incident radiation field contains beta particles, for example, then the chamber must be constructed so that these particles can enter the volume. This is achieved by placing a very thin "window" on one end of the tube.

There are three basic types of gas-filled radiation detectors: ionization chambers, proportional counters and Geiger-Mueller counters. All three are known as ionization chambers, but they each have a unique process for forming the total number of ion pairs that are collected at the electrodes. All three operate by forming initial ion pairs from the incident radiation. Once these ion pairs are formed, it is important that they do not recombine and thereby fail to contribute to the electrical signal.

Figure (7-2) shows the various operational regions of gas-filled chambers. Region I represents the recombination region where the potential difference between the anode and cathode is not sufficient to collect all the initial ion pairs. Ion chambers operating in this region are not useful radiation detectors.

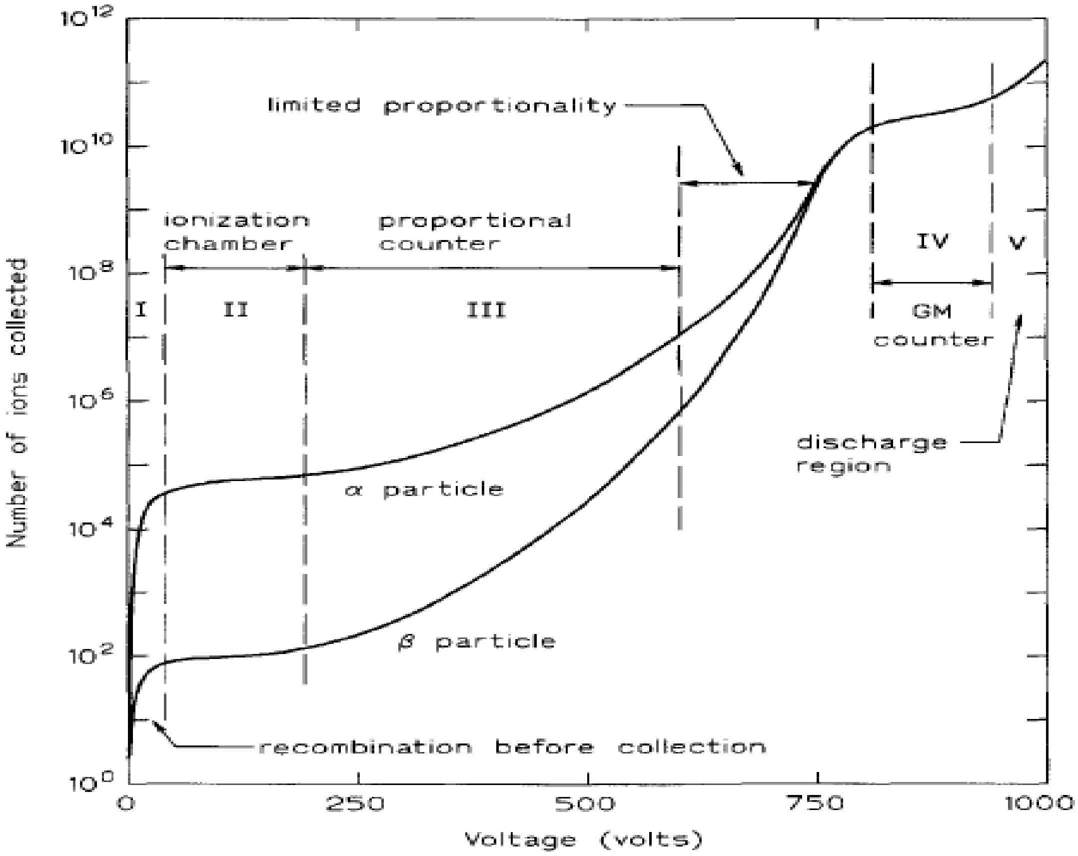

Figure (7-2) Operational regions for gas-filled radiation detectors.

As the potential difference between the anode and cathode is increased, the ionization chamber Region II is entered. In this region the resulting output current is referred to as the ionization chamber saturation current. Region III represents the proportional counter region. In this region, electrons acquire sufficient energy to induce secondary ionization, and hence multiplication. This internal ion-pair multiplication increases the total number of ion pairs in the active volume and, hence, the output current increases by a multiplicative factor M > 1. This region is called the proportional counter region since the output current, or total collected charge per interaction, is proportional to the initial number of ion pairs created by the incident radiation. Next is entered a limited proportionality region where the number of ion-electron pairs collected is relatively independent of the initial number of ion-electron pairs created by the incident radiation. This region generally is not useful operationally.

The region of Geiger-Mueller (GM) counter operation, Region IV, exhibits a "plateau" over which M reaches a nearly constant value. In this region one avalanche produces secondary photons whose interactions produce other local avalanches until the entire anode is surrounded by ion-electron pairs. In this region, the charge collected per interaction is no longer proportional to the initial number of ion pairs created. Therefore, it is very difficult to distinguish between different types of incident radiation or to gain knowledge about the energy of the incident radiation.

If the tube voltage is too large, the tube undergoes continuous avalanches around the central anode, one leading to another. This region V, is known as the continuous discharge region. Its entry normally leads to failure of the ion chamber.

(7-1-1) Ionization Chambers

Ionization chambers or ion chambers are widely used as radiation monitors. They can be designed to respond to alpha particles, beta particles, gamma rays, x rays, and neutrons. The ion chamber is the most basic type of gas-filled radiation detector since it operates without gas multiplication. They are often operated by directly measuring the output current. When operated at the saturation current level (region II of Figure (7-2)), the output current level is proportional to the intensity of the incident radiation and permits a direct measurement of the exposure rate. In an ion chamber with parallel-plate electrodes and a uniform electric field, current pulses from individual events can be registered, thereby allowing energy spectroscopy of the incident radiation. In their most common cylindrical geometry, however, ionization chambers cannot be used for this purpose since the pulse amplitude is dependent upon where the ion-electron pairs are formed in the detector.

(7-1-2) Proportional Counters

Proportional counters are gas-filled chambers operated in region III of Figure (7-2). In this region, there is an internal multiplication in the chamber gas of the original ion-electron pairs created by the incident radiation. The physical mechanism for this multiplication process is discussed in the next section. This internal multiplication M is typically from 10 to 10,000. Because of the location of the gas multiplication avalanche, near the central wire, the output voltage pulse is not only amplified by a factor of M but the pulse amplitude is proportional to the total ionization energy deposited inside the active volume of the detector. This feature allows the proportional counter to be used as a spectrometer by using the output pulse amplitude to infer the energy of the incident radiation. Also, since the number of ion pairs is proportional to the initial ionization caused by the incident radiation, proportional counters can be used to distinguish between different types of charged particles. For example, one common application is to use a gas-flow counter to distinguish between beta particles and alpha particles.

(7-1-3) Geiger-Mueller Counters

Geiger and Mueller developed the Geiger-Mueller (GM) detector in 1928. These radiation detectors are simple and robust devices that continue to be an important tool for sensing the presence of ionizing radiation. These gas filled detectors operate in region IV of Fig. (7-2), and have the remarkable property that the size of the pulse, or total charge produced in the active volume is independent of the ionization energy deposited by the initial ion pairs. Consequently, these detectors do not have the inherent capability of distinguishing between different types of radiation or measuring radiation energy. They can, however, be configured so that they are sensitive to both charged particles (alpha particles and beta particles) and electromagnetic radiation (x rays and gamma rays).

A GM detector's sensitivity to charged particles is limited only by the thickness of the entrance window. The entrance window must be just thick enough to ensure that the chamber's filling gas does not escape. Once charged particles enter the active volume of the detector, they are detected with almost 100% efficiency since it takes only one ion-electron pair to initiate the pulse formation process.

Operating Voltage

One of the first steps in characterizing the operation of any gas-filled radiation detector is establishing the correct operating voltage. GM counters have a fairly wide range over which they can be operated. However, each counter should be operated near the center of its plateau within the GM region shown as region IV in Fig. (7-2), this assures the best long-term performance because, at this voltage, small changes in the applied voltage have an insignificant effect on the amplitude of the output pulse. If the applied voltage is too low, then the gas multiplication is less than desired and the counting rate is very sensitive to small changes in voltage.

Applications

GM counters are often the detectors of choice for applications requiring information about only the magnitude or intensity of the radiation field. As such they find wide application in hand-held survey meters used to detector radiation fields. Other types of radiation detectors are more suitable if information is needed on the type or energy of the radiation. GM counters can be made in essentially any size and shape. Their low cost and high efficiency make them suitable as sensors of beta particles, x-rays and gamma rays. This is especially true if the radiation level is low enough that dead time losses are not a concern. These detectors are seldom used to detect neutrons although, with a cadmium cover surrounding the tube, the GM detector is sensitive to thermal neutrons and may be calibrated for thermal neutron flux density. Because of their poor energy response, inability to distinguish among different types of radiation, care must be taken to assure that some knowledge of the radiation field is available before making measurements with these counters.

(7-2) Scintillation Detectors

There are two types of scintillation detectors, (1) solid crystals of inorganic material, and (2) plastics and liquids consisting of organic molecules. Their modes of excitation differ but the final result is the same. As charged particles pass through the material the energy that they lose is transferred into excitation energy of the inorganic crystals or molecular excitation of the organic molecules. The excitation energy is released in fluorescence, i.e., scintillation. The number of light photons emitted in any one event is proportional to the energy lost by the initial charged particle in that event. The time dependence of the fluorescence emission, and hence the output pulse shape, is dependent upon the specific type of material. Although scintillator material has been used for almost 100 years to detect ionizing radiation, their widespread application dates from the development of the photomultiplier tube (PMT) some 50 years ago. This vacuum tube device allows the measurement of extremely low levels of light. In a PMT the incident photons strike a photocathode thereby liberating photoelectrons. These photoelectrons are then accelerated towards another electrode at a higher potential where the energetic impinging electrons cause more electrons to be emitted. This electron multiplication process continues along a series of electrodes, each at higher potential than the previous and, at each, the electron population is increased. The number of electrons finally collected at the last electrode may be millions of times greater than the number of electrons that began the cascade. In essence, the PMT is a photon to electron amplifier.

A typical scintillator detector assembly consists of a hermetically sealed scintillation material optically mounted to the PMT's photocathode, a voltage divider string in the PMT, and a preamplifier to produce a voltage pulse from the electrons collected at the last PMT electrode. These components are usually bound together in a single assembly By using this common configuration, the detector assembly is a stand-alone device that only requires an external voltage for the PMT and an external power supply for the preamplifier. Such an assembly is often called a scintillation detector.

The amplitudes of the output voltage pulses are proportional to the energy deposited by charged particles produced in the scintillation material. A gamma ray penetrating the scintillator material may give up its energy to the scintillator material through photoelectric interactions, Compton scattering and pair production reactions. If all of the incident gamma-ray energy is deposited in the scintillator material, the number of scintillation photons produced is proportional to the incident gamma-ray energy. Thus, by measuring the distribution of pulse sizes or the pulse height distribution (PHD) produced by the scintillation detector, the energy distribution of the incident gamma rays can be determined. Thus, one of the most important applications of scintillation detectors is gamma-ray spectroscopy.

(7-2-1) NaI(Tl) Scintillation Detectors

The most popular inorganic scintillation material is NaI(Tl). These detectors are available in a variety of sizes and shapes. Because the maximum wavelength of light emitted by this material is 415 nm, it is easy to find commercially available PMTs whose maximum sensitivity matches the fluorescence emission spectrum. The relatively large decay time constant is normally not a problem since a very high efficiency for x-rays and gamma-rays dominates their radiation response. Of all the different NaI(Tl) detectors available to characterize gamma-ray radiation fields, the 3x3 inch right circular cylindrical detector, has historically been the favorite. This is the most extensively characterized NaI(Tl) detector and extensive efficiency data are available in the literature. A typical NaI(Tl) pulse height distribution is shown in Fig. (7-3). Because of its very high efficiency for electromagnetic radiation, NaI(Tl) is widely used to measure x rays and gamma rays. X-ray detectors with a thin entrance window containing a very thin NaI(Tl) detector are often used to measure the intensity and/or spectrum of low energy electromagnetic radiation. Because NaI(Tl) detectors do not require cooling, they can be used in a great variety of applications. Field applications are possible since they can operate over a long time period in warm and humid environments, resist a reasonable level of mechanical shock, and are resistant to radiation damage. Basically, for any application requiring a detector with a high gamma-ray efficiency and a modest resolution, the NaI(Tl) detector is clearly a good choice.

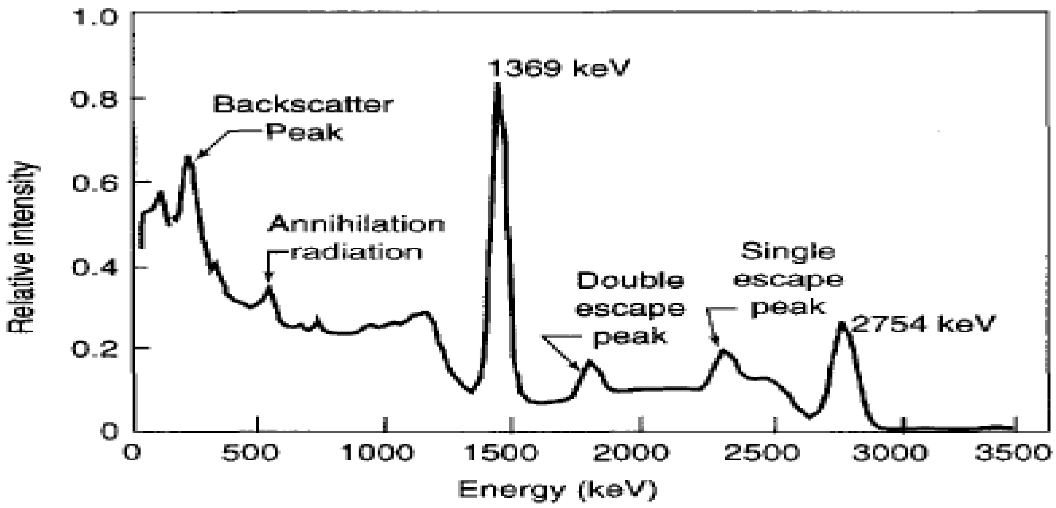

Figure (7-3) Pulse height distribution of the gamma rays emitted by the radioactive decay of ^{24}Na as measured by a NaI(Tl) scintillation detector. In addition to the two photopeaks, corresponding to the complete absorption of the ^{24}Na 2.754 and 1.369-MeV gamma rays, several other peaks are also apparent. The single and double escape peaks arise from the escape of one and both 0.511MeV annihilation photons generated in the NaI crystal by the annihilation of positrons created in pair-production interactions. The annihilation peak is caused by 0.511MeV annihilation photons produced outside the NaI crystal and subsequently depositing their energy in the crystal. The backscatter peak arises from photons scattered from the source material into the NaI detector.

(7-3) Semiconductor Ionizing-Radiation Detectors

Functioning of these radiation detectors is based upon the newest technologies. The impact on radiation detection and measurement has been revolutionary because of unique semiconductor properties, especially outstanding energy resolution. New semiconductor detectors continue to be introduced into the market place.

(7-3-1) Germanium Semiconductor Detectors

There are two main types of germanium semiconductor detectors: (1) Ge(Li) a germanium crystal doped with lithium ions to cancel the effect of natural impurities in the germanium crystal, and (2) the more recent (HPGe) high purity germanium crystal in which impurity atom concentration are less than 10^{10} atom/cm^3. The more expensive HPGe detectors have replaced the older Ge(Li) technology since they can be kept at room temperature when not in use whereas Ge(Li) crystals must always be kept at liquid nitrogen temperatures (-196 ^{o}C).

Germanium detectors, besides having exceptional energy resolution, are very efficient for detecting photons. Their efficiency ranges from excellent for low energy x-rays too good for medium to high-energy gamma rays over an energy range of 1 keV to 10 MeV. The performance of these detectors is often compared to NaI(Tl) and Cd/Zn telluride (CZT) detectors. Because of the higher atomic number arid larger size, NaI(Tl) detectors often have a higher efficiency for high energy gamma rays than do germanium detectors, but a much poorer energy resolution. The dramatic difference in the energy resolution between NaI(Tl) and Ge(Li) spectrometers is shown in Fig. (7-4).

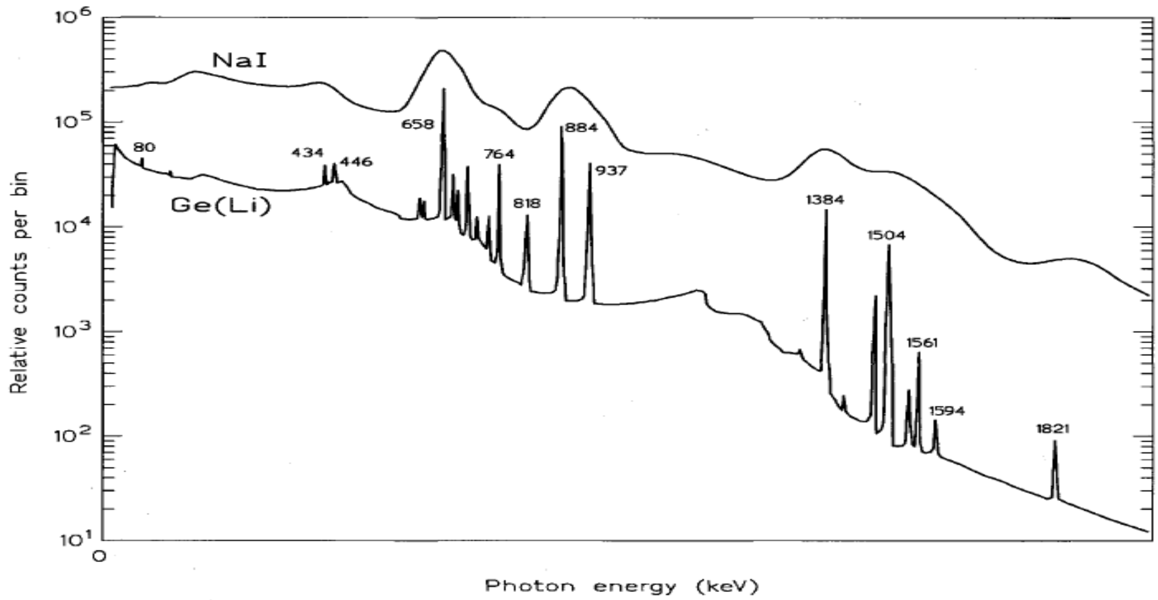

Figure (7-4) Comparison of the energy resolution of Ge(Li) and NaI(Tl) detectors. The gamma-ray source is a mixture of ^{108m}Ag and ^{110m}Ag.

(7-3-2) Silicon Semiconductor Detectors

Si(Li) detectors with thin entrance windows are commonly used in alpha and beta particle spectrometers. They can be configured to achieve essentially 100% intrinsic efficiency and have excellent resolution. They also offer an inexpensive option for x-ray spectroscopy. Since Si(Li) detectors have a much lower atomic number than CZT. NaI(Tl), and HPGe, their relative efficiency per unit thickness is significantly lower for electromagnetic radiation. However, for x-ray or gamma ray energies less than about 30 keV, commercially available Si(Li) detectors are thick enough to provide performance which is superior to CZT, NaI(Tl), and HPGe. For example, a 3 to 5 mm-thick detector with a thin entrance window has an efficiency of 100% near 10 keV. Based upon the fact that a majority of the applications require a thin window, Si(Li) detectors are often manufactured with very thin beryllium windows.

(7-3-3) Cadmium Zinc Telluride Detectors

Cadmium zinc telluride (CZT) is a new high-resolution and high-atomic number semiconductor detector material. A reasonable degree of cooling for the detector and the directly coupled preamplifier enhances detector system performance. CZT detectors offer an excellent option for low energy x-ray spectroscopy where cooling is not possible. Keeping the detector and preamplifier at about -30 °C, is adequate to achieve optimum energy resolution. By contrast, HPGe detectors must be cooled at liquid nitrogen temperatures to achieve optimum resolution. These detectors are not available in large sizes. Their small size diminishes the possibility of making detectors with large efficiencies for high-energy electromagnetic radiation. Therefore, the major application is low energy x or gamma-ray spectroscopy.

(7-4) Personal Dosimeters

(7-4-1) Pocket Ion Chamber

Very familiar to radiation workers over many, many years are the self-reading pocket ionization chamber (PIC) and the film badge dosimeter. The pocket ionization chamber is an ion chamber, as described in Section (7-1), in the form of a cylinder about the size of a fountain pen. A charge is placed on the electrodes of the ion chamber and the corresponding voltage is displayed through an eyepiece using an electroscope. As the ion chamber receives radiation exposure, the electrodes are discharged and the voltage change of the electroscope is presented in a reticule scaled to radiation dose or exposure. More commonly, the PIC is sensitive only to gamma radiation. However, neutron sensitive ionization chambers are also used, calibrated in dose equivalent.

(7-4-2) Film Badge

The film badge consists of a packet of photographic film sealed in a holder with attenuating filters. Ionizing radiation darkens the film, as in the production of an x-ray image. The filtration is designed to render the degree of film darkening as nearly as possible a known function of gamma-ray exposure, independent of the energy of the incident gamma rays. After the badge is carried by a radiation worker for a period of time, the film is processed, along with calibration films with the same emulsion batch exposed to known radiation doses. The worker's radiation dose for the period is assessed and ordinarily maintained in a lifetime record of exposure. In some cases special attenuation filters are used to relate the darkening of portions of the film to beta-particle or even neutron dose. Special badge holders in the form of rings or bracelets are used to monitor the radiation exposure of hands, wrists, and ankles.

(7-4-3) Thermo luminescent Dosimeter (TLD)

The thermo luminescent dosimeter (TLD) is a solid state radiation detector, whose radiation dose may be gauged by measurement of the release of light upon heating of the detector after exposure. TLDs are inorganic crystals such as LiF or $CaSO_4$ to which impurity elements, or dopants, such as Mg. P, Mn, or Cu are added in small concentrations. The TLD matrix is an insulator but the dopant adds hole and electron with energy levels within the insulator band gap. Upon radiation exposure, traps are filled. They remain filled until the TLD is heated, thereby releasing the trapped charge carriers. Recombination of newly mobile charged carriers leads to light emission. Natural Li, in which the abundance of ^{6}Li is 7.4%, is somewhat sensitive to thermal neutrons. TLD neutron sensitivity may be enhanced by increasing the abundance of the lighter isotope. Similarly, neutron insensitive LiF employs only ^{7}Li. Dosimetry of mixed neutron and gamma-ray radiation may be accomplished by using pairs of neutron-sensitive and neutron-insensitive TLDs.