Physics of X-RAY Production

When fast-moving electrons slam into a metal object, x-rays are produced. The kinetic energy of the electron is transformed into electromagnetic energy. The function of the x-ray machine is to provide a sufficient intensity of electron flow from the cathode to anode in a controlled manner. The three principal segments of an x-ray machine - ca control panel, a high-voltage power supply, and the x-ray tube are all designed to provide a large number of electrons focused to a small spot in such a manner that when the electrons arrive at the target, they have acquired high kinetic energy.

Kinetic energy is the energy of motion. Stationary objects have no kinetic energy; objects in motion have kinetic energy proportional to their mass and the square of their velocity.

The equation used to calculate kinetic energy is:

$$\mathbf{KE = 1/2\ mv^2}$$

where m is the mass in kilograms, v is the velocity in meters per second, and KE is the kinetic energy in joules. In determining the magnitude of the kinetic energy of a projectile, the velocity is more important than the mass.

In a x-ray tube, the projectile is the electron. As its kinetic energy is increased, both the intensity (number of x-rays) and the energy (their ability to penetrate) of the created x-rays are increased.

The x-ray machine is a remarkable instrument. It conveys to the target an enormous number of electrons at a precisely controlled kinetic energy. At 100 mA, for example, 6×10^{17} electrons travel from the cathode to the anode of the x-ray tube every second.

The distance between the filament and the target is only about 1 to 3 cm. Imagine the intensity of the accelerating force required to raise the velocity of the electrons from zero to half the speed of light in so short a distance.

The electrons traveling from the cathode to anode in a vacuum tube comprise the x-ray current and are sometimes called projectile electrons. When these projectile electrons impinge on the heavy metal atoms of the target, they interact with these atoms and transfer their kinetic energy to the target. These interactions occur within a very small depth of penetration into the target. As they occur, the projectile electrons slow down and finally come nearly to rest, at which time they can be conducted through the x-ray anode assembly and out into the associated electronic circuitry.

The projectile electron interacts with either the orbital electrons or the nuclei of target atoms. The interactions result in the conversion of kinetic energy into thermal energy and electromagnetic energy in the form of x-rays.

By far, most of the kinetic energy of projectile electrons is converted into heat. The projectile electrons interact with the outer-shell electrons of the target atoms but do not transfer sufficient energy to these outer-shell electrons to ionize them. Rather, the outer-shell electrons are simply raised to an excited, or higher, energy level. The outer-shell electrons immediately drop back to their normal energy state with the emission of infrared radiation. The constant excitation and restabilization of outer-shell electrons is responsible for the heat generated in the anodes of x-ray tubes.

Generally, more than 99% of the kinetic energy of projectile electrons is converted to thermal energy, leaving less than 1% available for the production of x-radiation. One must conclude, therefore, that, sophisticated as it is, the x-ray machine is a very inefficient apparatus.

The production of heat in the anode increases directly with increasing tube current. Doubling the tube current doubles the quantity of heat produced. Heat production also varies almost directly with varying kVp.

The efficiency of x-ray production is independent of the tube current. Regardless of what mA is selected, the efficiency of x-ray production remains constant. The efficiency of x-ray production increases with increasing projectile-electron endery. At 60 kVp, only 0.5% of the electron kinetic energy is converted to x-rays; at 120 MeV, it is 70%.

Characteristic Radiation

If the projectile electron interacts with an inner-shell electron of the target atom rather than an outer-shell electron, characteristic x-radiation can be produced. Characteristic x-radiation results when the interaction is sufficiently violent to ionize the target atom by total removal of the inner-shell electron. Excitation of an inner-shell electron does not produce characteristic x-radiation.

When the projectile electron ionizes a target atom by removal of a K-shell electron, a temporary electron hole is produced in the K shell. This is a highly unnatural state for the target atom and is corrected by an outer-shell electron falling into the hole in the K shell. The transition of an orbital electron from an outer shell to an inner shell is accompanied by the emission of an x-ray photon. the x-ray has energy equal to the difference in the binding energies of the orbital electrons involved.

Example:

A K-shell electron is removed from a tungsten atom and is replaced by an l_shell electron. What is the energy of the characteristic x-ray that is emitted?

Answer:
For tungsten, K electrons have binding energies of 69.5 keV, and L electrons are bound by 12.1 keV. Therefore, the characteristic x-ray emitted has energy of 69.5 - 12.1 = 57.4 keV

In summary, characteristic x-rays are produced by transitions of orbital electrons from outer to inner shells. Since the electron binding energy for every element is different, the characteristic x-rays produced in the various elements are also different. This type of x-radiation is called characteristic radiation because it is characteristic of the target element. The effective energy characteristic x-rays increases with increasing atomic number of the target element.

Discrete X-ray Spectrum

We saw earlier that characteristic x-rays have precisely fixed, or discrete, energies and that these energies are characteristic of the differences between electron binding energies of a particular element. A characteristic x-ray from tungsten, for example, can have one of fifteen energies and no others.

Bremsstrahlung Radiation

The production of heat and characteristic x-rays involves interactions between the projectile electrons and the electrons of target atoms. A third type of interaction in which the projectile electron can lose its kinetic energy is an interaction with the nucleus of a target atom.

In this type of interaction, the kinetic energy of the projectile electron is converted into electromagnetic energy.

A projectile electron that completely avoids the orbital electrons on passing through an atom of the target may come sufficiently close to the nucleus of the atom to come under its influence. Since the electron is negatively charged and the nucleus is positively charged, there is an electrostatic force of attraction between them. As the projectile electron approaches the nucleus, it is influenced by a nuclear force much stronger than the electrostatic attraction. As it passes by the nucleus, it is slowed down and deviated in its course, leaving with reduced kinetic energy in a different direction. This loss in kinetic energy reappears as an x-ray photon. These types of x-rays are called bremsstrahlung radiation, or **bremsstrahlung x-rays**. Bremsstrahlung is the German word for slowing down or braking; bremsstrahlung radiation can be considered radiation resulting from the braking or projectile electrons by the nucleus.

A projectile electron can lose any amount of its kinetic energy in an interaction with the nucleus of a target atom, and the bremsstrahlung radiation associated with the loss can take on a corresponding range of values. For example, an electron with kinetic energy of 70 keV can lose all, none, or any intermediate level of that kinetic energy in a bremsstrahlung interaction; the bremsstrahlung x-ray produced can have an energy in the range of 0 to 70 keV. This is different from the production of characteristic x-rays that have specific energies.

Continuous X-ray Spectrum

If it were possible to identify and quantitative the energy contained in each bremsstrahlung photon emitted from an x-ray tube, one would find that these energies extend from that associated with the peak electron energy all the way down to zero. In other words, when an x-ray tube is operated at 70 kVp, bremsstrahlung photons with energies ranging from 0 to 70 keV are emitted. Thus, creating a typical continuous, or bremsstrahlung, x-ray emission spectrum.

This emission spectrum is sometimes called the continuous emission spectrum because, unlike in the discrete spectrum, the energies of the photons emitted may range anywhere from zero to some maximum value. The general shape of the continuous x-ray spectrum is the same for all x-ray machines. The maximum energy that an x-ray can have is numerically equal to the kVp of operation. The greatest number of x-ray photons is emitted with energy approximately one-third of the maximum photon energy. The number of x-rays emitted decreases rapidly at very low photon energies and below 5 keV nearly reaches zero.

Radiation Measurements

Definition: technique for detecting the intensity and characteristics of ionizing radiation, such as alpha, beta, and gamma rays or neutrons, for the purpose of measurement.

The term ionizing radiation refers to those subatomic particles and photons whose energy is sufficient to cause ionization in the matter with which they interact. The ionization process consists of removing an electron from an initially neutral atom or molecule. For many materials, the minimum energy required for this process is about 10 electron volts (eV), and this can be taken as the lower limit of the range of ionizing radiation energies. The more common types of ionizing radiation are characterized by particle or quantum energies measured in thousands or millions of electron volts (keV or MeV, respectively). At the upper end of the energy scale, the present discussion will be limited to those radiations with quantum energies less than about 20 MeV. This energy range covers the common types of ionizing radiation encountered in radioactive decay, fission and fusion systems and the medical and industrial applications of radioisotopes. It excludes the regime of high-energy particle physics in which quantum energies can reach billions or trillions of electron volts. In this field of research, measurements tend to employ much more massive and specialized detectors than those in common use for the lower-energy radiations.

Radiation interactions in matter

For the purposes of this discussion, it is convenient to divide the various types of ionizing radiation into two major categories: those that carry an electric charge and those that do not. In the first group are the radiations that are normally viewed as individual subatomic charged particles. Such radiation appears, for example, as the alpha particles that are spontaneously emitted in the decay of certain unstable heavy nuclei. These alpha particles consist of two protons and two neutrons and carry a positive electrical charge of two units. Another example is the beta-minus radiation also emitted in the decay of some radioactive nuclei. In this case, each nuclear decay produces a fast electron that carries a negative charge of one unit. In contrast, there are other types of ionizing radiation that carry no electrical charge. Common examples are gamma rays, which can be represented as high-frequency electromagnetic photons, and neutrons, which are classically pictured as subatomic particles carrying no electrical charge. In the discussions below, the term quantum will generally be used to represent a single particle or photon, regardless of its type.

Only charged radiations interact continuously with matter, and they are therefore the only types of radiation that are directly detectable in the devices described here. In contrast, uncharged quanta must first undergo a major interaction that transforms all or part of their energy into secondary charged radiations. Properties of the original uncharged radiations can then be inferred by studying the charged particles that are produced. These major interactions occur only rarely, so it is not unusual for an uncharged radiation to travel distances of many centimeters through solid materials before such an interaction occurs. Instruments that are designed for the efficient detection of these uncharged quanta therefore tend to have relatively large thicknesses to increase the probability of observing the results of such an interaction within the detector volume.

Interactions of heavy charged particles

The term heavy charged particle refers to those energetic particles whose mass is one atomic mass unit or greater. This category includes alpha particles, together with protons, deuterons, fission fragments, and other energetic heavy particles often produced in accelerators. These particles carry at least one electronic charge, and they interact with matter primarily through the Coulomb force that exists between the positive charge on the particle and the negative charge on electrons that are part of the absorber material. In this case, the force is an attractive one between the two opposite charges. As a charged particle passes near an electron in the absorber, it transfers a small fraction of its momentum to the electron. As a result, the charged particle slows down slightly, and the electron (which originally was nearly at rest) picks up some of its kinetic energy. At any given time, the charged particle is simultaneously interacting with many electrons in the absorber material, and the net result of all the Coulomb forces acts like a viscous drag on the particle. From the instant it enters the absorber, the particle slows down continuously until it is brought to a stop. Because the charged particle is thousands of times more massive than the electrons with which it is interacting, it is deflected relatively little from a straight-line path as it comes to rest. The time that elapses before the particle is stopped ranges from a few picoseconds (1 10-12 second) in solids or liquids to a few nanoseconds (1 10-9 second) in gases. These times are short enough that the stopping time can be considered to be instantaneous for many purposes, and this approximation is assumed in the following sections that describe the response of radiation detectors.

Several characteristics of the particle-deceleration process are important in understanding the behavior of radiation detectors. First, the average distance traveled by the particle before it stops is called its mean range. For a given material, the mean range increases with increasing initial kinetic energy of the charged particle. Typical values for charged particles with initial energies of a few MeV are tens or hundreds of micrometers in solids or liquids and a few centimeters in gases at ordinary temperature and pressure. A second property is the specific energy loss at a given point along the particle track (path). This quantity measures the differential energy deposited per unit path length (dE/dx) in the material; it is also a function of the particle energy. In general, as the particle slows down and loses energy, the dE/dx value tends to increase. Thus, the density with which energy is being deposited in the absorber along the particle's track tends to increase as it slows down. The average dE/dx value for charged particles is relatively large because of their short range, and they are often referred to as high dE/dx radiations.

Interactions of fast electrons:

Energetic electrons (such as beta-minus particles), since they carry an electric charge, also interact with electrons in the absorber material through the Coulomb force. In this case, the force is a repulsive rather than an attractive one, but the net results are similar to those observed for heavy charged particles. The fast electron experiences the cumulative effect of many simultaneous Coulomb forces, and undergoes a continuous deceleration until it is stopped. As compared with a heavy charged particle, the distance traveled by the fast electron is many times greater for an equivalent initial energy. For example, a beta particle with an initial energy of 1 MeV travels one or two millimeters in typical solids and several meters in gases at standard conditions. Also, since a fast electron has a much smaller mass than a heavy charged particle, it is much more easily deflected along its path. A typical fast-electron track deviates considerably from a straight line, and deflections through large angles are not uncommon. Because a fast electron will travel perhaps 100 times as far in a given material as a heavy charged particle with the same initial energy, its energy is much less densely deposited along its track. For this reason, fast electrons are often referred to as low dE/dx radiations.

There is one other significant difference in the energy loss of fast electrons as compared with that of heavy charged particles. While undergoing large-angle deflections, fast electrons can radiate part of their energy in the form of electromagnetic radiation known as bremsstrahlung, or braking radiation. This form of radiation normally falls within the X-ray region of the spectrum. The fraction of the fast-electron energy lost in the form of bremsstrahlung is less than 1 percent for low-energy electrons in light materials but becomes a much larger fraction for high-energy electrons in materials with high atomic numbers.

Interactions of gamma rays and X rays

Ionizing radiation also can take the form of electromagnetic rays. When emitted by excited atoms, they are given the name X rays and have quantum energies typically measured from 1 to 100 keV. When emitted by excited nuclei, they are called gamma rays, and characteristic energies can be as high as several MeV. In both cases, the radiation takes the form of photons of electromagnetic energy. Since the photon is uncharged, it does not interact through the Coulomb force and therefore can pass through large distances in matter without significant interaction. The average distance traveled between interactions is called the mean free path and in solid materials ranges from a few millimeters for low-energy X rays through tens of centimeters for high-energy gamma rays. When an interaction does occur, however, it is catastrophic in the sense that a single interaction can profoundly affect the energy and direction of the photon or can make it disappear entirely. In such an interaction, all or part of the photon energy is transferred to one or more electrons in the absorber material. Because the secondary electrons thus produced are energetic and charged, they interact in much the same way as described earlier for primary fast electrons. The fact that an original X ray or gamma ray was present is indicated by the appearance of secondary electrons. Information on the energy carried by the incident photons can be inferred by measuring the energy of these electrons. The three major types of such interactions are discussed below.

Photoelectric absorption

In this process, the incident X-ray or gamma-ray photon interacts with an atom of the absorbing material, and the photon completely disappears; its energy is transferred to one of the orbital electrons of the atom. Because this energy in general far exceeds the binding energy of the electron in the host atom, the electron is ejected at high velocity. The kinetic energy of this secondary electron is equal to the incoming energy of the photon minus the binding energy of the electron in the original atomic shell. The process leaves the atom with a vacancy in one of the normally filled electron shells, which is then refilled after a short period of time by a nearby free electron. This filling process again liberates the binding energy in the form of a characteristic X-ray photon, which then typically interacts with electrons from less tightly bound shells in nearby atoms, producing additional fast electrons. The overall effect is therefore the complete conversion of the photon energy into the energy carried by fast electrons. Since the fast electrons are now detectable through their Coulomb interactions, they can serve as the basis to indicate the presence of the original gamma-ray or X-ray photon, and a measurement of their energy is tantamount to measuring the energy of the incoming photon. Because the photoelectric process results in complete conversion of the photon energy to electron energy, it is in some sense an ideal conversion step. The task of measuring the gamma-ray energy is then reduced to simply measuring the equivalent energy deposited by the fast electrons. Unfortunately, two other types of gamma-ray interactions also take place that complicate this interpretation step.

Compton scattering

An incoming gamma-ray photon can interact with a single free electron in the absorber through the process of Compton scattering. In this process, the photon abruptly changes direction and transfers a portion of its original energy to the electron from which it scattered, producing an energetic recoil electron. The fraction of the photon energy that is transferred depends on the scattering angle. When the incoming photon is deflected only slightly, little energy is transferred to the electron. Maximum energy transfer occurs when the incoming photon is backscattered from the electron and its original direction is reversed. Since in general all angles of scattering will occur, the recoil electrons are produced with a continuum of energies ranging from near zero to a maximum represented by the backscattering extreme. This maximum energy can be predicted from the conservation of momentum and energy in the photon-electron interaction and is about 0.25 MeV below the incoming photon energy for high-energy gamma rays. After the interaction, the scattered photon has an energy that has decreased by an amount equal to the energy transferred to the recoil electron. It may subsequently interact again at some other location or simply escape from the detector.

Pair production

A third gamma-ray interaction process is possible when the incoming photon energy is above 1.02 MeV. In the field of a nucleus of the absorber material, the photon may disappear and be replaced by the formation of an electron-positron pair. The minimum energy required to create this pair of particles is their combined rest-mass energy of 1.02 MeV. Therefore, pair production cannot occur for incoming photon energies below this threshold. When the photon energy exceeds this value, the excess energy appears as initial kinetic energy shared by the positron and electron that are formed. The positron is a positively charged particle with the mass of a normal negative electron. It slows down and deposits its energy over an average distance that is nearly the same as that for a negative electron of equivalent energy. Therefore both particles transfer their kinetic energy over a distance of no more than a few millimeters in typical solids. The magnitude of the deposited energy is given by the original photon energy minus 1.02 MeV. When the positron member of the pair reaches the end of its track, it combines with a normal negative electron from the absorber in a process known as annihilation. In this step both particles disappear and are replaced by two annihilation photons, each with an energy of 0.511 MeV. Annihilation photons are similar to gamma rays in their ability to penetrate large distances of matter without interacting. They may undergo Compton or photoelectric interactions elsewhere or may escape from detectors of small size.

Role of energy and atomic number

The probability for each of these three interaction mechanisms to occur varies with the gamma-ray energy and the atomic number of the absorber. Photoelectric absorption predominates at low energies and is greatly enhanced in materials with high atomic number. For this reason, elements of high atomic number are mostly chosen for detectors used in gamma-ray energy measurements. Compton scattering is the most common interaction for moderate energies (from a few hundred keV to several MeV). Pair production predominates for higher energies and is also enhanced in materials with high atomic number. In larger detectors, there is a tendency for an incident photon to cause multiple interactions, as, for example, several sequential Compton scatterings or pair production followed by the interaction of an annihilation photon. Since little time separates these events, the deposited energies add together to determine the overall size of the output pulse.

Interactions of neutrons

Neutrons represent a major category of radiation that consists of uncharged particles. Owing to the absence of the Coulomb force, neutrons may penetrate many centimeters through solid materials before they interact in any manner. When they do interact, it is primarily with the nuclei of atoms of the absorbing material. The types of interaction that are important in the detection of neutrons are again catastrophic since the neutrons may either disappear or undergo a major change in their energy and direction.

In the case of gamma rays, such major interactions produce fast electrons. In contrast, the important neutron interactions result in the formation of energetic heavy charged particles. The task of detecting the uncharged neutron is thus transformed into one of measuring the directly observable results of the energy deposited in the detector by the secondary charged particles. Because the types of interaction that are useful in neutron detection are different for neutrons of different energies, it is convenient to subdivide the discussion into slow-neutron and fast-neutron interaction mechanisms.

Slow neutrons

These are conventionally defined as neutrons whose kinetic energy is below about 1 eV. Slow neutrons frequently undergo elastic scattering interactions with nuclei and may in the process transfer a fraction of their energy to the interacting nucleus. Because the kinetic energy of a neutron is so low, however, the resulting recoil nucleus does not have enough energy to be classified as an ionizing particle. Instead, the important interactions for the detection of slow neutrons involve nuclear reactions in which a neutron is absorbed by the nucleus and charged particles are formed. All the reactions of interest in slow neutron detectors are exoenergetic, meaning that an amount of energy (called the Q-value) is released in the reaction. The charged particles are produced with a large amount of kinetic energy supplied by the nuclear reaction. Therefore, the products of these reactions are ionizing particles, and they interact in much the same way as previously described for direct radiations consisting of heavy charged particles. Some specific examples of nuclear reactions of interest in slow-neutron detection are given below in the section Active detectors: Neutron detectors.

Fast neutrons

Neutrons whose kinetic energy is above about 1 keV are generally classified as fast neutrons. The neutron-induced reactions commonly employed for detecting slow neutrons have a low probability of occurrence once the neutron energy is high. Detectors that are based on these reactions may be quite efficient for slow neutrons, but they are inefficient for detecting fast neutrons.

Instead, fast neutron detectors are most commonly based on the elastic scattering of neutrons from nuclei. They exploit the fact that a significant fraction of a neutron's kinetic energy can be transferred to the nucleus that it strikes, producing an energetic recoil nucleus. This recoil nucleus behaves in much the same way as any other heavy charged particle as it slows down and loses its energy in the absorber. The amount of energy transferred varies from nearly zero for a grazing angle scattering to a maximum for the case of a head-on collision. Hydrogen is a common choice for the target nucleus, and the resulting recoil protons (or recoiling hydrogen nuclei) serve as the basis for many types of fast-neutron detectors. Hydrogen provides a unique advantage in this application since a fast neutron can transfer up to its full energy in a single scattering interaction with a hydrogen nucleus. For all other elements, the heavier nucleus limits the maximum energy transfer in a single scattering to only a fraction of the neutron energy. In any elastic-scattering interaction, the energy that is not transferred to the recoil nucleus is retained by the scattered neutron which, depending on the dimensions of the detector, may interact again or simply escape from the detector volume.

Applications of radiation interactions in detectors

A number of physical or chemical effects caused by the deposition of energy along the track of a charged particle are listed in the first column of the table. Each of these effects can serve as the basis of instruments designed to detect radiation, and examples of specific devices based on each effect are given in the second column.

One category of radiation-measurement devices indicates the presence of ionizing radiation only after the exposure has occurred. A physical or chemical change is induced by the radiation that is later measured through some type of processing. These so-called passive detectors are widely applied in the routine monitoring of occupational exposures to ionizing radiation. In contrast, in active detectors a signal is produced in real time to indicate the presence of radiation. This distinction is indicated for the examples in the table. The normal mode of operation of each detector type is also noted. These include pulse mode, current mode, and integrating mode as defined below (see Active detectors: Modes of operation). An indication is also given as to whether the detector is normally capable of responding to a single particle or quantum of radiation or whether the cumulative effect of many quanta is needed for a measurable output.

In the descriptions that follow, emphasis is placed on the behavior of devices for the measurement of those forms of ionizing radiation consisting of heavy charged particles, fast electrons, X rays, and gamma rays. Techniques and devices of primary interest for the measurement of neutrons are discussed separately in a later section because they differ substantially in operation or composition or both. The detection methods that are included also are limited to those that are relatively sensitive to low levels of radiation. There are a number of other physical effects resulting from exposure to intense radiation that can also serve as the basis for measurements, many of which are important in the field of radiation dosimetry (the measurement of radiation doses). They include chemical changes in ionic solutions, changes in the colour or other optical properties of transparent materials, and calorimetric measurement of the heat deposited by intense fluxes of radiation.

Passive detectors

Photographic emulsions

The use of photographic techniques to record ionizing radiations dates back to the discovery of X rays by Röntgen in the late 1800s, but similar techniques remain important today in some applications. A photographic emulsion consists of a suspension of silver halide grains in an inert gelatin matrix and supported by a backing of plastic film or another material. If a charged particle or fast electron passes through the emulsion, interactions with silver halide molecules produce a similar effect as seen with exposure to visible light. Some molecules are excited and will remain in this state for an indefinite period of time. After the exposure is completed, this latent record of the accumulated exposure can be made visible through the chemical development process. Each grain containing an excited molecule is converted to metallic silver, greatly amplifying the number of affected molecules to the point that the developed grain is visible. Photographic emulsions used for radiation detection purposes can be classified into two main subgroups: radiographic films and nuclear emulsions. Radiographic films register the results of exposure to radiation as a general darkening of the film due to the cumulative effect of many radiation interactions in a given area of the emulsion. Nuclear emulsions are intended to record individual tracks of a single charged particle.

Radiographic films

Radiographic films are most familiar in their application in medical X-ray imaging. Their properties do not differ drastically from those of normal photographic film used to record visible light, except for an unusually high silver halide concentration. Thickness of the emulsion ranges from 10 to 20 micrometers, and they contain silver halide grains up to 1 micrometer in diameter. The probability that a typical incident X ray will interact in the emulsion is only a few percent, and so methods are often applied to increase the sensitivity so as to reduce the intensity of the X rays needed to produce a visible image. One such technique is to apply emulsion to both sides of the film base. Another is to sandwich the photographic emulsion between intensifier screens that consist of thin layers of light-emitting phosphors of high atomic number, such as calcium tungstate, cesium iodide, or rare earth phosphors. If an X ray interacts in the screen, the light that is produced darkens the film in the immediate vicinity through the normal photographic process. Because of the high atomic number of the screens, they are more likely to cause an X ray to interact than the emulsion itself, and the X-ray flux needed to achieve a given degree of darkening of the emulsion can be decreased by as much as an order of magnitude. The light is produced in the normal scintillation process (see below Active detectors: Scintillation and Cerenkov detectors) and travels in all directions from the point of the X-ray interaction. This spreading causes some loss of spatial resolution in X-ray images, especially for thicker screens, and the screen thickness must therefore be chosen to reach a compromise between resolution and sensitivity.

Nuclear emulsions

In order to enable visualization of single particle tracks, nuclear emulsions are generally made much thicker than ordinary photographic emulsions (up to 500 micrometers) and they have an even higher silver halide content. Special development procedures can reveal the tracks of individual charged particles or fast electrons as a nearly continuous trail of developed silver grains that is visible under a microscope. If the particle is stopped in the emulsion, the length of its track can be measured to give its range and therefore an estimate of its initial energy. The density of the grains along the track is proportional to the dE/dx of the particle, and therefore some distinction can be made between particles of different type.

Film badge dosimeters

Small packets of photographic emulsions are routinely used by workers to monitor radiation exposure. The density of the developed film can be compared with that of an identical film exposed to a known radiation dose. In this way, variations that result from differences in film properties or development procedures are canceled out. When used to monitor exposure to low-energy radiation such as X rays or gamma rays, emulsions tend to over respond owing to the rapid rise of the photoelectric cross section of silver at these energies. To reduce this deviation, the film is often wrapped in a thin metallic foil to absorb some of the low-energy photons before they reach the emulsion.

One of the drawbacks of photographic film is the limited dynamic range between underexposure and overexposure. In order to extend this range, the holder that contains the film badge often is fitted with a set of small metallic filters that cover selected regions of the film. By making the filters of differing thickness, the linear region under each filter corresponds to a different range of exposure, and the effective dynamic range of the film is extended. The filters also help to separate exposures to weakly penetrating radiations (such as beta particles) from those due to more penetrating radiations (such as gamma rays).

Thermoluminescent materials

Another technique commonly applied in personnel monitoring is the use of thermoluminescent dosimeters (TLDs). This technique is based on the use of crystalline materials in which ionizing radiation creates electron-hole pairs (see below Active detectors: Semiconductor detectors). In this case, however, traps for these charges are intentionally created through the addition of a dopant (impurity) or the special processing of the material. The object is to create conditions in which many of the electrons and holes formed by the incident radiation are quickly captured and immobilized. During the period of exposure to the radiation, a growing population of trapped charges accumulates in the material. The trap depth is the minimum energy that is required to free a charge from the trap. It is chosen to be large enough so that the rate of detrapping is very low at room temperature. Thus, if the exposure is carried out at ordinary temperatures, the trapped charge is more or less permanently stored.

After the exposure, the amount of trapped charge is quantified by measuring the amount of light that is emitted while the temperature of the crystal is raised. The applied thermal energy causes rapid release of the charges. A liberated electron can then recombine with a remaining trapped hole, emitting energy in the process. In TLD materials, this energy appears as a photon in the visible part of the electromagnetic spectrum. Alternatively, a liberated hole can recombine with a remaining trapped electron to generate a similar photon. The total intensity of emitted light can be measured using a photomultiplier tube and is proportional to the original population of trapped charges. This is in turn proportional to the radiation dose accumulated over the exposure period.

The readout process effectively empties all the traps, and the charges thus are erased from the material so that it can be recycled for repeated use. One of the commonly used TLD materials is lithium fluoride, in which the traps are sufficiently deep to prevent fading, or loss of the trapped charge over extended periods of time. The elemental composition of lithium fluoride is of similar atomic number to that of tissue, so that energy absorbed from gamma rays matches that of tissue over wide energy ranges.

Memory phosphors

A memory phosphor consists of a thin layer of material with properties that resemble those of TLD crystals in the sense that charges created by incident radiation remain trapped for an indefinite period of time. The material is formed as a screen covering a substantial area so that it can be applied as an X-ray image detector. These screens can then be used as an alternative to radiographic films in X-ray radiography.

The incident X rays build up a pattern of trapped charges over the surface of the screen during the exposure period. As in a TLD, the screen is then read out through the light that is generated by liberating these charges. The energy needed to detrap the stored charges is supplied in this case by stimulating the crystal with intense light from a laser beam rather than by heating. The luminescence from the memory phosphor can be distinguished from the laser light by its different wavelength. If the amount of this luminescence is measured as the laser beam scans across the surface of the screen, the spatial pattern of the trapped charges is thereby recorded. This pattern corresponds to the X-ray image recorded during the exposure. Like TLDs, memory phosphors have the advantage that the trapped charges are erased during readout, and the screen can be reused many times.

Track-etch detectors

When a charged particle slows down and stops in a solid, the energy that it deposits along its track can cause permanent damage in the material. It is difficult to observe direct evidence of this local damage, even under careful microscopic examination. In certain dielectric materials, however, the presence of the damaged track can be revealed through chemical etching (erosion) of the material surface using an acid or base solution. If charged particles have irradiated the surface at some time in the past, then each leaves a trail of damaged material that begins at the surface and extends to a depth equal to the range of the particle. In the materials of choice, the chemical etching rate along this track is higher than the rate of etching of the undamaged surface. Therefore, as the etching progresses, a pit is formed at the position of each track. Within a few hours, these pits can become large enough so that they can be seen directly under a low-power microscope. A measurement of the number of these pits per unit area is then a measure of the particle flux to which the surface has been exposed.

There is a minimum density of damage along the track that is required before the etching rate is sufficient to create a pit. Because the density of damage correlates with the dE/dx of the particle, it is highest for the heaviest charged particles. In any given material, a certain minimum value for dE/dx is required before pits will develop. For example, in the mineral mica, pits are observed only from energetic heavy ions whose mass is 10 or 20 atomic mass units or greater. Many common plastic materials are more sensitive and will develop etch pits for low-mass ions such as helium (alpha particles). Some particularly sensitive plastics such as cellulose nitrate will develop pits even for protons, which are the least damaging of the heavy charged particles. No materials have been found that will produce pits for the low dE/dx tracks of fast electrons. This threshold behavior makes such detectors completely insensitive to beta particles and gamma rays. This immunity can be exploited in some applications where weak fluxes of heavy charged particles are to be registered in the presence of a more intense background of gamma rays. For example, many environmental measurements of the alpha particles produced by the decay of radon gas and its daughter products are made using plastic track-etch film. The background to omnipresent gamma rays would dominate the response of many other types of detectors under these circumstances. In some materials the damage track has been shown to remain in the material for indefinite periods of time, and pits can be etched many years after the exposure. Etching properties are, however, potentially affected by exposure to light and high temperatures, so some caution must be exercised in the prolonged storage of exposed samples to prevent fading of the damage tracks.

Automated methods have been developed to measure the etch pit density using microscope stages coupled to computers with appropriate optical-analysis software. These systems are capable of some degree of discrimination against "artifacts" such as scratches on the sample surface and can provide a reasonably accurate measurement of the number of tracks per unit area. Another technique incorporates relatively thin plastic films, in which the tracks are etched completely through the film to form small holes. These holes can then be automatically counted by passing the film slowly between a set of high-voltage electrodes and electronically counting sparks that occur as a hole passes.

Neutron-activation foils

For radiation energies of several MeV and lower, charged particles and fast electrons do not induce nuclear reactions in absorber materials. Gamma rays with energy below a few MeV also do not readily induce reactions with nuclei. Therefore, when nearly any material is bombarded by these forms of radiation, the nuclei remain unaffected and no radioactivity is induced in the irradiated material.

Among the common forms of radiation, neutrons are an exception to this general behavior. Because they carry no charge, neutrons of even low energy can readily interact with nuclei and induce a wide selection of nuclear reactions. Many of these reactions lead to radioactive products whose presence can later be measured using conventional detectors to sense the radiations emitted in their decay. For example, many types of nuclei will absorb a neutron to produce a radioactive nucleus. During the time that a sample of this material is exposed to neutrons, a population of radioactive nuclei accumulates. When the sample is removed from the neutron exposure, the population will decay with a given half-life. Some type of radiation is almost always emitted in this decay, often beta particles or gamma rays or both, which can then be counted using one of the active detection methods described below. Because it can be related to the level of the induced radioactivity, the intensity of the neutron flux to which the sample has been exposed can be deduced from this radioactivity measurement. In order to induce enough radioactivity to permit reasonably accurate measurement, relatively intense neutron fluxes are required. Therefore, activation foils are frequently used as a technique to measure neutron fields around reactors, accelerators, or other intense sources of neutrons.

Materials such as silver, indium, and gold are commonly used for the measurement of slow neutrons, whereas iron, magnesium, and aluminum are possible choices for fast-neutron measurements. In these cases, the half-life of the induced activity is in the range of a few minutes through a few days. In order to build up a population of radioactive nuclei that approaches the maximum possible, the half-life of the induced radioactivity should be shorter than the time of exposure to the neutron flux. At the same time, the half-life must be long enough to allow for convenient counting of the radioactivity once the sample has been removed from the neutron field.

Bubble detector

A relatively recent technique that has been introduced for the measurement of neutron exposures involves a device known as a superheated drop, or bubble detector. Its operation is based on a suspension of many small droplets of a liquid (such as Freon [trademark]) in an inert matrix consisting of a polymer or gel. The sample is held in a sealed vial or other transparent container, and the pressure on the sample is adjusted to create conditions in which the liquid droplets are superheated; i.e., they are heated above their boiling point yet remain in the liquid state. The transformation to the vapor state must be triggered by the creation of some type of nucleation center.

This stimulus can be provided by the energy deposited from the recoil nucleus created by the scattering of an incident neutron. When such an event occurs, the droplet suddenly vaporizes and creates a bubble that remains suspended within the matrix. Over the course of the neutron exposure, additional bubbles are formed, and a count of their total number is related to the incident neutron intensity. The bubble detector is insensitive to gamma rays because the fast electrons created in gamma-ray interactions have too low a value of dE/dx to serve as a nucleation center. Bubble detectors have found application in monitoring the exposure of radiation personnel to ionizing radiation because of their good sensitivity to low levels of neutron fluxes and their immunity to gamma-ray backgrounds. Some types can be recycled and used repeatedly by collapsing the bubbles back to droplets through recompression. The same type of device can be made into an active detector by attaching a piezoelectric sensor. The pulse of acoustic energy emitted when the droplet vaporizes into a bubble is converted into an electrical pulse by the sensor and can then be counted electronically in real time.

Active detectors

In many applications it is important to produce a signal that indicates the presence of ionizing radiation in real time. Such devices are classified as active detectors. Many types of active detectors can produce an observable signal for an individual quantum of radiation (such as a single alpha particle or an X-ray photon). Others may provide a signal that corresponds to the collective effect of many quanta interacting in the detector within its response time.

Modes of operation

In many types of detectors, a single particle or quantum of radiation liberates a certain amount of charge Q as a result of depositing its energy in the detector material. For example, in a gas, Q represents the total positive charge carried by the many positive ions that are produced along the track of the particle. (An equal charge of opposite sign is carried by the free electrons that are also generated.) This charge is created over a very short time, typically less than a nanosecond, as the particle slows down and stops; it is then collected over a much longer period of time, ranging from a few nanoseconds to several microseconds. In a gas or a semiconductor, the charge is collected through the motion of individual charge carriers in the electric field that is established within the detector. As these moving charges represent an electric current, detector response to a single quantum of radiation can then be modeled as a momentary burst of current that begins with the stopping of the charged particle and ends once all the charge carriers have been collected. If the detector is undergoing continuous irradiation, a sequence of these current bursts will be produced, one for each interacting quantum. In most applications the time of arrival of each quantum of radiation is randomly distributed. For purposes of this discussion, it is assumed that the average time between events in the detector is long compared with the charge collection time. Each burst of current is then distinct, and the integral or area under the current versus time profile for each burst is the charge Q formed for that event. Because the amount of energy deposited may be different for individual events, each of these current pulses may represent a different total charge Q. Furthermore, the charge collection time may also be variable, so the length of each of these current bursts may be different.

Current mode

One way to provide an electrical signal from such a detector is to connect its output to an ammeter circuit with a slow response time. If this response time is long compared with the average time spacing between current bursts, then the ammeter will measure a current that is given by the mean rate of charge formation averaged over many individual radiation quanta. This mode of operation is called current mode, and many of the common detector types can be operated in this way. The measured current represents the product of the rate at which quanta are interacting in the detector multiplied by the average charge Q created by a single quantum of radiation. For a given source of radiation, doubling its intensity will double the observed current. However, different currents will result from radiations that have equal interaction rates but deposit a different average energy per interaction.

Integrating mode

There are circumstances in which the current from the detector is simply integrated during the time of exposure, and the accumulated total charge is measured at its completion. This integration mode of operation produces information that is related to the total exposure, but it cannot provide detail on possible variation of the intensity during the exposure time. In that sense, it is similar to the operation of passive detectors. Portable ion chambers are sometimes used in this manner; the total ionization charge is measured by noting the drop in voltage across the chamber after it has been initially charged using a reference voltage source. The integration mode can be useful when a direct measurement of small signal currents may be difficult or impractical.

Pulse mode

In many applications information is sought about the properties of individual quanta of radiation. In such cases, a mode of detector operation known as the pulse mode is employed, in which a separate electrical pulse is generated for each individual radiation quantum that interacts in the detector. The detector output may be connected to a measuring circuit as indicated in Figure 1.

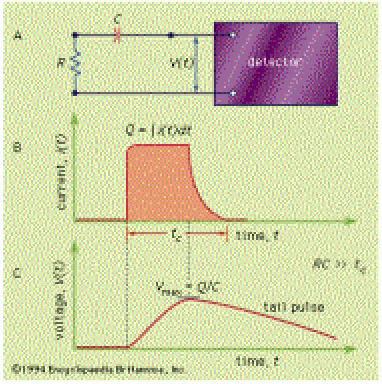


Figure 1: (A) A simple equivalent circuit for the development of a voltage pulse at the output of a detector. R represents the resistance and C the capacitance of the circuit; V(t) is the time (t)-dependent voltage produced. (B) A representative current pulse due to the interaction of a single quantum in the detector. The total charge Q is obtained by integrating the area of the current, i(t), over the collection time, t_c. (C) The resulting voltage pulse that is developed across the circuit of (A) for the case of a long circuit time constant. The amplitude (V_{max}) of the pulse is equal to the charge Q divided by the capacitance C.

This circuit could represent, for example, the input stage of a preamplifier unit. The basic signal is the voltage observed across the circuit consisting of a load resistance (R) and capacitance (C). This type of configuration has an associated time constant given by the product of the resistance and capacitance values (RC). For simplicity, it will be assumed that this time constant is long compared with the charge collection time in the detector but small relative to the average time between interactions of individual quanta in the detector.

Under these circumstances each interacting quantum gives rise to a voltage pulse of the form sketched in Figure 1C. The voltage pulse rises over the charge collection time, reaches its maximum when all the charge has been collected, and then exponentially decays back to zero with a characteristic time set by the time constant of the measuring circuit. This type of signal pulse is called a tail pulse, and it is observed from the preamplifier used with many kinds of common radiation detectors.

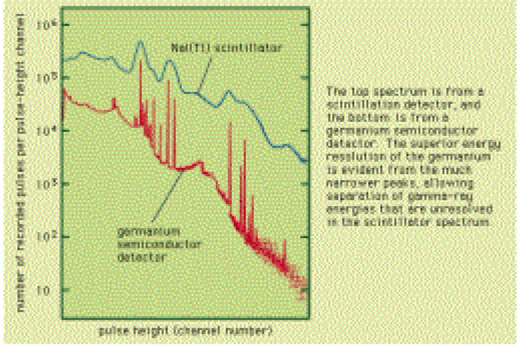
The most important property of the tail pulse is its maximum size, or amplitude. Under the conditions described, the amplitude is given by Vmax = Q/C, where Q is the charge produced by the individual quantum in the detector and C is the capacitance of the measuring circuit. Under typical conditions tail pulses are then amplified and shaped in a second unit known as a linear amplifier in a manner that preserves the proportionality of the pulse amplitude to the charge Q produced in the detector.

Counting and spectroscopy systems

Detector systems operating in pulse mode can be further subdivided into two types: simple

counting systems and more complex spectroscopy systems. The basic elements of both types of

pulse-processing systems are shown in Figure 2.



The top spectrum is from a scintillation detector, and the bottom is from a germanium semiconductor detector. The superior energy resolution of the germanium is evident from the much narrower peaks, allowing separation of gamma-ray energies that are unresolved in the scintillator spectrum.

Figure 2: (Left) Pulse-processing units commonly used in a pulse-counting system. (Right) The units constituting a spectroscopy system

Counting systems

In simple counting systems, the objective is to record the number of pulses that occur over a given measurement time, or alternatively, to indicate the rate at which these pulses are occurring. Some preselection may be applied to the pulses before they are recorded. A common method is to employ an electronic unit known as an integral discriminator to count only those pulses that are larger than a preset amplitude. This approach can eliminate small amplitude pulses that may be of no interest in the application. Alternatively, a differential discriminator (also known as a single-channel analyzer) will select only those pulses whose amplitudes lie within a preset window between a given minimum and maximum value. In this way, the accepted pulses can be restricted to those in which the charge Q from the detector is within a specific range. When the number of pulses meeting these criteria are accumulated in a digital register over the measurement time, the measurement consists of reporting the total number of accepted events over the time period.

One property that must be considered in counting systems is the concept known as dead time. Following each event in a detector, there is a period of time in which the measurement system is processing that event and is insensitive to other events. Because radiation events typically occur randomly distributed in time, there is always some chance that a true event will occur so soon after a previous event that it is lost. This behavior is often accounted for by assigning a standard dead time to the counting system. It is assumed that each accepted event is followed by a fixed time period during which any additional true event will be ignored. As a result, the measured number of counts (or the counting rate) is always somewhat below the true value. The discrepancy can become significant at high radiation rates when the dead time is a significant fraction of the average spacing between true events in the detector. Corrections for dead-time losses can be made assuming that the behavior of the counting system and length of its dead time are known.

As an alternative to simply registering the total number of accepted pulses over the counting time, the rate at which the accepted events are occurring in real time can be indicated electronically using a rate meter. This unit provides an output signal that is proportional to the rate at which accepted pulses are occurring averaged over a response time that is normally adjustable by the user. Long response times minimize the fluctuations in the output signal due to the random nature of the interaction times in the detector, but they also slow the response of the rate meter to abrupt changes in the radiation intensity.

Spectroscopy systems

The pulse-mode counting systems described above provide no detailed information on the amplitude of the pulses that are accepted. In many types of detectors, the charge Q and thus the amplitude of the signal pulse is proportional to the energy deposited by the incident radiation. Therefore, an important set of measurement systems are based on recording not only the number of pulses but also their distribution in amplitude. They are known as spectroscopy systems, and their main application is to determine the energy distribution of the radiation that is incident on the detector.

In spectroscopy systems the objective is to sort each pulse according to its amplitude. Every pulse from the linear amplifier is sorted into one of a large number of bins or channels. Each channel corresponds to signal pulses of a specific narrow amplitude range. As the pulses are sorted into the channels matching their amplitude, a pulse-height spectrum is accumulated that, after a given measurement time, might resemble the example given in Figure 3.

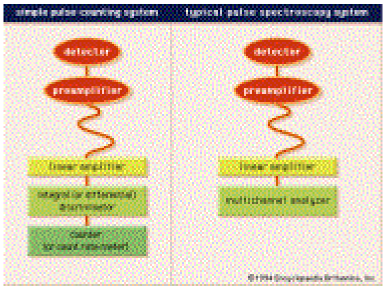


Figure 3: Representative pulse-height spectra for a source emitting gamma rays of many different energies. The top spectrum is from a scintillation detector, and the bottom is from a germanium semiconductor detector. The superior energy resolution of the germanium is evident from the much narrower peaks, allowing separation of gamma-ray energies that are unresolved in the scintillator spectrum.

In this spectrum, peaks correspond to those pulse amplitudes around which many events occur. Because pulse amplitude is related to deposited energy, such peaks often correspond to radiation of a fixed energy recorded by the detector. By noting the position and intensity of peaks recorded in the pulse-height spectrum, it is often possible to interpret spectroscopy measurements in terms of the energy and intensity of the incident radiation.

This pulse-height spectrum is recorded by sending the pulses to a multichannel analyzer, where the pulses are electronically sorted out according to their amplitude to produce the type of spectrum illustrated in Figure 3. Ideally, every incoming pulse is sorted into one of the channels of the multichannel analyzer. Therefore, when the measurement is completed, the sum of all the counts that have been recorded in the channels equals the total number of pulses produced by the detector over the measurement period. In order to maintain this correspondence at high counting rates, corrections must be applied to account for the dead time of the recording system or the pileup of two pulses spaced so closely in time that they appear to be only one pulse to the multichannel analyzer.

One important property of spectroscopy systems is the energy resolution. This concept is most easily illustrated by assuming that the detector is exposed to radiation quanta of a single fixed energy. (A radioisotope emitting a single gamma-ray energy in its decay comes very close to this ideal.) Many radiation quanta then deposit the same energy in the detector and ideally should produce exactly the same charge Q. Therefore, a number of pulses of precisely the same amplitude should be presented to the multichannel analyzer, and they all should be stored in a single channel. In actual systems, however, some fluctuations are observed in the amplitude of these pulses, and they are actually spread out over a number of channels in the spectrum, as illustrated in Figure 4

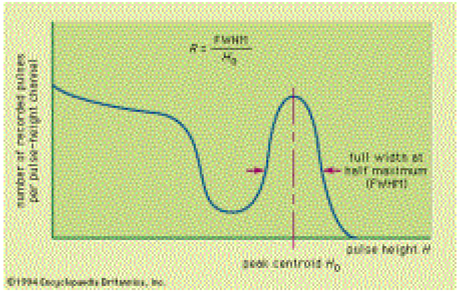


Figure 4: A simple pulse-height spectrum (such a spectrum might be recorded from a scintillator for a single energy gamma-ray source) showing the definition of energy resolution R.

A formal definition of energy resolution is shown in the figure, expressed as the ratio of the full-width-at-half-maximum (FWHM) of the peak divided by the centroid position of the peak. This ratio is normally expressed as a percentage, and small values correspond to narrow peaks and good energy resolution. If the incident radiation consists of multiple discreet energies, good energy resolution will help in separating the resulting peaks in the recorded pulse-height spectrum.

Some potential causes of fluctuations that broaden the peaks include drifts in the detector-operating parameters over the course of the measurement, random fluctuations introduced by the noise in the pulse-processing electronics, and statistical fluctuations due to the fact that the charge Q consists of a finite number of charge carriers. This latter statistical limit is in some ways the most fundamental determinant in energy resolution since, as opposed to the other sources of fluctuation, it cannot be reduced by more careful experimental procedures. Poisson statistics predicts that the fractional standard deviation that characterizes these fluctuations about the average number of charge carriers N should scale as 1/N. Therefore, detectors that produce the largest number of carriers per pulse show the best energy resolution. For example, the charge Q from a scintillation detector normally consists of photoelectrons in a photomultiplier tube. The average number produced by a 1-MeV particle is normally no more than a few thousand, and the observed energy resolution is typically 5-10 percent. In contrast, the same particle would produce several hundred thousand electron-hole pairs in a semiconductor, and the energy resolution is improved to a few tenths of a percent.

Detection efficiency

The intrinsic detection efficiency of any device operated in pulse mode is defined as the probability that a quantum of radiation incident on the detector will produce a recorded pulse. Especially for radiations of low intensity, a high detection efficiency is important to minimize the total time needed to record enough pulses for good statistical accuracy in the measurement. Detection efficiency is further subdivided into two types: total efficiency and peak efficiency. The total efficiency gives the probability that an incident quantum of radiation produces a pulse, regardless of size, from the detector. The peak efficiency is defined as the probability that the quantum will deposit all its initial energy in the detector. Since there are almost always ways in which the quantum may deposit only part of its energy and then escape from the detector, the total efficiency is generally larger than the peak efficiency.

For a given detector, efficiency values depend on the type and energy of the incident radiation. For incident charged particles such as alpha particles or beta particles, many detectors have a total efficiency that is close to 100 percent. Since these particles begin to deposit energy immediately upon entering the detector volume, a pulse of some amplitude is inevitably produced if the particle reaches the active volume of the device. Very often, any departure from 100 percent efficiency in these cases is due to absorption or scattering of the incident particle before it reaches the active volume. Furthermore, if the detector is thick compared with the range of the incident particle, most particles are fully stopped in the active volume and deposit all their energy. Under these circumstances, the peak efficiency also will be near 100 percent.

For incident gamma rays, the situation is quite different. Except for low-energy photons, it is quite possible for an incident gamma-ray photon to pass completely through the detector without interacting. In such cases, the total efficiency will then be substantially less than 100 percent. Furthermore, many of the gamma-rays may deposit only a fraction of their energy in the detector. These events do not contribute to the peak efficiency so, although they produce pulses, their amplitude does not indicate the initial energy of the incident gamma ray. Thus the peak efficiency values incorporate only those gamma-ray photons that interact one or more times in the detector and eventually deposit all their energy. The total efficiency for gamma rays may be enhanced by increasing the detector thickness in the direction of the incident gamma-ray flux. For a given thickness, the peak efficiency is enhanced by choosing a detector material with a high atomic number to increase the probability that all the energy of the original photon will eventually be photoelectrically absorbed. Full energy absorption could take place in a single photoelectric interaction but, more likely, it happens after the incident photon has Compton-scattered one or more times elsewhere in the detector. Alternatively, full absorption is also observed if pair production is followed by subsequent full absorption of both annihilation photons. Since these multiple interactions are enhanced in detectors of large volume, the peak efficiency for gamma-ray detectors improves significantly with increasing size.

Timing characteristics

One of the added benefits of pulse-mode operation is the fact that the arrival time of an individual quantum of radiation is closely related to the time of appearance of a pulse at the detector output. In many nuclear measurements, it is advantageous to be able to determine that two quanta are emitted in the same nuclear process and therefore may be sensed by two separate detectors in virtual time coincidence. Another example of the application of timing information is in the determination of the velocity or energy of a particle by measuring its flight time between its point of origin and a distant detector.

The timing information is carried by the leading edge or rising portion of the detector output pulse. The precision of timing measurements is enhanced in detectors that produce a prompt output pulse with a fast rise time. The time characteristics of the leading edge are related to the charge collection time from the detector, and the best timing performance is generally obtained from detectors in which the charges are collected most rapidly. For example, timing precision of less than one nanosecond can be obtained using organic scintillators for which the light (that is subsequently converted to charge in a photomultiplier tube) is emitted within a period of several nanoseconds following the deposition of the particle energy. On the other hand, timing measurements from gas-filled detectors may have an imprecision of up to one microsecond or more owing to the relatively long and sometimes variable charge-collection time of these devices.

Gas-filled detectors

The passage of a charged particle through a gas results in the transfer of energy from the particle to electrons that are part of the normal atomic structure of the gas. If the charged particle passes close enough to a given atom, the energy transfer may be sufficient to result in its excitation or ionization. In the excitation process, an electron is elevated from its original state to a less tightly bound state. Energy levels in typical gas atoms are only spaced a few electron volts apart, so that the energy needed for excitation is a small fraction of the kinetic energy of typical radiation quanta. The excited state exists for a specific lifetime before the atom decays back to the original ground energy state. Typical mean lifetimes for excited atomic states in gases are normally only a few nanoseconds. When the atom spontaneously returns to the ground state, the excitation energy is liberated, generally in the form of an electromagnetic photon. The wavelength of electromagnetic radiation for typical gases is in the ultraviolet region of the spectrum. Thus, for every excited gas atom that is formed, the observable result is the appearance of an ultraviolet photon. As a typical charged particle will create thousands of excited atoms along its track, a resulting flash of ultraviolet photons appears, originating along the track of the particle. Some detectors, based on directly sensing this ultraviolet light and known as gas scintillators, are described below (see Scintillation and Crenkov detectors). Similar ultraviolet photons also play an important part in the generation of a pulse from a Geiger-Müller tube.

For close encounters between an incident charged particle and a gas atom, enough energy may be transferred to totally remove an electron. This is the process of ionization, and it results in the creation of an ion pair. Because the ionized atom is electron-deficient, it carries a net positive electric charge and is called a positive ion. The other member of the ion pair is the electron that is no longer bound to a specific atom and is known as a free electron. Most free electrons are formed with low kinetic energy, and they simply diffuse through the gas, taking part in the random thermal motion of all the atoms. Some free electrons are formed with enough kinetic energy to cause additional excitation and ionization. These are called delta rays, and their motion follows short branches away from the primary ionization and excitation that is created directly along the track of the incident charged particle.

The ionization potential, or the minimum energy required to remove an electron, is about 10 eV for the gases typically used in radiation detectors. Approximately 30 eV of energy loss by the incident charged particle is needed on average to create one ion pair. The remainder of the energy is expended in various excitation processes. For a 1-MeV charged particle that transfers all its energy to the gas, about 30,000 ion pairs will be formed along its track. Both the positive ions and the free electrons can be made to drift in a preferred direction by applying an external electric field. It is the movement of these charges that serves as the basis for the electrical signal produced by the important category of gas-filled detectors that includes ion chambers, proportional counters, and Geiger-Müller detectors.

Ion chambers

An ion chamber is a device in which two electrodes are arranged on opposite sides of a gas-filled volume. By applying a voltage difference between the two electrodes, an electric field is created within the gas. The ion pairs formed by incident radiation experience a force due to this electric field, with the positive ions drifting toward the cathode and the electrons toward the anode. The motion of these charges constitutes an electric current that can be measured in an external circuit.

Ion chambers are frequently operated as current-mode devices. The current-voltage characteristics of a typical ion chamber under constant irradiation conditions are shown in Figure 5.

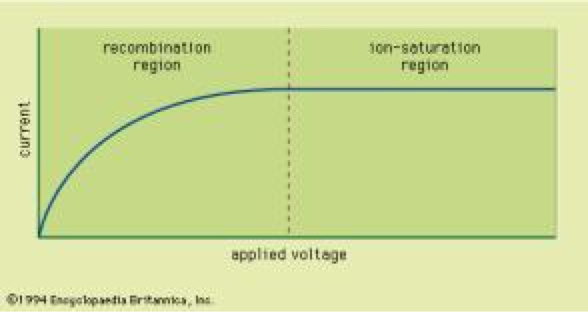


Figure 5: Current-voltage characteristics of an ion chamber.

At low applied voltages, there is some tendency for the positive and negative charges to collide and recombine, thereby neutralizing them and preventing their contribution to the measured current. As the voltage is raised, the stronger electric field separates the charges more quickly, and recombination is eventually made negligible at a sufficient applied voltage. This point marks the onset of the ion-saturation region, where the current no longer depends on applied voltage; this is the region of operation normally chosen for ion chambers. Under these conditions the current measured in the external circuit is simply equal to the rate of formation of charges in the gas by the incident radiation.

Air-filled ion chambers operated in current mode are a common type of portable survey meter used to monitor potential personnel exposure to gamma rays. One reason is that the historical unit of gamma-ray exposure, the roentgen (R), is defined in terms of the amount of ionization charge created per unit mass of air. Because of the close connection of the signal produced in an ion chamber with this definition, a measurement of the ion current under proper conditions can give an accurate measure of gamma-ray exposure rate over a wide range of incident gamma-ray energies.

The magnitude of the current observed from a typical ion chamber for a modest gamma-ray exposure rate is quite small. For example, at a gamma-ray exposure rate of 10-3 roentgen per hour (a small but significant level for personnel monitoring purposes), the expected ion current from a one-liter ion chamber at atmospheric pressure is about 0.1 picoampere (pA). These low currents require the use of sensitive electrometers for their accurate measurement.

Ion chambers are sometimes operated in a manner similar to passive detectors in integration mode. In this case, the ion chamber is first connected to a constant voltage source V0. The chamber has an inherent capacitance C, and this initial charging step has the effect of storing an electrical charge on it equal to CV0. The chamber is then disconnected from the voltage source and exposed to the radiation. During the exposure period, ion pairs are formed in the gas and are swept to their corresponding electrodes by the electric field created by the voltage on the chamber. At the end of the exposure period, the voltage on the chamber will have dropped, as the ionization charge that is collected serves to partially discharge the stored charge CV0. The chamber is then read out by recording the voltage drop V that has occurred. If there are no other losses (such as leakage current across insulators), the amount of ionization charge created during the exposure is simply given by CV. Small pocket chambers of this type are frequently used to monitor exposure of personnel at radiation-producing facilities.

Ion chambers are rarely operated in pulse mode, and this mode of operation is only considered for high-dE/dx particles that can deposit large amounts of energy in the gas. The main problem is the small size of the voltage pulse that is produced by the interaction of a single quantum of radiation. The deposition of 1 MeV of energy in an ion chamber with a typical capacitance of 100 picofarads (pF) results in a voltage pulse with amplitude of only about 50 microvolts (V). While it is possible to work with signals of such low level using careful techniques, it is much more common to use gas-filled detectors in pulse mode in the form of proportional or Geiger-Müller counters.

Proportional counters

The small pulse amplitude encountered in ion chambers can be remedied by using gas-filled detectors in a different manner. A proportional counter utilizes the phenomenon of gas multiplication to increase the pulse size by factors of hundreds or thousands. As a result, proportional-counter pulses are in the millivolt rather than microvolt range and therefore can be processed much more easily.

Gas multiplication is a consequence of the motion of a free electron in a strong electric-field. When the strength of the field is above about 104 volts per centimeter, an electron can gain enough energy between collisions to cause secondary ionization in the gas. After such an ionizing collision, two free electrons exist in place of the original one. In a uniform electric field under these conditions, the number of electrons will grow exponentially as they are drawn in a direction opposite to that of the applied electric field. The growth of the population of electrons is terminated only when they reach the anode. The production of such a shower of electrons is called a Townsend avalanche and is triggered by a single free electron. The total number of electrons produced in the avalanche can easily reach 1,000 or more, and the amount of charge generated in the gas is also multiplied by the same factor. The Townsend avalanche takes place in a time span of less than one microsecond under the typical conditions present in a proportional counter. Therefore, this additional charge normally contributes to the pulse that is observed from the interaction of a single incident quantum.

In a proportional counter, the objective is to have each original free electron that is formed along the track of the particle create its own individual Townsend avalanche. Thus, many avalanches are formed for each incident charged particle. One of the design objectives is to keep each avalanche the same size so that the final total charge that is created remains proportional to the number of original ion pairs formed along the particle track. The proportionality between the size of the output pulse and the amount of energy lost by the incident radiation in the gas is the basis of the term proportional counter.

Virtually all proportional counters are constructed using a wire anode of small diameter placed inside a larger, typically cylindrical, cathode that also serves to enclose the gas. Under these conditions, the electric-field strength is nonuniform and reaches large values in the immediate vicinity of the wire surface. Almost all of the volume of the gas is located outside this high-field region, and electrons formed at a random position in the gas by the incident radiation drift toward the wire without creating secondary ionization. As they are drawn closer to the wire, they are subjected to the continually increasing electric field, and eventually its value becomes high enough to cause the initiation of a Townsend avalanche. The avalanche then grows until all the electrons reach the wire surface. As nearly all avalanches are formed under identical electric-field conditions regardless of the position in the gas where the free electron was originally formed, the condition that their intensities be the same is met. Furthermore, the high electric-field strength needed for avalanche formation can be obtained using applied voltages between the anode and cathode of no more than a few thousand volts. Near the wire surface, the electric-field strength varies inversely with the distance from the wire center, and so extremely high field values exist near the surface if the wire diameter is kept small. The size of the output pulse increases with the voltage applied to the proportional tube, since each avalanche is more vigorous as the electric-field strength increases.

In order to sustain a Townsend avalanche, the negative charges formed in ionization must remain as free electrons. In some gases there is a tendency for neutral gas molecules to pick up an extra electron, thereby forming a negative ion. Because the mass of a negative ion is thousands of times larger than the mass of a free electron, it cannot gain sufficient energy between collisions to cause secondary ionization. Electrons do not readily attach to noble gas molecules, and argon is one of the common choices for the fill gas in proportional counters. Many other gas species also are suitable. Oxygen readily attaches to electrons, however, so air cannot be used as a proportional fill gas under normal circumstances. Proportional counters must therefore either be sealed against air leakage or operated as continuous gas-flow detectors in which any air contamination is swept out of the detector by continuously flowing the fill gas through the active volume.

For proportional counters of normal size, only heavy charged particles or other weakly penetrating radiations can be fully stopped in the gas. Therefore, they can be used for energy to the particles formed in the reaction. Helium works well as a proportional gas even at high pressure; thus helium-3 proportional tubes filled to 20 atmospheres or more provide neutron detection with relatively high intrinsic efficiency.

Also common are slow-neutron detectors in the form of scintillators in which either boron or lithium is incorporated as a constituent of the scintillation material. Europium-activated lithium iodide is one example of a crystalline scintillator of this type, and boron-loaded plastic scintillators are also available.

The fission reaction is often used as a neutron converter in conjunction with ion chambers. The enormous energy released in a fission reaction appears primarily as the kinetic energy of the two fission products. These fission fragments are highly ionizing charged particles, and they result in an unusually large energy deposition in the detector. Uranium-lined ion chambers (fission chambers) are common neutron sensors employed to monitor nuclear reactors and other intense sources of neutrons.

Fast-neutron detectors

The probability of inducing one of the reactions listed in the table is expressed as the magnitude of its neutron cross section. These values are relatively large for slow neutrons but decrease by several orders of magnitude for fast neutrons. Therefore, slow-neutron detectors such as the boron trifluoride tube become inefficient for the direct detection of fast neutrons. One method used to increase this efficiency is to surround the detector with a material that effectively moderates or slows down the fast neutrons. For example, a polyethylene layer with a thickness of 20 to 30 centimeters will cause some incident fast neutrons to scatter many times from the hydrogen nuclei that are present, giving up energy in the process. A fraction of these moderated neutrons may then diffuse to the detector as slow neutrons with a high interaction probability.

Since the moderation process obscures any information on the original energy of the fast neutron, these devices are useful only in simple neutron-counting systems.

The preferred conversion reaction for the direct detection of fast neutrons tends to be the elastic-scattering interaction. The resulting recoil nuclei can absorb a significant fraction of the original neutron energy in a single scattering and then deposit that energy in a manner similar to that of any other charged particle. The scattered neutron, now with a lower energy, may either escape from the detector or possibly interact again elsewhere in its volume. The most common scattering target is hydrogen, and a fast neutron can transfer up to all its energy in a single collision with a hydrogen nucleus. The amount of energy transferred varies with the scattering angle, which in hydrogen covers a continuum from zero (corresponding to grazing-angle scattering) up to the full neutron energy (corresponding to a head-on collision). Thus, when monoenergetic fast neutrons strike a material containing hydrogen, a spectrum of recoil protons is produced that ranges in energy between these limits. Some information about the original energy of the neutrons can be deduced by recording the pulse height-spectrum from a hydrogen-containing detector. This process generally involves applying a computer-based deconvolution code to the measured spectrum and is one of the few methods generally available to experimentally measure fast-neutron energy spectra.

The result of a fast-neutron scattering from hydrogen is a recoiling energetic hydrogen nucleus, or recoil proton. One type of detector based on these recoil protons is a proportional counter containing a hydrogenous gas. Pure hydrogen can be used, but a more common choice is a heavier hydrocarbon such as methane in which the range of the resulting recoil protons typically is short enough to be fully stopped in the gas. Recoil protons also can be generated and detected in organic liquid or plastic scintillators. In instances such as these, many more hydrogen nuclei are present per unit volume than in a gas, so that the detection efficiency for fast neutrons can be many times larger than in a proportional counter. (G.F.K.)