Chapter 9

GAMMA AND X-RAYS DETECTION

6/22/2017

9.1 INTRODUCTION

Selecting a particular type of radiation detection approach for a given application depends upon the photons energy range of interest and the application's detector resolution and efficiency needs as well as the cost for a given application. The chosen detector must have a sufficiently large amount of material to yield a measurable interaction of the x ray or gamma photon at its energy level.

For instance, 14.4-keV gamma or x-rays could be detected with a neon gas filled proportional counter. This counter would not detect 1-MeV gamma rays since, having a large energy and consequently high penetration, the probability of its interaction with the neon gas of the proportional counter will be very low. For these higher energy gamma photons a high atomic number Z element such as xenon as a fill gas would increase the probability of interaction in the detector volume.

Other considerations in the choice of a suitable detector for the job are the counting rate capability and pulse rise time if timing applications are considered.

9.2 DETECTOR RESOLUTION

The detector resolution is a measure of the width, specifically the Full Width at Half Maximum or FWHM of a single energy peak at a specific energy, either expressed in absolute keV in the case of germanium detectors, or as a percentage of the energy at that point for sodium iodide detectors (NaI). A better or smaller FWHM value resolution enables the system to more clearly separate the peaks within a spectrum. Two spectra collected from the same source but using two different detectors are shown in Fig. 1 and Fig. 2.

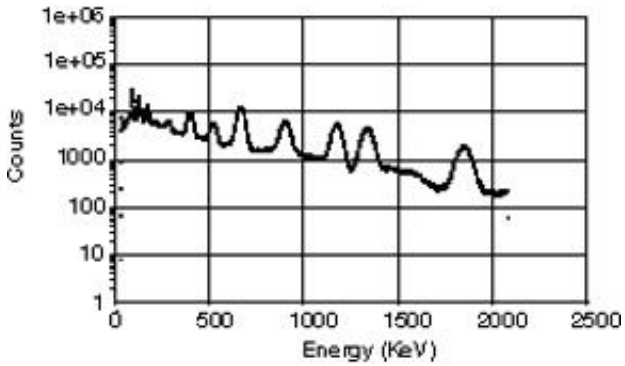

Figure 1. Sodium iodide (NaI) crystal detector resolution.

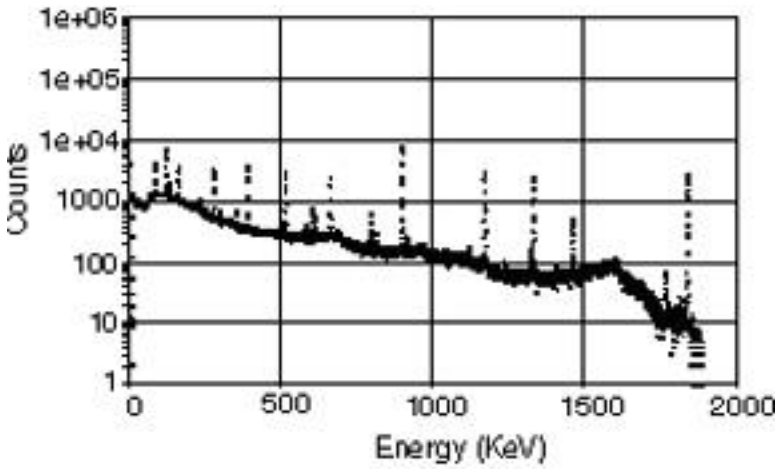

Figure 2. Germanium semi-conductor detector resolution.

Even though this is a rather simple spectrum, the peaks presented by the sodium iodide detector are overlapping to some degree, while those from the germanium detector are clearly separated. In a complex spectrum, with peaks numbering in the hundreds, the use of a higher resolution detector becomes paramount for a successful analysis

9.3 DETECTOR EFFICIENCY

The efficiency of a detector is a measure of how many pulses are generated in the detector for a given number of gamma rays emitted by the source. Many definitions of the efficiency of a detector are in common use for gamma and x ray detectors:

Absolute Efficiency: Is the ratio of the number of counts produced by the detector to the number of gamma rays emitted by the source in all directions.
Intrinsic Efficiency: Is the ratio of the number of pulses produced by the detector to the number of gamma rays striking the detector.
Relative Efficiency: Is the efficiency of one detector relative to another detector. A commonly used combination is that of a germanium detector relative to a 3 inches in diameter by 3 inches in length long sodium iodide scintillator NaI crystal, each at 25 cm from a point source, and specified at 1.33 MeV.
Full Energy Peak or Photo Peak Efficiency: This is the efficiency for producing full-energy peak pulses only, rather than a pulse of any size for the x or gamma ray. To be useful, the detector must be capable of absorbing a large fraction of the gamma ray energy. This is accomplished by using a detector of suitable size, or by choosing a detector material of suitable high Z. An example of a full energy peak efficiency calibration curve for a germanium semi conductor detector is shown in Fig. 3.

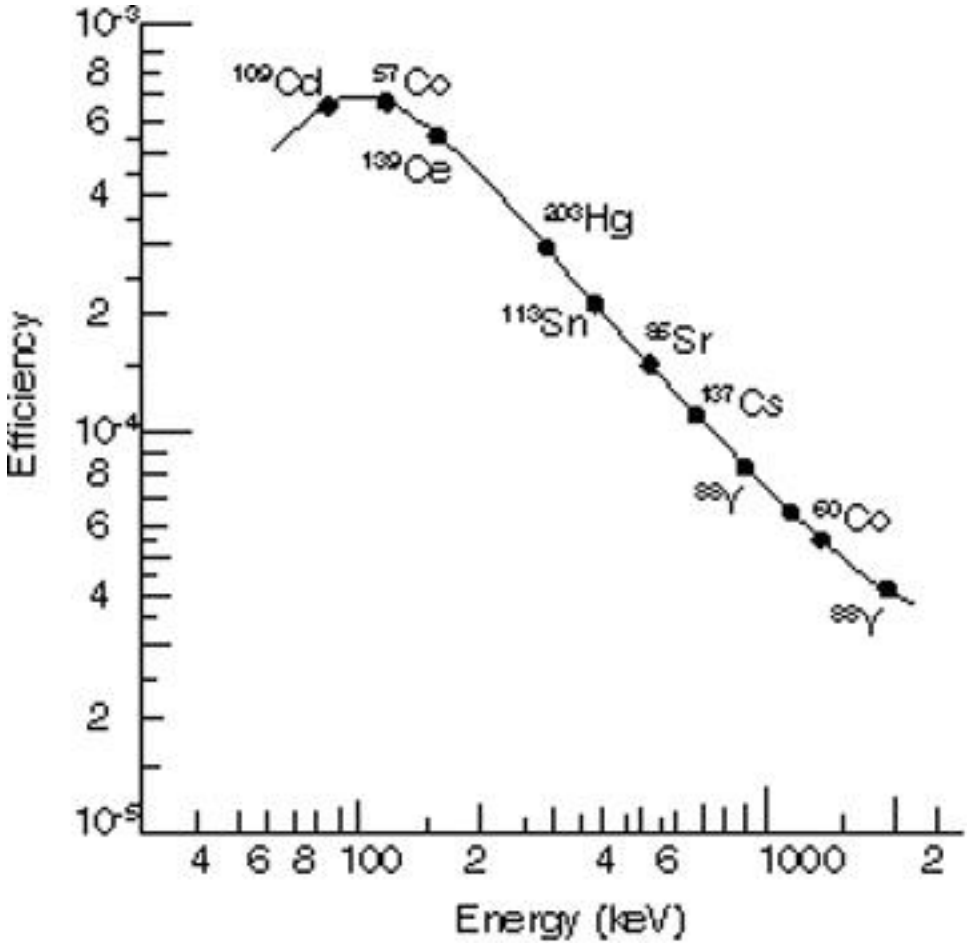

Figure 3. Full energy peak or photo peak germanium semiconductor detector efficiency calibration curve for different isotopes.

9.4 GAS FILLED DETECTORS

These are used for x-rays or low energy gamma rays. They include ionization chambers, proportional counters and Geiger-Müller counters.

A gas-filled detector consists of a metal enclosure filled with gas and containing a positively biased anode wire. A photon that passes through the gas produces free electrons and positive ions in its path. The electrons are attracted to the anode wire and collected to produce an electric pulse.

If the anode voltage is low, the electrons may recombine with the ions and not all of them are collected at the anode. Recombination could also occur for a high density of ions. As the anode voltage is increased nearly all electrons are collected, and the detector becomes known as an ionization chamber.

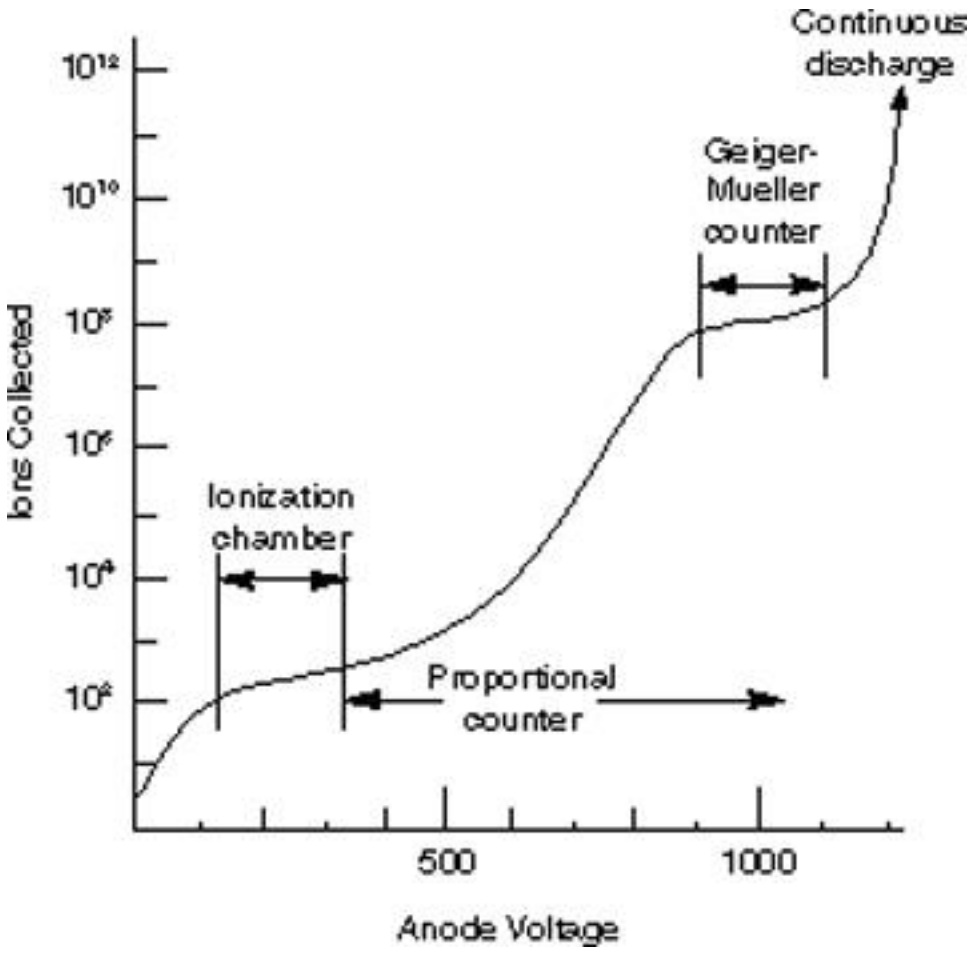

Figure 4. Different types of gas filled detectors result from the choice of the operational range of its anode voltage.

At a higher anode voltage the generated electrons are accelerated toward the anode at energies high enough to ionize other atoms, thus creating a cascade process and a larger number of electrons. The number of electrons collected is proportional to the initial ionization. This type of detector is known as a proportional counter.

At still higher voltages on the anode, the electron multiplication is even greater, and the number of electrons collected is independent of the initial ionization. This region of operation yields the Geiger-Müller counter. The large output pulse in this type of detector is the same for all photons.

If we increase the anode voltage further, a continuous discharge occurs and this region is unsuitable for the counting process.

The used anode voltages can vary over a large range from one detector to the next, depending upon the detector geometry, the filling gas type and its pressure.

Ionization Chamber

The very low signal output makes it difficult to use the ionization chamber detector for detecting individual gamma rays. It finds wide usage in situations of high

radiation fluxes such as research reactors or radiotherapy sites in which the total current produced can be significantly large.

Figure 5. Cold war period fallout shelter survey meter, ionization chambers and their charger.

Because of its low cost, most radiation monitoring instruments use ionization chambers. Absolute ionization measurements can be made using an electrometer that is initially charged, then allowed to discharge through the ionization caused by the radiation (Fig. 1). The degree of discharge is measured and recorded to yield a measure of the radiation exposure.

Proportional Counter

Proportional counters are used for x ray measurements where moderate energy resolution is required such as a spectrum containing 14.4 keV gamma rays from ^{57}Co and the 6.4-keV x rays from iron.

Proportional counters are manufactured in different sizes and shapes, ranging from cylindrical shapes with end or side windows to pancake shaped flat cylinders. They may be sealed detectors or operate with gas flow, and may have thin beryllium windows or be windowless. A proportional detector is typically specified in terms of its physical size, effective window size and gas path length, operating voltage range and resolution for the 5.9-keV Mn^{55} x ray from an ^{55}Fe source. Typical resolutions are about 16 to 20 percent full width at half maximum (FWHM).

Operating voltages depend upon the fill gas as well as the geometry. For x rays detection, noble gases are used, such as xenon, krypton, neon and argon. Xenon and krypton are selected for higher energy x rays or to get higher efficiencies. Neon is selected when it is desired to detect low energy x rays in the presence of unwanted higher

energy x rays. Gas mixtures are used, such as the P-10 gas, which is a mixture of 90 percent argon and 10 percent methane. The gas pressure is around one atmosphere.

Sealed and flow proportional large area detectors are used in hand and foot, whole body surface, laundry and floor monitors, as well as in frisker applications along with a rate meter. These detectors are available in size from 56 cm^2 up to 800 cm^2. They have either fixed or detachable mesh protection.

These detectors are also ideally suited in hot particle detection applications, as they can operate in elevated background fields up to 10 [mR/hr] ^{60}Co gamma, without saturating or swamping.

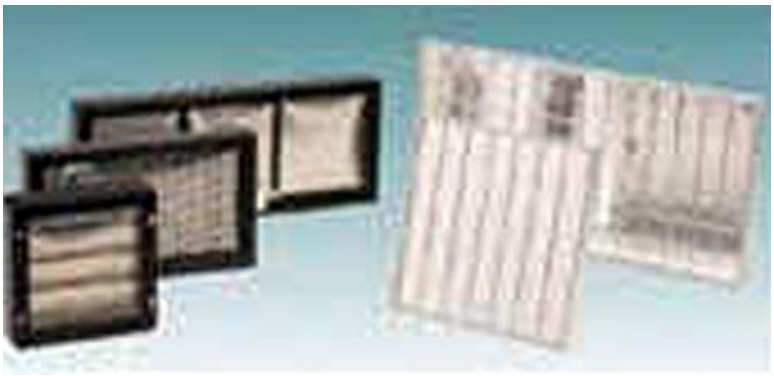

Figure 6. Proportional counters.

Sealed detectors come with a 4.5 mg/cm^2 titanium window and are best for beta detection. They have all the advantages associated with not requiring a P-10 gas supply (mobility, no purging, no bottle changing, etc.). Sealed xenon detectors are ideal for isotopes used in nuclear medicine such as ^{125}I. Flow proportional detectors come with an ultra-thin 0.8 mg/cm^2 Mylar window and are the detectors of choice for simultaneous alpha and beta detection.

Geiger-Müller Counter

The Geiger-Müller counter produces a large voltage pulse that is easily counted without further amplification (Fig. 7). No energy measurements are possible since the output pulse height is independent of initial ionization. Geiger-Müller counters are available in a wide variety of sizes, generally with a thin mica window (Fig. 8). The operating voltage is in the plateau region, which can be relatively flat over a range of bias voltage. The plateau is determined by measuring the counting rate as a function of the anode voltage.

The discharge produced by ionization must be quenched in order for the detector to be returned to a neutral ionization state and be ready for the next pulse. This is achieved by using a fill gas that contains a small amount of a halogen in addition to a noble gas. The voltage drop across a large resistor between the anode and bias supply will also serve to quench the discharge since the operating voltage will be reduced below the plateau.

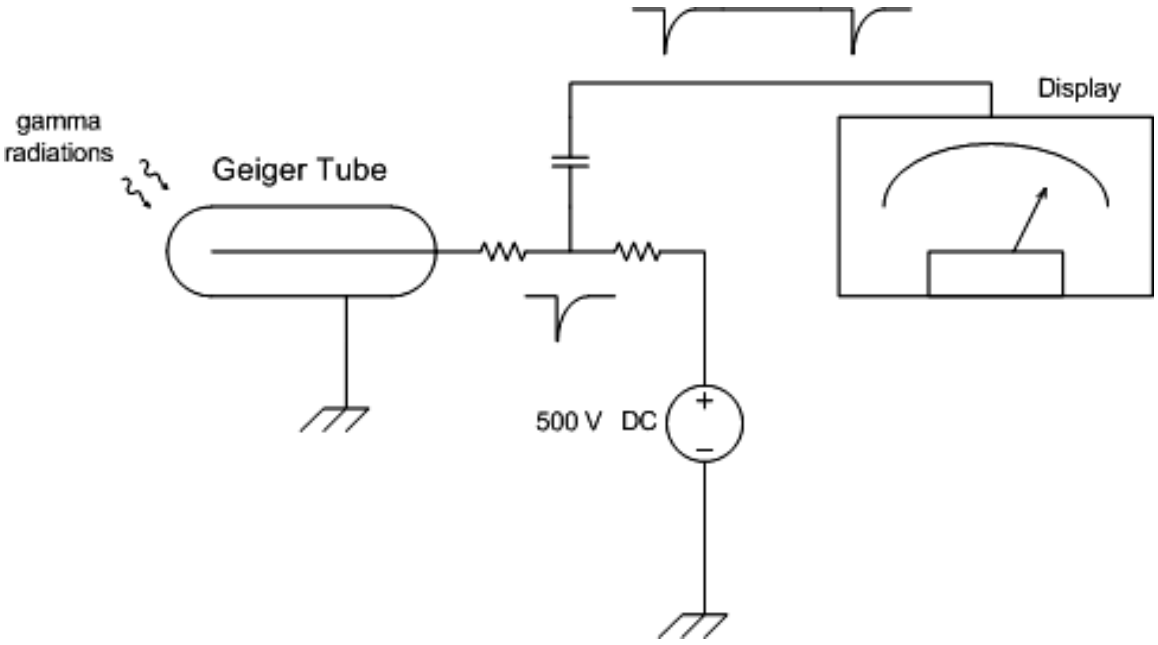

Figure 7. Geiger Müller detector setup.

Figure 8. Geiger Müller tubes shapes and geometries.

The Geiger-Müller counter is insensitive or dead after each pulse until the quenching is complete. This dead time can be hundreds of microseconds long, which limits the counter to low count rate applications.

9.5 SCINTILLATION DETECTORS

The English physicist William Crookes in 1896 discovered that x rays react with certain chemicals to produce glow called fluorescence. The New Zealand born Ernest Rutherford found that this fluorescence consisted of many individual flashes of light or scintillations..

Several crystals, liquids and plastics are effective in showing scintillations caused by nuclear radiations.

There exist solid crystal scintillators such as cesium iodide (CsI) or sodium iodide (NaI) as well as plastic and liquid scintillators.

The properties of scintillation material required for good detectors are transparency, availability in large size, and large light output proportional to x ray or gamma ray energy. Relatively few materials have good properties for detectors. Thallium activated NaI and CsI crystals are commonly used, as well as a wide variety of plastics. NaI is the dominant material for x ray and gamma detection because it provides good resolution and is economical. However, plastics have much faster pulse light decay and find use in timing applications, even though they often offer little or no energy resolution.

9.6 MULTICHANNEL PULSE-HEIGHT ANALYZERS

The fluorescence and the number of light photons produced in the scintillation detector is proportional to the energy transferred by the incoming gamma rays.

For instance, the energy of gamma rays emitted by potassium^{40} is 1.46 MeV. The gamma rays energy of the photons from cesium^{137} is 0.66 MeV. When both these radionuclides are producing flashes of light in the scintillator at once, the photomultiplier tubes produce two different strengths of electrical pulses. Electronic devices called multichannel pulse height analyzers sort and record the number of each as shown in Figs. 1 and 2..

9.7 PHOTOMULTIPLIER TUBES

Scintillation detectors are used in conjunction with photomultiplier tubes. The photon causes a light scintillation in the scintillator which is amplified by the photomultiplier tube and the light pulse is converted into an electric pulse

The photomultiplier tube consists of a photocathode, a focusing electrode and 10 or more dynodes that multiply the number of electrons striking them several times each. The anode and dynodes are biased by a chain of resistors typically located in a plug on tube base assembly. Assemblies including the scintillator and photomultiplier tube are commercially available.

Photomultiplier tubes are used for light detection of very weak signals. They are a photoemissive device in which the absorption of a photon results in the emission of an electron. These detectors work by amplifying the electrons generated by a photocathode exposed to a photon flux.

Figure 9. Photomultiplier tube.

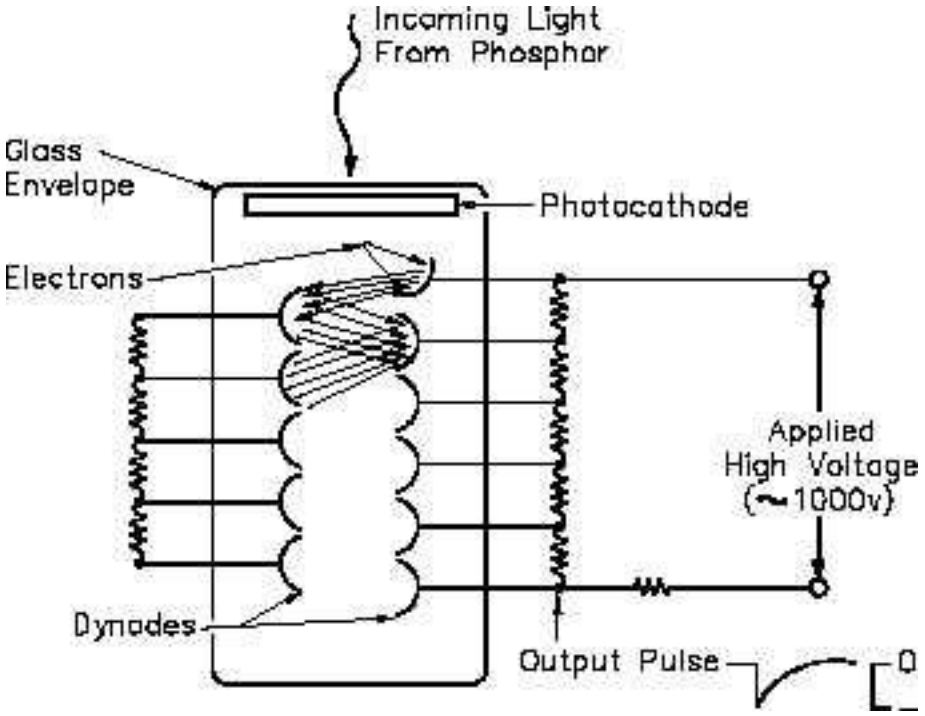

Figure 10. Operation of a photomultiplier tube showing its metal channel dynodes.

Photomultipliers acquire light through a glass or quartz window that covers a photosensitive surface, called a photocathode, which then releases electrons that are multiplied by electrodes known as metal channel dynodes. At the end of the dynode chain is an anode or collection electrode. Over a very large range, the current flowing from the anode to ground is directly proportional to the photoelectron flux generated by the photocathode.

The spectral response, quantum efficiency, sensitivity, and dark current of a photomultiplier tube are determined by the composition of the photocathode. The best photocathodes capable of responding to visible light are less than 30 percent quantum efficient, meaning that 70 percent of the photons impacting on the photocathode do not produce a photoelectron and are therefore not detected. The photocathode thickness is an important variable that must be considered to ensure the proper response from the absorbed photons. If the photocathode is too thick, more photons will be absorbed but fewer electrons will be emitted from the back surface, but if it is too thin, too many photons will pass through without being absorbed. Photoelectrons are ejected from the front face of the photocathode and angled toward the first dynode.

Electrons emitted by the photocathode are accelerated toward the dynode chain, which may contain up to 14 elements. Focusing electrodes are usually present to ensure that photoelectrons emitted near the edges of the photocathode will be likely to land on the first dynode. Upon impacting the first dynode, a photoelectron will cause the release of additional electrons that are accelerated toward the next dynode, and so on. The surface composition and geometry of the dynodes determines their ability to serve as electron multipliers. Because gain varies with the voltage across the dynodes and the total number of dynodes, electron gains of 10 million are possible if 12-14 dynode stages are employed.

Photomultipliers produce a signal even in the absence of light due to a so called dark current arising from thermal emissions of electrons from the photocathode, leakage current between dynodes, as well as stray high-energy radiation. Electronic noise also contributes to the dark current and is often included in the dark-current value.

Confocal microscopes, spectrophotometers, and many high-end automatic camera exposure bodies utilize photomultipliers to gauge light intensity. Spectral sensitivity of the photomultiplier depends on the chemical composition of the photocathode with the best devices having gallium arsenide elements, which are sensitive from 300 to 800 nanometers. Photomultiplier photocathodes are not uniformly sensitive and typically the photons are spread over the entire entrance window rather than on one region. Because photomultipliers do not store charge and respond to changes in input light fluxes within a few nanoseconds, they can be used for the detection and recording of extremely fast events. Finally, the signal to noise ratio is very high in scientific grade photomultipliers because the dark current is extremely low and it can be further reduced by cooling and the gain may be larger than one million.

SODIUM IODIDE NaI(Tl) SCINTILLATORS

The high Z value of iodine in NaI gives good efficiency for gamma ray detection. A small amount of thallium (Tl) is added in order to activate the crystal, so that the designation is usually NaI(Tl) for the crystal. The best resolution achievable ranges from 7.5 percent to 8.5 percent for the 662 keV gamma ray from Cs^{137} for 3 inches diameter by 3 inches long crystal, and is slightly worse for smaller and larger sizes.

Figure 11. Sodium iodide (NaI) scintillation detectors.

Figure 12 and Fig. 13 show, respectively, the absorption efficiencies of various thicknesses of NaI crystals, and the transmission coefficient through the most commonly used entrance windows.

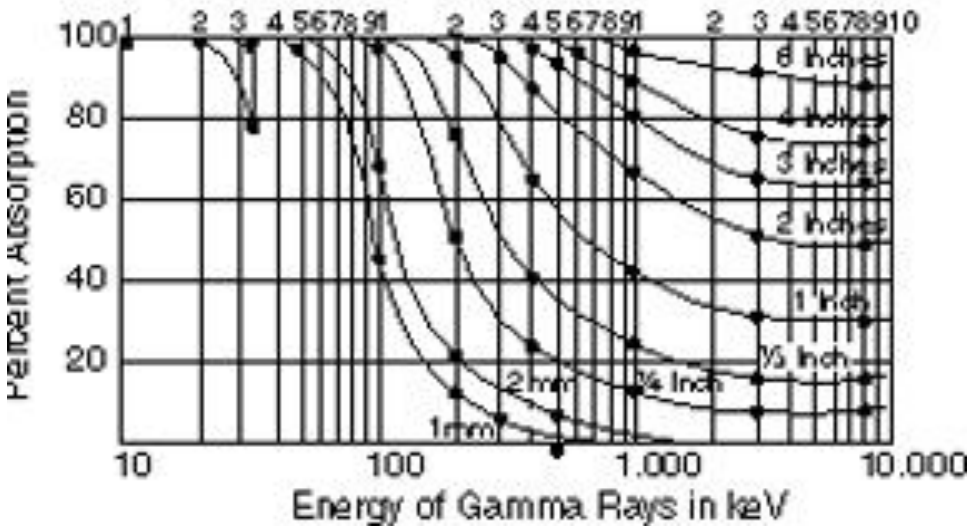

Figure 12. Absorption efficiency for a parallel beam of gamma rays normally incident on the face of a NaI crystal.

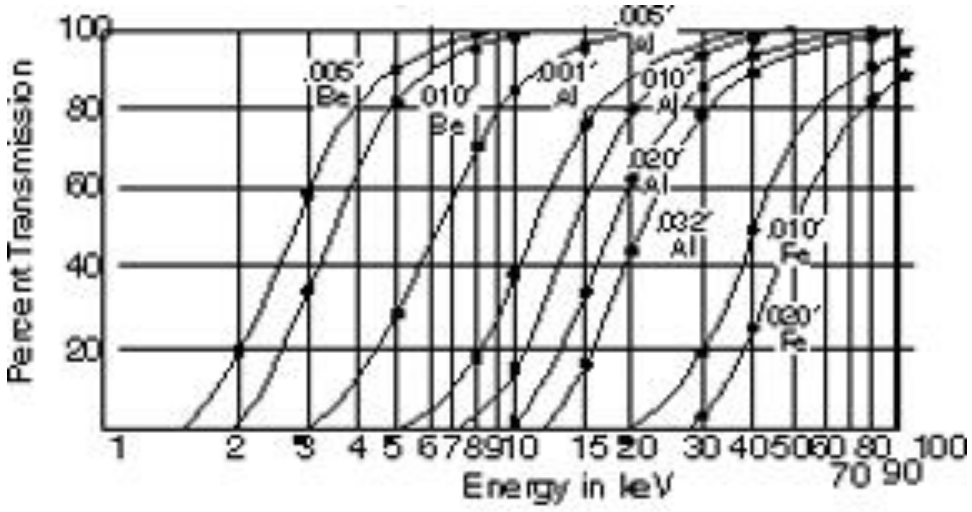

Figure 13. Transmission efficiency for a parallel beam of x or gamma rays normally incident on the face of a NaI crystal.

Many configurations of NaI detectors are used, from crystals for x-ray measurements in which the detector is relatively thin, to optimize resolution at the expense of efficiency at higher energies, to large crystals with multiple phototubes. Crystals built with a well to allow nearly spherical 4π geometry counting of weak samples are a widely-used configuration

The light decay time constant in NaI is about 0.25 microseconds, and typical charge sensitive preamplifiers translate this into an output pulse rise time of about 0.5 microseconds. For this reason, NaI detectors are not as well-suited as plastic detectors for fast coincidence measurements, where very short resolving times are required.

PLASTIC SCINTILLATORS

Many types of plastic scintillators are commercially available and find applications in fast timing, charged particle or neutron detection, as well as in cases where the rugged nature of the plastic, compared with NaI, or very large detector sizes, are appropriate. Sub nanosecond rise times are achieved with plastic detectors coupled to fast photomultiplier tubes, and these assemblies are ideal for fast timing work.

Separate outputs are usually used for timing, with the positive dynode output to a preamplifier and amplifier for energy analysis, and the larger negative anode output to a fast discriminator.

9.8 SEMICONDUCTOR DETECTORS

These are made of single crystals of highly purified germanium or silicon. They possess the highest performance among detectors with a high resolution.

A semiconductor is a material that can act as an insulator or as a conductor. In electronics the term "solid state" is often used interchangeably with semiconductor, but in the detector field the term can obviously be applied to solid scintillators. Therefore,

semiconductor is the preferred term for those detectors which are fabricated from either elemental or compound single crystal materials having a band gap in the range of approximately 1 to 5 eV.

The periodic table of the elements group IV elements: silicon and germanium are the most widely-used semiconductors, although some compound semiconductor materials are finding use in special applications. Table 1 shows some of the key characteristics of various semiconductors as detector materials.

Table 1. Properties of semiconductor detectors.

Material	Number of electrons, Z	Band gap, eV	Energy per e-p pair, eV
Silicon, Si	14	1.12	3.61
Germanium, Ge	32	0.74	2.98
Cadmium telluride, CdTe	48-52	1.47	4.43
Mercuric iodide, Hgl2	80-53	2.13	6.5
Gallium arsenide, GaAs	31-33	1.43	5.2

Semiconductor detectors have a P-I-N diode structure in which the intrinsic (I) region is created by depletion of charge carriers when a reverse bias is applied across the diode. When photons interact within the depletion region, charge carriers as holes and electrons are freed and are swept to their respective collecting electrode by the electric field. The resultant charge is integrated by a charge sensitive preamplifier and converted to a voltage pulse with an amplitude proportional to the original photon energy.

The depletion depth being inversely proportional to net electrical impurity concentration, and since the counting efficiency is also dependent on the purity of the material, large volumes of very pure material are needed to ensure high counting efficiency for high energy photons.

Figure 14. Germanium detectors and their background radiation shields and cooling cryostats.

Earlier on, the required purity levels of Si and Ge could be achieved only by counter-doping P-type crystals with the N-type impurity, lithium, in a process known as lithium-ion drifting. Although this process is still widely used in the production of Si(Li) x ray detectors, it is no longer required for germanium detectors since sufficiently pure crystals are now available.

The band gap values in Table I correspond to the temperature sensitivity of the materials and the practical ways in which these materials can be used as detectors. Just as Ge transistors have much lower maximum operating temperatures than Si devices, so do Ge detectors. As a practical matter both Ge and Si photon detectors must be cooled in order to reduce the thermal charge carrier generation or white noise to an acceptable level. This requirement is quite aside from the lithium precipitation problem which made the old Ge(Li), and to some degree Si(Li) detectors, perishable at room temperature.

The most common medium for detector cooling is liquid nitrogen, however, recent advances in electrical cooling systems have made electrically refrigerated cryostats a viable alternative for many detector applications.

In liquid nitrogen, LN_2 cooled detectors, the detector element, and in some cases the preamplifier components, are housed in a clean vacuum chamber which is attached to or inserted in a LN_2 Dewar. The detector is in thermal contact with the liquid nitrogen which cools it to around 77 °K or –200 °C. At these temperatures, reverse leakage currents are in the range of 10^{-9} to 10^{-12} amperes.

In electrically refrigerated detectors, both closed-cycle Freon and helium refrigeration systems have been developed to eliminate the need for liquid nitrogen. Besides the obvious advantage of being able to operate where liquid nitrogen is unavailable or supply is uncertain, refrigerated detectors are ideal for applications requiring long-term unattended operation, or applications such as undersea operation, where it is impractical to vent LN_2 gas from a conventional cryostat to its surroundings. A cross-sectional view of a typical liquid nitrogen cryostat is shown in Fig. 15.

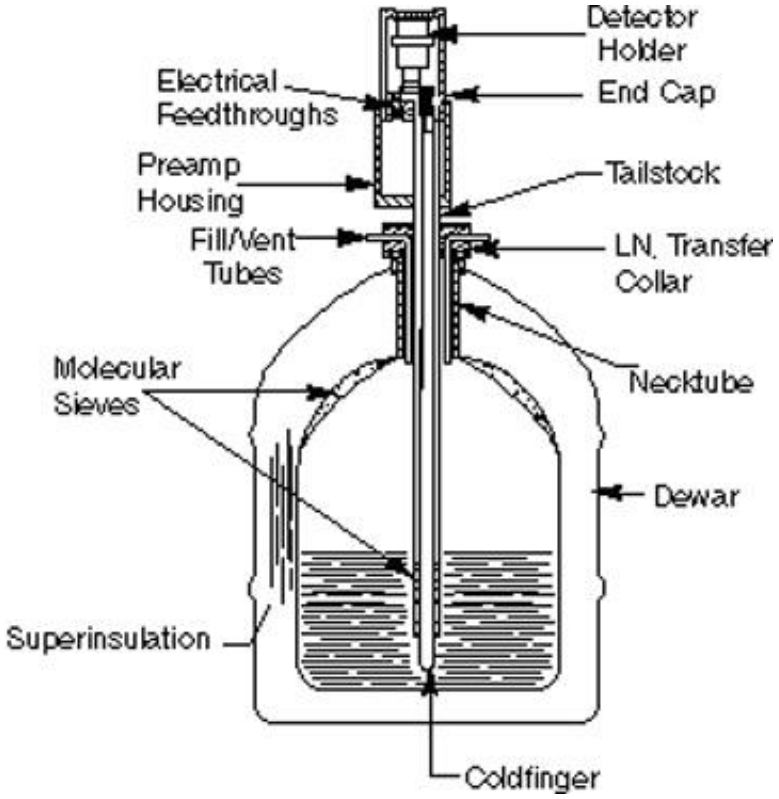

Figure 15. Liquid nitrogen vertical dipstick cryostat.

9.9 DETECTORS COMPARISON

The earliest semiconductor photon detectors had a simple planar structure similar to their predecessor, the Silicon Surface Barrier (SSB) detector. The grooved planar Si(Li) detector evolved from attempts to reduce leakage currents and thus improve resolution.

A coaxial Ge(Li) detector was developed in order to increase overall detector volume, and thus detection efficiency, while keeping depletion or drift depths reasonable and minimizing the capacitance

Semiconductor detectors provide greatly improved energy resolution over other types of radiation detectors for several reasons. The resolution advantage can be attributed to the small amount of energy required to produce a charge carrier and the consequent large output signal relative to other detector types for the same incident

photon energy. At 3 eV/e-h pair the number of charge carriers produced in Ge is about one and two orders of magnitude higher than in gas and scintillation detectors respectively. The charge multiplication that takes place in proportional counters and in the electron multipliers associated with scintillation detectors, resulting in large output signals, does nothing to improve the fundamental statistics of charge production.

The resultant energy reduction in keV (FWHM) against energy for various detector types is shown in Table 2.

Table 2. Energy Resolution in keV at Full Width Half Maximum (FWHM) for different detector types.

Energy	5.9 keV	1.22 keV	1.332 keV
Proportional Counter	1.2	-	-
X ray NaI(Tl)	3.0	12.0	-
3 x 3 NaI(Tl)	-	12.0	60
Si(Li)	0.16	-	-
Planar Ge	0.18	0.5	-
Coaxial Ge	-	0.8	1.8

At low energies, detector efficiency is a function of cross-sectional area and window thickness while at high energies total active detector volume more or less determines counting efficiency. Detectors having thin contacts, such as Si(Li) detectors, Low-Energy Ge and Reverse Electrode Ge detectors, are usually equipped with a Be cryostat window to take full advantage of their intrinsic energy response.

Coaxial Ge detectors are specified in terms of their relative full-energy peak efficiency compared to that of a 3 inches by 3 inches NaI(Tl) Scintillation detector at a detector to source distance of 25 cm. Detectors of greater than 100 percent relative efficiency have been fabricated from germanium crystals ranging up to about 75 mm in diameter. About two kg of germanium is required for such a detector.

9.10 RADIOLOGICAL SECURITY

The recent home land security modality in industrialized nations aims at preserving and securing their acquired wealth. This has turned the security industry into a high growth one. In turn, this led to the evolution of radiation detection instruments from applications in the scientific, medical and power generation fields into a new generation of instruments. These address the new security needs of the reality of what some people designate as the new surveillance paradigm. This is bound to stay with us for the foreseeable future.

The new areas of radiological security application include:

1. Emergency Management

Emergency management groups are expected to be prepared to cope with radiological incidents quickly and efficiently. The assumed incidents include the dispersion of radioactive material through the use of conventional explosives; better known as a Radiological Dispersion Device (RDD), a reactor or nuclear installation accident involving the release of radioactivity or the unlikely detonation of a nuclear device.

2. First Responding

First responders include fire, police and emergency medical technicians. They are expected to know what they are up against at every accident scene. The global fear of terrorism adds the radiological threat to their list of anticipated natural and man made hazards.

3. Transportation

The transportation industry is expected to deal with the threat of radiological security as a possibility. The first objective is to detect illegal or illicit materials before they can be misused while not impeding the legitimate and normal flow of commerce. The second objective is to be prepared with proper actions if a radiological event is perpetrated.

4. Border security

Securing national borders including harbors and airports, while not impeding the legitimate flow of commerce, is a demanding job preventing the flow of illegal entry, contraband and illegal drugs. Customs operations have the added burden of quickly screening people, packages and vehicles for possible illegal and illicit radioactive materials.

The new perceived needs for radiological security led to the burgeoning and the wide spread of a new class of instruments beyond the laboratory and scientific fields.

Personal electronic dosimeters measure dose and dose rates and generate an alert of unsafe radiation levels (Fig. 16).

Figure 16. Personal electronic dosimeter.

Pedestrian portal monitoring systems allow the screening of people at points of possible entry for radioactive materials (Fig. 17).

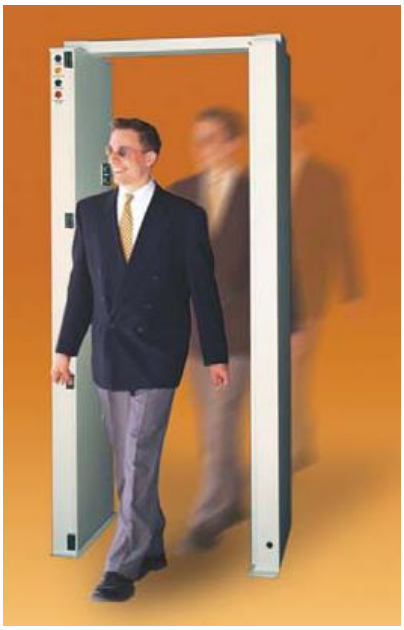

Figure 17. Pedestrian gamma and neutron monitor.

Vehicle portal monitoring systems allow the detection of radioactive materials inside packages in moving vehicles (Fig. 18).

Figure 18. Special Nuclear Material (SNM) and other radio nuclides vehicle portal.

Seal and clandestine imaging Systems ensure cargo container and area security by detecting unauthorized tampering or access to containerized materials or secured enclosures and photographs any perpetrator (Fig. 19).

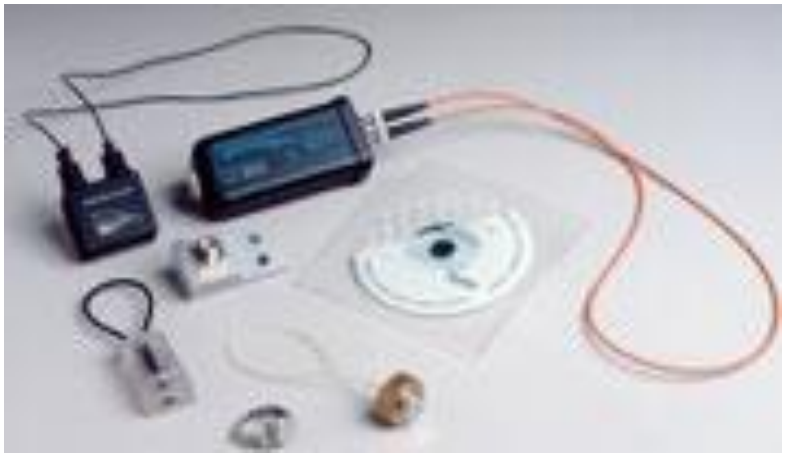

Figure 19. Seal and clandestine imaging system.

Surveillance cameras are integrated with the pedestrian or vehicular portal systems to automatically photograph anyone found to emit a radioactive signal (Fig. 20).

Figure 20. Surveillance camera.

Handheld identifiers, distinguish between naturally occurring radioactive nuclides or legitimate shipments of radioactive materials and illicit and illegal materials in packages, vehicles, and on people (Fig. 21).

Figure 21. Hand-held identifier checks the contents of a drum.

A neutron detection capability can be added to the hand held identifier by using a neutron probe (Fig. 22).

Figure 22. Hand held neutron probe.

Personal radiation monitors designed for use in rugged environments display dose and dose rate information on large easy to read and backlit Liquid Crystal Displays (LCDs). They also provide audio, visual as well as vibration alarm features. They are used by first responders and Hazardous Materials (HAZMAT) teams (Fig. 23).

Figure 23. Personal radiation monitor.

An Emergency Response Survey Kit provides a survey meter and smart probes to quickly and accurately detect and measure alpha, beta, and gamma and x-ray radiation. These meters are light weight, easy to use and rugged. A teleprobe option allows the user to monitor suspicious packages or areas from a safe distance (Fig. 24).

Figure 24. Survey meter and smart probes for beta, alpha and x-ray and gamma radiation.

Survey meters are compatible with a number of smart probes to measure alpha, beta and gamma radiations quickly. These meters are light weight, easy- to- use and rugged. Users can monitor suspicious packages or areas from a safe distance (Fig. 25).

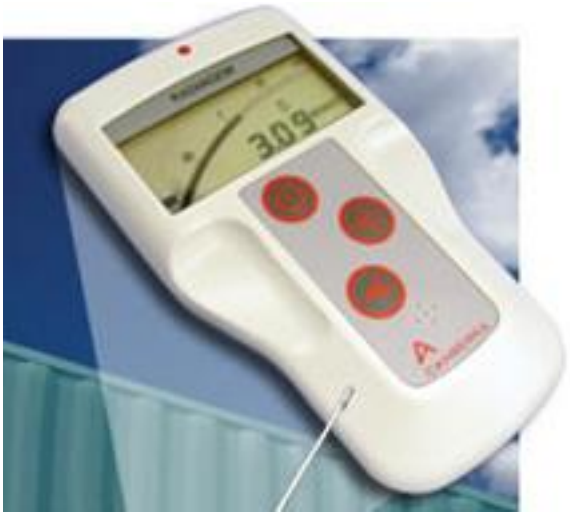

Figure 25. Survey meter.

External, whole body contamination monitors allow the screening of people for alpha and beta contamination, and show where on the person the contamination is located so that it can be decontaminated (Fig. 26).

Figure 26. External whole body contamination monitor.

Internal, whole body counting systems identify and measure the radioactive contamination inside a person's thyroid, lungs, gastro intestinal tract and the whole body. This allows medical personnel to quickly select the best treatment minimizing the long term impact of the contamination.

Area Monitoring Systems allow the constant monitoring of both the interior and the exterior of the secured facilities for radiation. It will automatically generate an alert in the case of any significant increases in radiation levels (Fig. 27).

Figure 27. Area radiation monitor.

Radiation patrol mobile systems identify and track gamma ray emissions remotely (Fig. 28). Mobile vehicles, helicopters and possibly satellites monitor whole stretches of the Earth's surface, countries, cities, airports, harbors, special events such as football or baseball games or incident areas and transmit the data to a command control center to assess possible evacuation and decontamination strategies (Fig. 29).

Figure 28. Radiation patrol mobile monitoring van.

Figure 29. Radiation patrol mobile monitoring system display.

REFERENCES

1. A.C. Melissinos, “Experiments in Modern Physics,” Academic Press, New York, p. 178, 1966.
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3. “Mass Attenuation Coefficients for NaI(Tl),” National Bureau of Standards (NBS) circular 583,, Table 37, 1956.

EXERCISES

1. Proportional detectors are typically specified in terms of the resolution for the 5.9 keV Mn^{55} x ray from a ^{55}Fe source.
Considering that Fe^{55} is a proton rich isotope which has a half life of 2.7 years, does not emit gamma rays, and decays through electron capture, deduce the nuclear reaction involved, then data mine for its decay diagram.
2. Find the decay diagrams for the K^{40} Co^{60} and Cs^{137} isotopes and identify their different gamma ray emissions.
3. Whole body counters can be used to estimate the amount of K^{40} in the human body. The naturally occurring isotope K^{40} is widely spread in the environment. In fact, the average concentration of potassium in the crustal rocks is 27 [g/kg] and in the oceans is 380 [mg/liter]. K^{40} occurs in plants and animals, has a half-life of 1.3 billion years and an abundance of 0.0119 atomic percent. Potassium's concentration in humans is 1.7 [g/kg]. In urine, potassium's concentration is 1.5 [g/liter].
a) Calculate the specific activity of K^{40} in Becquerels per gram and in Curies/gm of K^{40}.
b) Calculate the specific activity of K^{40} in Becquerels per gram and in Curies per gm of overall potassium.

c) Calculate the specific activity of K^{40} in urine in [Bq/liter].
d. A beta activity above 200 transformations (disintegrations) per minute per liter of urine following accidental exposure to fission products is indicative of an internal deposition in the body, and requires intervention. How does this "body burden" criterion compare to the activity caused by the one due to the naturally occurring potassium?