Measuring Radiation:
An Introductory Discussion

It's what's Inside that Counts®

- **What is radiation?**
- **How is it detected?**
- **How does it interact with matter?**
- **How is a radiation detector designed for my application?**

CRYSTALS

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Contents –

I. Introduction

The purpose of this publication is to introduce the concepts and terminology needed to understand the operation and use of gas-filled and scintillation systems that are used in the detection of radiation. The text is intended to be at an introductory level so that those who are looking at a radiation detection system for the first time may find it comprehensible.

<u>What is radiation and how is it detected?</u>

We have all heard about X-rays. They are a form of radiation that is accepted as useful. With X-rays, it is possible to see inside objects of without cutting them open. It is the basis of diagnostic tools that can show cavities in teeth, broken bones, tumors, tuberculosis and other diseases. X-rays are also familiar to us as the basis for the luggage inspection stations at airports.

X-rays are photons of electromagnetic radiation, e.g., light or radio waves, but have more energy and are more penetrating. Gamma radiation is less familiar because it does not enter into our daily lives as much as X-rays, and it has a bad reputation because it is associated with nuclear power plants and bombs. It should not be forgotten, however, that gamma rays are also used in cancer therapy (cobalt treatments), in medical imaging and in PET (Positron Emission Tomography) scanning. X-rays and low energy photons can be detected with gas-filled detectors. Gamma rays and high and low energy X-rays are the radiation that is most often detected with scintillation detectors. Radiation such as electrons, positrons and neutrons, as well as other particles can be detected also.

To be able to detect the presence of gamma ray or X-ray radiation, it is necessary to convert the energy it carries to another form — an electric current, light pulse or chemical change. (Photographs of examples of gas-filled and scintillation detectors are shown in Figure 1.) The energy range of interest for these photons is about 5 keV to 5 MeV. An eV is 1.6×10^{-19} watt-second; so 5 keV to 5 MeV is about 1×10^{-15} to 1×10^{-12} watt-second. This is a very small amount of energy and explains why a human being cannot feel the radiation! Compare it, for example, to a night light that uses about 5 watt-second of energy each second.

On the atomic scale, however, this represents an enormous amount of energy — sufficient energy to knock out or liberate hundreds and thousands of electrons. These electrons are measurable and observable. In the typical medical X-ray, these freed electrons cause chemical changes in photographic film which show up as an image when developed. Photographic film is one way to detect radiation, but it is difficult to be quantitative with a high degree of accuracy using this chemical means.

Measuring the liberated electrons directly (electric charge) would be quantitative and is the most accurate way to measure radiation; but it is limited for technical reasons to small volumes or low density detectors.

Good examples are CdTe, silicon surface barrier and lithium drifted silicon Si(Li) detectors. These can be up to a few cm in diameter and a few mm thick.

Gas-filled detectors have low densities but are very efficient for low energies and can be made quite large. These offer excellent energy resolution for low energy x-rays. Section II describes the basics of X-ray measurements with gas-filled detectors.

A surface barrier detector is used primarily for particle detection at room temperature and can do better than 0.5% energy resolution at 5.5 MeV. Germanium gamma-ray detectors can be fairly large, up to approximately 3 inches in diameter by 3 inches in length, but must be operated in a vacuum at liquid nitrogen temperatures. These detectors can achieve energy resolutions of better than 0.2% for 1.3 MeV gamma rays.

The most efficient detectors that can be made in large volumes and are quite dense are scintillation detectors. These convert the energy of the incoming radiation to a light pulse. Section III describes the basic operation of these detectors along with applications and uses.

Figure 1
Photograph of a variety of our products including scintillating plastic and fiber materials, scintillation crystal arrays, gas tubes and scintillation detectors with integrally mounted phototubes.

II. Gas-filled Detectors

1. Basic Technology

Gas-filled radiation detectors have been used in various forms since the early 20th century. They are devices which are relatively simple, very reliable, and have proven their worth against the test of time. The typical geometry is a metal tube with a small diameter wire electrode (anode) along the axis of the cylinder (cathode) as seen in Figure 2. There are many different types and geometries that can be organized into three general categories: ionization chambers, proportional counters, and Geiger-Müller (G-M) tubes. The difference between these three modes of operation depend on the high voltage and are illustrated in Figure 3.

Incident radiation causes ionization in the gas, which creates positive ions and electrons (ion pairs) within the gas volume. With no applied voltages the ion pairs recombine to form neutral gas molecules.

As voltage is applied between anode and cathode, the electric field causes electrons to be swept toward the anode and positive ions toward the cathode. The output current provides a measure of the number of ion pairs created and, therefore, the amount of incident radiation; this is the ionization region.

If the applied voltage is increased, electrons traveling toward the anode acquire enough kinetic energy to further ionize the gas by collision. A cascading electron multiplication amplifies the output signal of the detector. This is the region in which proportional counters operate. The size of the output pulse is proportional to the number of initial ion pairs, which provides a measure of the energy of the incident radiation.

As the voltage is further increased, the detector will enter the Geiger region. In this region the detector will provide a constant maximum output pulse, independent of the number of ions formed from the indicident radiation event. Any information as to energy of the incident radiation is lost.

2. Interaction with Matter: Photoelectric

The counting gas used in X-ray proportional counters is normally a mixture of a noble gas and a small amount of a polyatomic quench gas. The detector uses photoelectric absorption as the detection mechanism. When an X-ray photon enters the gas volume, it is completely absorbed by a gas atom which then ejects an energetic photoelectron from a bound energy shell. The energy of the photoelectron is the difference between the energy of the incident photon and the energy of the bound state of the electron.

Electrons are accelerated toward the anode wire under the influence of an electric field. As electrons move toward the anode, they collide with neutral gas molecules. Some of these collisions will have sufficient energy to create more ion pairs. The secondary electrons generated from collisions amplifies the electron signal and leads to a larger output pulse. A proportional counter is operated so that the output pulse size is proportional to the initial number of ion pairs. The number of output pulses provides information as to the amount of incident radiation, and the size of the pulses provides information as to the energy of the incident radiation.

A pulse height measuring system can be used to provide information about the incident photon energy. In most cases, the photoelectron is ejected from the tightest bound energy level, the K energy shell. The positive ion that is created will capture a free electron with a possible rearrangement of the electron energy shells; this leads to the emission of a characteristic X-ray that is reabsorbed in the gas volume. The characteristic K-alpha energies for Neon, Argon, and Xenon are 0.85, 2.97 and 29.1 keV respectively. These characteristic X-rays may lead to an "escape peak" at the corresponding energy below the full energy peak. See the same effect in a NaI(Tl) detector in Figure 6. This can be avoided by choosing a gas with a characteristic X-Ray of higher energy than the incident radiation.

3. Resolution and Noise

An important characteristic of proportional counters is the width of the total energy peak. It is usually measured with a multi-channel analyzer on the full width half maximum (FWHM). In an ideal case, pulses caused by monoenergetic radiation would all be the same height, and the multichannel analyzer would display a single line that would represent the radiation energy. In practice, a peak with a measurable width is observed. There are several contributing factors to the width of the energy peak, including statistical variations, detector geometry, gas purity and electronic noise. The statistical variations set a minimum possible resolution for a given geometry.

The electronic noise contribution can be limited by careful selection of electronic components and by limiting stray capacitances. It is desirable to keep the distance between the detector and the preamplifier as short as possible. The detector and electronics should be shielded from electrical interference and properly grounded in order to exclude extraneous noise from the counting system. (See SGC Scintillation Operating Manual - Ground Loop)

Proportional counters have very small diameter anode wires. Exposure to high vibration environments may produce spurious pulses due to movement of the anode wire. (This movement is like the vibrational modes of a string instrument.) This effect is known as microphonics. Saint-Gobain Crystals has developed proprietary manufacturing techniques to produce ruggedized detectors with minimal microphonic response.

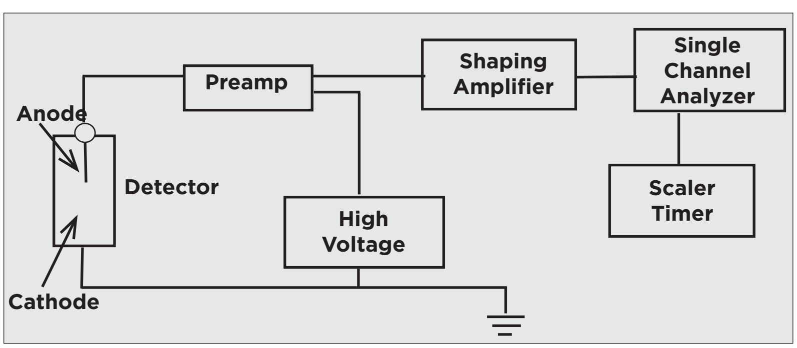

Figure 2
Typical counting circuit of a gas detector

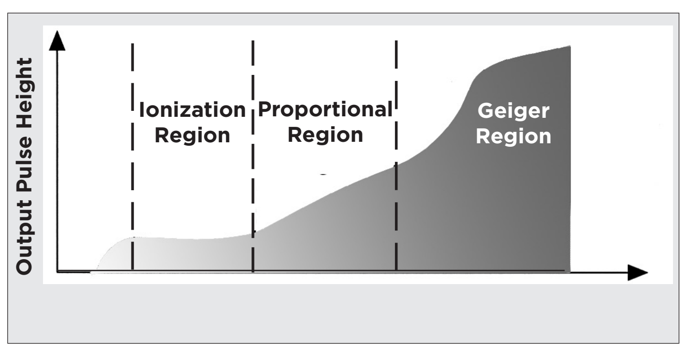

Figure 3
Types of gas-filled radiation detectors

III. Scintillation Detectors

1. Basic Technology

The most efficient detectors that can be made quite large and are quite dense are scintillation detectors. These convert the energy of the radiation to a light pulse. The light is converted to electrons (an electric current) in a vacuum tube called a photomultiplier tube (PMT), which also amplifies the electron current by 5 or 6 orders of magnitude. A diagram of a basic scintillation detection system is shown in Figure 4.

The PMT is biased by a high voltage (HV) power supply that connects to a voltage divider (VD). The VD divides the HV into discrete steps through a bank or series of resistors. About 100 volts (V) is dropped per stage. The 100V supplies the accelerating voltage to move the electrons from one PMT stage to the next PMT stage. At each stage, there is a multiplication factor of 4 to 5 giving a typical 8 or 10 stage PMT an overall gain of approximately 1×10^6.

The preamplifier is a charge integrating amplifier that collects the charge output of the PMT and generates a voltage pulse. The amplitude of the voltage pulse is proportional to the input charge. The output pulse has a slow exponential decay constant of 30 to 50 microseconds typically and is called a tail pulse.

The main amplifier is often referred to as a linear amplifier or a shaping amplifier. It increases the gain of the preamplifier signal from a few hundred millivolts to a few volts for input to the multi-channel analyzer (MCA). It also shapes the tail pulse, changing it to a near Gaussian-shaped pulse that is appropriate for the MCA.

The MCA is a sophisticated voltmeter with a memory. It measures the voltage amplitude of the input pulse and stores a count in the appropriate memory location. Alternately, the MCA is called a pulse height analyzer (PHA). When many pulses have been collected and binned, the result is called a histogram of counts vs. voltage or counts vs. channel. This histogram is referred to as a spectrum and the system or instrument is doing spectroscopy. All of the electronics are designed to be linear such that each bin is proportional to the energy of the photon that was detected and inversely proportional to the wavelength. Thus, an increasing channel number is indicative of increasing energy.

2. Interaction with Matter: Photoelectric, Compton and Pair Production

Figure 5 depicts a histogram (an energy spectrum) obtained with a 2-inch diameter by 2-inch thick detector (2x2) made of NaI(Tl) and a ^{137}Cs radioactive source. ^{137}Cs decays or disintegrates by emitting a 662 keV gamma ray, a 32 keV X-ray, and a beta ray. The beta ray is a particle (an electron) that cannot pass through the crystal housing, but the 662 keV and 32 keV photons do.

Both the gamma ray and the X-ray are seen as peaks in the figure. Another feature is the Compton edge at 477 keV. This edge occurs when a photon scatters from an electron back out of the crystal at 180°. Photon electron scattering is called Compton scattering. The energy of the scattered photon (E_s) can be calculated knowing the incident photon energy E_i and the scattering angle θ by the equation:

$$E_s = E_i/[1+E_i(1-\cos\theta)/511], \qquad E_s, E_i \text{ in keV}$$

For E_i = 662 keV and θ = 180°, E_s (the energy of the scattered photon) is 477 keV. This is the maximum energy that can be deposited by a Compton scattered 662 keV photon. At angles less than 180° backscatter, less energy is deposited in the crystal and those events generate the continuum from the Compton edge to the low end of the spectrum. Compton scattering is the dominant mode of interaction in NaI(Tl) in the energy range of 0.3 to 5 MeV. Photons from the ^{137}Cs radioactive source can be scattered by electrons in surrounding material (such as table tops, and lead collimators) into the NaI(Tl) detector. This is called backscattering, and a peak is observable near 185 keV corresponding to 180° backscattering from objects near the detector or radioactive source. If a lead block is placed close behind the ^{137}Cs source, the number of backscattered photons would increase and the peak at 185 keV would become more pronounced.

For a photon below 300 keV, the photoelectric effect dominates and, via that mechanism, the photon transfers all of its energy to a single electron, which in turn liberates secondary electrons that produce the scintillation light. This presents an advantage for spectroscopy at these lower energies because there is no Compton continuum under the peaks. The interaction, if it occurs, is total absorption of the photon. Sometimes the single electron is the innermost electron of iodine. When another electron fills this vacancy, a K-shell X-ray characteristic of iodine is emitted at 33.2 keV.

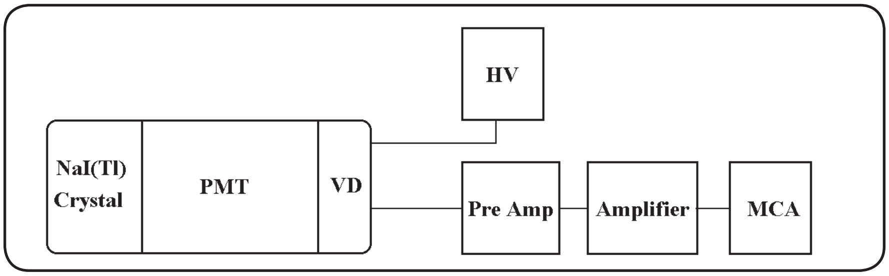

Figure 4
Diagram of basic scintillation detection system

This X-ray can escape from the NaI(Tl) crystal and produce an extra peak in the spectrum called an escape peak. The escape peak energy is the photopeak energy less the energy of the 33.2 keV X-ray that exits the scintillator. In the spectrum in Figure 6, this escape peak is at 26.3 keV. An escape peak can be observed when the scintillator is thin or when the interaction is near the surface — as it is with lower energy photons.

Pair production is a process whereby 1022 keV of energy of the incident photon is converted into the masses of a positron and an electron pair — a particle and its anti-particle. The positron will slow down and eventually meet with an electron and annihilate into two photons of 511 keV sharing the energy and momentum equally and going away from each other at 180°. One or both of the 511 keV photons can escape and generate extra peaks in the spectrum, these are called one escape or two escape peaks depending on how many of the 511 keV photons left the crystal.

3. Detector Considerations

In a lower mass material such as plastic scintillator, the Compton effect dominates over a very broad energy range from about 20 keV to above 10 MeV. For that reason, unless a plastic scintillator is extremely large, no single peak or photopeak can be seen in the spectrum. Thus, plastic scintillator is normally used for gamma detection only when energy information of the photon is not needed; e.g., in gross counting applications and anti-Compton shields.

If spectroscopic information is needed (i.e., energy and intensity), then the scintillators with the higher atomic number (often referred to as high Z material) are used. NaI(Tl) has been very popular (the workhorse) with sizes up to 20″ x 20″ single piece detectors being available. Bismuth Germanate (BGO) gives a better ratio of peak counts to total in the spectrum and performs as well as NaI(Tl) at higher energies. $LaBr_3$(Ce) crystal gives better energy resolution than NaI(Tl) by a factor of 2 and has sub nanosecond timing cabability.

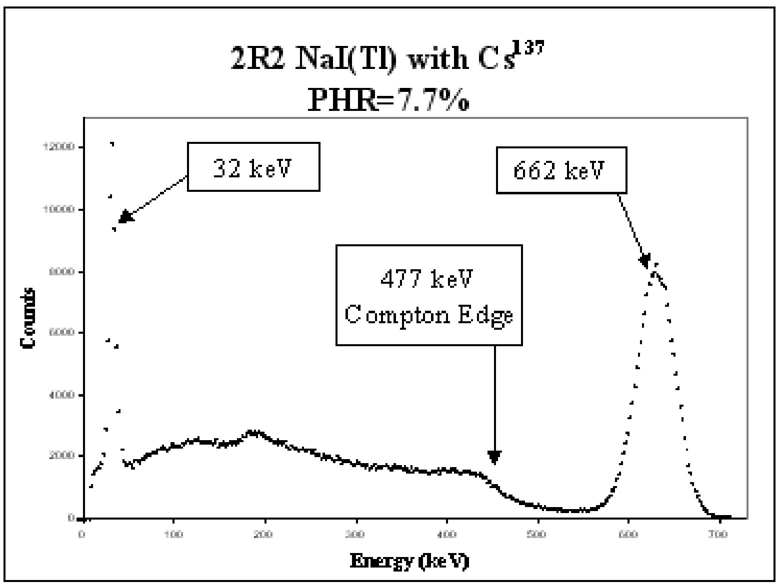

Figure 5
A histogram of the spectrum of pulses from the ^{137}Cs radioactive source, measured with a 2-inch by 2-inch NaI(Tl) detector

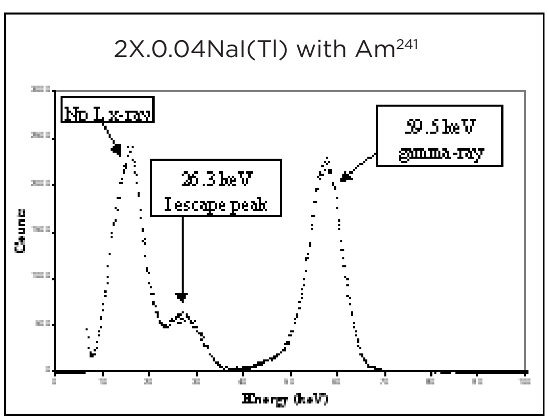

Figure 6
A histogram of the spectrum of pulses from an ^{241}Am radioactive source, measured with a 2-inch diameter by 0.04-inch thick NaI(Tl) detector

IV. Design Considerations (A)

1. Describing the Application

Before a new detector can be designed properly to fulfill its design goals, it is necessary to carefully define those goals, the environment, and the circumstances of operation. In other words, it is necessary to define the system that the detector is part of. One way to define a system is to answer the following questions:

What is to be measured? (Radiation type.)

Why measure it? (Time, position, number or energy.)

Where is it to be measured? (Physical environment.)

How much data is expected? (Data rate and volume.)

How well is it to be measured? (PHR, CRT.)

Saint-Gobain Crystals personnel can design a detector and/or a system to meet a list of specifications, but a much better job can be done if the entire project is understood. The difference between designing to meet specifications only and designing to satisfy an application can be compared to a computer program doing what it was programmed to do versus doing what it is expected to do.

2. Definition of the System

What type of radiation or what type of particle is to be measured? Knowing the type of radiation to be measured affects the container design, materials and thickness. Most often, the scintillation detector is used to detect photons and the container can be 0.8 mm of aluminum or 0.5 mm of stainless steel. For other forms of radiation — particles, X-rays or low energy photons — it is important to have thinner containers or thinner entrance windows so that the radiation can pass through. Table 1 lists entrance windows and thicknesses for various combinations of radiation and energy:

Why Measure it? It is useful to know what the desired information or result is. During the design stage this information can be most helpful in answering other questions that might come up. Saint-Gobain Crystals technical personnel have a vast amount of experience in radiation measurements. This experience can be utilized to best advantage if complete information about the measurement application is known.

Window Material	Thickness (0.001″)	Energy Range (keV)	Radiation
Be	5 to 10	>3	photon
Al	1	>6	photon
Al	10	>13	photon
Al	32	>20	photon
Fe	10	>40	photon
Fe	20	>50	photon
Al	1	>60	electron
Al	10	>250	electron
Al	1	>5000	alpha
Al	0.1	>450	alpha

Table 1
The thickness and type of material that is appropriate for transmitting radiation of various types of energies

Where is it to be measured? The environment critically affects design. For example, a detector for the vacuum of space has to be able to withstand the stresses encountered during launch. A detector that measures the activity in an oil well while drilling has to survive severe shock and vibration conditions.

How much data is expected? The number of particles or photons that impinge the detector per second is the counting rate. Parameters or parts of the detector such as crystal, photomultiplier tube (PMT), voltage divider (VD), high voltage supply (HV), preamplifier, amplifier and multichannel analyzer (MCA) may need to be optimized for different count rate applications or systems. (High count rate equipment tends to be more specialized and expensive.) The units that are used to specify count rate are counts in a time interval or flux units. These two ways of specifying can be related by the detector efficiency. Sometimes the efficiency is difficult to specify, so the counts per unit time and geometry are preferred or sufficient.

The simplest gross counters measure the current output of the PMT and are operated in the DC mode. This DC operation is used when flux is so high that individual pulses cannot be separated in time from each other. Current mode is only possible when the PMT is operated with negative HV. Gross counting is possible with the PMT operating in the pulse mode also. No energy information is determined except that it is above a minimum which is referred to as a threshold.

Dose units are a measure of the amount of energy deposited into some material that could be air, water, tissue, silicon or other material. Dose is supposed to be an indicator of the amount of physical damage done to the material. Dose units are r, rad and rem. These are all approximately equivalent for soft tissue (e.g., flesh) such that:

1 r = 1 rad = 1 rem

A measuring device that is calibrated in dose units can be converted to flux or count units if the energy of the radiation is known.

V.Design Considerations (B)

What parameter and how well is it to be measured? There are many parameters or aspects of the radiation that is measured including energy, number, position, time and type.

1. Energy

How energetic or how much energy the photon has is measured in keV, MeV or GeV. It is usually determined with a multichannel analyzer (MCA) and referred to as the pulse height (PH). The MCA can also be called a pulse height analyzer. If only the number of photons or particles is of interest, without any need for energy information, then this system is referred to as a gross counting system. The simplest gross counters measure the current output of the PMT operated in the DC mode. This mode of operation is used when the radiation flux is so high that individual pulses cannot be separated from each other. (See above, *How much data is expected*?)

2. Position

To find out where in the detector the particle hit or the event took place takes a minimum of two PMT's. Using the pulse height signal from the PMT's on the two ends, the position can be calculated. The most common unit of position measurement is the millimeter (mm), and therefore, the resolution of a position measurement is given in mm or sometimes its inverse (lines/mm).

3. Time

If a time signature or a time of interaction of the photon or particle is needed, special timing electronic modules are needed. These additional modules include constant fraction discriminators (CFD), timing filter amplifiers (TFA) delay modules and a time to amplitude converter (TAC). Time is always measured relative to a start channel or other reference such as a cyclotron or linac (linear accelerator) beam pulse signal. Time of flight (TOF) of particles and photons is measured this way, but it is actually a time interval, not an absolute time measurement. How well the TOF is measured is determined by the coincidence resolving time (CRT) of the system (see Table 2).

4. Particle Identification

In order to determine the type of particle, i.e., proton or alpha, it is necessary to measure more than just the energy. Generally, two parameters are measured; for example, (1) the fast and slow component of a two component scintillator like BaF_2, or (2) the two pulse heights in a detector telescope consisting of a minimum of two detectors, or (3) two types of scintillators with vastly different decay constants (in a phoswich). In a two-dimensional histogram of the parameters, the particle signatures will show up as offset bands. Then to select a certain particle, one simply selects the appropriate band.

5. Resolution

The quality of the detector performance depends on the width of the peak in the histogram. For scintillation detectors, the energy resolution for a monoenergetic gamma ray from ^{137}Cs, 662 keV, is most often specified. The narrowness of the peak is defined as the full width of the response peak at half the maximum height of the peak (FWHM). For a gaussian-shaped peak, it is 2.35 times the standard deviation (s) of the distribution. For a Ge detector the FWHM is given in keV for the ^{60}Co 1173 or 1332 keV emission. For scintillation detectors, the FWHM is usually given as a fraction of the energy or pulse height.This pulse height resolution (PHR) is expressed in % and is defined as the full width of the peak at one-half its height divided by the channel number or energy (See SGC FWHM Analsys for Arbitrary Peak Shape). Side on (SO) or broad beam (BB) are terms referring to the resolution as measured with the source of radiation impinging on the side of the detector. BrilLanCe™380 crystal is the scintillator with the best pulse height resolution at about 3% for 662 keV. BrilLanCe™350 and NaI(Tl) scintillators are the next best at 4% and 7% respectively.

The quality of performance is measured the same way for other detector generated parameters also. Position resolution is the full width at half maximum or height of a peak in a calibrated position spectrum expressed in mm. *Lines per mm* or *line pairs per mm* is a way of defining the position resolution, e.g., in an Anger camera or on a video screen. It is determined by viewing an image of a known collimator pattern (much like the test pattern seen on a TV screen before regular programming starts). One looks at the image of this mask with a calibrated spacing for the slits. The resolution in lines/mm is chosen from the screen where the eye can resolve (or distinguish) separate lines.

In order to have a good SO or BB PHR, the uniformity of response along the length of the detector as observed in a PH versus position plot must be fairly constant. For example, an all polished crystal will have a uniformity of response as a function of length that looks like a flat smile. If the pulse height at the ends of the crystal are significantly higher than at the center, the BB measurement will show all these different pulse heights and result in a broad peak with a poor PHR.

The coincidence resolving time is the FWHM of a time peak which is measured with a time to amplitude converter (TAC). A block diagram of a possible coincidence measuring set up is shown in Figure 7.

A coincidence measurement measures the time delay between the signal from the start channel and the stop channel. The start channel is often a “good” timing detector. Such a detector consists of a fast scintillator like plastic or CsF on a fast timing PMT like the Hamamatsu R329 or the Burle 8575. Typical CRT’s measured with various stop channels opposite a “good” start channel with low energy threshold settings are:

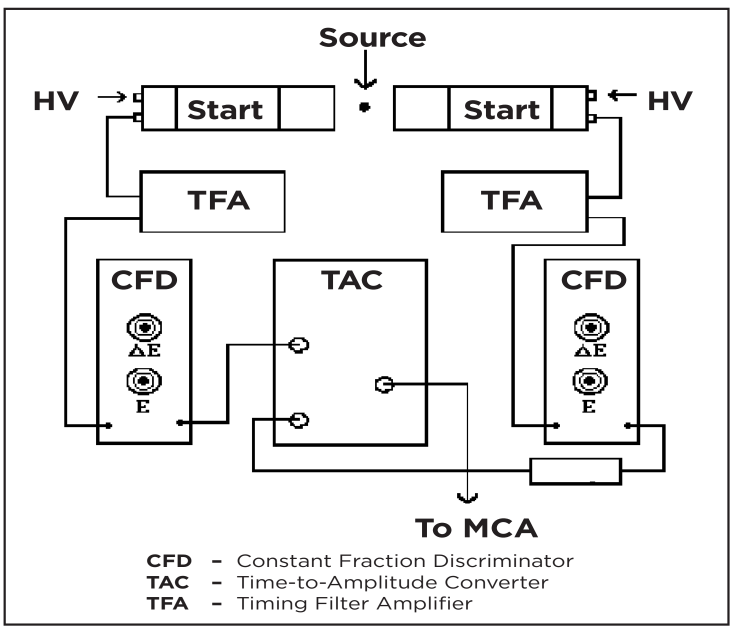

Figure 7
Block diagram of the electronic modules and connections for coincidence measurements

Stop channel (nsec)	CRT*
1″ dia. x 1″ BrilLanCe 380	0.2
1″ dia. x 1″ BaF_2	0.2
1″ dia. x 1″ BrilLanCe 350	0.3
1″ dia. x 1″ PreLude 420	0.4
1″ dia. x 1″ plastic	0.4
1″ dia. x 1″ CsF	0.4
1″ dia. x 1″ NaI	1.0
1″ dia. x 1″ BGO	2.0
2″ dia. x 2″ NaI	1.4
3″ dia. x 3″ NaI	1.7
BGO anti-Compton	5 to 10
NaI anti-Compton	3 to 6
*Threshold dependent	

Table 2
The coincidence resolving times (CRT) as measured with various scintillators using the electronics of Figure 7.

VI. Summary

The interaction of radiation with the gas in a gas-filled detector generates a charge pulse directly. The interaction of radiation with matter in a scintillation detector generates light pulses .

These light pulses are collected by a photomultiplier tube and converted to charge pulses.

A preamplifier integrates the charge and converts it into a voltage pulse that is further amplified and shaped by the main amplifier. The pulses are counted directly by an SCA and a scaler (as shown in Figure 2 in Section II) or are collected by a sophisticated voltmeter called an MCA (as shown in Figure 4 in Section III). The quality of this data is determined by the narrowness of the peaks in the spectrum and is measured as the full width of the peak at half of its maximum amplitude (FWHM).

Gas-filled and scintillation detectors are used in many applications from space astronomy and exploration to nuclear medicine and downhole oil well logging. Gauging and non-destructive testing with X-rays, gamma rays and neutrons are important applications where detectors can inspect or see through solid metal parts and containers.

Many detector designs of basic geometries are available. Literature on the Saint-Gobain Crystals web site shows the designs. Also there are technical papers about some typical applications. Special or new designs require a clear definition of the application and the conditions of measurement. Applications support is available through the Saint-Gobain Crystals offices.

VII. Glossary of Selected Terms

background – Used to describe the counting rate that is a result of radiation that occurs naturally from cosmic radiation, geophysical radiation, inherent material radiation, etc.

cps — Counts per second seen by the detector at a given energy or in an energy interval.

cpm — Counts per minute are the counts measured in 60 seconds instead of one second.

dead time — The interval of time when a Geiger-Mueller tube becomes insensitive to radiation after an ionizing event, represented in microseconds.

energy (PH) — How energetic or how much energy does the photon or particle have? This is measured in keV, MeV or GeV. It is usually determined with a multichannel analyzer (MCA) and referred to as the pulse height (PH). The MCA is often referred to as a pulse height analyzer.

FWHM — *Full width at half maximum* is a term referring to the narrowness of a peak. For a gaussian shaped peak, this is 2.35 times the standard deviation. (See PHR below.)

flux — Cps or cpm per unit area such as cps/cm^2 or cpm/m^2. Thus counts per second per meter squared, counts per second per inch squared or counts per minute per inch squared etc. .... are all flux units.

gross counting — If only the amount of the radiation is of interest without any need for energy information, then this system is referred to as a gross counting system.

operating voltage — The recommended applied voltage at which a Geiger-Mueller tube should be operated.

PHR — Pulse height resolution is expressed in % and is defined as the full width of the peak at one half its height divided by the channel number or energy. Side on (SO) or broad beam (BB) are terms referring to the resolution as measured with the source of radiation impinging on the side of the detector.

particles —

beta particle (b^-) — An electron.

beta plus particle (b^+) — The anti-particle of the electron that is also referred to as a positron.

neutron (n) — A radioactive particle when not in the nucleus with protons. It is about the same mass as the proton but neutral in charge.

proton (p) — Or H^1 is the nucleus of the hydrogen atom that is stripped of its electron.

deuteron (d) — Or H^2 is the nucleus of heavy hydrogen, a proton and neutron held together by nuclear forces.

triton (t) — Or H^3 is the nucleus of a heavier hydrogen, a proton and two neutrons held together. This particle is radioactive with half life of 12.3 years.

He^3 — The light isotope of helium with two protons and one neutron in the nucleus.

He^4 — Helium four is the nucleus of the most abundant isotope of helium which has two protons and two neutrons in the nucleus.

heavy — Refers to other heavier particles that are not normally detected with scintillators but with silicon or gas detectors, e.g., heavy ions such as Xe and Ar nuclei.

particle type — In order to determine the type of particle, it is necessary to measure more than just the energy. The two parameters that are measured most often are the fast and slow component of a two component scintillator like BaF_2 or the two pulse heights in a detector telescope consisting of a minimum of two detectors.

photons — The X-ray and the gamma ray are both electromagnetic wave packets and differ only in how they are produced. A gamma ray is produced by the nucleus whereas an X-ray is produced by the electrons surrounding the nucleus.

plateau — Region on a Geiger-Mueller tube plateau curve that has a minimum change in counting rate as the applied voltage changes.

plateau slope (gas tube) — The percent change in counts over a chance in applied voltage, usually calculated for 100 volt intervals.

position — Where in the detector did the particle hit or the event take place. Usually it takes a minimum of two PMT's to measure position in one dimension. The most common unit of position measurement is the millimeter (mm), and therefore, the resolution of a position measurement is given in mm or sometimes its inverse - line pairs per mm. Position resolution (PR) is the FWHM of a peak in a calibrated position spectrum expressed in mm.

starting voltage — The minimum applied voltage across a gas-filled detector at which pulses are first detected by a counting system, generally assumed to be a 1.0 volt pulse.

time (TAC, TOF, CRT) — When did the photon or particle hit the detector. This is most often measured with a time to amplitude converter (TAC), and it is relative to a start channel or other reference such as a cyclotron or linac beam pulse signal. The time of flight (TOF) of particles and photons is measured. How well the TOF is measured is called the coincidence resolving time (CRT), which is the FWHM of a time resolved peak.

VIII. Applications

This section gives a perspective on some of the uses of radiation detectors, which go hand-in-hand with the uses of radiation. Although scintillation detectors are emphasized, other types of detectors are mentioned. (This list is not intended to be complete.)

Application	Material	Characteristics	Application Benefit	Configuration Example
Medical				
SPECT (Gamma Camera)	NaI(Tl)	Good Energy Resolution Good Detection Efficiency Large Sizes	Cost-effective solution for large area coverage with energy discrimination to reject Compton-scattered events	24" x 18" x .375" single plate
SPECT (Organ Specific)	$LaBr_3$	Superior Energy Resolution Excellent Spatial Resolution Highest Light Output	Best resolution for scintillators allows for improved resolution and Compton rejection	100 X 100 X 8mm single plate with PMT, PSPMT or Photodiode
	NaI(Tl)	Good Energy Resolution Good Detection Efficiency Small pixels	Good energy resolution, high light output and small pixels enable organ-specific and small animal imaging	Pixellated arrays for use with PMTs or PSPMTs
Whole body counting	NaI(Tl)	Good Energy Resolution Good Counting Efficiency	Good energy resolution and stopping power allow for identification of isotopes over a range of energies	3" X 5" X 16" with PMT 4" X 4" X 16" with PMT
Positron Emission Tomography (PET)	BGO	Highest Stopping Power Non-hygroscopic	Fast decay time and low afterglow in addition to high nuclear absorption properties make BGO useful in PET.	4 X 4 X 30mm Pixels
	$LaBr_3$	Excellent Energy Resolution Short Decay Time	Best in class speed offers superior time of flight (TOF) performance with excellent resolution and acceptable stopping power	4 X 4 X 30mm Pixels
	LYSO	High Stopping Power Short Decay Time Good Energy Resolution	Excellent timing characteristics enable time of flight (TOF) applications	4 X 4 X 30mm Pixels
Computed Tomography (CT)	$CdWO_4$	Good light and short decay time	High resolution by making a pixillated array	50x50x5mm overall array size
Radioimmunoassay (RIA)	NaI(Tl)	Good Energy Resolution Good Counting Efficiency	Well configuration and scintillator sensitivity allow for efficient measurement of the presence of target antigens in samples	1" dia. x 1" (with well) with PMT
Geophysical				
Well logging	PolyScin® NaI(Tl)	High Durability	Withstands extreme shock/vibration	1" dia. x 5"
	$LaBr_3$	60% more light than NaI	Best choice for nuclide ID and down-hole spectroscopy	1" dia. X 5"
	BGO	Highest stopping Power	Good choice for spectroscopy and high energy detection	3" dia. x 6"
Aerial Survey	NaI(Tl)		Provides good pulse height resolution and uniformity	4" X 4" X 16" with PMT
Security				
Luggage or container scanning	$CdWO_4$	Low after glow	Its high density makes it a good choice for 300+ keV imaging for container and vehicle scanning.	Linear array 16/32 elements
	CsI(Tl)	High Light output Emission wavelength at 550nm compatible with PD	Non hygroscopic and good stability in varying environmental conditions - Emission matches well with silicon photodiodes.	Linear array 16/32 elements
Cargo Scanning	CdWO4	High Stopping Power Short Decay Time Good Energy Resolution Non-hygroscopic	High energy applications up to 10 Mev	Linear arrays coupled to diode
	Plastic Scintillator			3" dia. X 3" with PMT
Handheld and Personal Monitors	CsI(Tl)	High Light output Non-hygroscopic	Good stability in varying environmental conditions Emission wavelength at 550nm compatible with Photodiode	10x10x10 CsI(Tl) with Photodiode

Application	Material	Characteristics	Application Benefit	Configuration Example
	NaI(Tl)	Good Energy Resolution	Cost-effective solution for isotope identification	3” dia. X 3” with PMT
	$LaBr_3$	Excellent Energy resolution Excellent T° stability	Better peak separation Higher accuracy of detection systems to reduce false alarms Stability with T° change	1.5” dia. x 1.5” with PMT
Portal Monitoring	Plastic Scintillator		Available in large areas and can identify the presence of radioactive material.	48″ x 14″ x 2″
	NaI(Tl)	Good Energy Resolution Good Detection Efficiency	Allows for coverage of large areas with reasonable cost while providing good energy resolution for isotope identification	2”X4”X16” or 4”X4”X16”
Thermal neutron activation	NaI(Tl)			3” dia. X 3” with PMT
	$LaBr_3$	Excellent Energy Resolution Fast Decay Time		3” dia. X 3” to 6” with PMT

Industrial

Application	Material	Characteristics	Application Benefit	Configuration Example
Gauging - Thickness or Density	NaI(Tl)			2″ dia. x 2″
	CsI(Tl)	High Light output Emission wavelength at 550nm compatible with PD	Compact designs with Photodiode Insensitivity to magnetic fields No HV required	10x10x10mm to 18x18x40mm CsI(Tl) with Photodiode
	Gas-Filled Detectors	Emission wavelength at 550nm compatible with PD	used at lower energies where they are most efficient	
	Plastic Scintillator	Emission Wavelength: 425 nm	Large rods or bars provides more efficiency than gas-filled and are more cost-effective than inorganic alternatives	2″ rods or bars
Coal/ mineral assay	NaI(Tl)			4″ X 4″ X 16″ or 6″ dia. X 6″
	$LaBr_3$	Density / Excellent Energy resolution / fast decay time	Higher accuracy and reduced analysis time	3′′x3′′ to 3′′x6′′
X ray Fluorescence	$LaBr_3$	Fast decay time, high count rates capabilities	Ultra high count rates capabilities at low x and gamma energies without iode emission penalty	dia< 30mm x 2,5mm to 5mm
Steel recycling	Plastic Scintillator			18″ X 36″ X 2″
Alpha/Beta Counting	BC-400 or -404 with ZnS(Ag) coating		High efficiency Cost effective alpha beta counting solution	circular dia. 2’’ to 4’’ square 3’’X 4’’

Physics

Application	Material	Characteristics	Application Benefit	Configuration Example
	$LaBr_3$	Density Excellent Energy resolution Fast decay time	Capture and separation of fast events	3″ X 6″ to 3.5″ X 8″
Nuclear Physics	BaF2	Decay Constant: 0.7 ns fast component 630 ns slow component	Capture of fast events	2’’ X 4’’ to hexagonal shapes
Total Absorption Spectrometer	NaI(Tl)			
	BC-412	Very long sheets, length>3m	The longer emission spectrum of -412 means a longer attenuation length and more uniform response. Uniformity is important for long strips in a colorimeter.	

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