

# 7 Radiation Detection and Measurement

## 7.1 Radiation Detectors

Radiation is detected using special systems which measure the amount or number of ionizations or excitation events that occur within the detector's sensitive volume. A radiation detection system can be either passive or active, depending upon the device and the mechanism used to determine the number of ionizations. **Passive** devices are usually processed at a special processing facility before the amount of radiation exposure can be reported. Examples of passive devices are radiation dosimeters used in determining individual radiation exposure and radon detectors. **Active** devices provide an immediate indication of the amount of radiation or radioactivity present and consist primarily of portable radiation survey meters and laboratory counting devices. Table 7-9 located at the end of this chapter (and the manual's end page), lists approximate efficiencies for commonly encountered radioisotopes using different types of survey instruments.

## 7.2 Radiation Dosimeters

It would be quite impractical to follow each worker around with a radiation survey meter to try to keep track of the radiation exposure fields they enter because: (a) very likely the dose rates will vary considerably over time depending upon the procedures performed, and (b) the workers usually move around from one radiation level to another during the course of their work. To overcome these problems, the Safety Department monitors a radiation worker's external radiation exposure with a **personal dosimeter** or radiation badge. This device essentially stores-up the radiation energy over the period it is used and is then sent to a vendor to read the exposure and report the results. Although there are several types of radiation dosimeters commonly used, the most common are film badges, thermoluminescent dosimeters track-etch and optically stimulated devices.

### 7.2.a Film Badge

Photographic film is the oldest monitoring device and worldwide it is the most common type of personal dosimeter primarily because of its low cost, simplicity and ease of use. The film badge employs one or several dental-sized pieces of photographic film held in a special holder. With 2-film packets, one film generally has a sensitive emulsion and the other a relatively insensitive emulsion. Such a packet is then useful over a gamma-ray exposure range of from 10 mR to about 1800 R. Film is also sensitive to high-energy beta particles whose maximum energy exceeds about 400 keV (i.e.,  $E_{max} \geq 400$  keV). With an appropriate type of film, thermal and fast neutron exposures may also be measured.

Radiation exposure darkens film. The degree of blackening or **density** is related to the amount of exposure. However, film is extremely photon energy dependent. In the energy region between 15 and 50 keV (Figure 7-1), film may over respond by a factor of 20 compared to exposures above 100 keV. To compensate for this problem and to measure beta doses, the film packet is used with a specially designed film holder (Figure 7-2). This type of badge has an open window area to measure beta doses and several different types of filters. Common filters include aluminum, copper or tin, cadmium, and lead. Reading the film employs relatively elaborate algorithms based upon the density or darkening of the film under each of the filter elements. For example, the beta dose is determined from the ratio of the open window film density to that behind the filters. If only beta is involved, then the film darkening is seen only behind the open "beta" window. The aluminum and copper filters help differentiate and quantify the energies of low-energy x-rays. The copper filter absorbs more of an x-ray beam than the aluminum filter, so the film under the copper filter should be less exposed (i.e., lighter) if x-rays are the only source of the exposure.

Neutrons, especially fast neutrons (i.e.,  $E > \frac{1}{2}$  MeV), can be monitored using a special neutron track film added to a film badge. Fast neutron irradiation of the film results in proton recoil tracks created by elastic collisions between the neutrons and hydrogen nuclei

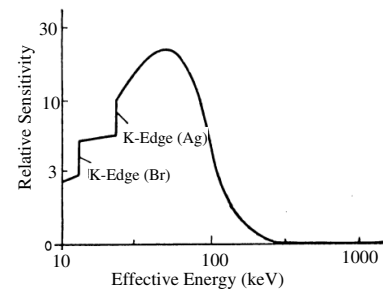


Figure 7-1. Energy Response

of the filter elements. For example, the beta

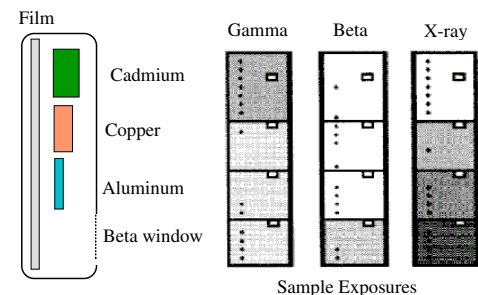


Figure 7-2. Typical Film Badge

in the film and wrapper. The developed film is automatically scanned and the number of tracks counted using a high-powered microscope. The number of tracks per  $\text{cm}^2$  is proportional to the absorbed dose. A neutron dose of 100 mrem corresponds to a track density of approximately 2600 per  $\text{cm}^2$ , or approximately 1 track per two microscopic fields. This type of device is only useful for neutron energies between 0.5 MeV and 10 MeV because below  $\frac{1}{2}$  MeV, the recoil protons do not have enough energy to make recognizable tracks.

Cadmium and tin absorbers are used in monitoring a mix of neutrons and beta/gamma radiation. Cadmium has capture cross sections (see **Chapter 12**) of 2500 b and 7400 b for thermal (0.025 eV) and slow (0.179 eV) neutrons, respectively. Tin has a low capture cross section. To differentiate thermal from fast neutrons, the track density under the tin and cadmium filters are counted and compared. Because the cadmium filter absorbs thermal (0.025 eV) and epithermal (0.1 eV) neutrons, the tracks under the cadmium filter will be due to all neutrons except thermal neutrons. The fast neutron track density would be the same under both filters. The dose is determined by counting the neutron tracks and measuring the gamma-ray film density.

Film provides a permanent record of the exposure that can be reevaluated should any question arise. The image made on the film by the filters and other objects in the badge provide a visual record of the exposure conditions and allow the dosimetry vendor to determine whether the wearer actually received the dose assessed. Sharp edges indicate static exposure conditions in which the geometry remained unchanged during the exposure (e.g., leaving the badge in the x-ray room). Typically, filter images are blurred from movement of the person during the exposure. Radioactive contamination of the film usually appears as small blotches or hot spots.

### 7.2.b Thermoluminescent Dosimeter (TLD)

The thermoluminescence phenomenon had been noted as early as 1663 when it was reported that certain fluorites and limestones were observed to emit light when slowly heated over low heat. **Thermoluminescence** (TL), for our purposes, is the phenomenon by which certain crystals are able to store energy transmitted to them by radiation and then emit this energy in the form of visible light when heated. Over  $\frac{2}{3}$  of the transparent minerals are known to thermoluminesce to some degree. In 1953 it was proposed that thermoluminescence be used as a radiation detector. To be useful for dosimeters, a TL material must have a relatively strong light output and be able to retain trapped electrons for reasonable periods of time at temperatures encountered in the environment. Thermoluminescent detectors often use crystals that are purposely flawed by adding a small concentration of impurity as an activator. Some thermoluminescent detectors do not require the addition of an activator but rely instead upon inherent impurities and defects in the natural crystal.

A simple model (Figure 7-3) can be used to explain the thermoluminescent process. In an inorganic perfect crystal lattice the outer atomic electronic energy levels are broadened into a series of continuous allowed energy bands separated by **forbidden** energy regions. The highest filled band is called the **valence band** and is separated by several electron volts from the lowest unfilled band called the **conduction band**. When a crystal is exposed to ionizing radiation electrons are excited out of the valence band into the conduction band, leaving a vacancy in the valence band called a **hole**. The electron and hole are free to wander independently throughout their respective bands. The presence of lattice defects or impurities gives rise to discrete local energy levels within the forbidden region between the valence and conduction bands. These discrete energy levels trap electrons which on subsequent heating and recombination causes thermoluminescence (i.e., light emission). The energy gap between the valence and conduction bands determines the temperature required to release the electron and produce the thermoluminescence and is characteristic of the material used. Usually, many trapped electrons and holes are produced. As the temperature of the crystal is increased, the probability of releasing an electron from a trap is increased, so the emitted light will be weak at low temperatures, pass through one or more maxima at higher temperatures, and decrease again to zero as no more electron-filled traps remain.

A graph of the light emitted as a function of time or temperature is called a **glow curve** (Figure 7-4). Usually the glow curve plots temperature versus light emitted. A typical glow curve would show one or more peaks (maxima) as traps at various energy levels are emptied. The relative heights of the peaks indicate approximately the relative numbers of electrons in the various traps. Either the total light emitted during part or all of the glow curve or the

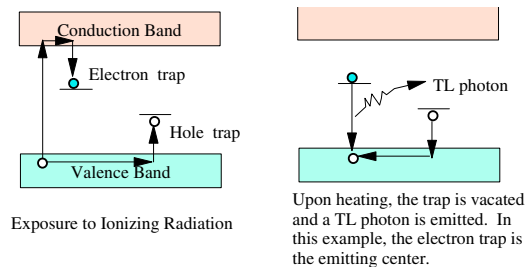


Figure 7-3. Thermoluminescence

height of one or more peaks may be used as a measure of the absorbed dose in the TL material or the exposure in air. However, if a peak height is used to measure the dose, the heating cycle must be reproducible to avoid any peak-height fluctuations.

Unlike film which can only be used once, an advantage of TLDs is that they may be reused. To prepare the dosimeter material for reuse, it must be heated again at a high temperature or *annealed*, to empty all of the traps. The reading process is fast (e.g., approximately 20 seconds per chip) and can be automated. While the reusability of TLDs is one of their major advantages, the annealing process destroys any information stored in the dosimeter and thus the loss of any previous records the dosimeter may represent (i.e. it can't be reinterpreted).

There are several different TLD crystals in use depending upon application. One popular TLD material used for personal monitoring is lithium fluoride (LiF) because:

- ✓ It exhibits a nearly flat response per roentgen over a wide range of photon energies. The response at 30 keV is only 125% larger than at 1.25 MeV.
- ✓ The light emitted shows little fading (only 10 to 15% within 3 weeks after irradiation) with storage time at room temperature.
- ✓ Response versus exposure is linear from about 10 mR to about 700,000 mR (700 R).

Lithium fluoride TLDs come in several different compositions: TLD-100 is 7.5%  $^6\text{Li}$  and 92.5%  $^7\text{Li}$ ; TLD-600 is 99.993%  $^6\text{Li}$ ; TLD-700 is 4.38%  $^6\text{Li}$  and 95.62%  $^7\text{Li}$ . It is thus possible to measure neutron-gamma fields using TLD-600 because  $^6\text{Li}$  has a very high affinity for thermal neutrons while the TLD-700 which has no response to thermal neutrons has a gamma response similar to the TLD-600.

### 7.2.c Other Types of Dosimeters

LiF is just one of several types of TL material. Several calcium compounds (e.g.,  $\text{CaF}_2:\text{Mn}$ ,  $\text{CaF}_2:\text{Dy}$ ,  $\text{CaSO}_4:\text{Mn}$ ) are useful in environmental monitoring where exposures as low as 1 - 2 mrem (10 - 20 mSv) can be detected. Some TLD systems employ both Li- and Ca-type chips.

As noted above,  $^6\text{Li}$  is highly sensitive to thermal neutrons and special nuclear track film can also be used. Another type detector used for neutrons is the *track-etch* detector. In track-etch, radiation impinging on a solid foil causes damage along the track of the radiation. These damaged regions can be etched by chemicals so they become visible either microscopically or to the human eye. The number of tracks produced per unit area can then be related directly to the amount of radiation incident on the material, and the absorbed dose. This type of device is useful in a mixed gamma-neutron field because the foil is not damaged by beta-gamma radiation. Track etch material can be either inorganic crystals and glasses or organic polymers. However, because only particles that lose energy at a rate  $> 15 \text{ MeV/mg/cm}^2$  can be detected in inorganic materials, the more sensitive organic polymers are normally used to record particles which transfer energy at rates less than  $4 \text{ MeV/mg/cm}^2$ .

Research with optically stimulated materials have also yielded new dosimeter materials. The most recent innovation is *optically stimulated luminescence (OSL)* dosimetry (i.e., Luxel<sup>®</sup> by Landauer, Inc.). Certain crystals exposed to ionizing radiation can be made to luminesce following stimulation with selected frequencies of (laser) light. The amount of luminescence is directly proportional to the radiation dose.

This material has many similarities to film dosimetry. It is provided in thin wafers and sealed in a light- and humidity-tight envelope (Figure 7-5). The holder has several filter elements as with other dosimeters. Radiation exposure causes electrons in the material to move into traps. To read the device, a laser beam scans the material and stimulates molecules with trapped electrons. The stimulated molecules become more excited and radiate light of a different frequency than the laser beam. Thus, the intensity of this second type of light is related to the amount of radiation exposure. However, unlike a TLD chip where reading destroys the information, the Luxel<sup>®</sup> material can be stored and, like film, reread later if a question about the exposure arises.

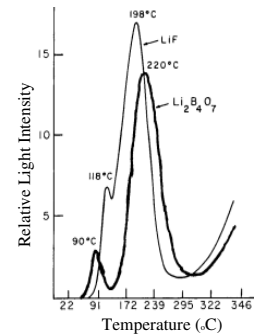


Figure 7-4. Glow Curve



Figure 7-5. Luxel<sup>®</sup>

### 7.2.d Personal Dosimetry Program

The University's radiation badges (Figure 7-6) use LiF chips to record exposure to ionizing radiation. Unlike active detectors, this thermoluminescent dosimeter (TLD) has no display or readout. Radiation workers wear the dosimeter for a given period (monthly or quarterly) and return the dosimeter to the Medical Physics Department for processing. Just as with film, different filters cover different TLD elements and the whole body dose is calculated by an algorithm based on the ratio or two chip values. A report is generated and the worker learns his/her radiation exposure several months after it has occurred.

Radiation badges are used to monitor personnel who handle large quantities ( $> 37 \text{ MBq}$  or  $1 \text{ mCi}$ ) of high-energy beta or gamma emitters or who work in areas where x-/ $\gamma$ -ray radiation sources are used. Regulations requires personnel monitoring if a worker is "likely to receive, in 1 year ... doses in excess of 10% of the applicable limits." The University requires personnel to wear radiation badges when handling or using more than  $37 \text{ MBq}$  ( $1 \text{ mCi}$ ) of radioactive material which decays by gamma or beta emission with  $E_{\text{max}} \geq 300 \text{ keV}$ . These dosimeters will not register exposure to beta radiation with energy less than  $300 \text{ keV}$  and dosimeters are not issued for  $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{33}\text{P}$ ,  $^{35}\text{S}$ , and  $^{45}\text{Ca}$ . TLDs are also used to monitor exposure to a worker's hands. These extremity dosimeters are ring badges with a single TLD chip. The dosimeters are processed by special readers in Medical Physics (Figure 7-7).

If you are a radiation worker and have been issued a TLD to monitor your radiation exposure, you should follow a few simple practices to insure that the dosimeter accurately records your radiation exposure.

- ◆ Wear only your TLD, never wear another person's badge.
- ◆ Wear whole body badges between the collar and waist.
- ◆ To avoid contamination, wear ring badges underneath gloves with the chip on the palm side of the hand that handles radiation sources.
- ◆ Do not store your badge near radiation or high-heat sources.
- ◆ Do not leave your badge attached to your lab coat (when not wearing your lab coat).
- ◆ If you suspect contamination on your badge, return it immediately to Medical Physics; you will be given a new, uncontaminated badge.
- ◆ Never intentionally expose your badge to any radiation.
- ◆ Do not wear your badge when receiving medical radiation exposure (e.g., x-rays, nuclear medicine, etc.).
- ◆ Return your badge to your badge group leader for processing at the end of the wearing period. You / your lab group will be charged for late and lost badges.

### 7.3 Gas-Filled Radiation Detectors

Many active radiation detectors use a gas-filled tube to detect radiation. Figure 7-8 illustrates the basic principle used by portable radiation survey instruments for the detection and measurement of ionizing radiation. Consider for example, the Geiger counter. The detector is a gas-filled, cylindrical tube with a long central wire that has a 900-volt positive charge applied to it and is then connected, through a meter, to the walls of the tube. Radiation enters the sensitive volume of the detector and ionizes gas molecules. The electron part of the ion pair is attracted to the positively charged central wire where it enters the electric circuit. The meter then shows this flow of electrons (i.e., the number of ionizing events) as pulses or counts per minute (cpm).

The only requirement for radiation detection by this type of detector is that the radiation must have enough energy to penetrate the walls of the detector tube and create ion pairs in the gas. Particulate (alpha and beta) radiation has a limited range in solid materials. Radiation detectors designed for this type of radiation must be constructed with thin walls that allow the radiation to penetrate. The most common types of gas-filled radiation survey meters are ion chamber, (gas-flow) proportional counters and Geiger-Müller (GM) detectors.

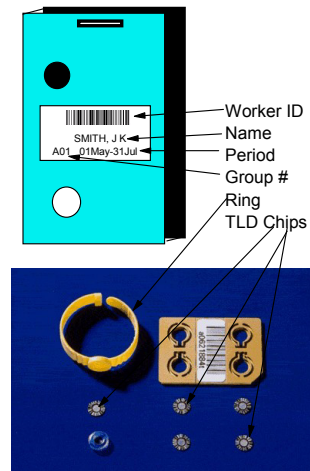


Figure 7-6. UW TLD Badge



Figure 7-7. TLD Reader

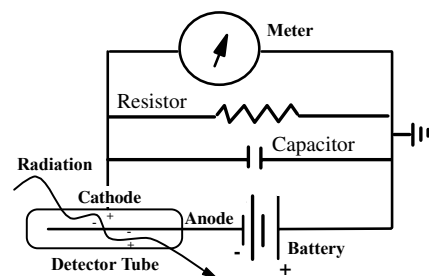


Figure 7-8. Radiation Detection

### 7.3.a Ion Chamber Survey Meters

Ion chamber survey meters are radiation detectors designed to collect all of the ion pairs produced in the detector tube and then measure the current flow. These meters are primarily used to measure x- or gamma ray exposure in air and the readings are usually expressed as milliroentgen per hour (mR/hr) or roentgen per hour (R/hr). Because research labs use only small quantities of predominantly beta emitters, they do not use ion chamber survey meters. However ion chambers are extremely useful for measuring high levels of x- or gamma radiation exposure as seen in reactor and accelerator operations.

Depending upon application, the sensitive volume is designed to be either air equivalent or tissue equivalent. It is usually filled with air and is often sealed (i.e., pressurized), but some chambers may be open to the air. The detector consists of two charged electrodes. In circular detectors (Figure 7-8), the chamber walls are negatively charged and an anode wire or electrode is positively charged. A resistor of  $10^9$  to  $10^{20}$  ohms is placed in the circuit to measure the current by measuring the voltage change after amplification of the current. An electrometer designed as the readout device is used to measure the voltage change.

Ion pairs are formed when ionizing radiation interacts with gas molecules in the chamber (Figure 7-9). When ion pairs are formed the normal motion of the ionized particles in the chamber take on a new behavior; the ions are attracted to the electrodes with the opposite charge. When electrons arrive at the anode they are quickly collected and produce an electrical current that is proportional to the amount of the energy deposited within the chamber. Positively charged particles are attracted to the negatively charged wall of the chamber and upon arrival are quickly neutralized. These molecules then migrate back towards the center of the chamber in order to balance the distribution of the molecules within the chamber. The current produced is amplified and measured or the voltage change is measured and the current value is sent to the readout device.

The voltage applied to the electrodes is one of the most important factors affecting the operation of the ionization chamber. If there is zero voltage, the ions will recombine and the chamber will not work. Applying less voltage than is optimal will cause some of the electrons to be collected, however, the system will exhibit a lower counting efficiency because there is not enough charge on the electrodes to pull distant electrons to the anode and many electrons will therefore recombine with their parent or other nearby molecules. The optimum voltage is designed to collect all the free electrons produced. This voltage level results in a **saturation current**, characterized by all of the ions produced being collected. Depending upon chamber design, the voltage range for saturation current is from 50 to 200 volts. Applying too much voltage will create secondary and tertiary ions (Figure 7-11) which will turn the ionization chamber system into a proportional counter.

Another factors affecting efficiency is the air pressure. Increasing the air pressure in the chamber will increase the air density and thereby increase the number of ion pairs produced within the chamber for high energy x or gamma rays. But, because there are more molecules per unit area near the electrodes, increased pressure will also increase the chance of recombination of ion pairs. Gas molecules are in constant motion and have some tendency to diffuse away from regions of high density. A charge transfer may occur during random motion or when the charged ion is traveling towards the electrode and interacts with other molecules within the chamber. Recombination occurs if the electron reassociates either with the parent or with another molecule. Recombination is most severe at high gas pressures where diffusion is slowed by the increased density of the gas.

Ion chambers are often used for measuring x-/γ-ray exposure and the exposure reading are normally expressed in milliroentgen per hr (mR/hr), roentgen per hour (R/hr), or Coulomb per kilogram per hour (C/kg-hr) where  $1 \text{ C/kg} = 3876 \text{ R}$ . An ion chamber system is stable to within plus-or-minus 0.1% over several years, so it can be used to reliably measure calibration sources, dosages of radiopharmaceuticals (see **Chapter 13**), and x-ray / teletherapy machine exposure. Research labs do not use ion chamber survey meters.

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### 7.3.b (Gas-Flow) Proportional Counter

A proportional counter is characterized by the fact that that the magnitude of the output pulse from the chamber is proportional to the total energy absorbed within the sensitive volume. Recall from Chapter 1, alpha particles have large masses, high energies (~ 4 - 6 MeV) and deposit all or almost all of this energy within the chamber's sensitive volume. Beta particles are smaller, less energetic (0.2 - 1.7 MeV), less densely ionizing so they may only deposit

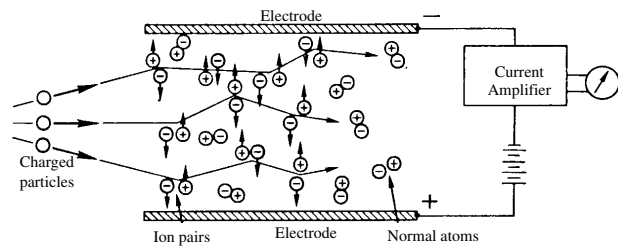


Figure 7-9. Ion Chamber

part of their low energy ( $E_{avg} \approx 0.3 E_{max}$ ) within the chamber, and the absorption results in a smaller pulse. Thus, an  $\alpha$ -particle pulse is larger than  $\beta$ -particle pulse. Also, in a proportional counter, the size of the pulse is proportional to applied voltage. Therefore, the  $\alpha$ -particle pulse, being larger than the  $\beta$ -particle pulse at the same voltage, can be detected at lower voltages.

This phenomenon results in the unique 2-plateau feature of counts versus high voltage. Because of this, the counter can be set to reject pulses below a given size by use of bias levels or sensitivity settings making it easy to count for  $\alpha$ -particles only in a mixed  $\alpha/\beta$  sample either by lowering the high voltage to the  $\alpha$ -plateau level or only counting pulses above a certain energy level. Similarly, one can count only smaller  $\beta$  pulses by not allowing large pulses to be counted.

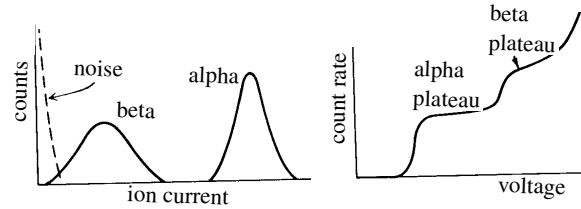
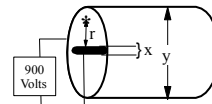


Figure 7-10. Alpha and Beta Pulse Height

Proportionality is enhanced by a feature called **gas amplification**. In a parallel plate chamber (Figure 7-9, 7-11), the electric field strength,  $\xi$ , experienced by an ion is related to it's distance from the plate (i.e.,  $\xi = V/d$ ). But in a circular tube with one conductor inside the other (e.g., anode inside the cathode), a non uniform electric field is created. The electric field strength,  $\xi$ , at distance,  $r$ , from a central anode with a radius of  $x$  meters and a tube radius of  $y$  meters is:

$$\xi \left( \frac{V}{cm} \right) = \frac{V}{r \cdot \ln \left( \frac{y}{x} \right)}$$



Thus, the nearer a charged particle is to the anode, the greater the electric field strength attracting it. Consider a tube with a diameter of 2 cm (radius = 1 cm) that has a 0.1 mm anode wire (radius = 0.005 cm) with an applied voltage of 1000 V. The field strength experienced by an electron midway between the anode and cathode (i.e.,  $r = 0.5 \text{ cm} = 0.005 \text{ m}$ ) would be 37,748 V/m while the force felt by an electron 0.03 mm from the anode (i.e.,  $r = 0.003 \text{ cm} = 3 \times 10^{-5} \text{ m}$ ) would be 6,291,300 V/m.

As the voltage between the anode and chamber wall increases, the ion pairs are accelerated toward their respective electrodes and acquire enough energy to be capable of producing secondary ionizations by collision (Figure 7-11). These secondary ionizations occur in the region of the primary ionization (as opposed to the entire chamber). These secondary ions also experience the attractive force of the electrodes. Depending on the voltage and the type of radiation, there are approximately  $10^3 - 10^6$  secondary ions created for each primary ion pair. This multiplication of ions in the gas is called a **Townsend avalanche**. Because the electric field force follows the inverse square law, the avalanche depends upon the diameter of the collecting electrode. As seen in Figure 7-11, the electric field near the anode becomes stronger as the diameter of the anode decreases.

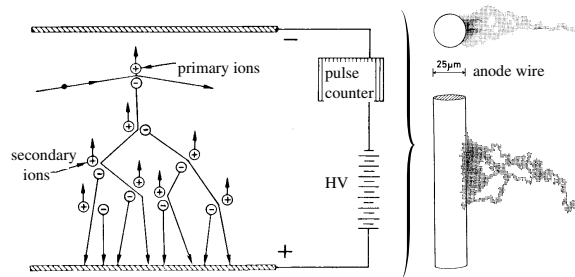


Figure 7-10. Gas Amplification

Decreasing the pressure of the fill gas also increases the gas multiplication, probably because this allows the ionizing particle to travel farther in the chamber and create ion pairs over a much greater path. Denser tubes cause the radiation to expend its energy in a smaller volume and the molecules, once ionized, resist farther ionization. In the region of the collecting electrode, a small change in voltage results in a very large change in the number of ion pairs collected. Thus, the output pulse is "proportional" to the high voltage.

Another characteristic of proportional counters is the **alpha multiplication factor ( $\alpha MF$ )**. This factor takes into account the number of alpha counts on the beta voltage plateau (beta channel). Pulse size increases with applied voltage. The discriminator in the  $\beta$  channel is set lower because the  $\beta$  pulses are smaller than the  $\alpha$  pulses (Figure 7-10). Several of the localized Townsend avalanches caused by  $\alpha$  particles may produce small pulses which might possibly be counted as separate  $\beta$  events. The  $\alpha MF$  is used to determine the count increase due to the increase in  $\alpha$  particles counts when counting a mixed sample. All samples counted which have  $\alpha$  and  $\beta$  emissions must be corrected for the increase in  $\alpha$  counts by using this  $\alpha MF$  which is calculated by counting a pure  $\alpha$  sample on both the  $\alpha$  and  $\beta$  voltage plateaus and calculating the ratio.

$$\alpha MF = \frac{\alpha \text{ counts in the } \beta \text{ channel}}{\alpha \text{ counts in the } \alpha \text{ channel}} (> 1)$$

The  $\alpha MF$  is used to determine the count increase due to the higher applied voltage in the  $\beta$  channel. All samples counted which have  $\alpha$  and  $\beta$  emissions are corrected for the increase in  $\alpha$  counts in the  $\beta$  channel by using the  $\alpha MF$ . Essentially the  $\beta$  counts would be:  $\beta_{cpm} = (\text{Sample})_{cpm} - (\text{Background})_{cpm} - (\alpha MF \times \alpha_{cpm})$ .

Because most alpha particles have similar energies ( $\sim 5$  MeV), the  $\alpha MF$  value is relatively constant regardless of the  $\alpha$  emitter. Various systems use this factor differently. Some automatically subtract the  $\alpha$  from the  $\beta$  counts, some provide gross counts only. Read the manufacturer's literature to see how your system operates.

A typical proportional counter (Figure 7-12) has a chamber approximately 2 1/4" in diameter to allow for 2" diameter sample planchets. The chamber may be either windowless or have a very thin window (e.g., 0.9 mg/cm<sup>2</sup>). The electrodes consist of an anode, a very fine tungsten wire approximately 0.001 - 0.003" in diameter formed into a loop, and the cathode is the wall of the chamber and is also used as reference ground. The chamber is made from high Z material to shield against gamma and background with gas inlet and outlet ports to allow gas to flow through chamber. The filling gas may flow continuously during the counting cycle or may only purge the chamber after each count. The gas normally used for mixed  $\alpha/\beta$  samples is P-10 gas, consisting of 10% methane and 90% argon; however, pure argon may be used for analyzing samples emitting only  $\alpha$  particles.

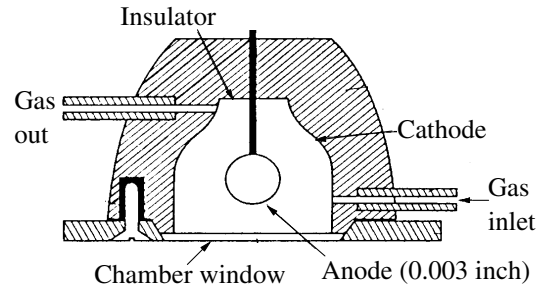


Figure 7-11. Proportional Counter Chamber

Proportional counters are simple pulse counting devices versus exposure measuring instruments like ion chambers. They are used primarily in the laboratory for beta, alpha, and neutron detection (see 7.3.d) in which a special chamber is required for neutron detection because of the need to moderate and then capture the neutrons and subsequently count the resultant radiation. At one time portable proportional counters were employed and some (windowless) detectors were fabricated for tritium detection. While these may still be used in some facilities, LSC counting is by far more sensitive in checking for removable contamination.

In laboratory counting, because there is a minimum sample to window distance, or perhaps a windowless configuration, the sample is practically in intimate contact with sensitive volume. Some sample self-absorption may occur so the maximum sample thickness should be between 1/2 - 1/4 inch to allow all particulate events to have a good probability of being counted. Most systems are  $2\pi$ , that is the sensitive volume forms a hemispherical dome around the sample. Therefore, the maximum efficiency is about 50%. However,  $4\pi$  systems are available with ultra-thin windows. Given this geometry, the intrinsic efficiency is greater than 99% for alphas and betas which can pass through the window. Some typical efficiencies to be expected are: <sup>14</sup>C - 40%, <sup>90</sup>Sr - 55%, <sup>210</sup>Po - 35%, and gamma - 0.5 - 1% for 0.1 to 2 MeV.

### 7.3.c Geiger-Müller (GM) Survey Meter

A Geiger-Mueller counter is characterized by the fact that almost all radiation ionizing in the sensitive volume is detected. Any incident particle that ionizes at least one fill-gas molecule will institute a succession of ionizations and discharges in the counter that causes the central wire to collect a multitude of additional electrons. This tremendous avalanche of charge (about 10<sup>9</sup> electrons) produces a signal of about 1 volt.

Ionizing radiation enters the chamber and strikes a filling gas molecule or  $x/\gamma$ -ray photons interact with the wall material, kicking electrons into the gas to cause secondary ionization. Ion pairs produced accelerate toward their respective electrodes due to the high voltage potential (i.e., approximately 900 V). Secondary ions are produced due to the rapid movement of the initial ion pair towards the electrodes so the entire sensitive volume of the tube is ionized (Townsend avalanche). The ions reaching electrodes are neutralized and produce the voltage pulse which will be measured by the electronic processing unit.

GM systems are pulse counters but, unlike the proportional counter, the pulse height is independent of the energy of incident radiation and is relatively independent of applied voltage. However, because of this

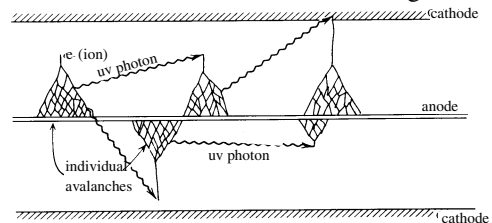


Figure 7-12. GM Avalanche

characteristic, a GM tube tells nothing about the energy of the radiation. GM systems are primarily used as survey type meters because of their high sensitivity. Practically every  $\beta$  particle that reaches the counter gas will cause a discharge and produce a count. However, because gamma photons are less densely ionizing than  $\beta$  particles, only a small fraction of the gamma-ray photons will interact with the walls and a much smaller fraction interacts with the gas. With a compensated GM, which has a thick ( $200 \text{ mg/cm}^2$ ) steel sheath around the tube, more interactions are possible in the wall, kicking off electrons into the gas to be counted.

The production, collection and neutralization of the ion pairs requires time. This time period is called the instrument's **resolving time** (Figure 7-13) and is the time required to attain the ion field and collect it. During this period, the GM is incapable of responding fully to a second radiation interaction. This resolving time is the sum of two other time elements: (1) the **dead time**, the time required for the positive ions created by the Townsend avalanche to move to the anode to be neutralized, and (2) the **recovery time**, the time interval between dead time and full recovery. During the recovery phase, an output pulse from ion avalanche is not large enough to pass the meter's discriminator and be counted. Thus, the resolving time is the minimum time that must elapse after detection before a second event can be detected. For GM tubes it is generally about 10 - 1000  $\mu\text{sec}$ .

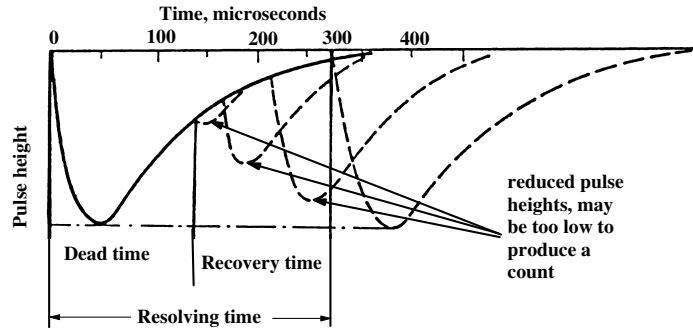


Figure 7-13. GM Resolving Time

A potential problem of older GM systems that is related to resolving time is **saturation** which may occur when a GM tube is exposed to a high radiation field. In such fields, the ionizing events are interacting with the gas in the GM tube with an average separation in time much shorter than the meter's dead time (i.e., too many ionizing events). If a new ionizing event occurs in the sensitive volume when the tube still has not fully recovered, a pulse much smaller than normal (or none at all) is produced. In saturation, the instrument will show a momentary upswing of the meter needle followed by a return of the needle to a point near zero. Thus, the meter may be indicating no radiation when the operator is actually in an extremely hazardous radiation field. This is why it's important to turn your meter on before entering a potentially high radiation field. Most new GM systems when saturated, fail upscale (i.e., "peg") so the operator will know there is a high field.

The gas in a GM tube is usually argon or helium and is kept at less than atmospheric pressure. Decreased pressure is used so excessively high voltages (and risk of saturation) are not required. Gases used are chemically inert and have a high specific ionization potential to enhance ion production in the sensitive volume. A **quenching gas** is also used to stop the Townsend avalanche effect by absorbing the characteristic x-rays produced by the filling gas when the positive ions reach the cathode. The quenching gas also prevents the filling gas ions from reaching the cathode wall and producing further ionizing events by neutralizing the positive ions moving toward the cathode. Common quenching gases are alcohol or chlorine. Organic quenching gases are used up in the quench process so the tube has a life expectancy about  $10^9$  pulses. Inorganic gases recombine within the tube and have essentially an infinite life expectancy.

There are two basic types of GM tubes (Figure 7-14), compensated (or side window) and thin window tubes. While all GM tubes have the same components, the construction of the steel wall differs depending upon use. The thickness of material used in GM tubes is usually stated as **density thickness** (cf. 1.2.f.3) and measured in  $\text{mg/cm}^2$ .

**Compensated** detectors are normally employed to measure x-/ $\gamma$ -ray exposure and consist of a moderately thin-walled GM tube ( $\sim 30 \text{ mg/cm}^2$ ) surrounded by a thick-walled shell ( $\sim 200 \text{ mg/cm}^2$ ). Detection occurs because photon radiation interacts with the thick shell and ejects energetic electrons which then penetrate the ( $30 \text{ mg/cm}^2$ ) GM tube to produce secondary ionizations and a pulse. This type of tube is usually calibrated to measure mR/hr exposures and will detect, but not quantify, high-energy beta ( $E_{\text{max}} > 300 \text{ keV}$ ) particles. To detect beta particles, the shell is usually rotated to expose a small section of the detector's  $30 \text{ mg/cm}^2$  tube. High-energy beta particles ( $E_{\text{max}} > \sim 300 \text{ keV}$ ) have enough energy to penetrate the wall and produce ionizations.

**Thin-window** detectors are either pancake or end-window tubes. The window is usually a very thin (e.g., 1.5 - 4  $\text{mg/cm}^2$ ) sheet of mica or mylar which allows for the penetration of both  $\alpha/\beta$  particulate radiation. A thin-window detector can detect beta particles with energies greater than 100 keV. Usually a pancake probe is a little more sensitive than an end-window probe (Figure 7-14), especially for low energy radiation. This is because in end-window



detectors, there is usually a small dead space just behind the window where the local electric field of the central wire is too small to attract the electrons and the ion pairs recombine. The pancake probe has several circular electrodes so the electric field is relatively uniform across the face of the tube.

At x-/γ-ray photon energies between 70 keV and 200 keV, a compensated GM tube over responds because the materials in the tube (gas and tube walls) are more efficient at stopping low energy photons. Thus, the meter reads high (Figure 7-15). At medium energies the tube will read correctly since the probability of Compton interactions is independent of Z. Geiger counters used to measure low energy photon fields (<sup>125</sup>I) need to be calibrated specifically for that energy.

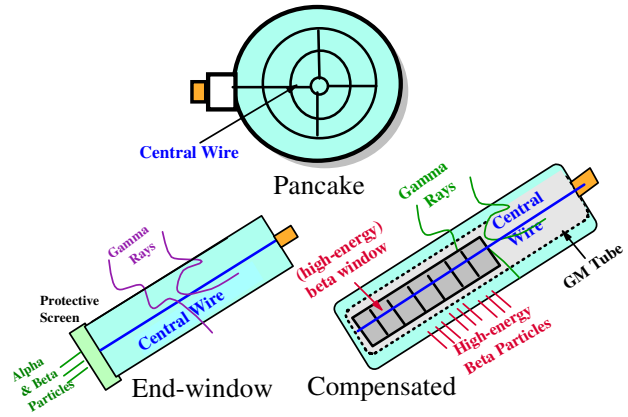


Figure 7-14. GM Detectors

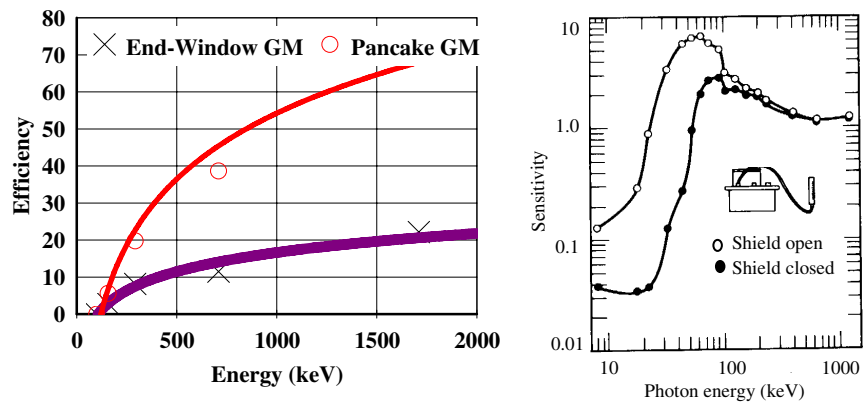


Figure 7-15. GM Detector Sensitivity

Most alpha particles are emitted with energy greater than 5 MeV. This radiation has high specific ionization, consequently all alphas that enter the sensitive volume will be counted and the GM counting efficiency is high. However, alpha particles are also easily absorbed. When determining efficiency, factors such as source absorption (i.e., attenuation of particles by source and source housing), air absorption (e.g., significant attenuation by the air requires the source to be close to the GM tube), and absorption by GM window (i.e., even the 1.5 - 4 mg/cm<sup>2</sup> thin-window attenuates some alphas) contribute to reduced efficiency. Generally, the GM system should have approximately the same efficiency for every alpha emitter.

Beta particles are emitted with lower energies than alpha particles, however, their small mass and charge insures that they have a longer range than alpha particles. Thus, geometry, particularly distance from the sensitive volume, is less critical. All beta particles that enter the sensitive volume will be counted. The wide range of beta energies results in a wide range of efficiencies for the same sample geometry. Higher energy beta particles will have a greater range, source absorption and absorption by the GM window will be less, and efficiency will be higher.

In summary, GM survey meters are radiation detectors used to **detect** radiation or to **monitor** for radioactive contamination. GM detectors usually have a **window** either at the end or on the side of the detector to allow alpha or beta particles to enter the detector. These detectors may have a variety of window thicknesses, however, if the radiation cannot penetrate the window it will not be detected. Depending upon the window thickness, GM systems can detect x-ray, gamma, alpha, and/or beta radiation. Radioactive materials that emit these types of radiation (e.g., <sup>14</sup>C, <sup>22</sup>Na, <sup>32</sup>P, <sup>35</sup>S, <sup>45</sup>Ca, <sup>51</sup>Cr, <sup>60</sup>Co, <sup>137</sup>Cs) can usually be detected using GM survey meters. Because appropriately configured GM detectors are more sensitive to x-rays, γ-rays, and high energy beta particles and less sensitive to low energy beta and alpha particles, they are usually not used to detect alpha or very low energy beta particles. Thus, GM tubes are not useful for monitoring <sup>3</sup>H or <sup>63</sup>Ni, nor are they sensitive enough to detect very small amounts (< 37 Bq or 1 nCi) of low energy beta or gamma emitting radionuclides such as <sup>14</sup>C or <sup>125</sup>I. GM meters at the University are usually read in units of counts per minute (cpm) for particle radiation.

### 7.3.d Neutron Detectors

Neutrons are particularly difficult to detect. Neutrons are often emitted in a wide spectrum of energies, from 0.025 eV (thermal) to 14 MeV, 9 orders of magnitude. Compare this with photon energies which range from 20 keV (x-rays) to 5 MeV (gamma) where the range only covers 2 orders of magnitude. Additionally, at different energies,

neutrons interact differently with different elements. It is therefore important to have a knowledge of the type (energy) of the neutrons to be measured if one is to properly select the detector and to determine the radiation dose equivalent from the neutron exposure. Because neutrons are uncharged particles they do not ionize directly. Therefore, some indirect means must be used to detect their presence and measure their flux. These indirect means are based on measuring the energy released in scatter, fission, or capture interactions.

### Boron trifluoride (BF<sub>3</sub>) Detectors

The most common neutron reaction used to detect thermal neutrons is  $^{10}\text{B}(n,\alpha)^7\text{Li}$ . Boron-10 has a 3840 b thermal neutron capture cross section (see **Chapter 11**) for this reaction. The  $\alpha$ -particles emitted from this reaction cause ionization which may then be detected. Two types of detectors employing boron are an ion chamber lined with a thin layer of boron and a proportional counter filled with boron trifluoride (BF<sub>3</sub>) gas. Only 19.8% of boron atoms are boron-10 and 80.1% are boron-11. To increase sensitivity, some systems enrich the quantity of the  $^{10}\text{B}$  isotope above its natural 19.8% abundance. For example, BF<sub>3</sub> gas containing 96%  $^{10}\text{B}$  is routinely available from commercial vendors.

A BF<sub>3</sub> counter (Figure 7-16) can be used for fast neutrons if it is surrounded by paraffin, polyethylene or another moderator which will slow down the neutrons and allow them to be captured by the  $^{10}\text{B}$ . The count rate of such a system increases with increasing moderator thickness. At the optimum thickness (e.g.,  $2\frac{3}{8}$ " of paraffin), the response is relatively flat over a broad range of neutron energies from about 10 keV to over 1 MeV. The detector may also be surrounded by a thin sheet of cadmium which absorbs thermal neutrons.

One detector of great use is the long counter. It is essentially a BF<sub>3</sub> chamber surrounded with paraffin or another moderator. A thickness of 2.375" of paraffin results in a flat response over the range 10 keV to 5 MeV. The name long counter was derived because of its long, energy-independent range. The counter is highly directional and is designed to measure neutrons that are incident only on the front face. The layer of paraffin outside the B<sub>2</sub>O<sub>3</sub> is a shield designed to remove neutrons that are incident on the sides.

### Proton Recoil Counters

The most common method used for fast neutron detection is to cause them to interact with a material containing a large proportion of hydrogen atoms. The hydrogenous material can be either as a gas or a solid (paraffin, polyethylene, methane etc.). If the neutron energy exceeds 500 keV, the neutrons can "knock out" protons from the hydrogenous material. The protons are then detected because they lose their energy by ionizing within the counting gas. These detectors are often enclosed in Cadmium to absorb thermal neutrons. One type of fast neutron monitor uses a proportional counter surrounded by a material like polyethylene. The fast neutrons transfer energy to the protons which cause ions in the gas. Such instruments can detect exposures as low as 50  $\mu\text{Sv/hr}$  (5 mrem/hr). A proton recoil detector usually has a lower sensitivity than a BF<sub>3</sub> counter because the scattering cross section of  $^1\text{H}$  is less than the capture cross section of  $^{10}\text{B}$  and the energy spectrum of the scattered protons is relatively wide with a large fraction of very low energy protons.

### Miscellaneous Neutron Detection Systems

Other methods have also been developed to measure neutron fluxes. **Fission chambers** use fission to measure fluxes. A chamber is coated with fissionable material (e.g.,  $^{235}\text{U}$ ) which will fission when neutrons interact with it. The fission fragments are highly ionizing. Because fissionable materials are more highly controlled than byproduct material, this type of detector requires a source material license or specific line items on a byproduct license which specifies the chambers being used. **Neutron foils** can be used to measure high neutron fluxes by measuring the amount of neutron activation in the foil. In this method a thin foil is inserted in the beam and the amount of induced activity in the foil is measured. Various materials can be used to measure either thermal neutrons or neutrons above a certain energy.

### Neutron Rem Counters

The problem with using the boron or proton recoil system is that the response of the instruments using boron falls off rapidly above energies of a few eV and instruments using proton recoil only start operating at energies above

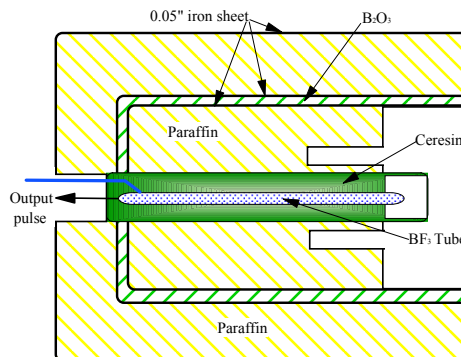


Figure 7-16. Long Counter

100,000 eV (i.e., 0.1 MeV). The intermediate energy neutrons in this undetected gap can make an appreciable contribution to neutron dose. To overcome these energy limitations, the neutron rem meter was developed. This instrument measures tissue dose (i.e., rem, Sv) over a very wide range of energies from thermal to 15 MeV. Such a meter uses a sphere of polyethylene to slow down (i.e., thermalize) fast neutrons by elastic collisions. There are also a series of cadmium filters arranged in the sphere to provide an energy response correction. The thermal neutrons are detected in a proportional counter filled with helium gas by the reaction  ${}^3\text{He}(n,p){}^3\text{H}$ , where the recoil protons cause ionization within the counter.

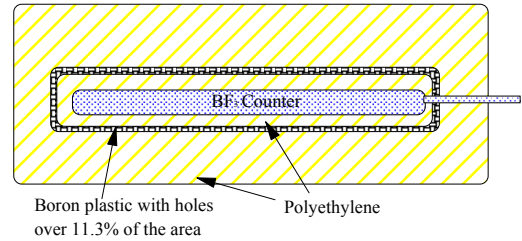


Figure 7-17. Neutron rem Counter

#### 7.4 Scintillation Detectors

Scintillation is a process by which energy deposited by ionizing radiation is absorbed and converted to light photons. There are many types of scintillators including organic crystal scintillators (e.g., anthracene), organic liquid (LSC, see 7.6) or solid scintillators, inorganic crystal scintillators (e.g., NaI(Tl), GeLi), and noble gas scintillators (e.g., xenon, helium). Scintillation detectors are superior to gas filled GM detectors because the number of light photons produced is proportional to the energy absorbed in the scintillator.

Consider sodium iodide (NaI) crystals. The purpose of the scintillation crystal is to stop the incident photon and convert the radiation energy into visible light. While incident photons can interact with the crystal by photoelectric, Compton, or by pair production (see 1.2.f.2), photoelectric interactions are preferred because the photon loses all of its energy in one interaction, hence the light produced in the scintillator will be proportional to the energy of the photon. Other interactions may result in only partial energy absorption (e.g., several Compton interactions, followed by a photoelectric interaction). The energized electrons are ejected from the regions in the crystal which they had occupied and travel a short distance transferring energy to other electrons along the way.

Sodium iodide (NaI) by itself, does not produce much light. In a pure NaI crystal the electrons move around and the energy transferred appears in the form of heat. To make them useful, NaI crystals are purposely flawed with thallium (Tl) ions which initially trap the energized electrons and subsequently increase light output by a factor of ten at room temperature. Because the NaI(Tl) crystal is hygroscopic, it is placed in a hermetically sealed can. If the crystal were left unsealed, it would dissolve in about one week. The excess energy of the thallium-trapped electrons is released as bluish light photons in the 3 eV (wavelength ( $\lambda$ ) = 4100 Å) energy range. Approximately thirty light photons, each of 3 eV are produced per keV of energy transferred to the crystal. The crystal is transparent to light photons with energies around 3 eV so these light photons pass freely through the crystal.

All sides of the interior of the hermetic can encasing the crystal, except at the face of the photomultiplier tube, are highly polished, produce a mirror-like surface. The light photons which pass through the crystal will reflect from the mirrored sides of the can and eventually exit through the surface of the crystal facing the photomultiplier tube. About 30% of the light photons produced in the crystal eventually reach the photocathode of the photomultiplier tube. The photocathode is selected to be maximally sensitive to light at wavelengths of 4100 Å (about 3 eV).

Just as with air filled detectors, it takes time for the photon to be absorbed in the scintillator, the electrons to de-excite and give off the 4100 Å light photons. For NaI(Tl) crystals, this dead time is approximately 0.25 microseconds. For best results, do not count samples with activities greater than 2 MBq (~50 µCi or 110,000,000 dpm). High activity samples may "swamp" the system and can result in inaccuracies.

The *photomultiplier* tube (Figure 7-18) then takes a light photon from the scintillator and converts it into a pulse of electrons and amplifies the pulse of electrons into a measurable electric current.

The *photocathode* is a thin, semitransparent layer on the inside of the tube that is facing the crystal and is a substance which will emit electrons when exposed to light from the scintillator. Cesium-antimony (CsSb) is the most common material used for NaI(Tl) crystals. Light photons from the crystal interact with electrons in the photocathode causing the electrons to be ejected from their orbits as photoelectrons. The number of electrons removed from the photocathode is proportional to the energy deposited in the crystal by the incident gamma photon. These photoelectrons, with the aid of a focusing grid, are accelerated to the first dynode.

A *dynode* is an electronic device which, as the name indicates, serves a dual electronic role: a dynode acts alternately as an anode and as a cathode. Seven to thirteen metal electrodes coated with a material similar to the photocathode are arranged in a special geometric pattern so each succeeding dynode will have more positive voltage applied to it than the one before.

The photocathode is maintained at ground or zero volts and emits electrons when struck by a  $4100 \text{ \AA}$  light photon. These photoelectrons will move toward the first dynode which usually has a potential of around 300 volts. Each photoelectron strikes the dynode and dislodges several secondary electrons from its surface. These secondary electrons are in turn accelerated toward the second dynode which is about 100 volts more positive than the first dynode. This process continues through the dynode chain. At each stage, a variable number of secondary electrons, averaging about 4, are released for each incident electron. This results in an overall "gain" ranging from  $10^5$  to  $10^8$  electrons produced per photoelectron (depending upon the voltage applied to the PM tube). The anode is the last dynode of the tube. The photoelectrons are collected here and then flow through a load resistor to form a voltage pulse, the output signal from the PM tube. This output signal will be in the millivolt range.

The output signal is shaped and matched by a preamplifier to insure that no signal distortion is introduced from the PM tube to the main amplifier. When it leaves the preamp, the signal is proportional to the energy deposited in the crystal. Finally, the signal is sent through a pulse height analyzer (PHA) which quantitatively measures the maximum amplitude reached during an electrical impulse and records the accepted pulses as counts.

At the UW several types of scintillation counters are normally used, low energy gamma (LEG) survey meters, liquid scintillation counters (LSC), auto-gamma counters (AGC), and multichannel analyzers (MCA).

LEG survey meters are radiation detection systems used to monitor radionuclides that emit low energy gamma radiation (e.g.,  $^{51}\text{Cr}$ ,  $^{125}\text{I}$ ). They can not detect alpha particles nor low energy beta particles. They can detect radionuclides that emit high energy gamma ( $^{22}\text{Na}$ ) and/or high energy beta (e.g.,  $^{32}\text{P}$  -- however pancake type GM detectors are normally more efficient) radiation. The meter is usually read in counts per minute. When measuring  $^{125}\text{I}$  with a LEG survey meter, a reading of approximately 1,000,000 cpm corresponds to a gamma exposure rate of about 1 mR/hr.

Liquid scintillation counting (cf. **Laboratory 1** and **7.6**) is a method of assaying a radioactive sample by dissolving it in a chemical solution called scintillation fluid or cocktail. When alpha or beta radiation energy is absorbed in the cocktail, it emits light. The light flashes are converted to electrical signals in the photomultiplier tube (PMT) and the electrical signals are related to the absorbed energy allowing the sample to be quantified. Liquid scintillation counters (LSC) are usually used to quantify radioactivity and to measure removable radioactive contamination. They are ideal for counting radionuclides that decay by alpha and beta particle emission (e.g.,  $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{32}\text{P}$ ,  $^{33}\text{P}$ ,  $^{35}\text{S}$ ,  $^{36}\text{Cl}$ ,  $^{45}\text{Ca}$ , etc.) and may also be used to measure some gamma emitters (e.g.,  $^{125}\text{I}$ ,  $^{51}\text{Cr}$ ) which emit auger electrons as part of their decay.

## 7.5 Radiation Detection and Measurement Techniques

Because radioactive material may pose a potential long term risk to workers, especially if it is deposited in the body because of loose contamination, all personnel who work with radioactive materials must understand how to use the various types of radiation detectors to verify that their work area continues to be contamination free. To detect and measure radiation, a worker must first understand how a detector works and then how to use the detector in the work place.

### 7.5.a Portable Survey Meter Components

All portable survey meters have certain components in common (Figure 7-19).

The **detector** (or **probe**) produces electrical signals when exposed to radiation. It usually has a **window** through which the radiation can penetrate to the sensitive volume of the detector.

The **readout dial** (or **dial**) is a gauge which indicates the amount of radiation present. It often has two scales, mR/hr and/or cpm. At the University, labs only use the **cpm** scale.

The **selector switch** is used to turn the meter On-Off, check batteries, or select a scale (range) multiplier. The scale multiplier is the number (e.g., 0.1, 1.0, 10, etc.) by which the dial readings must be multiplied to calculate the actual number of counts per minute indicated.

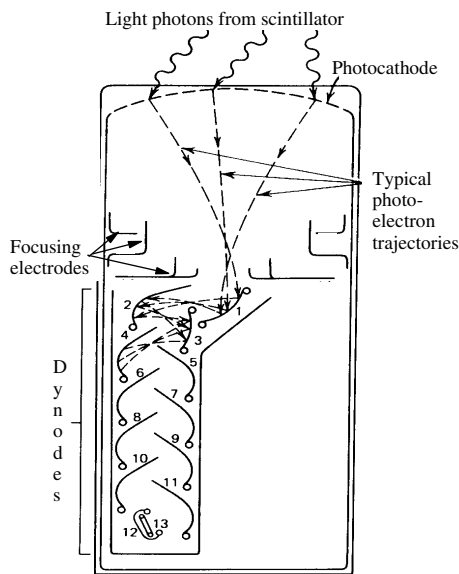


Figure 7-18 Photomultiplier Tube

The **reset** button allows the meter reading to be zeroed. When the radiation level causes the number of counts per minute (cpm) to exceed the highest reading on a particular range, switch the scale multiplier to a higher range, and push the reset button. This causes the readout needle to be reset to zero so the user can accurately determine count rate.

The **response** button adjusts the response time of the meter. When this switch is fully clockwise (or **fast**), the meter will have a fast response but the dial needle will be less stable (i.e., rapid and great fluctuations). For slow response times, the readout's needle moves slowly, but changes are not as erratic.

The **speaker** is an audible device connected to the radiation monitor. It may be located outside or inside the meter and may have its own battery. The speaker is in-line with the detector so each count produces an audible click on the speaker.

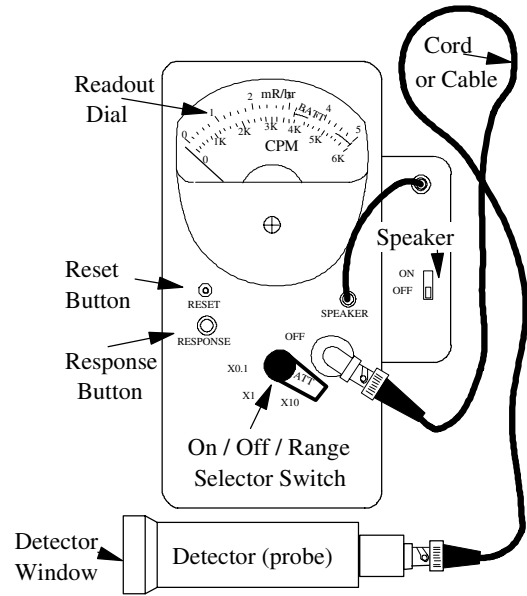


Figure 7-19. Radiation Survey Meter

**7.5.b Portable Survey Meter Calibration**

The UW license requires that labs have portable survey meters which are sufficiently sensitive to detect an exposure of 100 cpm ( $\alpha/\beta$  particles or  $\gamma$ -rays with LEG) or 0.1 mR/hr ( $x/\gamma$ -rays) and that these meters be calibrated at least annually (and after any major repair). A meter which is not within calibration is a potential license violation. To insure all meters are calibrated in a timely fashion, Radiation Safety sends letters to each PI one month prior to the calibration due month requesting the meter be brought to the Safety Annex for calibration. The calibration process normally requires about 2 - 4 working days and includes replacement of batteries if necessary. The Safety Department has loaner meters which a lab may use during the interim that their meter is being calibrated.

The American National Standards Institute (ANSI) recommends that portable survey instruments be calibrated using the type and energy of radiation that the meter will be measuring. ANSO requires when calibrating a survey instrument, the meter be calibrated at two points on each scale separated by a distance of approximately 50% of full scale (e.g.,  $\frac{1}{3}$  and  $\frac{2}{3}$  of full-scale). While these requirements are relatively easy to satisfy for ion chambers and compensated GM systems which are designed to measure  $x/\gamma$ -radiation exposures in units of milliroentgen per hour (mR/hr), they pose a problem for thin-window Geiger counters because the  $\beta$ -particle energies encountered in the lab usually run the spectrum from 160 keV ( $^{14}\text{C}$ ,  $^{35}\text{S}$ ) to 1.71MeV ( $^{32}\text{P}$ ) and the detection system has an intrinsic efficiency for such energies ranging from 2 - 5% to 60%, or more depending upon detector.

The calibration process for thin-window GM survey meters used for  $\beta$ -particle surveys consists of five major steps. The first step is to calibrate the meter electronics by using a signal generator to send a known number of electrical pulses through the cable normally connected to the GM tube. The signals are varied so each scale of the meter is calibrated at two points,  $\frac{1}{3}$  and  $\frac{2}{3}$  of full scale. Then the GM detector is connected to the meter and is exposed to 3 different calibrated  $^{99}\text{Tc}$  sources. Technetium-99 is a pure beta emitter with a maximum energy of 292 keV (0.292 MeV). The sources range in activity from approximately 800 dpm to 113,000 dpm. The detector efficiency for the three sources measured on three different ranges must be relatively consistent and not vary by more than  $\pm 20\%$ .

The detector is then used to measure both a low- and high-energy beta emitter,  $^{14}\text{C}$  and  $^{90}\text{Sr}$ . These energies are essentially equivalent to  $^{35}\text{S}$  and  $^{32}\text{P}$ , respectively. The meter efficiency for each of these three sources is recorded on the calibration sticker (Figure 7-20). The meter is then exposed to a  $^{137}\text{Cs}$  gamma-ray beam and the factor to convert a cpm reading from a gamma-ray source into mR/hr is recorded on the calibration sticker. Normally this factor is approximately 2000 cpm per mR/hr although it may vary by  $\pm 25\%$ . The last step is to record the meter's response to the calibration check source which Radiation Safety affixes to the meter. When using the check source to verify the functioning of

Use	CPM	scale only.	Cal Date:	7/18/xx
Window:	Fixed	Beam	$\perp$	to probe center
Battery:	O K	Check Source:	1500	CPM
Isotope:	C-14	Tc-99	P-32	
	160 keV	300 keV	1.71 MeV	
Efficiency:	2%	13%	27%	
@ Cs-137 energy:	2400	cpm / mR/hr		
DO NOT USE mR/hr SCALES				
UW Safety Dept. Calibration Lab 262-8769				

Figure 7-20. Calibration Sticker

your meter, the reading should not vary by more than  $\pm 20\%$ . Check source reading outside this range may indicate a problem. Call Radiation Safety for questions.

Low energy gamma probes (i.e., scintillation detectors) are used primarily to monitor  $^{125}\text{I}$ . These meters are calibrated in much the same manner as GMs except after the signal generator is used to calibrate the electronics, an  $^{241}\text{Am}$  source is used to determine the meter's response to the 60 keV (low-energy)  $\gamma$ -rays at several ranges and the efficiency is recorded on the calibration sticker. As with the GM meters, the meter is then exposed to a  $^{137}\text{Cs}$  gamma-ray beam and the cpm to mR/hr conversion factor is recorded. For LEG probes this factor is approximately 10,000 cpm per mR/hr although it may vary by  $\pm 20\%$ . In Section 7.4 it was noted that for  $^{125}\text{I}$ , a reading of 1,000,000 cpm was approximately 1 mR/hr. This is because the NaI(Tl) crystal over responds at energies less than 100 keV. Lastly, the calibration check source is metered and the meter response indicated on the calibration sticker.

After calibration, appropriate records are completed in the Safety Department, the meter database is changed to reflect the new calibration data, and the lab is called to pick up their meter at the Safety Annex.

### 7.5.c Radiation Survey Meter Operation

Before using a new meter, send it to Safety for calibration. Often the manufacturer calibrates these meters for  $^{137}\text{Cs}$  using the mR/hr scale. Such a calibration is not valid for  $\beta$ -particles. Read the operating manual to become familiar with the controls and operating characteristics. Each day, the first time you use your meter.

- Check the meter for physical damage and look on the calibration certificate (Figure 7-20) for the date the meter was calibrated. Meters are required to be calibrated yearly. If the date is more than 1 year ago, do not use the meter. Radiation Safety calibrates survey meters against known beta emitting radiation sources (or gamma sources, if required) free-of-charge.
- Check the batteries. Turn selector switch to the **BAT** position. The readout's needle must move into the **BAT TEST** (or **BATT OK**) range. If not, the batteries are weak and must be replaced. To conserve batteries, turn off the meter and speaker when not in use. When storing the survey meter for extended periods, remove the batteries and call Safety to have the meter posted with an *In storage, insert batteries and calibrate before use* label.
- Check the detector response. Radiation Safety places a check source on all meters and writes on the calibration sticker the meter's response with the detector on the source. With the meter and speaker turned on, choose the appropriate range, place the detector window over the check source affixed to the side of the meter, and measure the radiation of the source. Compare the response with that given on the calibration certificate. This response should be within  $\pm 15\%$  -  $25\%$  of the indicated response.
- Determine the background count-rate so you can compare your survey results with an "background" measurement. With the meter turned on and the selector switch on its lowest scale, point the detector away from any radiation fields and measure the background count-rate. Remember, the meter reading must be multiplied by the selector switch range (e.g., x 0.1, x 1, x 10, etc.). This result is the background reading. Normal background for thin-window GM meters is between 20 - 40 cpm and is about 150 - 200 cpm for LEG meters.
- With speaker on, point the probe window at the area or equipment you wish to monitor for radiation or radioactive contamination. Unless contamination is expected, place the selector switch on the lowest scale. When surveying or entering contaminated areas with unknown radiation levels, turn the meter on outside the area, place the selector switch on the highest range setting and adjust the switch downward to the appropriate scale. Multiply the meter reading by the selector switch setting. For example, in Figure 7-21, if the needle is on 3.7K cpm and the selector switch is on the "X 10" scale, the radiation count rate is 37,000 cpm.

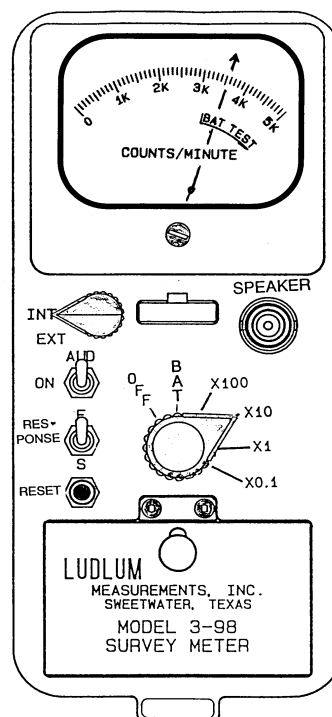


Figure 7-21. Meter Readout

### 7.5.d Radioactive Contamination / Radiation Exposure Level Survey Techniques

You must survey yourself and your work area when you finish working with radioactive material to check for contamination. This informal survey is standard practice to insure contamination is not spread from the lab. Additionally, labs and other rooms where beta and/or gamma emitting radionuclides (e.g.,  $^{14}\text{C}$ ,  $^{22}\text{Na}$ ,  $^{32}\text{P}$ ,  $^{33}\text{P}$ ,  $^{35}\text{S}$ ,

$^{36}\text{Cl}$ ,  $^{45}\text{Ca}$ ,  $^{51}\text{Cr}$ ,  $^{65}\text{Zn}$ ,  $^{86}\text{Rb}$ ,  $^{125}\text{I}$ ,  $^{131}\text{I}$ , etc.) are used or stored must be formally surveyed for radiation and radioactive contamination levels periodically using a calibrated radiation survey meter and wipes.

Surveys are done **monthly** in all rooms when total quantities of radioactivity used or stored in the lab exceed 74 kBq (200  $\mu\text{Ci}$ ), or **semiannually** when total quantities of radioactive material in the lab were less than 74 kBq (200  $\mu\text{Ci}$ ), or when radioactive materials are in storage **and** the user has requested an exception (see 5.5) to the monthly survey requirement. GM survey meters are appropriate to monitor for beta with  $E_{\text{max}} > 100$  keV and they are capable of detecting nanocurie (i.e., 2,200 dpm) amounts of  $^{14}\text{C}$ ,  $^{33}\text{P}$ ,  $^{35}\text{S}$  and  $^{32}\text{P}$ . For low energy gamma emitters (e.g.,  $^{125}\text{I}$ ,  $^{51}\text{Cr}$ ), a portable scintillation (LEG) meter must be used. Procedures for performing these surveys are:

- ♦ Wear lab coat, safety glasses, and disposable gloves; you may need to clean contamination found on the survey.
- ♦ Identify the areas where radioactive material is used and/or stored. Survey forms (see Figure 7-33) should include a floor plan of the room. Identify survey points on the survey form (Figure 7-33).
- ♦ Follow the Operating Procedures for Radiation Survey Meters in 7.5.b, above.
- ♦ Hold the window of the probe within 1 cm of the surface or piece of equipment you wish to monitor. Pay special attention to door knobs, telephones, log books, instrument handle(s) and computer keyboards (all of which may be accidentally cross-contaminated but should remain contamination free). Record the following information on the survey form:
  - ✓ Date and room number of survey
  - ✓ Initials of the person conducting the survey
  - ✓ Background radiation count rate
  - ✓ Meter information (make, model, type, and serial number)
- ♦ Slowly move the detector over each the designated area.
  - ✓ With speaker on, move detector about 2 inches per second and listen for a change in the rate of clicking from the speaker.
  - ✓ If the meter does not have a speaker, move detector about 1 inch every 2 seconds, observing the readout needle for rapid movement.
- ♦ Be careful when moving the detector, electrical noise may be generated in the cord and these may register as radiation counts. If you find an elevated spot, recheck it to see that it was not cable noise.
- ♦ Do not contaminate the probe. If you only use  $^{32}\text{P}$ , you may cover the probe with a thin sheet of plastic (e.g., saran) wrap. For  $^{14}\text{C}$ ,  $^{33}\text{P}$ ,  $^{35}\text{S}$  or  $^{45}\text{Ca}$ , do not cover the detector (cf. 4.3.b.3), use care to prevent contamination.
- ♦ Turn the meter and speaker off when completed or when the meter is not in use.
- ♦ Areas or survey points with meter count rates exceeding 650 cpm must be mitigated (e.g., decontaminated, shielded, etc.). If the exposure is due to radioactive contamination, the contamination must be cleaned and the successful decontamination must be documented and verified using wipe tests. Remember, efficiencies for  $^{35}\text{S}$  are about 1 - 3% and for  $^{32}\text{P}$  about 35%; this is a wide range of activities.

## 7.6 Liquid Scintillation Counter (LSC)

Liquid scintillation counting is an analytical technique which is performed by the incorporation of the radiolabeled analyte into uniform distribution with a liquid chemical medium capable of converting the kinetic energy of nuclear emissions into emitted photons. Although the liquid scintillation counter is a sophisticated laboratory counting system used to quantify the activity of particulate emitting ( $\beta$  and  $\alpha$ ) radioactive samples, it can also detect the auger electrons emitted from  $^{51}\text{Cr}$  and  $^{125}\text{I}$  samples.

### 7.6.a Liquid Scintillation Principles

Figure 7-22 is a graphic illustration of the way the beta radiation interacts with the cocktail (a mixture of a solvent and a solute) leading to a count being recorded by the system. In **Laboratory 2** there is a complete description of LSC counting and pulse processing.

**Step 1.** Beta particle emitted in radioactive decay. To assure efficient transfer of energy between the beta particle and the cocktail, the cocktail is a solvent for the sample material.

**Step 2.** In the relatively dense liquid, the beta particle travels only short distances before all of its kinetic energy is dissipated. Typically a beta particle will take a few nanoseconds to dissipate all its energy. The energy is absorbed by the medium in 3 forms: heat, ionization, and excitation. The key in LSC counting is excitation. Some of the beta energy is absorbed by solvent molecules making them excited (not ionized).

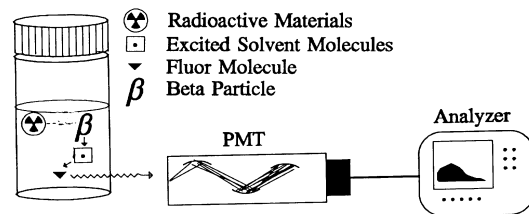


Figure 7-22. Liquid Scintillation Counting

**Step 3.** Energy of the excited solvent is emitted as UV light and the solvent molecule returns to ground state. The excited solvent molecules can transfer energy to each other and to the solute (Figure 7-23). The solute is a fluor. An excited solvent molecule which passes its energy to a solute molecule disturbs the orbital electron cloud of the solute raising it to a state of excitation. As the excited orbital electrons of the solute molecule return to the ground state, a radiation results, in this case a photon of UV light. The UV light is absorbed by fluor molecules which emit blue light (3700 Å) flashes upon return to ground state. Nuclear decay events produce approximately 10 photons per keV of energy. The beta energy is dissipated in a period of time on the order of 5 nanoseconds. The total number of photons from the excited fluor molecules constitutes the **scintillation**. The intensity of light in the scintillation is proportional to the beta particle's initial energy.

**Step 4.** Blue light flashes hit the photocathode of the PMT. The PMT is essentially a linear amplifier. Electrons, proportional in number to the blue light pulses, are ejected producing an electrical pulse that is also proportional to the number of blue light photons. The LSC usually has two PMTs. The amplitude of the PMT pulse depends on the location of the event within the vial. An event producing 100 photons will be represented by a larger pulse if the event is close to the PMT than if the event is more remote. The signal from each PMT is fed into a circuit which produces an output only if the 2 signals occur together, that is within the resolving time of the circuit, approximately 20 nanoseconds (coincidence circuit). By summing the amplitude of the pulses from each PMT, an output is obtained which is proportional to the total intensity of the scintillation. This analog pulse rises to its maximum amplitude and falls to zero.

**Step 5.** The amplitude of the electrical pulse is converted into a digital value and the digital value, which represents the beta particle energy, passes into the analyzer where it is compared to digital values for each of the LSC's channels. Each channel is the address of a memory slot in a multichannel analyzer which consists of many storage slots or channels covering the energy range from 0 - 2000 keV.

**Step 6.** Number of pulses in each channel is printed out or displayed on a video monitor. In this manner, the sample is analyzed and the spectrum can be plotted to provide information about the energy of the radiation or the amount of radioactive material dissolved in the cocktail.

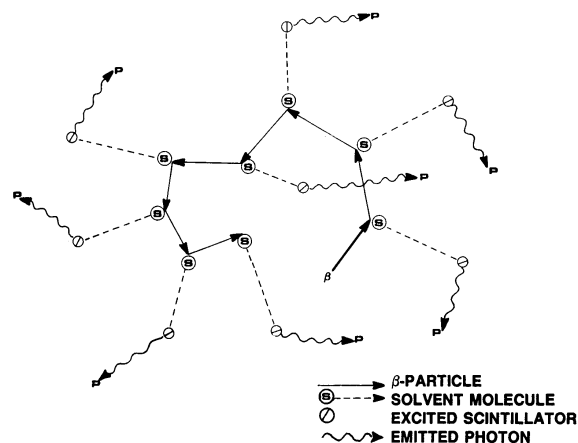


Figure 7-23. Cocktail Collision Process

### 7.6.b LSC Terminology

Liquid scintillation counting has a litany of specialized terminology describing the process and product of counting. Some of the more commonly encountered terms are listed below.

<b>Chemi-luminescence</b>	Random single photon events generated by the chemical interaction of sample components. Except at high rates, most chemiluminescence events are excluded by the coincidence circuit.
<b>Chemical Quenching</b>	A reduction in scintillation intensity (i.e., blue photons) seen by the photomultiplier tube because of materials present in the scintillation solution that interfere with the processes leading to the production of light. Quenching results in fewer photons per keV of beta particle energy and usually leads to a reduction in counting efficiency particularly for low energy beta.
<b>Cocktail</b>	The scintillation fluid, a mixture of 3 chemicals (solvent, emulsifier, and fluor) which produces light flashes when it absorbs the energy of particulate radioactive decay.
<b>cpm</b>	Counts per minute. The number of counts the LSC registered per minute. The number of radioactive decays in the sample is usually more than the number of cpm (cf. efficiency).
<b>Discriminator</b>	An electronic circuit which distinguishes signal pulses according to their pulse height or voltage. It is often used to exclude extraneous radiation counts or background radiation, or as the basis for pulse height analysis.



<b>dpm</b>	Disintegration per minute. The sample's activity in units of nuclear decays per minute.
<b>Efficiency</b>	The ratio, $\text{cpm} / \text{dpm}$ , the ratio of measured counts to the number of decays which occurred during the measurement time.
<b>Emulsifier</b>	A chemical component of the liquid scintillation cocktail that works to keep the radioactive sample suspended in the cocktail.
<b>Fluor</b>	A chemical component of the liquid scintillation cocktail that absorbs the UV light emitted by the solvent and emits a flash of blue light.
<b>Fluorescence</b>	The emission of light resulting from the absorption of incident radiation and persisting only as long as the stimulating radiation is continued.
<b>Luminescence</b>	A general term applied to the emission of light by causes other than high temperature.
<b>Optical Quenching</b>	A reduction in the scintillation intensity seen by the photomultiplier tubes due to absorption of the scintillation light either by materials present in scintillation solution or deposited on the walls of the sample container or optic (e.g., dirt). The result is fewer photons per keV of beta particle energy and usually a reduction in counting efficiency.
<b>PMT</b>	The photo-multiplier tube (Figure 7-18) is an electron tube that detects the blue light flashes from the fluor and converts them into an electrical pulse.
<b>Phosphor</b>	A luminescent substance or material capable of emitting light when stimulated by radiation.
<b>Photo-luminescence</b>	Delayed and persistent emission of single photons of light following activation by radiation such as ultraviolet.
<b>Pulse</b>	PMT output signal, amplitude is proportional to the radiation energy absorbed by the cocktail.
<b>Quench</b>	Anything which interferes with the conversion of the sample's radioactive decay energy into blue light photons. Quench results in a reduction in counting efficiency.
<b>QIP</b>	Quenching Index Parameter is a value that indicates a sample's level of quench.
<b>Secondary Scintillator</b>	Material in the scintillation cocktail which absorbs the emitted light of the primary scintillator and re-emits it at a longer wavelength, nearer the maximum spectral sensitivity of the photomultiplier tubes. It is added to improve the counting efficiency of the sample.
<b>Solvent</b>	A chemical component of the liquid scintillation cocktail that dissolves the sample, absorbs excitation energy and emits UV light which is absorbed by the fluor.

### 7.6.c LSC External Settings

All LSCs operate the way, however the different LSC manufacturers may use different terms when describing operational settings. Regardless of terminology, LSCs will have each of the following controls.

<b>Gain</b>	A control used to adjust the height of the signal received by the detecting system. The gain control for newer LS counters is often automatically set for the particular radionuclide selected.
<b>LLD</b>	The lower level discriminator is used to discriminate against (i.e., not count) betas with energy below that setting. This setting is also used to decrease system noise which often occurs in the region below 3 keV (e.g., set the LLD at 2 keV (Beckman Channel 156) for $^3\text{H}$ , $^{14}\text{C}$ / $^{35}\text{S}$ and $^{32}\text{P}$ to reduce noise).
<b>ULD</b>	The upper level discriminator is used to discriminate against beta energy higher than that setting (e.g., set the ULD to 18.6 keV for $^3\text{H}$ and 156 keV for $^{14}\text{C}$ , Beckman channel 427 and 686, respectively).

Because a certain LSC may have other external controls depending, it is important to read the instrument's operating manual to be familiar with the controls and operating characteristics. Typical Gain, LLD, and ULD settings are listed in Table 7-1.

Some systems allow the user to select the regions of interest by selecting a keV range of interest. Others offer several options (channel or keV). Two major vendors of LSC systems on campus. Packard / Canberra / Perkin Elmer are designed to allow the user to select energy regions. Packard channels correspond to energy in 0.5 keV increments; that is, the 4000 channels are each ½ keV wide, so the system can detect energies from 0 to 2000 keV (cf. **Laboratory 1**). Beckman is another vendor. In a Beckman LSC, the channel option is the default option for the count window. Beckman LSCs have 1000 channels and the energy is related to the channel by the equation:

$$\text{Channel \#} = 72 + 280 \log_{10}(E_{\max})$$

where  $E_{\max}$  is in keV. Thus, the ULD channel settings on a Beckman LSC to detect the maximum possible beta energy for  $^3\text{H}$ ,  $^{14}\text{C}/^{35}\text{S}$ , and  $^{32}\text{P}$  would be 427, 686/691, and 977, respectively (see **Table 7-1**). Similarly, the 2 keV LLD setting would correspond to channel 156.

Table 7-1. Typical LLD, ULD, and Gain Values

Isotope	LLD (keV)		ULD (keV)		Beckman Max Channel # <sup>1</sup>	Gain <sup>2</sup>
	Maximum	Optimum	Maximum	Optimum		
$^3\text{H}$	2	2	18.6	12	427	50%
$^{14}\text{C} / ^{35}\text{S}$	2	12	156	156	686	6%
$^{33}\text{P} / ^{45}\text{Ca}$	2	12	258	258	747	5%
$^{32}\text{P}$	5	5	1700	1700	977	2%

<sup>1</sup>The LLD and ULD can be set using keV or channel controls. If channel controls are used in a Beckman LSC, the corresponding channel numbers are listed (see 7.6.1)

<sup>2</sup>The gain control for newer LSC is automatically set

#### 7.6.d Considerations in Isotopic Analysis

The beta particle must have sufficient energy to produce at least 2 photons in the cocktail and one must interact with each PMT within the time set for the coincidence circuitry. Below a few (i.e., 2 - 4) keV of energy, the yield of photons under ideal conditions, is 7 - 8 photons per keV. The photocathode of a PMT is not 100% efficient. The conversion efficiency from a photon to a photoelectron is only about 30%. The coincidence threshold, and consequent lower detection limit, occurs below 1 keV.

LSC can be used for alpha emitters because it offers very high counting efficiencies (e.g., nearly 100%) and simplicity of sample preparation. Most  $\alpha$  radionuclides emit high-energy particles in the range of 4 - 6 MeV. A characteristic property of alpha particle interaction with liquid scintillation media is a low scintillation or photon yield as compared to beta or even gamma emitters (light yield is about a factor of 10 [i.e., 10%] lower). This is because almost all the kinetic energy associated with an alpha emission is given up to the media in a relatively short distance. The relative scintillation (i.e., light) yield from this absorption depends upon specific ionization. The higher the specific ionization, the lower the relative photon yield. This results in poor alpha radionuclide energy resolution. Even though alpha emission is monoenergetic, the pulse height distributions are relatively broad (Figure 7-24).

Because they are less dense, the organic scintillators used in LSCs have a lower gamma ray absorption coefficient than inorganic (NaI) scintillation crystals. The photoelectric effect is small when  $E\gamma > 300$  keV and Compton scattering becomes the main absorption process.

Thus, the pulse depends upon gamma energy. For  $E\gamma < 20$  keV, the photoelectric effect (i.e., all gamma energy is transferred to a single electron) predominates. For  $20 \text{ keV} < E\gamma < 100 \text{ keV}$ , both photoelectric and Compton effects contribute. And, for  $100 \text{ keV} < E\gamma < 3000 \text{ keV}$ , the Compton effects predominates. Thus, LSC can be used for counting x-/ $\gamma$ -ray emitters like  $^{49}\text{V}$ ,  $^{51}\text{Cr}$ ,  $^{125}\text{I}$  (i.e., these radionuclides also emit auger electrons with energies ranging

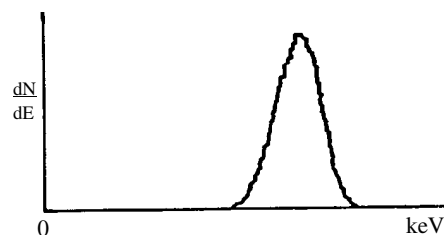
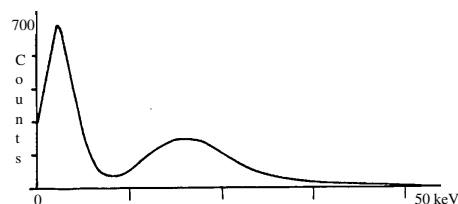


Figure 7-24. Typical Alpha Spectrum

Figure 7-25.  $^{125}\text{I}$  Spectrum

from 4 to 20 keV). In fact, for  $^{125}\text{I}$ , counting efficiency can be as high as 76% in a typical emulsifier type LSC (Figure 7-25). Efficiencies typically seen in LSCs are found in Table 7-9.

**LSC Energy Representation**

Remember, in liquid scintillation counting, the total energy we are dealing with can range from essentially 0 to 2,000,000 eV (2000 keV). Even tritium ( $^3\text{H}$ ) has an energy distribution from 0 to 18,600 eV. Representing this spectrum on linear paper is difficult. Even if the linear scale used is in units of keV (thousand electron volts), to represent the entire spectrum encountered in research labs (up to 2,000 keV) on linear scale requires a long scale. Often, what is used to simplify the graphing and analysis is a log scale. Logarithms to the base 10 (Log or  $\text{Log}_{10}$ ) consist of an integer (i.e., the characteristic) followed by decimal (i.e., the mantissa). The characteristic represents powers of 10. Thus, the characteristic for 1, 10, 100, 1000, 10,000, etc. are 0, 1, 2, 3, 4, etc., respectively. When looking at an LSC energy range of 0 to 2,000,000 eV, the characteristic ranges from 0 to 6. The mantissa is derived from a table, but for the same set of integers, it remains the same. For example, the logarithms of 2, 20, 200, 2000, 20,000, etc. are 0.3010, 1.3010, 2.3010, 3.3101, 4.3010, etc., respectively. Thus, the  $^3\text{H}$  spectrum plotted on log paper will look different than the same data plotted on linear paper, the log scale plot is more "bunched-up" at the end of the scale. Sometimes, representing information in one scale or the other (i.e., linear or log) makes it easier to visualize the information or manipulate the data. Thus, you should be aware that the graphs of the same data look different depending upon whether a linear or log scale is used and always look at the units used to represent the data.

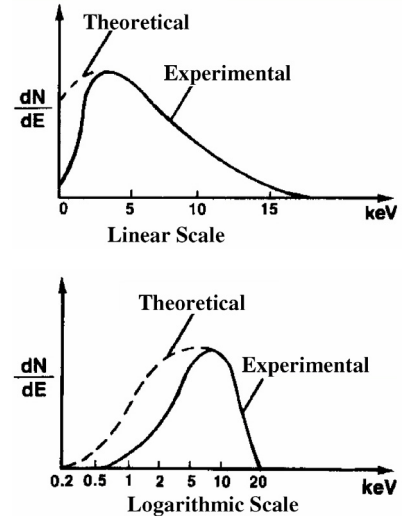


Figure 7-26. Linear vs. Log Scale

Each type of representation has advantages and disadvantages. Regardless, the representation of the lowest energies emitted (e.g., ~0 - 2 keV) is inaccurate. One reason for this is that the lowest energy required to produce a count in the analyzer is about 0.7 to 1 keV. Most manufacturers who use log scales use channel numbers instead of keV on the scale. Also, because the logarithmic scale is compressed at the upper end, it is difficult to determine energies and calculate average pulse height.

**Quench**

The color of the light emitted in the scintillation process is blue to UV (3700 Å). Samples containing colored materials (e.g., urine, plant and animal tissues, feces, etc.) can absorb this blue light before it can escape the vial and strike the photomultiplier tube. In fact, virtually anything added to a counting vial (color, filters, solvents, etc.) can reduce the efficiency of the scintillation process. This reduction in system efficiency as a result of energy loss in the liquid scintillation solution is called *quench*. Three major types of quench encountered are photon, chemical, and optical quench. *Photon* quenching is the incomplete transfer of beta particle energy to solvent molecule. *Chemical* (or impurity) quenching causes energy losses in the transfer from solvent to solute. *Optical* or *color* quenching causes the attenuation of photons produced in solute. The effect of quench is to shift the measured radioisotope's energy spectrum toward the

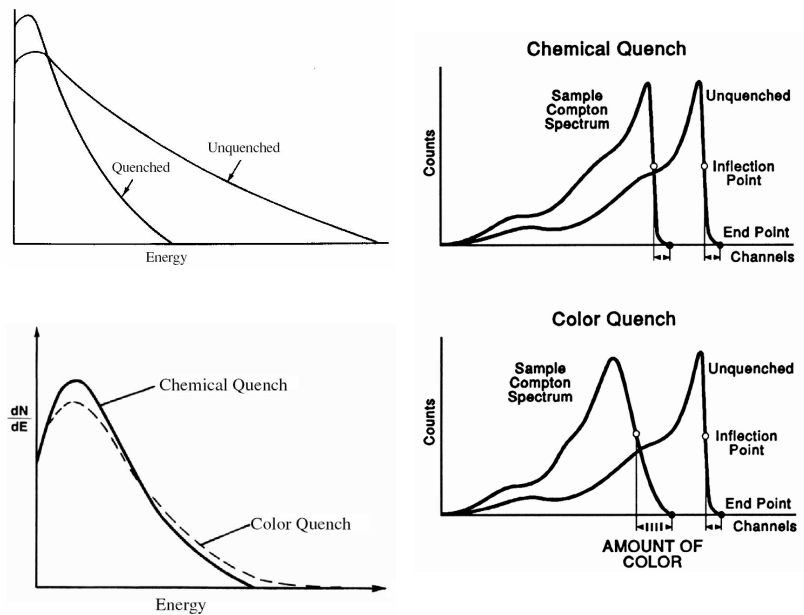


Figure 7-27. Quenching Effect

Three major types of quench encountered are photon, chemical, and optical quench. *Photon* quenching is the incomplete transfer of beta particle energy to solvent molecule. *Chemical* (or impurity) quenching causes energy losses in the transfer from solvent to solute. *Optical* or *color* quenching causes the attenuation of photons produced in solute. The effect of quench is to shift the measured radioisotope's energy spectrum toward the

low energy end of the graph (Figure 7-27). This shifting depends upon the type of quench as well as the type of display (i.e., linear versus log).

Photon quench often results from the incorporation of incompatible substances that are not soluble and may result in a heterogeneous mixture. In this situation, detector efficiency is reduced and light collection may also be incomplete.

In chemical quench, chemical agents (e.g., dissolved oxygen, water, etc.) added to the cocktail with the sample interfere with the transfer of kinetic energy so the chemical quenching agent absorbs beta energy and converts it to heat (e.g., infrared) before it can be converted to blue light photons. This leads to a reduction and loss of blue light and reduction of efficiency. Chemical quenching appears to affect all radiation energies equally.

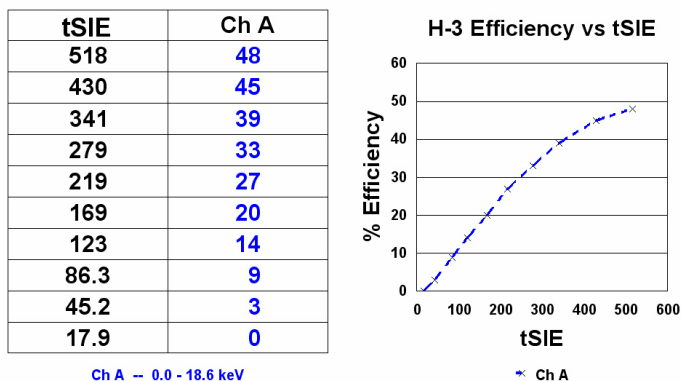
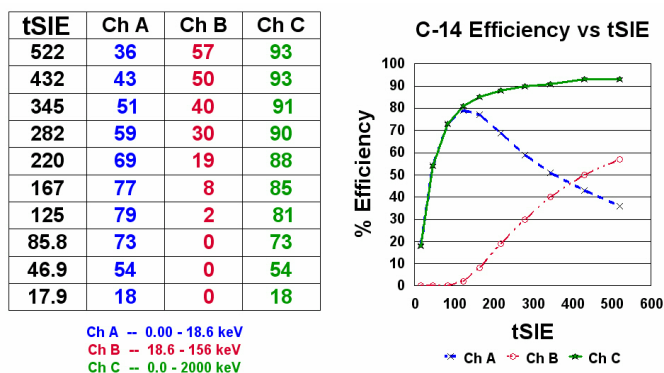
The cocktail ultimately produces blue light (3700 Å) light. Red, green and yellow colors in the cocktail may absorb some of this light resulting in reduced efficiency. Thus, color quenching results from the passage of the blue photons through the medium and depends on the color of the interfering chemical and the path length that the blue photon must travel. Events that take place near to one PMT will give rise to a large pulse and a smaller pulse in the other PMT. When these two pulses are summed in the coincidence circuit, the resultant pulse height may be as large as from an unquenched decay and usually only the number of events will be significantly reduced. While bleaching with hydrogen peroxide may reduce the color, it adds oxygen, a chemical quencher. Finally, at equal quench levels, the pulse height of colored samples are spread over a wider energy range than for chemical quench samples, therefore one should not use a chemical quench curve to correct for strong color-quenched samples.

Because quench affects the efficiency of sample detection, quench could have a significant impact on your LSC results. To better understand the importance of quench on your work note these three different quench curves and the resulting efficiencies. These quenched standards were counted on a Packard 1900 LSC in the Safety Department. On a different Packard system it is likely that the quench numbers and resultant efficiencies will be a little different, but not the effects of quench. The Packard allows the user to select keV regions of interest. For this demonstration we selected three channels: Channel A, 0.0 - 18.6 keV; Channel B, 18.6 - 156 keV; and Channel C, 0.0 - 2,000 keV (see 7.6.1 for Beckman LSC comments).

Two of the standards counted were  $^3\text{H}$  (Figure 7-28) and  $^{14}\text{C}$  (Figure 7-28). Channel A encompassed the entire energy region for  $^3\text{H}$ . Channel B was selected as a region from the top of Channel A to the maximum possible energy of  $^{14}\text{C}$ , 156 keV. Channel C was selected as the entire energy region (up to 2000 keV).

The  $^3\text{H}$  results are shown in Figure 7-28. Note the extremes of values for the quench parameter (tSIE). A maximum efficiency of approximately 48% is achieved with a quench parameter (tSIE) of 518. The minimum efficiency of 0.33% is obtained with a quench of 17.9. Thus, a quench of 45 or below would result in essentially background counts (efficiency  $\approx$  3%).

We deliberately counted  $^{14}\text{C}$  in two different channels to allow you to observe the shifting effect quench has on where the count is produced in the LSC. Figure 7-29 depicts the Channel A, Channel B, and Channel C (A + B) results. Again, the extremes from quench are evident. Looking only at Channel C, a maximum efficiency of approximately 92% is achieved with a quench parameter (tSIE) of 522. A minimum efficiency of 18% is

Figure 7-28.  $^3\text{H}$  Quench CurveFigure 7-29.  $^{14}\text{C}$  Quench Curves

is seen with a quench of 17.9. The higher energy beta ( $^{14}\text{C}$ ) sample means it is not as severely affected by quench as a low energy ( $^3\text{H}$ ) beta source. But, notice that as quench increases (tSIE decreases) the counts begin shifting from Channel B into Channel A even while the total efficiency remains above 80% (at tSIE = 167) as depicted in Channel C, the majority of counts are now occurring in channel A as opposed to Channel B.

As we saw with our analysis of quench on single isotopic samples (cf., Figures 7-28 and 7-29), quench shifts the energy spectrum into a lower region and reduces the efficiency (Figure 7-30). The situation is less important for very high energy emitters like  $^{32}\text{P}$  and  $^{86}\text{Rb}$ , and only slightly important for medium energy emitters if there is significant quench. As you can see from Figure 7-29; even with a lot of quench, if you are reviewing your results over the entire energy spectrum (e.g., for  $^{14}\text{C}$  or  $^{35}\text{S}$ , that would be 0 - 160 keV), the total efficiency is normally well above 50% efficiency. Only  $^3\text{H}$  is significantly affected by quench.

However, suppose you were counting a dual label such as  $^3\text{H}$  and  $^{14}\text{C}$ . Recall from Figure 7-29, quench will shift more of the  $^{14}\text{C}$  spectrum into the same region that you are counting the  $^3\text{H}$ . Because of this spill over, not all the counts in the  $^3\text{H}$  energy region will be due to  $^3\text{H}$ . Some will be  $^{14}\text{C}$  counts. Consider the quench samples used in Figures 7-28 and 7-29. The results of quench on a dual labeled sample are illustrated in Table 7-2.

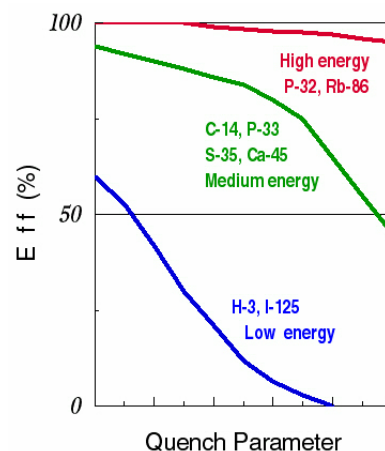


Figure 7-30. Quench vs Efficiency

Table 7-2. Quench Effect in Dual Label

tSIE	$^3\text{H}$ Quenched Standard <sup>§</sup>		$^{14}\text{C}$ Quenched Standard <sup>§</sup>				Ch A cpm	Ch B cpm
	Ch A: 0.0 - 18.6 keV <sup>†</sup>		Ch A: 0.0 - 18.6 keV <sup>†</sup>		Ch B: 19.0 - 156 keV <sup>†</sup>			
	efficiency	cpm	efficiency	cpm	efficiency	cpm		
520	47.9	93,172	36	49,118	57	77,771	142,290	77,771
430	44.5	86,600	43	58,669	50	68,220	145,269	68,220
345	38.7	75,245	51	69,584	40	54,576	144,829	54,576
280	33.3	64,668	59	80,500	30	40,932	145,168	40,932
220	26.9	52,380	69	94,144	19	25,924	146,524	25,924
170	20.4	39,567	77	105,059	8	10,915	144,626	10,915
125	13.8	26,909	79	107,787	2	2,729	134,696	2,729
85	8.6	16,624	73	99,601	0	0	116,225	0
45	2.8	5,463	54	73,678	0	0	79,141	0
18	0.3	641	18	24,559	0	0	25,200	0

<sup>§</sup>Sample activities:  $^3\text{H}$  = 194,433 dpm;  $^{14}\text{C}$  = 136440 dpm

<sup>†</sup>Counting regions: Ch A = 0.0 - 18.6 keV; Ch B = 18.6 - 156 keV

What's this mean for your results? Obviously, you can not use the cpm appearing in the appropriate channel to determine activity in your sample. Usually a set of  $^3\text{H}$  and a set of  $^{14}\text{C}$  standards can be used. If you have developed a quench curve, you can determine  $^{14}\text{C}$  activity by using the Quench number and cpm in channel B. You could also use the distribution of efficiencies (e.g., if quench = 430, efficiency is distributed 43% in channel A and 50% in channel B) to determine the expected cpm for  $^{14}\text{C}$  in Channel A, then subtract that cpm from the total in Channel A to determine cpm for  $^3\text{H}$  and then calculate subsequent activity of  $^3\text{H}$  from the quench number.

That's a lot of work, especially if you have 100 samples. Most LSCs have the ability to do dual spectrum analysis. For this process, one of the methods used is to use a dual (e.g.,  $^3\text{H}/^{14}\text{C}$ ) quenched standard set. Run the standards (see 7.6.i) and use the program generated to determine activity (i.e., dpm, mCi, etc.) directly.

A word of caution. When you do a quench calibration using a dual standard, some LSC units shift the channel separation points in an automatic process to assure that the greatest number of each isotopes counts appear in the proper channel. For that reason, you can not develop a quench curve from a dual labeled standard and then apply the curve to sample results obtained with exact energy channels (e.g.,  $^3\text{H}$ : 0 - 18.6;  $^{14}\text{C}$ : 18.6 - 156).

The Safety Department has several counters and programs which can be used to count either single (i.e.,  $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{35}\text{S}$ ) or dual label ( $^3\text{H}/^{14}\text{C}$  or  $^3\text{H}/^{35}\text{S}$ ) sample.

Lastly, we counted a set of  $^{125}\text{I}$  standards. The decay of  $^{125}\text{I}$  is by internal conversion and the decay energy interact with K- and L-shell electrons ejecting monoenergetic **Auger** electrons at 3.6 keV and, at a much lower abundance, 22 keV. Remember, Auger electrons are emitted monoenergetically. There may also be some interactions of the x-rays in the cocktail to provide relatively high efficiencies. An efficiency of 81% is achieved with a quench parameter (tSIE) of 607. The minimum efficiency of 52% is seen with a quench of 1717. Other nuclides which emit Auger electrons are  $^{55}\text{Fe}$  and  $^{51}\text{Cr}$ .

tSIE	Ch A
607	81
565	79
527	78
474	75
401	71
340	68
316	66
267	63
226	59
171	52

Ch A - 0.0 - 80 keV

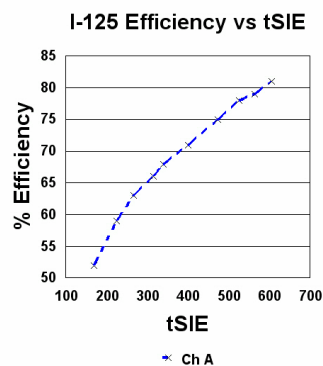


Figure 7-31.  $^{125}\text{I}$  Quench Curves

The point of this discussion: **Quench is important.** You must understand the impact of quench and how the system you are using represents it if you desire to obtain viable results.

Quench calibration delimits the valid ranges for quantifying a sample. Samples with quench numbers outside the calibration range will raise a **Flag** indicating the value is out of range. The conversion to dpm will be made, but will be an extrapolation from the highest/lowest recorded quench value.

### Chemiluminescence / Photoluminescence / Static Electricity

**Luminescence** is a single photon event. Each reaction results in the emission of a single photon. Up to a certain number of single events, the coincidence circuit can discriminate between luminescence and beta events. However, with a large number of these single events, some may be registered as counts if two single events occur within the time frame of the coincidence gate (see **Laboratory 1**). Thus, even though LSCs employ a coincidence circuit, luminescence becomes a problem when the production of single photons occurs at a rate sufficiently great that separate luminescence events stimulate each PMT within the resolving time of the coincidence circuits.

**Chemiluminescence** is the production of light as a result of a chemical reaction between components of the scintillation sample in the absence of radioactive material. This most typically occurs in samples of alkaline pH and/or samples containing peroxides when mixed with emulsifier-type scintillation cocktails, when alkaline tissue solubilizers are added to emulsifier-type scintillation cocktails, or in the presence of oxidizing agents in the sample. Reactions are usually exothermic and result in the production of a large number of single photons. **Photoluminescence** results in the excitation of the cocktail and/or vial by UV light (e.g., exposure to sunlight or sterile hood UV lights). Chemiluminescence has a relatively slow decay time (from 0.5 hr to > 1 day depending on the temperature) while photoluminescence decays more rapidly (usually < 0.1 hr).

The luminescence spectrum has a pulse height distribution which overlaps the  $^3\text{H}$  spectrum. The maximum pulse height is approximately 6 keV and the spectrum is (chemical) quench independent. The equivalent of a few keV of beta particle energy, the maximum number of events occurs between 0 and 2 keV and remains there independent of quenching. Contrary to popular belief, cooling the luminescent scintillation samples may reduce the photon intensity to low levels, but the interference is still present and provides a false indication of luminescence control. Chemiluminescence will decay with time or at elevated temperatures. It can be greatly reduced by acidifying the solution to be counted. The chemiluminescence count rate, although high, will decrease with time. Preparing and counting a control sample with no radioactivity will indicate the decay time of the luminescence.

**Static electricity** on liquid scintillation vials is also a single photon event with pulse height limited to about 10 keV. Many items used in the liquid scintillation counter environment are conducive to the development of static charges. In general, glass vials have less problems with static than plastic vials; small vials in adapters are particularly prone to static charge buildup. Most systems offer an option which employs a static discharge device or an electrostatic controller.

### Self-absorption

Self-absorption quench (Figure 7-32) occurs when a beta particle emitted by an isotope remains undetected because of entrapment in non-scintillating media (e.g., cell membranes, cells, precipitates). It may be particularly severe for

weak beta emitters like  $^3\text{H}$  which travels only about 0.000863 cm in a cocktail before the energy is completely absorbed. This form of quench occurs most frequently with assays that involve filtration steps (e.g., membrane and whole cell receptor assays and cell proliferation assays). Additionally, counts in particulate materials deposited on the surface of a filter may also be susceptible to self-absorption. This form of quench may be reduced only if adequate measures are taken to solubilize the material from the surface of the filter before counting.

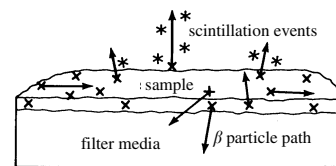


Figure 7-32. Self-absorption

#### Sample Volume / Dual Phase Samples

As the sample volume decreases (e.g., below 10 ml in 20 ml vials), the light output falls on less efficient areas of the PMT. Consequently energy detection becomes less efficient with low volumes. If you need to use small volumes, use small LSC vials. Phase separation is also a potential problem. If two phases are present (e.g., aqueous sample mixed with organic cocktail or samples which separate due to temperature variations), the activity may be distributed between the two phases. Because each phase will have its own counting efficiency, external standardization and dpm calculations may provide false results.

#### 7.6.d LSC Quench Correction / Quench Calibration

Thus, there are many factors which affect LSC counting efficiency. These include the degree of quenching, the nature of the sample, the scintillation cocktail used and the sample preparation method. Not all types of particle-emitting radiation ( $\alpha$ ,  $\beta$ ) are detected equally well by the LSC. In general, the higher the beta particle energy the higher the LSC efficiency. If you are counting one or two samples, looking for gross amounts of counts / activities (e.g., "all" or "none"), the impact of quench and these other factors may be of slight importance. However, if you need accurate results which reflect the correct activity in your assay / sample, you must determine system efficiency and use that efficiency to determine activity in dpm,  $\mu\text{Ci}$ , Bq, etc. The two most common methods used to make these corrections are the sample channel ratio (SCR) and the external standard.

#### Sample Channels Ratio (SCR)

As seen in Figures 7-27, 7-29 and 7-33 and Table 7-2, quench will produce a two-dimensional shift in the counting spectrum, that is a reduction in total number of counts and shifting of the energy peak toward the low energy end of the graph. The concept is to set up two counting regions, A and B. Region A would encompass the entire energy region and Region B would encompass a fraction of the entire region. One suggestion is to set the Lower Level Discriminator (LLD) of Region B to obtain approximately 70% of the count rate in Region A. Another suggestion for  $^3\text{H}$  counting is to select Region A to cover 0 to 19 keV and Region B to cover 2 to 19 keV.

Once these regions have been established, count LSC solutions containing a known amount of radioactivity and varying amounts of quench. Calculate the ratio of the two regions, B/A (or A/B). Then graph the channels ratio, B/A (or A/B), versus efficiency.

The benefit of using the SCR is that only two counting channels are required (i.e., A and B) and, while LSC computers may be capable of 4000 or more channels, this method will work with either older or newer LSC systems. On the negative side: (1) the SCR has limited use for highly quenched samples because of the spectrum's shift, (2) the precision depends upon the instrument's region settings, (3) optimizing regions is somewhat tedious, (4) longer counting times may be required to obtain statistical accuracy and (5) is of limited use in dual labeled counting or with low activity samples.

#### External Standard

Recall that as  $x$ -/ $\gamma$ -rays pass through matter, it ionizes by both Compton and photoelectric interactions. For a given energy gamma-ray and absorber (e.g., liquid scintillation cocktail), the spectrum of these Compton and photoelectric electrons will be the same. Quench will shift this spectrum into a lower energy region and reduce the total counts detected. This shifting can be analyzed and the amount of quench determined.

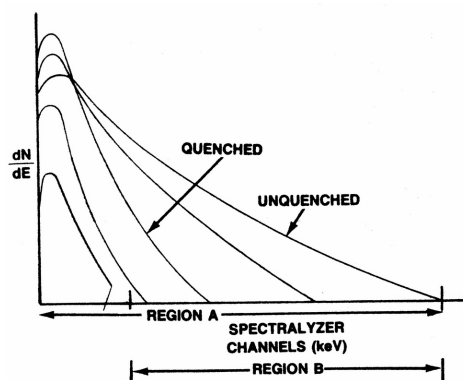
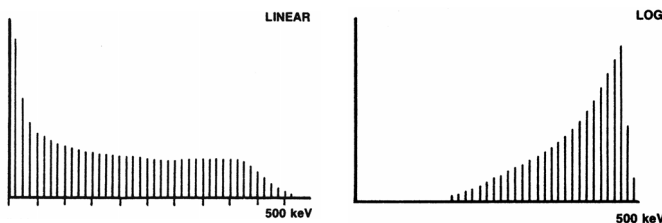


Figure 7-33. Sample Channels Ratio

One of the first methods was the Compton Edge developed by Dr. Horrocks and introduced by Beckman as the H-number. Originally, the H-number was defined as the projection on the log energy scale of the point located on the Compton Edge at half peak height. The technique was later modified to use a specific inflection point instead of the edge point (Figure 7-34). While various sources have been used in this determination, Beckman Instruments settled on a  $^{137}\text{Cs}$  source, allowing them to reduce the external standard counting time to 6 seconds. A log scale was used because in the linear scale, the inflection point is less obvious. One additional problem with the H-number concerned the difference between chemical and color quenching (Figure 7-27). Color quenching tends to flatten spectrum, fewer pulses are spread over a broader region. This flattening will introduce significant errors if the activity of a color-quenched sample is calculated using a chemical quench standard.

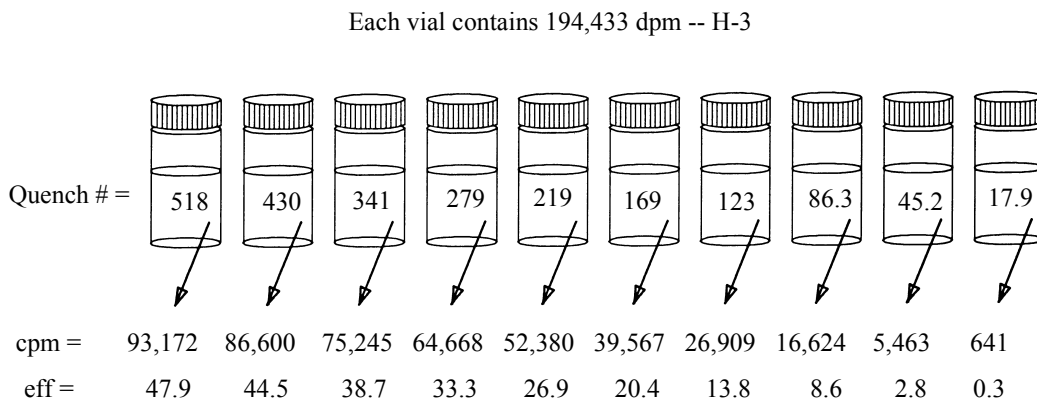
Figure 7-34.  $^{137}\text{Cs}$  External Standard (linear & Log)

The Packard Instruments (now PerkinElmer) LSC developed a transformed Compton spectrum. In this method, an algorithm is applied to the energy distribution to correct to spectral distortions (e.g., wall effect, volume variations, color quenching, etc.). This method was implemented using a  $^{133}\text{Ba}$  external standard and proprietary algorithms to reduce spectral distortion and allow for the use of only one quench curve per radionuclide, regardless of cocktail used.

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### Quench Calibration

Once you determine the method to be used for quench correction (i.e., SCR or external standard), you are now ready to calibrate the LSC counter for the type of sample that it will analyze. Although you could purchase components and make your own calibration standards, normally a vendor purchased quenched standard set is used following the method described below.

Figure 7-35. Set of  $^3\text{H}$  Quenched Standards

- ◆ A 10 vial standard set, Figure 7-35, each containing the same amount of radioactivity (i.e., dpm) but mixed with increasing amounts of a chemical quenching agent (e.g., nitromethane,  $\text{CCl}_4$ ) is used. Quenching agents absorb the radiation energy and, instead of emitting a pulse of UV light, they radiate infrared so the fluors do not get excited. Thus, the more quenched the sample, the fewer the counts detected in the desired channel. The reduced amount of light emitted per radiation energy absorbed usually results in a shifting of the spectrum into lower channels (Figure 7-27). These samples routinely come in  $^3\text{H}$ ,  $^{14}\text{C}$ , and mixed  $^3\text{H}/^{14}\text{C}$  sets.
- ◆ The quenched standards are placed into a LSC tray which is then placed into the LSC. Set the LLD, ULD (or Channel # for Beckman LSCs) and Gain as appropriate (Table 7-1), determine Regions A and B for SCR, and begin counting. Note that for statistical reasons, the ULD for  $^3\text{H}$  is usually set to a lower value than the end point of the  $^3\text{H}$  spectrum. Newer LSCs may allow you to program the calibration via the computer keyboard.
- ◆ The number of counts registered (cpm) for each of the standard vials and the amount of sample quench (QIP) are determined by the LSC and printed out or stored in a designated correction program. For the SCR method, the counts in each region will be printed for each sample.



- ◆ Because all the standards contain the same amount of radioactivity, the efficiency (i.e., ratio **cpm / dpm**) of the counter for each of the various levels of quenching can be plotted as in the graph in Figures 7-28 and 7-29. For the SCR method, calculate the ratio B/A and plot a graph of the ratio B/A versus efficiency.

### Sample Activity (i.e., dpm) Calculation

The benefit of quench correction / calibration is that it enables the user to convert sample results reported in cpm into activity units such as  $\mu\text{Ci}$ , pCi, dpm or Bq. Some liquid scintillation counters will do this automatically using programs stored on the computer. For others, the calculation is done manually.

- ◆ Count your samples, the **counts per minute** and the **quench** level are printed out for each sample. If using SCR method, calculate the ratio of B/A.
- ◆ Find the efficiency for the sample's quench level from the appropriate quench curve (e.g., Figure 7-28 or 7-29) or using the SCR efficiency curve.
- ◆ Calculate the activity (dpm) from the reported counts per minute (cpm) by dividing the number of counts by the efficiency (i.e.,  $\text{dpm} = \text{cpm} / \text{eff}$ ).

### 7.6.e Operating Procedures For LSC Counters

Remember, every instrument is a little different (e.g., different instrument, models, upgrades, rebuilds, etc.). Read the LSC's operating manual to gain familiarity with the controls and operating characteristics. To count your sample:

- ◆ Place samples into LSC vials and add the correct amount of liquid scintillation cocktail (e.g., 1, 5, and 10 ml, as appropriate). Include a background vial which contains scintillation cocktail and a non-radioactive sample similar in make-up (i.e., geometry) to your radioactive samples.
- ◆ Place your sample vials with the background vial into the LSC tray (or belt) and place into the LSC.
- ◆ Set count time to at least 2 minutes, shorter times give poor counting statistics.
- ◆ Set LLD, ULD, and Gain (see Table 7-1 for Beckman LSC channel settings) and begin counting.
- ◆ Calculate the true radioactivity of the sample in units of **dpm** by dividing the sample **cpm** by the counter efficiency for that energy of sample (i.e.,  $\text{dpm} = \text{cpm}/\text{eff}$ ). As discussed above, the counter efficiency may be different for different vials depending on the amount of quenching present. The general procedure to determine sample activity (i.e., dpm,  $\mu\text{Ci}$ , etc.) is:
  - ✓ Count your samples so the **counts per minute** and the **quench** level are printed out for each sample.
  - ✓ Find the efficiency for the sample's quench level from the appropriate quench curve (e.g., Figure 7-28 or 7-29).
  - ✓ Calculate the activity (dpm) from the reported counts per minute (cpm) by dividing the number of counts by the efficiency (i.e.,  $\text{dpm} = \text{cpm} / \text{eff}$ ).

### 7.6.f Cerenkov Counting

Some beta emitting isotopes can be analyzed on an LSC without using any cocktail. The literature of several manufacturers discusses counting high energy ( $E_{\text{max}} > 800 \text{ keV}$ ) beta emitters without using any cocktail or with only a little water, using a technique called *Cerenkov* counting.

When high energy beta particles travel faster than the speed of light in the medium they are traversing (e.g., water, etc.) Cerenkov radiation (i.e., light) is produced. Cerenkov radiation is the blue light you see when you look into a reactor pool. Cerenkov radiation allows some beta emitting radionuclides to be analyzed using a liquid scintillation counter without using any cocktail. For Cerenkov radiation to be produced, the beta particle energy must exceed a minimum threshold energy ( $E_{\text{th}}$ ) which is calculated by:

$$E_{\text{th}} = \frac{511 n}{\sqrt{n^2 - 1}} - 511$$

In this equation, **511** is the rest mass of an electron in keV and **n** is the refractive index of the medium (e.g.,  $n_{\text{glass}} = 1.5$ ,  $n_{\text{water}} = 1.33$ ). Consider, for example, using water instead of cocktail. Then, for water,  $E_{\text{th}} = 263 \text{ keV}$ . If you were counting filter papers in glass vials, then  $E_{\text{th}} = 175 \text{ keV}$ .

Given these energy constraints,  $^{32}\text{P}$ ,  $^{36}\text{Cl}$ ,  $^{86}\text{Rb}$  and  $^{90}\text{Sr}/^{90}\text{Y}$  have sufficient energy to be analyzed using Cerenkov counting. From a practical point of view, at the UW the only beta emitting radionuclides likely to be analyzed by Cerenkov counting are  $^{32}\text{P}$  and  $^{86}\text{Rb}$  which emits a beta particles with  $E_{\text{max}} \sim 1,710 \text{ keV}$ .

Table 7-3. Cerenkov Efficiency

mm water	% efficiency
0	30.8
1	42.2
2	44.1
4	48.0
8	46.8
12	46.9
16	46.3

Because beta particles are emitted in a spectrum of energies, approximately 86% of the  $^{32}\text{P}$  beta particles have energies exceeding the  $E_{\text{th}} = 263 \text{ keV}$  for counting in water. With proper LSC adapters (if needed), researchers could directly analyze their samples in 0.5 and 1.5 ml microfuge tubes.

Consider an example of Cerenkov counting of a  $^{32}\text{P}$  labeled compound that Radiation Safety conducted. Safety used an aliquot from a vial containing 185 MBq (5 mCi) in a 10 ml aliquot of [alpha-P-32] UTP. The radioactive sample was placed in a 20 ml glass vial and counted with various quantities of water added (Table 7-3). The samples were counted at ambient temperature using a Packard 1900 with the counting window / region set at 5 - 1700 keV. The activity used was estimated by counting an identical sample in LSC cocktail and assuming 90% efficiency. As seen from Table 7-3, counting  $^{32}\text{P}$  in a 20 ml glass vial, with 4 - 12 ml of added water gives optimum efficiency. However, note that relatively good efficiencies were obtained for all samples. Typically the counting efficiency of  $^{32}\text{P}$  in 4 - 12 ml of water is expected to be approximately 40 - 50% compared to the efficiency obtained by using LSC cocktail for the same  $^{32}\text{P}$  sample of nearly 100%.

As with any counting method, Cerenkov counting has advantages and disadvantages. Advantages include simple sample preparation (i.e., only add water, the volume is not too critical), less expensive, (i.e., no LSC cocktail used), sample can be recovered, no chemical quench (i.e., light is given up directly to the medium, no cocktail is employed), and waste can be treated as solid if no water was used or as aqueous. Disadvantages include lower efficiency, higher color quench, volume dependence (particularly if using less than 2 ml of water), and medium dependence (e.g., glass / plastic vials, water, air, etc.).

The biggest factor preventing universal use of Cerenkov counting is beta energy. In order to achieve adequate efficiency, the average beta energy ( $E_{\text{avg}} \approx \frac{1}{3}E_{\text{max}}$ ) must be greater than the required threshold energy,  $E_{\text{th}}$ . Thus, from a practical point of view, this criteria limits Cerenkov counting to beta emitters with maximum energies greater than 1 MeV. The only commonly used radionuclides fitting this criteria are  $^{32}\text{P}$  and  $^{86}\text{Rb}$ .

## 7.7 Removable Contamination Wipe Survey Techniques

Loose surface contamination is radioactive material in a form that is easily spread, is in a place where it shouldn't be or places we are unaware of. If a person walks through a contaminated area, some radioactive contamination will be picked up by their shoes and spread as they go about their work. Loose surface contamination can be cleaned up using conventional janitorial methods, although the rags and other cleaning materials will then have to be treated as contaminated waste. Removable contamination poses three potential problems, it might:

- ✓ be inadvertently ingested if not quickly discovered and cleaned.
- ✓ be spread beyond the laboratory and cause undue stress to families and friends of the workers involved.
- ✓ become airborne and become a potential inhalation hazard.

If loose contamination is absorbed into or worked into surfaces, it becomes more difficult to remove. Although it would now appear to be **fixed contamination**, it may once again become loose contamination due to grinding or abrasive actions (e.g., walking) or may simply leach from the surface.

Labs where radionuclides are used and/or stored must be surveyed for removable radioactive contamination by a wipe or smear survey. At a minimum, these surveys must be done monthly when a lab has had 74 kBq (200  $\mu\text{Ci}$ ) or more used within the lab (receipt, use, storage, etc.) in a month, semiannually when less than 74 kBq (200  $\mu\text{Ci}$ ) is in the lab or when radioactive materials are in storage (with approved exception), or in counting rooms only.

The wipe survey is performed by wiping areas with a small piece of filter paper or cotton swab. The Safety Department recommends that absorbent wipes be moistened to aid in surfacing contamination. It is estimated that a moist wipe may remove approximately 20 - 30% of the removable contamination compared to only 10% for a dry wipe. The survey is performed over an area of approximately 300 - 400  $\text{cm}^2$  because that is the approximate surface area that would be brushed by a person walked through the lab. Even though this area is equivalent to a square approximately 7-inches on a side, the preferred method of performing this survey is to wipe an area in an S-shaped pattern over a distance of about 12 - 14 inches (Figure 7-36). If the item to be surveyed is small and does not have 300  $\text{cm}^2$  of surface to wipe, attempt to wipe the entire surface and report the results as activity per total surface area.

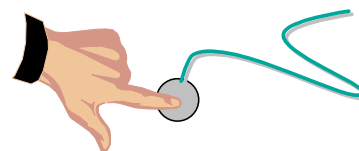


Figure 7-36. Wipe Survey

Wipe surveys are usually counted on low background, high efficiency laboratory equipment such as liquid scintillation counters, gas flow proportional counters, or auto-gamma counters, as appropriate for the radiation. LSCs are routinely used to analyze alpha, beta, and auger electron emitting radionuclides ( $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{32}\text{P}$ ,  $^{33}\text{P}$ ,  $^{35}\text{S}$ ,  $^{36}\text{Cl}$ ,

<sup>49</sup>Vr, <sup>51</sup>Cr, <sup>86</sup>Rb, <sup>125</sup>I, etc.). Proportional counters may be used to count alpha or beta emitting radionuclides (<sup>14</sup>C, <sup>32</sup>P, <sup>33</sup>P, <sup>35</sup>S, <sup>45</sup>Ca, etc.). Auto gamma counters are used to measure gamma emitting radionuclides (<sup>51</sup>Cr, <sup>57</sup>Co, <sup>125</sup>I, etc.).

**7.7.a Wipe Survey Terminology**

- Auto-Gamma Counter** A laboratory radiation detection instrument specially adapted to detect the presence of radionuclides which emit gamma or x-rays (e.g., <sup>51</sup>Cr, <sup>57</sup>Co, <sup>86</sup>Rb, <sup>125</sup>I, <sup>141</sup>Ce, etc.).
- Contamination** The presence of radioactive material where it is not supposed to be. Table 7-4 delineates the levels of radioactivity at which a work surface is considered contaminated. Some areas (desks, floors, telephones, doorknobs, etc.) should remain contamination free.
- Gas Flow Counter** A radiation detection system (also called proportional counter - see 7.3.b) designed to detect alpha and beta emitting radionuclides but can also detect (at very low efficiencies) x-rays.
- Non-Removable Contamination** Radioactive contamination present on a surface that cannot be readily removed or reduced using routine cleaning methods.
- Removable Contamination** Radioactive contamination on a surface which can be readily removed or reduced using routine cleaning methods.
- Survey** A deliberate evaluation of the presence or radiation / contamination related to the production, use, release, disposal, or presence of sources of radiation under a specific set of conditions.

**7.7.b Wipe Survey Procedures (see Laboratory 2)**

Although a meter survey is not required for laboratories using only <sup>3</sup>H or <sup>125</sup>I in kits (or other low energy emitters or very small quantities), because many labs are shared, it is prudent to use a meter in conjunction with all surveys.

The wipe survey must also be performed monthly and is usually done in conjunction with the meter survey. The meter survey (see 7.5.c) is usually done first to identify the radiation levels in the lab and point to potentially contaminated areas. After performing the meter survey, a wipe survey at the same points must be performed.

- ♦ Wear lab coat, safety glasses, and disposable gloves. Protective gloves should be worn while taking wipes.
- ♦ Identify locations where radioactive material is used/stored and the equipment used for radioactive work. A minimum of 10 wipes should be taken per lab, including at least 2 on the floor. Key these locations to the room's floor diagram with letters or numbers (Figure 7-37). Recommended areas for survey points include sinks, benches where radioisotope work was performed, near waste containers, refrigerator handles and storage locations. The idea is to survey the areas that are most likely to be contaminated.
- ♦ Moisten pieces of filter paper, cloth smears, cotton-tipped swabs or Kimwipes® or use parafilm. Key each swab to the identified locations on the floor diagram (e.g., label the vial into which they will be placed).
- ♦ Wipe an area of at least 300 cm<sup>2</sup> (48 in<sup>2</sup>, e.g., 7" x 7", 8" x 6", 16" x 3", etc.) at each

Radionuclide Facility Survey

Principle Investigator: ZERMAT MT Date: 13 Oct Xx  
 Building / Room: Bardeen 536 Surveyor: WAR

Code: B - Bath, C - Centrifuge, D - Desk, F - Freezer, H - Hood, I - Incubator, LB - Lab Bench, R - Refrigerator, RW - Rad Waste, S - Sink, SC - Storage Cabinet, ES - Equipment Storage, T - Table.

Action Levels		Wipes		β,γ		<sup>3</sup> H, <sup>14</sup> C, <sup>35</sup> S	
Meter	cpm (above background)	cpm		cpm		cpm/100 cm <sup>2</sup>	
	650			230		770	
Survey Meter Results				Wipe Test Results			
Make / Model: <u>LUDLUM 3</u>		Make: <u>PACKARD</u>		Model: <u>1900</u>			
SN: <u>133139</u>		Background Region A: <u>20</u> cpm		B: <u>17</u> cpm		C: <u>37</u> cpm	
Probe: End-window / Pancake / LEG / β,γ		Background: <u>40</u> cpm		X <input checked="" type="checkbox"/> All points are background except:			
Location	cpm	Wipe #	cpm	Wipe #	cpm	Wipe #	cpm
5	420	1	42	10	313		
8	280	2	10	11	20		
10	530	3	8	12	7		
		4	157				
		5	21				
		6	34				
		7	12				
		8	210				
		9	22				

RESURVEY 16 OCT Xx  
BACKGROUND - 35CPM  
# 10 123

Figure 7-37. Radiation Survey Form

identified location or piece of equipment. It is preferable to wipe a larger area, but use only one swab per area. Don't wipe too large an area because you may not be able to identify the contaminated point if one is found. Also, be careful not to spread contamination by wiping multiple areas with a single wipe.

- ◆ Once taken, the wipe is considered radioactive. Handle wipes to avoid cross-contaminating the other wipe samples. Do not place them in your pocket as they may contaminate your clothing.
- ◆ Place each wipe into its appropriate vial, tube, or planchet. For LSC counting, pipette about 5 - 10 ml of liquid scintillation cocktail into the vial. Place and secure caps on vials.
- ◆ Include a background sample, that is a sample vial which contains the same type of wipe material, but one which has not wiped any laboratory surfaces. Place all vials into counter trays including the background vial, and place trays in the counter.
- ◆ Set the counter windows as appropriate. We recommend that one counting region be kept *wide open*, that is to cover the entire energy range 0 - 2000 keV. In this mode, contamination spread from other labs may be detected and cleaned. It may be convenient to use the background subtract mechanism if the system has one. To insure good counting statistics, set the count time for at least 2 minutes and then count the wipes.
- ◆ Review the results for any indication of contamination. Areas with removable contamination in excess of the levels in Table 7-4 must be decontaminated and then re-wiped.
- ◆ Meter and wipe survey results must be recorded (or posted) on the survey sheet (Figure 7-37). For the monthly survey include: date of survey; room number; initials of person conducting survey; type of counter used; background counts; and any re-wipe results for decontaminated and re-surveyed areas.
- ◆ Post the most recent survey in or near the room (or post the location where survey results are kept), keep the previous surveys on file. The UW license requires that survey records, including counter results, be kept for a minimum of 3 years.

Table 7-4. Removable Contamination Action Levels

Contamination Units	Type of Radioactive Emitter		
	Alpha ( $\alpha$ )	$\beta^1$ , $\gamma$ , x	Low Risk $\beta^2$
dpm/100 cm <sup>2</sup>	66	660	2,200
Net cpm/100 cm <sup>2</sup>	23	230	770

<sup>1</sup> $\beta$  emitter values are applicable for all  $\beta$  except **Low Risk**  $\beta$

<sup>2</sup>Low Risk are  $\beta$  with  $E_{\max} < 300$  keV (e.g., <sup>3</sup>H, <sup>14</sup>C, <sup>33</sup>P, <sup>35</sup>S, <sup>45</sup>Ca)

## 7.8 Counting Statistics

Before getting into the actual subject, a quick review of statistics will help define a few terms. Suppose 10 students took a test and received the following grades (arrayed from highest to lowest): 97, 88, 88, 87, 80, 79, 78, 76, 72, and 70. The three common statistical terms used are mean, median, and mode. The **mean** is the arithmetic average of the 10 scores. If the sum of the 10 scores is 815, then the mean is 815/10 or 81.5. The **median** score is the middle most score. With these ten scores, the median score is 79.5, the average of 80 and 79 (scores 5 and 6, respectively). The range of scores is 27, the difference between the highest and lowest score. If we were to divide the range of scores into 3 groups; > 90, 80 - 89, and 70 - 79, then the frequency distribution of the scores is: > 90 -- 1; 80 - 89 -- 4; and 70 - 79 -- 5. The mode is the observed value with the largest relative frequency, 88, which occurs twice. In nuclear counting the mean is an important quantity.

Continuing on with the basics. Suppose you tossed a penny into the air. It will land with either a head or not a head (i.e., a tail). For each toss, there is a 50 - 50 chance of coming up heads. We say the probability of getting a head is 50%.

Now, suppose you tossed the coin two times. The outcome of two tosses may be: head, tail; head, head; tail, head; or tail, tail. Obviously, the chance of getting a head and a tail is better than getting either both heads or both tails. The probabilities for these three outcomes are 50%, 25% and 25%, respectively.

Suppose we tossed the coin 100 times. Although 50 heads is most likely, there is a very good chance that we may not get exactly 50 heads. The probability of flipping a certain number of heads is related to how close that number of heads is to 50. For example, you would have a better chance of getting 49 heads out of 100 tosses than only 1 head. If you repeated this 100 coin toss experiment 100 times and looked at the distribution of heads per 100 tosses, the greatest number of 100 coin tosses would have outcomes between 40 and 60 heads. The curve of this 100-toss frequency distribution would look a bit like a bell-shaped curve; the greatest number of 100 coin tosses with between 45 - 55 heads; the least number of 100 coin tosses with < 10 heads or > 90 heads.

Tossing a coin is a random event. The probability of each toss is not dependent on any other toss and the outcome will either be a head or not a head. The frequency distribution seen for such random events as coin tossing is a **binomial distribution** (i.e., only 1 of 2 outcomes possible).

Radioactive decay is also a random event. In radioactive decay, either an atom decays or it does not decay. Consequently, the frequency distribution for radioactive decay is also a binomial (bell-shaped) distribution.

When the probability of an event occurring is small and constant (e.g., disintegrating atomic nuclei), the **Poisson distribution**, a limiting case of the binomial distribution, can be used to describe the frequency of occurrence. The benefit of using the Poisson distribution is that it can be characterized by a single parameter, the mean.

Radioactive decay follows Poisson statistics. If you were to observe a sample containing a large number of radioactive atoms for a time period which is short compared to the half-life of the radioactive material, then the probability that a single atom will decay during the observation time is small, but constant, for equal time intervals. When the occurrence of an event is highly improbable such as when the half-life is long compared to the counting time and the probability of the event (i.e., radioactive decay) occurring is small compared to the number of atoms present, then radioactive decay follows Poisson statistics.

Recall that the mean is the average count. When the mean number of observed events is moderately large, the Poisson distribution can be approximated by a special normal distribution for which the standard deviation of the population is equal to the square root of the mean ( $\sigma = \sqrt{\text{mean}} = \sqrt{\bar{x}}$ ).

The standard deviation is the expected deviation from the most probable count (i.e., mean). For nuclear counting considerations, the standard deviation of the sample which is less than the entire population is approximated by the square root of the mean sample count ( $s \doteq \sqrt{\bar{x}}$ ).

The binomial and Poisson distributions pertain to discontinuous variables which take on successive whole number integral values (e.g., particle counting). For a relatively large number of events ( $\geq 30$ ), the "normal" or **gaussian distribution** provides an adequate approximation easily applied to nuclear counting statistics. The statistical theory of errors used in nuclear counting is ordinarily based on this normal distribution.

The familiar "bell-shaped" curve is a plot of the normal distribution. As in Figure 7-38, it shows the frequency of occurrence of some event,  $x$ , plotted against the numerical value measured for that event (e.g., in nuclear counting, the  $x$ -axis depicts the different counts or count rates measured while the  $y$ -axis depicts the number of times (i.e., frequency) these different counts or count rates were observed. Some of the statistical terms used are:

The **mean**,  $\bar{x}$ , is the average value of the number of counts at the center (peak) of the distribution. If two counts were obtained, 5 and 7, the mean would be 6 [i.e.,  $(5+7)/2$ ].

The **standard deviation**,  $\sigma$ , is a parameter that describes the uncertainty of a measurement. It concerns the distribution of deviations ( $\bar{x} \pm \sigma$ ) from the mean,  $\bar{x}$ . In Figure 7-38, if the total area under the curve is considered to be 1 or 100%, then the individual observations that deviate from the mean value,  $\bar{x}$ , by more than one standard deviation ( $\pm\sigma$ ) should be about 32% and 68% of the individual observations should lie within the band  $\bar{x} \pm \sigma$ . Thus, if a sample were counted many times, 68% of the observations (counts) should fall close to the mean value ( $\pm 1\sigma$ ) while 32% of the counts should be outside the one standard deviation. The standard deviation estimates the uncertainty (error) in a measurement and is not a discrepancy (false measurement). The uncertainty in counting radioactive samples comes from the statistical (i.e., random) nature of radioactive decay.

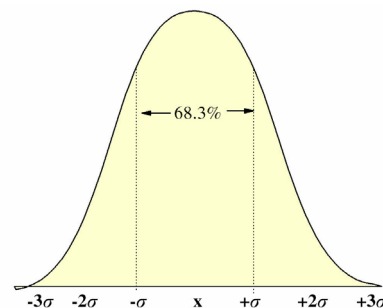


Figure 7-38. Frequency of Occurrence

Confidence Level, C.L., indicates the certainty (i.e., confidence) the experimenter has in a measurement. In a "normal" curve, 68% of the area falls within  $\pm 1\sigma$  (standard deviation) of the mean value,  $\bar{x}$ . The use of  $\pm 1\sigma$  shows a level of confidence of 68% in the results, that the chance of the observed value falling within 1 standard deviation of the mean value is 68%. Similarly, a standard deviation of  $\pm 1.64\sigma$  results in a 90% confidence level. Table 7-5 provides a listing of common confidence levels.

### 7.8.a Standard Deviation in Nuclear Counting

Before we begin, a short note about abbreviations. We use capital letters (e.g.,  $N$ ,  $\sigma$ , etc.) when discussing gross items (gross counts, population standard deviation, etc.) and lower case letters (e.g.,  $n$ ,  $s$ , etc.) when discussing rate items (e.g., net count rate, sample standard deviation, etc.). If used, a subscript further refines the definition (e.g.,

$N_b$  refers to the background gross count). In sample counting, the **gross count**,  $N_g$ , is defined to be the total number of counts obtained by counting the sample. The **gross count rate**,  $n_g$  (versus the total number of counts), is then the gross counts,  $N_g$ , divided by the counting time,  $t_g$ .

The standard deviation is related to the minimum value of the sum of the squares of the deviations from the average value such that one standard deviation expresses the range of values about the average count in which 68% of all similar counts should fall. In nuclear counting, the standard deviation of a count is approximately equal to the square root of the count. If the sample yields a large enough number of decays, most of the counts fall within one standard deviation and a single count,  $N_g$ , can be used to calculate the standard deviation.

$$\sigma = \sqrt{\bar{X}} \quad \text{and} \quad s_{N_g} = \sqrt{N_g}$$

For example, to calculate the standard deviation of a sample if the sample gross count is 40,000 counts.

$$s_{N_g} = \sqrt{40,000 \text{ counts}} = \pm 200 \text{ cts } (@ 1 \text{ std dev})$$

This means, on the average, two-thirds (i.e., 68%) of the number of counts would be within the range 39800 -- 40200 counts and one-third (i.e., 32%) would be outside this range.

Many of the counting instruments used in radiation actually report a count rate (e.g., cpm) for a sample. If  $t_g$  is the counting time, then the standard deviation for the gross ( $N_g$ ) or net ( $n_g$ ) count rate is calculated by:

$$s_{n_g} = \sqrt{\frac{N_g}{t_g} / t_g} = \sqrt{\frac{n_g}{t_g}}$$

Thus, from our example, suppose the sample had been counted for 10 minutes to give a gross count of 40,000 counts, the standard deviation of the count rate is:

$$s_{n_g} = \sqrt{\frac{40,000 \text{ counts}}{10 \text{ min}} \cdot \frac{1}{10 \text{ min}}} = \sqrt{\frac{4000 \text{ cpm}}{10 \text{ min}}} = \sqrt{400 \text{ cpm}^2} = \pm 20 \text{ cpm } (@ 1 \text{ std dev})$$

When counting a radioactive sample, there is always a background count,  $N_b$ , or background count rate,  $n_b$ . This background must be subtracted to yield the actual net sample counting rate,  $n_n$  (i.e.,  $n_n = n_g - n_b$ ). However, the addition or subtraction of counts means that there are now two sources of deviation, or error, to contend with; the deviation associated with the gross counts and the deviation associated with the background count. The standard deviation for such a calculation is:

$$\sigma_n = \sqrt{\sigma_g^2 + \sigma_b^2} = \sqrt{\left(\sqrt{\frac{n_g}{t_g}}\right)^2 + \left(\sqrt{\frac{n_b}{t_b}}\right)^2} = \sqrt{\frac{n_g}{t_g} + \frac{n_b}{t_b}}$$

and the standard deviation in net count rate (as opposed to gross count rate) is calculated by:

$$s_{n_n} = \sqrt{\frac{n_g}{t_g} + \frac{n_b}{t_b}}$$

For example, suppose that a sample is counted for 10 minutes yielding a count of 40,000 counts and that a background sample counted for 20 minutes yields a count of 3600 counts, then the net count rate,  $n_n$ , and the standard deviation of that net count rate,  $s_{n_n}$  are calculated as 3820 cpm and  $\pm 20.2$  cpm, respectively.

$$n_n = n_g - n_b = \frac{40,000 \text{ counts}}{10 \text{ min}} - \frac{3600 \text{ counts}}{20 \text{ min}} = 4000 \text{ cpm} - 180 \text{ cpm} = 3820 \text{ cpm}$$

$$s_{n_n} = \sqrt{\frac{4000 \text{ cpm}}{10 \text{ min}} + \frac{180 \text{ cpm}}{20 \text{ min}}} = \sqrt{400 \text{ cpm}^2 + 9 \text{ cpm}^2} = \sqrt{409 \text{ cpm}^2} = \pm 20.22 \text{ cpm } (@ 1 \text{ std dev})$$

### 7.8.b Relative Standard Error and Confidence Level

As can be seen in Figure 7-38, a count of a radioactive sample can return a value relatively close to the mean value. The actual difference is not as important as the relative difference. Consider a sample with a true count rate of 10,000 cpm. Not every counting will return 10,000 cpm. Many will be close. The **relative standard error**, or precision, is a measure of how close a sample count is to the expected value. It is calculated by dividing the deviation or error,  $\sigma$  (or  $2\sigma$ , etc.), by the count and multiplying by 100% to obtain the percent relative error. Thus, the relative standard errors for a count and a sample,  $R_g$  and  $R_s$ , are:

$$R_g = \frac{\sigma}{N_g} (\times 100\%) @ 1 \text{ std dev} \quad \text{and} \quad R_s = \frac{\sqrt{n_g}}{n_g} \times 100\% = \frac{100\%}{\sqrt{n_g}} = \frac{100\%}{s_{n_g}}$$

Continuing with our 40,000 cpm example, if the net count rate is 3820 cpm and the standard deviation,  $s_{n_g}$ , is 20.22 cpm, then the relative standard error is:

$$R_s = \frac{\sqrt{n_g}}{n_g} \times 100\% = \frac{100\%}{\sqrt{n_g}} = \frac{100\%}{S_{ng}} = \frac{100\%}{20.22 \text{ cpm}} = 4.9\% \approx 5\%$$

The resultant is usually written as:

$$n_n = (n_g - n_b) \pm R_s = (4000 \text{ cpm} - 180 \text{ cpm}) \pm 5\% \equiv 3280 \text{ cpm} \pm 5\% (@ 1 \text{ std dev})$$

Thus, the amount of deviation provides a measure of confidence in the results. In nuclear counting applications, the most common levels of statistical confidence are listed in Table 7-5. When we express a value plus or minus one standard deviation ( $\pm 1\sigma$ ), we are 68% confident that this value will actually be between  $-1\sigma$  and  $+1\sigma$  of the mean or "true" value. When we express a value plus or minus two standard deviations ( $\pm 2\sigma$ ), we are 95% confident that the value will be somewhere between  $-2\sigma$  and  $+2\sigma$  of the mean or "true" value. When we express a value plus or minus three standard deviations ( $\pm 3\sigma$ ), we are 99% confident that the value will fall between  $-3\sigma$  and  $+3\sigma$  of the mean or "true" value.

Table 7-5. Confidence Level

# Std. Dev.	C.L.
0.65 $\sigma$	50%
1 $\sigma$	68%
1.65 $\sigma$	90%
2 $\sigma$	95%
3 $\sigma$	99%

Suppose you have a sample which returns a value of 10,000 counts, how would you calculate the percent error at the 68%, 95%, and 99% confidence levels (C.L.)? First calculate the standard deviation and relative standard deviation of the count.

$$s_{ng} = \sqrt{10,000 \text{ cts}} = 100 \text{ cts} \quad \text{and} \quad R_s = \frac{\sqrt{N_g}}{N_g} \cdot 100\% = \frac{100\%}{100} = 1\% (@ 1 \text{ std dev})$$

At the 68% confidence interval would thus be  $10,000 \pm 100$  counts meaning we are 68% confident that the "true" mean number of counts lies within the range of 9,900 to 10,100 counts. The  $2\sigma$  or 95% confidence interval would thus be  $10,000 \pm 200$  counts meaning we are 95% confident that the "true" mean number of counts lies within the range of 9,800 to 10,200 counts. The 99% confidence interval would similarly be  $10,000 \pm 300$  counts and we are 99% confident that the "true" mean number of counts lies within the range of 9,700 to 10,300 counts.

Another important fact to remember when considering count rates is that the actual counting time is very important when calculating the relative error of a count. Table 7-6 shows the relationship between three identical count rates obtained from different counting times.

We can also use the information we have discussed to determine the minimum number of counts that are required to achieve a desired relative standard error and confidence level. Suppose you

Table 7-6. Relative Error versus Count Time

counts	time	count rate	$\sigma$	Error	Relative Error
100	5 min	20 cpm	10	2 cpm	10%
1,000	50 min	20 cpm	31.6	0.63 cpm	3.16%
10,000	500 min	20 cpm	100	0.2 cpm	1%

desire to obtain results with a relative standard error no greater than 3% (or 4%, etc.) at a confidence level of 95%, how would you find the minimum number of counts required to achieve these conditions? Table 7-5 indicates

a 95% level of confidence corresponds to approximately (plus / minus) two ( $\pm 2$ ) standard deviations from the mean. Solving for  $N_g$  in the equation yields 4,444 counts.

$$\frac{(2 \text{ std dev})(100\%)}{\sqrt{N_g}} = 3\% \text{ -----} > N_g = \left(\frac{200}{3}\right)^2 = 4,444 \text{ counts}$$

Suppose instead that you wanted to get a relative standard error that was no greater than 10% at a confidence level of 99%; how would you calculate the minimum number of counts required to achieve these levels? The 99% level of confidence corresponds to plus or minus three ( $\pm 3$ ) standard deviations from the mean. Solving for  $N_g$  in the equation yields 900 counts

$$\frac{(3 \text{ std dev})(100\%)}{\sqrt{N_g}} = 10\% \text{ -----} > N_g = \left(\frac{300}{10}\right)^2 = 900 \text{ counts}$$

When counting samples which have very low activity, very long counting times may be required to achieve an acceptable statistical accuracy. Under such circumstances, it is desirable to choose the most efficient distribution of time between the sample + background and the background counts. The highest accuracy is achieved when  $t_g/t_b = \sqrt{k}$  where  $t_g$  is the time spent counting the sample + background,  $t_b$  is the time spent counting the background, and  $k$  is the ratio of total counting rate to the background rate ( $n_g/n_b$ ).

Often you don't know the actual activity of a sample until it is counted. In instances when you have a sample of unknown activity, it may be worthwhile to perform a cursory check of the counting rates to be expected to provide you with an estimate of relative error. This entails a short, 1 or 2 minute, sample + background count followed by a background count. From this, the expected counting rates are roughly determined and the length and distribution of time for the accurate assessment of the sample are estimated.

For example, if the total count rate of a sample + background,  $n_g$ , is 360 cpm and the background count rate,  $n_b$ , is 40 cpm, how much time should you spend counting the background compared with the sample? Using our equation we see that the sample should be counted 3-times as long as the background. This means there are 4 counting time units and the background should be counted for 25% of the total time available.

$$\frac{t_g}{t_b} = \sqrt{k} = \sqrt{\frac{360 \text{ cpm}}{40 \text{ cpm}}} = 3 \quad \text{---} \rightarrow t_g = 3 t_b \quad \text{and total time} = t_g + t_b = 4 t_b$$

Notice that this implies you must normally count your sample for at least as long a time period as you count the background. Generally radiation safety wipe samples and background are counted for the same time. If desired, once a sample is identified as being different from background, the difference can be quantified.

### 7.8.c Low Level Nuclear Counting

So far we have been assuming that there were sufficient number of decays so the binomial distribution of radioactive decay can be approximated by a normal distribution. For samples which have count rates near background it may be difficult to determine if there is actually some radioactivity in the sample or if the indicated counting activity is due to statistical variation of the background. The *minimum detectable count (MDC)* is the number of counts, which for the same counting time, gives a count which is different from the background count by three times the standard deviation of the background (i.e.,  $MDC = 3 \cdot \sqrt{n_b/t_b}$ ). The MDC implies that the sample count must be greater than a  $3\sigma$  (i.e., 99%) variation of the background count rate. If that is the case, you are assured that only 1% of the time will you have a false positive (i.e., suspected contamination when only background is present). Suppose you have a sample which, when counted for 20 minutes, provides a background count rate of 30 cpm, what would be the minimum detectable counts?

$$MDC = 3 \cdot \sqrt{n_b/t_b} = 3 \cdot \sqrt{30 \text{ cpm}/20 \text{ min}} = 1.22 \text{ cpm}$$

It should be pointed out that the MDC is not a measure of activity, rather it provides a 99% confidence level that counts at the MDC or less will not represent contamination. In this example, a sample would be considered to be radioactive if a 20 minute count returned a gross count exceeding 31.22 cpm.

The *minimum sensitivity, MS*, is a more useful concept in counting because it tries to correlate all of the items peculiar to the specific sample (LSC vial, 1 liter water sample, etc.) being counted with the minimum detectable count for that sample and the isotopes of interest. The MS is defined as that activity concentration which is detectable under specific conditions such as known sample volume, background, counting time, chemical yield and efficiency of counter.

$$MS = \frac{MDC}{(2.22 \frac{\text{dpm}}{\text{pCi}}) \cdot (\text{Eff}) \cdot (\text{Yield}) \cdot (\text{Volume})}$$

Suppose a low-level beta counter is used to analyze a  $^{137}\text{Cs}$  environmental sample. The sample is evaporated and scraped into a planchet from a 1 liter sample, the background is 0.6 cpm, the counting time is 100 min, the efficiency of the system is 25%, and the chemical yield for this sample is 75% (i.e., in processing the liquid sample, only 75% of the  $^{137}\text{Cs}$  was collected). Then the MDC and MS of the  $^{137}\text{Cs}$  sample is 0.23 cpm and 0.55 pCi/l, respectively.

$$MDC = 3 \cdot \sqrt{\frac{n_b}{t_b}} = 3 \cdot \sqrt{\frac{0.6 \text{ cpm}}{100 \text{ min}}} = 0.23 \text{ cpm}$$

$$MS = \frac{MDC}{(2.22 \frac{\text{dpm}}{\text{pCi}}) \cdot (\text{Eff}) \cdot (\text{Yield}) \cdot (\text{Volume})} = \frac{0.23 \text{ cpm}}{(2.22 \frac{\text{dpm}}{\text{pCi}}) \cdot (0.25) \cdot (0.75) \cdot (1 \text{ liter})} = 0.55 \frac{\text{pCi}}{\text{liter}}$$

Consequently, 0.55 pCi/l is the minimum concentration that could be detectable

Although you may have only a single MDC, each radionuclide will have a unique MS for a given sample configuration, counter and background count. This is because the detector system efficiency is a component of the MS calculation and this factor varies from counter to counter, even when using the same type counter (e.g., LSC, GM, etc.). In general, the higher the system efficiency, the lower the MS. For example, suppose you ran a 10



minute background count on a liquid scintillation counter and get 37 cpm. If the efficiency of this LSC for  $^3\text{H}$ ,  $^{14}\text{C}$ , and  $^{32}\text{P}$  is 35%, 75%, and 98%, respectively, what would be the MDC and MS for each of the isotopes?

$$\text{MDC} = 3 \cdot \sqrt{\frac{n_b}{t_b}} = 3 \cdot \sqrt{\frac{37 \text{ cpm}}{10 \text{ min}}} = 5.77 \text{ cpm}$$

Using the general equation for MS, you calculate a minimum sensitivity of 16.49 dpm for  $^3\text{H}$ , 7.69 dpm for  $^{14}\text{C}$ , and 5.89 dpm for  $^{32}\text{P}$ .

$$\text{MS} = \frac{\text{MDC}}{(2.22 \frac{\text{dpm}}{\text{pCi}}) \cdot (\text{Eff})} = \frac{5.77 \text{ cpm}}{(2.22 \frac{\text{dpm}}{\text{pCi}}) \cdot \text{eff}}$$

Notice that for many types of counting there are only two ways to change the MDC (and consequently the MS), either change the counting time or the background count rate. Increasing the counting time will decrease the MDC. Suppose in our  $^{137}\text{Cs}$  example above, instead of counting for 20 minutes you counted the background for 30 minutes. The MDC would then be:

$$\text{MDC} = 3 \cdot \sqrt{\frac{n_b}{t_b}} = 3 \cdot \sqrt{\frac{30 \text{ cpm}}{30 \text{ min}}} = 1.00 \text{ cpm}$$

Similarly, you might be able to reduce the background count rate by using shielding. Suppose in the same example we were able to reduce the background count rate to 25 cpm, then the resulting MDC would be:

$$\text{MDC} = 3 \cdot \sqrt{\frac{n_b}{t_b}} = 3 \cdot \sqrt{\frac{25 \text{ cpm}}{20 \text{ min}}} = 1.12 \text{ cpm}$$

The Safety Department actually reduced the MDC for the system we use to count thyroids (see **Chapters 3 and 5**). We had been counting thyroids for 200 seconds, getting a background count of approximately 150 counts. The problem with this MDC value (11.0 cpm) was that the minimum sensitivity was too close to the investigational level and any count statistically different than background resulted in an investigation. By increasing the counting time to 300 seconds, the 230 count background reduced the MDC to 9.1 cpm and were able to provide a region in which a worker may have a small thyroid burden but not above our investigational limit.

One additional method of reducing the MS is to change the volume size of the sample. A 2-liter sample will have a lower per liter MS than a 1-liter sample, if all other parameters are constant. There are certain methods of concentrating large samples into small volumes. These include evaporating a liquid sample down to its solid contents and counting the solid or passing a liquid through anion / cation resins to concentrate an ionic radionuclide and then counting the resins. Additional methods are to increase the chemical yield of a process or count a sample on a system with a higher efficiency.

Suppose you have to determine the  $^3\text{H}$  activity (pCi/l) of a worker's urine sample. You are using an LSC which has a background count-rate of 33 cpm when counted for 100 minutes. The system's efficiency for  $^3\text{H}_2\text{O}$  is 35%. Because of volume constraints with the LSC vial and the necessity to avoid phase separation between the cocktail and the solute (i.e., if you place too much urine with the LSC cocktail, it will not mix and will separate into 2 phases), you can only use 2 ml of sample in each LSC vial. Furthermore, your system must be capable of detecting 1000 pCi/l as its MS. How long must you count each sample to ensure that you obtain this MS? Solving the MS equation for MDC and putting our values into this equation gives an MDC of 1.554 cpm.

$$\text{MS} = \frac{\text{MDC}}{(2.22 \frac{\text{dpm}}{\text{pCi}}) \cdot (\text{Eff}) \cdot (\text{Yield}) \cdot (\text{Volume})} \quad \text{----} \rightarrow \quad \text{MDC} = \text{MS} \cdot (2.22 \frac{\text{dpm}}{\text{pCi}}) \cdot (\text{Eff}) \cdot (\text{Yield}) \cdot (\text{Volume})$$

$$\text{MDC} = 1000 \frac{\text{pCi}}{\text{l}} \cdot (2.22 \frac{\text{dpm}}{\text{pCi}}) \cdot (0.35 \frac{\text{dpm}}{\text{cpm}}) \cdot (2 \text{ ml}) \cdot (\frac{1 \text{ liter}}{1000 \text{ ml}}) = 1.554 \text{ cpm}$$

Then going back to the original MDC equation and calculating for counting time yields 122.98 minutes.

$$\text{MDC} = 3 \cdot \sqrt{\frac{n_b}{t_b}} \quad \text{----} \rightarrow \quad t = 9 \cdot \left( \frac{9 \cdot (33 \text{ cpm})}{(1.554 \text{ cpm})^2} \right) = 122.98 \text{ minutes}$$

Perhaps a more practical way to determining the MS is to state it in relation to the desired precision. This may be stated as the MS is "that activity where the percent counting error does not exceed x% (e.g., 25%, 33%, etc.) under the specific conditions of sample analysis." When using this method, the normally accepted error used in this calculation is the  $2\sigma$  error. Thus, if you needed to find the MS from the  $^{137}\text{Cs}$  environmental sample we used above, if the precision is 25% at the 95% (i.e.  $2\sigma$ ) confidence level. Using this precision and our background numbers, we calculate N

$$0.25 = \frac{2 \sqrt{\frac{N}{t_N^2} + \frac{B}{t_B^2}}}{\frac{N}{t_N} - \frac{B}{t_B}} = \frac{2 \sqrt{\frac{N}{100 \text{ min}^2} + \frac{0.6 \text{ cpm}}{100 \text{ min}^2}}}{\frac{N}{10 \text{ min}} - \frac{0.6 \text{ cpm}}{10 \text{ min}}} \text{ --- } \rightarrow N = 1.25 \text{ cpm}$$

From the Minimum Sensitivity equation we then calculate 3 pCi/l.

$$MS = \frac{1.25 \text{ cpm}}{(2.22 \frac{\text{dpm}}{\text{pCi}}) \cdot (0.25 \frac{\text{cpm}}{\text{dpm}}) \cdot (0.75) \cdot (1 \text{ liter})} = 3 \frac{\text{pCi}}{\text{l}}$$

The 95% (2σ) error associated with a 3 pCi/l minimum sensitivity is 0.75 pCi/l (i.e. (0.25)x(3 pCi/l). Although 3 pCi/l is a larger value than the 0.55 pCi/l obtained above, it is more precise (i.e. at this value you are more able to replicate the results).

**7.8.d Lower Limit of Detection (LLD)**

The Nuclear Regulatory Commission has provided guidance for analyzing low count rate (e.g., environmental and bioassay) samples. The need for this guidance arose because some facilities performing environmental monitoring were counting the samples under conditions in which a significant level of radioactivity would have to be present before the results showed other than "background". In other words, the procedures were not sensitive enough to detect activity at the desired levels. The NRC thus requires the demonstration of a counter's LLD.

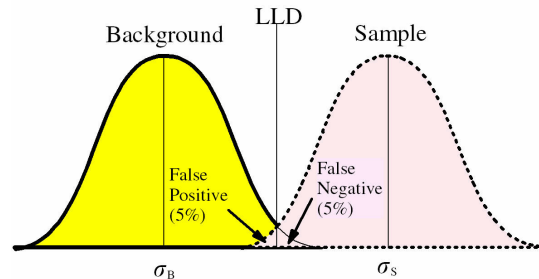


Figure 7-39. LLD

In concept, the LLD is intended to be used as a "figure of merit" or "seal of approval" to demonstrate that a counting system and analysis procedures are sufficiently sensitive to perform in the desired manner. Many individuals mistakenly treat the LLD as another parameter to be calculated for each sample along with the standard deviation. This misuse has resulted in the Nuclear Regulatory Commission stating, "It should be recognized that the LLD is defined as an *a priori* (before the fact) limit representing the capability of a measurement system and not as an *a posteriori* (after the fact) limit for a particular measurement."

The technical definition of the LLD (Figure 7-39) is "the smallest concentration of radioactive material in a sample that will yield a net count (above system background) that will be detected with 95% probability with only 5% probability of falsely concluding that a blank observation represents a real signal." In other words, the LLD amount of activity will yield a net count rate in a system that just barely exceeds two standard deviation (i.e., 2σ or 95% confidence level) for the net count rate. Thus, that sample will be reported as containing radioactivity.

The LLD strongly depends on the standard deviation of the background count rate (s<sub>nb</sub>) of the counter. In theory, even if the sample + background is counted for an infinite time, the net rate will still have an uncertainty which is the square root of the background rate divided by the counting time for the background. The equation recommended by the NRC for calculating the LLD of a system is:

$$LLD \left( \frac{\text{pCi}}{\text{l}} \right) = \frac{4.66 \cdot s_{nb}}{(2.22 \frac{\text{pCi}}{\text{dpm}}) \cdot (\text{Eff}) \cdot (\text{Vol}) \cdot (\text{Yield}) \cdot (\text{Decay Factor})}$$

For Example, the UW conducts urine bioassays to check for potential <sup>3</sup>H ingestion. Urine samples for this relatively long-lived isotope (i.e., decay factor = 1) will be 2 ml aliquots and the fractional yield is 1. The system efficiency is 0.33 cpm/dpm for <sup>3</sup>H. If a 10 minute background count results in a count rate (n<sub>b</sub>) of 30 cpm, what will be the system's lower level of detection?

$$LLD \left( \frac{\text{pCi}}{\text{l}} \right) = \frac{4.66 \cdot \sqrt{\frac{30 \text{ cpm}}{10 \text{ min}}}}{(2.22 \frac{\text{pCi}}{\text{dpm}}) \cdot (0.33 \frac{\text{cpm}}{\text{dpm}}) \cdot (0.0021) \cdot (1) \cdot (1)} = 5509 \frac{\text{pCi}}{\text{l}}$$

When the LLD is determined for a wipe sample or for samples which have the same volume, if the isotopes have a relatively long half life compared to the counting time (and consequently will not appreciably decay during the counting time), and you are dealing with the count rate instead of activity then the LLD equation is

LLD = 4.66 · √n<sub>b</sub>/t<sub>b</sub>. The 4.66 in LLD is derived by the equation:

$$LLD = 2k \sqrt{\frac{2 n_b}{t_b}} = 2 \sqrt{2} k \sqrt{\frac{n_b}{t_b}} = 2.83k \sqrt{\frac{n_b}{t_b}}$$

In the LLD, we are concerned with a 90% confidence level, so  $k = 1.65$ . However, from Figure 7-39, to the left of the mean of the background count there is 50% confidence level and to the right there is only 45% confidence. Thus a total of 95% confidence level is actually achieved.

$$LLD = 2.83 \cdot (1.65) \sqrt{\frac{n_b}{t_b}} = 4.66 \cdot \sqrt{\frac{n_b}{t_b}}$$

**7.8.e Chi-square ( $X^2$ ) Test**

One of the most important applications of statistics to measurements is the investigation of whether or not a particular set of measurements fit an assumed statistical distribution. The test most often used for this purpose on nuclear counting is Pearson's chi-square test. By definition, the chi-square test is a measure of the discrepancy that may exist between the observed frequency and the expected frequency. In other words, the chi-square is an assessment of the "goodness of fit" of the observed data to the assumed expected statistical distribution. The chi-square is calculated by:

$$X^2 = \frac{1}{\bar{x}} \sum_{i=1}^n (x_i - \bar{x})^2$$

where  $x_i$  are individual counting events and  $\bar{x}$  is the arithmetic mean of the "i" counting events. To determine the chi-square:

- ◆ Compute the arithmetic average of the data.
- ◆ Compute chi-square ( $X^2$ ) from the above formula.
- ◆ Determine the number of "degrees of freedom" (F). F is the number of ways the observed distribution may differ from the assumed distribution. For our applications,  $F = n - 1$ .
- ◆ From a chi-square table (Table 7-8), find P using your computed values of chi-square and F.

The probability, P, that larger deviations than those observed would be expected due solely to chance if the observed distribution is actually identical to the assumed distribution.

From this definition, it is obvious that too little deviation is possible as well as too much. The closer P is to 0.5, the better the observed distribution fits the assumed distribution, for larger deviations than those observed are just as likely as not. The interpretation of P is for  $0.1 \leq P \leq 0.9$ , the observed and assumed distributions are very likely the same. If  $P < 0.02$  or if  $P > 0.98$ , the equality of the distributions is very unlikely. Any other value of P would call for additional data to better define the observed distribution.

As an example of calculating chi-square, consider the data in Table 7-7 which are from a series of ten, two-minute counts of an LSC background standard source made with a liquid scintillation counter. We wish to determine whether these data reflect proper instrument operation.

After calculating  $X^2$ , go the chi-square table. For 9 (i.e.,  $n - 1$ ) degrees of freedom, determine if the chi-square value is within two standard deviations (95%) confidence limits. From Table 7-8, chi-square values, for 9 degrees of freedom, we see:

$$3.325 \leq X^2 \leq 16.919 \text{ @ } 95\% \text{ C.L.}$$

Since our calculated value of chi-square, 14.5, lies between these lower and upper limits, we can conclude that our data belongs to the same normal distribution and that our instrument is operating reliably.

Table 7-7. Chi-Square Example

$x_i$	$(x_i - \bar{x})$	$(x_i - \bar{x})^2$
29	3.8	14.44
36	10.8	116.64
19	-6.2	38.44
26	0.8	0.64
24	-1.2	1.44
14	-11.2	125.44
21	-4.2	17.64
32	6.8	46.24
24	-1.2	1.44
27	1.8	3.24
$\Sigma x_i = 252$		$\Sigma = 365.60$
$\bar{x} = (1/n) * \Sigma x_i = 252 / 10 = 25.2$		
$X^2 = 365.6 / 25.2 = 14.51$		

**7.9 Review Questions** - Fill-in or select the correct response

1. Radiation is detected by measuring the amount of \_\_\_\_\_ in the device.
2. GM meters can be used to \_\_\_\_\_ radiation or \_\_\_\_\_ contamination.
3. LEG meters are used to monitor low-energy \_\_\_\_\_ emitting radionuclides.
4. Liquid scintillation counters are ideal for counting \_\_\_\_\_ emitting radionuclides and can also measure most low-energy gamma emitters.
5. Wear the whole body dosimeter between your \_\_\_\_\_ and your \_\_\_\_\_.

6. A portable survey meter's dial often has scales with units of \_\_\_\_\_ and \_\_\_\_\_, however, at the UW the \_\_\_\_\_ scale is the one routinely used.
7. The user can check the \_\_\_\_\_ of the portable survey meter's detector by placing the detector window over the meter's operational check source.
8. Beta particles absorbed by a LSC cocktail produce \_\_\_\_\_ flashes.
9. To calculate dpm, the \_\_\_\_\_ of the LSC must first be determined for the type (i.e., radiation and energy) of sample which it is expected to analyze.
10. A wipe test is a survey for \_\_\_\_\_ radioactive contamination.
11. When performing a wipe test, you should normally wipe an area of approximately \_\_\_\_\_ sq. cm ( $\text{cm}^2$ ) at each identified location.
12. Areas with removable  $^{32}\text{P}$  activity in excess of \_\_\_\_\_ cpm/100  $\text{cm}^2$  above background (i.e., net cpm) or \_\_\_\_\_ dpm/100  $\text{cm}^2$  must be cleaned and re-wiped.
13. Survey records must be kept for a minimum of \_\_\_\_\_ years
14. Dosimeters are routinely issued to individuals who may handle stock vials with more than \_\_\_\_\_ MBq or (\_\_\_\_\_ mCi) quantities of high-energy beta or gamma ray emitting radioactive material.
15. Radiation dosimeters are not issued to persons who only work with  $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{35}\text{S}$  or to individuals who only work with RIA kits. **true / false**
16. Ion chamber survey meters normally express exposure in units of \_\_\_\_\_.
17. Gas amplification / Townsend avalanche is feature of proportional counters and GM counters which make them so sensitive to detecting  $\alpha$  and  $\beta$  particle radiation. **true / false**
18. The alpha multiplication factor ( $\alpha\text{MF}$ ) is always (**greater than**) (**less than**) one.
19. The resolving time for a GM tube is generally about \_\_\_\_\_  $\mu\text{sec}$ .
20. For detecting low-energy beta particles, a pancake type GM detector is normally (**more**) (**less**) sensitive than an end-window type GM detector.
21. Compensated GM detectors are usually used to measure x-/ $\gamma$ -ray exposure. **true / false**
22. A Long Counter is used to monitor \_\_\_\_\_.
23. Your survey meter indicates a reading of 250 cpm. You initially measured the background count rate as 30 cpm. If the selector switch is on the x 10 range, the net count rate is \_\_\_\_\_ cpm.
24. The counting efficiency of an LSC for  $^{35}\text{S}$  is (**greater than**) (**less than**) the counting efficiency for  $^{32}\text{P}$ .
25. If the counting efficiency for your counter is 75% and the printout indicates a net count (net = gross - background) rate of 450 cpm, the activity of your sample is \_\_\_\_\_ dpm.
26. Proton recoil is a method to monitor neutron fields. **true / false**
27. Low risk beta particles have maximum energies less than 300 keV and include \_\_\_\_\_, \_\_\_\_\_, and \_\_\_\_\_.
28. If the counting time for a sample is shortened, the MDC would (**increase**) (**decrease**).
29. The mean and median values are always the same. **true / false**
30. The \_\_\_\_\_ is the arithmetic average of a set of measured values while the \_\_\_\_\_ is the middle most score.
31. A 90% confidence level (CL) expresses the probability that \_\_\_\_\_ out of \_\_\_\_\_ counts fall within the range.
32. If an sample returns a count rate of 100 cpm, then the standard deviation of the count rate is \_\_\_\_\_.
33. The \_\_\_\_\_ or \_\_\_\_\_ expresses the range of values about true count in which  $\frac{2}{3}$  (i.e., 68.3%) of all similar count should fall.
34. The LLD is (**a priori**) (**a posteriori**) limit representing the capability of a measuring system.
35. The \_\_\_\_\_ is the same as precision.
36. Low-energy gamma (LEG) and liquid scintillation (LSC) are types of \_\_\_\_\_ detectors.
37. Cerenkov counting can be used to count  $^{32}\text{P}$  samples in a LSC without using cocktail. **true / false**

### 7.10 References

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Table 7-8. Chi-Square Values

Degrees of Freedom	Probability						
	0.99	0.95	0.9	0.5	0.1	0.05	0.01
2	0.02	0.1	0.21	1.39	4.61	5.99	9.21
3	0.12	0.35	0.58	2.37	6.25	7.82	11.35
4	0.3	0.71	1.06	3.36	7.78	9.49	13.28
5	0.55	1.15	1.61	4.35	9.24	11.07	15.09
6	0.87	1.64	2.2	5.35	10.65	12.59	16.81
7	1.24	2.17	2.83	6.35	12.02	14.07	18.48
8	1.65	2.73	3.49	7.34	13.36	15.51	20.09
9	2.09	3.33	4.17	8.34	14.68	16.92	21.67
10	2.56	3.94	4.87	9.34	15.99	18.31	23.21
11	3.05	4.58	5.58	10.34	17.27	19.68	24.73
12	3.57	5.23	6.3	11.34	18.55	21.03	26.22
13	4.11	5.89	7.04	12.34	19.81	22.36	27.68
14	4.66	6.57	7.79	13.34	21.06	23.68	29.14
15	5.23	7.26	8.55	14.34	22.31	25	30.58
16	5.81	7.96	9.31	15.34	23.54	26.3	32
17	6.41	8.67	10.09	16.34	24.77	27.59	33.41
18	7.01	9.39	10.86	17.34	25.99	28.87	34.81
19	7.63	10.12	11.65	18.34	27.2	30.14	36.19
20	8.26	10.85	12.44	19.34	28.41	31.41	37.57
21	8.9	11.59	13.24	20.34	29.61	32.67	38.93
22	9.54	12.34	14.04	21.34	30.81	33.92	40.29
23	10.2	13.09	14.85	22.34	32.01	35.17	41.64
24	10.86	13.85	15.66	23.34	33.2	36.41	42.98
25	11.52	14.61	16.47	24.34	34.38	37.38	44.31
26	12.2	15.38	17.29	25.34	35.56	38.88	45.64
27	12.88	16.15	18.11	26.34	36.74	40.11	46.96
28	13.57	16.93	18.94	27.34	37.92	41.34	48.28
29	14.26	17.71	19.77	28.34	39.09	42.56	49.59

Table 7-9. Detector Efficiencies for Common Radioisotopes

Isotope	Symbol	Radiation <sup>1</sup>	Energy (MeV)	Counting Method <sup>2</sup>	Beckman Channel <sup>3</sup>	Typical Efficiency <sup>4</sup>
Tritium	<sup>3</sup> H	β <sup>-</sup>	0.0186	LSC	427	40%
Carbon-14	<sup>14</sup> C	β <sup>-</sup>	0.157	LSC GM	686	85% 2 - 5%
Sodium-22	<sup>22</sup> Na	β <sup>+</sup>	0.546	LSC GM	838	95% 20%
		γ	1.274	LEG		5%
Phosphorus-32	<sup>32</sup> P	β <sup>-</sup>	1.709	LSC GM	977	95% 45%
Phosphorus-33	<sup>33</sup> P	β <sup>-</sup>	0.249	LSC GM	742	85% 10%
Sulfur-35	<sup>35</sup> S	β <sup>-</sup>	0.167	LSC GM	691	85% 2 - 5%
Calcium-45	<sup>45</sup> Ca	β <sup>-</sup>	0.258	LSC GM	747	90% 10%
Chromium-51	<sup>51</sup> Cr	γ	0.320 (10%)	LEG	252	10%
		e <sup>-</sup>	0.0043	LSC		20%
Cobalt-57	<sup>57</sup> Co	γ	0.122	LEG	282	40%
		e <sup>-</sup>	0.0056	LSC		30%
Nickel-63	<sup>63</sup> Ni	β <sup>-</sup>	0.067	LSC	583	60%
Zinc-65	<sup>65</sup> Zn	γ	1.115	LEG	309	5%
		e <sup>-</sup>	0.007	LSC		15%
Rubidium-86	<sup>86</sup> Rb	β <sup>-</sup>	1.774	LSC GM	982	95% 45%
		γ	1.076 (9%)	LEG		
Technetium-99m	<sup>99m</sup> Tc	γ	0.140	LEG		35%
Iodine-125	<sup>125</sup> I	γ	0.035	LEG	213	90%
		e <sup>-</sup>	0.032	LSC		20%
Iodine-131	<sup>131</sup> I	β <sup>-</sup>	0.606	LSC GM	851	95% 25%
		γ	0.364	LEG		10%
Cesium-137	<sup>137</sup> Cs	β <sup>-</sup>	0.514	LSC GM	832	95% 20%
		γ	0.662 (85%)	LEG		7%

<sup>1</sup>Electrons are either Auger or conversion electrons, the efficiency given accounts for abundance.

<sup>2</sup>GM - GM thin end-window (e.g., HP-190) probe, pancake has slightly higher (1.5 - 2 x) efficiency.

LEG - Low Energy Gamma Probe

LSC - Liquid Scintillation Counter

<sup>3</sup>Equation for Beckman's channel is: **Channel # = 72 + 280 Log<sub>10</sub>(E<sub>max</sub>)**

<sup>4</sup>LSC efficiency will depend on the amount of quenching present in the sample. Values listed are based on 50% quench. GM efficiency is based on probe's end-cap being "off," efficiency with the cap "on" is ½ these values. Also, the GM efficiency is percent of 2π emission rate.