

Lab #1 Introduction to Gamma Detection & Pulse Height Analysis

Objective

To study the operation of gamma-ray detectors and techniques of data analysis using energy dispersive spectrometers. This will include attempting to identify an unknown radioactive source.

Theory

There are three principal ways in which gamma ray and X-ray photons interact with matter: (1) Photoelectric Effect, (2) Compton Scattering, and (3) Pair Production. The likelihood of each of these processes occurring is related to the energy of the photon.

The Photoelectric Effect is a process by which a photon is completely absorbed by an atom and subsequently emits a photoelectron from a bound shell. The electron energy is equal to the energy of the photon minus the binding energy. The probability of the photoelectric effect increases strongly with the Z (atomic number) of the material, depending on Z^4 to Z^5 . The effect is much less likely to occur as the energy of the photon increases.¹

Compton scattering involves a collision between a photon and an electron. The photon loses some of its energy to the electron and scatters off in a different direction as a lower energy photon. The amount of energy lost depends on the angle of the collision. The energy of the scattered photon and the photoelectron are given by:

$$E_g = E_o [1 + (E_o / mc^2)(1 - \cos q)]^{-1}$$
$$E_e = E_o - E_g = E_o \left[\frac{(E_o / mc^2)(1 - \cos q)}{1 + (E_o / mc^2)(1 - \cos q)} \right]$$

where E_o is the incident photon energy, E_g is the scattered photon energy, E_e is the electron energy, m is the electron mass, c is the speed of light, and q is the angle between the incident and scattered gamma ray directions. The maximum energy loss by a photon is for a head-on collision ($q = 180^\circ$) and is equal to:

$$E_o - E_g = \frac{E_o}{1 + mc^2 / 2E_o}$$

This corresponds to what is called the *Compton Edge*. If the unabsorbed portion of the original photon escapes from the detector, then all we detect is the Compton electron. This tells us little about the original photon energy, since Compton scattering occurs across a broad range of energies. If, however, a detector is fairly large, the probability rises that the balance of the photon will be absorbed within the detector (by Compton or photoelectric effect), thereby capturing all the original photon energy and contributing to the "full energy peak". Compton is also dependent on Z but is less dependent on photon energy than the photoelectric effect.

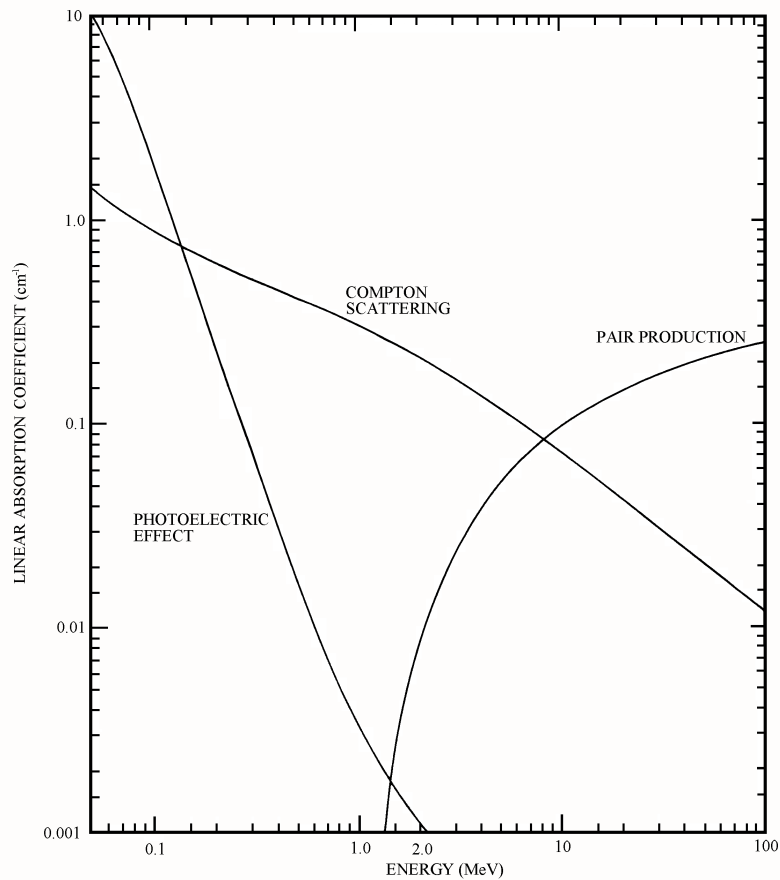


Figure 1: The linear absorption coefficients for photoelectric effect, Compton scattering, and pair production in germanium. To obtain the absorption cross sections in barns/atom, divide by 4.42×10^{-2} ; to obtain the mass absorption coefficients in cm^2/gm multiply by 120.

Pair Production is the spontaneous creation of matter from energy. In close proximity to a nucleus an energetic gamma ray spawns a positron-electron pair. Each particle requires 511 keV for formation, putting a lower limit requirement of 1.022 MeV on the incident photon. Any photon energy over 1.022 MeV goes into the kinetic energy of the pair. The probability of this effect occurring increases rapidly with higher photon energies. As both the positron and electrons lose their energy to the detector, this portion of the original photon is captured. Once the positron reaches a very low speed, it will annihilate with an electron, producing two 511 keV photons which fly apart in opposite directions. If both the 511 keV photons is captured in the detector, their energies will tally into the full energy peak. If, on the other hand, either or both of these 511 keV photons escapes from the detector, the result will tally into either a “single escape peak” or a “double escape peak”.

The probability of interacting with matter in one of these three processes can be expressed as an absorption coefficient. For all three processes, the total attenuation coefficient μ is the sum of the three partial attenuation coefficients:

$$\mu_{total} = \mu_{photoelectric} + \mu_{Compton} + \mu_{pair\ production}$$

The linear attenuation coefficients for each process are shown in Figure 1 for the material germanium and in Figure 2 for the material sodium iodide.

What is called “ionizing” radiation is normally detected by means of the ionization caused by a charged particle or photon interacting by one of the three processes above. If the detecting material is a gas, the ionization potential is in the range of 10 to 50 electron volts. For example, a charged particle moving through air loses 30 to 35 eV for each electron-ion pair formed.

By collecting the free charges created in a gas, we can obtain an electrical pulse signalling the passage of the charged particle or photon. The Geiger-Mueller tube is an example of a gas-filled detector. The G-M tube contains a gas and has a positively-charged wire running down its centre. A high voltage on the wire causes the charged particles to crash into atoms of the gas at high enough speeds to produce multiple ionizations from a single photon or charged particle. The wire attracts all the resultant electrons and the tube wall attracts all the ions. An electrical pulse results which can be processed to deflect the meter’s needle and to produce an audible “click”.

Scintillation detectors

While gas-filled detectors, like the G-M tube, are excellent as a small, light-weight survey meter, they are poor for any application requiring accurate numbers of high energy photons. This is because of the low atomic number (Z) of the gases used and the low density of gases. A G-M tube also has a lot of “dead time” after a detection, during which it cannot detect subsequent radiation.

The most efficient method of gamma detection is the scintillator, of which Sodium Iodide (doped with Thallium) is a common example. The passage of a charged particle or a gamma ray produces a series of ionizations. This is followed by the emission of a large number of weak scintillations as excited molecules of NaI return to the ground state. The NaI crystal is well suited to X-ray and gamma ray detection due to the high Z of iodine and the consequent large number of electrons to interact with.

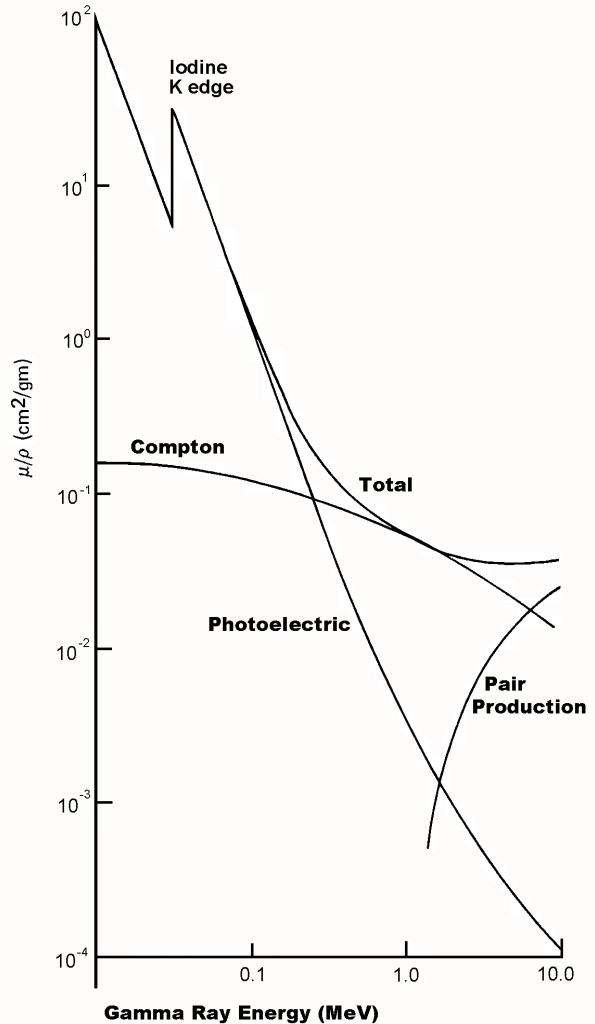
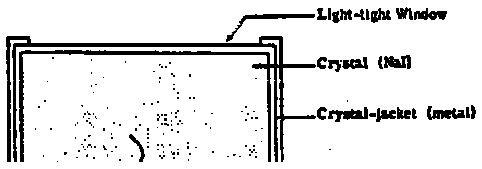


Figure 2: Absorption Coefficients for NaI



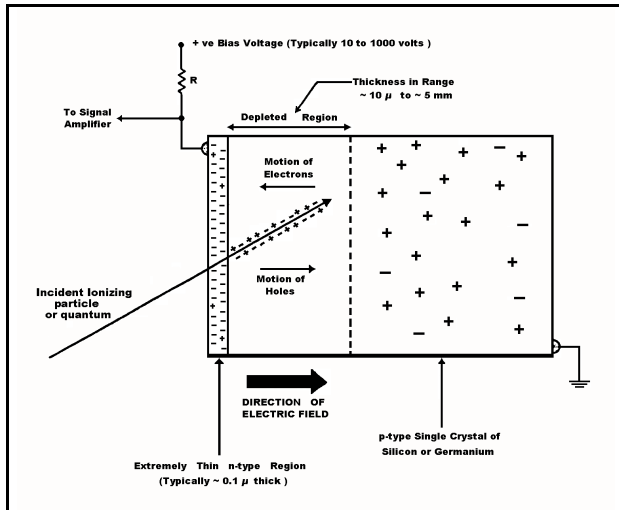


Figure 5: Crystal ionization by passage of charged particles (or by passage of gammas creating charged particles).

hole pairs. This is somewhat analogous to the production of electron-ion pairs in a gas-filled detector. Cooling is necessary to reduce the thermal charge carrier generation (noise) to an acceptable level.

Collection of the current of these electron-hole pairs produces electrical pulses which are of lower initial current than those from the scintillator photo multiplier tube and so require somewhat more sophisticated electronic pulse processing systems.

The most important advantage of a semiconductor-based detector over scintillators and gaseous-based detectors is a large improvement in resolution. Resolution depends on a succession of factors. Both scintillator and semiconductor are limited by noise generation in the crystal, pre-amplifier noise and the statistical limit created by the numerical uncertainty involved in gathering all the signal. While the current from a scintillator PMT is more intense, only a percentage of the initial scintillations can be captured by the photocell. There are more steps involved in the gathering of a scintillator signal. Every step is a source of error and the accumulation of these errors causes poorer scintillator resolution. Each source of error is a random effect, so, the statistical broadening of an energy peak can be approximated by Poisson or Gaussian statistics, where the full width at half maximum (FWHM) of the peak is $2.354 S$. “ S ” is the Standard Deviation and S^2 is the Variance of the distribution.

energy resolution. On the other hand, compared to NaI, semiconductors possess much less efficiency for detection of gamma rays due to the lower Z of Germanium and Silicon. Germanium detectors also require liquid nitrogen cooling, representing a large extra operating expense plus the weight and size burden of the liquid nitrogen Dewar. Germanium detectors also require a bias supply voltage of about 1000 volts.

Semiconductor detectors have a P-I-N diode structure in which the intrinsic (I) region is formed by depletion of charge carriers with application of reverse bias across the diode. When photons interact within the depletion region, charge carriers (holes and electrons) are freed and are swept to their respective collecting electrode by the electric field. Figures 5 and 6 show the production in a semiconductor of electron-

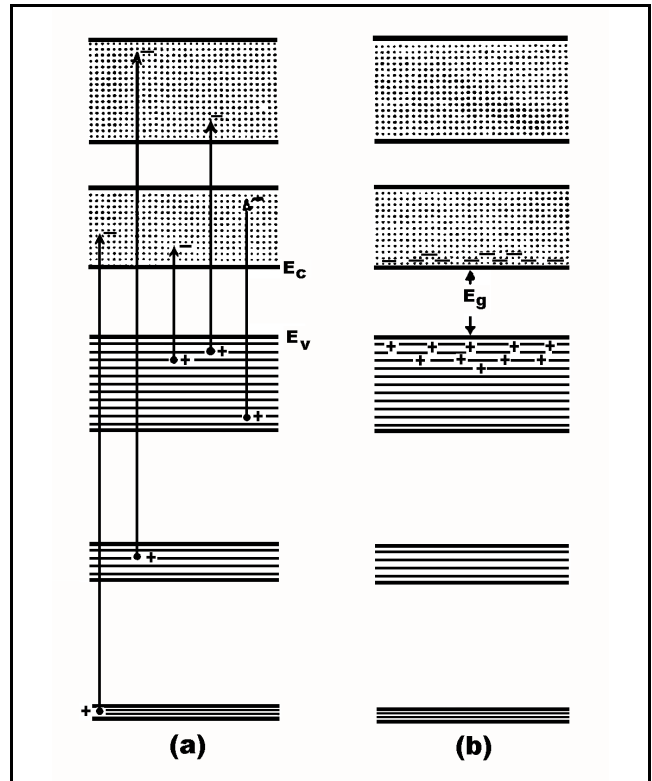
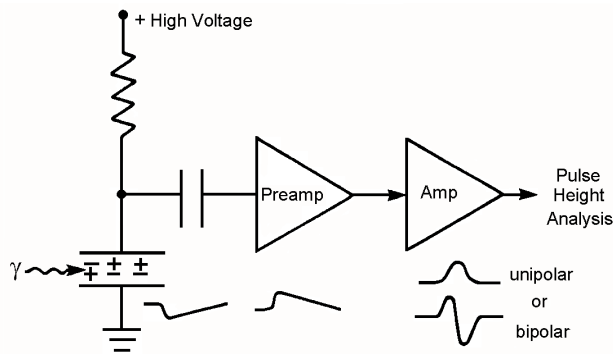


Figure 6:
 (a) Excitation of electrons in a semiconductor due to an energetic charged particle or photon.
 (b) Residual hole-electron excitation after a time $\sim 10^{-12}$ sec.

Nuclear Electronics (Nucleonics):

Most detectors can be represented as a capacitor into which a charge is deposited, as shown in Figure 7. The detector bias provides an electric field to collect the charge. During charge collection a small current flows, producing a voltage pulse across the bias resistor.

The preamplifier is isolated from the high voltage by another capacitor. The rise time of the pulse is related to the collection time of the charge, while the decay time of the pulse is the RC time constant characteristic of the preamplifier itself. Preamplifiers serve to provide a match between the high impedance of the detector and the low impedance of coaxial cables to the amplifier, which may be located at great distances from the preamplifier.



The amplifier serves to shape the pulse as well as further amplify it. The long decay time of the preamplifier pulse may not return to zero voltage before another pulse occurs, so it is important to shorten it and only preserve the detector information in the pulse rise time. The RC clipping technique can be used, in which the pulse is differentiated to remove the slowly varying decay time, and then integrated somewhat to reduce noise. The unipolar pulse which results is much shorter. An active filter can also be used for selected frequencies, producing a near-Gaussian pulse shape.

Figure 7: Basic Detector and Amplification Electronics

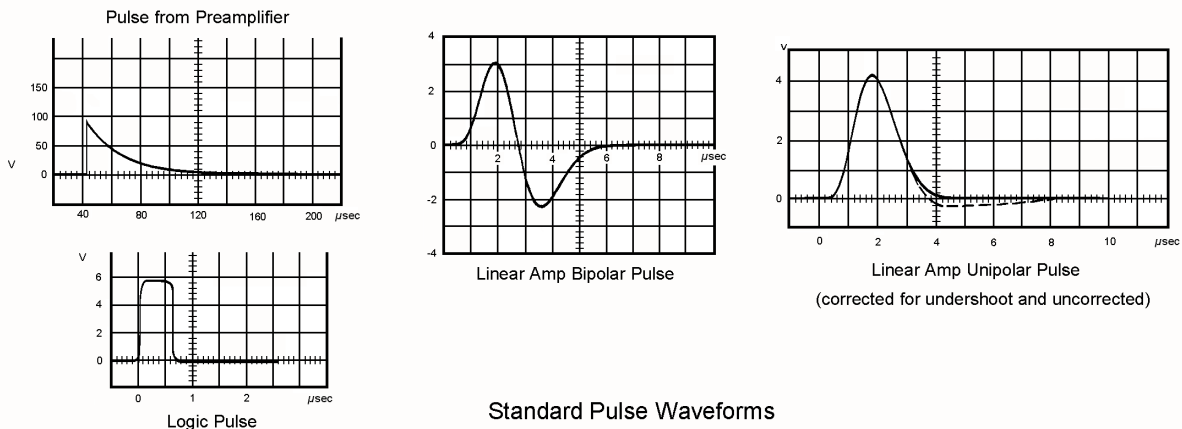


Figure 8: Standard Pulse Waveforms

A second differentiator produces a bipolar pulse option. The bipolar pulse has the advantage of nearly equal amounts of positive and negative area so that the net voltage is zero. When a bipolar pulse passes from one stage of a circuit to another through a capacitor, no charge is left on the capacitor between pulses, allowing the baseline to remain steady. A unipolar pulse leaves a charge which must leak off through associated

resistances or be reset to zero with a baseline restorer. Failure to deal with undershoot from a unipolar pulse can degrade the accuracy and resolution of pulse height information. On the other hand, the unipolar pulse has lower noise and is preferred for some applications.

Pulse Height Analysis:

At one time a Single Channel Analyzer was used for pulse height analysis. The SCA has a lower and an upper level discriminator, and produces an output logic pulse when an input pulse lies between the discriminator levels. All pulses in a specific range can be routed to a scalar (counter). The SCA can be set to a narrow ΔV range and then the lower level discriminator can be swept through a series of voltages using an SCA Sweep device. All pulses outside the SCA window are lost, so that the smaller the window for better resolution, the longer the time required to get adequate counts.

A multichannel analyzer (MCA) is an electronic instrument which can collect the entire spectrum at once. The MCA consists of an analog-to-digital convertor (ADC), memory, and a method of display (either an oscilloscope or a computer monitor). The ADC is a specialized type which measures the only the maximum height of the pulse corresponding to a radiation event. Since it takes a finite amount of time to measure a pulse, the MCA must close off its entrance to further pulses to prevent corruption of the measurement of the one it is working on. This processing period is called "dead time" and must be accounted for. Most MCAs show the percent of dead time while they are working. The faster the clock frequency of the MCA, the lower the dead time. Dead time errors can be controlled, however, by conducting experiments for *live time* -- the time during which the MCA is available for work.

Once the MCA has measured the pulse height, it finds the memory bin which most closely corresponds to this pulse height and adds one count to it. Each memory bin corresponds to a *Channel #* on the horizontal axis of the display. The more the number of memory bins (or channels), the greater the potential resolution of the instrument. MCAs do not come pre-calibrated so they can be optimized for a wide range of gamma ray energies. The energy to channel # calibration is performed in the field using sources of known gamma ray energies.

Experiment

- 1.1 Use the Sodium Iodide (NaI) detector to detect background radiation. Display this on the oscilloscope as positive unipolar pulses. Note the relative background signal strength.
- 1.2 Acquire a spectrum of a Cobalt-60 source on the Multi-Channel Analyzer. Integrate the count for all channels which are within the first peak at full-width-half-maximum (FWHM). Print this and note on the plot:
 - the peak channel numbers for all peak(s);
 - the acquisition time;
 - the integrated peak width (at FWHM);
 - the value of the gross integral
- 1.3 Lower the gain on the linear amplifier and acquire once again a spectrum from the Co-60 source. Integrate over the first peak. Compare this with the result from 1.2. Restore the gain.
- 1.4 Reduce the acquisition time and acquire. Integrate over the same channels as in 1.2. Note any change in spectrum statistics.

- 1.5 Move the source 2 cm from the detector and acquire again. Integrate. Now move the source 4 cm from the detector and acquire again. Once again, integrate. Compare.
- 1.6 Change the linear amplifier to produce bipolar pulses and acquire again. Do the peaks seem to shift if the source is now put at zero distance from the detector? Integrate over a single peak at the full width half-maximum point. Print the integrated spectrum for this last acquisition. Note the beginning and ending channel numbers of the integrated peak.
2. Connect the Germanium (Ge) detector to the multi-channel analyzer. Acquire a spectrum of Cobalt-60 using a similar source/ detector spacing and for the same length of time as was done with the NaI detector. Integrate over the peaks and once again note the acquisition time, pulse width, the amount of the integral, etc. Print the spectrum.
3. Use Cobalt-60 and Cobalt-57 to calibrate the MCA for energy versus channel number. Plot these spectra.
4. Acquire a spectrum for an unknown radioactive source. Plot the spectrum. Record all relevant channel numbers, as well as the integrals for any visible peaks.

Analysis

1. Comment on the pros and cons of Ge and NaI detectors in terms of:
 - (i) efficiency;
 - (ii) resolution;
 - (iii) cost;
 - (iv) applications.
2. Comment on the effect of pulse shaping electronics on the quality of the data collected. What is the reason for any spectrum shift? How does one know when results are reliable?
3. Comment on the low energy broad-band spectra observed and how the features differ between Ge and NaI detectors.
4. Discuss the advantages and disadvantages of using an MCA versus a Single Channel Analyzer (used in the Neutron Attenuation Lab).
5. Generate an Energy versus Channel # calibration curve for the MCA.
6. Use the above curve to determine the energy of the peaks for the unknown source. If there is more than one peak, the relative intensity of the peaks may be important in identifying the unknown. Use a standard table of gamma-ray energies for man-made isotopes to identify the unknown, e.g. C.E. Crouthamel, Applied Gamma-Ray Spectroscopy.

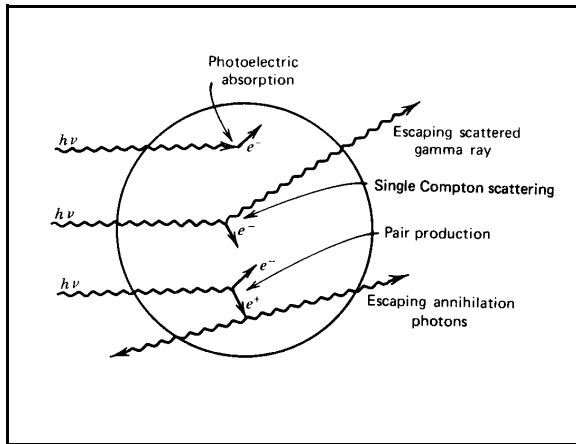


Figure 9: "Small" detector

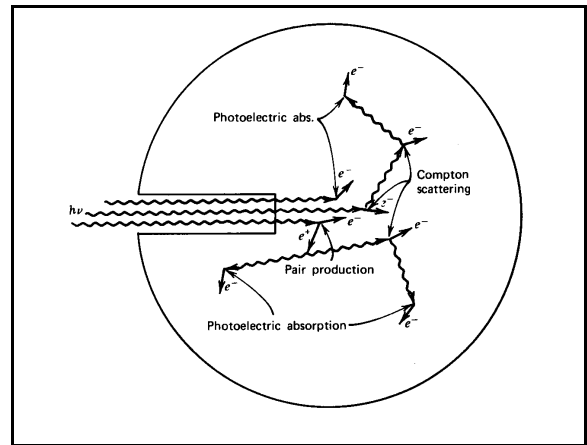


Figure 10: "Large" detector

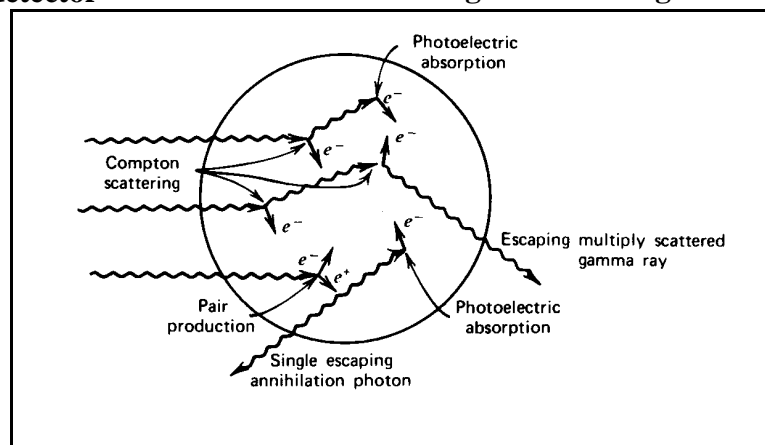


Figure 11: Intermediately sized detector

Discussion

Figures 9, 10, and 11 show the nuclear interaction processes for the extremes of small and large detectors as well as for an intermediate sized detector.

1. What spectrum would you expect to result from a 2 MeV gamma-ray entering a small Ge detector? This would be best shown with a drawing. Repeat for a medium size and for an infinite size Ge detector.
2. What do the terms "live time" and "dead time" mean and how do they differ from "real time"? Why is it important to measure in units of live time?
3. What are the possible sources of error in using the Ge detector to identify unknowns?

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