UNIVERSITY of GUELPH

DEPARTMENT OF PHYSICS
INTEGRATED LABORATORY

Gamma-Ray Spectroscopy Using A NaI(Tl) Detector

Objectives: Become familiar with some of the basic techniques used for measuring gamma rays with a sodium iodide (NaI) detector that is thallium (Tl) activated.

Reference:

- R.A. Dunlap, Experimetal Physics, (Oxford University Press: New York, 1988). Chapters 11 & 12.
- A. Melissinos, Experiments in Modern Physics, (Academic Press: New York, 1966). Chapter 5.

Acknowledgements: Experiments in Nuclear Science, published by EG&G ORTEC, was the primary source for much of the material discussed in this outline.

Apparatus:

Bin and power supply

NaI(Tl) crystal and phototube assembly

Amplifier (Ortec 575 or equivalent)

High voltage power supply (Ortec 456 or equivalent)

Multichannel analyzer (MCA) (TN7200) and personal computer

Radioactive sources: ^{137}Cs, ^{60}Co, ^{22}Am

Important: **During this experiment, always remember that you are working with radioactive sources. You can not begin this experiment until you have discussed how to safely handle the radioactive sources. Always wash your hands after working with any radioactive source. When working with the sources, always use the tweezers provided and ensure that the radiation safety signs provided are posted in the relevant area. WHEN THE RADIOACTIVE LOCKBOX IS NOT IN USE, IT MUST BE LOCKED.**

Introduction: Most isotopes that are used for γ-ray measurements also have β-particles in their decay schemes. The typical decay scheme for the isotope will include a β-decay to a particular level followed by a γ-ray emmission to the ground state of the final isotope. The β-particles will usually be absorbed in the surrounding material and not enter the scintillator at all, but this absorption is normally assured with aluminum absorbers. For this experiment, the β-particles offer no real problem and absorbers are therfore not necessary. There will be some β-particle absorption by the light shield over the phototube, but the γ-rays are quite penetrating and will therefore pass easily through the light aluminum shield.

Generally there are two unknowns for a given γ-source that we would like to investigate. One is the energies of the γ-rays from the source, while the other is the number of γ-rays that leave the source per unit of time (*activity*). In this experiment, the student will become familiar with some of the basic NaI(Tl) measurements associated with γ-ray emitting unknowns.

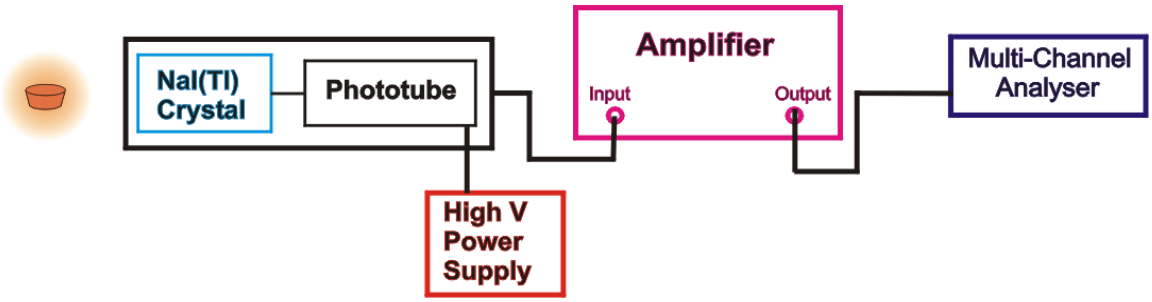

Figure 1: Electronic block diagram for γ-ray spectroscopy system with NaI(Tl) detector.

Experiment: This experiment will be broken up into a series of exercises, each of which should be completed by the student. Before beginning the exercises, the student should become familiar with the computer's multichannel analyzer. For this experiment, the MCA will be run as a pulse-height analyzer (PHA), where each channel (or bin) corresponds to a small range of energies. Each event in the detector produces a voltage proportional to the energy of the γ-ray which caused the event. The event is then added to the channel corresponding to its voltage (energy) range, and the resulting spectrum is thus a plot of intensity (number of counts) versus voltage (energy).

Exercise I - Energy Calibration: In this exercise, the 0.662 MeV photopeak from ^{137}Cs and the 1.17 and 1.33 MeV photopeaks from ^{60}Co are used to calibrate the NaI(Tl) detection system.

1. Set up the electronics as shown in Figure 1. There are two parameters that ultimately determine the overall gain of the system: the high voltage that is furnished to the phototube and the gain of the linear amplifier. Ther gain of the photomultiplier tube is quite dependent on its high voltage. A general rule for most phototubes is that a 10% change of the high voltage will change the gain by a factor of 2. The high voltage value depends on the phototube being used.

2. Set the high voltage to 900 V.

3. Set the amplifer for positive input and bipolar output.

4. To set up the MCA, see the operating manual for the TN7200.

5. Place the ^{137}Cs source $\sim$ 10 cm in front of the NaI(Tl) crystal.

6. Adjust the coarse and fine gain controls of the linear amplifier so that the 0.662 MeV photopeak for ^{137}Cs falls at approximately channel 280. For the illustrations shown in Figure 2, the gain of the system has been set so that 1 MeV falls at about channel 420 to 425. Since the system is linear, 2 MeV would therefore fall at $\sim$ channel 840-850. Do not change the high voltage or amplifier gain until the exercise is completed.

7. Accumulate the ^{137}Cs spectrum long enough to determine the peak position. Note the channel number for the photopeak, Compton edge and backscatter peak. Dump the spectrum to a file on the computer. *Note that all files should be saved to the D: drive on the computer, as any files saved to the C: drive will be automatically erased when the computer is rebooted!*

8. Replace the ^{137}Cs source by the ^{60}Co and accumulate the spectrum. A sample spectrum is shown in Figure 3. Again note the channel numbers for the photopeaks, Compton edge and backscatter peak. Store the spectrum as a file on the computer.

9. Make a plot of the photopeak energies for ^{137}Cs and ^{60}Co versus channel number and generate a calibration curve with which you can convert channel number to energy for later exercises.

Exercise II - Analyses of the ^{137}Cs and ^{60}Co Gamma-Ray Spectra: The purpose of this exercise is to explain some of the features, other than the photopeaks, that are usually present in a pulse-height spectrum. These are the Compton edge and the backscatter peak.

The Compton interaction is a pure kinematic collision between a γ-ray photon and what might be termed a free electron in the NaI(Tl) crystal. By this process, the incident γ-ray gives up only part of its energy to the electron. The amount given to the recoil electron (and the intensity of the light flash) depends on whether the collison is head-on or glancing. For a head-on collision, the γ-ray imparts the maximum allowable energy for the Compton interaction. The energy of the scattered γ-ray can be determined by solving the energy and momentum equations for this billiard ball collision. The solution for these equations in terms of the scattered γ-ray can be written approximately as:

$$E_{\gamma'} \cong \frac{E_\gamma}{1 + 2|E_\gamma|(1 - \cos\theta)} \tag{1}$$

where $E_{\gamma'}$ is the energy of the scattered γ-ray in MeV, E_γ is the energy of the incident γ-ray in MeV, $|E_\gamma|$ is the dimensionless magnitude of the incident γ-ray and θ is the scattering angle for γ'. *The student should derive the above equation to verify that it is correct.* If $\theta = 180°$ due to a head-on collision in which γ' is scattered directly back, Eq. 1 becomes:

$$E_{\gamma'} \cong \frac{E_\gamma}{1 + 4E_\gamma} \tag{2}$$

As an example, we will calculate $E_{\gamma'}$ for an incident γ-ray energy of 1 MeV:

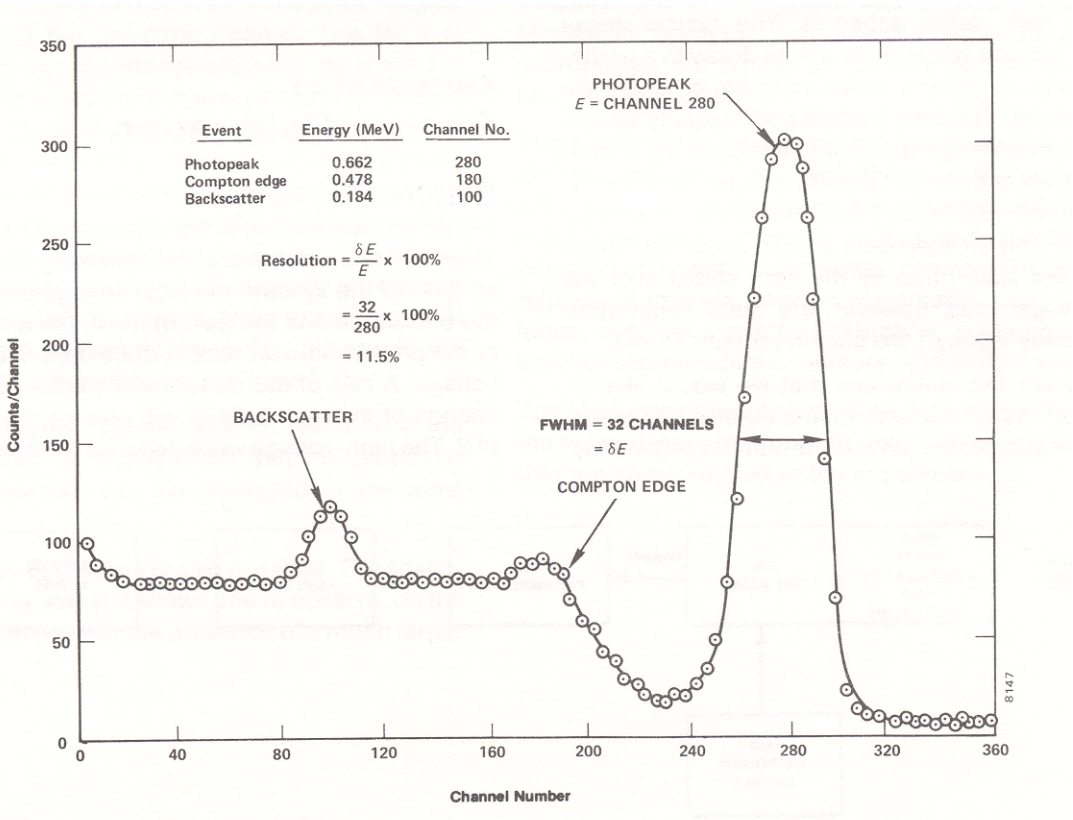

Figure 2: Typical ^{137}Cs spectrum measured using a NaI(Tl) detector.

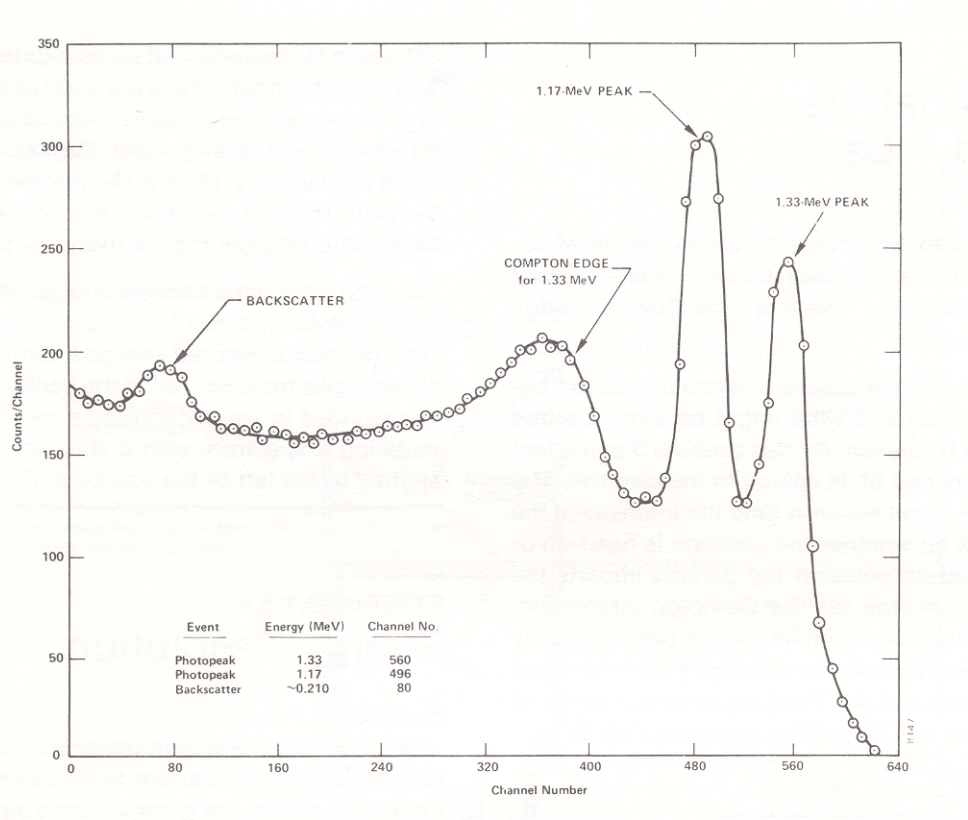

Figure 3: Typical ^{60}Co spectrum measured using a NaI(Tl) detector.

$$E_{\gamma'} \cong \frac{1MeV}{1+4E_\gamma} = 0.20MeV \tag{3}$$

The energy of the recoil electron, E_c, for this collision would be 0.80 MeV. This is true since

$$E_c = E_\gamma - E_{\gamma'} \tag{4}$$

Then the position of the Compton edge, which is the maximum energy that can be imparted to an electron by the Compton interaction, can be calculated using Eq. 4.

Backscatter occurs when γ-rays make Compton interactions in the material surrounding the detector. Figure 4 demonstrates the various events that can take place in a typical source-NaI(Tl)-lead shield arrangement. Backscattered γ-rays from these interactions ($E_{\gamma'}$) make photoelectric interactions in the NaI(Tl) when they enter the crystal. The energy of the backscattered peack can be found by solving Eq. 2.

1. Calculate the energy of the Compton edge for the 0.662 MeV γ-rays from ^{137}Cs. Using the channel number for the edge and your calibration chart, does the measured value agree with the calculation?

2. Solve Eq. 2 for the backscattered γ-rays from ^{137}Cs and for the 1.33 MeV γ-rays from ^{60}Co and compare with the measured energies.

Exercise III - Energy Resolution: The resolution of a spectrometer is a measure of its ability to resolve two peaks that are fairly close together in energy. Figure 2 shows the γ spectrum that was plotted for the ^{137}Cs source. The resolution of the photopeak is found by solving the following equation:

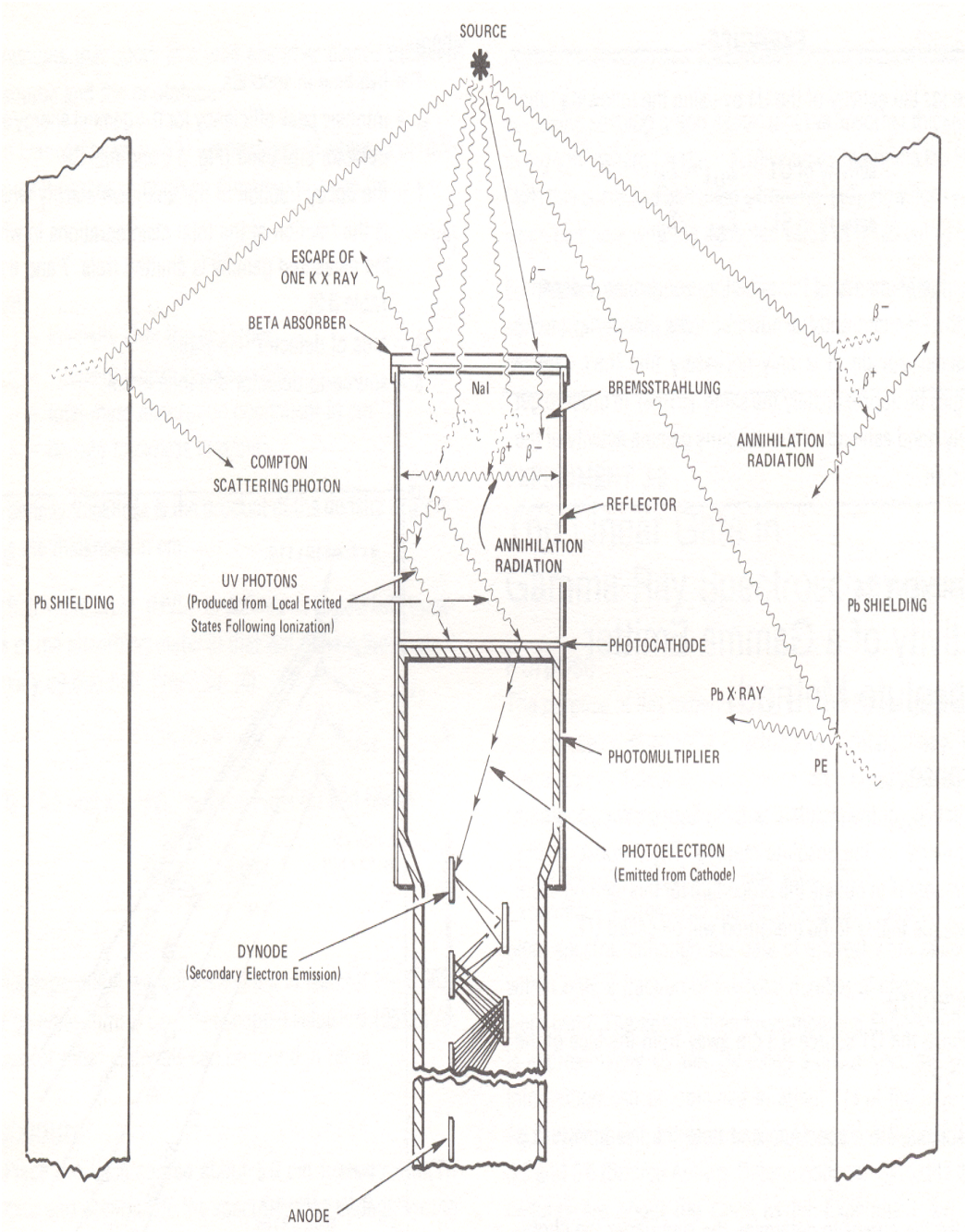

Figure 4: Various events in the vicinity of a typical source-crystal detector-shield configuration.

$$R = \frac{\delta E}{E} \text{ x } 100\% \tag{5}$$

where R is the resolution (in percent), δE is the full width of the peak at half of the maximum count level (FWHM) measured in number of channels and E is the channel number at the centroid of the photopeak. In Figure 2, the photopeak is in channel 280 and the FWHM = 32 channels. From Eq. 5, the resolution is calculated to be 11.5%.

1. Calculate the resolution of the system from your ^{137}Cs spectrum.

Exercise IV - The Activity of a γ-Emitter: Another unknown associated with the gamma source is the activity of the source, which is usually measured in Curies (Ci), where 1 Ci = 3.7 x 10^{10} disintigrations per second. Most of the sources that are used in nuclear laboratory experiments have activities of the order of microcuries (μCi).

1. Place the ^{137}Cs source 9.3 cm away from the face of the detector.
2. Accumulate a spectrum for a fixed length of time t.
3. Determine the sum under the photopeak, Σ_{Cs}, referring to the manual for the multichannel analyzer if necessary.
4. Erase the spectrum, remove the source and accumulate the background for the same length of time t and determine Σ_{ref}.
5. Use the formula below to caclulate the activity of the source.

$$\text{Activity} = \left(\frac{\Sigma_{\mathrm{Cs}} - \Sigma_{\mathrm{ref}}}{t}\right)\frac{1}{G\epsilon_p f} \tag{6}$$

where t is the live time in seconds, ϵ_p is the intrinsic peak efficiency for the gamma energy and detector size used, f is the decay fraction of the unknown activity which is a fraction of the total disintegrations in which the measured gamma is emitted (see Figure 6), G is the area of the detector in cm^2/$(4\pi d_s^2)$ and d_s is the source-to-detector distance in cm. You will need to use Figure 5 to determine ϵ_p, but note that the detector you are using is not represented, so you will have to extrapolate the needed values as best you can.

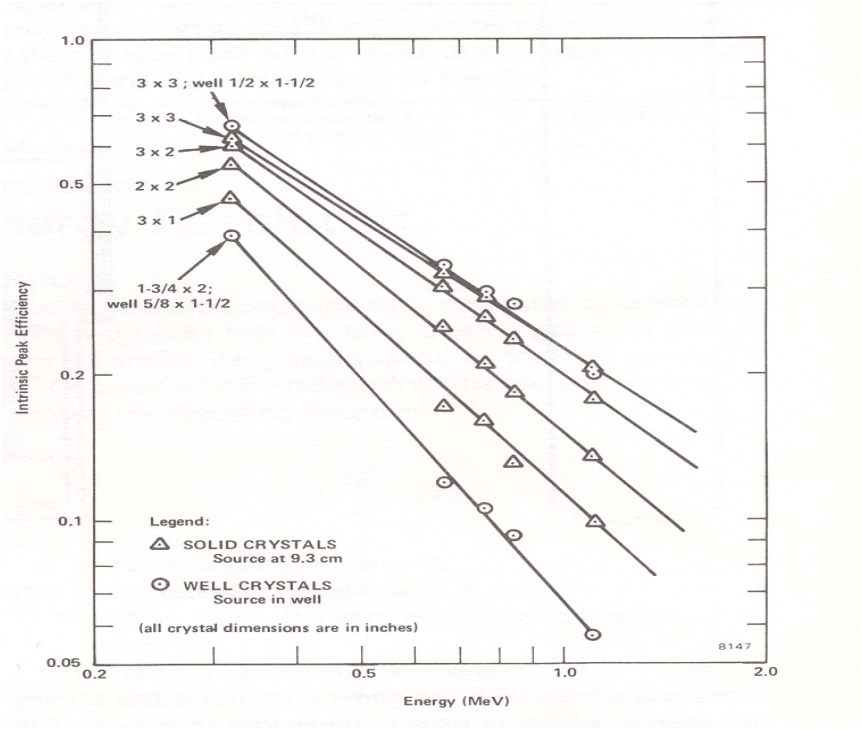

Figure 5: Intrinsic peak efficiency of various NaI(Tl) crystals versus γ-energy.

Isotope	Gamma Energy (MeV)	f
^{137}Cs	0.662	0.92
^{51}Cr	0.323	0.09
^{60}Co	1.17	0.99
^{60}Co	1.33	0.99
^{22}Na	1.276	0.99
^{22}Na	0.511	0.99
^{54}Mn	0.842	1.00
^{65}Zn	1.14	0.44

Figure 6: Gamma decay fraction f for some common isotopes.

Exercise V - The Mass Absorption Coefficient: In this exercise, the student will measure experimentally the mass absorption coefficient in lead for 662 keV γ-rays.

The references point out that γ-rays interact in matter primarily by photoelectric, Compton, or pair-production interactions. The total-mass absorption coefficient μ can be easily measured with a γ-ray spectrometer. In this exercise, we will measure the number of γ-rays that are removed from the photopeak by the photoelectric or Compton interactions that occur in a lead absorber placed between the source and the phototube.

From Lambert's law, the decrease in intensity of radiation as it passes through an absorber is given by:

$$I = I_o \ \exp(-\mu\chi) \tag{7}$$

where I_o is the intensity before the addition of the absorber, I is the intensity after the addition of the absorber and χ is the density thickness in g/cm^2. The density thickness is the product of the density (in g/cm^3) and the thickness (in cm).

The half-value layer (HVL) is defined as the density thickness of the absorbing material that reduces the original intensity I_o by 50%. Using Eq. 7, it is a relatively simple matter to show that:

$$\text{HVL} = \frac{0.693}{\mu} \tag{8}$$

In this experiment, we will measure μ in lead for the 0.662 MeV γ-rays emitted by ^{137}Cs. The accepted value is 0.105 cm^2/g.

1. Place the ^{137}Cs source about 5.0 cm from the NaI(Tl) detector and accumulate the spectrum long enough for the sum under the 0.662 MeV peak (Σ_{Cs} - Σ_{ref}) to be at least 6000 counts. Determine (Σ_{Cs} - Σ_{ref}).

2. Erase the MCA and insert a piece of lead from the absorber kit between the source and the detector. Accumulate the spectrum for the same period of live time as in Step 1 above. Determine (Σ_{Cs} - Σ_{ref}).

3. Erase the MCA and insert another piece of lead. Determine (Σ_{Cs} - Σ_{ref}). Repeat with additional thicknesses of lead until the count-sum is < 1000.

4. On a semilog scale, plot the intensity I versus absorber thickness in mg/cm^2, where I = (Σ_{Cs} - Σ_{ref})/live time. Determine the HVL from this curve and calculate μ from Eq. 8. How does your value compare with the accepted value of 0.105 cm^2/g?

5. Repeat the above exercise using aluminum absorbers. Compare your experimenally measured value for μ with the accepted value of 0.074 cm^2/g.

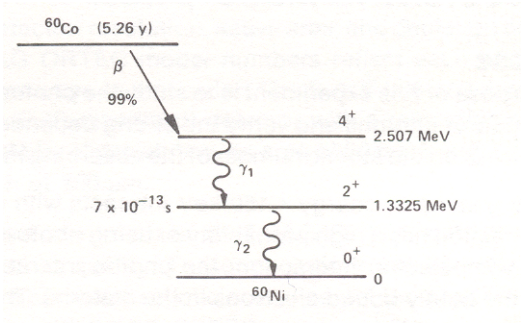

Figure 7: Decay scheme for ^{60}Co

Exercise VI - Sum Peak Analysis: Figure 3 shows the two pronounced peaks in ^{60}Co. Figure 7 shows the decay scheme of ^{60}Co. Most of the time, the decay occurs by β-particle emission to the 2.507 MeV excited state of ^{60}Ni. Subsequent decay to the ground state always occurs by γ-ray emission to the 1.3325 MeV level (a 1.174 MeV γ-ray), followed almost instantaneously by the 1.3325 MeV γ-ray emission to the ground state. These two events are in coincidence and have an angular correlation that deviates from an isotropic distribution by only 16%. For the purposes of this exercise, we can assume that each of these γ-rays are isotropically distributed. In other words, if γ_1 goes in a particular direction, γ_2 can go in any of the 4π steradians that it wishes. There is a certain probability that it will go in the same direction as γ_1. If this occurs within the resolving time of the detector, γ_1 and γ_2 will be summed and hence a sum peak will show up in the spectrum. The number of counts under the γ_1 photopeak is given by:

$$\Sigma_{\gamma_1} = \epsilon_1 G f_1 t A \tag{9}$$

where A is the activity of the sample and t is the time. In a similar calculation, the sum under the photopeak corresponding to γ_2 is:

$$\Sigma_{\gamma_2} = \epsilon_2 G f_2 t A \tag{10}$$

From Eqs. 9 and 10, the number of counts in the sum peak, Σ_s is given by:

$$\Sigma_s = \epsilon_1 \epsilon_2 G^2 f_1 f_2 t A[W(0^\circ)] \tag{11}$$

where $W(0^\circ)$ is a term that accounts for the angular correlation function. For the case of ^{60}Co, Eq. 11 reduces to:

$$\left(\Sigma_s\right)_{^{60}\mathrm{Co}} = \epsilon_1 \epsilon_2 G^2 t A \tag{12}$$

since $W(0^\circ) \cong 1.0$.

In this experiment, we will show that the sum peak for ^{60}Co has an energy of 2.507 MeV and that its sum is given by Eq. 12.

1. Set up the apparatus as shown in Figure 1.
2. Use the ^{137}Cs and ^{60}Co sources to calibrate the MCA such that the full scale is $\sim$ 3.0 MeV. For 1024 channels, this would put the ^{137}Cs (0.662 MeV) photopeak at approximately channel 225.
3. Construct a calibration curve as in Exercise I.
4. Place the ^{60}Co source from the source kit at exactly 9.3 cm from the face of the detector. Acquire a spectrum for a period of time that is sufficiently long that the area under the sum peak is $\sim$ 1000 counts. This procedure was outlined in Exercise IV.

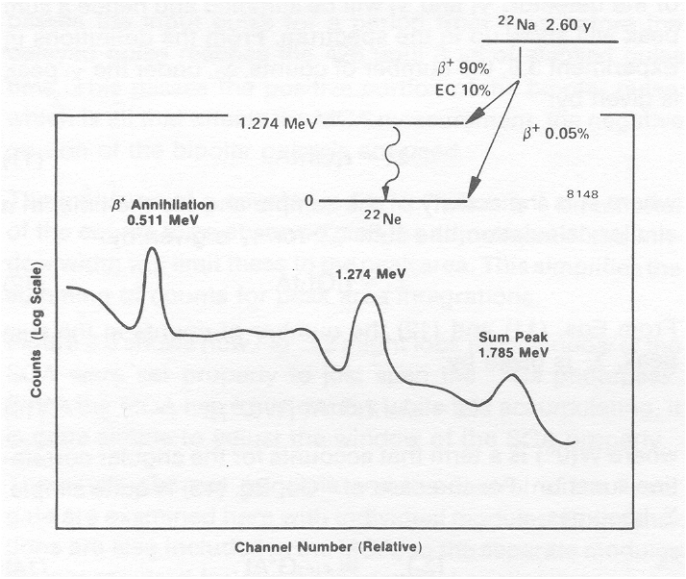

Figure 8: Decay scheme for ^{22}Na (inset) and typical spectrum measured using NaI(Tl) detector.

5. Verify that the energy of the sum peak is 2.507 MeV. Subtract the background from the sum peak and verify its sum from Eq. 12.

6. Repeat this sum peak analysis for the ^{22}Na source. Figure 8 shows the decay scheme for ^{22}Na and a typical spectrum with the sum peak.