Gamma Spectroscopy

Objectives:

- To become familiar with the detection of gamma rays using a scintillation-photomultiplier tube detector, associated electronics, and with the pulse height analysis technique for determining gamma ray energies.
- To understand the origin and location of the Compton edge and the backscatter peak in the pulse height spectrum.
- To calibrate the energy scale of the pulse height analyzer and use that calibration to measure the gamma ray energies in KeV of a number of other samples.
- Understand the origin of the system energy resolution, and systematic errors.
- Experiment with absorption, shielding, and back-scatter spectra.

Procedure:

It is important to follow procedure below, and not jump over sections. First, set up your detector and amplifier chain using the scope. Fully understand what you see. Adjust pole-zero for optimal unipolar pulse. Then adjust spec amplifier gain to give 0-10V over the range of energies you want. All this takes several days. Only then begin calibrating energies using the multi-channel analyzer. Once calibrated with known sources, you can begin a series of Compton scattering experiments. Those experiments will take another week. Then write your report.

Introduction:

The principle component in the scintillation detector is a Tl doped sodium iodide crystal (NaI). When a gamma ray from a radioactive sample enters the crystal, some combination of three physical processes can occur: 1) photoelectric emission of an electron that absorbs all of the gamma's energy, 2) Compton scattering of the gamma ray photon off electrons in the crystal, or 3) pair-production of an electron–positron pair. In order for the last process to occur with any likelihood, the incoming gamma must have an energy that is at least twice the rest mass energy of the electron (2 X 0.511 MeV = 1.022 MeV). Although a couple of your radioactive samples will emit gammas in this range, unless the gamma is substantially more energetic than 1.022 MeV, the pair-production mechanism is not observable.

The electron liberated by the photoelectric effect is quite likely to scatter around in the NaI crystal, losing energy, until it is captured by an atom in the crystal with an electron vacancy. In the process of scattering, photons in the visible and UV region of the spectrum are emitted. Likewise with the Compton scattering process, the recoil electron will ultimately deliver most of its energy as visible and UV photons. The difference between the photoelectric and the Compton scattering process is that the former process is likely to deposit all or nearly all of the incoming gamma energy it the crystal, while in the latter process, the scattered gamma ray photon may *escape the scintillator crystal* and therefore deposit only a fraction of its total energy in the crystal. These energy conversion mechanisms in Tl doped NaI are summarized in the photon attenuation plot at the end of this guide.
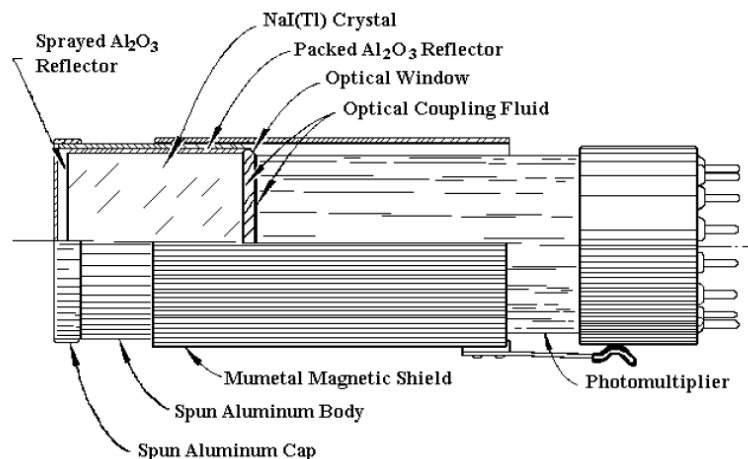
The low frequency (visible and UV) photons produced when a gamma interacts with the scintillator crystal, enter a photomultiplier tube (PMT), in which a cascade of electrons is generated, again via the photoelectric (and secondary electron) effect. This has the effect of turning a light pulse into a current pulse, which is then converted into a voltage pulse as the current flows through the 50 ohm resistor at the anode. In general, the more energy the original gamma ray had, the larger the voltage pulse that the PMT will produce. The scintillation detector and PMT are shown above. Read the tutorial on PMTs on the 122 web page for this experiment. Starting with a ^{60}Co source placed in front of the NaI scintillator, gradually turn the high voltage on the PMT up from 500 to 800V while monitoring the pulse heights at the output of the preamp with your oscilloscope (see layout of electronics below). Normal HV is 800V.

The pulse height analyzer (PHA) divides the range of all possible voltages into bins, or channels, and keeps a running count of how many pulses arrive in each bin, thus producing a histogram of the number of counts versus PMT output voltage. Unfortunately, while the PMT voltage varies *directly* with gamma ray energy, that variation is *not* a simple proportion and it may not even be linear. This means that the scintillation detector must be calibrated with gamma rays of a number of known energies before it can be used to measure the energy spectrum of an unknown sample. The calibration results in a relationship that allows you to associate a given channel number with its appropriate energy.
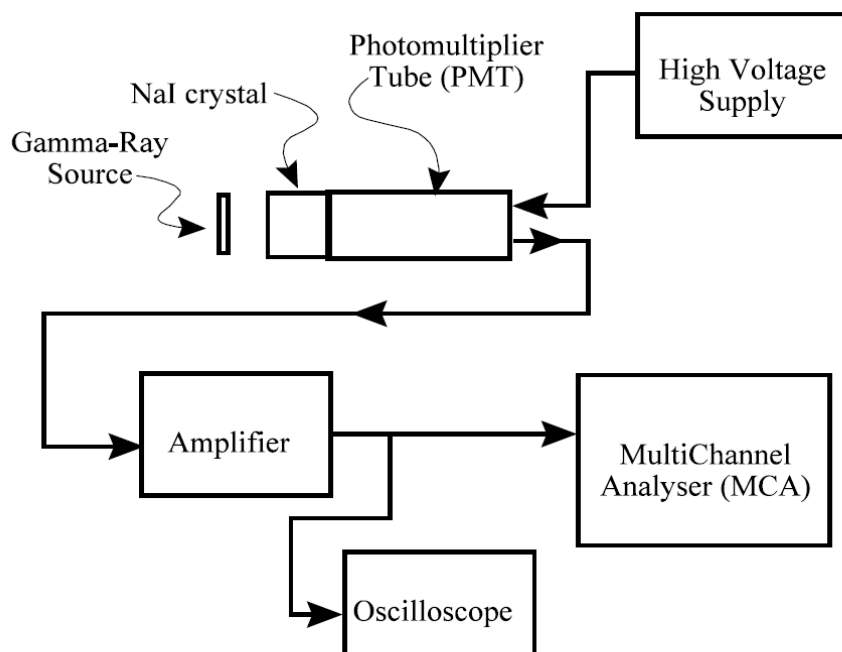
With   your

scope, carefully follow the pulse through the system, from the PMT, preamp, and spectroscopy amplifier. Carefully read the manuals for each of these, so you understand how they work. The preamp has adjustable time constant so your pulse is long enough for sampling. There is a tradeoff between this time constant and system voltage gain. Explore. Optimize gains for maximum dynamic rage [don't saturate!].

The multi-channel analyzer (MCA) for this spectroscopy experiment is in a data acquisition system (DAQ) in the computer. Feed the output of the linear amplifier into this ["direct" BNC on back of white box: scale = 0-8V] via a BNC cable. Launch the UCS20 software from the Programs menu on the PC. To test the DAQ use the ^{137}Cs source since there is one photopeak corresponding to the 667KeV decay. Be sure that the 667KeV pulses that you see on the scope have appropriate pulse heights and then check the spectra displayed by the DAQ/UCS20. This may require several DAQ spectra run + delete operations. Information on the UCS20 program is available on the 122 website for this experiment under "Related material." You should not use any of the automated data processing features of the UCS20 MCA; simply use it as a MCA to collect data, and then do your own data processing using Python.

Experiment with the system gain vs PMT HV by using the position of the ^{137}Cs photopeak on the MCA output. Plot this gain relation and discuss in your lab book and report. Read about pulse pileup (Knoll) at high rates and experiment with this by moving the source close to the detector. Write this in your lab book and report. What do you find for the dependence of energy resolution on pulse rate?

- Start data acquisition.
- You should see a pulse height spectrum. Adjust the COARSE GAIN and the FINE GAIN until you obtain a spectrum for ^{60}Co that has the two prominent peaks near the right end of the spectrum. These are the "photopeaks" associated with the photoelectric effect detection process discussed in the introduction for the 1.173 and 1.333 MeV gammas. Find the combination of gain and HV that gives best energy resolution. Usually this is around 800V for the PMT HV. Once you find the right gain settings, do not alter them for the rest of the run.
- Acquire a good spectrum for ^{60}Co and identify the channel numbers that are at the center of each prominent peak. Consider how many counts you need in each bin. Note that the software has feature to help you determine the center of a peak. You should put a printout of the spectra you obtain with labeled axes in your notebook. Repeat with other radioactive samples as described below. Do NOT change the gain settings.
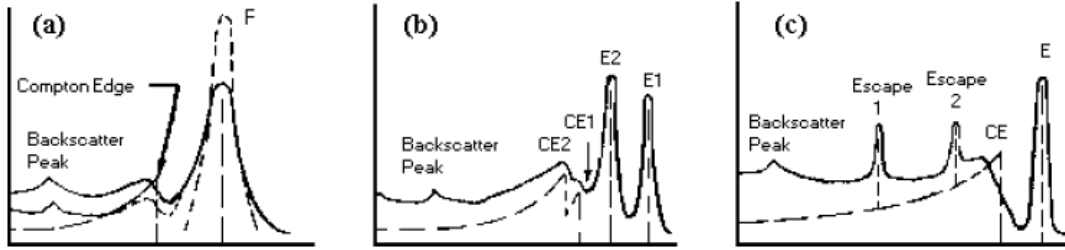
Theoretical and actual spectra of detected γ rays. (a) Single γ ray < 1 MeV, (b) Double γ ray < 1 MeV, (c) Single γ ray > ~2 MeV.
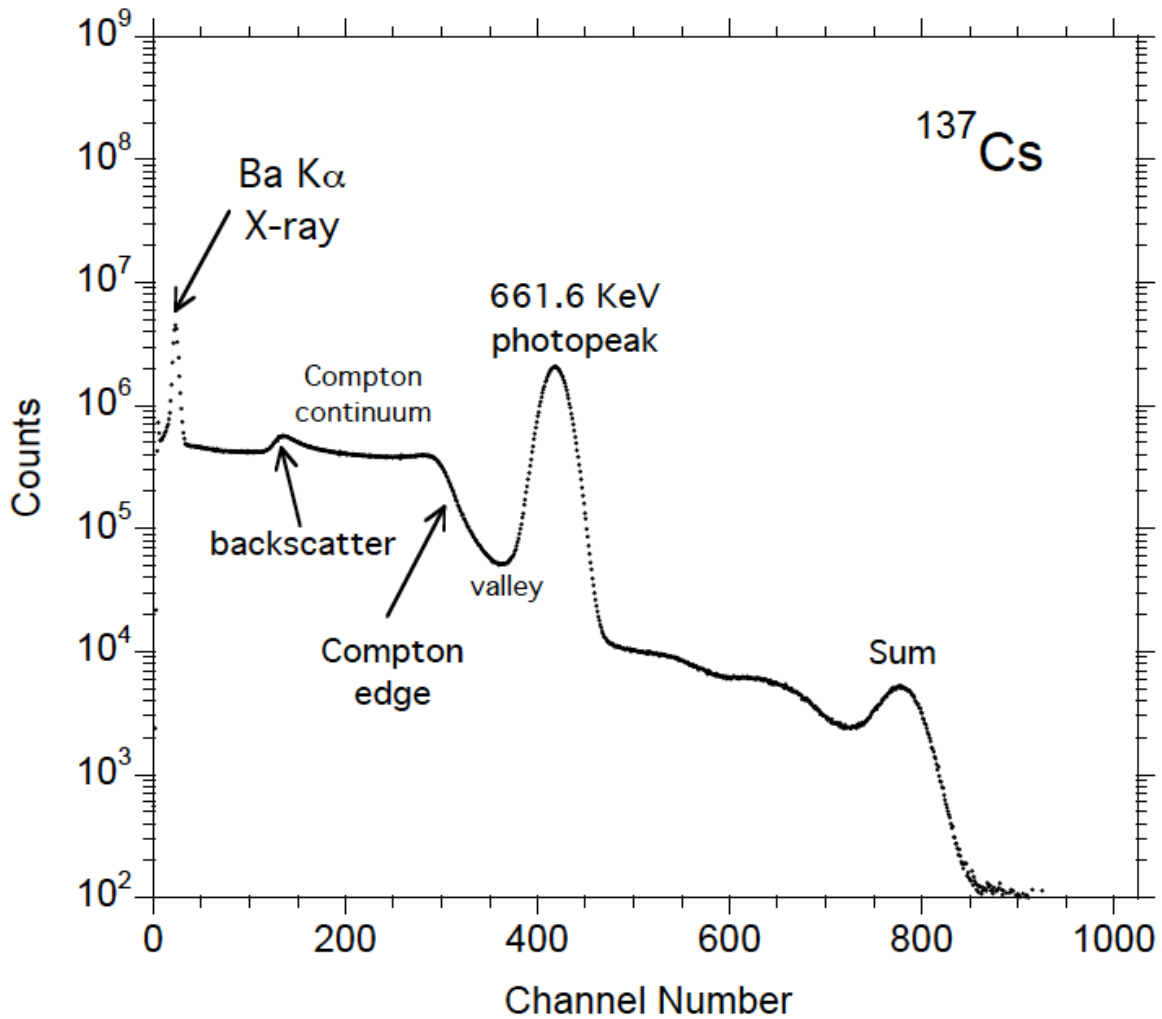
Detector Energy Resolution

Resolution describes the ability of a spectrometer to distinguish the presence of gamma rays closely spaced in energy. The practical measure of resolution is the width of the photopeak at half its amplitude known as the Full Width at Half Maximum (FWHM). For NaI(Tl) scintillation detectors, the convention adopted is to define the resolution as the relative FWHM of the 137Cs 662 KeV photopeak. Hence, the resolution will be the FWHM divided by the position of this photopeak centroid expressed on the pulse height (or channel number) scale as shown in the figure below.
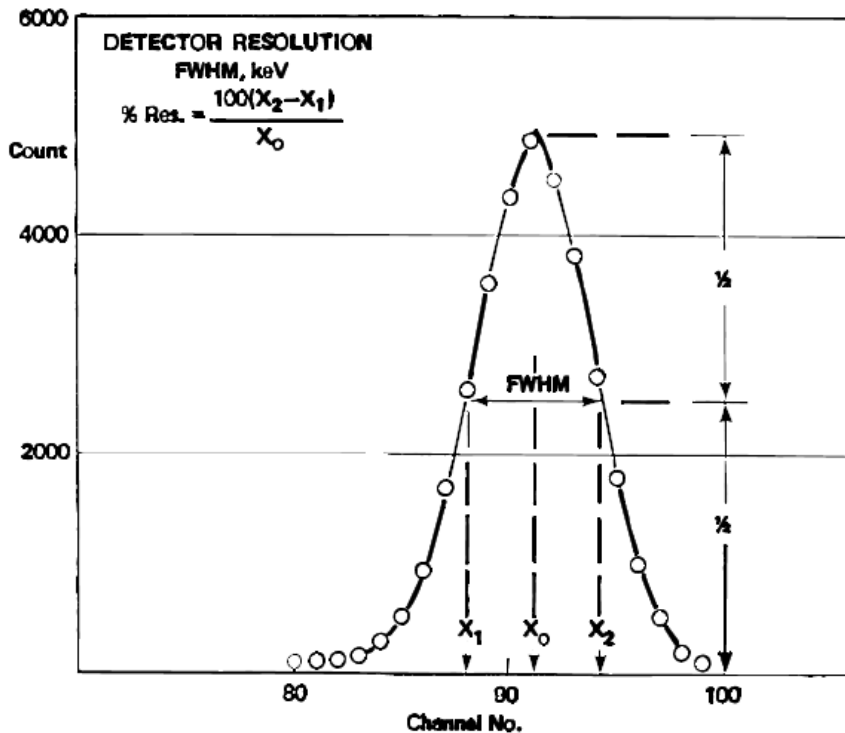
Expressed as a percent, the resolution of a good NaI (Tl) detector should be about 7-8%. This should be established for the particular detector in use to know about its limitations and also to monitor performance with time. An early indication of detector failure is loss of resolution. Use one of your 137Cs spectra to determine the resolution of our detector. This resolution is of course affected by the shape of your pulses going into the MCA as well as the major source of noise in your detector (which may be a function of the PMT HV). Carefully read the section in Knoll regarding limitations to detector resolution. Experiment with this, to see if you can optimize the resolution. Write up these detector + electronics notes in your lab notebook and explain the physics of this, and your explorations, in a separate section of your lab report.

Calibrating your Detector:

Once you have your system electronics optimized, the first goal is to calibrate it by deriving a relation between peak pulse height [thus MCA channel number] and gamma ray energy in

physical units. Calibrate your NaI detector and system electronics by finding the linear relation between channel number and energy. This is done using gamma lines of known energy. Look up the decay scheme in a nuclear decay catalogue of radioactive sources for NaI (R. Heath), of each of the following radioactive sources: ^{137}Cs, ^{60}Co, ^{57}Co, and ^{133}Ba. For each radioactive source, create an individual spectrum and identify the channel number where each photopeak is centered. Put this in your lab book and include in your report. Measure and record the Full Width Half Max (FWHM) of each photopeak, a measure of the energy resolution of your detector (i.e. the error in your estimation of the energy, see relevant section in photocopied version of Knoll). Perform a linear fit of your energy-channel# data and obtain the energy calibration for the detector. Quote the χ^2 of your linear fit and find the energy range that your detector is sensitive to. Look at your error distribution. Are outlying points causing a large error in your fit? Regarding systematic error, estimate the effects of the above error on your results and consider the possibility of mis-identification and nonlinearity. How would you test for it? Undertake these tests.

Notes on the experimental setup while making your measurements
- Clear the surrounding of the detector from ALL foreign objects.
- Do not readjust any electronic settings (any gain setting on the Ortec dual spectroscopy amplifier or the PMT HV) once you begin any serious measurement.

<u>Verifying your Calibration:</u>
Get a spectrum of the gammas from your ^{22}Na source and use your calibration to estimate the energy of all the photopeaks. You should observe two prominent peaks. Determine the energies of each. The higher energy peak is associated with a transition from an excited state to the ground state in ^{22}Ne, the daughter nucleus produced by the positive beta decay of ^{22}Na. Positive beta decay involves the emission of a positron (or anti-electron). The positron eventually finds an electron and the two annihilate to produce two gamma ray photons that emerge at 180° to one another (to conserve momentum) and each has an energy equal to the rest mass energy of the electron (or positron). Only one of these two "annihilation" gammas can enter your detector. *Verify that the energy associated with the lower energy peak in the spectrum of ^{22}Na has energy about equal to the rest mass energy of the electron.*

<u>Exploring and Interpreting Spectroscopic Features:</u>

1. Obtain individual spectra for ^{60}Co and ^{22}Na with a logarithmic vertical scale. In the presence of noise, how might you get a good estimate of the photopeak energy? [Hint: Use more than the highest data point. For an optimally weighted estimate, consider a Gaussian peak finder. Since you already have taken the log, consider an appropriate polynomial fit.]

2. Estimate the energy of the Compton Edges for ^{60}Co, ^{137}Cs, ^{22}Na. Explain the gradual slope of the Compton Edge. Do you expect a Compton Edge for each principle gamma ray of a particular source? Explain.

3. Obtain a high signal-to-noise ratio background spectrum with no radioactive sources nearby. What are the causes of this background? How might you use it to decontaminate your other spectra? This is important. Do you want to do this only once?

4. Obtain a spectrum for ^{137}Cs and save it as your reference. Obtain a second spectrum with the following arrangement: Place a block of aluminum <u>behind</u> the radioactive source such that the ^{137}Cs source stands between the detector and the block. Overlay with the reference spectrum and compare, identify and explain all the additional features in the spectrum. Why is the 662 KeV peak not affected? Explain the origin of the excess in the number of events in the Compton continuum (Hint: what does the sum of the Compton edge and secondary peak equal to?)

5. Place a sheet of lead between the ^{137}Cs source and the detector; make sure to remove the aluminum block from the table. Obtain a third spectrum for ^{137}Cs and overlay with your reference ^{137}Cs spectrum. Identify and explain all the observed changes and lack thereof. To understand the spectrum, consider the following question: Which energy loss process has the highest probability (cross section) at 662 Kev and below 100 Kev (X-ray range). Repeat for two thicknesses of aluminum between the source and detector. Of course keep the source-detector spacing the same during these measurements.

6. Finally, recalibrate for 3 MeV full scale (you can easily do this my changing amplifier gain). Place the ^{60}Co source 9cm in front of the NaI scintillator. Take a long integration. Look for a high energy peak at energies higher than the photopeak corresponding to the known radioactive decay. Repeat for ^{22}Na. What is going on? [Hint: Consider the time resolution of your electronics (pulse length), and the count rate] This is called the "sum peak"

Analysis and Questions:

- Calculate the rate of change of PMT amplification with respect to changes in HV. You can do this by getting spectra of a source under various HV levels (try 20 volt steps). Considering what you find, does this suggest a protocol for calibration because of HV drift? Do not exceed 900V.

- Return to the spectrum of ^{137}Cs. Consider whether the width of the peak you measure is determined by the resolution of your instrument or whether you are seeing the true "uncertainty" or "natural linewidth" in the excited state of ^{137}Ba. Hint: use the decay time and Heisenberg's uncertainty relation between time and energy.

- Now consider the other features of the spectrum of ^{137}Cs. Note that the channels just below the 0.662 MeV photopeak have very few counts, but that the "continuum" counts display a "shelf" somewhat below the energy of the photopeak. This continuum is called the Compton scattering continuum and it results from the Compton scattering of the incoming gamma off an electron in the crystal, and the subsequent escape of the gamma from the crystal after having lost some energy in the scattering process. Only the energy that the gamma loses inside the crystal is detected. The remaining energy in the photon is carried out of the detector and is not measured. Does the Compton "shelf" appear at the energy predicted? There may be another peak on the Compton scattering continuum

called the backscatter peak that coincides with a Compton scattering event in which the electron escapes and the scattered gamma ray photon is absorbed. Can you identify this peak? If so, at what energy does the backscatter peak occur and does this make sense? Discuss.

- Measure the energies of the photopeak, Compton edge, and backscatter peak for a number of sources where they are clearly identifiable. Look for a relationship between these 3 energies, and test your relation by plotting residuals from it. What is going on?

- Use the Chart of the Nuclides to identify the decay scheme for all the samples you use. In particular, identify the isotope associated with the nuclear transition that produced each gamma ray line you observed. For example, the 0.662 MeV gamma from ^{137}Cs is actually due to a transition in ^{137}Ba, the daughter nucleus produced in the beta-decay of ^{137}Cs.

Conclusions:

Along with your major conclusions, include such considerations as: How reliable is your calibration curve? What sort of uncertainty would be reasonable in your energies? What is the origin of your finite energy resolution? For weak gamma sources, how much does the uncertainty in your background run affect your results?

**Important notes on the experimental setup**

- It is very important that the surrounding of the detector be clear of all foreign objects.

- DO NOT move the ^{137}Cs source while taking measurements.

- Time all the ^{137}Cs spectra to have the same integrated exposure.

- It is necessary to know if the channel where a pulse is stored is precisely proportional to its amplitude (is the MCA ADC linear?), and if a hypothetical zero - amplitude pulse is actually stored in channel zero (is the zero offset?). The latter is the most critical parameter, since the design of the ADC provides inherently excellent linearity.

- Once calibrated, all your plots should have KeV on the x-axis.

Source	Gamma Energies of interest (MeV)	Principle Decay mode
Barium (Ba) 133	0.081, 0.276, 0.303, 0.356, 0.384	Electron capture
Cadmium (Cd) 109	0.088	Electron capture
Cesium (Cs) 137	0.662	Negative Beta

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Cobalt (Co) 57	0.122, 0.136	Electron capture
Cobalt (Co) 60	1.173, 1.333	Negative Beta
Manganese (Mn) 54	0.835	Electron capture
Sodium (Na) 22	0.511, 1.275	Positive Beta

Photon Attenuation in NaI(Tl)

Half-Value Thickness for Gamma Rays
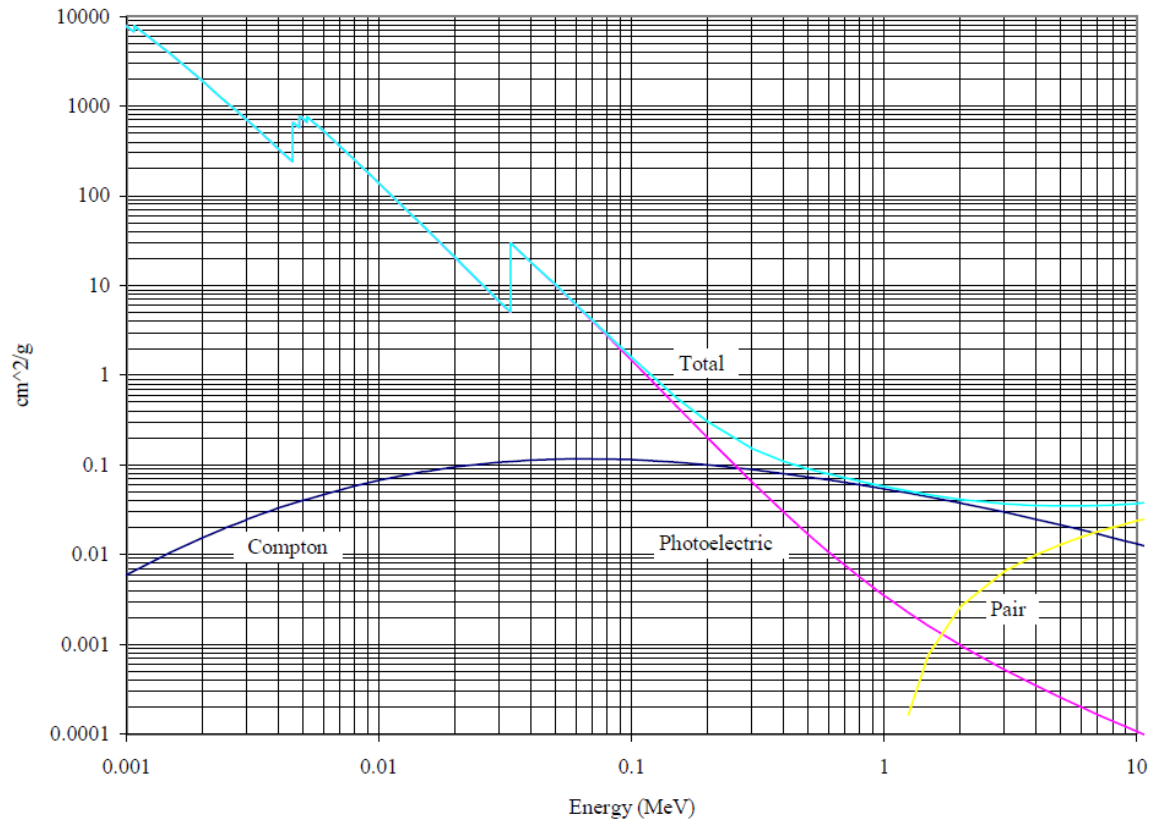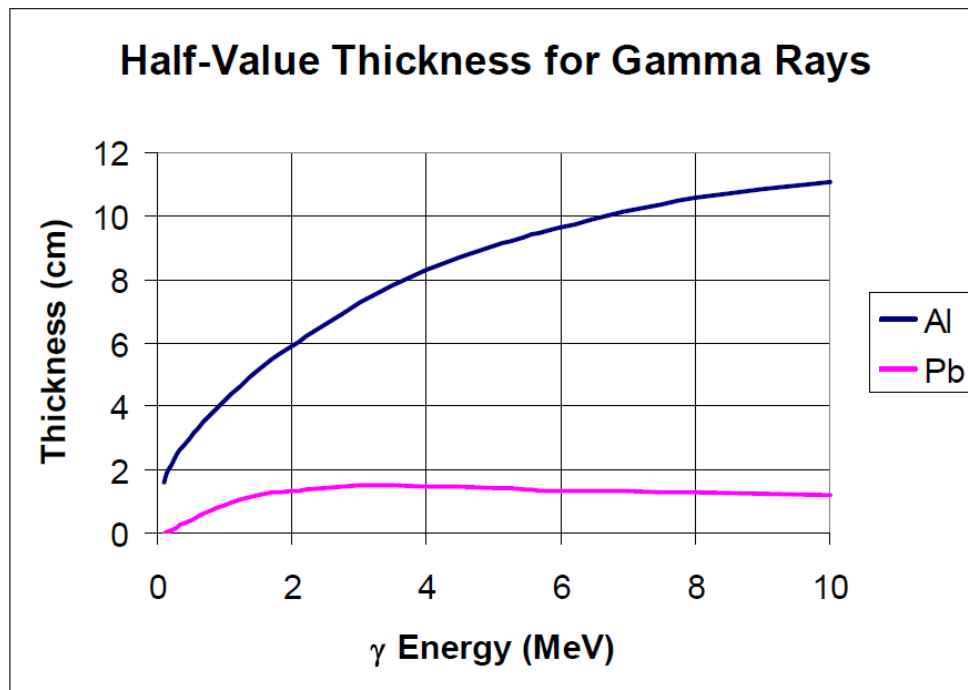
SODIUM IODIDE - ACTIVATED ALKALI-HALIDE SCINTILLATORS:

Energy absorption and photon emission by activated alkali-halide scintillators are complex processes most conveniently described by means of the band theory of solids. A pure single crystal is represented in the figure below by a **valence band**, which is normally filled with electrons, and the normally empty conduction band above it.
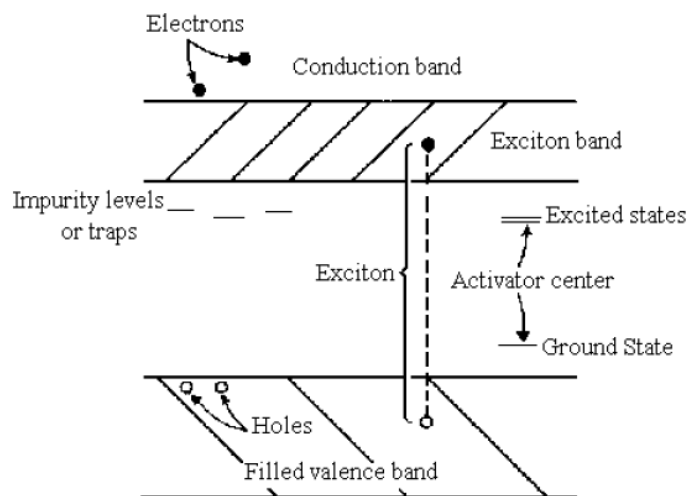
Separating them is a forbidden band of energies (~8 eV), called the **band gap**, where free electrons cannot exist. A particle interacting with the crystal may cause an electron to move from

the valence band up to the conduction band by an ionization process, producing a vacancy in the valence band that is called a hole. Conduction band electrons, and the valence band holes, are free to move independently throughout the crystal. When a conduction band electron decays to the ground state, the emitted photon has a short wavelength (UV) with a high probability of being re-absorbed, and eventually contributing to the excitation of activator sites. There is a finite probability that the quantity of energy that is deposited will be insufficient to produce ionization, but large enough to cause excitation, i.e., the elevation of an electronic state above the valence band. This electron will remain electrostatically bound to the hole it left in the valence band, to constitute an electron-hole pair called an ***exciton***. The exciton states form a thin band (width ~1 eV) whose upper level will coincide with the lower edge of the conduction band.

Lattice imperfections such as ***vacancies***, or *impurity atoms* that are supplied by an "***activator***", produce relatively low energy states in the band gap at isolated sites in the crystal lattice. The elevation of an activator atom to an excited state may result from the absorption of a photon produced by the decay of an excited state in the conduction band, the capture of a migrating electron and hole (in any order), or the capture of an exciton. The decay of an excited activator state (the predominant mode of scintillation) produces a photon in a decay time of the order of 200 ns, at a wavelength in the short blue or long UV region. Because the energy that is needed to produce an activator photon is always lower than what is required to excite a conduction band electron, very little reabsorption takes place, *i.e.,* ***the parent crystal is highly transparent to the scintillation photons.***

The most common alkali-halide scintillator is single-crystal Sodium Iodide with about 0.1% Thallium Iodide activator content [NaI(Tl)], developed by Robert Hofstadter in 1948. See the links on the 157 web page for this experiment. It provides relatively high Z and density, with the highest currently available luminescent efficiency. Principal deficiencies are extreme toxicity from the Thallium content, <u>mechanical fragility</u>, and the need for a hermetic sealed enclosure for protection from water.

γ rays generate about 5×10^4 ion-pairs/MeV of energy deposited in NaI(Tl), giving a detection conversion efficiency of ~12%, or about 4×10^4 photons/MeV, with each photon having an average energy of ~3 eV, or about 1 emitted photon per ion-pair generated.

Relevant parameters for NaI(Tl) are:

** Density : 3.67 g/cm^3.
** Z : Na=11, I=53, Tl=81.
** Luminescent efficiency: 12% of energy of incident radiation.
** Temperature coefficient of luminescence: 0.2 to 2%/oC.
** Wavelength of maximum emission: 420 nm.
** Index of refraction: 1.85 at 420 nm.
** Decay time: 230 ns @ 25 °C.
** Energy resolution: 6.5% @ 662 KeV at best. (7.5% typical)

Your primary reference text for this experiment is Knoll, *Radiation Detection and Measurement.* A copy of this is available for use IN THE LAB.

References:

G.F. Knoll, *Radiation Detection and Measurement* (John Wiley & Sons, New York, 2000)
W. R. Leo, *Techniques for Nuclear and Particle Physics Experiments: A How-to Approach*, 2nd. rev. ed., (Springer-Verlag, 1994).
A.C. Melissinos and J. Napolitano, Experiments in Modern Physics (Academic Press, 2003) chapter 9.2.
One copy of these books is available for use in the lab.