Energy Measurements

In this lab you will learn about pulse-height measurements and how to use pulse-height spectra to measure the energy of gamma rays emitted by different radioactive sources. You will study the relationship between high-voltage bias and the output of a photomultiplier tube, and compare the spectra made with plastic and sodium-iodide scintillator detectors.

Photomultiplier response

For this exercise you will use the 10 stage Electron Tubes 9266KB photomultiplier tubes available in the laboratory. This tube has a maximum rated voltage of 1000 volts; you would typically operate it from about 750 to 900 volts. ***One should always look at the pulses on the scope as the voltage is raised for the first time to check for light leaks or abnormal behavior.***

To explore the gain of photomultiplier tubes (PMTs) we use a light pulser to simulate the light output of the scintillator. The pulser provides a *fixed* intensity of light pulses, and it makes it easier to study the PMT itself without worrying about the amount of light produced by a scintillator+source. The light pulser is a simple instrument in which a capacitor is charged and then discharged through an LED using a Field Effect Transistor (FET) as a switch. The light pulser requires a DC voltage in the +25 to +40 volts range and a positive trigger input pulse of 2–4 volts.

Before using the light pulser with a photomultiplier tube, you should check that the pulser is working by looking at the (green) LED with your eye, as follows.

Figure 1: Left: Light pulser module. Note the little LED at the end opposite the terminals. Right: PMT inserted into the light-pulser housing (not taped up, though).

First, make pulses of the appropriate type. Connect the trigger output of a square pulse generator (i.e., the HP 8011A stand-alone or BNC 8010 NIM pulser) to the external trigger input of the scope and the signal output to the channel 1 input of the scope. Terminate the signal with 50Ω. Adjust the pulser to make pulses of width of 30–40 nanoseconds, height of about 4 volts, and a pulse period (interval between pulses) of 20 to 30 microseconds, equivalent to a pulse frequency of 30–50 kHz.

After setting the pulser appropriately, connect the signal output to the BNC input connector of the light pulser and connect a benchtop DC power supply to the red and black terminals and adjust the voltage to about 30 volts. With these settings you should be able to see a faint light from the

LED by holding the pulser housing up to your eye and cupping your hands to block any stray light coming in between the housing and your face. If you don't see anything, try widening the pulse width a bit. When you think you see something, diconnect the pulse generator from the light-pulser input, and then reconnect it to verify that the light from the LED disappears and reappears. (What you see looks like a steady glow. Do you understand why you don't see the LED flickering on and off?)

After verifying that the light pulser is working, you are ready to attach it to the PMT.

First disconnect the the pulse generator and turn off the DC power supply. Then insert a 9266KB PMT an inch or so into the light pulser housing and tape the PMT to the housing so that the joint is light tight. See Fig. 1.

Apply a high voltage to the PMT of +700 volts. ***Remember to follow the correct protocol for bringing up the high voltage.***

Turn the DC power supply voltage *all the way down.*

Then turn on the DC power supply and reconnect the pulse generator. Slowly increase the pulser power supply voltage and observe the PMT output pulses on the scope. You should see pulses with a well defined amplitude in the range of tens to hundreds of millivolts. If saturation effects seem to be present reduce the light level of the pulser by either narrowing the pulse width or reducing the power supply voltage. Saturation is indicated by a notable distortion in the pulse shape.

Set the PMT high voltage to +850 volts, and adjust the light pulser inputs as to achieve a PMT pulse height in the range of 500 millivolts. Watch what happens as you vary the DC voltage on the light pulser power supply, the pulse width, and the pulse amplitude. Your settings should be in the following ranges:

- DC voltage: 25 to 40 volts.
- Pulse width: 30 to 50 nanoseconds (if the pulse width exceeds 50 nanoseconds, the PMT output pulse will begin to distort—check for yourself).
- Pulse height: 3 to 4 volts.

Again, the pulse *period* (time between pulses) should be 20 to 30 microseconds (about 40 kHz). This will allow for plenty of recovery time between pulses, but is still a high enough repetition rate to make for a readily visible display on the scope.

Now you should be ready to record the PMT's response to changes in high voltage with a fixed light input. Keep the pulse width, pulse height and pulser power supply voltage constant. Vary the high voltage between +400 and +950 volts in 50 volt steps and record the pulse amplitude (peak pulse "height", or in this case "depth") from the oscilloscope screen. Do not exceed +1000 volts, as this may damage the photomultiplier tube.

Plot pulse height vs. high voltage on a suitable kind of graph to reveal the functional dependence. Leo gives the following formula for the gain G of a PMT:

$$G = \delta^n = (KV_d^\alpha)^n \ , \tag{1}$$

where δ is the secondary emission factor, n is the number of dynode stages, V_d is the dynode-to-dynode voltage, and K is a proportionality constant. In Eq. (1) Leo assumes that exponent $\alpha = 1$ which would make the stage gain δ directly proportional to the dynode voltage. If we assume that the pulse amplitude is proportional to G, how might you plot your data to reveal the functional dependence given by Eq. (1) which is a "power-law"? Could you verify that $n = 10$, as predicted by the description in Leo? If you assume $n = 10$, what should α be? Also, could you estimate K?

After recording your voltage vs. pulse amplitude data, look for noise pulses from the PMT, as follows. Turn the pulse generator and the pulser power supply off. Switch the scope triggering to "Internal", with a negative slope. Decrease the time/div settings (i.e., speed up the timebase), and watch the scope as you turn turn the channel sensitivity up (i.e., decrease the volts/div) until you see some action. You will need to fuss with the trigger level.

Observe and record the noise pulses for a few values of the applied PMT voltage. These noise pulses are very short and they do not have a sharply defined pulse height spectrum so consequently your "measurement" of their pulse height will be a very rough estimate. (Note: depending on your particular PMT and scope, you may have a hard time seeing noise pulses. If you cannot seem to find them, please confirm that they are too small to detect with the instructor or TA.)

Now you are ready to study the fluctuations of the PMT output using a pulse-height analyzer. Turn the light-pulser power supply and pulse generator back on, and adjust the settings so that you get pulse heights of about 100 mV with minimum distortion.

Connect the output of the PMT to the input of an Ortec 575A pulse-shaping amplifier. Look at the output of the amplifier on the scope. Adjust the gain of the amplifier so that you see clean, undistorted, positive-going shaped pulses of about 5 volts peak height. You may also need to adjust the the light pulser parameters (input pulse width and/or height) if your amplifier output is saturated (i.e., has a flat top as seen on the scope trace).

The shaping amplifier does two things that are important to this experiment: it inverts the pulse, and it amplifies it so that it can be measured with a pulse height analyzer—these units typically require positive pulses between 0 and 10 volts. Note: it is easy to overdrive these amplifiers. If you see a flat-topped pulse, you need to reduce the gain. Notice that there are two knobs to set the gain, a "coarse" and a "fine". The total gain is the product of the two.

The shaping amplifier output is connected to the input of a digital pulse-processing unit made by AmpTek, that performs pulse height analysis. This unit is the AmpTek MCA8000D "Pocket MCA". *MCA* stands for Multi-Channel Analyzer. The device measures the incoming pulse waveform, determines the heights of the positive-voltage peaks, and creates a pulse-height histogram. The user of the program may select the resolution of the histogram, i.e., the number of bins, along with other parameters. The resulting data can also be analyzed with the unit's software to find peak locations and widths in terms of the pulse-height voltage, measured in units called "channels." The range of allowed input voltages is 0–10 volts, and this range may be subdivided in factors of two from 256 up to 8192 channels

Start the AmpTek application **DppMCA** according to the instructions from the TA or lab manager. You should set the channel number to 1024, which gives plenty of resolution for this experiment. Too see how to do this, consult the Help files accessible from the top menu. In particular, read through the *Overview* and the *Quick Start Guide.*

Start data collection by clicking the *Stoplight* icon (or select MCA>Start Acquisition from the menu bar).

After a short delay you should see the histogram begin to accumulate. Let the data taking run until you can see a clear peak, and then a bit more until the spectrum is well established. (Note: by default the acquisition continues indefinitely. You may set it up to run for a pre-defined time or pre-defined total number of counts under MCA>Acquisition Setup.)

Stop the data acquisition (Stoplight again). Then adjust the pulser to make the amplifier pulses lower in amplitude (say 2 volts), and restart data acquisition. Repeat this action one or two more times with different pulse heights until you see a collection of peaks spanning the range of the spectrum analyzer (5 is plenty). Save the data set (File>Save As). Then you or your partners may analyze the data by selecting *regions of interest* or *ROIs* dialog box to fit a Gaussian peak shape to the important peaks. Detailed instructions for using the pulse height analysis features are available under Help. Look for *Analyzing Data.*

Record the peak positions and widths in a table. Notice and comment on how the peak width changes as the peak position changes. Is the width directly proportional to the position, or does if follow some other rule?

The data collection and analysis program is free and may be downloaded for use on your own computer. (Note: the software runs on Microsoft Windows only.) To obtain a copy, look for the links on the course website, or perform an internet search on "AmpTek."

Energy response of a scintillation detector

See W. Leo, Ch. 7 and Knoll Ch. 10 for background information.

To study energy response and energy resolution we will observe gamma rays from various gamma ray sources. For these measurements you will use an existing 2-inch thick plastic detector/photomultiplier tube combination (already taped up) and a NaI scintillator+PMT combination. See Fig. 2 to see what each looks like.

Note that the plastic and NaI detectors should be powered from separate high voltage power supplies. The high voltage for the NaI detectors is always +1000 volts. The voltage to apply to the plastic detector PMT is marked on the outside.

Figure 2: Top: Plastic scintillator detector. Bottom: Bicron NaI detector.

Comparison of plastic and NaI

Connect the signal output of each detector to a channel on the oscilloscope, and terminate the input to the scope with 50Ω. Place a ^{137}Cs source near the pair and adjust the gain on the scope so that you can see pulses on both channels. (You may need to switch the trigger between the channels to see things clearly on each channel. This is one place where using the “VERT MODE” setting on the trigger source is appropriate.)

Look at the output pulses from both the plastic scintillating material and the NaI crystal using the source. Note any differences and explain them in your notebook. In particular, pay attention to the decay time of the pulses and the height of the pulses. As noted in Leo, section 8.5.4, the 50Ω termination on the cable means that the RC constant of the PMT load should be small. Hence, the decay time should be dominated by the scintillator response.

Estimate (roughly, of course) the decay time for each type of detector. Discuss, in your report, whether your measurements are consistent with Leo’s claims about scintillator response.

Now get ready to take some pulse height spectra. Connect the output of the plastic detector to the Ortec 113 preamp and then the output of the preamp to the 575A shaping amplifier.

The purpose of the preamp is to boost the level of the signal and to match the time characteristics of the signal to the input of the 575A. When using an NaI detector, you can see a well-shaped single-polarity pulse on the scope screen when the “pole-zero” adjustment on the 575A is properly set. In this case, one minimizes the baseline offset, and thus optimizes the resolution of the detector system.

However, the plastic detector is not well suited to the preamp for this purpose, and you will always see an undershoot in the amplifier signal. For the purposes of comparing the plastic and NaI spectra, this does not matter, but when you set up to make good NaI spectra, you should adjust the pole-zero carefully.

Look at the output of amplifier on the scope. Adjust the gain of the amplifier so that the maximum pulse height using a ^{137}Cs source is about 5 volts. Take a photo of the pulse from the amplifier, and annotate it in your notebook, paying attention to its width and any particular “bright regions” that you can see. Given what you saw with the light pulser, what do these bright regions signify?

Use a TEE to feed the output of the amplifier into the pulse height analyzer while keeping it visible on the scope. Take some pulse height spectra until you see clearly defined features (typically 10,000 to 30,000 total counts is sufficient). Save copies of the spectrum for your notebook.

Repeat the above procedure for the NaI detector: plug it into the preamp+shaping amp and look at the output, set the gain to give 5 volt pulses. Now see if you can dial the pole-zero setting to minimize the baseline over or undershoot. Once you have it looking good, take a picture of the pulses you see from the amp, and then take spectra.

Compare the features of the pulse scope-images and spectra from plastic and NaI detectors in your notebook. Comment on the different features you see, and how they might correlate between each spectrum. Your discussion should make use of the information in Leo, in particular, sections 5.4 and 7.7.

Also discuss how the shape of the pulses is affected by the pulse shaping amplifier. Discuss the purpose of the “shaping” property of the amplifier. See Leo, Ch. 14.

Features of the pulse height spectrum

Obtain a ^{60}Co source. Look at the pulses created by this source and set the gain of the 575A so that the top bright line is a little less than 9 volts. Record the amplifier gain and preamp capacitance setting you use. ***Important: After setting the gain, do not change it! Use this amplifier gain setting to measure the spectrum of every source for the NaI detector in***

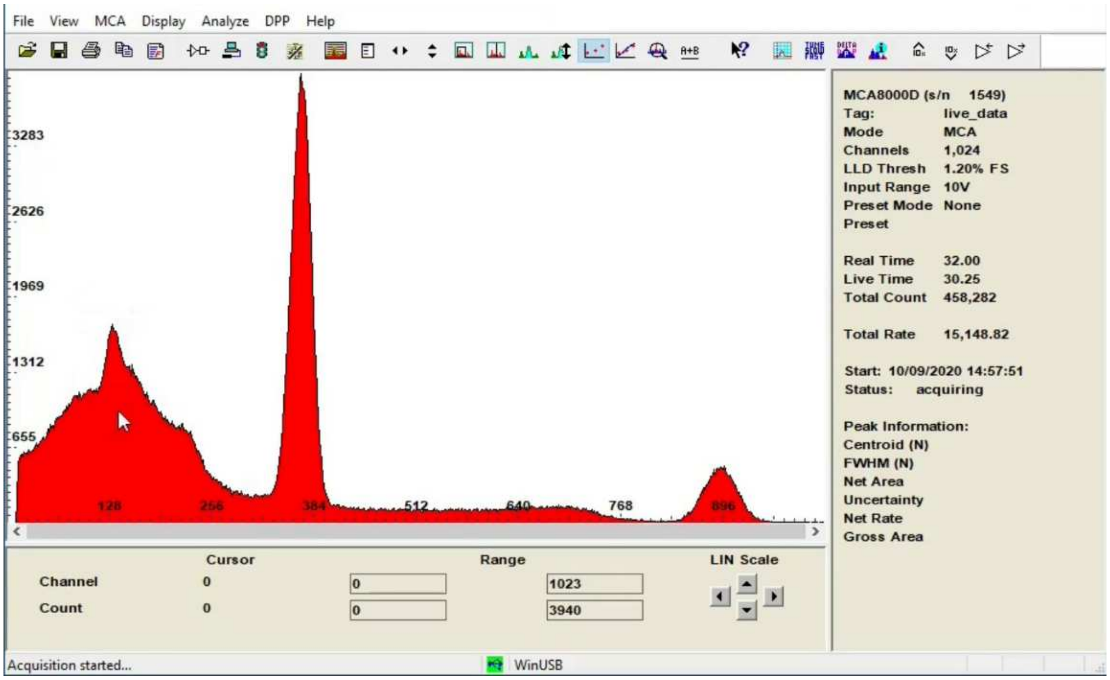
this section. You will want to quantitatively compare the spectra that you take from each source in the remaining exercises.

Before recording a spectrum, make sure you do not have the source too close to the detector. You will know it is too close if you get a lot of "pulse pile-up" visible on the scope. Pulse pile-up happens when two output pulses occur almost at the same time, and so the resulting signal is higher than a single pulse. The effect is to smear out the spectrum peaks and give many counts above the highest photopeak. Avoid swamping your detector!

Once you have everything set, record all settings (PHA gain, capacitance on the Ortec 113, number of MCA channels) and take careful spectra to analyze. Record spectra with the NaI detector for the following sources: ^{133}Ba, ^{137}Cs (now with the revised amp gain setting), ^{22}Na and ^{60}Co. In each case, record data long enough to get clear peak features that may be measured with the software.

Important: Only have one source at a time out in use and immediately return each source to the storage box after you have taken your data. There are two reasons for this: first, you want to minimize your overall exposure to the radiation, and second, if you have another source near your detector you will contaminate your spectra.

Identify the various features of the pulse height spectra, as recorded by the NaI detector. These include the photopeak, the Compton edge, the Compton continuum, the Compton backscatter peak, and in some cases, x-ray peaks. Which of these features measures the energy of the incoming photon? It is very important that you understand completely the photo-peak and the Compton edge and explain these clearly in your notebook.



MCA8000D (s/n	1549)
Tag:	live_data
Mode	MCA
Channels	1,024
LLD Thresh	1.20% FS
Input Range	10V
Preset Mode	None
Preset	
Real Time	32.00
Live Time	30.25
Total Count	458,282
Total Rate	15,148.82

Start: 10/09/2020 14:57:51
Status: acquiring

Peak Information:
Centroid (N)
FWHM (N)
Net Area
Uncertainty
Net Rate
Gross Area

	Cursor	Range		LIN Scale
Channel	0	0	1023	
Count	0	0	3940	

Acquisition started...

WinUSB

Figure 3: The PC screen when running the AmpTek pulse height analyzer to take pulse height spectra. The spectrum shown is from a ^{22}Na source.

For each isotope, look up the nuclear level diagram showing the decay mode and principle transitions that produce the γ energies that we use in this experiment. Sketch the level diagram. It should indicate the type of decay mode, and what the original isotope becomes after the decay is done.

Energy scale and resolution of spectrometer

The NaI detector, preamp, pulse-shaping amp, and pulse height analyzer together comprise a type of gamma-ray spectrometer. You could, in principle, use this instrument to measure the gamma-ray spectrum of other sources and identify them. But to do so requires a *calibration curve*: something to relate the pulse height in terms of volts or channel number to the energy of the gamma rays in units of MeV.

The table "Commonly used radioactive sources" (by E. Browne, Lawrence Berkeley National Laboratory) lists the most common emission type and energy of a number of sources. Look up the energies for the sources you used, and note which peaks on your spectra correspond to which energy.

Load each spectrum data file into the DppMCA program. Set ROIs for the photopeaks and obtain the centroid and width for each peak. Record these numbers in a table along with the isotope and the known energies in MeV.

Plot the peak positions (in channel units) along the x-axis, and the corresponding energies along the y-axis, and fit the results to a line. This is your calibration curve. Your line fit parameters should also show their uncertainty, as determined by the line fit.

From your calibration curve, determine the peak widths in terms of the energy spread ΔE (in electron volts). On a separate graph, plot the peak widths (ΔE) versus the peak locations E. How well does the plot follow the model given in Leo, section 5.4? Can you estimate the product of the Fano factor times the average energy of ionization, Fw, that is described by equation (5.5) in Leo?

Prepared by D. Pengra and H. Lubatti
`energy_measurements_2021.tex -- Updated 27 October 2021`