Energy Measurement Using a Photomultiplier Tube (PMT)

Scintillator detectors consisting of scintillating material coupled to a photomultiplier tube are widely used for precision energy measurements of photons, electrons and hadrons. An example of large plastic scintillator–PM arrays used by the ATLAS collaboration at the LHC to measure the energy of very high energy hadrons was given in Lecture 2 (see posted slides).

In this week's 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.

Prior to coming to lab you should open and study the three links *Multichannel Analyzer (MCA), Light Pulser* and *Radioactive Sources* found under Laboratory Apparatus Information on my web page. You also should calculate the energy value of the Compton edge of the ^{133}Ba, ^{137}Cs and ^{60}Co sources before coming to the lab.

2.1 Photomultiplier Response

To explore the gain of a photomultiplier tube we use a light pulser to simulate the light output of the scintillator. The light pulser provides a light pulse of short duration at an intensity that depends on the applied voltage. Using this device we can explore the response of the phototube (PMT gain) as a function of the light intensity striking the photocathode. In effect we are simulating the light output of a scintillator. 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 roughly in the +25 to +40 volts range and a positive trigger input pulse of 2- 4 volts.

The first step is to make the pulser give appropriate light pulses. Connect the trigger output of a square pulse generator (i.e. the HP 8011A standalone 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 30-40 nanoseconds, height of about 4 volts, and a pulse period (interval between pulses) of 20 to 30 microseconds.

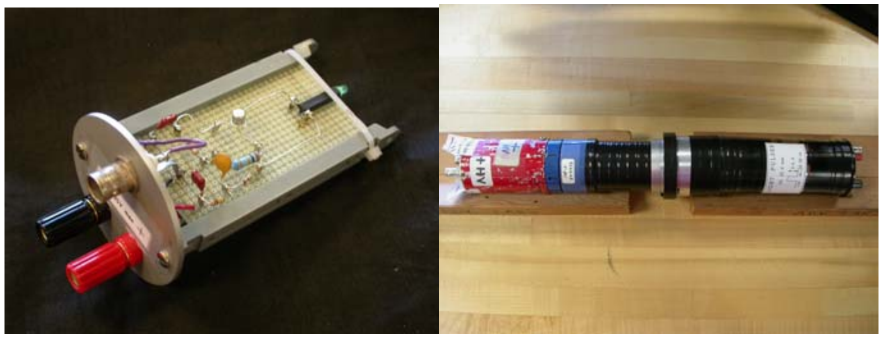

Figure 1 (Left): Light pulser circuit (note the green LED bulb) and PM inserted in light pulser enclosure. (Right): Light pulser connected to the PM.

For this experiment 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. For our application we will operate the tubes in the 750-800 V range. If saturation effects seem to be present reduce the light level of the pulser, which can be done by either narrowing the pulse width or reducing the pulser power supply voltage. **One should always look at the PM output pulses on the scope as the voltage is raised for the first time to check for light leaks or abnormal behavior.**

Connect the pulser supply and trigger voltages. With the voltage set at about 25-30 volts trigger the light pulser and look at the LED to be sure that you observe light pulses. Once you verify that light pulses are visible insert the bare phototube into the pulser housing and tape the end of the housing with the black electrical tape to make a light tight seal.

Observe the output of the photomultiplier on an oscilloscope. Trigger the scope internally to look at noise. Observe and record the noise pulses as a function of the applied PM tube voltage. These noise pulses do not have a sharply defined pulse height spectrum so consequently your "measurement" of their pulse height will be a very rough estimate. The light pulser will result in a well-defined voltage output of the PMT. If you have difficulty seeing noise pulses ask the TA for assistance.

Set the PMT high voltage to +850 volts, and adjust the light pulser inputs to result in a PMT pulse height in the range of 500 mV. Observe and note what happens as you vary the DC voltage of the light-pulser power supply, the pulse width, and the pulse amplitude over the following ranges. Make several measurements (at least 5 for each item below) and and plot the dependence and discuss results in you lab report. Give special attention to the measured values of the PM output pulse values as a function of the light pulser supply voltage for a fixed PM high voltage. Why would this dependence be important for calorimeters that use scintillator detectors?

- DC voltage: 25 to 40 volts.
- Pulse width: 30 to 50 nanoseconds (observe what happens to the PMT output if the pulse width exceeds 50 ns).

- Pulse height: 3 to 4 volts.

Setting the time between pulses (pulse period) in the range 20 to 30 μs (about 40 kHz) allows for sufficient recovery time between pulses, and is a high enough repetition rate to give a visible display on the scope. The next step is to record the PMT's response as you change the PM high voltage while keeping the input light input constant; i.e., the pulse width, pulse height and pulser power supply voltage are held constant. Vary the high voltage over the range +400 to +900 V in 50 V steps and record the pulse height observed on the oscilloscope screen. **(NB: do not exceed +1000 V on the PMT) .**

The pulse peak amplitude should be proportional to the gain (G) of the PMT. In section 8.5 W. Leo gives the following functional dependence of G on applied voltage, where δ is the secondary emission factor, V_d is the dynode-to-dynode voltage, and K is a proportionality constant:

$$G = \delta^n = (KV_d)^n$$

What value do you obtain for n? ***What is the best way to plot the data to reveal the expected functional dependence?*** Make such a plot in your lab report.

Now you are ready to study the fluctuations of the PM output using a pulse-height analyzer. Set the light pulser voltage to 25 volts. Connect the output of PM 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.

The shaping amplifier does two things that are important for this experiment: it inverts the pulse, and amplifies it so that it can be measured with a pulse height analyzer (PHA) PHA 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. There are two controls available for setting the gain: “coarse” and “fine”. The total gain is the product of the two.

For this fixed voltage setting collect several pulses (10 or so) and save them to a file and/or print out the distribution. The observed distribution is a measure of the fluctuations of the PM for a fixed light intensity (See W. Leo section 5.3). Use the LabVIEW peak analysis program to fit the peak and find the full width at half maximum, using a Gaussian fit. ***Use these results to discuss the resolution of the NaI photo-peaks in section 2.2. While these measurements are in progress, part of the group should set up for 2.2.***

2.2 Energy Response of a Scintillation Counter

See W. Leo, Ch. 7 and Knoll Ch. 10

To study energy response and energy resolution of NaI and plastic scintillator detectors, we will observe gamma rays from the following sources: ^{133}Ba, ^{137}Cs, ^{60}Co, ^{22}Na. For these measurements we will use an existing 2-inch thick plastic detector/photomultiplier tube combination and a NaI scintillator PMT combination. ***In the lab report, compare and discuss the spectra of pulse heights observed from the two scintillator counters for each of the sources.***

Plastic scintillator and PMT

NaI crystal and its PMT

Figure 2. Plastic and NaI detectors used in this lab.

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 scintillator detector PMT is marked on the outside.

2.2.1 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 see pulses on both channels. (It may be necessary to switch the trigger between the channels to observe clearly each channel. This is one situation 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 one of the sources. ***Note any differences and explain them in your lab report. Pay particular attention to the decay time of the pulses and the height of the pulses.*** As noted in W. Leo, section 8.5.4, the 50Ω termination cable results in a small PMT load. Consequently, the decay time should be dominated by the scintillator response.

For each detector make an approximate (rough) estimate of the decay time of the pulse (τ_S), which is the time for the pulse to fall to 1/e of its peak value (see W. Leo section 8.5.4 (it is). ***In the lab report, discuss whether your measurements are consistent with W. Leo's claims about scintillator response.***

2.2.1.1 Pulse Height Spectra

Connect the output of the plastic detector to the Ortec 113 preamp and the output of the preamp to the 575A shaping amplifier. The preamp not only boosts the level of the signal, but also matches the rise and fall times of the pulses to the expected input to the 575A. A well-shaped, single-polarity pulse should be seen on the oscilloscope screen.

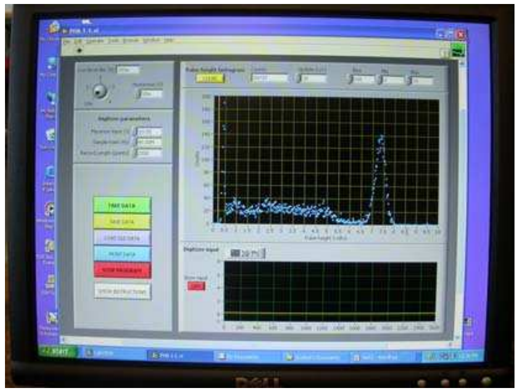

Figure 3: The PC screen when using the LabVIEW pulse height analyzer to take pulse height spectra. The spectrum shown is from a ^{137}Cs source.

While observing the output of the amplifier on the oscilloscope, adjust the gain of the amplifier so that the maximum pulse height from a ^{137}Cs source is about 5 volts. Make a sketch of the pulse from the amplifier, noting its width and any particular "bright lines" that you notice (relate to what you observed with the light pulser). What do these bright lines signify?

Input the amplifier signal to the pulse light analyzer, while continuing to observe the output of the amplifier on the oscilloscope. Take pulse height spectra until you see clearly defined features (usually 20,000 to 30,000 total counts are sufficient). Repeat for the ^{60}Co source. Save and print copies of the ^{137}Cs and ^{60}Co spectra for each member of your group.

Repeat the above procedure for the NaI detector. Connect the output to the preamp and shaping amplifier and look at the output; set the gain to give 5 volt pulses and sketch the amplifier pulse for use in the lab report.

In your lab report: Compare the spectrum of the ^{137}Cs and ^{60}Co sources taken with the two different scintillator detectors. Comment on the different features you see, and how they might correlate between each spectrum. Your discussion should make use of the information in W. Leo (see in particular sections 5.4 and 7.7). Also discuss how the shape of the pulses is affected by the pulse shaping amplifier. What is the purpose of the "shaping" property of the amplifier? See W. Leo, Ch.14.

Features of the pulse height spectrum

Obtain a ^{60}Co source and set the gain of the 575A so that the top bright line is a little less than 9 volts. ***Important: Use this amplifier gain setting to measure the spectrum of each***

source for the NaI detector. You will need to quantitatively compare the spectra that you take from each source in the remaining exercises.

Record spectra with the NaI detector for the following sources: ^{133}Ba, ^{137}Cs (again, with the new amp setting), ^{22}Na and ^{60}Co. In each case, record data long enough to get clear peak features that may be fitted with a peak-fitting program.

Important: Only the source you are currently studying should be at your lab station; return each source to the storage box after you have taken your data. If you have another source near your detector, you risk contaminating your spectra.

Identify the various features of the pulse height spectra recorded by the NaI detector: the photopeak, the Compton edge, the Compton continuum, the Compton backscatter peak, bremsstrahlung and, if possible, x-ray peaks. Which of these features measure 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 lab report.

In your lab report discuss carefully the differences between the spectra observed for the same source by the NaI and Plastic Scintillator and discuss/explain any differences.

Exercise 1 *(For the lab report.) 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 a spectrometer

The NaI detector, preamp, pulse-shaping amplifier, and pulse height analyzer together form 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. To do so requires a *calibration curve*: something that relates 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” available on the class website (Radioactive Sources link at the bottom of the main page) lists for a number of sources the particles emitted and their energy. **For lab report:** Using the table to determine the energy of each peak you observe in your energy spectra and note on the spectra the energy of each peak.

Load each spectrum data file into the relevant LabVIEW program. If you used the Norland MCA, use the “Norland Interface” program; if you used the “Pulse Height Analyzer” program, use that again. You can look at previous data sets by clicking the LOAD OLD DATA button.

Click on ANALYZE DATA to open up the peak fitting window. Click on the

ANALYZE DATA button for instructions. Fit each important photo peak to obtain the peak position and width with a Gaussian line shape. (Note: you can only fit one peak at a time, so make sure that you only see one peak when you run the fitting routine.) There is no need to print out a copy of every peak you fit, but recording the fit results is a must!

For your report. For each of the Gaussian peaks you identified, plot the peak positions (in channel or voltage units) along the x-axis and the corresponding known energies along the y-axis. Fit the results to a straight line (y = A + Bx). Excel or KaleidaGraph can be used to make the fit. If you have one point that seems to be an outlier, make sure you have it correctly identified. This is a calibration curve. Your line fit parameters should also show their uncertainty, as determined by the line fit.

Report extra credit exercise

The widths of the Gaussian you fit to each peak can be used to determine the energy resolution of the scintillator. Use your calibration curve to convert the peak widths given by the fit (in voltage units) into an energy spread ΔE (in electron volts). On a separate graph, plot the spread ΔE versus the peak locations E. **For your lab report**: discuss how well does the plot follow the model given in W. Leo, section 5.3 and estimate the product of the Fano factor times the average energy of ionization, *Fw*, equation (5.5) in W. Leo?

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