3 WEEKS

Gamma Ray Spectroscopy —
Measurement Gamma Ray Energies and Radioactive Assay

ABSTRACT

This experiment gives you the opportunity to study high energy photons from radioactive decays. These photons have energies that are characteristic of the specific initial- and final- state nuclear energy levels and therefore provide a means of studying the energy levels (similar to the use of optical photons to study electronic energy levels in atoms), nuclear reactions, and also provide a way to identify radioactive nuclear species in test samples. The experiment provides for open-ended investigation of gamma ray spectroscopy; it typically requires three weeks of lab work.

I. INTRODUCTION

Nuclei can change their state in a variety of ways. They can split up (fission) or they can emit particles of various types. There are α particles which contain two neutrons and two protons, ß particles which are either an electron(ß-) or a positron (ß+), or γ rays, which are simply high energy photons. If the nucleus emits an alpha or beta, the number of protons and neutrons must change (why?). However, when it emits a gamma it remains the same except it changes its energy state. All of these particles can be detected. However, they interact with matter in very different ways, as is discussed in the references. Alphas can only penetrate a very small amount of material before they loose all their energy. Betas can penetrate modest thicknesses of material, depending on their energy. Gammas on the other hand can penetrate rather substantial thicknesses of most materials. This means they are more dangerous because it is difficult to prevent them from reaching the researcher's body. On the other hand, it makes them easier to study since they can easily escape the radioactive source and get into detectors. Most radioactivity you will encounter in this experiment will be in the form of gamma rays. Since they are produced by a nucleus changing energy states, there will be characteristic energy gammas for each nucleus. By measuring the energy of the emitted gammas, we can determine which nuclei are in a sample. By observing the energy of the gamma rays produced in a nuclear reaction, we can also learn about the reaction. You will do both of these experiments in this lab.

We detect the gamma rays using a NaI crystal. When the gammas go through the crystal they give up energy. They can either scatter from electrons (Compton scatter), which causes them to lose a variable fraction of their energy, they can create electron-positron pairs which gives up an amount of energy just equal to the rest mass of the pair, or they can just give up all their energy in the crystal through scintillation (direct release of lower energy photons). The energy the gamma loses is converted into a pulse of light in the crystal which is detected by a photomultiplier tube (PMT) which is a sensitive instrument for detecting light. The amount of light which is produced, and hence the output of the photomultiplier, is directly proportional to the amount of energy which is lost. In this experiment you determine the size of these pulses, and thereby learn about the gamma rays. To do this, you convert the pulses of current which come out of the PMT into voltage pulses and then do a "pulse height analysis" of the various pulses.

Pulse height analysis is simply the cataloging of the number of pulses that have been observed in each size interval. This analysis is done using a analogue-to-digital converter to convert the amplitude of each pulse into an appropriate digital number and storing in memory the number of pulses falling within each unit interval (known as a "bin" or "channel"). In this experiment, you will use a multichannel analyzer (MCA) board interfaced to a computer. After all this processing one ends up with a plot of the number of events detected for each energy interval, which is just the gamma ray spectrum. The spectrum is different for each gamma ray source.

In the first part of this experiment, you will observe spectra from a variety of sources (Co, Ba, Cs and Mn) with known gamma ray energies and fluxes, and use these to calibrate the apparatus for later measurements of unknown gamma ray energies and activity. You will also observe Compton scattering.

In the next part of the experiment you will use the energy and efficiency calibration you have made of the system to analyze the constituents of a radioactive sample of dirt which was found during construction of an apartment building at 4th and Pearl. This dirt was left over from radium processing.

Equipment:

Refer to the diagram in Figure 1.

The detector is a thallium activated sodium iodide (NaI(Tl)) crystal scintillator in a silver colored aluminum can. Be careful, the aluminum is made quite thin to minimize energy loss of particles passing through it. This means it is easy to poke a hole in it if you are not careful. Inorganic crystal scintillators and their advantages for detecting gamma rays are presented in Melissinos and other references. The crystal is directly mounted on the front of the PMT so that to you they look like one piece.

The light from the crystal goes into the PMT where it knocks electrons off the photocathode. These electrons are then amplified by the dynode chain. The amount of amplification depends on the type of PMT and the applied voltage, but can easily be 10^6 or more. **Applying too large a voltage or the wrong polarity of voltage to a PMT will generally destroy it.** The polarity and max voltage should be given on the tube. If you have any doubt, check with the instructor before applying voltage. See the references for a more extensive discussion of PMTs. There are two different power supplies provided. You can use whichever gives the best experimental results.

The pulsed current output of the PMT goes into an amplifier which has an adjustable gain. This amplifier also converts the input pulse shape (time dependence) into the pulse shape which the MCA likes best. The pulse shaping controls on the amplifier should not be changed but you should adjust the gain to whatever you choose.

The output of the amplifier goes into the multichannel analyzer. This is an EG&G interface board and software which goes into a PC. The manuals and some condensed instructions for the MCA are next to the apparatus. Among the many things it can do are, 1) acquire and plot spectra, 2) save spectra on discs, 3) subtract two spectra (for example a 20 minute run with a source and a 20 minute background run with no source), and 4) calibrate a spectrum if given two calibration peaks.

There are a variety of radioactive sources you can use in this experiment. The standard sources are in small bright colored plastic housings labeled with the material, the age, and the initial activity of the sample.

There are also several small pill bottles filled with radioactive dirt to be used in the sample analysis experiment. If you are unsure of the radiation danger from any of these samples you should use the geiger counter to measure the radiation at various distances from the samples and compare with background radiation and the safe dosage levels.

II. PROCEDURE:

You should become familiar with the operation of the data acquisition program and the nature of the spectra from the sources. You should find the best settings of the PMT voltage and the amplifier. In doing this you should use your various sources to calibrate the MCA spectrum, and evaluate various sources of error including such things as saturation or other nonlinearities, drift in the gains of any parts of the system and resolution limits due to noise or insufficient points on the spectrum. An example of a typical spectrum is shown in Fig. 2. You will have to work out strategies of taking data to evaluate and reduce these sources of uncertainty. You may encounter lines that are present even when all sources are removed. Information in Melissinos and elsewhere may provide clues to the origin of this "background". You should also consider how it might effect your results and how any such effects might be avoided.

We could have provided you with equipment which

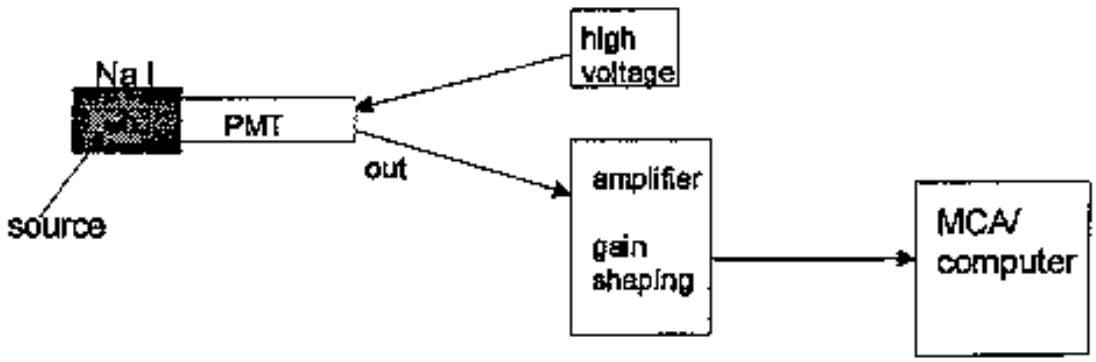

Figure 1. Block diagram of the experimental apparatus.

was carefully selected and tested so that it gave optimum results with no thought on your part. We have intentionally avoided doing that. You should understand that the primary objective of this lab is to learn how to evaluate the limitations of your apparatus, and how to get the best possible results given those limitations.

In addition to calibrating the energy scale, you should obtain a calibration of the detection efficiency versus energy. This can be obtained using the given activity of the calibration sources and figuring the best way to extrapolate between the calibration points.

III. CALIBRATION AND COMPTON EDGE

When you look at any of the gamma peaks there is a rather flat spectrum below the peak due to Compton scattering What is the energy of the "Compton edge" in terms of the gamma ray energy? Calculate the energy of the Compton edge for the ^{137}Cs peak and compare to your measured value. (A discussion of the Compton effect can be found in Melissinos.)

IV. RADIOACTIVE ASSAY

Observe the sample of radioactive dirt with your gamma spectrometer to determine the energies of the principal gamma rays emitted. Since the sources may be weak you will want to take data for as much as an hour. Remember to consider the possible contribution of background radiation. Before taking extensive data see if additional shielding is of any value.

From your data identify the nuclear parents of the gamma peaks seen in your spectrum. You are left to use some ingenuity, given the origin of the material and some radioactivity reference manuals in the lab. Once you have identified the sources of the gammas, determine the relative amounts of each of the several possible radioactive decay chains and compute the level of contamination in nanocuries (nCi) per gram. This will use your calibration of detection efficiency.

V. IMPORTANT QUESTIONS TO CONSIDER:

1. How does one calibrate the detector efficiency given sources of a known radioactivity?
2. Assuming one has a calibrated detector, how do you find the radioactivity of an unknown sample?
3. What would be the effect of the PMT or amplifier gain changing with time?
4. How could you test for such effects?
5. If observed, what are the likely causes?
6. How would you check whether or not the energy scale is linear?
7. If they exist, what might cause nonlinearities and how could you avoid them?
8. How might the single and/or double escape peaks be used to improve your calibration and accuracy in the measurement of E_γ?

Some useful numbers:

Proton: $mc^2 = 938.272$ MeV
Deuteron: $mc^2 = 1875.613$ MeV
^{1}H: 1.00782522 atomic mass units
^{2}H: 2.01410222 atomic mass units
$m_e c^2 = 0.5110034$ MeV
MeV/amu = 931.49432

VI. REFERENCES:

1. A. Melissinos Experiments in Modern Physics pp. 194-208, 252-265.
2. Ferway, Moses & Moyer, Modern Physics (1989), C Chapter 13, pp. 372-396. This gives agood basic introduction an to nuclear processes
3. D. Preston and E. Dietz, The art of experimental physics, see experiments 18 and 19, and Appendix B for a discussion of apparatus
4. J. Moore, C. Davis, and M. Coplan, Building Scientific. Apparatus, pg 242-257 on PMTs.

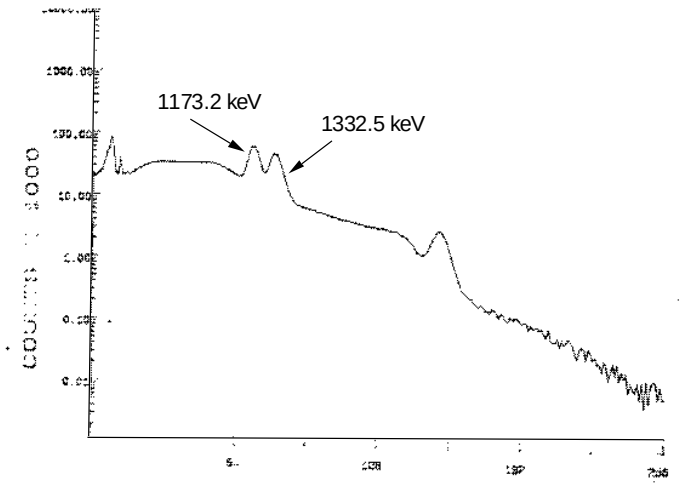

Figure 2. Gamma ray spectrum from a calibration sample of ^{60}Co. Image is scanned from a printout from the multi-channel analyser program. Notice the two closely-spaced peaks at 1173.2 keV and at 1332.5 keV respectively.