THE SCINTILLATION COUNTER

PHYSICS 359E

INTRODUCTION

The development of detectors for both counting and measuring the energy of particles and photons has played an important role in the evolution of nuclear physics. In this experiment, you will be introduced to one such detector - the scintillation counter - which is particularly suitable for detecting γ-ray photons. You will use it to observe the energy spectrum of γ-rays from several nuclei and study the absorption of γ-rays in Pb and Al. You will also become familiar with some of the standard components of pulse electronics that may be used with any detector producing a pulse output.

PRE-LABORATORY PREPARATION

1. Read Secs. 8.1, 8.2.1, 8.2.5 and 8.4, and Appendix E2, in Ref. 2.
2. Read the material given below under heading APPARATUS.

APPARATUS

When certain types of crystals are bombarded with energetic charged particles, the crystal emits visible radiation. The amount of radiation is proportional to the energy lost in the crystal, so that a measurement of the total amount of radiation emitted may be used to determine this energy loss. The radiation is commonly measured with a photomultiplier, to be described below.

Crystals

There are two principal types of scintillating crystals, broadly described as organic and inorganic. In either type, the details of the physical processes by which particle kinetic energy eventually appears as light are fairly complex. No attempt will be made to discuss this matter here, but a fairly comprehensive treatment is given in Ref. 2.

The commonest type of inorganic crystal is sodium iodide with thallium ions as activator. This has the advantage of high density, so that energetic particles can be brought to rest in a fairly small crystal. The major disadvantage is that NaI is very hygroscopic, so that the crystals must be carefully mounted in sealed housings. After passage of a particle, the light output from the crystal decays with a time constant of about $2.5\,10^{-7}$ s. This is a rather long time as rates of atomic processes go, and sodium iodide, along with most inorganic crystals, is regarded as a "slow" scintillator. Incidentally, the screens of cathode ray tubes and T.V. picture tubes employ inorganic scintillators which convert the kinetic energy of 15 keV electrons to visible light.

Organic crystals used at one time were mainly of the condensed benzene ring structure such as anthracene, stilbene or phenanthrene. These were relatively fragile, and have now been largely superseded by plastic or liquid scintillators. These can be made of a wide variety of ring compounds (the scintillator) dissolved in a suitable aromatic solvent, or polymeric plastic such as polystyrene. They are usually obtained now as proprietary commercial products. In general, organic scintillators are "fast" in the sense that their light output takes place in a time < 1 ns.

Photomultipliers (PMT)

These devices utilize the two phenomena of photoelectric effect and secondary electron emission. A diagram of a typical photomultiplier is shown in Fig.1. Actual examples of tubes are available in the laboratory. The whole structure is contained in an evacuated glass envelope. Light from the scintillator produces photoelectrons at the photocathode, and these electrons are then accelerated through a potential difference of a few hundred volts and directed against the first dynode. This is a metal electrode with a special surface which emits several low energy electrons (on the average) when struck by an electron or ion of a few hundred electron volts energy. The mean number of secondary electrons per primary electron is known as the secondary emission ratio. In the multiplier structure these secondary electrons are again accelerated and directed against another dynode where the secondary emission process is repeated for each electron coming from the first dynode. If the secondary emission ratio is α and the tube contains n stages of multiplication, then each photoelectron will produce α^n electrons at the output of the multipliers. Thus, α^n is the gain of the photomultiplier.

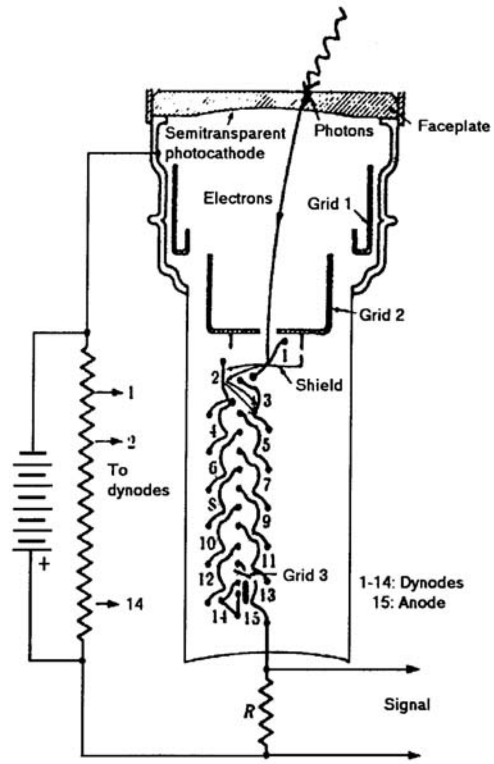


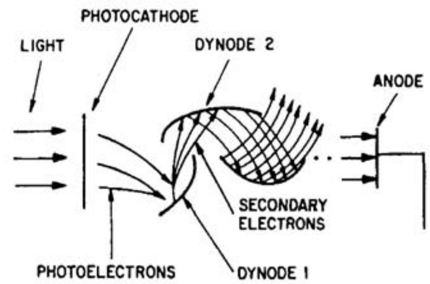
Figure 1: Operation of a photomultiplier tube

Multipliers are commonly built with ten stages ($n = 10$), though fourteen stage tubes are not unusual. The secondary ratio depends on the accelerating voltage per stage, with values in the range of 3 to 5 for usual voltages. Thus the total gain can be quite high ($3^{10} \approx 10^5$). Because of the dependence of on accelerating voltage, the gain is a very sensitive function of total voltage applied to the multiplier, and carefully regulated power supplies must be used. The electrons from the output of the photomultiplier charge a capacitor, and the resulting voltage pulse can be observed on an oscilloscope, or amplified and used to drive a single- or multi-channel analyzer.

PROCEDURE

N.B.: This laboratory makes use of radioactive sources. These are sealed sources of low activity, and present no potential health hazards. You should become familiar with the standards for permissible radiation exposure, and standard procedures for handling and monitoring sources. These are described in the Radiation Safety manual in the lab. You should also read Appendix D of Reference 2. Please discuss these issues with your instructor if you have any questions.

N.B. In a scintillator-photomultiplier combination, electrons play crucial roles in each device, but they are not the same electrons. Gamma rays entering the scintillator produce fast electrons whose kinetic energy is partly converted to visible and ultraviolet light. These photons leave the scintillator and strike the photocathode of the photomultiplier where they produce slow photoelectrons. These electrons are then accelerated in the PM tube and each one produces a large number of electrons at the anode via secondary emission along the dynode chain.



Schematic Representation of a Photomultiplier Tube and its Operation

Figure 2: Multiplication on PMT dynodes

1. Look over the controls on each unit in Figure 3, and be sure that you understand its operation. Most of the instruments are called NIM (Nuclear Instrumentation Module) instruments and reside in the NIM bin which provides their power. Pertinent excerpts from operating manuals are available in the lab. The dashed line from the pulser in Fig 3 indicates that it may be connected to the amplifier instead of the detector. For the first few exercises you will look at the output of the detector directly on the oscilloscope and will not use the amplifier, single channel analyzer or scaler.

2. Place a ^{137}Cs radioactive source close to the sodium iodide crystal of the detector. Turn on the HV supply, and set the voltage to the normal operating value (see tube specifications, but definitely do not excee 1500 V). Trigger the oscilloscope display on negative pulses, and set the horizontal scan speed to about 2 μs/cm. You should observe negative pulses with varying amplitudes. Why are the heights of the pulses not all the same?

   Measure the variation in maximum pulse height as the photomultiplier voltage is varied from 500 volts to 1500 volts. From a log-log plot of output signal amplitude vs. photomultiplier voltage, find the dependence of overall photomultiplier gain on voltage. *Express your result as an equation.* Explain why you would expect the gain to depend on voltage.

3. The photomultiplier used has 10 stages of multiplication. Explain how the gain should depend on the secondary emission ratio α. Use the results of the previous exercise to deduce the dependence of α on electron energy.

4. Assuming that the interaction of a gamma ray with the scintillation detector results in the production of one photoelectron at the cathode of the photomultiplier for every 10^3 eV of energy lost by the γ-ray, use your results to find the actual magnitude of the gain of the photomultiplier. To do this you will need to know the value of the capacitor to which the photomultiplier is connected in your apparatus. This value should be written on the underside of the photomultiplier base. Deduce the value of α.

5. Using the normal operating high voltage on the PM tube, record the maximum pulse heights observed with each of the following sources: ^{137}Cs, ^{60}Co, ^{22}Na, ^{57}Co, and ^{133}Ba. Look up the energies of the γ rays emitted by these various radioactive sources (look at the course Web

page for links to suitable sites), and explain how the maximum pulse heights are related to the γ-ray spectra of the sources.

6. To become familiar with the use of the pulse amplifier and single channel analyzer (SCA), connect the test pulser to the input of the amplifier and use the oscilloscope to measure the gain of the amplifier for a few settings of the gain controls. Then, using the amplifier output, verify that the SCA produces an output pulse only when the input pulse has an amplitude lying between the limits set by the analyzer controls.

7. Now connect the detector to the input of the amplifier. With the ^{137}Cs source in place and normal operating high voltage on the PM tube, adjust the amplifier gain to give pulses of about 3 V maximum amplitude. Set the window on the SCA to a width of 0.2 V and measure the pulse height spectrum from the detector. Explain the main features of the spectrum in terms of the processes occurring when the γ-rays from the source interact with the sodium iodide crystal. Explain the finite width of the photoelectric peak distribution.

8. Repeat 7. with a ^{60}Co source, without changing the amplifier gain.

9. Mount the detector inverted in the lead holder provided. Place the ^{137}Cs source beneath the counter and set the SCA so that the window takes in the photoelectric peak in the pulse height spectrum. Using the standard absorbers provided, measure the count rate as a function of absorber thickness for Al and Pb, subtract an appropriate background count rate, and deduce the mass absorption coefficients μ in cm^2 g^{-1} (or m^2 kg^{-1}) of the γ-rays for these materials. Make a fit to the log(count rate) vs absorber thickness data to achieve this. To interpret your plot, take logs of both sides of Eq. (8.6) in Ref. 2, and compare the resulting expression to your data. Compare your measurements with values from Ref. 3, or from Ref. 4 (p. 195) and discuss the systematic errors arising from the geometry of your set-up. (Reread the discussion in Ref. 2., Sec 8.2.1, that you read before coming to class.)

10. Repeat this measurement with the ^{57}Co source. Be sure that the window on the SCA is set to accept the 0.122 MeV γ-ray from this source.

REPORT

Your report should include the following:

- Answers to the questions posed in 2. and 3. above, and particularly plots and equations describing the dependence of overall photomultiplier gain and α on applied high voltage.

- A determination of the actual values of the overall PMT gain and α as discussed in 4.

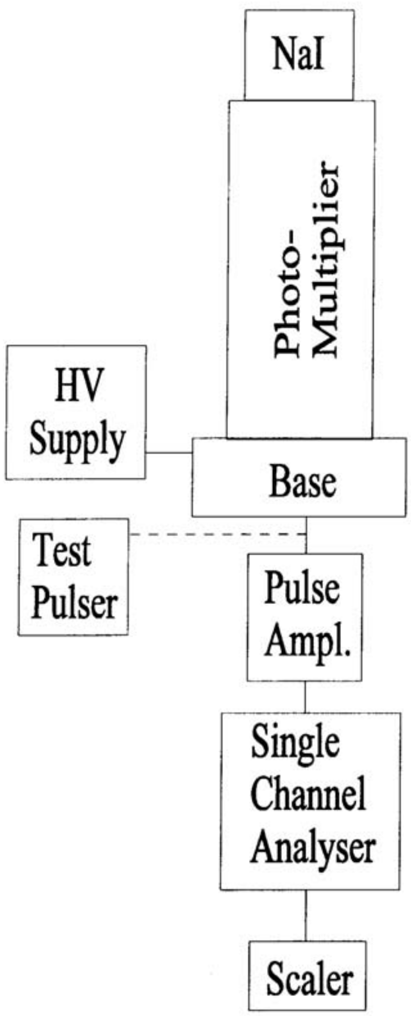
- A report on 5, explaining the relationship of the pulse heights to the accepted energies of emitted γ-rays.

- Your pulse height spectra from 7. and 8., and a discussion of the features in these spectra (you may find it useful to check out the lab write-up on making graphs with Excel or Matlab).

- A short explanation of how you determined the absorption coefficients in Al and Pb (9. and 10.) from your data, including a discussion of measurement uncertainties and a comparison of your results to accepted values.

References

1. R. Eisberg and R. Resnick, Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles (Wiley, New York, 1985), Secs 2-8 and 16-5
2. A. C. Melissinos & J. Napolitano, Experiments in Modern Physics (San Diego, CA: Academic Press, 2003)
3. Handbook of Chemistry and Physics, (CRC Press; available in the lab).
4. Enge, H., "Introduction to Nuclear Physics" (Reading, Mass.: Addison-Wesley, 1966; available in the lab)



(a) Absorption or scattering of γ-ray produces a burst of uv and visible photons. Total energy of the photons is proportional to the energy lost by the ray in the crystal.

(b) Photons reaching the photocathode cause the emission of electrons via the photoelectric effect. Through secondary electron emission at each dynode, each electron emitted at the cathode results in a burst of $10^5 - 10^7$ electrons at the anode.

(c) Amplifies and shapes the photomultiplier output pulse. (NIM module Ortec 485 or other)

(d) Outputs a standard pulse suitable for counting only if the input pulse amplitude lies within a preset range. (NIM module 406A or other)

(e) Counts the pulses for a fixed time interval. (NIM module, also called a counter or timer/counter)

Figure 3: Block diagram of electronics used in scintillation detector