Experiment 251: Radioactivity

Aim

The purpose of this experiment is to study qualitatively some properties of α, β and γ radiations and the Geiger-Muller counter used for their detection.

References

1. R.A. Serway, C.J. Moses & C.A. Moyer: "Modern Physics" Saunders
2. R.D. Evans: "The Atomic Nucleus" McGraw-Hill
3. H. Enge: "Introduction to Nuclear Physics" Addison-Wesley
4. C.M. Lederer, J.M. Hollander & I. Perlman: "Table of Isotopes" John Wiley
5. T.B. Brown (Editor): "The Taylor Manual" Addison-Wesley
6. H. Mark & N.T. Olson: "Experiments in Modern Physics" McGraw-Hill.

References 2 – 6 are available in the Advanced Laboratory.

Introduction

As part of this experiment you should revise the basic facts about radioactive decay by reading the appropriate sections of Reference 1 or Reference 6, or Chapter 8 of Reference 3, or Chapter 15 of Reference 2.

You will already have met the absorption of photons by matter in first year physics. The absorption of charged particles you may not have met. A quick review will be found in Section 14.1 of Reference 1. If you are interested in a more detailed account, read Chapter 7 of Reference 3 or Chapter 18 of Reference 2.

The detector used is a Geiger-Muller (GM) tube. A brief description of its principle of operation is given in Section 14.8 of Reference 1 or in Reference 5. Its efficiency depends on the type of radiation being detected and one object of the experiment is to measure this. The other main object of the experiment is to determine the effect of a magnetic field on the radiations and the approximate absorption characteristics of γ rays in matter.

Because of the statistical nature of radioactive decay you must be certain that you have detected a sufficient number of particles for the required degree of precision. The Poisson distribution is applicable here and if you are not familiar with this you can do little better than to read Chapter 26 of Reference 2, especially Section 1c. The main fact which comes from this is that if N events are detected the standard deviation in the number is $\sqrt{N}$.

Note: The experiment uses radioactive sources that are not normally present in the laboratory. Ask your demonstrator for your sources, and note which of the sets of sources he assigns to you. As this experiment involves a number of unfamiliar concepts for most second year students, it is essential that you discuss it fully with a demonstrator before or during the laboratory work.

Apparatus

The GM tube is powered by a high-voltage supply in the display housing. Electrical pulses produced in the tube by a charged particle are fed to the scaler for counting. α, β and γ radiation can be detected by means of this tube which consists of two concentric electrodes in a low pressure gas mixture.

Before operation, the operating voltage across the electrodes of 800 V will need to be set. Turn on the counter unit with the red switch on the back. Press "Display select" on the front panel repeatedly until the "Voltage" is displayed. Use the "Up" button to set the voltage to 800 V. Then, press "Display select" repeatedly until "Counts" are displayed. **Be sure not to exceed 1000 V on the detector!** Normally no current will flow but when an α or a β particle enters the tube the gas is ionized and a current pulse passes.

The Geiger tube is also sensitive to γ radiation. However, to cause ionization the γ ray or photon must first interact with an electron in an atom of the gas or the walls of the chamber to produce a free electron which in turn produces ionization.

The Geiger tube takes a finite time (a hundred μs or so) to recover from a current pulse and if during this time a further particle enters the tube it will not be counted. This is termed the *dead* time of the tube.

The Geiger tube used in this experiment is halogen-quenched and has a typical dead time of 150 μs, a window diameter of 25 mm and a window thickness of 2 mg/cm^2. Its active length is 10 cm. The window of the detector is 0.3 cm behind the front surface of the mount. Three radioactive sources are supplied:

(i) An α source of Americium 241 (half-life = 432.1 years)

(ii) A β source of Strontium 90 (half-life = 28.78 years)

(iii) A γ source of Cobalt 60 (half-life = 5.272 years)

Warning

1. Do not touch the front surfaces of the sources. If you do accidentally, wash your hands thoroughly with several changes of hot soapy water.
2. Do not remove the sources from their holders. This is normally not necessary for this experiment.
3. The amount of radiation emitted by these sources is well below the legal maximum. The only real danger that could arise would be from ingestion of some of the radioactive material.

Source Strengths

The strength of a radioactive source is specified in terms of the becquerel (Bq). It is simply defined as 1 nuclear transmutation per second. Although the becquerel is the correct S.I. unit, an older unit is still often used. This is the curie (Ci) and 1 curie = 3.7×10^{10} nuclear disintegrations per second. The sources used in this experiment are very weak, of the order of 10^4 becquerel.

To determine the present strength of a source you need to know its original strength S_0 and the date of its calibration.

Its present strength will be given by the exponential decay law:

$$S = S_0 \exp\left(-0.693\, t/T_{1/2}\right) \tag{1}$$

where $T_{1/2}$ is the half-life of the source.

(1) Examine the back of each of the three sources and note its original strength and its date of calibration. Calculate the present strength of each source in both units of microcuries and becquerels.

Determination of background radiation

It is first of all necessary to measure the background count rate. This is due to cosmic radiation and natural radioactivity of the environment and must be subtracted from all subsequent measurements, *i.e.*

$$T = O - B \tag{2}$$

where O is the observed count due to some source, B is the background count detected **in the same time interval**, and T is the true count due to the source.

(2) Remove all known sources from the vicinity of the Geiger tube. Measure the number of counts, N, in a two minute interval. An estimate for the standard deviation in this result is $\sqrt{N}$ (Poisson statistics). Work out the background count rate, B, (in counts per minute) and its standard deviation, σ_B. What is the percentage error? If the number of counts had been measured over a longer time interval, the percentage error would be smaller. What time interval would give an error of $\sim 10\%$?

(3) In all measurements with the γ source it should be covered with the thin shield provided. Place the γ source about 25 cm from the Geiger tube window. Make a preliminary measurement of the observed count rate, O, (in counts per minute). From this result, and your experience in (2), over what time interval should counts be collected to determine O to 10 %? Make a suitable measurement to determine O to at least 10%.

(4) Determine the true count rate T and its standard error $\sigma_T = \sqrt{\sigma_O^2 + \sigma_B^2}$. Is the percentage error in T less than 10 %? If not, make appropriate measurements of O and B to reduce the error in T below 10%.

    Note: Throughout the remainder of this experiment you should choose time intervals for counting that give uncertainties in true count rates of $\simeq 10\,\%$. However, if achieving this precision requires a time interval exceeding 4 minutes, use a time interval of 4 minutes and be content with a larger error.

Qualitative penetration properties of nuclear radiations

(5) Place the γ source 1 cm from the Geiger counter and measure the count rate. Insert a single thickness of steel between the source and the counter and measure the new count rate. Repeat these measurements using the β source.

(6) Place the β source about 5 mm from the detector and measure the count rate with and without a single thickness of ordinary paper as absorber.

(7) Repeat this with the α source placed about 1 mm from the detector. As well as emitting α particles the ^{241}Am source also emits γ rays which will be detected. This fact should be kept in mind when studying the effects of absorbers with this source.

(8) Comment on the relative penetrating power of α, β and γ radiation.

Interaction of nuclear radiations with a magnetic field

(9) Set up the equipment with the collimator close to the detector and the magnet between the elements of the collimator. Place the source under investigation close to the collimator.

(10) Determine the effect of the magnet on the count rate from the γ and β sources. Remember to correct for background.

(11) What conclusions can you draw from this? Suggest a way of determining whether the magnet is affecting the detector.

Inverse square law for nuclear radiations

For a point source radiating uniformly in all directions (see Figure 1) the flux of particles per unit area must decrease inversely as the square of the distance from the source.

If the source emits n particles per second, they all pass through both spheres and the intensity I or energy flux per unit area is:

$$I_1 \propto \frac{n}{4\pi d_1^2} \qquad \text{and} \qquad I_2 \propto \frac{n}{4\pi d_2^2}$$

so

$$\frac{I_2}{I_1} = \frac{d_1^2}{d_2^2}$$

This holds true only if the radiation goes in straight lines, is not absorbed and the source can be approximated by a point.

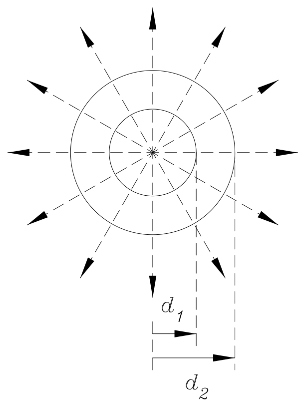

Figure 1:

Although these conditions do not hold perfectly in this apparatus, the effectiveness of distance in reducing count rate can be determined as follows.

Since the count rate N is expected to be of the form:

$$N = \frac{N_0}{d^2}$$

a log-log plot will give:

$$\ln N = \ln N_0 - 2 \ln d$$

which is a straight line of slope -2. As the detector is about 10 cm long, the value of d is not just the reading from the ruler. A correction will need to be added to the ruler reading to give d.

(12) Determine the count rate as a function of distance for the γ source with the steel shield, remembering to correct for background at the larger distances.

(13) From a consideration of how the detector works for γ rays, choose a reasonable correction to be added to the ruler reading to give d. Plot a graph of $\ln N$ -vs- $\ln d$ and determine its slope. What conclusions can you draw from the result?

Detection efficiency of Geiger counter

The detection efficiency η of any counter is usually expressed as a percentage and defined as:

$$\eta = \frac{\text{number of counts recorded by counter}}{\text{number of particles incident on the counter}} \times 100$$

It is then a simple exercise to establish that for $d \gg r$, η is given by:

$$\eta = \frac{4Td^2}{Sr^2} \times 100 \tag{3}$$

where T is the number of true counts detected/unit time, S is the number of particles radiated/unit time by the source, r is the radius of the Geiger tube, and d is the source-detector distance.

(14) Determine the detection efficiency of the Geiger counter for both β and γ radiations. Measure T for d of about 15 cm. Also note the ^{60}Co source emits two γ rays simultaneously for each nuclear transmutation in this source. (You can check this by looking up the decay scheme for ^{60}Co in Reference 4.)

Attenuation of γ rays

A γ ray travelling through a material substance has a certain probability of interacting with the substance after travelling through a certain thickness.

Assume there are initially n γ rays in a beam. After travelling through a thickness dx, if dn of the γ rays interact then:

$$dn \propto n\,dx$$

i.e.

$$dn = \mu_0 n\,dx$$

where the constant of proportionality μ_0 is the linear absorption coefficient.

Solving the above differential equation will give:

$$n = n_0 \exp\left(-\mu_0 x\right)$$

where n_0 is the initial number of γ rays in the beam.

(15) Measure the count rate for the γ ray source placed as close to the detector as the absorber holder will allow.

(16) Place a single thickness of steel between the source and the detector and measure the count rate. Now repeat for $2, 3, \ldots, 11$ pieces of steel and plot a graph on semilog paper of number of counts -vs- distance travelled through iron. Plot the graph as you go. Determine μ_0.

Note: If the thin steel shield is not on the source the first point on the graph will not fall on the straight line formed by subsequent points. Check this. (An explanation of this is required in question 5).

Questions

These are to be answered as part of the normal write-up.

1. Derive equation (3).
2. Explain why the detection efficiencies for β and γ radiation are so different. Should the nature of the detection process for γ rays have any effect on the value of d used in the section on Inverse square law for nuclear radiations? Discuss briefly.
3. Taking the dead time of the counter as 150 μs, for what fraction of the time is the counter rendered dead in your highest counting rate measurement? Does this justify ignoring "dead time corrections" in this experiment? Explain.
4. Calculate the thickness of iron necessary to reduce the γ intensity by a factor of 100. Now consider a source at distance 10 cm from the detectors. Assuming only inverse square attenuation, at what distance will the γ intensity be a factor of 100 less than at 10 cm?
5. Why is it recommended that a steel shield be placed over the ^{60}Co source?

Write-up

The experiment write-up must include:

1. Calculation of the current strength of the α, β and γ sources supplied.
2. Calculation of the duration of measurement required for 10% overall statistical accuracy when source count rate and background count rate are comparable.
3. Effect of magnetic field on β and γ radiation and on the detector.
4. Graphs (with error bars included) of $\ln N$ -vs- $\ln d$, investigating the inverse square law for γ rays. Comments on results.
5. Calculation of Geiger counter detection efficiency for β and γ radiation.
6. Comment on the relative penetrating powers of α, β and γ radiation.
7. Answers to questions 1 – 5 listed above.

APPENDIX

Radiation Hazards

All the radioactive sources used in the Advanced Laboratory are sealed and do not present a hazard in normal use.

Although source strength is measured in becquerels (number of disintegrations per second) the biological effect depends on absorbed energy which in turn depends on the type of radiation.

The unit of absorbed energy from radioactive sources is the gray (Gy) which is 1 J kg^{-1}. Since different types of radiation can have different biological effect for the same energy absorbed a further unit, the sievert (Sv), is used. This unit is defined as:

$$1 \text{ Sv} = 1 \text{ Gy} \times \text{ quality factor}$$

The quality factor ranges from about 1 for X rays, γ and β radiation up to 20 for α particles and neutrons. The number of sieverts is referred to as the "dose". To get a feel for the dose from various sealed sources examine the following table:

Nuclide	**Dose rate** (μSv/hr) **at one metre from 1 GBq**
^{241}Am	3.2
^{137}Cs	89
^{60}Co	360
^{22}Na	320

This should be compared with the neutral background radiation which is about 1 – 10 mSv/yr depending on location. The maximum dose allowed in any one year is 50 mSv. Clearly the sealed sources in the laboratory present little hazard. For instance in this experiment a ^{60}Co source of strength of the order of 30 kBq is used. At a distance of 10 cm this gives a dose rate of about 1 μSv/hr. A dose of 50 mSv would then be received after about 6 years of continuous exposure.

As there is no known threshold below which radiation can be said to have no effect, the dose should be minimised at all times. The only way the small sources used in this experiment would be hazardous is if they were ingested and their chemical composition was such that they remain in the body for a long time.

List of Equipment

1. Geiger tube and stand
2. Counter
3. Permanent magnet and stand.
4. Steel absorbers and holder
5. Steel collimator
6. Thin steel source shield
7. ^{241}Am α source
8. ^{90}Sr β source.
9. ^{60}Co γ source

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