# α, β, and γ

Nuclear radiation can be broadly classified into three categories. These three categories are labeled with the first three letters of the Greek alphabet: α (alpha), β (beta) and γ (gamma). Alpha radiation consists of a stream of fast-moving helium nuclei (two protons and two neutrons). As such, an alpha particle is relatively heavy and carries two positive electrical charges. Beta radiation consists of fast-moving electrons or positrons (an antimatter electron). A beta particle is much lighter than an alpha, and carries one unit of charge. Gamma radiation consists of photons, which are massless and carry no charge. X-rays are also photons, but carry less energy than gammas.

After being emitted from a decaying nucleus, the alpha, beta or gamma radiation may pass through matter, or it may be absorbed by the matter. You will arrange for the three classes of radiation to pass through nothing but a thin layer of air, a sheet of paper, and an aluminum sheet. Will the different types of radiation be absorbed differently by the air, paper and aluminum? The question can be answered by considering which radiation type will interact more strongly with matter, and then tested by experiment.

In this experiment you will use small sources of alpha, beta, and gamma radiation. *Follow all local procedures for handling radioactive materials.*

## OBJECTIVES

- Develop a model for the relative absorption of alpha, beta, and gamma radiation by matter.
- Use a radiation counter to measure the absorption of alpha, beta, and gamma radiation by air, paper, and aluminum.
- Analyze count rate data to test for consistency with your model.

## MATERIALS

computer
Vernier computer interface
Logger *Pro*
Vernier Radiation Monitor or
Student Radiation Monitor
Polonium-210 0.1μC alpha source
Strontium-90 0.1μC beta source
Cobalt-60 1μC gamma source
paper sheet
aluminum sheet, about 2 mm thick

## PRELIMINARY QUESTIONS

1. Most nuclear radiation carries energy in the range of a few million electron volts, or MeV ($1 \text{ MeV} = 10^6 \text{ eV} = 1.6 \times 10^{-13} \text{ J}$), regardless of its type (alpha, beta, or gamma). This means that more massive particles generally travel more slowly than light particles. Make a preliminary guess as to which radiation type will in general interact most strongly with matter, and therefore would be most strongly absorbed as it passes through matter. Consider electrical charge, mass and speed. Explain your reasons.

2. Which radiation type do you predict would interact, in general, least strongly with matter, and so be less absorbed than others? Why?

3. Which radiation type do you predict would have an intermediate level of interaction with matter? Why?

4. You will be using paper and aluminum sheet metal as absorbers for the radiation. Which material has the greatest areal density (that is, a density per unit area, which could be measured in g/cm$^2$), and so would present more matter to the passing radiation? Which material would have less?

5. Is your radiation monitor sensitive to all three types of radiation? How can you tell? Devise a test and carry it out. If your radiation monitor does not detect one form of radiation, then you will be able to compare the absorption of the remaining two types.

## PROCEDURE

1. Connect the radiation monitor to DIG/SONIC 1 of the computer interface.

2. Prepare the computer for data collection by opening the file "01 Alpha Beta Gamma" from the *Nuclear Radiation w Computers* folder of Logger *Pro*.

3. If you are using the Radiation Monitor (brown plastic case with meter) place the source near the metal screen, and when using an absorber, place the absorber between the source and the screen. If you are using the Student Radiation Monitor (black plastic case with no readout), place the source near the Geiger tube window on the underside, and when using an absorber, place the absorber between the source and the window. In either case, use approximately the same position for the sources each time, with and without an absorber. The sources are usually mounted in small plastic discs, with the most radiation emitted from the underside of the disc.

   Begin with no source, to determine the background count rate. Move all sources away from the monitor. Click **Collect** to begin collecting data. While it may appear as if data collection did not start, Logger *Pro* is collecting data. Wait 50 s for the number of counts to appear in the meter. Record the number of counts in the no-source row of your data table, no shielding.

4. Using no absorber, place the beta source near the appropriate region of your radiation monitor, with the underside of the disc facing the monitor. Click **Collect** to begin collecting data. Wait for Logger *Pro* to complete data collection. Record the number of counts in the beta row of your data table, no shielding.

5. Place a single sheet of paper between the beta source and the monitor, and measure the counts as before. Take care to keep the source in the same position with respect to the radiation monitor. Record the count rate in the appropriate place.

6. In a similar manner, record the counts for the following used as absorbers for each of the three sources:

   a. a single sheet of paper
   b. a single sheet of aluminum

   Record each count in your data table.

## DATA TABLE

| Counts in 50 s interval | | | |
|---|---|---|---|
| | no shielding | shielding | |
| source | | paper | Al sheet |
| none | | | |
| alpha | | | |
| beta | | | |
| gamma | | | |

## ANALYSIS

1. Compare the no-source, or background, count with the no-absorber counts for the sources. Is the background count number a significant fraction of the counts from the sources? Do you need to consider a correction for the background counts?

2. Inspect your data. Does the count rate appear to follow your initial guesses for the relative absorption of the various types of radiation by matter? Be specific, considering which source should be the most penetrating (least interacting), and which absorber is more difficult to penetrate.

3. X-rays are photons, just like gamma rays. X-rays carry lower energy, however, and so historically received a different name. If you have had an X-ray film picture of your teeth taken by a dentist, the dentist probably placed a lead-lined apron on your chest and lap before making the X-ray. What is the function of the lead apron? Support any assertion you make from your experimental data.

## EXTENSIONS

1. If you were presented with a safe, but unknown, radiation source, and assuming that it emitted only one type of radiation, devise a test that would allow you to tentatively identify the type of radiation as primarily alpha, beta, or gamma. Write instructions for another student to follow in performing the test.

2. Your monitor detected some radiation even without a source present. Devise a method to correct for this background radiation. Do the corrected data still agree with your prediction?

# Experiment 2: Distance and Radiation

Scientists and health care workers using intense radiation sources are often told that the best protection is distance; that is, the best way to minimize exposure to radiation is to stay far away from the radiation source. Why is that?

A physically small source of radiation, emitting equally in all directions, is known as a point source. By considering the way radiation leaves the source, you will develop a model for the intensity of radiation as a function of distance from the source. Your model may help explain why users of radiation sources can use distance to reduce their exposure.

In this experiment you will use a small source of gamma radiation. Gamma rays are high-energy photons. If your source behaves as a point source, and if the air absorbs little or none of the gamma radiation, then the radiation intensity should be described well by your model. *Follow all local procedures for handling radioactive materials.*

## OBJECTIVES

- Develop a model for the distance-dependence of gamma radiation emitted from a point source.
- Use a counter to measure radiation emitted by a gamma source as a function of distance.
- Analyze count rate data in several ways to test for consistency with the model.

## MATERIALS

computer
Vernier computer interface
Logger *Pro*
Vernier Radiation Monitor or Student Radiation Monitor
Cobalt-60 1 μC source
meter stick

## PRELIMINARY QUESTIONS

1. Place your cobalt-60 source on a table. Turn on the radiation monitor to the audio mode, so that it beeps when radiation is detected. (If your monitor has a range switch, set it to the X1 position.) By holding the monitor near the source, determine the most sensitive place on the detector. That is, roughly where inside the monitor case is the radiation being detected?

2. Starting about a meter from your source, slowly move the monitor closer to the source until they nearly touch. How does the beep rate vary with distance from the source? Would you say that the beep rate is proportional to distance from the source? Or is it an inverse relationship?

3. Sketch a qualitative graph of the beep rate *vs.* distance from the source.

4. Suppose a small radiation source (a point source) is placed at the center of two spheres. The spheres are transparent to the radiation. One sphere has a radius $r$, and the other a radius $2r$. $N$ particles leave the source each second and travel outward toward the spheres. How does the number of particles passing through the inner sphere *per unit area* compare to the number per unit area passing through the outer sphere? Solve this problem by considering the following:

    a. How many total particles pass through the first sphere? How many pass through the second sphere?
    b. How do the surface areas of the two spheres compare?

5. From your answer to the previous question, write down an expression for the intensity of radiation (number of particles passing through a unit area each second) as a function of distance from a point source. Assume that $N$ particles leave the source each second. This expression is your model for the way radiation intensity varies with distance. Record your model in the data table.

6. Is your model consistent with the qualitative sketch you drew in question 3 above?

## PROCEDURE

1. Connect the radiation monitor to DIG/SONIC 1 of the computer interface

2. When your source is far from the radiation monitor, the monitor still detects background counts from cosmic rays and other sources. You will need to correct for this background by determining the average count rate with no source near the monitor. Prepare the computer for data collection by opening the file "02a Distance" from the *Nuclear Radiation w Computers* folder. One graph is displayed: counts *vs*. time. The vertical axis is scaled from 0 to 15 counts/interval. The horizontal axis is distance scaled from 0 to 300 seconds. Logger *Pro* will count for ten 30 second intervals. Move all sources at least 2 meters from the radiation monitor, and click Collect. Wait five minutes for data collection to complete.

3. After Logger *Pro* has finished data collection, click once on the graph to make it active. Notice that the number of counts in each interval varies. This is to be expected since radioactivity is a random process. Click the statistics button on the toolbar to determine the average number of counts in an interval. Record the mean value in the data table.

4. Prepare the computer for data collection by opening the file "02b Distance" from the *Nuclear Radiation w Computers* folder of Logger *Pro*. One graph is displayed: Corrected Radiation (counts/int) *vs*. Distance (m). The vertical axis is scaled from 0 to 300 counts/interval. The horizontal axis is distance scaled from 0 to 0.50 m.

5. Enter your correction for the count rate by modifying a column in the Logger *Pro* data table. To do this, choose Column Options ▸ Corrected Radiation from the Data menu. The Equation field will read "Radiation" – 0. Change the zero to your average background count rate. For example, if your average rate was 7.3, your equation should read "Radiation" – 7.3. Click Done to complete the modification.

6. If you are using the Radiation Monitor (brown plastic case) measure all distances from the center of the metal screen, perpendicular to the screen. If you are using the Student Radiation Monitor (black plastic case), stand the case on edge, with the Geiger Tube window near the table. Measure distances from the middle of this window, perpendicular to the window. Place the center of the source 6 cm from the monitor.

7. Click Collect to begin collecting data. Logger *Pro* will begin counting the number of gamma photons that strike the detector during each 30 second count interval.

8. After at least 30 seconds have elapsed, click the Keep button. In the entry field that appears, enter **0.06**, which is the distance in meters from the detector to the center of the source. Complete your entry by clicking OK. Data collection will now pause for you to adjust the apparatus.

9. Move the source 0.02 m farther from the source. Click Continue to collect more data, and wait 30 seconds.

10. Click Keep, and enter the new distance of **0.08** meters.

11. In the same way as before, move the source away an additional 0.02 m, click Continue, wait thirty seconds, and click Keep. Enter the distance in meters. Repeat this process until the distance is at least 0.24 m or the counts in one 30 second interval drops below ten.

12. Click Stop Collection instead of Continue to end data collection.

## DATA TABLE

| | |
|---|---|
| Model expression | |
| Average background counts | |

## ANALYSIS

1. Inspect your graph. Does the count rate appear to follow your model?

2. Fit an appropriate function to your data. To do this, click once on your graph to select it, then click the curve fit button. Select an equation that has the same mathematical form as your model from the equation list, and then click Try Fit. A best-fit curve will be displayed on the graph. If your data follow the model, the curve should closely match the data. If the curve does not match well, try a different fit and click Try Fit again. When you are satisfied with the fit, click OK.

3. Print or sketch your graph.

4. From the evidence presented in your two graphs, does the gamma radiation emitted by your source follow your model? Does the relationship seem to fail at larger or smaller distances?

## EXTENSIONS

1. Replot your data using a suitable transformation of the *x*-coordinate so that the resulting plot should be linear if the data follow your model. For example, if your model were an inverse-cube function, replot the data using the inverse-cube of the distance values for the horizontal axis. Do your data follow the model well using this test?

2. Why were you instructed to place the source no closer than 0.06 m from the detector? Repeat the experiment, using distances of 0, 0.02, 0.04… out to 0.24 m. Hint: Is the detector a spherical surface?

3. Use a longer counting interval so that you collect at least 300 counts at 0.06 m. Is the agreement with the inverse-square relationship any different? Try a much shorter count interval. How is the resulting graph different? Why?

4. Sometimes the table surface can scatter gamma rays, interfering with data collection. Use a ring stand or other support to hold the sample above the monitor, so that there are no surfaces near the source. Repeat data collection. Do your data agree any better with your model?

# Counting Statistics

Radioactive decays follow some curious rules that are a consequence of quantum mechanics. Regardless of when a particular nucleus was created, all nuclei of the same species (Cobalt-60 in this experiment) have exactly the same probability of decay. We might expect that the longer a nucleus has been around, the more likely it is to decay, but that is not what is observed. Even though the *probability* that a given nucleus will decay is fixed, there is no way to predict *when* it will decay. In this sense the decay process is completely random. Despite this randomness, a collection of many identical and independent nuclei will exhibit certain predictable behaviors, such as a consistent average decay rate when measured over a long time

There are still variations in the average count rate when measured over a shorter time, however. Suppose we collect data on the number of decays during a five-second interval. We count decays for five seconds, and then another five, and so forth. If the average number of counts during each interval is $n$, then we will find that the standard deviation of the collection of measurements is on average $n^{1/2}$. The standard deviation is a measure of how far away, on average, a measurement is from the mean value. A histogram of the measurements of the number of decays detected each interval will show the characteristic distribution known as the *Poisson distribution*.

When the average number of decays each interval is small, such as one or two, then the Poisson distribution is not symmetric. An asymmetric distribution means that the most common value is different from the average value. If the average number of decays in each time interval is larger, such as more than twenty, the shape of the Poisson distribution approaches the shape of the Normal, or Gaussian, distribution. The Normal distribution is sometimes called the *bell-shaped curve*, although there are other distributions that also look like a bell! The Normal distribution is symmetric, with the average value being identical to the most common value.

In this experiment you will collect data from a source that exhibits an essentially constant decay rate. Because the lifetime of the source is so long, the average decay rate will not change during your experiment. The interval-to-interval count rate will vary, however, but in a way consistent with the Poisson distribution.

## OBJECTIVES

- Use a radiation counter to determine the distribution of count rates from a nearly constant-rate source.
- Compare the distribution of experimental nuclear counting data to the Poisson distribution.
- Observe the gradual transition of count distribution from Poisson statistics to Gaussian statistics as the average count rate increases.

## MATERIALS

computer
Vernier computer interface
Vernier Radiation Monitor or Student Radiation Monitor

- Logger *Pro*
- Cobalt-60 1 μC disc gamma source

## PRELIMINARY QUESTIONS

1. Switch your radiation monitor to AUDIO mode, and place it about ten centimeters from your Co-60 source. When the monitor detects a by-product of a decaying Co-60 nucleus (a gamma ray, in this case) it emits a beep and the red LED flashes. Is there a uniform time between beeps? Or does the time vary? From listening to the sequence of beeps, can you predict when the next beep will occur?

2. Now move the source closer to the monitor. Did the average rate of beeps appear to change? If so, how did it change? Is there any more or less uniformity to the time interval between beeps compared to the slower rate?

## PROCEDURE

1. Connect the radiation monitor to DIG/SONIC 1 of the interface. Switch the Monitor to the ON (no audio) position.

2. Prepare the computer for data collection by opening the file "04 Statistics" from the *Nuclear Radiation w Computers* folder of Logger *Pro*. Two graphs are displayed: a histogram of the count rate and the counts *vs*. time.

3. Place the radiation monitor on top of or adjacent to the Co-60 source so that the rate of flashing of the red LED is maximized.

4. Click Collect to begin collecting data. Logger *Pro* will begin counting the number of gamma photons that strike the detector during each one-second count interval. Data collection will continue for just 30 seconds. Do not move the detector or the source for the remainder of data collection.

5. After data collection is complete, the Collect button will reappear.

6. To study the variation in count rate distributions, you will need to change the length of one time interval so that the average number of counts is first small (about 1) and then larger (30 or so). The count rate from your particular source depends on its age and initial activity, so you will need to first determine the average count rate from your sample. To do this, click on the graph of counts/interval *vs.* time. Then click on the statistics button to see the average count rate. Enter this value in your data table. Now determine the necessary interval lengths to achieve an average of 1 count per interval and an average of 30 counts per interval. Round these values up to the next 0.05 second. For example, let's say your average count rate was 4.67 counts per one-second interval. To get about one count per interval with the same source, you would use an interval of $4.67^{-1}$ or 0.21 seconds, rounded to 0.25 seconds. For 30 counts, multiply this by 30, getting 6.45 s after rounding up. Enter these values in your data table.

7. Set the counting interval to the value needed to obtain an average count of approximately one. To do this, select Data Collection from the Experiment menu. Change the number of seconds/sample to the low count rate value in your data table. Take care not to use the samples/second field. Then, change the Experiment Length field so that 200 samples will be collected (*i.e.*, enter a value 200 times the seconds/sample time). Click Done.

8. Click the **Collect** button to begin counting. Observe the histogram as data are collected. Is there a regular pattern as to the next count rate that appears? Do the values appear to be clustered around a most-common value? When data collection is complete, the **Collect** button will reappear.

9. After data collection is complete, click the Counts *vs.* Time graph to make it active, and then click on the statistics button to calculate statistics for the data. Record the average and standard deviation in your data table. Rescale your graph if needed.

10. Print your screen by selecting Print from the File menu.

11. Set the counting interval to the value needed to obtain an average count of approximately one. To do this, select Data Collection from the Experiment menu. Change the number of seconds/sample to the high count rate value in your data table. Then, change the Experiment Length field so that 200 samples will be collected (*i.e.*, enter a value 200 times the seconds/sample). Click **Done**.

12. Click the **Collect** button to begin counting. Observe the histogram as data are collected. Is there a regular pattern as to the next count rate that appears? Do the values appear to be clustered around a most-common value? When data collection is complete, the **Collect** button will reappear. Rescale your graph as needed.

13. Click the counts/interval *vs.* time graph to make it active, and then click on the statistics button to calculate statistics for the data. Record the average and standard deviation in your data table.

14. Print your screen by selecting Print from the File menu.

15. The standard deviation is a measure of how far away, on average, a typical measurement (of counts during each interval) is from the average of all the measurements. The interval defined by (average ± one standard deviation) contains most of the measurements. From your average and standard deviation values, determine this interval, rounded to the nearest integer. From the Histogram data table window, determine the fraction of the measurements that fall within the interval.

## DATA TABLE

| | |
|---|---|
| Average count rate (1 s interval) | |

| | Low count rate (~1/interval) | High count rate (~30/interval) |
|---|---|---|
| Interval length (s) | | |
| Average rate (counts/interval) | | |
| Square root (average rate) | | |
| Standard deviation (counts/int) | | |
| Fraction within ± std dev | | |

## ANALYSIS

1. Is your first histogram (with the low average count rate) symmetric? How can you tell? Was that shape consistent with the Normal distribution?

2. Is your second histogram (with the high average count rate) symmetric? How can you tell? Is the symmetry of your data distribution consistent with the Normal distribution?

3. Calculate the square root of the average count rate for your low- and high-count-rate trials. The square root of the number of counts measured in one interval is an estimate of the standard deviation of a set of measurements, when those measurements follow the Poisson distribution. How does the square-root estimate compare to the actual standard deviation of your set of measurements?

4. Use the comparison in the previous question to answer this question: An experiment yields 900 counts in one interval. Predict the standard deviation of a set of 200 additional measurements made under the same conditions.

5. For your high-count-rate data, is the fraction of the measurements that fall within the interval close to two-thirds? The Normal distribution is symmetric and has two-thirds of its values within one standard deviation of the average. Is the distribution of your data consistent with the Normal distribution?

## EXTENSIONS

1. Consult a statistics or nuclear physics reference book to learn the mathematical form of the Poisson distribution. Plot a Poisson distribution with the same average and standard deviation as your low-count-rate data on the same graph with those data.

2. Consult a statistics or nuclear physics reference book to learn the mathematical form of the Normal distribution. Plot a Normal distribution with the same average and standard deviation as your high-count-rate data on the same graph with those data.

3. Determine the fraction of your measurements falling with two standard deviations of the average for the high-count-rate measurements. The Normal distribution includes 90% of the measurements within two standard deviations of the average.

4. Determine the fraction of your measurements falling with three standard deviations of the average for the high-count-rate measurements. The Normal distribution includes 99% of the measurements within two standard deviations of the average.

5. Collect additional data at the high count rate. Use intervals with 500 to 1000 counts. Is the histogram different in shape from your earlier data?