The study of radiation at the introductory college level usually includes experiments to determine the half-life of a radioactive isotope and also a study of the absorption of nuclear radiation by metal foils. These experiments are straightforward to do using a Geiger-Müller tube and scaler, and allow for the determination of well-known constants. The underlying theory behind these experiments is also easy to understand, but fails to take into account background radiation that will be present, regardless of the source being used. The purpose of this article is to show how students can measure the effect of background radiation on these experiments by modifying the standard textbook theory.

**Determination of Half Life**

The decay of a radioactive isotope is described by the equation

\[ N(t) = N_0 e^{-\lambda t}, \]  

where the symbols have their usual meaning. The half-life is defined as the time required for the activity to fall to half of its original value, or

\[ t_{1/2} = \frac{\ln 2}{\lambda}. \]  

The usual method of performing this experiment is to use a Geiger-Müller tube and scaler to record the number of counts over successive time intervals. Plotting the data on a semilogarithmic scale should give a straight line, the slope of which determines \( \lambda \).

We performed the experiment using a Ba-137m source. This isotope is easily prepared in situ using an Isogenerator.\(^1\) It decays to stable Ba-137 by gamma ray emission with a half-life of about 2.5 min. It is particularly suitable for a student laboratory because its activity diminishes completely after about 20 minutes.

Figure 1 shows typical data that was obtained in our laboratory. It can be seen that a significant fraction of the data does not follow the predicted straight-line trend, shown by the dashed line, when plotted on a semilogarithmic scale.

The data points begin to deviate from the straight line after about 10 minutes because background radiation starts to dominate. Two obvious methods of

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**A Background to Background Radiation**

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Fig. 1. Experimental data to show the decay of Ba-137m with time. “Counts” is the number of counts measured in successive 30-s intervals. The dashed line represents the predicted behavior due to the source alone.
dealing with this are to (a) perform a regression analysis on the first part of the data only, or (b) obtain a value for the background level first and subtract this from each of the raw data points before plotting. The first method is flawed because it means that more than half of the data must be ignored; the second is flawed, too, because some of the low-count data points will turn out negative due to the statistical nature of radioactive decay. A third method, described here, recognizes that the measured number-of-counts rate is greater than predicted due to background. Hence Eq. (1) becomes

$$N(t) = N_0 e^{-\lambda t} + B,$$

where the background level, $B$, is presumed to be constant.

The objective of this exercise is to perform the half-life experiment by allowing students to use all data points to obtain optimal values for $N_0$, $B$, $\lambda$, and hence the half-life of Ba-137m. We used a nonlinear regression routine to fit the raw data in Figs. 1 and 2 to Eq. (3). Optimal values of $\lambda$ and $B$ were determined to be 0.0044 s$^{-1}$ and 16.1 counts, respectively. The half-life, determined from the optimal value of $\lambda$, is $t_{1/2} = 156$ s.$^2$

Figure 2 shows that when we include the additional background counts in the decay function described by Eq. (3), the line of best fit follows the data exactly. The average background radiation level will, of course, be a whole number of counts: an independent measurement of background radiation gave 19 counts in a 30-s interval. This is consistent with the result from the optimal curve fit because of the $n \pm \sqrt{n}$ property of radioactive decay statistics.

The Absorption of Radiation by Metal Foils

The absorption of radiation by a metal foil is described by the expression

$$I(x) = I_0 e^{-\mu x},$$

where $\mu$ is the absorption coefficient and $x$ is the foil thickness. When comparing the effectiveness of different metals as absorbers, $\mu$ is replaced by the mass absorption coefficient $\mu_m$ and Eq. (2) becomes

$$I(x) = I_0 e^{-\mu_m z},$$

where $z$ is the foil thickness multiplied by the density of the metal and has units mg/cm$^2$. We can assume that $I_0$ is constant because the half-life of the isotope is long compared to the duration of the experiment.

The standard experimental procedure is to measure the intensity of radiation as it passes through foils of increasing thickness and determine the absorption coefficient, $\mu$ (or $\mu_m$) from the slope of a loglinear graph. We used aluminum foils and measured the ab-
sorption of beta particles from Tl-204. For each foil, we used a Geiger-Müller tube to measure the number of counts received in five minutes. Typical results are plotted on a semilogarithmic scale in Fig. 3. It can be seen that the data points quickly deviate from the expected straight line when the foil thickness is more than 100 mg/cm². Furthermore, the count rate corresponding to the thickest foils approaches a constant level, independent of foil thickness. Clearly, once the foil thickness exceeds about 200 mg/cm², the aluminum has effectively absorbed all the beta particles from the source and the measured rate is due to background alone. Rewriting Eq. (5) for the measured intensity gives

\[ I'(z) = I(z) + B. \]  

When the thinnest foils are used, the radiation that is measured is considerably greater than background, and hence the absorption coefficient can be determined from the first few data points alone. The line of best fit in Fig. 3 was obtained by subtracting background from the raw data for the first five data points. The value of \( \mu_m \) obtained in this way is 0.029 ± 0.003 cm²/mg. The dashed line shows the intensity predicted from Eq. (6), using this value of \( \mu_m \) and a constant background rate of 103 counts in five minutes. The data points corresponding to foils of intermediate thickness closely follow the predicted curve, confirming that Eq. (6) is a realistic description of the observed count rate. When the thickest foils are used, \( I \) is small relative to \( B \), resulting in the straight horizontal line corresponding to the background level only.

**Summary**

These two investigations demonstrate that when the outcome of an experiment is not exactly as expected, an alternate explanation must be considered. Here, the presence of background radiation adds to the predicted count rate. Data from the half-life experiment can be analyzed using nonlinear regression instead of subtracting a constant value for background from each data point. This is an advantage because at low count rates, the number of counts may become negative for some data points and hence meaningless when background is subtracted. Furthermore, nonlinear regression is a data analysis technique that is available to many students as increased computer use has become an integral part of the introductory laboratory.

The absorption experiment shows that the observed behavior can be accounted for simply by adding background to the predicted intensity. In addition, the results show that there is a maximum foil thickness (i.e., the range) beyond which all radiation from the source is absorbed and background only is detected. This experiment ignores the low energy (0.345 MeV) gamma rays that are emitted in addition to the beta particles. However, the relative yield of the gamma rays is only 3% and therefore can be ignored if we assume that this is much weaker than background. This assumption is justified when we compare the number of counts from the thickest foils to background alone.

**References**

1. The Cs-137/Ba-137 Isogenerator may be obtained from any supplier of educational apparatus for nuclear physics experiments, such as Sargent-Welch, Daedalon, or Canberra Industries.

2. The exact syntax for nonlinear curve fitting will depend on the software being used.

3. A weighted fitting procedure should be used in this case because the deviation associated with each data point is not constant. This is discussed in texts such as P.R. Bevington, *Data Reduction and Error Analysis for the Physical Sciences* (McGraw-Hill, 1969), pp 108–118.

4. The range \( R \) in mg/cm² is related to the energy \( E \) in MeV of the beta particles by Feather’s empirical formula, \( R = 543E - 160 \). The energy of the beta particles from Tl-204 is 0.763 MeV.

PACS codes: 01.50Lc, 01.50Pa, 23.60+e

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The Physics Teacher • Vol. 41, February 2003

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