PHY224 Radioactivity in the Air Lab

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Tuesday, the 19th of November, 2019.

Abstract:

This experiment studied the incidence of observable radioactive nuclides in the air around McLennan Physical Laboratories. The daughter nuclides of Uranium-238, Thorium-232, and Uranium-235 were examined due to their natural occurrence in Earth's atmosphere. Due to the relatively short half-lives of the daughter nuclides of Thorium-232 and Uranium-235, the presence of Uranium-238's daughters were observed in order to study the incidence of radioactive decay in the atmosphere. Effectively, this resulted in the determination of the atmospheric activity of Radon-222 -- a daughter of Uranium-238 -- given that its half-life of 3.82 days enables it to be present and decay in the atmosphere longer than other nuclides. This decay was determined to occur at a rate of of $33 \pm 3.79\text{e-}5\ \frac{counts}{minute}$. In addition, the decay of Uranium-238 was modelled by the Whyte-Taylor model. This model was found to be a good representation of the decay of Uranium-238 in the air when compared to experimental observations of the decay of radioisotopes in the air.

Introduction:

The radioactivity of Radon-222 in the air was observed by detecting the radioactive decay of its longer-lived daughter isotope Lead-214 (assuming secular equilibrium).

Equipment:

- Geiger-Muller Tube
- Picker Scaler
- Cesium-137 Sample
- "Radioactivity in Air" (RIA) program
- Pulse Shaper
- Data Acquisition Card (DAQ Card)
- Air Sampler
- Air filter

Materials and Methods:

Before measuring the operating voltage of the Geiger counter, the background radioactivity of the laboratory room was determined by allowing the Geiger counter to run without a sample underneath it for roughly 45 minutes, from 9:12 AM to 9:57 AM. In order to determine the operating voltage of the Geiger counter, a small sample of radioactive Cesium-137 was placed under the window of the Geiger-Muller tube. The voltage was then varied between 650 and 1050 volts at 100 volt increments (for ~4.5 minutes, with the incidence of radiation being recorded every 20 seconds) in order to identify a range of voltages within which the plateau could reasonably be found. The voltage was then varied between 650 and 820 volts at 10 volt increments, with the Geiger counter recording the incidence of radioactive decay 12 times as 20 second intervals at each voltage setting for a total of 4 minutes per voltage increment. The average number of counts as a function of the potential across the charged plates of the Geiger-Muller tube was then plotted and the operating voltage was extrapolated as the point where the slope of the plot flattened out.

In the next lab session, the air sampler was started and allowed to run from 9:16 AM to 10:17 Am. Again, the background radiation in the laboratory room was determined by allowing the Geiger counter to run without a sample in it. However, in this session, the background radiation was measured from 9:17 AM to 10:10 AM. The sample of filtrate from the air was then immediately transferred from the sampler and placed underneath the window of the Geiger-Muller tube, and the incidence of radioactive decay was recorded for ~2 hours.

<u>Results:</u>

To ensure the maximal functionality of the Geiger-Muller Tubes, the operating voltage of the apparatus was determined prior to measuring the decay of radioactive isotopes in the air. For each voltage setting in the determination of the operating voltage, the incidences of radioactive decay per measurement interval (20s) was averaged. The average of the incidence of radioactive decay ("counts") was then plotted against the voltages each interval was measured at. From this plot, it was qualitatively observed that the detection of radioactive decay as recorded by the ionization of gases in the the Geiger-Muller Tubes plateaued around 740V. At this plateau, increases in the voltage across the Geiger-Muller tube plates no longer significantly affected the incidence of radioactive decay detected (within the counting error of 32.56 counts for each sample). Accordingly, the incidence of radioactive decay of the air filtrate was determined at an input voltage of 850V. This voltage (above the extrapolated operating voltage) was used in order to ensure that the sensitivity of the Geiger-Muller tube was maximized.

The background radiation was taken to be the average of the observed incidence of radioactive decay in the absence of a sample was 10.82 incidences per time 20 second interval. Taking into account the fact that counts of the incidence of radiation must be integers, average rate of background radiation observed during the experiment was in fact $\frac{10.82\ counts}{\frac{1}{3}\ minutes} = 32.46 \frac{counts}{minute} \approx 32 \frac{counts}{minute}$. This rate was subtracted from observations of radioactivity from the air filter sample in order to ensure that measurements of the incidences of radioactive decay only reflect the activity of the nuclides in question.

The air filter sample activity was demarcated into two distinct intervals: activity preceding the 91st sample, and activity following this sample. Given that samples were taken at 20 second intervals, measurements taken before the 91st sample represent the first half hour of observation (the approximate time interval within which when the shorter-lived daughter nuclides of Uranium-238 are more active). On the other hand, the time period after the 91st sample is the period within which the activity of longer-lived daughter nuclides dominate. Thus, observations made after the 91st sample reflect the activity of the longer-lived daughter nuclides of Thorium-232.

Because the activity of longer-lived daughter nuclides of Thorium-232 is more present in the first 91 samples than when compared to the activity of shorter-lived daughter nuclides of Uranium-238, the activity of the longer-lived nuclides was analyzed first, to allow for its activity to be corrected out of earlier observations. To this end, the natural logarithm of observed counts was plotted against the sample number, yielding a 'semi-log plot'. The *curve_fit()* function of Scipy's optimize package was used to fit a curve to the data (using a propagated error of 0.2833 logarithmic counts per observation). A reduced χ^2 test on the resultant linear relationship yielded a statistic of 0.01885. Given that the half-lives of these nuclides is in the magnitude of hours, it is probable that certain nuclides of this family would have been active for the entirety of the observation period. As such, this linear model of decay was extrapolated into time from before the 91st sample. This projection was then removed from the overall air sample measurements, correcting for the activity of longer-lived Thorium-232 daughter nuclides in the observed decay of shorter-lived Uranium-238 daughter nuclides.

In the decay of Uranium-238, the daughter of interest was Radon-222 as its half life of 3.82 days affords it enough time to diffuse into the atmosphere. This behavior is atypical for Radon isotopes that are daughters in other decay chains. Radon-222 eventually decays into Polonium-218, which in turn decays into Lead-214. However, these two decay events are undergone via alpha decay, and would thus not be detected by the Geiger-Muller Tubes due to the thickness of the aluminum shield between the sample and the detecting window. However, the next two nuclides in the chain, Bismuth-214 and Polonium-214, are formed via beta decay and thus, and these transformations are detectable by the apparatus.

In accordance with this chain of decay, a model function was constructed based on the relationship illustrated by G. N. Whyte and H. W. Taylor in the *American Journal of Physics* (as seen in the lab manual). Along with known detector efficiencies for each isotope and the respective radioactive decay constants of these isotopes, a model of this chain of decay was constructed with two parameters: the initial activity of Lead-214 as it decays into Bismuth-214 at the beginning of observations, and the ratio between the initial activities of Bismuth-214 and Lead-214 in mind. This model approximates the combined activity of Lead-214 and Bismuth-214, as observed by the Geiger-Muller Tubes. By using the *curve_fit()* function, the parameters of this model were estimated to be 10.95 incidences every 20 seconds ($\frac{10.95\ counts}{\frac{1}{3}\ minutes} = 32.85 \frac{counts}{minute} \approx 33 \frac{counts}{minute}$) and 1.562 incidences per 20 seconds respectively. The relationship between this theoretical model and the experimentally observed data had a reduced χ^2 statistic of 2.146, and an error of 6.069 counts per sample.

Discussion:

In attempting to determine the operating voltage of the Geiger-Muller tube, many functions were attempted to be fit to the relationship computationally. All attempts at doing so failed. While this potentially have been a result of an error in executing the Python code, it could also conceivably be due to the fact that the stochastic process by which radioactive incidences are detected by the Tubes obeys no simple mathematical relationships. This conclusion is further supported by manipulation of the data sets by inversion, natural logarithms, exponentiation, and many other common nonlinear relationships failing to linearize the data. As such, the qualitative value of 740V was taken to be the lowest voltage of the operating plateau given the lack of any more precise estimation of an operating voltage.

It is interesting to note that after each pulse of electrical activity in the Geiger-Muller tube (signifying the incidence of radioactive decay) that the electrical activity of the tube “dies”. This time of inactivity (the “dead time”) arises as a consequence of the way Geiger-Muller tubes detect the incidence of radiation. Geiger-Muller tubes take advantage of a phenomenon known as the Townsend avalanche, wherein free electrons accelerated by an electric field (generated by an electric potential in this case) collide with gas molecules, freeing additional electrons. This collision occurs exponentially, with electrons being freed from gas particles freeing other more electrons, which go on to free more electrons, etc. This results in electrons being freed to a degree that can be detected as a pulse of electrical activity in the terminal of the Geiger counter, which is used to determine the absolute presence of a particle of radioactive decay at the time. This system results in a “dead time” as following an avalanche, the free electrons must rejoin their gas particles before another ionization event can occur. This issue is very similar to the refractory period of the neuron, wherein electrical signals are generated by the sudden depolarization of the neuron membrane due to the opening of membrane-bound ion channels. This method of impulse generation has an associated refractory period analogous to the dead time of the Geiger counter as the cell must regenerate the resting membrane potential (and associated ion gradients) before another action potential can fire, just as the gas molecules of the Geiger-Muller tube must regain their electrons before another detection impulse may fire. This is a source of systematic error as radioactive particles could potentially have interacted with the gas during this dead time without triggering an electrical impulse.

The reduced χ^2 values of both models are appropriate for their respective sets of data. For the linearised logarithmic plot of Thorium-232’s daughters’ activities, the Chi-squared statistic of 0.01885 implies that the linear model of this decay was likely fitted to noise. This noise-fitting behavior is likely explained by the simple nature of the model and the fact that the relationship has 234 degrees of freedom (based on 236 observations and 2 parameters).

The Whyte and Taylor model of the decay of Uranium-238's daughters yielded a χ^2 value of 2.146. This value indicates that the Whyte and Taylor model is well fitted to the experimental data.

Finally, it is important to make note of what the final observations of Lead-214's activity -- $33 \frac{counts}{minute}$ -- implies about radioactive activity in the air. The daughters of Radon-222 can exist in a state of secular equilibrium in correct conditions. It just so happens to be that the atmosphere satisfies these conditions. In secular equilibrium, the relative long life of a local parent nuclide and relative short life of its daughter allows resulting masses of the daughter nuclide to exist in a state of relatively unchanging mass, wherein the daughter decays exactly as fast as the parent's decays replenishes them. In the atmosphere, this decay is observed with Radon-222 and Lead-214. Because Lead-214 exists in a known state of secular equilibrium in the atmosphere, its activity (of $33 \pm 3.79\text{e-}5 \frac{counts}{minute}$) is also the activity of Radon-222. Thus, although the alpha decays of Radon-222 are unobservable by the Geiger-Muller Tubes, its activity -- and the resultant radioactivity in the air due to the decay of Radon-222 -- can be observed through the decay of its daughters.

<u>Appendix: Relevant Code & Plots as Vector Graphics</u>