Counting Nuclear Radiation

Physics 128AL Summer 2025

Lab report due **Saturday, July 19, at 11:55 P.M.**

Introduction

The Geiger counter you built in the soldering lab uses a Russian surplus SBM-20 tube. This tube is sensitive to gamma rays, the most energetic form of electromagnetic radiation, and beta particles, which are fast electrons. Alpha particles, the third common type of nuclear radiation, consist of two protons and two neutrons, the same as nuclei from the most frequently encountered isotope of helium. Because of their significant mass and charge, alpha particles interact strongly with matter, and cannot typically penetrate a solid material even a fraction of a millimeter thick. Geiger tubes made for detecting alpha particles have very thin mica windows, and are usually quite a bit more expensive than the SBM-20.

Nuclear radiation is produced when radioactive isotopes decay. This typically begins a cascade of decays called a "series," which ends after several decays when the nucleus reaches a stable form (often lead). You will measure a background count that comes mostly from decays in the Earth, and to a lesser extent from astrophysical sources. You will also measure radiation from a piece of granite floor tile. Granite contains small amounts of naturally radioactive thorium and uranium, and produces a signal that is a small but measurable fraction of the background. These tiles are nothing out of the ordinary, and were purchased at Home Depot.

Units and Safety

The radioactivity of a sample is measured in decays per second (of any type). The corresponding SI unit is the becquerel: $1\ \mathrm{Bq} = 1\ \mathrm{s}^{-1}$. Note that the becquerel unit has the same dimensions as the hertz, but they are not the same. The hertz is used only for periodic phenomena. An older unit for radioactivity is the curie: $1\ \mathrm{Ci} = 3.7 \times 10^{10}\ \mathrm{Bq}$. For example, in water quality reports, you will still see radioactivity reported in pCi/L (picocuries per liter).

The SI unit for absorbed dose of ionizing radiation is the gray: $1\ \mathrm{Gy} = 1\ \mathrm{J/kg}$. If you know the mass of an object being irradiated, the energy of each particle of radiation, and the number of particles absorbed, you can calculate the absorbed dose. An older unit of absorbed dose is the rad: $1\ \mathrm{rad} = 0.01\ \mathrm{Gy}$.

To determine whether a dose is safe, you also need to take into account biology. For small amounts of radiation, for example what we receive from the natural background, our bodies are able to repair damage to our DNA resulting from absorption of ionizing radiation. If the dose is large, however, the DNA repair machinery can be overwhelmed, resulting in radiation poisoning or cancer.

To measure the danger of a dose, we must also account for the fact that some types of radiation do more damage than others. We therefore use a "dose equivalent" that is measured in sieverts (Sv). To find the dose equivalent in sieverts, we take the absorbed dose in Gy and multiply by a dimensionless radiation weighting factor W_R, which represents the relative damage done by a particular type of radiation. Here are some approximate weighting factors:

Type	$\mathbf{W}_R$
x-rays	1
gamma rays	1
beta particles	1
alpha particles	20
neutrons, $<$ 10 keV	5
neutrons, 10 keV $\rightarrow$ 100 keV	10
neutrons, 100 keV $\rightarrow$ 2 MeV	20
neutrons, 2 MeV $\rightarrow$ 20 MeV	10
neutrons, $>$ 20 MeV	5

An older unit of equivalent dose is the rem ("roentgen equivalent man"): 1 rem = 0.01 Sv.

The quantities of radiation we measure in this lab are safe. Unless you happen to be in an area where there has been a reactor accident or nuclear waste contamination, the background level is by definition safe. For our Geiger counters, this level is around 20 counts per minute (cpm). The granite tile produces a level of radiation that is a fraction of the background, and is also safe. If it were not, it is unlikely that it would be sold as a flooring material. Here are some typical doses you can compare:

Exposure	**Dose**
Typical daily background	10 µSv
Dental x-ray	5 µSv
Cross-country flight	40 µSv
Chest x-ray	20–100 µSv
Mammogram	0.4-1 mSv
Typical annual background	3.5 mSv
Maximum annual dose for radiation workers	50 mSv
Severe radiation poisoning	2 Sv
Lethal dose	8 Sv

See here for more examples.

The Importance of Geometry

To figure out how much signal or dose is produced by a radioactive source with a given activity, you need to figure out how much of the emitted radiation intercepts the detector or person in question. A single radioactive atom, or a collection of atoms that is small compared with other distances in the problem, behaves as a point source, and emits radiation uniformly in all directions.

If we consider a detector with cross sectional area A perpendicular to the radius vector $\mathbf{r}$ from the source to the detector, we can determine how much radiation it will intercept by figuring out what fraction f of the spherical shell of radius $r = |\mathbf{r}|$ is covered by A. We express this fraction using the *solid angle* $\Omega \equiv A/r^2$. Solid angle is measured in dimensionless units called *steradians*. With this definition, we can see that the entire shell would be 4π steradians, since the area of the shell is $4\pi r^2$. Then the fraction $f = A/4\pi r^2 = \Omega/4\pi$. If we multiply f by the activity of the source in Bq, we will get the average number of emitted particles intercepted by the detector in each second. One must then also account for the detector's efficiency to get the measured count rate.

If a source is not a point, or equivalently is not very far away compared with its size, you must consider it to be a collection of infinitesimal sources. To find the amount of radiation intercepted by the detector, you compute the solid angle of the detector as seen by each infinitesimal source, then integrate. In practice, for any non-trivial geometry the two strategies you are most likely to use to find the amount of radiation arriving at the detector are approximations and exact calculation using a computer. If you choose to approximate, you should keep track of your expected uncertainty.

Equipment

Make sure your FTDI cable is properly oriented (compare the wire colors with the markings on the Geiger counter board). Connect the cable from the Geiger counter to your computer.

Download `geiger.py` from the course web page. To run this program on your computer, you will need to install Python, version 3, which you may already have. Otherwise, you can find it here. You will also need the `pyserial` package, which you can install as follows:

Debian-based Linux: `sudo apt-get install python3-serial`
Other Linux, Mac: `sudo pip3 install pyserial`
Windows: `pip3 install pyserial`

If your computer uses Windows, it may be easier to download a Linux distribution, for example here, load it on a flash drive, and boot from that.

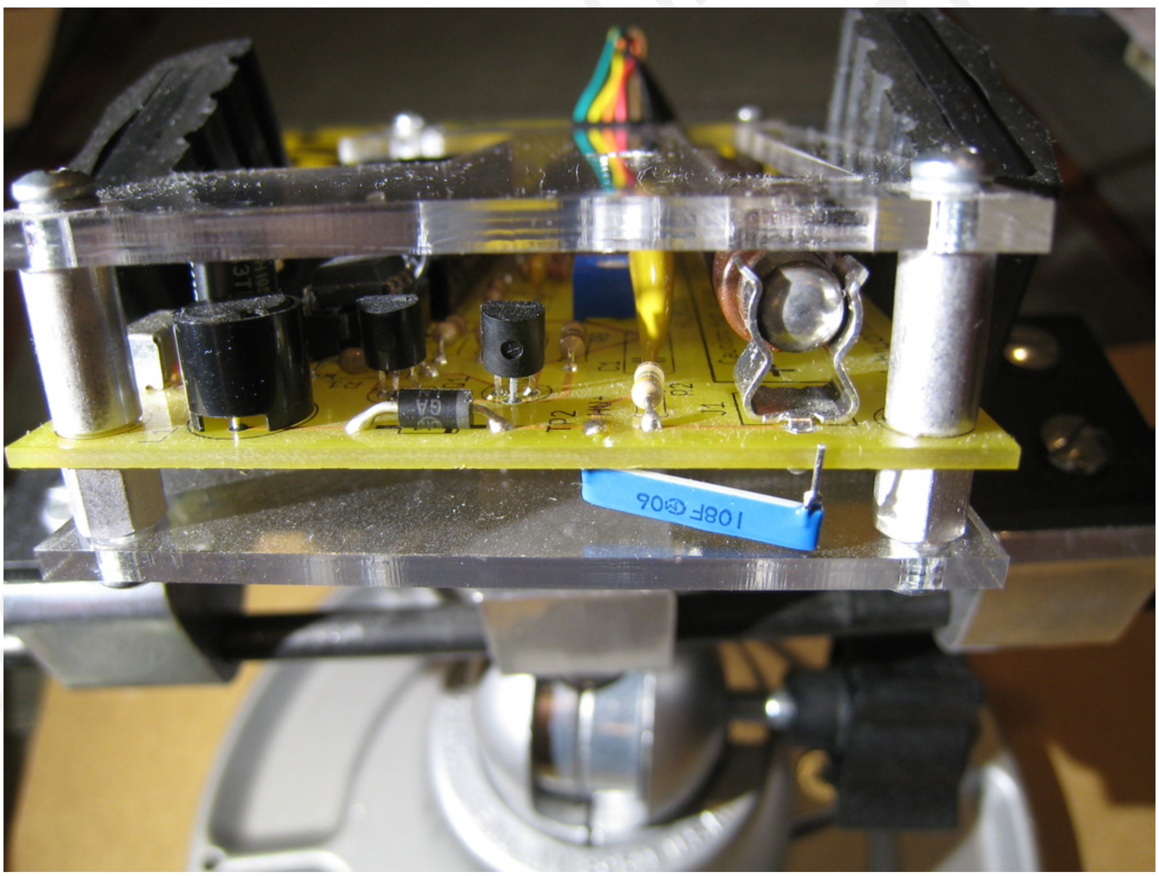
To run `geiger.py`, you will need to edit the code and make sure the variable `SERDEV` is set to the appropriate device name. The suggestions in the code may not work, in which case you will need to figure out what to use for your computer.

Once you have specified the serial device, you should be able to invoke `geiger.py` from the command line. It takes one command line argument, the amount of time to count in seconds.

The SBM-20 tube in your Geiger counter is supposed to have an operating voltage between 350 and 475 V, with the ideal setting being 400 V. Unfortunately it is not possible to measure the tube voltage directly with a standard multimeter. A typical meter's input impedance is only 10 MΩ, and the source resistance of the high-voltage supply is about 15 MΩ. You also cannot count on the source resistance remaining at 15 MΩ if you put a 10 MΩ load on the supply. So if you set the meter to the appropriate range and place its leads across the tube, you will draw far too much current from the high voltage supply, and the meter reading will be a small fraction of the nominal tube voltage. Note that the tube's resistance is effectively infinite except during a counting event.

I happen to have a Fluke 80K-40 high voltage probe from my lab, which has a 1 GΩ input impedance, so I was able to measure the tube voltage while developing this experiment. You will use the 1 GΩ resistor from your equipment kit in conjunction with a multimeter's 10 MΩ input impedance to form a voltage divider that will enable you to determine the tube voltage under normal operating conditions.

Tape the 1 GΩ resistor to your Geiger counter board so that, as shown in the photo below, one lead protrudes from below up through the "TP2 HV+" test point connection, and the other lead rests on the edge of the circuit board. Solder the protruding lead to the TP2 HV+ pad, let the connection cool, then remove the tape.



To measure the tube voltage, set a multimeter with 10 MΩ input impedance to measure DC volts, then place the positive probe on the unconnected lead of the 1 GΩ resistor, and the negative probe on the clip holding the far end of the Geiger tube. Figure out how to calculate the voltage at the HV+ test point from the meter reading. The tolerance of the

1 GΩ resistor is 1%, and the meter's input impedance is typically quite a bit more accurate than that (at least mine was, when I measured it with a Fluke 189 multimeter).

Have a look at the Geiger counter schematic diagram in the soldering experiment section of the course web page. If you watch the tube voltage carefully, you should be able to see capacitor C1 discharge and recharge during and after a counting event.

As a matter of principle, you should carefully avoid contact with any conductor that could be at a high voltage. At the open lead of the 1 GΩ resistor, however, the available current is not dangerous. The threshold of perception for electrical shocks is about 1 mA. What is the maximum current available at the open lead, assuming your body is grounded and has no resistance? The HV+ test point is significantly different, so you should avoid contact with that part of the circuit.

The MightyOhm Geiger counter is great for $80, but it is not what we would consider high-precision scientific equipment. In particular, it does not have feedback control for the tube voltage, so the tube voltage varies as the battery voltage changes. It also changes with the room temperature, which may be related.

The tube voltage rises as the battery voltage drops, by something like −250 V/V. So if the battery voltage drops by 0.1 V, the tube voltage rises by

$$(-250\ \mathrm{V/V}) \times (-0.1\ \mathrm{V}) = +25\ \mathrm{V}.$$

Why do we care? The proper operation of the Geiger tube depends on it being on a part of the count rate vs. tube voltage curve that looks like a gently sloped plateau. So we do not want the tube voltage to be outside the specified range when the batteries are fully charged, or after they have run down part way.

For most measurements, as long as you are somewhere on the plateau, the counter will operate properly. However, for this tube the plateau has a typical slope of about 4%/100 V. So if your tube voltage increases by 25 V, your count rate will increase by about 1%. I have seen my tube voltage drift by up to 45 V over 9 hours. This could be a problem if you are trying to see a small signal, for example from a banana. When you make long counting measurements, you should set the tube to 400 V at the beginning, then check at the end to see how much the voltage drifted during the measurement.

Procedures

Record all experimental details, procedures, and results in your lab notebook.

First, find a location

- that is not on a granite countertop,
- that has as constant a temperature as possible (not in the sun),
- where you can leave your counter and computer for an extended period of time.

If you are using alkaline batteries, gently turn the potentiometer counter-clockwise until it stops. Then turn it clockwise until the screwdriver slot is pointing straight into the board, toward the 12 o'clock position.

If you are using NiMH rechargeable batteries, gently turn the potentiometer counterclockwise until it stops. Then turn it clockwise about 90 degrees until the screwdriver slot is pointing in the 10–11 o'clock direction.

Use the measurement procedure described above to fine tune the tube voltage to 400 V.

Before the first measurement and at least once every few hours, check the supply voltage across the series combination of the two batteries. If the total is less than 2.5 V, the batteries need to be changed.

1. Take 16 9-minute measurements of the background with no sample and the granite tile at least 3 m away from the counter. The background can vary throughout the lab or your home, so make sure all measurements are made in the same location. A typical background rate for the SBM-20 tube is around 20 cpm.

2. Take 16 9-minute measurements with the granite tile resting on one of its long edges, with its length parallel to and centered with respect to the tube. Its face should be up against the counter so that the tube looks out the long side of the counter through air directly at the granite.

3. Devise an experiment to measure the distance dependence of radiation from the granite tile. Carefully consider the geometry and estimate the dependence theoretically. Compare your result with your theory. At what distance do you calculate that the radiation signal from the tile will be equal to the 1-σ Poisson fluctuation in the background for a 1-hour count? Is this consistent with your measurement? For simplicity, keep the tile on its edge, parallel to and centered on the tube as you move it away.

Extra Credit

A banana contains about 3.6 mg of potassium per gram of banana. A small fraction of the potassium is naturally radioactive. Using the Internet to find out what you need to know, figure out how to measure the radioactivity of the banana. Hint: the signal will be small compared with the background, so you will need to make a precise measurement to have any chance of detecting the signal. This will require long measurments, so you will probably want to take your counter home if you decide to do this part of the experiment.

Report Suggestions

You are expected to figure out on your own how to report the results of the measurements described above in the Procedures section. Here are some questions to help you focus your thoughts:

1. We expect counting measurements to be described by the Poisson distribution. Do your measurements of the background and the stationary granite tile match this expectation? A plot of your data overlaid with the corresponding distribution will help to visualize this. Don't forget about `inthist.py` on the course web page.

2. What is the value and associated uncertainty in an individual background measurement if you express it in counts per minute? What is the uncertainty in the combination of all of your background measurements expressed in counts per minute?

3. If you answer the previous question also for your stationary tile measurements, you should be able to see how your confidence that you are measuring a real signal from the tile improves with time. What is the uncertainty in the difference between a single tile measurement and a single background measurement expressed in counts per minute? What is the uncertainty in the difference when you combine all background and all stationary tile measurements? Note that the uncertainty in a measurement is not the same as the uncertainty in the difference of two measurements.

4. If you consider the answers to the previous question, what is the probability for a pair of single measurements (background and tile) that your tile produces no signal and the rate you observed was just a random fluctuation? When you use the combined totals, what is this probability?

5. If you were to count the background and stationary tile for only 10 seconds each, it is unlikely you could determine whether the tile actually produces any signal. Given the rates you have measured for the background and the tile, what is the shortest period of time for which you could count and have 95% confidence that you have detected a non-zero signal from the tile?

6. As you learned in introductory physics, the electric field from a point charge falls off as $1/r^2$, while the electric field from an infinite plane of charge does not change at all with distance from the plane. So if you have a finite sheet of charge, you would expect it to behave like a plane when you observe at a distance small with respect to the extent of the sheet, but like a point when you are very far away compared with that size. How does this relate to your measurement of the signal from the tile as a function of distance? A plot of the two limits overlaid on your theory and data will help you to visualize this.