Design of Nuclear Labs for PH1130

An Interactive Qualifying Project Report

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by

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Abstract

This IQP project aims at designing two nuclear physics labs for the first-year physics course PH1130 (Modern Physics). Two labs were designed to introduce the basic principles of nuclear science, radiation and detection to the students. In the first lab, students learn about alpha, beta, and gamma radiation by examining the penetrating properties of each type of radiation through different materials. In the second lab, students investigate how radioactive strength varies as a function of distance from the source. After the labs were designed and tested, a few student volunteers performed and evaluated the lab.

I. Introduction

This IQP project aims at providing PH1130 students with basic introduction to nuclear physics with a new set of radioactivity experiments. In this project, two labs are designed: the penetration of alpha, beta, and gamma radiation, and modeling gamma radioactivity as a function of distance. The two labs would take place during two sessions respectively, in which students would be working in groups of two to finish the lab.

I.1 Radioactivity

Radioactivity is a natural occurrence in atoms. It is the process of the nucleus of an unstable atom losing energy from emitting radiation. Nucleus can be visualized as a bunch of small balls held together in a tiny space in range of only a few femtometers (10^{-15} m) [1.1.4]. At such a small distance, gravity is practically negligible. The natural force that works here is the strong nuclear force [1.1.4], which is a strongly attractive force that binds protons, neutrons and other subatomic particles together at distances of around 1 femtometers. But it decreases rapidly to almost non-existence beyond 2.5 femtometers [1.1.10]. Inside the nucleus, the strong nuclear force overcomes the repulsive electromagnetic force between the protons (carrying one positive charge each) and the neutrons (having no charge) and holds the nucleus together [1.1.4]. The nucleus splits when the binding energy (the energy needed to split the protons and neutrons apart) inside nucleus is not strong enough to hold the nucleus together. When this occurs, the emitted particles are called radiation, which is the main topic of this IQP project [1.1.4]. There are many different types of radiation and each originates from a different mechanism. This IQP project mainly focuses on alpha (α) radiation, beta (β) radiation and gamma (γ) radiation, which are the most common types of radiation in nature. An alpha particle is a helium nucleus (a particle with two protons and two neutrons) that carries two positive charges. Within a nucleus' tiny space, the attractive strong nuclear force is so strong that it overcomes the Coulomb repulsion (as a result of electromagnetic force) between the alpha particle and rest of the nucleus (both carrying positive charges) and confines the alpha particles within the range of nuclear force. However, the quantum tunneling effect allows the alpha particle to be accidentally far enough from the nucleus where the nuclear force is weaker than Coulomb repulsion, and the alpha particle escapes from the nucleus as a result of Coulomb repulsion [1.1.5]. Beta particles are literally electrons travelling with high speed (large kinetic energy). Beta particles are produced from neutron-rich atoms. In such atoms, a neutron emits an electron and an antineutrino (antimatter of a neutrino) and transforms into a proton [1.1.6]. Neutrino is almost massless and carries away some of the energy from the atom as a result of energy conservation. The emitted electron is called a beta particle to be distinguished from the normal electrons orbiting the nucleus [1.1.6]. Gamma radiation, which is massless and carries no charge, consists of photons, the same particle comprising visible light yet with much higher energy (greater than 100keV) and shorter wavelength (less than 10 picometers, or 10^{-11} meters) [1.1.11]. A nucleus in an unstable excited state might emit photons of discrete energy. The loss of high-energy photons enables the nucleus to move down to a stable state with less energy [1.1.7]. Gamma radiation frequently occurs in nature, some common examples are lightning strikes, fission in nuclear reactors, and supernova explosion (as shown in Figure 1.1.1). There are other types of radiation such as neutron radiation (which is usually observed in nuclear fission) and proton radiation (which is usually used to treat cancer [1.1.8]). But since these radiations are not as common as α, β, γ radiation, they are not a topic of this IQP project.

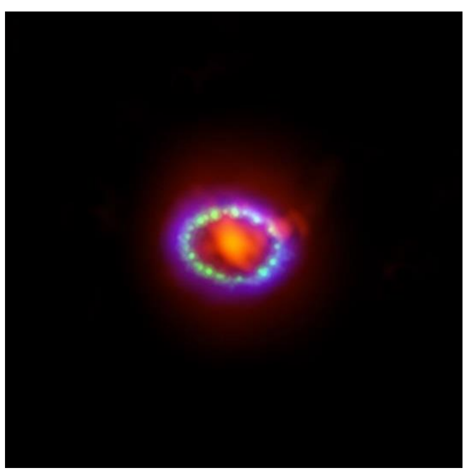


Fig 1.1.1: Image of Supernova 1987A. Supernova explosion often brings in intense gamma-ray burst (GRB) [1.1.9]

Radiation plays a hugely important role in modern science and engineering. For example, alpha particles are often used inside smoke alarms to provide a small current [1.1.4]; beta radiation can be used in medical therapy to kill cancer cells; and astronomers detect gamma radiation to reveal the secrets of supernova and structure of our universe.

I.2 Geiger counter

Fig1.2.1 Geiger counter made in 1932 by Hans Geiger [1.2.4]

Geiger counter is a radiation detection device that is widely used in nuclear engineering and experimental physics. The detection principle was first discovered in Cavendish laboratory in the year 1908, but it was not until the year 1928 when the first practical instrument came into being [1.2.1]. Figure 1.2.1 is a picture of one Geiger counter made by Hans Geiger. The core of the instrument is a Geiger-Muller tube which is filled with inert gas such as helium at low pressure. When the radiation enters the tube it ionizes the gas whose particles are split to ions and electrons. The electrons are attracted by the positively charged high-voltage wire and produce a measurable pulse [1.2.2]. A visual illustration of the working mechanism of a Geiger counter is shown in Figure 1.2.2.

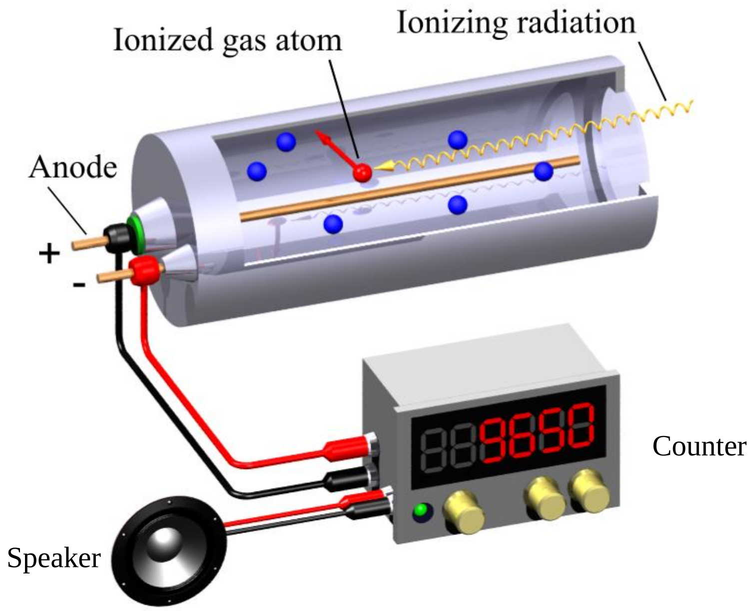


Fig1.2.2 schematic of a basic Geiger tube detector [1.2.5]

Geiger counter is one of the most popular devices used in radiation detection, but it also has two significant drawbacks: First, it cannot differentiate the radiation type, as each pulse generated from radiation is of almost equal duration; second, it cannot accurately measure a radiation with high density as it takes time for gas molecules to be ionized [1.2.3]. However, it is a perfect tool for teaching basic radiation theory for its low price and simple usage. In addition, since it is so popular in everyday applications, it is beneficial for the students to learn its method, especially in the context of the PH1130 Modern Physics course at WPI.

I.3 Theory

The first lab guides the students to investigate the penetration ability of the three radiations. Among the three types of radiation, alpha particles have the weakest penetration ability, and one sheet of paper is enough to block it. This is because alpha particle is the largest and heaviest particles among the three types of radiation; it does not travel even for a few centimeters through the air in that it collides and ionizes nitrogen and oxygen molecules. In this process the alpha particle loses energy and eventually it absorbs two electrons and becomes a stable helium atom. Beta particles are lighter and smaller than the alpha particles and carry only one negative charge, therefore they interact less strongly while travelling through the same material. Beta particles could easily penetrate paper but could be blocked by “denser” materials and especially metals such as an aluminum sheet (through which it will be absorbed since aluminum is conductor). Gamma particles are the most energetic electromagnetic radiation which typically do not interact with other molecules. Therefore they exhibit the strongest penetrating ability, and even aluminum sheet is unable to block it completely [1.3.1].

In the second lab the students will be determining the radiation density as a function of distance. Radiation can be weakened as it travels through space (think about how light becomes dimmer as the source is moved away from the observer). This is a result of the inverse square law, which is what the students would investigate. Any point source that emits equally over all space follows the inverse square law. The reason is purely geometrical as illustrated in Figure 1.3.1. The source’s influence (or the strength) at a particular distance r is determined by dividing the strength by the area at r [1.3.3]. So the source strength is related to distance in an inverse square relationship.

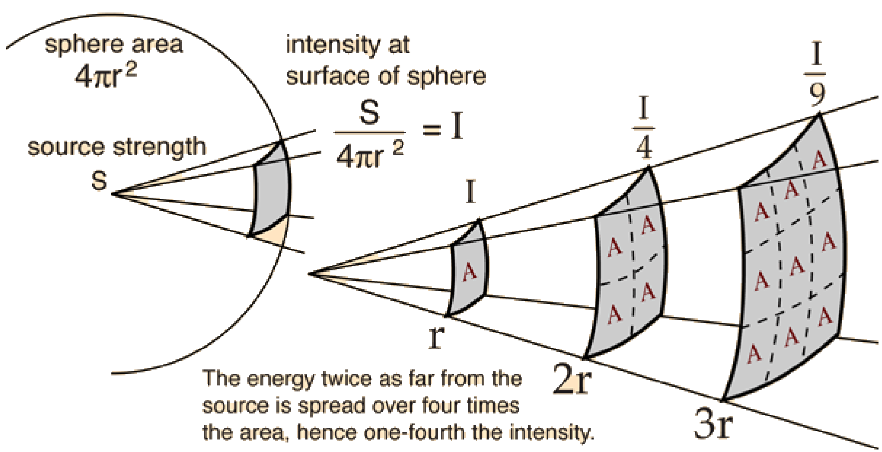


Fig 1.3.1 schematic of inverse square law [1.3.2]

The inverse square law is very common in physics. Some examples that follow the inverse square relationship are gravitational force, electromagnetic force, radiation and sound. Gamma radiation, as explained in Section I.1, is a type of electromagnetic radiation, thus it follows the inverse square law.

I.4 Project Description

A number of principles are followed in the process of designing the labs. First, the labs should be as straightforward as possible, since these labs are intended to teach the first-year students with little background in nuclear physics. Second, the labs should try to use fewest materials, preferably the materials that can be reused in the future lab sessions. This is because PH1130 is a large class with a maximum capacity of 72 students. It has three lab sections, and each section has 24 students. At least 12 sets of lab apparatus are needed if students work in a group of two people as typical. Third, since each week the students have two 50-minute lab sessions to work on one major lab topic, the two labs are designed with each lab to be completed in one session. Fourth, since students performing the labs have different background and aptitude, the length of each lab should be around 35-40 minutes, leaving a 10-minute margin for the students who do not finish the labs very quickly.

The first lab is about investigating the penetration ability of alpha, beta, and gamma radiation (designated as lab 1). It is designed to give the students a basic introduction to the three types of nuclear radiation, and examining their different penetration ability is a very concise way to bring in the introduction since the particle's penetration ability is directly linked to the physical properties of the radiation as discussed in section I.3. The second lab is about investigating the inverse square law of gamma radiation (designated lab 2). Gamma radiation has been chosen as the primary teaching tool because, as students would discover in lab1, gamma radiation has the strongest penetrating ability; using gamma radiation in lab2 can minimize the radiation loss as a result of unintentional blockage (such as the loss from air). And to reinforce the point in lab1, students would also be measuring the gamma particle's decreasing pattern when it is blocked by a paper and an aluminum sheet.

Both student instructions and teaching assistant instructions have been written and the labs have been tested by both the designer and the student volunteers. A survey was distributed to the student volunteers for feedback and any possible further improvement.

II. Methodology

II.1 Lab1: Penetration ability of α, β, γ radiation

II.1.1 Lab materials

Vernier VRM-BTD Radiation Monitor (It is connected with Vernier computer interface, which in turn connects with the computer through a USB)

4 sheets of paper (paper ripped off spiral notebook is sufficient)

4 sheets of aluminum (each is of 7.5mm thickness)

Beta source (strontium-90 0.1uC disk source, Atlantic Nuclear Corporation)

Gamma source (cobalt-60 1uC disk source, Atlantic Nuclear Corporation)

Logger Pro software (operating system: windows7, windows8, windows 8.1, windows10, Macintosh OS X 10.10.5, 10.11.6 or 10.12)

II.1.2 Preliminary Question

1. Most nuclear radiation (regardless of the types of radiation) carries energy that ranges within a few million electron volts. This implies that the heavier the particle, the slower it travels (kinetic energy $= \frac{1}{2}mv^2$). Based on the information provided in the Introduction part, make a preliminary guess as to which type of radiation would interact most strongly (therefore easier to be blocked) with the shielding? And which type of radiation would interact least strongly (therefore most difficult to be blocked) with the shielding?

2. Paper sheet and aluminum sheet would be used in this lab. The areal density (kilogram per square meter kg/m^2) of paper sheet is larger than the aluminum sheet. Do you think the two materials would have different ability to let the radiation pass?

II.1.3 Lab Procedure Design

1. Check the Geiger counter is connected with the computer interface
2. Prepare the computer for data collection by opening the file “01 Alpha Beta Gamma” from “Nuclear Radiation w Vernier” folder of Logger Pro. (File-> Open -> Nuclear Radiation w Vernier folder-> 01 Alpha Beta Gamma) The folder is shown in grey in Figure 2.1.3.1.

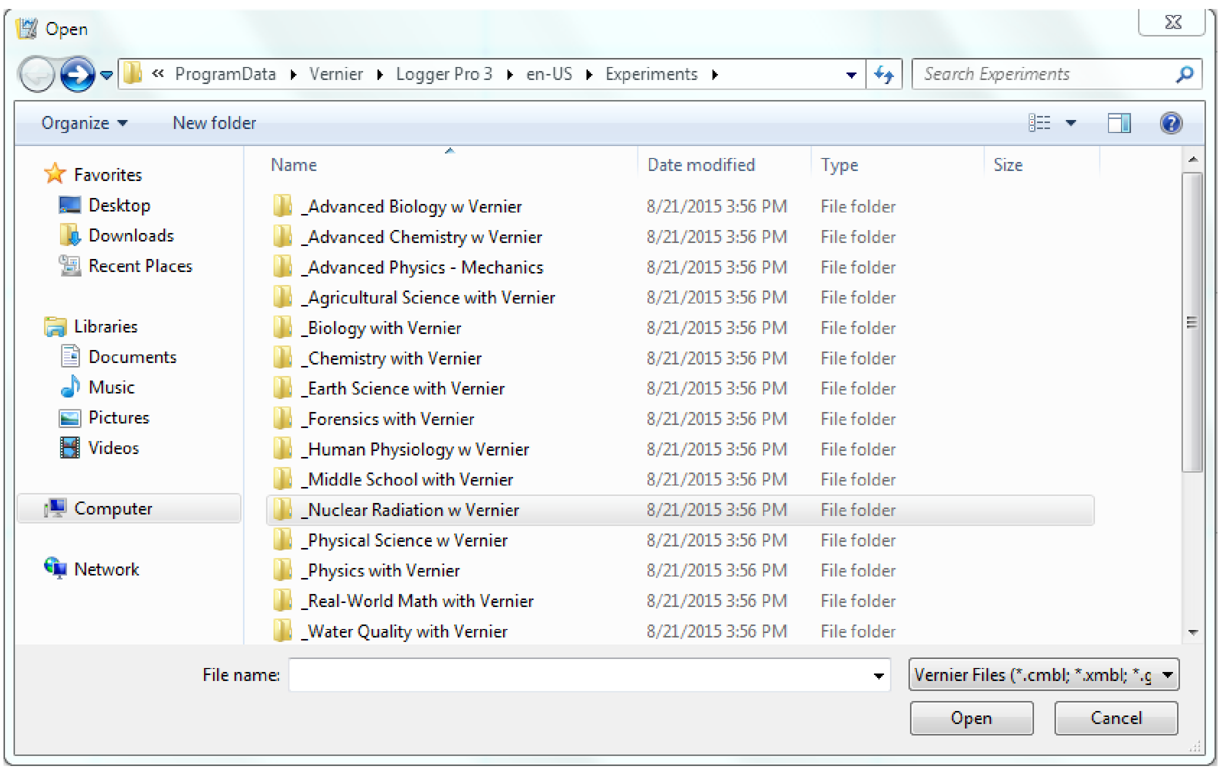
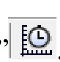


Fig 2.1.3.1 Folder “Nuclear Radiation w Vernier”

3. Determine the **background radiation for 30s**. Adjust the counting period in Logger Pro to **30s**. To do this, click the icon “data collection” . A box will appear as shown in Figure 2.1.3.2.

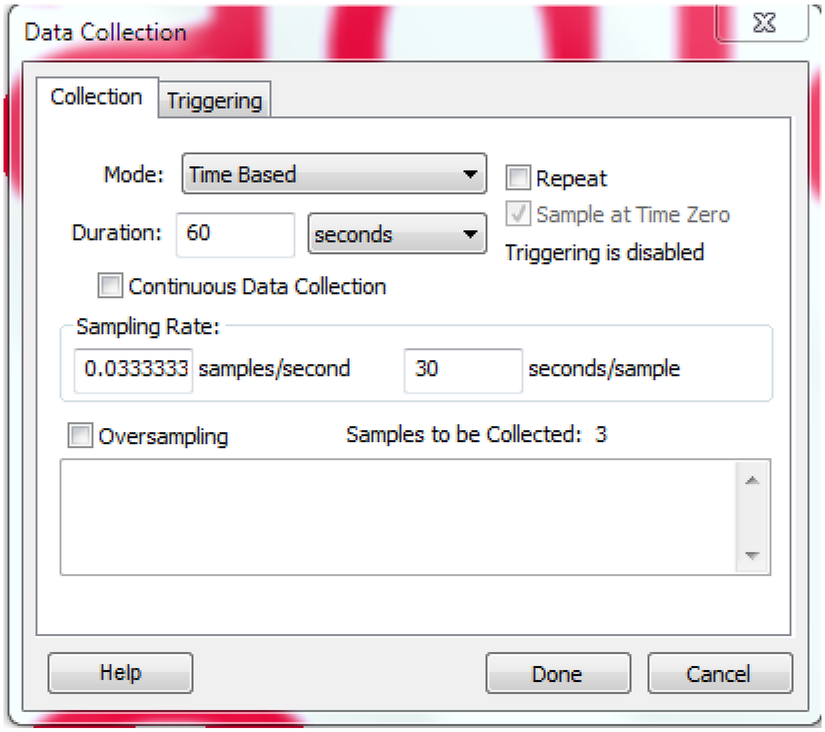


Fig 2.1.3.2: Data collection box

Change "Duration" to 60s, and change "**sampling rate**" to "**30seconds/sample**". Nothing else needs to be changed. Please note the "duration" must be larger than "sampling rate". **Move all radiation sources far away (1 meter) from Geiger counter**, click "collect" 

to collect data. The data may not appear very soon but the collection process has already started. **It takes 30s for the data to appear in the meter.** When the total number of counts is displayed, record the value in the table 2.1.4.1 (background counts, 30s) and calculate the average value and the standard deviation (STD) in table 2.1.4.2.

4. Place a single sheet of paper in front of the counter, and measure the counts as before. Record the displayed counts in the data table.

5. Repeat the **background measurement** for the following scenarios, and fill in table 2.1.4.1

   i) No shielding **(You already did this in step 3)**

   ii) A single sheet of paper **(already did in step 4);** 2 sheet of paper; 4 sheet of paper

   iii) Single sheet of aluminum; 2 sheet of aluminum; 4 sheet of aluminum

6. Put the gamma source near the Geiger counter (about 5 centimeters) with underside of the disc facing the monitor screen (**with no shielding**). Click to begin data collection. Wait for Logger Pro to display the number of counts and record the value in data table.
7. Similarly, measure and record the counts of gamma sources for **the three scenarios in Step 5**, and record your results in the data table. Note: The distance between the Geiger counter and the source should be relatively the same in each data collection process.
8. Calculate the mean and standard deviation of the background and gamma count and fill in table 2.1.4.2 and 2.1.4.4.
9. Repeat the above step for beta radiation.
10. Step1-9 measures the background, gamma, beta counts in 30s, now adjusting the counting period in Logger pro to **60s** (data collection-> sampling rate-> 60seconds/sample), and measure the background, gamma, beta counts in 60s. Record the data in the table.

II.1.4 Data Table

Table 2.1.4.1 to 2.1.4.6 are the number of counts recorded in 30 seconds.

Background counts

Table2.1.4.1 background counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
Background							

Table2.1.4.2 average and standard deviation for background counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
Background				

Gamma radiation

Table2.1.4.3 gamma counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
gamma							

Table2.1.4.4 average and standard deviation for gamma counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
gamma				

Beta radiation

Table2.1.4.5 beta counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
beta							

Table2.1.4.6 average and standard deviation for beta counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
beta				

Table 2.1.4.7 to 2.1.4.12 are the number of counts recorded in 60 seconds

Background counts

Table2.1.4.7 background counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
Background							

Table2.1.4.8 average and standard deviation for background counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
Background				

Gamma radiation

Table2.1.4.9 gamma counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
gamma							

Table2.1.4.10 average and standard deviation for gamma counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
gamma				

Beta radiation

Table2.1.4.11 beta counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
beta							

Table2.1.4.12 average and standard deviation for beta counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
beta				

II.1.5 Data analysis

1. Are background counts a significant portion of the sources' counts? Do you need to consider a correction in the beta and gamma counts?
2. Based on observation of the result, which type of radiation is more penetrating, beta or gamma? Which material is more absorbing (difficult to penetrate), paper or aluminum?
3. X-ray consists of photons. Do you think its property is closer to gamma radiation or beta radiation? Explain.

II.2 Lab2: Radiation strength as a function of distance

II.2.1 Lab materials

Vernier VRM-BTD Radiation Monitor (It is connected with Vernier computer interface, which in turn connects with the computer through a USB)

4 sheets of paper (paper ripped off spiral notebook is sufficient)

4 sheets of aluminum (each is 7.5mm thickness)

Beta source (strontium-90 0.1uC disk source, Atlantic Nuclear Corporation)

Gamma source (cobalt-60 1uC disk source, Atlantic Nuclear Corporation)

Logger Pro software (operating system: windows7, windows8, windows 8.1, windows10, Macintosh OS X 10.10.5, 10.11.6 or 10.12)

II.2.2 Preliminary questions

1. In this lab students would investigate how gamma radiation density pattern changes as a function of distance in the following three different scenarios: no shielding, one sheet of paper; one sheet of aluminum. Based on observation in lab1, is there going to be significant differences among the three types of scenarios? Explain.
2. Turn on the speaker of the Geiger counter. The Geiger counter would beep every time it detects one radiation event. Place the gamma source around 4cm from the Geiger counter and slowly move it away. How does the beep rate change? Does it increase or decrease?
3. What does Question 2 suggest? Plot a qualitative sketch of the number of counts as a function of distance.

II.2.3 Lab Procedure Design

1) Check the Geiger counter is connected with the computer interface
2) Prepare the computer for data collection. Still open the file “01 Alpha Beta Gamma” from “Nuclear Radiation w Vernier” folder of Logger Pro.
3) Adjust the count rate in the Logger Pro to 60s (data collection-> sampling rate-> 60seconds/sample). Move all sources at least 1 meter from the Geiger counter, and click “collect”. Wait 60s for the data to appear. This is the background counts. Repeat this step for 5 times and take the average. Notice that the number of background counts in each measurement varies. This is to be expected since radioactivity occurs randomly. Record the mean value in the data table.
4) Place the gamma source 4cm from the center of the Geiger counter with **no shielding**. Click to begin collecting data. Logger Pro will count the number of gamma photons that strike the detector during the 60 second count interval. Record the data in the table
5) Move the source 0.02 m further from the source. As before, click “collect” to collect data, and wait for 60s seconds.
6) In the same way as before, move the source away for an additional 0.02 m, and collect the measurement. Enter the distance in meters. Repeat this process until the counts does not show significant differences from background counts for three successive recordings (which should happen when the source is 0.14m-0.2m away from the source).
7) Step 2-6 is the measurement of the scenario of *no shielding*. Repeat the steps to measure the following scenario: (i) one sheet of paper (ii) one sheet of aluminum. Corrected counts = counts – background counts

II.2.4 Data Table

Table 2.2.4.1: Background counts and analysis (60 seconds)

Trail	Background reading
1	
2	
3	
4	
5	

average	
standard deviation	

Gamma counts (No shielding) in 60 seconds

Table2.2.4.2: Gamma counts (no shielding, 60s)

Distance (m)	Counts	Corrected counts
0.04		
0.06		
0.08		
0.1		
0.12		
0.14		
0.16		
0.18		
0.2		

Gamma counts (one sheet of paper) in 60 seconds

Table2.2.4.3: Gamma counts (one sheet of paper, 60s)

Distance (m)	Counts	Corrected counts
0.04		
0.06		
0.08		
0.1		
0.12		
0.14		
0.16		
0.18		
0.2		

Gamma counts (one sheet of aluminum) in 60 seconds

Table2.2.4.4: Gamma counts (one sheet of aluminum, 60s)

Distance (m)	Counts	Corrected counts
0.04		
0.06		
0.08		
0.1		
0.12		
0.14		
0.16		
0.18		
0.2		

II.2.5 Data analysis

1) Graph the data in Excel for the three scenarios. Inspect the graphs; does the graph follow the predicted model?
2) Use curve fit to model the graph with a function. What function (exponential? Logarithm? Quadratic function? Or others?) best fit in the model?
3) Are there significant differences among these three scenarios? Explain and state the reasons based on observation in lab1.

II.3 Lab Validation

This section shows the data from the designer's test. It is normal for the students' data to show some deviations from designer's data, since radioactivity is a random process. But they should produce similar conclusion at the data analysis part.

II.3.1 Lab1: Penetration ability of α, β, γ radiation

Table 2.3.1.1 to 2.3.1.2 are the number of counts recorded in 30 seconds

Table2.3.1.1: background counts and gamma counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
Background	10	15	12	12	10	14	9
gamma	21	24	23	21	21	20	13

Table2.3.1.2: average and standard deviation for background counts and gamma counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
Background	13	1.732	11	2.646
Gamma	22.67	1.528	18	4.359

Table 2.3.1.3 to Table 2.3.1.4 are the number of counts in 60 seconds

Table2.3.1.3: background counts and gamma counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
Background	23	23	18	24	20	19	21
gamma	38	39	41	38	36	37	25

Table2.3.1.4: average and standard deviation for background and gamma counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
Background	21.67	3.214	20	1
Gamma	39.33	1.528	32.67	6.658

As the data shows, there is no significant difference between 30s and 60s. Both results tell us gamma can penetrate paper and aluminum pretty well. But gamma count of both 30s and 60s scenario has dropped in the case of 4 aluminum. This indicates 4 aluminum sheets could prevent the penetration of gamma radiation. (Note: the beta radiation count was not performed since the designer didn't acquire a beta source. But the measurement of beta counts is exactly the same as gamma counts, so it should not be an issue in real applications.)

II.3.2 Lab2 Radiation strength as a function of distance

Background counts in 60 second seconds.

Table2.3.2.1: background counts 60s

23
22
20
22
28

And the average counts in 60 seconds are $\mathbf{23 \pm 2.72.}$

Gamma counts (No shielding) in 60 seconds

Table2.3.2.2: gamma counts (no shielding) 60s

Distance (m)	counts	Corrected counts
0.04	56	33
0.06	39	16
0.08	34	11
0.1	29	6
0.12	36	13
0.14	23	0

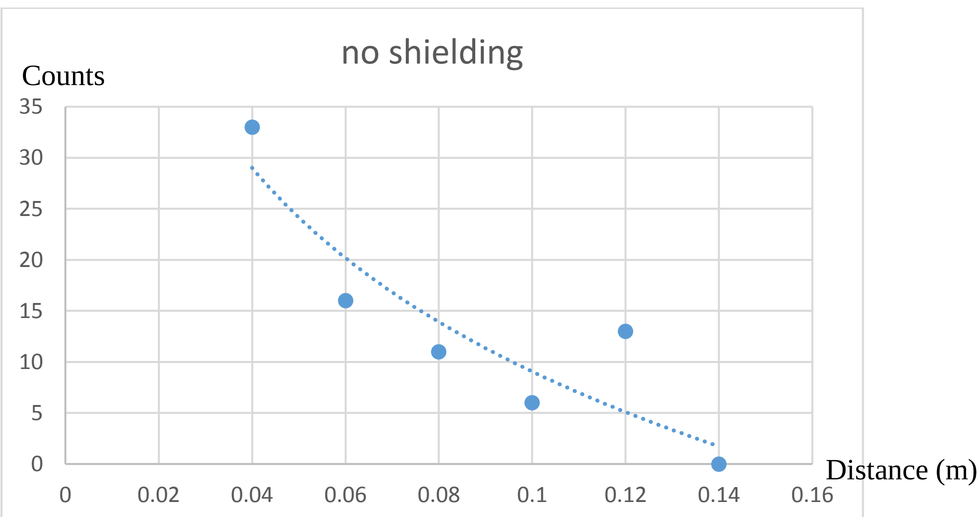


Fig 2.3.2.1: gamma counts (no shielding)

Note: only the counts up to 0.14m are measured in this no shielding case as compared with 0.18m in the other two scenarios.

Gamma counts (one sheet of paper) in 60 seconds

Table2.3.2.3: gamma counts (one sheet of paper, 60s)

Distance (m)	counts	Corrected counts
0.04	56	33
0.06	44	21
0.08	40	17
0.1	22	-1
0.12	38	15
0.14	21	-2
0.16	34	11
0.18	29	6

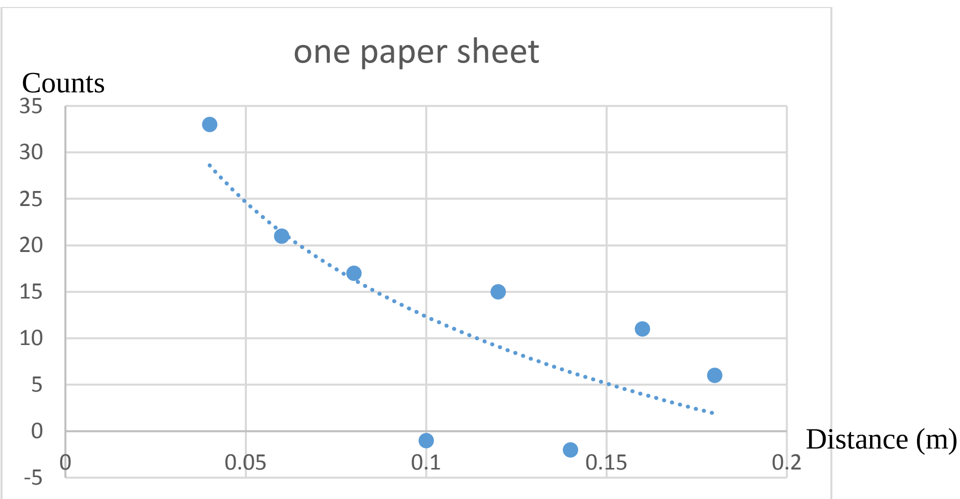


Fig 2.3.2.2: gamma counts (one sheet of paper)

Gamma counts (one sheet of aluminum) in 60 seconds

Table2.3.2.4: gamma counts (one sheet of aluminum, 60s)

Distance (m)	counts	Corrected counts
0.04	44	21
0.06	42	19
0.08	25	2
0.1	19	-4
0.12	27	4
0.14	24	1
0.16	21	-2
0.18	25	2

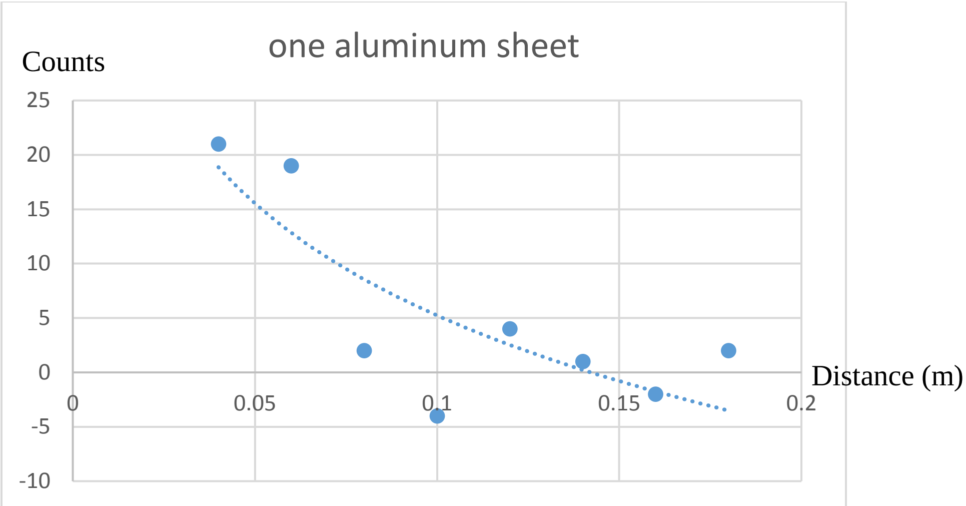


Fig 2.3.2.3: gamma counts (one sheet of aluminum)

These graphs are plotted in Excel, and the trend line is added. According to these three set of data, no matter what the shielding is, the further the gamma source, the weaker the radiation density. And the shielding has no significant effect on the relationship between gamma radiation count and distance. This agrees with the results from Lab1 which says gamma source would not be affected by either paper or aluminum. But there are a few “jumps” at the further position. This is due to the fact that radiation is a random activity, and it is possible to have some radiation events with a particularly large count.

II.4 Teaching Assistant Instruction

II.4.1 Lab1

Before the lab:

1. The Geiger counter is connected to the computer.
2. Have the beta, gamma sources ready on the lab stage for each group.
3. Prepare 4 sheet of A4-sized paper ready 4 sheet of aluminum on the lab stage for each group.

During the lab:

1. Give students a demonstration of alpha source penetration experiment. Turn on the projector which shows the screen of the lab computer. Put the alpha source about ten centimeters away

from the Geiger counter. Hold the source and Geiger counter in midair to make sure all students see the orientation of the source and the counter. Collect counts in 30s. Then put a sheet of paper between the source and the Geiger counter. Collect the counts in 30s. Students would see that when a single sheet of paper is inserted between the source and the counter, the total counts would drop significantly.

2. Make sure that all students answer the preliminary questions correctly before letting them proceed to the lab. When the students raise hands, simply approach them and check their answer (either written answer or verbal answer). If the students were wrong, give them another opportunity to think about it and check the answer a few minutes later. If the students were wrong again, explain the answer and let them retell it.

After the lab:

1. Put all radioactive sources back into the box. Turn off the projector and computers.
2. Tidy up the paper and the aluminum sheets. If the paper were damaged, simply throw them away.

II.4.2 Lab2

Before the Lab:

1. The Geiger counter is connected to the computer.
2. Have the gamma sources ready on the lab stage for each group.
3. Prepare the meter stick, paper sheet and aluminum sheet on each lab stage.

During the lab:

1. Since the students already learned how to use the Geiger counter in the lab1, there is no need for demonstration.
2. Make sure that all students answer the preliminary questions correctly before letting them proceed to the lab. This step is exactly the same as lab1.

3. Remind the students that the file they should be using is “01 Alpha Beta Gamma”

After the lab:

1. Put all radioactive sources back into the box. Collect the meter sticks.
2. Tidy up the paper and the aluminum sheets. If the paper were damaged, simply throw them away.

III. Result

This section displays the data from the two volunteers. Please note their beta measurement is missing.

III.1 Student 1

III.1.1 Lab1

Table 3.1.1.1 to 3.1.1.6 are the number of counts recorded in 30 seconds.

Background counts

Table 3.1.1.1 background counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
Background	5	13	13	12	15	14	11

Table 3.1.1.2 average and standard deviation for background counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
Background	13.67	0.5774	13.33	2.082

Gamma radiation

Table 3.1.1.3 gamma counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
gamma	204	155	116	101	89	67	28

Table 3.1.1.4 average and standard deviation for gamma counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
gamma	124	27.87	61.33	30.89

Beta radiation

Table 3.1.1.5 beta counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
beta							

Table 3.1.1.6 Average and standard deviation for beta counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
beta				

Table 3.1.1.7 to Table 3.1.1.12 are the number of counts in 60 seconds.

Background counts

Table 3.1.1.7 background counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
Background	19	30	21	16	29	26	23

Table 3.1.1.8 Average and STD for background counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
background	22.33	7.095	26	3

Gamma radiation

Table 3.1.1.9 gamma counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
gamma	55	41	42	37	152	116	65

Table3.1.1.10 Average and STD for gamma counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
gamma	40	6.458	111	43.72

Beta radiation

Table 3.1.1.11 beta counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
beta							

Table 3.1.1.12 Average and STD for beta counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
beta				

III.1.2 Lab2

Table 3.1.2.1: Background counts and analysis (60 seconds)

Trail	Background reading
1	26
2	33
3	25
4	29
5	30

Mean value	28.6
STD	3.209

Gamma counts (No shielding) in 60 seconds

Table 3.1.2.2: Gamma counts (no shielding, 60s)

Distance (m)	Counts	Corrected counts
0.04	49	20.4
0.06	44	15.4
0.08	31	2.4
0.1	39	10.4
0.12	34	5.4
0.14	36	7.4
0.16	33	4.4
0.18	26	-2.6
0.2	16	-12.6

Gamma counts (one sheet of paper) in 60 seconds

Table 3.1.2.3: Gamma counts (one sheet of paper, 60s)

Distance (m)	counts	Corrected counts
0.04	38	9.4
0.06	30	1.4
0.08	35	6.4
0.1	26	-2.6
0.12	26	-2.6
0.14	37	8.4
0.16	29	0.4
0.18	22	-6.6
0.2	35	6.4

Gamma counts (one sheet of aluminum) in 60 seconds

Table 3.1.2.4: Gamma counts (one sheet of aluminum, 60s)

Distance (m)	counts	Corrected counts
0.04	58	28.4
0.06	38	9.4
0.08	30	1.4
0.1	41	12.4
0.12	18	-10.6
0.14	27	-1.6
0.16	28	-0.6
0.18	28	-0.6
0.2	26	-2.6

III.2 Student 2

III.2.1 Lab1

Table 3.2.1.1 to 3.2.1.6 are the number of counts recorded in 30 seconds

Background counts

Table 3.2.1.1 background counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
Background	11	15	12	13	8	8	13

Table 3.2.1.2 average and standard deviation for background counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
Background	13.33	1.527	9.667	2.887

Gamma radiation

Table 3.2.1.3 gamma counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
gamma	27	29	14	17	22	16	23

Table 3.2.1.4 average and standard deviation for gamma counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
gamma	20	7.937	20.33	3.786

Beta radiation

Table 3.2.1.5 beta counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
beta							

Table 3.2.1.6 average and standard deviation for beta counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
beta				

Table 3.2.1.7 to Table 3.2.1.12 are the number of counts recorded in 60 seconds

Background counts

Table 3.2.1.7 background counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
Background	30	26	32	28	31	16	25

Table 3.2.1.8 Average and standard deviation for background counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
Background	28.67	3.055	24	7.541

Gamma radiation

Table 3.2.1.9 gamma counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
gamma	773	633	528	445	99	105	67

Table 3.2.1.10 Average and standard deviation for gamma counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
gamma	535.3	94.21	90.33	90.33

Beta radiation

Table 3.2.1.11 beta counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
beta							

Table 3.2.1.12 Average and standard deviation for beta counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
beta				

III.2.2 Lab2

Table 3.2.2.1: Background counts and analysis (60 seconds)

Trail	Background reading
1	22
2	22
3	26
4	13
5	24

Average	21.4
standard deviation	4.45

Gamma counts (No shielding) in 60 seconds

Table 3.2.2.2: Gamma counts (no shielding, 60s)

Distance (m)	Counts	Corrected counts
0.04	54	32.6
0.06	54	32.6
0.08	48	26.6
0.1	33	11.6
0.12	30	8.6
0.14	20	-1.4
0.16	29	7.6
0.18	27	5.6
0.2	24	2.6

Gamma counts (one sheet of paper) in 60 seconds

Table 3.2.2.3: Gamma counts (one sheet of paper, 60s)

Distance (m)	counts	Corrected counts
0.04	56	34.6
0.06	37	15.6
0.08	28	6.6
0.1	39	17.6
0.12	29	7.6
0.14	27	5.6
0.16	22	0.6
0.18	31	9.6
0.2	32	10.6

Gamma counts (one sheet of aluminum) in 60 seconds

Table 3.2.2.4: Gamma counts (one sheet of aluminum, 60s)

Distance (m)	counts	Corrected counts
0.04	49	27.6
0.06	45	23.6
0.08	31	9.6
0.1	31	9.6
0.12	49	27.6
0.14	25	3.6
0.16	29	7.6
0.18	23	1.6
0.2	32	10.6

IV. Survey and Feedback

IV.1 Student 1

Questionnaire for IQP: Radioactive lab for PH1130

The rating of each question is "1 2 3 4 5", with 1 being the worst and 5 being the best

1. My overall ratings of the lab is 5
2. The amount I learned from the lab is 5
3. The intellectual challenge of the lab is 4
4. The instruction's clarity in communicating course objectives 5
5. The instructions are clear and straightforward 5
6. The amount of work in the lab is 5
7. The instruments and computer software are in good operating condition 5

Are there any other comment you would like to add to the lab?

It's good and entertaining. It takes a lot of time but not boring.

Fig 4.2.1.1 questionnaire from Student 2

IV.2 Student 2

Questionnaire for IQP: Radioactive lab for PH1130

The rating of each question is "1 2 3 4 5", with 1 being the worst and 5 being the best

1. My overall ratings of the lab is 4
2. The amount I learned from the lab is 5
3. The intellectual challenge of the lab is 4
4. The instruction's clarity in communicating course objectives 5
5. The instructions are clear and straightforward 5
6. The amount of work in the lab is 4
7. The instruments and computer software are in good operating condition 4

Are there any other comment you would like to add to the lab?

Overall it's pretty good. However There's one thing that u could improve is to control some random variables in the lab to make the measurements more reliable. For example there should keep more space between groups To avoid the interference from other group's gamma sources.

Fig 4.2.1 questionnaire from student 2

V. Discussion

V.1 Volunteer suggestions

Below is a list of items that could further improve the lab based on feedback from the volunteers.

1. Clearly say open the "Logger Pro" in the student instructions, as some students could feel confused about what software they are going to use.
2. Move the tables inside the instruction texts in lab1, or students would need to scroll back and forth to read the instructions and fill in the data table. This could be very inconvenient.
3. The disk radioactive source can easily fall down. It would be better if the students are supplied with a shelf to hold the source in place.
4. Students could be confused with how many significant figures they need at the data table.
5. Students with no background knowledge might spend quite a long time reading the introduction part if they have not read it prior to the lab. A new part shall be added in TA (teaching assistant) instructions to let the TA explain the relevant concept to shorten the time student would spend on reading background information.

V.2 Future improvement

Both volunteers have given a 4 to "intellectual challenge". This means the two labs are not difficult and should be very appropriate for first-year physics student with little background in nuclear engineering. In addition, both volunteers have given 5 to the clarity of the instructions and the amount of knowledge learned from the lab. The two volunteers have a varied view on the amount of work of the lab. Student 1 reflected the lab is long and has a lot of things to do, and student 2 reflected the work is not too arduous and gave 4 to this question. One volunteer has made a great proposal: leave some distance between each group to avoid interference. However, later this has been decided not to be a serious issue, as the lab2 data already shows, the radioactivity of the source decreases almost to the same level of background counts at a distance of 20cm. And the distance between each group usually ranges around 1 meter; interference at this level should be negligible.

One major issue in the labs is the distance between the radioactive source and the Geiger counter. In lab 1, both volunteers have put the source right in front of the Geiger counter, and as a result they both got some gigantic counts that were up to a few hundred in some cases. These result are of course not valid since when they were measuring the counts in the four aluminum sheets scenario, the thickness of the aluminum sheets already created a significant effect on the number of counts (because the further the Geiger counter is from the source, the less particles the counter would receive). The issue of distance will be emphasized in the revised version of lab1 procedure.

Another issue is the beta counts. In both the designer's data and the volunteer data, the beta radiation counts are missing. This is because the designer didn't have a beta source for measuring. But the measurement method of beta source is exactly the same as gamma source, so the students should be able to do it without trouble in real lab.

The fourth issue needs to be solved is the number of counts decrease rapidly once the source is kept even only a little further (4cm) from the Geiger counter. Even at only 5cm the counts rapidly decreased and were almost the same as background counts. The source is not allowed to be pressed tightly against the Geiger counter because there will be a distance of at least 3cm between the Geiger counter and the source in the scenario of four aluminum sheets in lab1. If the source is pressed tightly against the Geiger counter the data from the four-aluminum sheets would not be valid. One way to improve this issue is to use a more power gamma radiation source than the Co-60 0.1uC disk source.

VI. Conclusion

In this IQP project two labs have been designed for PH1130, teaching students the basic principles of radioactivity. In the first lab the students will investigate the penetration ability of alpha, beta and gamma particles. In the second lab the students will reinforce what they learned in lab 1 by measuring the radioactive strength as a function of distance through different materials. Based on the feedback of the two volunteers, the lab instruction is clear and straightforward, and the lab is not very difficult even for students with little background knowledge. The volunteers have made a number of suggestions to revise the original lab setup (such as making a holder to fix the source and place the data table right below the instruction to avoid the trouble of scrolling back and forth). Overall the students have given good feedback to the two labs, and have enjoyed the lab.

VII. Appendix

VII.1 Appendix A: Revised student instruction for lab1

VII.1.1 Lab materials

Vernier VRM-BTD Radiation Monitor (It is connected with Vernier computer interface, which in turn connects with the computer through a USB)

4 sheets of paper (paper ripped off your spiral notebook is sufficient)

4 sheets of aluminum (each is 7.5mm thickness)

Beta source (strontium-90 0.1uC disk source, Atlantic Nuclear Corporation)

Gamma source (cobalt-60 1uC disk source, Atlantic Nuclear Corporation)

Logger Pro software (operating system: windows7, windows8, windows 8.1, windows10, Macintosh OS X 10.10.5, 10.11.6 or 10.12)

VII.1.2 Preliminary Question

1. Most nuclear radiation (regardless of the types of radiation) carries energy that ranges within a few million electron volts. This implies that the heavier the particle, the slower it travels (kinetic energy $= \frac{1}{2}mv^2$). Based on the information provided in the Introduction part, make a preliminary guess as to which type of radiation would interact most strongly (therefore easier to be blocked) with the shielding? And which type of radiation would interact least strongly (therefore most difficult to be blocked) with the shielding?
2. Paper sheet and aluminum sheet would be used in this lab. The areal density (kilogram per square meter kg/m^2) of paper sheet is larger than the aluminum sheet. Do you think the two materials would have different ability to let the radiation pass?

VII.1.3 Lab Procedure Design

1. Check the Geiger counter is connected with the computer interface

2. Open the software “Logger Pro”. Prepare the computer for data collection by opening the file “01 Alpha Beta Gamma” from “Nuclear Radiation w Vernier” folder of Logger Pro. (File-> Open -> Nuclear Radiation w Vernier folder-> 01 Alpha Beta Gamma) The folder is shown in grey in Figure 7.1.3.1.

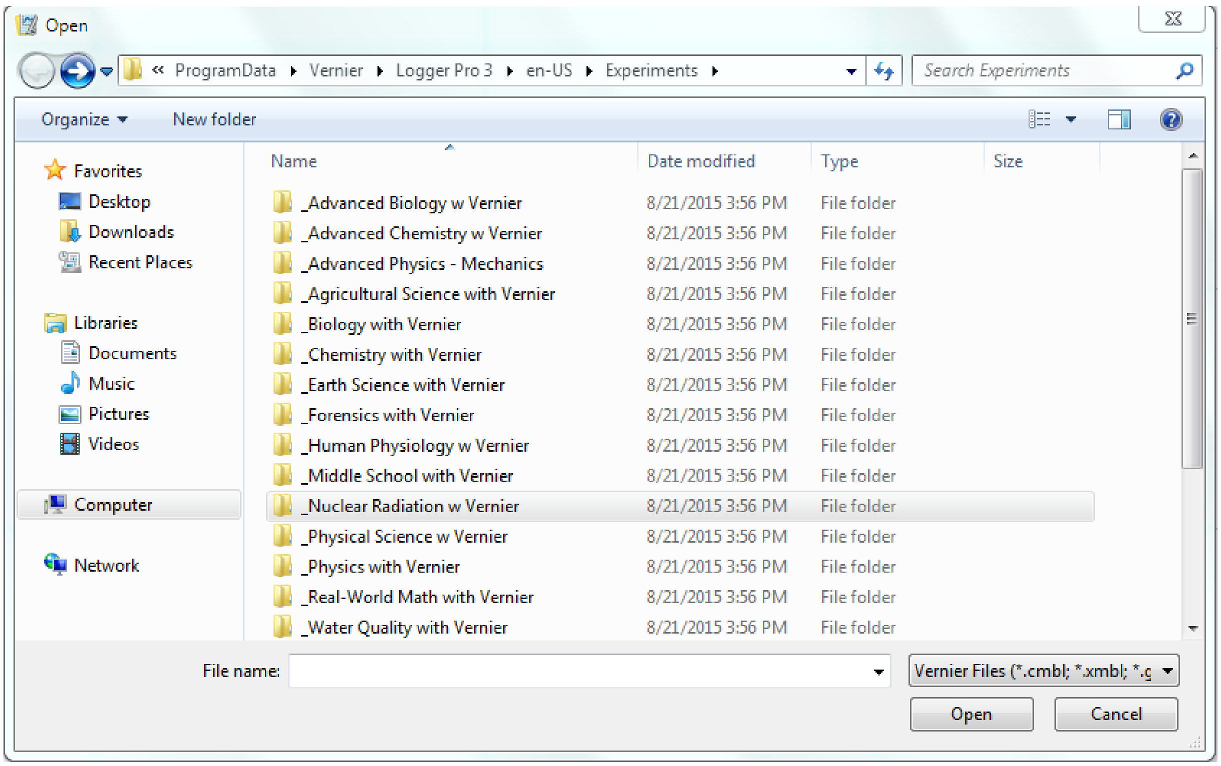


Fig 7.1.3.1 Folder “Nuclear Radiation w Vernier”

3. Now the student needs to determine the **background radiation for 30s**. Adjust the counting period in Logger Pro to **30s**. To do this, click the icon “data collection” . A box will appear as shown in Figure 7.1.3.2.

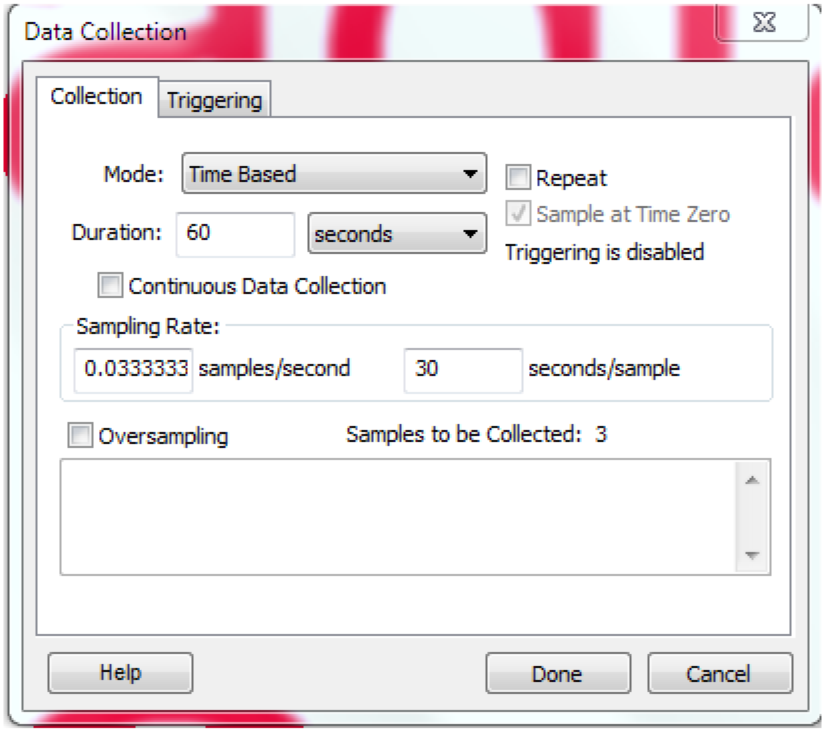


Fig 7.1.3.2: Data collection box

Change "Duration" to 60s, and change "**sampling rate**" to "**30seconds/sample**". Nothing else needs to be changed. Please note the "duration" must be larger than "sampling rate". **Move all radiation sources far away from Geiger counter**, click "collect" 

to collect data. The data collection may not appear as you expect them to be, but the collection has already started. It takes **30s** for the data to appear in the meter. When the total number of counts is displayed, record the value in the data table 7.1.3.1 (background counts, 30s). Calculate the average value and standard deviation (STD). If time is tight student can do the calculation after all data has been collected. Please remember to **keep four significant figures**.

4. Place a single sheet of paper in front of the counter, and measure the counts as before. Record the displayed counts in the data table 7.1.3.1.

Table7.1.3.1 background counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
Background							

Table7.1.3.2 Average and standard deviation for background counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
Background				

5. Repeat the **background measurement** for the following scenarios, and fill out Table 7.1.3.1.

   iv) No shielding **(You already did this in step 3)**

   v) A single sheet of paper **(already did in step 4);** 2 sheet of paper; 4 sheet of paper

   vi) Single sheet of aluminum; 2 sheet of aluminum; 4 sheet of aluminum

6. Put the gamma source around **5 centimeters** from the Geiger counter with underside of the disc facing the monitor screen (**with no shielding**). Click to begin data collection. Wait for Logger Pro to display the number of counts and record the value in data table 7.1.3.3.

Table7.1.3.3 gamma counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
gamma							

Table7.1.3.4 average and standard deviation for gamma counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
gamma				

7. Similarly, measure and record the counts of gamma sources for **the three scenarios in Step 5**, and record the results in the data table. Note: The distance between the Geiger counter and the source should be relatively the same each time when collecting data.
8. Calculate the mean and standard deviation of the background and gamma count rates for cases of both paper and aluminum.
9. Repeat the above step for beta radiation and record your value in data table 7.1.3.5

Table7.1.3.5 beta counts 30s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
beta							

Table7.1.3.6 average and standard deviation for beta counts 30s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
beta				

10. In Step1-9, you have measured the background, gamma, beta counts in 30s, now adjusting the counting period in Logger pro to **60s** (data collection-> sampling rate-> 60seconds/sample), and measure the background, gamma, beta counts in 60s. Record your data in the table.

Table7.1.3.7 background counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
Background							

Table7.1.3.8 average and standard deviation for background counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
Background				

Gamma radiation counts in 60 seconds

Table7.1.3.9 gamma counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
gamma							

Table7.1.3.10 Average and standard deviation for gamma counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
gamma				

Beta radiation counts in 60 seconds

Table7.1.3.11 beta counts 60s

Counts	No shielding	Paper			Aluminum		
		1	2	4	1	2	4
beta							

Table7.1.3.12 Average and standard deviation for beta counts 60s

	Average value (Paper)	Standard deviation (Paper)	Average value (aluminum)	Standard deviation (aluminum)
beta				

VII.1.4 Data analysis

1. Is the background count a significant portion of the sources' count? Do you need to consider a correction in the beta and gamma counts?
2. Based on observation of the result, which type of radiation is more penetrating, beta or gamma? Which material is more absorbing (difficult to penetrate), paper or aluminum?
3. X-ray consists of photons. Do you think its property is closer to gamma radiation or beta radiation? Explain.

VII.2 Appendix B: Revised Teaching Assistant instruction for Lab1

Before the lab:

1. The Geiger counter is connected to the computer.
2. Have the beta, gamma sources ready on the lab stage for each group.
3. Prepare 4 sheet of A4-sized paper ready 4 sheet of aluminum on the lab stage for each group.

During the lab:

1. Give the students a brief lecture (around 5mins) about the alpha, beta and gamma particles. Issues need covering are composition of alpha (helium nucleus), beta (electrons) and gamma (photons) particles, their penetration depth, and the inverse square law.

2. Give students a demonstration of alpha source penetration experiment. Turn on the projector which shows the screen of one lab computer. Put the alpha source about ten centimeters away from the Geiger counter. Hold the source and Geiger counter in midair to make sure all students see the orientation of the source and the counter. Collect counts in 30s. Then put a sheet of paper between the source and the Geiger counter. Collect the counts in 30s. Students would see that when a single sheet of paper is inserted between the source and the counter, the total counts would drop significantly.
3. Make sure that all students answer the preliminary questions correctly before letting them proceed to the lab. When the students raise hands, simply approach them and check their answer (either written answer or verbal answer). If the students were wrong, give them another opportunity to think about it and check the answer a few minutes later. If the students were wrong again, explain the answer and let them retell it.

After the lab:

1. Put all radioactive sources back into the box. Turn off the projector and computers.
2. Tidy up the paper and the aluminum sheets. If the paper were damaged, simply throw them away.

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