Verification and Analysis of Background Radiation Using a Diffusion Cloud Chamber

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Abstract:

Everywhere around us, there's radiation bombarding everything, even as you read this! Pew! Pew! But don't worry, it's completely safe. We can't see, hear, or feel these particles, but they're always there. They're called background radiation and they might even travel through you without ever interacting with the molecules in your body. This project presents the verification and analysis of such background radiation. By using a diffusion cloud chamber, the project aims to visualize and quantify the radiation particles' trajectories and thus, study the nature and randomness of background radiation.

Introduction

What is Background Radiation?

What is this mysterious thing called background radiation? Where does it come from? Is it everywhere? Is it safe?

Before we tackle these questions, let’s review our basics once. Everything around us is made of extremely small particles called atoms. As shown in Figure 1, atoms consist of an even smaller, positively charged nucleus surrounded by a cloud of negatively charged electrons. The negative charge of the electrons balances the positive charge of the nucleus, resulting in the atom being electrically neutral.

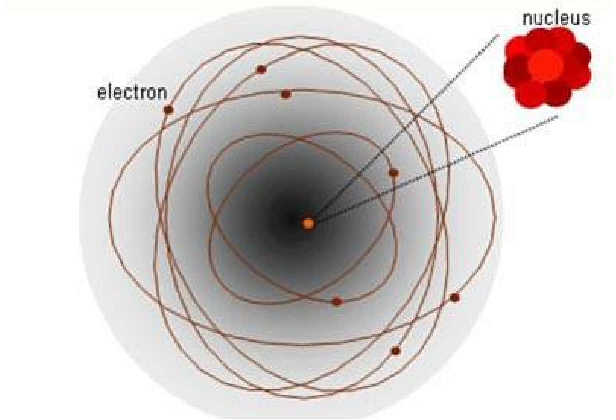


Figure 1. Representation of an atom with its nucleus and an electron cloud around it.

Atoms can both gain and lose electrons. The process by which an atom gains or loses an electron is called ionization, and an atom that has lost or gained one or more electrons through this process is called an ion.

Radiation is any type of wave or particle that transmits energy. Radiation can be encountered in a lot of places around us. For example, light bulbs radiate visible light; microwave ovens radiate waves that cook our food; an x-ray machine emits (or releases) x-rays.

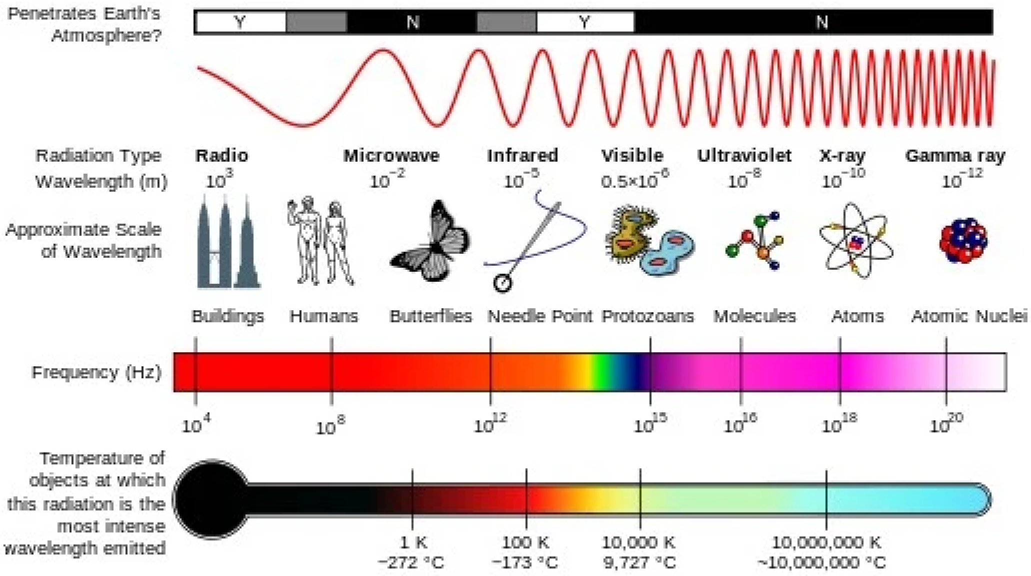


Figure 2. Types of Radiation

Radiation that transmits large amounts of energy that can ionize the matter around them is called high-energy radiation or ionizing radiation. They can change or damage other materials and living cells that it comes into contact with. In small amounts, however, ionizing radiation does not do significant harm, and in fact, it’s a part of our everyday life. Ionizing radiation that naturally occurs on our planet is called background radiation and is a natural part of our planet’s environment.

There are two primary sources of background radiation: one being cosmic radiation from space beyond Earth's atmosphere and other from the materials on Earth itself. Cosmic radiation is the radiation that Earth is constantly bombarded with from outside the solar system, in addition to high-energy ion radiation emitted by the Sun during solar flares. This radiation consists primarily of particles with extremely high energy. They interact in Earth's atmosphere to create secondary, lower-energy background radiation, some of which travels to Earth's surface.

On Earth, radioactive material (material that emits ionizing particles) is present all around us. In the soil, radioactive materials like potassium, uranium, thorium, and radon are present throughout the world in varying concentrations. Some radioactive materials (such as carbon 14) are present in any living being as part of the building blocks of life. Human beings have learned to use radioactive materials in a number of applications (such as in nuclear power plants and in some types of medical treatments).

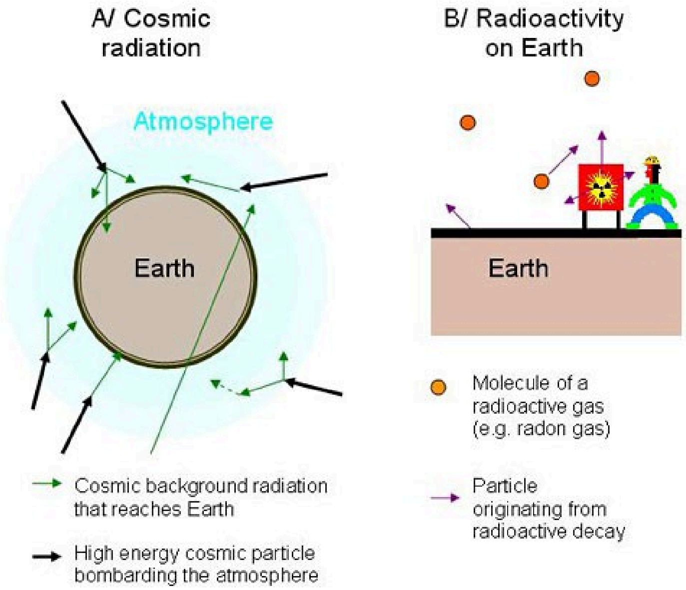


Figure 3. Secondary radiation formed in the atmosphere as ionizing cosmic particles collides with atoms in the atmosphere (part A) and background radiation formed from radioactive material on earth (part B).

Both of these types of background radiation consist of various particles, each carrying distinct properties. For instance, alpha particles are composed of two protons and two neutrons, resembling a helium nucleus. Beta particles are high-speed electrons or positrons emitted from the decay of unstable atomic nuclei. Gamma rays are electromagnetic waves of high energy and frequency. These particles, along with muons, neutrons, positrons and other cosmic rays contribute to the complex mixture of background radiation.

Even though we can't see any of these different kinds of radiation directly, we can indirectly observe them when they interact with substances that we can see. Interactions like this are often physical collisions between a radioactive particle or wave and a non-radioactive atom. Detecting radiation by looking for its interactions with atoms is similar to how you might indirectly observe wind: you can't see wind itself, but you can see leaves, trees, or plastic bags move in the wind and deduce that the wind is there.

Scientists build cloud chambers, also known as Wilson chambers, to study background radiation by looking at tracks in cloud chambers left by the passage of radiation particles. In this project, we will build a version of the Wilson chamber to observe the ghostly particle tracks that become visible to the naked eye when a cosmic ray zips through our environment.

Some Other Definitions:

Here are the definitions of some terms and concepts that will be used in this project:

1. Radiation: Radiation refers to the emission or transmission of energy in the form of particles or waves.

2. Electromagnetic radiation: Electromagnetic radiation is a type of radiation that consists of oscillating electric and magnetic fields propagating through space. It includes various forms such as radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays.

3. Ionizing radiation: Ionizing radiation refers to high-energy radiation that can ionize atoms or molecules by removing tightly bound electrons from them. It includes X-rays, gamma rays, and certain particles such as alpha and beta particles.

4. Background radiation: Background radiation refers to the low-level radiation that is constantly present in the environment, originating from natural and man-made sources. It includes cosmic radiation, natural radioactive elements, and other sources like medical procedures and nuclear activities.

5. Cosmic radiation: Cosmic radiation consists of high-energy particles, primarily protons and atomic nuclei, originating from outer space. It reaches the Earth from various sources, including the sun, stars, and galaxies.

6. Radioactive material: Radioactive material is any substance that contains unstable atomic nuclei, which undergo radioactive decay, emitting radiation in the process.

7. Vapor: Vapor refers to the gaseous state of a substance that is normally a liquid or solid at room temperature and pressure.

8. Condensation: Condensation is the process by which a substance changes from its gaseous state to its liquid state, typically occurring when the temperature decreases or the pressure increases.

9. Saturated vapor: Saturated vapor refers to a state where a vapor or gas has reached its maximum capacity to hold or dissolve another substance at a specific temperature and pressure. A saturated vapor is a vapor ready to condense.

10. Condensation nuclei: Condensation nuclei are tiny particles or surfaces in the atmosphere on which vapor can condense, forming droplets. They can include dust, pollutants, or other microscopic particles. They usually produce the transition from vapor to liquid.

11. Supersaturated vapor: Supersaturated vapor refers to a state where a vapor or gas contains more of a dissolved substance than would be present at equilibrium under normal conditions, typically achieved by cooling or reducing pressure. This is usually when a vapor should have condensed into a liquid, but it lacks the condensation nuclei to undergo condensation.

12. Alpha Particles: Alpha particles are composite particles composed of two protons and two neutrons, essentially a helium-4 nucleus. They are relatively large and carry a positive charge. They are commonly emitted by radioactive materials during alpha decay.

13. Muons: Muons are elementary particles similar to electrons but with a larger mass. They belong to the lepton family of particles and are negatively charged. Muons are created when high-energy cosmic rays from space interact with the Earth's atmosphere. They have a relatively short lifespan and quickly decay into other particles.

14. Neutrinos: Neutrinos are elementary particles with extremely low mass and no electric charge. They belong to the lepton family, like electrons and muons. Neutrinos interact only weakly with matter, making them difficult to detect. They are produced in various natural processes, such as nuclear reactions in the Sun, and are constantly passing through us in vast numbers.

15. Positrons: Positrons are the antiparticles of electrons. They carry a positive charge, unlike the negative charge of electrons. Positrons are produced in certain types of radioactive decay or particle interactions. When a positron collides with an electron, they annihilate each other, releasing energy in the form of gamma rays.

Cloud Chamber:

We have discussed background radiation well enough and have also defined most of the terms and concepts used in this project. Let's now talk about cloud chambers and how we can use them to observe background radiation.

The cloud chamber was invented by Scottish physicist Charles Thomson Rees Wilson in 1911 and this discovery earned Wilson the 1927 Nobel Prize in Physics. The cloud chamber and a related device called a bubble chamber led to discoveries of the positron in 1932, muon in 1936, and kaon in 1947.

A cloud chamber or Wilson chamber is a scientific device used to visualize the tracks of charged particles, such as ionizing radiation, by creating a supersaturated vapor environment where the particles cause condensation trails.

There are different types of cloud chambers. The cloud chamber in this project is called a diffusion-type cloud chamber. It is a sealed container that is warm at the top and cool at the bottom. The "cloud" consists of supersaturated alcohol vapor. Isopropyl or methyl alcohol are good choices because they readily vaporize at ordinary temperatures and are polar molecules. The warm part of the chamber vaporizes the alcohol, which cools as it descends toward the cold container base. The temperature difference forms a volume of supersaturated vapor.

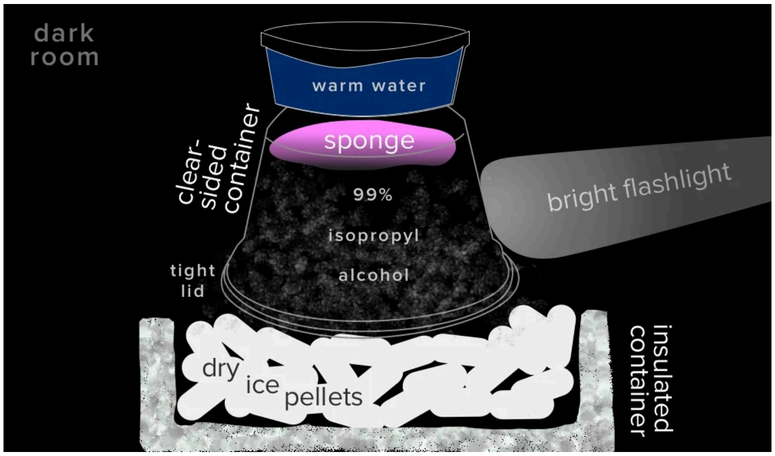


Figure 4. Diagram of Diffusion Cloud Chamber

When ionizing particles from background radiation (like muons or electrons) travel through the vapor in the chamber, they collide with the surrounding molecules, creating ions (charged atoms) along the way. Because the alcohol vapor inside the chamber is polar, they are attracted to the electrical charge of the ionized particles. When the polar molecules move toward the ionized region, they draw closer together causing the ionized particles to act as condensation nuclei and supersaturated vapor to condense into misty droplets.

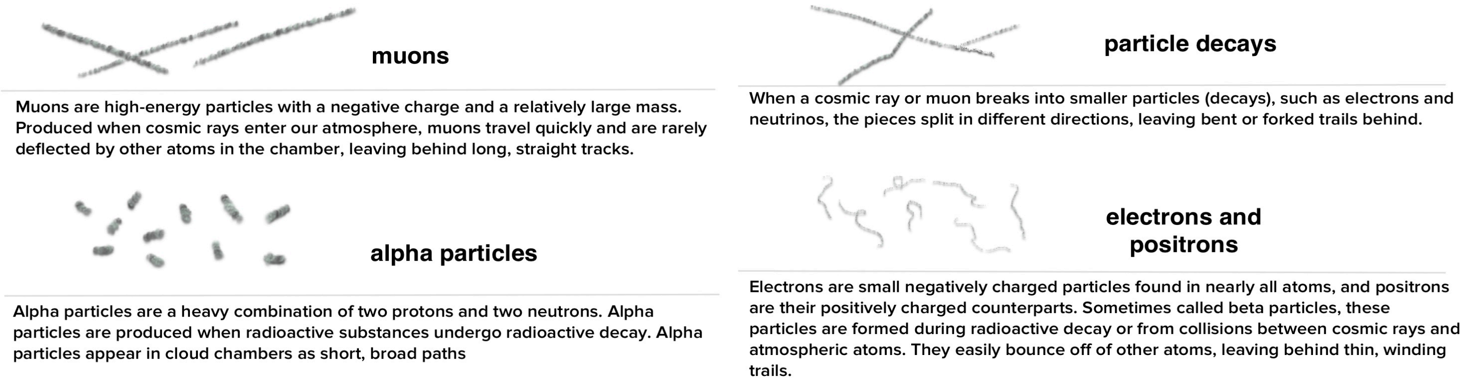
A bright beam of light can bounce off these droplets and there you have it — a visible track! In short, you see droplets of alcohol form on ion trails left by a particle of background radiation passing through the cloud chamber.

Did you note that only muons and electrons were listed in the explanation? Why? Would the other background radiation particles not provide a track in the cloud chamber?

This is because different particles have different capacities to penetrate materials and interact with the atoms in the chamber. Some are not able to penetrate through a layer of plastic (like alpha particles) and others can fly through Earth without any interaction (like neutrinos). The muon and some high-energy electrons can penetrate easily through the chamber's plastic walls and interact enough with material to show tracks in the chamber.

Identifying Particle Tracks:

The background radiation particle tracks left behind in a cloud chamber are those of many different types of particles that pass through the cloud chamber. Figure 5 shows a guide to finding the different types of radiation/particle tracks.



Muons are high-energy particles with a negative charge and a relatively large mass. Produced when cosmic rays enter our atmosphere, muons travel quickly and are rarely deflected by other atoms in the chamber, leaving behind long, straight tracks.

When a cosmic ray or muon breaks into smaller particles (decays), such as electrons and neutrinos, the pieces split in different directions, leaving bent or forked trails behind.

Alpha particles are a heavy combination of two protons and two neutrons. Alpha particles are produced when radioactive substances undergo radioactive decay. Alpha particles appear in cloud chambers as short, broad paths

Electrons are small negatively charged particles found in nearly all atoms, and positrons are their positively charged counterparts. Sometimes called beta particles, these particles are formed during radioactive decay or from collisions between cosmic rays and atmospheric atoms. They easily bounce off of other atoms, leaving behind thin, winding trails.

Figure 5. Types of Particle Tracks

The Experiment

Now that we thoroughly understand background radiation, how a cloud chamber works and how we can use it to study the presence of background radiation, especially muons present in the environment, let's see how we can build one to experimentally verify the presence of background radiation.

Materials and Equipments:

Here's the list of materials and equipments that are needed to perform the experiment:

- A clear plastic cup with a lid, approximately 8 cm tall and 9 cm in diameter is a size that works well, but similar sizes also work.
- Thick felt (15 x 15 cm).
- Fine-point marker or pen
- Scissors
- Small amount of Plasticine or modeling clay (size of a ping pong ball)
- Black construction paper (1 sheet)
- Glue or tape
- Room that can be made dark
- Protective gloves
- Safety glasses or goggles
- Block of dry ice (about 1kg).
- Baking tray of a size larger than the clear plastic cup.
- Hammer
- Isopropyl alcohol 91% or higher (40 ml).
- Eye dropper
- Small bowl with warm water in it
- Bright-beam LED flashlight or headlamp
- Lab notebook

Precautions:

Here are some precautionary measures that needs to be kept in mind and followed before and during the experiment:

1. Store the dry ice carefully in a container with a lid that shuts to prevent evaporation, but at the same time do not seal the dry ice in an airtight container because this can cause a buildup of gas that may result in an explosion.

2. Direct skin contact with dry ice can cause burns. Avoid direct contact with dry ice by using insulating gloves when you handle it. Always wear the safety goggles too.
3. Isopropyl alcohol is toxic to ingest and also highly flammable. Make sure there are no open flames in your work area, clean spills promptly, and avoid contact with skin or clothing. Safely allow any of the remaining alcohol in the cloud chamber to evaporate in a well-ventilated area away from open flame at the end of the experiment.

Experimental Procedure:

STEP: 1 Preparing the Cloud Chamber

1. Cut and place a piece of felt inside the bottom of the clear plastic cup.
    a. Cut a piece of felt to fit in the bottom of your cup. The felt will hold the alcohol.
    b. Place the cup on the square piece of felt (bottom down, lid side up).
    c. Use a fine-point marker or pen to trace around the bottom of the cup on the felt.
    d. Cut out the circular piece you traced from the larger square of felt.
    e. Place the felt on the inside bottom of the plastic cup.
2. Mold and use the Plasticine or modeling clay to hold the felt in place at the bottom of the cup.
    a. Roll the clay (or Plasticine) into a long, skinny (about .5 cm in diameter) rope long enough to place around the circumference of the inside bottom of the cup.
    b. Place the clay roll around the border of the felt in the cup and push it in so the clay holds the felt in place, as shown in Figure 6.
    c. Test if the felt stays put by turning your cup upside down.

Figure 6. The first steps in preparing a cloud chamber should result in a cup whose inside bottom is covered with felt and Plasticine or clay holding the felt in place.

3. Use the black construction paper to make a black background that will fit inside the lid of the cup. When the cloud chamber is complete, the cup will be turned upside down, so that the black background will be on the bottom. This is because the particle tracks will be more visible against a black background.
    a. Cut a circle the size of the inside of the lid of the cup from the black construction paper.
    b. Cover the inside of the lid with the circle of black construction paper. Use glue or tape to make the construction paper adhere to it.
4. Close your cup, put it upside down (resting on the rim) as shown in Figure 7, and there is your cloud chamber!

Figure 7. Picture of a cloud chamber ready to use, with the cup turned upside down, the felt held in place by the clay on the inside bottom of the cup, and the circle of black construction paper fitting inside the lid of the cup.

STEP: 2 Observing the Background Radiation

1. In the lab notebook, make a data table similar to one below:

S.No.	Horizontal Track	Vertical Track	Slant Track	Total Number of Tracks
Total				

We will be recording how many tracks you see, and the angles at which they are visible in this data table. From the observations, we will determine if the observed radiation appears random in direction.

   a. Classify the tracks you see depending on their inclination with respect to the vertical and horizontal planes:
      i. Horizontal tracks: tracks with a relatively small inclination with respect to the horizontal plane.
      ii. Vertical tracks: tracks with a relatively small inclination with respect to the vertical axis.
      iii. Slant tracks: tracks that are neither vertical nor horizontal.

   Note: You will not be able to measure the angle of inclination exactly. Your best estimate will do fine for this project. Figure 8 shows how to classify tracks.

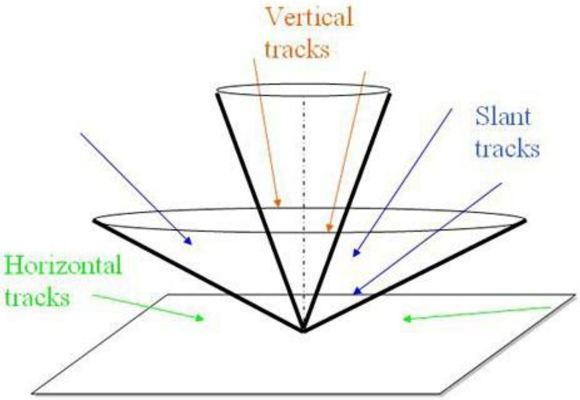


Figure 8. Classification of tracks. The cones indicate the area in which to classify a track as vertical (small inner cone), slant (wide cone, but not in the smallest cone), or horizontal (outside the cones).

2. Take a moment to think about these questions:
   a. Do you expect tracks to appear randomly in their direction or take a specific incident inclination?
   b. Do you expect tracks to appear randomly in time?
3. Choose an environment that can be made dark (it can be inside or outside) and away from any heat source. Along with your cloud chamber, bring all the materials listed below "Room that can be made dark" in the materials list with you.

4. Create a bed of small pieces of dry ice for your cloud chamber.
    a. Put on the protective gloves and glasses or goggles to handle the dry ice.
    b. Place the dry ice on the baking tray and crush it into small pieces with your hammer. Smaller pieces create a more even contact with the lid of your cup and avoid relatively cooler and warmer spots in the cloud chamber during the experiment.
    c. You can take the gloves off, but be aware that the baking tray will get cold — really cold. Avoid touching it with your bare skin.
5. Soak your felt with the isopropyl alcohol using the eyedropper.
    a. Though you should not make the felt dripping wet, it is important to thoroughly soak it.
6. Trap alcohol vapor inside the cold chamber by quickly snapping on the lid of your cup.
7. Place the cup upside down on the dry ice. Your setup should now look similar to the one in Figure 9.

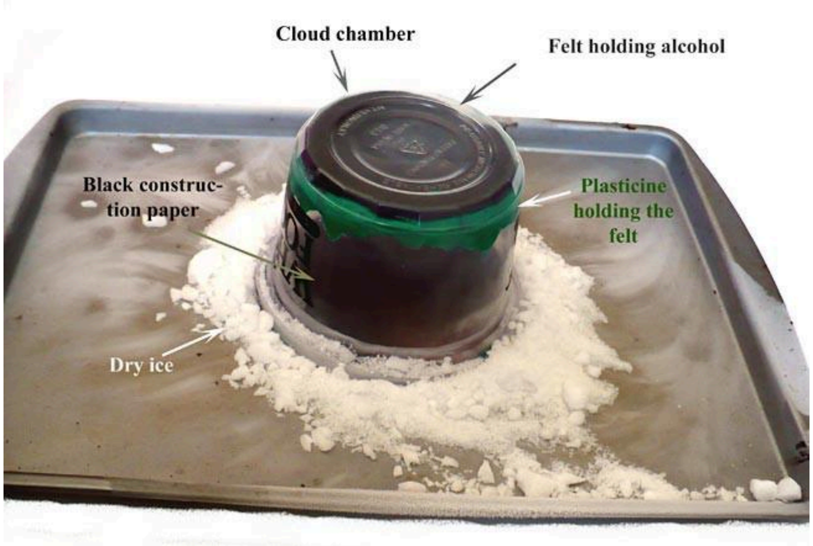


Figure 9. In your setup of the cloud chamber, the cup should be positioned upside down on the layer of crushed dry ice you made on the baking tray.

8. Warm the cup so the isopropyl alcohol will evaporate and create a fine vapor in the chamber.
    a. Place the bowl with warm water on top of the inverted cup to warm the alcohol-soaked felt. A gradual evaporation of the alcohol works best, so do not put something warmer than luke-warm water on the cloud chamber.
9. Kill the lights and light up the cloud chamber with a flashlight. Start looking for tracks, but keep in mind that it can take from a few minutes up to 20 minutes to see any tracks, so you may need to be patient. Once you start seeing tracks, move on to the next step, where you will start recording your observations.

a. The creation of alcohol vapor is necessary to see the tracks. You will not see the alcohol vapor immediately — it will only be apparent when it condenses into microscopic droplets, forming a mist. Depending on the size of your chamber and the specifics of your environment, it can take a few minutes up to 20 minutes to see the thin fog of alcohol vapor, so be patient.
b. Although it may take a few minutes for the alcohol vapor to form, you can start trying to see tracks by holding your flashlight at a 45-degree angle with respect to the baking tray, as shown in Figure 10 on the left.
c. As shown in Figure 10 on the right, experiment holding the flashlight at the 2 o'clock position if you are observing from the 9 o'clock position. You might have to tinker around with these suggested positions. The idea is to make the light reflect off droplets, but eliminate any glare. Additionally, sometimes ideal conditions for the supersaturation are met only in particular areas of the cloud chamber. The best place to observe tracks is where you see the thin mist, which may take up to 20 minutes to appear.

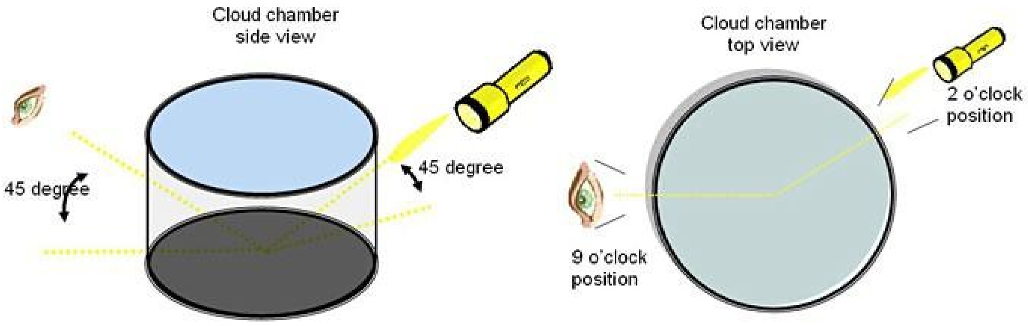


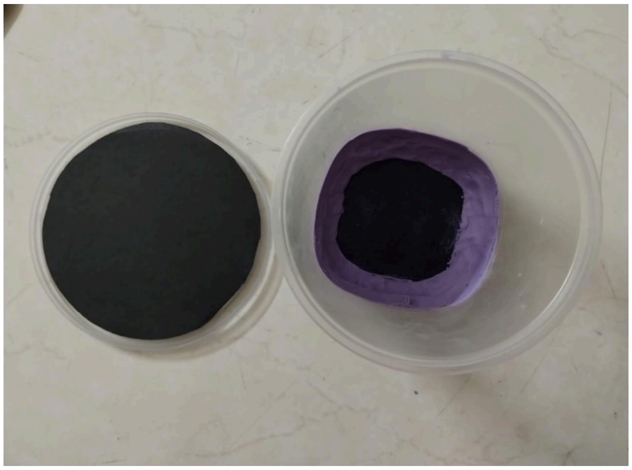
Figure 10. These drawings illustrate the recommended position of the observer and the flashlight with respect to the cloud chamber to achieve good observations.

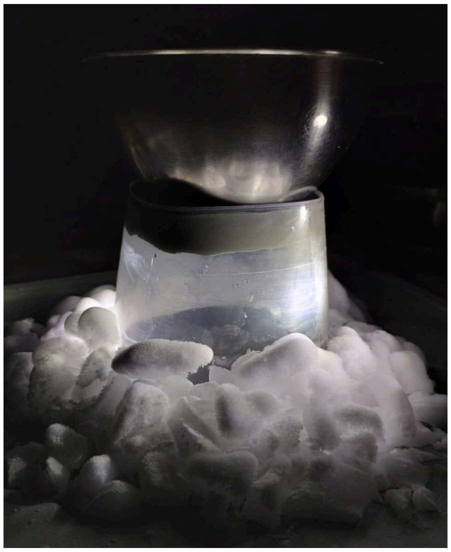
d. Once you start seeing tracks, move on to step 10 to start recording your observations.
e. If you do not see any tracks within 30 minutes, you might not have the right conditions in your cloud chamber. Before you start all over again, evaluate the following questions and see what you could do differently:
    i. Was the felt well-soaked with alcohol when you started, without excess alcohol dripping off the sides?
    ii. Is the cloud chamber nicely sealed or can vapor escape? If vapor does escape, seal the hole and try again.
    iii. Is there enough dry ice to keep the bottom of your chamber cool?

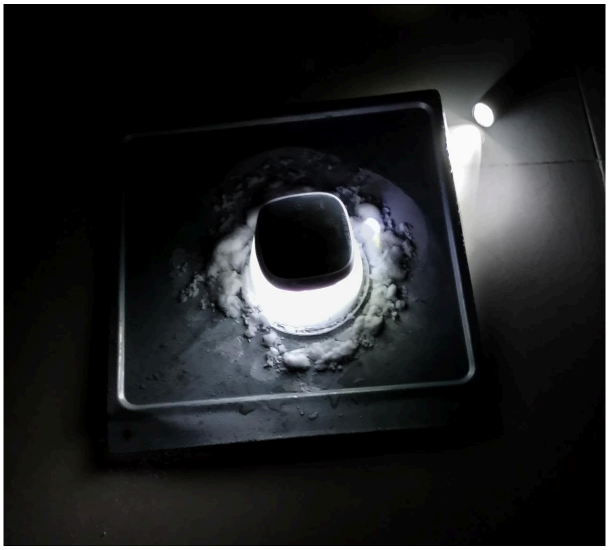
    iv. Did you warm the top of the chamber with the bowl of warm water properly? Faster warming with a much warmer heat source or not warming enough will result in a failing cloud chamber.
    v. Is your flashlight strong enough to illuminate the chamber?
    vi. Did you try positioning yourself and the light source at various angles?
    vii. If you tried to tweak all of these variables and are still having problems seeing tracks, start over from step 5.

10. Once you observe tracks, take notes of what you observe.
    a. Note down whether the track is more or less horizontal, more or less vertical, or slant (more or less at 45 degrees) with respect to the baking tray.
    b. Note down the number of tracks you observe by tallying them in the appropriate box in the data table (similar to Table 1) in your lab notebook.
    c. Note down what kind of tracks you see.
    d. Stop observing when tracks become faint. This will probably happen after roughly 10 minutes.
    e. Turn on the light and take a breather.
11. In your lab notebook, record some further general-impression notes on your observations:
    a. Would you say the tracks came randomly in time (for example, at 1 second, then 3 seconds, then 10 seconds, etc.) or at a regular time interval (for example, every 5 seconds).
    b. Were some/most/all tracks straight tracks? Or curved tracks or spirals? Did you observe other configurations?
    c. Was there a variation in thickness of tracks? Were some clear and others faint?
    d. Any other observations that caught your attention?
12. Clean up or prepare for another observation if you need to or like to repeat this experiment. It is advised to observe tracks at least three times. You could choose to change the time of day to see if background radiation is different at different times of day.
13. Finalize the observations and analyze the results.
    a. In your data table, calculate the total number of tracks and write this down in the far right column of your data table.
    b. What does your data tell you? Is there a pattern or consistency in the angles at which you see the tracks? Do the observations support or contradict your knowledge of background radiation?

Experimental Setup: Here are the images of my experimental setup (Figures 11-17).







Figures 11-17. My Experimental Setup

Observations:

I conducted the experiment 4 times in total — two during the night at around 427 meters above sea level and two during the day on the first floor at around 437 meters above sea level — each for around 5 minutes. Here are my observations from the experiments:

S.No.	No. of Horizontal Tracks (in 1 min)	No. of Vertical Tracks (in 1 min)	No. of Slant Tracks (in 1 min)	Total No. of Tracks (in 1 min)
Night #1	5	3	5	13
Night #2	9	2	5	16
Day #1	3	4	2	11
Day #2	5	3	4	12

- Yes, the tracks came randomly in time. However, there was a difference between the tracks seen during the first observation done at night and the second observation done during the day at a different altitude.
- Almost all of them were straight tracks and many of the straight tracks split into two or more tracks. Some of the tracks were also curvy and/or wiggly.
- There wasn't much variation in the thickness of the tracks but some tracks were certainly more clear than the rest.

Inferences/Results:

- There exists background radiation around us.
- The tracks formed by background radiation exhibit a certain level of randomness in its occurrence arising from the inherent nature of the radioactive decay processes.
- The distribution of background radiation can vary depending on factors such as geographic setting, diurnal variations, altitude, and proximity to radioactive materials.
- Almost all of the tracks that were observed were those of muons and a very few of them were electrons. Particle decay of muons were also observed in a regular frequency. However, no alpha particles were observed.

Conclusion

The experiment conducted helped verify the existence of background radiation around us. The tracks observed in the cloud chamber were mostly muons with an occasional electron and these tracks exhibited randomness. The occurrence of these tracks changed with change in the setting of the experiment.

All of these are consistent with our knowledge about background radiation and cloud chambers. Thus, we can say that building cloud chambers is an excellent way to verify the existence of background radiation and observe the patterns of such radiation.

For years now, cloud chamber experiments have provided valuable inferences and results regarding the behavior and properties of subatomic particles, as well as the nature of background radiation including:

1. identifying and characterizing various subatomic particles by analyzing the tracks left by particles in the chamber,
2. providing insights into the interactions between particles and matter by observing the deflection or scattering of particle tracks in the chamber
3. estimating the energy and velocity of charged particles based on the curvature and length of their tracks by studying the tracks and applying principles of particle dynamics
4. understanding the origin, composition, and energy distribution of cosmic rays by observing the tracks of cosmic ray particles in cloud chambers
5. studying the decay of radioactive isotopes and the lifetimes of particles by observing the tracks of decay products in cloud chambers.

Cloud chamber experiments still continue to be instrumental in numerous scientific discoveries and advancements in the field of particle physics.

Therefore, in conclusion, we can say that cloud chamber experiments are an effective and efficient way to study radiation and this is not only true for a small-scale, home-made cloud chamber but also for larger, much more precise ones built in laboratories.

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