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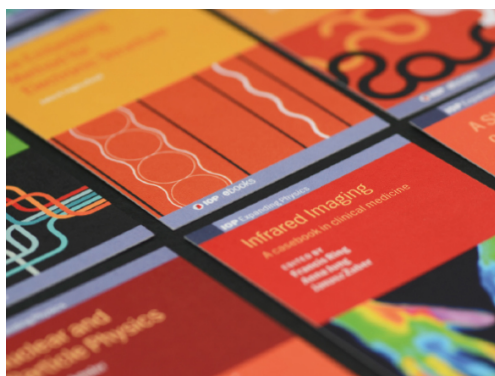
Cloud chamber kit for active learning in a first-year undergraduate nuclear science seminar class

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Cloud chamber kit for active learning in a first-year undergraduate nuclear science seminar class

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Abstract

This paper presents the design and reports on the use of a simple and inexpensive cloud chamber kit that is compatible with active learning, experiential learning, and project-based learning strategies. The kit was developed for use in a first-year undergraduate nuclear science seminar class at a university in the US. Diffusion cloud chambers are commonly used in classroom demonstrations to teach students about cosmic rays and ionizing radiation. A variety of clever and novel cloud chambers found in the literature were built and tested as part of this work and are all suitable for instructor-led classroom demonstrations. However, each has drawbacks that limit its use in hands-on classroom activities as part of active learning, experiential learning, and project-based learning in the classroom. The purpose of this work was to develop a cloud chamber ‘kit’ that can be built in less than 10 min by students during class and guarantees student success in observing background radiation. The cloud chamber kit was found to be highly sensitive to background radiation, and several different types of high-energy particles, including muons or anti-muons, electrons or positrons, photoelectrons, and alpha particles, were detected and identified using the kits at a rate of over 20 tracks per minute measured indoors at sea level at



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latitude 42.3601° N. The simplicity of the cloud chamber kit presented here makes it compatible with a variety of best practices for active learning in the classroom and requires little preparation time outside of class.

Keywords: cloud chamber, cloud chamber kit, cosmic rays, ionizing radiation, background radiation, active learning, project-based-learning

1. Introduction

Cloud chambers are devices used to create the conditions required to detect radiation using supersaturated vapors [1, 2]. Originally developed around 1900 by physicist C. T. R. Wilson, cloud chambers hold a special place in particle physics. While studying cosmic rays, Carl Anderson observed a particle of antimatter, the positron, for the first time. Cloud chambers also hold a special place in classroom teaching, with articles on using cloud chambers to reveal the ‘sub-microscopic’ world to students appearing in the mid-1930s [3, 4].

Diffusion cloud chambers are most commonly used in classroom demonstrations [5], and are typically based on the cooling of saturated alcohol vapor with liquid helium or solid carbon dioxide (dry ice). As high-energy particles pass through the cooled alcohol vapor in the chamber, they ionize the vapor particles in the chamber. This results in an ion pair (free electrons and ions). The vapor condenses readily around the charged particles, leaving visible ‘tracks’. This is similar to how clouds condense and form around particles in Earth’s atmosphere.

In the past decade, there have been a variety of innovative and novel approaches for optimizing cloud chambers for classroom teaching, including a fish tank cloud chamber [6]. Because procurement of dry ice can be a barrier to its use in the classroom, several authors have focused on using more readily available coolants, such as cans of compressed air [7], gel ice packs [8], and mixtures of salt and ice [9]. Other authors have focused on eliminating dry ice to extend operation times so that students can observe tracks for longer periods, thus making cloud chambers more suitable for laboratory-based instruction. This includes the sophisticated use of Peltier cooler modules [10] and chips [11] to cool the base of the viewing chamber.

However, the elimination of the use of dry ice tends to create another potential barrier for classroom use: the need for a radioactive source because chambers without dry ice that were built and tested [7–9] could not be used to reliably detect background radiation. In the United States, radiation sources can be expensive and their use may be controlled or discouraged in classroom settings. Some authors avoid the need for a radioactive source by imposing an electric field [8]; however, this introduces another potential barrier.

One of the simplest and most elegant cloud chambers for classroom demonstration found in the literature uses dry ice and ethanol (ethyl alcohol), and is sensitive to background radiation without requiring the application of electric fields [12], owing to the introduction of a black anodized aluminum heat sink as a base plate and a projector used to illuminate the chamber. For a classroom demonstration, this offers an excellent option, but requires substantial time investment for the instructor outside the class. Furthermore, ethanol is classified as a hazardous and dangerous item that requires special procurement procedures at the author’s university (creating another logistical barrier for its use during instruction).

Overall, the cloud chambers found in the literature [5–12] and tested by the authors [7–9, 12] are all suitable for instructor-led classroom demonstrations. However, each has drawbacks that do not allow them to be used in hands-on classroom activities as part of active, experiential, or project-based learning in the classroom [13, 14].

The purpose of this study was to develop a simple, inexpensive cloud chamber that can be rapidly assembled by students while guaranteeing student success when observing background radiation. The simplicity of the cloud chamber ‘kit’ presented here makes it compatible with

a variety of best practices for active learning in the classroom [13]; importantly, it requires little time outside of class for the instructor to prepare.

2. Method

2.1. Considering curriculum alignment for a cloud chamber active learning project

The cloud chamber kit project was undertaken to support a first-year (freshman) undergraduate seminar. The course provides students with an introduction to nuclear science and engineering and includes one hour of class time and two hours of work outside of class per week. The class period was 50 min, and the typical class size was 20 students. In addition to short technical lectures, students worked in pairs on hands-on projects throughout the semester. The course included a series of learning objectives, covering topics such as radiation, radioactivity, radiation detection, electronics, programming, and robotics.

The learning objective for the first class of the semester is for students to understand that natural background ionizing radiation is ubiquitous and is primarily caused by terrestrial sources such as radon gas and cosmic rays. In the following class period, there was a more in-depth lecture on radiation and radiation safety, and students used a Geiger counter and an Arduino board to quantitatively measure background radiation. The learning objective for the second class was to understand how alpha, beta, and gamma radiation interact with matter via scattering and ionization, and to learn how more sophisticated ionization detectors work (specifically, Geiger Mueller tubes).

When seeking a hands-on project to achieve the learning objective of the first class of the course, we considered both cloud chamber construction [5, 7–9, 12] and a Geiger counter construction project from the Massachusetts Institute of Technology (MIT) Open Courseware [15]. Both the MIT Geiger counter and cloud chamber examples would take students several dedicated class sessions to build and would leave little

time in the semester for other hands-on projects aimed at other learning objectives. In addition, there are educational benefits of having time to perform the cloud chamber experiment twice during the same class session [16]. Students can test the idea of how to improve the cloud chamber results. Something as simple as choosing more or less alcohol, or a different viewing angle, is beneficial for building confidence and fostering critical scientific thinking skills.

As a hands-on activity in the undergraduate seminar course, the new cloud chamber kit will be assembled by the students during class. The class includes a 10 min presentation that introduces ionizing radiation, cosmic rays, and natural sources of background radiation, and includes a description of how to build the cloud chamber. Students then spent 30 min building the cloud chambers and observing the tracks. For successful active learning, it is important to align an activity with the course and ensure that multiple topics are connected [13]. For this reason, a 5 min summary discussion is included at the end of class, which connects the cloud chamber project the students just completed to the next project in the course (programming an Arduino to record counts-per-minute using a pre-assembled Geiger counter).

2.2. Materials used to assemble the cloud chamber kits

This list of materials is for ten cloud chamber kits used in a class of 20 students working in pairs.

Item	Quantity	Notes
Regular Scissors	10	n/a
Dish sponges	20	Size $4.5 \times 6 \times 1.5$ inches
16 oz bottle of 91% or 99% isopropyl (rubbing) alcohol	1	Amount: use 8–10 ml or 0.5 oz per sponge.
Black construction paper sheets	10	Size 8.5×11 inches

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(Continued.)

Item	Quantity	Notes
16 oz clear plastic food storage jar with tight fitting, aluminum, screw-top lid	10	Size $3.5 \times 3.5 \times 4$ inches
Square silicone baking pan	10	Size $8 \times 8 \times 2$ inches.
Dry ice pellets	20 pounds	The baking pan is filled approximately $\frac{1}{4}$ of the way full with pellets (a little less than 2 lbs per kit.
Aluminum heat sink	10	Does not need to be anodized. Size $3.54 \times 3.54 \times 0.59$ inches.
Flash lights	10	LED works well, short in length, the size used was 4.5 inches long and 1.5 inches wide.
Gloves	5 pairs	Used by students if they handle the dry ice or cold plate
Eye protection	10 pairs	Used by the student who pours the rubbing alcohol



Figure 1. (a): A photo of an unassembled kit is shown: black construction paper, sponge, heat sink, gloves, scissors, eye protection, and plastic jar with lid. (b): A photo of an unassembled kit in storage is shown. All components fit in the silicone baking pan for organized storage of each kit as an individual unit.

2.3. Outside class preparation

Outside class preparation included purchasing and opening the materials and arranging each kit for a total time of approximately 2 h. A photograph of the unpacked unassembled kit components is shown in figure 1(a) and a photograph of the same components during storage is shown in figure 1(b). The materials fit for storage in the silicone baking pan. Ten kits (without dry ice) were stored in a medium-sized cardboard box (e.g. $30 \times 30 \times 24$ inches) together with alcohol weighing less than 10 pounds.

On the day of the class, the instructor ensured that the room was well-ventilated by opening a window or door. Immediately before class started, the instructor placed the unassembled kits on the tables in the classroom for approximately three minutes. To allow time for the student pairs to operate the cloud chamber kits twice during the class, a cold plate was prepared prior to class,

which took approximately three minutes for the ten kits. Approximately 2 pounds of dry ice pellets was added to each baking pan. The instructor then prepared the heat sink for use as a cold plate in each kit by pressing it firmly, fin side down, into dry ice. It is beneficial to obtain dry ice pressed between heat sink fins for maximum thermal conduction. It is very noisy when the heat sinks owing to the cold temperatures of dry ice.

After class, the removal of the kits from the classroom took less than 5 min, and the instructor needed another 10 min outside the classroom to rinse the dish sponges and recycle the used construction paper. The dry ice was left to evaporate

in a well-ventilated office in a reusable shopping bag. After the dish sponges were fully dry, each kit was repacked in a storage box and ready for reuse for the next term. Dry ice and rubbing alcohol were the only materials that had to be replenished.

2.4. Instructions for assembling the cloud chamber kits

- Step 1: Cut a circle of black construction paper inside the screw-top lid of the jar. If the lid of the jar had a foam liner, it was removed before placing construction paper in the lid. To enhance viewing, a strip of black construction paper was cut and inserted into the jar and wrapped halfway through three-quarters of the way around the circumference of the jar. Tape is not needed, as tension keeps the paper in place.
- Step 2: Wedge the sponge to the bottom of the plastic jar so that it is held in place by the walls of the jar by tension forces. Tape can be used, but because most adhesives become ineffective due to the alcohol and cold temperatures, they fail rapidly, and longer viewing is achieved by using tension to hold the sponge in place.
- Step 3: While wearing eye protection, carefully add alcohol to the sponge, not soaking it, but definitely wet, typically 0.3–0.5 oz.
- Step 4: Place the lid tightly on the jar and place the jar lid down onto dry ice or a cold plate.
- Step 5: Turn off the lights and watch with the flashlight as the chamber ‘primes’ and the saturated vapor forms. After a few minutes, fine mist or rain was visible.
- Step 5: Watch the appearance lines or wisps of clouds in the mist. These are the ‘tracks’ seen that are created by the energetic particles (ionizing radiation from natural background sources) passing through the saturated alcohol vapor and ionizing it.

An image of the track observed using this kit is shown in figure 2. The ‘track’ is created by radiation (a high energy particle) ionizing the saturated alcohol vapor. Videos were captured using a smartphone. This track is most likely caused by muons or antimuons [17].

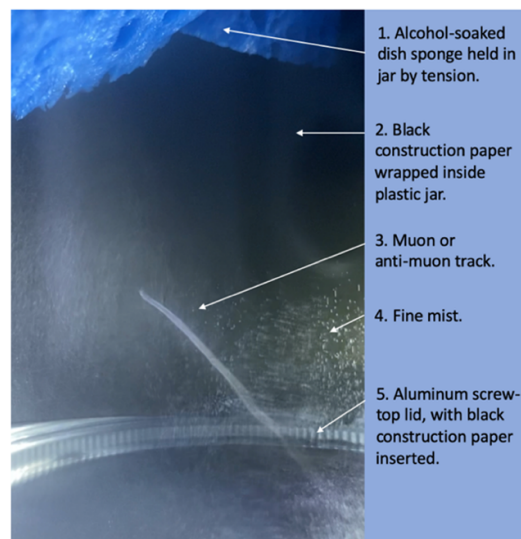


Figure 2. A still image from a video frame showing top to bottom the dish sponge, a particle track in the fine mist of the saturated alcohol vapor, and the screw top lid with construction paper inserted to create a black backdrop.

3. Results

3.1. Class experience using the kits

The class period was divided into four phases: lecture phase (10 min), project phase—part 1 (15 min), project phase—part 2 (15 min), and wrap-up phase (5 min). The class ended on time, and all student pairs successfully constructed working cloud chambers and observed a variety of tracks caused by the background radiation. Feedback from the students was positive.

During the lecture, safety precautions for the project phases were explained to students in class: use gloves for handling dry ice or cold plates and wearing eye protection when pouring alcohol.

After the lecture, to begin the first project phase, one student in each pair was tasked with wetting the dish sponge with alcohol, whereas the other student in the pair prepared a dark background using the construction paper provided. The class had 18 students and the total time for all students to prepare the chambers was approximately 5 min. While the chambers were primed (between 3–5 min), the instructor engaged the students in a discussion of what they would observe in the cloud chamber, including asking them if

they thought they would be able to distinguish between different kinds of tracks (and different kinds of particles), and whether or not they could tell the energy of a particle based on track characteristics.

After the chambers were primed, students observed the tracks for approximately 10 min. During the project phase part 1, it was necessary for the instructor to circulate around the room and help students troubleshoot the operation of cloud chambers. Common issues: the dish sponge was not sufficiently wet or too wet, students had not closed the jar tightly enough, or students were not aligning the flashlight correctly.

At the end of the first project phase, the instructor encouraged the students to reset the cloud chambers (which amounted to removing the original sponge and replacing it with a new dish sponge soaked in alcohol and priming the chamber again). The instructor encouraged the students to make changes based on what had worked or did not work well for the first time.

During the second project phase, the instructor used two facilitation strategies [13] to increase student engagement: approaching students who were working in pairs and encouraging them. The instructor walked around the classroom, provided students with feedback and clarification, and asked them questions regarding the activity. The instructor exhibited a positive demeanor throughout, was respectful of the students, and gently encouraged them to try something different if they were (at first) unable to view the tracks. During the second round of operations, students became fully engaged in observing the tracks.

The students' questions about the different tracks were an opportunity for the instructor to discuss differences in the mass and energy of different particles and to introduce the concept of radiation shielding, which would be presented more deeply in a later class. Students asked why some tracks were longer and thinner (muons, electrons, positrons), why some curved or twisted (photoelectron), and why some tracks were not tracks at all, but wide oval puffs of mist (alpha particle clusters). In anticipation of the questions about different tracks, the instructor prepared slides using materials from the CERN

S'Cool LAB team [17] for track identification and projected this on a screen after the students started to discuss the different tracks they were observing.

Approximately three-quarters of the students used their smartphones to record videos of the tracks in the cloud chamber to share their observations with the instructor. As noted by previous authors, cloud chamber videos can enhance teaching for both demonstration and student research purposes [18].

3.2. Detailed performance of the kits

Approximately 20 tracks per minute were reported, which is consistent with background measurements taken in the classroom using a Geiger counter (16 ± 4 counts per minute). Because of the energy range limits on the Geiger counter (the Geiger-Mueller tube is sensitive only to beta and gamma radiation), it is not surprising that the simple cloud chamber can be as sensitive if it is not more sensitive to background radiation.

Figure 3 shows examples of different tracks observed in the kits; all images are still from a video taken with a smartphone and cropped to 135×98 pixels during kit development prior to class.

Figure 4 shows an alpha particle cluster observed in the kits prior to class during the development and testing phases. This is a much more diffuse 'track' and appears as an oval-shaped cloud of much smaller clouds.

4. Discussion

Because students assemble the kits without the use of tools and electronics, and because radioactive sources are not needed to successfully observe many types of tracks, this project presents few barriers for implementation as a hands-on-project in a variety of courses at the middle school, high school, or early college levels.

This cloud chamber kit may be of particular interest to instructors in traditional lecture-based courses, who seek to inject projects into the curriculum. The cloud chamber kit 'strikes a balance between being too difficult and too simple' [13]. The assembly of kits requires very little preparation time outside the class. Since students

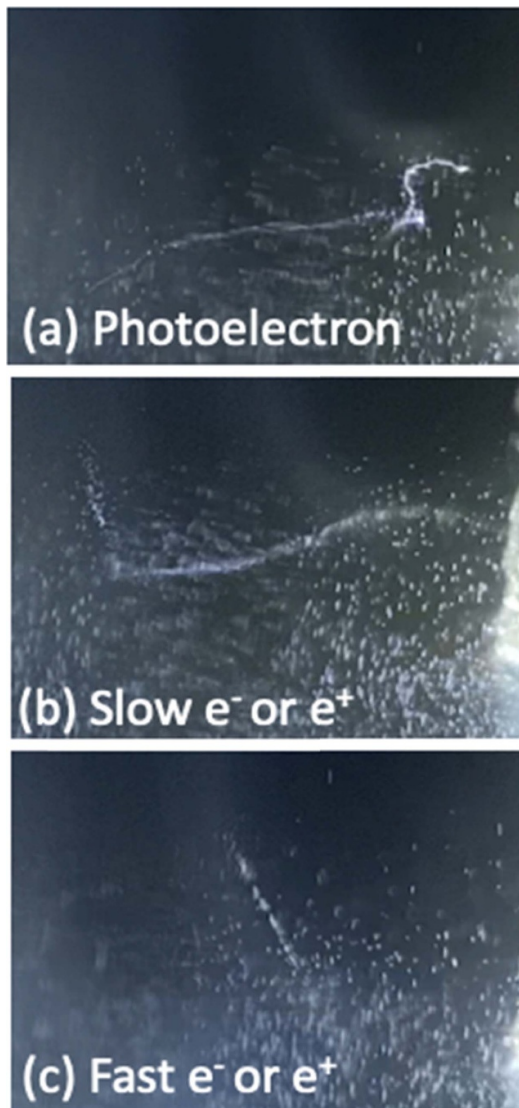


Figure 3. Examples different tracks observed in the kits; (a) photoelectron, (b) slow electron or positron, (c) fast electron or positron. All images are stills from the same video taken with a smartphone (cropped to 135×98 pixels in all images). Identification is based on [17].

assemble the kit during class, the instructor must merely set the items out at the beginning of the class and pick them up at the end. Building the kit and operation is straightforward. The project is engaging and enables student participation.

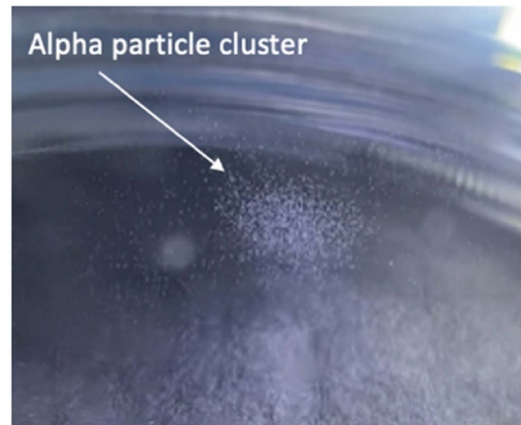


Figure 4. An alpha particle cluster, cropped from a still image of a smartphone video. The inner rim of the lid of the jar is shown for scale. Identification is based on [17]. Unfortunately, some out of focus drops of liquid are also in the frame (smaller circles on left and right).

Although this kit does not require the use of a radioactive source, different radiation sources can easily be incorporated to teach a variety of lessons on radiation, radiation safety, shielding, and health physics. In addition, the reliable operation and sensitivity of cloud chamber kits to background radiation may make them suitable for inclusion in high school physics programs to introduce particle physics [19, 20] or combined with more detailed studies of cosmic rays in the classroom [21].

5. Conclusions

This paper presents the design and reports on the use of a simple and inexpensive cloud chamber kit that is compatible with active learning, experiential learning, and project-based learning strategies. The kit was developed for use in a first-year undergraduate nuclear science seminar class at a university in the USA. The kit worked very well, and was found to be highly sensitive to background radiation. Several different types of high-energy particles, including muons or anti-muons, electrons or positrons, photoelectrons, and alpha particles, were detected and identified using the kits, at a rate of over 20 tracks per minute measured indoors at sea level at latitude 42.3601° N.

Data availability statement

All relevant data are within the paper and its supporting information files.

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The author has no conflicts of interest.

Ethics statement

This study did not include studies on human subjects, human data, tissues, or animals.

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