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High school particle detector using Peltier cooling modules

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ABSTRACT

This project aims to design a cloud chamber for use in a high school to educate and get students interested in particle physics. The cloud chamber shows the tracks of particles in real time, which is excellent for engaging students. They will be able to identify different types of particles based on the appearance of their tracks and will therefore gain a more intuitive understanding of particle physics. The inclusion of two compartments separated by a lead divider allows students to infer direction of particle motion by observing its loss of energy. This cloud chamber also includes an interactive element, which comes from the introduction of a school-safe sample of radioactive metal and the manipulation of magnetic fields using an electromagnet. The cart is on wheels and is easily portable. It requires almost no time from the instructor outside of class, except for replacing the supply of isopropyl alcohol, which is inexpensive and easy to access.

Keywords: *Physics, Particle Detector, Cloudchamber, Cosmic Radiation*

1. INTRODUCTION: DIFFUSION CLOUD CHAMBER

1.1 Differentiation from different Particle Detectors and Cloud Chambers

The most important aspects of a particle detector used in ahigh school are that it's engaging for the students, it is affordable for the school, and that it is portable from classroom to classroom. For all these reasons, a cloud chamber is perfectly suited for use in a classroom setting. Typically, a particle detector somehow amplifies the charge of a particle or otherwise converts its energy into an electrical signal, such as the method in a Geiger counter or a wire chamber. The benefits of measuring an electrical signal output are that its data can be stored in the computer, while the tracks in a cloud chamber can be observed by the human eye, making it more engaging for students.

Since its invention in the early 20th century by C. T. R. Wilson, the cloud chamber has been improved on and modified many times. While originally, the cloud chamber used a piston to expand the air inside, forcing water droplets to form around the tracks of charged particles, the modern cloud chamber uses a temperature gradient, which allows it to be sensitive without dead time [1]. Thisis referred to as a diffusion cloud chamber, because a temperature gradient is used to condense the alcohol vapor into a liquid. The diffusion cloud chamber is more standardly used because of its advantage in being active continuously, whereas the expansion cloud chamber requires periodic intervals of time in which it is not sensitive. One of the most commonly known achievements made possible by the diffusion cloud chamber is the discovery of the positron [2]. It is the cloud chamber's design that lends itself so well to observing particles.

1.2 Components of our Diffusion Cloud Chamber

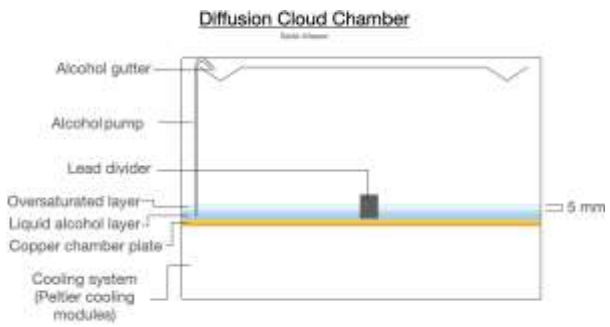

Figure 1 (above) shows the inside of our diffusion cloud chamber.

Figure 2 (above) shows the full side view of our diffusion cloud chamber, including a cart with wheels and width and height dimensions.

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As seen in Figure 1, the cloud chamber is an acrylic box that contains a mixture of alcohol and air. There is an alcohol reservoir below the chamber that contains a supply of 100 mL of isopropyl alcohol (C_3H_8O). A pump is connected to the alcohol reservoir, pumping alcohol liquid into alcohol wells at the top of the chamber. The alcohol then evaporates into a vapor from the wells and falls down the chamber. Charged electrical wires on top of the chamber remove ions from the air so that the tracks of other particles, such as electrons or muons, can be viewed easier. These wires also work in conjunction with a cooling system below the chamber to create a temperature difference of approximately 60 degrees. The cloudchamber is 15cm tall, making the temperature gradient 4 deg/cm. Traditionally, dry ice is used to create the temperature gradient. However, this diffusion chamber uses thermoelectric Peltier chips, which allows the cloud chamber to be active continuously without the need to replenish the dry ice. This causes the alcohol at the bottom to condense into a liquid and the alcohol at the top to remain a gas, mixed in with the air.

1.3 Temperature Gradient

The temperature gradient in the diffusion cloud chamber can be achieved in a variety of different methods. While dry ice is traditionally used, because it makes the cloud chamber easier to construct in classroom project-based demonstrations, it has its drawbacks [3]. For example, dry ice must be replaced, and therefore is not practical for multiple lessons across a long span of time. Thetemperature gradient in the cloud chamber in this present study is made using Peltier chips [4]. The temperature gradient in the diffusion cloud chamber creates a zone between the vapor layer and liquid layer that is approximately 5mm thick, known as the oversaturated layer. This is the layer where the tracks of charged particles are visible. In the oversaturated layer, there is too much alcohol vapor for the air to hold, meaning that it "wants" to condense into a liquid. It is in astate that is not stable or unstable, rather meta-stable. Due to the Rayleigh effect, when a charged particle, such as a muon or an electron, passes through the oversaturated layer, it ionizes the alcohol vapor, encouraging it to condense around the track of the charged particle. This happens because the particle creates ions in the air that actas condensation nuclei. This creates droplets of alcohol liquid, which are visible to the naked eye, providing a visual for the tracks of charged particles. Observing the movement of charged particles through the trails they leave is similar to observing the wind by looking at the movement of the trees. It is impossible to see particles with the naked eye, but that does not mean that it is impossible to see their effects. This visual format engages students by transforming something that's completely intangible into something they can directly observe, to which they can tie everything else they learn about particle physics.

1.4 Lead Divider & Energy Loss of Particles

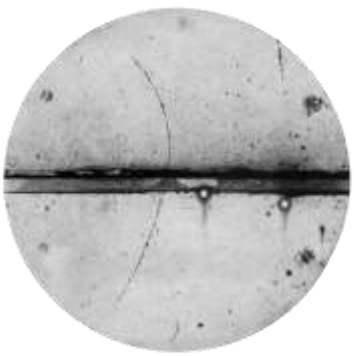

Figure 3 (above) shows the discovery of the positron using a cloud chamber [2].

What makes our cloud chamber unique is the presence of two different compartments, separated by a layer of lead (Fig 3). When a particle travels through one compartment with high energy, it follows only a slightly curved trajectory. However, when it passes through the lead wall to the other compartment, it loses a significant amount of energy. This effect is most notably known for being the cause of the discovery of the positron, as it allows one to see the direction in which a particle travels [2]. This causes its track to curve in the next compartment, as the particle loses energy, and it is sucked in by the magnetic field of the electromagnet inside the chamber. The electromagnet can be turned on and off by students using a dial on the side of the chamber. This allows the studentsto determine the kinetic energy of the particle, as well as its direction, as they will be able to observe on which sideof the lead divider the particle has more energy.

2. METHODS

2.1 Cooling System

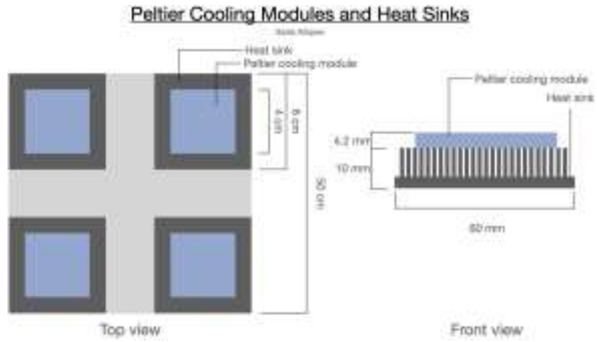

Figure 4 (Above). Front and side views of Peltier cooling modules paired with heat sinks. Dimensions used match the ETX2.5-12-F1-4040-TA-RT-W6 Peltier cooling module from Laird Systems and the HSB22-606010 heat sink from CUI devices.

This cloud chamber design, as seen in Figure 4 (above), uses four Peltier cooling modules to achieve a temperature gradient. Peltier modules are semiconductors that transfer heat from one side of the module to the other when a current is run through it. While Peltier modulesare most commonly used for cooling electronic components, they can be used in a variety of situations to cool small areas to low temperatures. They are not often used for large air conditioners, which normally use coolants, because their downside is that they aren't very efficient on a large scale.

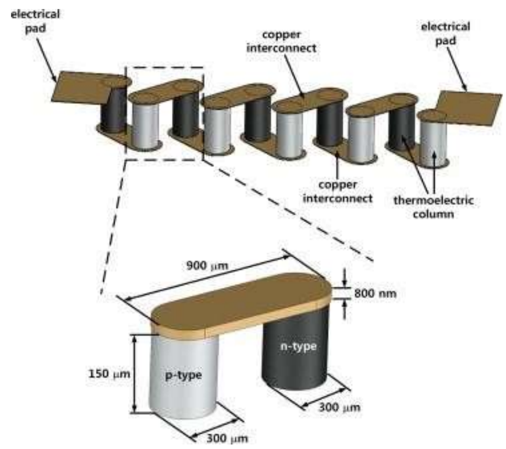

Figure 5 (above) The P/N sequencing used in Peltier cooling modules. By allowing a current to flow through alternating P-types (electron deficiency) and N-types (electron excess), Peltier modules create a temperature difference between their warm and cool sides [5].

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When using isopropyl alcohol, it's necessary that the temperature of the lower plate is low enough to condense it into a liquid. That's what allows for the tracks of charged particles to be visible. Specifically with Peltier cooling modules in cloud chambers, it is crucial to cool the lower part of the cloud chamber to -30 degrees Celsius[4]. In order to bring the cold side of the Peltier module tolow enough temperatures (in the range of -30 degrees Celsius), they are often paired with heat sinks, such as in this present study. Heat sinks are relatively inexpensive items commonly used to disperse heat in electronic components. By placing a heat sink on the warm side of a Peltier module, it's possible to dissipate the heat being released, and bring the temperature of the entire module down. Peltier modules don't cool or warm areas to a certain temperature, rather, they simply create a temperature difference. Therefore, dissipating heat from its warm side can bring the cool side to very low temperatures.

This property of Peltier modules, their ability to reach low temperatures, is exactly what makes them appropriate for use in a cloud chamber. Cooling the lower chamber plate to -30 degrees Celsius, and electrical heating at the top of the chamber bringing it to 30 degrees Celsius, this cloud chamber has a temperature difference of 60 degrees. It's 15cm tall, which is standard for this type of cloud chamber, making the temperature gradient 4 deg/cm. Any temperature gradient above 3.6 deg/cm is sufficient for picking up on background radiation [6]. This is in addition to being able to pick up on radiation from radioactive sources.

2.2 Electromagnet

This cloud chamber uses an electromagnet, which can be turned on and off, to alter the paths of charged particles. When a current runs through an electromagnet, it creates amagnetic field, which can attract or repel charged particles. This will help students observe the energy of different particles based on how much their paths change (a particle that spirals inward toward the electromagnet has less energy than one whose path is slightly bent). The equation for B, the strength of the magnetic field, can be shown as pictures and make observations as to the identification and direction of particles.

2.4 Setup and Measurements

Make sure to turn on the LED strip lights on the sides of the cloud chamber container so that the tracks may be illuminated and visible. It may help if the instructor turns off the lights in the classroom. Against the black background of the chamber plate, it should be easy to see the tracks of the particles.
(See Appendix A)

$$B = \frac{p}{qr} \qquad (1)$$

For measuring particle direction and identifying different particle types, it is recommended that the students use their phones to take pictures of the cloud chamber while it is active. This will allow them to look back at their Where p is the momentum, q is the charge, and r is the radius of the track of the charged particle (Jackson, 1962).The momentum of a radioactive particle is typically $p = 3\ MeV$. Setting the radius to be 10m, so as toslightly curve the tracks of the particles, means that $B = 0.001T$.

The electromagnet runs on low voltage (12 V) and functions by allowing a current of about $I = 0.01A$ to flow through a coil with about 10^4 rounds of wire. This should make it safe and appropriate for a classroom setting. The coil costs around $31.

2.3 Working Substance

This cloud chamber uses a mixture of air and isopropyl alcohol vapor. One benefit of using isopropyl alcohol is that, due to it being a secondary alcohol, it has a high vapor pressure and high volatility. That means that it readily evaporates at room temperature. This is crucial for the cloud chamber, as it is necessary for the liquid isopropyl alcohol, which is pumped into the alcohol gutterat the top of the cloud chamber, to evaporate and fall slowly down the chamber as a vapor. It is also important to note that isopropyl alcohol has a boiling point at 82.3 degrees Celsius and a freezing point at -88.5 degrees Celsius. That means that within this cloud chamber, (with a minimum temperature of -30 degrees Celsius and a maximum temperature of 30 degrees Celsius) isopropyl alcohol will remain in a liquid or vapor form, depending on its saturation in the air [7]. These conditions are crucialfor the oversaturated layer to form, and for the Rayleigh effect to be visible.

Many of these characteristics, such as volatility, freezing point, and boiling point, are all characteristics of alcohols in general, not specifically isopropyl alcohol [7]. In fact, many cloud chambers use ethanol or methanol as a working substance, for example, the cloud chamber constructed by Langsdorf, who used methanol [8]. However, isopropyl alcohol is very readily available, and is easy for instructors to access outside of class.

Instructors are required to periodically replenish the isopropyl alcohol supply.

Students will be able to identify different types of particles based on how curved their tracks are, as well as their tracks' thicknesses and lengths. For example, alpha particles leave short, thick tracks. Alpha particles have a charge of +2, and ionization is proportional to the square of the charge (Bethe-Bloch law), so their ionization trackshave a thickness 4 times greater than that of beta particles, or electrons, which leave short thin tracks. Cosmic rays, such as muons, leave long and straight tracks. This is due to their having a higher energy and greater mass. The addition of a magnetic field allows for even more clear differentiation between different particle types, as it will curve the tracks of low energy particles, such as alpha particles and beta particles, much more dramatically than it will curve the tracks of high energy particles such as muons.

3. MATERIALS

For four Peltier cooling modules, each one with a width and length of 40 mm, each one costs around $40, with a total of $160. Four heat sinks cost about $13 in total. It should also be noted that a thermal compound should be used to increase thermal conduction between the Peltier module and the heat sink, costing generally around $7.

Table -1: Conductivities of four metals: Aluminum,Brass, Copper, and Iron [9].

Metals	Thermal conductivity (W/m*K)	Electrical Conductivity(S/m)* 10^6	Electrical resistivity (ohm*m) *10^{-8}
Aluminium	237	36.9	2.7
Brass	150	15.9	8.5
Copper	401	58.5	8.9
Iron	80	10.1	7.9

The most expensive item to acquire is the 50cm x 50cm copper sheet. As seen in Table 1, copper has excellent thermal conductivity in comparison to other metals. This is crucial to achieving the temperature gradient needed forthe cloud chamber to work.

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Table -2: Approximate Prices of Components

Item name	Approx. price
Acrylic sheets Top sheet: 50cm x 50cm x 0.5cm Side sheets: 15cm x 50cm x 0.5cm (x4)	~$50
Copper sheet (50cm x 50cm)	~$200
Black electrical tape	~$2
Electric pump For example, SmarTopus Electric Liquid Transfer Siphon Pump on Amazon	~$20
Peltier cooling modules (40mm x 40mm) For example, ETX2.5-12-F1-4040-TA-RT-W6 from Laird Thermal Systems (x4)	~$160
Heat sinks (60mm x 60mm) For example, HSB22-606010 from CUI devices (x4)	~$13
Thermal compound For example, ARCTIC MX-4 (4 g) - Premium Performance Thermal Paste on Amazon	~$7
Electromagnet	~$12
User-safe radioactive source* For example, a smoke detector and a banana peel	~$8
Metal cart with wheels	~$73
Total	**~$545**

*optional

4. DISCUSSION

This cloud chamber, unlike other cloud chambers mostly chamber, and only require a low voltage to be run throughthem, making it a much lower maintenance system for theinstructor [4].

Out of all particle detectors, cloud chambers are mostcommonly used in classroom demonstrations because of their visual format. Being able to see the tracks of chargedparticles allows particle physics, a concept that can feel very hard to grasp, more tangible. It is rare that a particle physics experiment in a classroom setting can be as hands-on as a cloud chamber.

5. APPENDIX A: DERIVATION OF MAGNETIC FIELDEQUATION

In this appendix we prove eq (1) which relates the radius of curvature R of the trajectory taken by a charged particle q to its momentum p and to the induction field B acting on it. Four fundamental ingredients enter the derivation:

1. Newton's Law: $F = ma$
2. Definition of momentum: $p = mv$
3. Centripetal acceleration: $a = v/r$
4. Lorentz Force Law: $F = qvB$

By combining 1 and 4, ma = q v B. Substituting 3, m v^2/R = q v B. Finally, dividing both sides by v and introducing momentum by equation 2, p / R = q B, which is equivalent to equation (1) in the text. Though it was derived by adopting classical mechanics, this equation is valid even in special relativity [11].

6. ACKNOWLEDGEMENT

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[4] Nar, S. Y., & Cakir, A. (2018, February). Peltier-basedcloud chamber. In *AIP Conference Proceedings* (Vol. used in classroom demonstrations or at-home experiments, does not use dry ice for cooling. While dry ice is cheaper than other cooling systems such as what is used in research labs, it needs to be replenished for each use, and can be hard for the instructor to access outside of class [10]. Peltier cooling modules are a reliable way to achieve the temperature gradient necessary for the cloud 1935, No. 1, p. 180003). AIP Publishing LLC.

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