Cloud Chamber

R.C. Dennis, Tuan Le, M.J. Madsen, and J. Brown

Department of Physics, Wabash College, Crawfordsville, IN 47933

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Cloud chambers were among the first devices used for detecting the radiation and particles that we cannot see with the naked eye. These devices work by creating vapor trails from the trajectories of particles, such as cosmic ray muons. Cloud chambers were once vital to the study of subatomic particles, but have since been replaced by more sophisticated methods of study. Even so, they hold an important historical significance and can still reveal much about the world around us. In this paper, we present measurements for the lower bound of the speed of particles entering our apparatus and the average length of the vapor trails.
I. INTRODUCTION

For decades, cloud chambers have been used as rudimentary windows into the world of particle physics. They were the first reliable apparatuses used to study subatomic particles [5][6]. Because subatomic particles are not typically detectable by the human eye, prior to this apparatus, scientists had difficulty imagining and studying these invisible particles that bombard us on a daily basis. Cloud chambers are also used to study the phenomenon of supersaturation which is currently not very well understood [1]. However, as we continue to study this phenomenon, we are beginning to properly characterize the nucleation of supersaturated vapor [2] and have even created theoretical models for the condensation in expansion cloud chambers [4].

For our purposes, the simple nucleation model will suffice. In fact, the creation of cloud chambers is becoming increasingly commonplace and has even been done in the high school physics laboratory [7][3]. Some cloud chambers use low temperatures to create supersaturation [3] while others create supersaturated alcohol with pressure in what is known as an expansion cloud chamber [7]. There are several methods for creating and cooling a cloud chamber and in this paper we explore the most common method–dry ice.

II. HOW CLOUD CHAMBERS WORK

Nothing more than an airtight vessel, a cloud chamber works by causing a vapor inside to supersaturate. This can be done in a variety of ways, with a variety of fluids, but the most common way to achieve this is by creating a temperature gradient in the chamber. By cooling the bottom of the chamber, supersaturation may occur. These were first created by C.T.R. Wilson, which is why they are sometimes known as Wilson chambers [5][7]. Cloud chambers were among the first apparatuses used for particle detection; when ionizing radiation enters the vessel, it strips the supersaturated molecules (in our case alcohol) of electrons causing them–as the name suggests–to become ionized. This happens because the alcohol has very loosely bound electrons and the radiation passes through the vessel with such high energy that these electrons are stripped, forming ions. The ions are sometimes called cloud seeds because they act as nucleation sites for which the surrounding vapors form a thick mist. What this means is that when ionizing radiation enters the vessel, it will travel through the
supersaturated solution ionizing the alcohol molecules in its path, which will then form a trail of condensed alcohol vapor. Obviously the trail will not form at the same speed that the molecule travels, but a cloud chamber still gives us information about the path that was taken.

It is important to realize that this cloud formation will only happen if the vapor is supersaturated and can be easily persuaded to condense (See Figure 1). In the case of cloud chambers, this requires the temperature of the vessel to be very low.

![Figure 1](image1.png)

FIG. 1. In this figure we see the effects of ionizing radiation on our setup. When ionizing radiation enters the system, it strips the ions from the alcohol molecules in its path (a) and these molecules then become seed nuclei (b). These seed nuclei attract the other molecules in the supersaturated solution causing them to condense and create a visible stream. Through ionizing the supersaturated alcohol solution, we can see the path of the radiation.

If a cloud chamber is also placed in a uniform magnetic field, we can utilize the Lorentz Force Law to further characterize and identify the particles in our chamber. The basic idea is that charged particles in motion create magnetic fields and these fields will interact with the uniform magnetic field that the experimenter creates. What this means is that positively charged particles and negatively charged particles will move in opposite directions in our cloud chamber. Moreover, because we can now see the path that they take in this field, we
can extrapolate how fast they must have been traveling. This will allow us to create a model to determine the speeds of particles in our cloud chamber.

III. LORENTZ FORCE LAW

By using our cloud chamber to identify and trace the particle trajectories, we can find the radius of curvature for the particle in the chamber. We now need a model to find the particle speed based on this radius. Of course, our particles have the potential to travel at relativistic speeds and as such, we need to account for the relativistic effects. We know that the motion for our particles is centripetal and we can describe the centripetal force using the formula

\[ \vec{F}_c = \frac{d\vec{p}}{dt} \]  

where \( \vec{p} \) is our momentum. Of course, our momentum is relativistic and can be described by

\[ \vec{p} = \gamma m_0 \vec{v} \]  

where \( m_0 \) is the mass of the particle and \( \gamma \) is the Lorentz factor

\[ \gamma = \frac{1}{\sqrt{1 - v^2/c^2}}. \]

Because the speed of an object undergoing centripetal motion is constant, this means that our Lorentz factor does not depend on time and so

\[ \vec{F}_c = m_0 \gamma \frac{d\vec{v}}{dt}. \]  

Aside from the added Lorentz factor, this equation is the same as the classical case which tells us that

\[ F_c = m_0 \gamma \frac{v^2}{r} \]  

where \( r \) describes the radius of the trajectory.

Now we know that this centripetal acceleration is a result of the Lorentz force (assuming no electric field is present),

\[ \vec{F}_c = q\vec{v} \times \vec{B}, \]

which describes the force a charge \( q \) experiences while traveling at velocity \( \vec{v} \) in a magnetic field \( \vec{B} \). Our model is limited because we cannot determine at what angle the particle enters
the chamber. To simplify things, we assume that the particle enters the chamber at a 90 degree angle from the normal so that the particle velocity is perpendicular to the magnetic field and the magnitude of the centripetal acceleration is

\[ F_c = qvB. \]

This means that

\[ qvB = m_0\gamma\frac{v^2}{r}. \]

(5)

This can be further simplified to give

\[ r = \frac{m_0 v\gamma}{qB}. \]

(6)

If we solve for \( v \), we find that

\[ v = \frac{Bcq\gamma}{\sqrt{c^2m_0^2 + B^2q^2r^2}}. \]

(7)

and this gives us the model to find the speed of the particles in the chamber given that we can accurately measure the radius of the trajectory and we know the type of particle that made the track. Unfortunately, we can easily see that for a particle like a cosmic ray muon that is traveling at close to the speed of light, in the absence of a very strong magnetic field or a very large viewing box, will have a radius so large that it cannot be measured accurately. We may take the nonrelativistic analog of this equation and apply it to the decay products of the muons (electrons) and to the atomic electrons the muons strip from the molecules in our cloud.

In Figure 2, we see an example of the Lorentz force law. Here the cosmic ray muons are decaying and the charged electrons or positrons become visible. By noting the direction that these curve in the magnetic field, we can find the relative quantities of positive and negative muons. Because their decay rates are different, this may prove useful in measuring the decay rate of cosmic ray muons.

IV. SETUP

The setup consists of a Helmholtz coil to create a strong magnetic field vertically. The chamber is cubic in nature and has sides of length 20 cm. We use a strong light for illumination and capture videos from the side (and will later do this from the top) using a camera.
FIG. 2. In (a), we demonstrate the actual trajectory of a positive muon decay [5] and in (b) we show the theoretical trajectory as viewed from the top down of our setup. The magnetic field produced by our apparatus is approximately uniform and points up. By the Lorentz force law, a positively charged particle traveling to the right will be deflected downward. This law also tells us that the negatively charged particle experiences an upward force. Notice that because the charge to mass ratio for the muon is much smaller in magnitude than the electron’s or positron’s, its trajectory does not curve as much.

Our system is cooled with dry ice which has a temperature of $-79^\circ C$ and we use 99.5% pure isopropanol. The chamber is put inside the Helmholtz coil to make sure that there is a magnetic field at the center of the apparatus. We then put the dry ice underneath the chamber to cool the system down. Our aim is to decrease the temperature to around $-30^\circ C$ to achieve supersaturation. We soak the black felt covering the bottom of the chamber with about 3-4 ounces of alcohol, and try to pour a thin layer on the aluminum plate. We also tape the same black felt to the bottom of the lid and similarly soak it in alcohol. To make sure the system is airtight, we seal the four sides of the chamber with strong tape. We use a hot wet sponge to warm the felt underneath the lid through the chamber’s wall. Because the black felt below the lid is warmed up, the alcohol vapor will travel down in the bottom
of the chamber, where it becomes supersaturated. After completing the setup, we wait 15 minutes for the aluminum plate to cool down before recording a video. Below is a figure describing the basic setup based on the physics of the experiment (See Figure 3).

![Figure 3](image)

FIG. 3. This figure shows the basic setup for a cloud chamber. We see that this is comprised of a cold surface which causes a supersaturated alcohol solution to form (in the hashed region). The entire setup is in a uniform magnetic field and illuminated from the side. When a particle enters the chamber, we can capture its trajectory using a camera from the side. In order to create the temperature necessary for the supersaturated solution to form, temperatures below freezing are necessary. In this setup, dry ice is placed in reservoir at $-79^\circ C$ and the lid is made warm with a sponge that was placed in hot water. The lid also has liquid alcohol at the top that will evaporate and fall to the bottom of the chamber. These two regions create a temperature gradient inside the chamber, which we need to be at least $-30^\circ C$ to allow for the supersaturation of our fluid. We notice that the alcohol falls from the top to the bottom along the heat flow lines in a manner that looks like snowfall.

V. RESULTS

We were able to capture several events in our cloud chamber which shows that the apparatus is in working order. Taking video from the side, we were able to not only capture
some of the events (See Figure 4), but we analyzed the formation of the clouds as well. We wanted to find a lower bound for the speed of the particles that were entering the chamber. It makes sense that the speed of the cloud formation would be less than the actual speed of the particle. Because the ionization of alcohol molecules causes the clouds to form and the particles cause the ionization, we can be assured that the cloud forms in the direction of the particle's trajectory and that it forms more slowly than the particle is moving. We found that the speed of the cloud formation was on average $17.03 \pm 0.77$ mm/s (95% CI). Because these particles are most likely muons, we did not find this result to be surprising as the muons that are reaching Earth are traveling at relativistic speeds. This method of analysis also allows us to see clearly which end of the trail is the head and which end is the tail, which is a useful piece of information to have. We also wanted to find the length of the vapor trails. Knowing this helps identify the particles and indicates the energy and functional effectiveness of our chamber. We found the average particle trajectory length to be $5.70 \pm 0.48$ mm (95% CI). This data is a solid launching point for future experimentation.

VI. FUTURE WORK

A. Muon flux

One possible experiment to do with the cloud chamber is to determine the muon flux on Earth. In other words, we count the number of muon going into the chamber relative to time and divide it by the area of the chamber. Assuming we have a chamber with high efficiency, this should give us a good estimate of the muon flux. The downside to this approach is that we have no method of determining how efficient our setup is and will therefore have issues with determining this parameter using this method.

B. Determine the Sign of the Muons

To see if a muon is negative or positive, we need to measure the trajectory of the decay product that results from the muon decay. From the Lorentz Force Law, we expect electrons and positrons to curve in opposite directions. Because they are oppositely charged, the trajectories in the magnetic field created by the Helmholtz coil must be different. With the muon flux calculated before that, we can predict the ratio of negative and positive muons
FIG. 4. This is an example of an event that was captured in our apparatus. We were able to track the formation of the cloud as it was moving and find the length of the entire event. Compiling the data with a number of other events allowed us to find the average speed and length of the cloud formation. This gives us a lower limit for the speed of the particles in our chamber. We found that the average vapor trail length was $5.70 \pm 0.48$ mm (95% CI). We also tracked the cloud to find the average speed which was $17.03 \pm 0.77$ mm/s (95% CI). Clearly the particles are moving much more quickly than this reflects, but we can be assured that the particles are not traveling faster than the cloud that forms.
coming through the chamber assuming that our chamber has no bias for one type of muon over the other—an assumption that our theory supports. Unfortunately, we have yet to see electron or positron tracks in our apparatus. Another issue with this is that capturing a muon decay is also relatively rare and so it will take a very long time to collect an appropriate amount of data.

VII. CONCLUSION

Cloud chambers are extremely useful and provide a more intuitive view of the physical subatomic world. There is a lot that can be done with these devices and we have merely scratched the surface. We had success in using our cloud chamber to view cosmic ray muons and were able to find a lower bound for the velocity of these particles as well as the length of the tracks. However, we have not experimented with the uniform magnetic field as our current setup requires further fine-tuning to produce the desired result. In summation, our chamber works adequately to view the phenomenon, but currently lacks the ability to acquire quantitative data.


