

The Cloud Chamber Experiment

Ken Clark

January 3, 2019

Abstract

The cloud chamber was one of the primary tools used to conduct the first experiments in the starting of the field of particle physics. Experiments were conducted from the 1920s to the 1950s, at which point more elaborate detectors were conceived which had several benefits. Nonetheless, the cloud chamber is still a very valuable tool to look at particle interactions.

In this experiment you will use a version of the Wilson Cloud Chamber [1] to study several aspects of both the operation of the chamber itself and the use of the chamber to explore the nature of the particles. This lab allows a great deal of flexibility in terms of the specific experiment chosen, and has the possibility for extension of any of the suggested procedures.

1 General description of Cloud Chambers

The first cloud chambers (such as those used by Wilson) relied on changing the pressure in the chamber to produce the supersaturated environment necessary to have droplets form on the ions. These chambers were filled with water under pressure, which was quickly released to cause adiabatic expansion. The cooler temperature then reduces the capacity of the air to have water in saturation, so it begins to condense. As described above, the ions produced by charged particles traveling through the chamber provide an ideal location for the condensation to occur, revealing their tracks.

The chamber used in this lab does not require pressure changes to function. This type of chamber is referred to as a “diffusion cloud chamber” and relies on the temperature gradient set up by having a very cold surface at the bottom of the sensitive area. As alcohol falls down through the chamber, it experiences this dramatic temperature change and the air in the chamber becomes supersaturated at a level near the cold surface. This removes the need for “moving parts” to do the pressurization, and means that the chamber is sensitive at all times while cold, but does restrict the sensitive area of the medium to a small range above the cold surface.

A sketch of the setup is shown in Figure 1, in which the setup has been expanded to make things more clear.

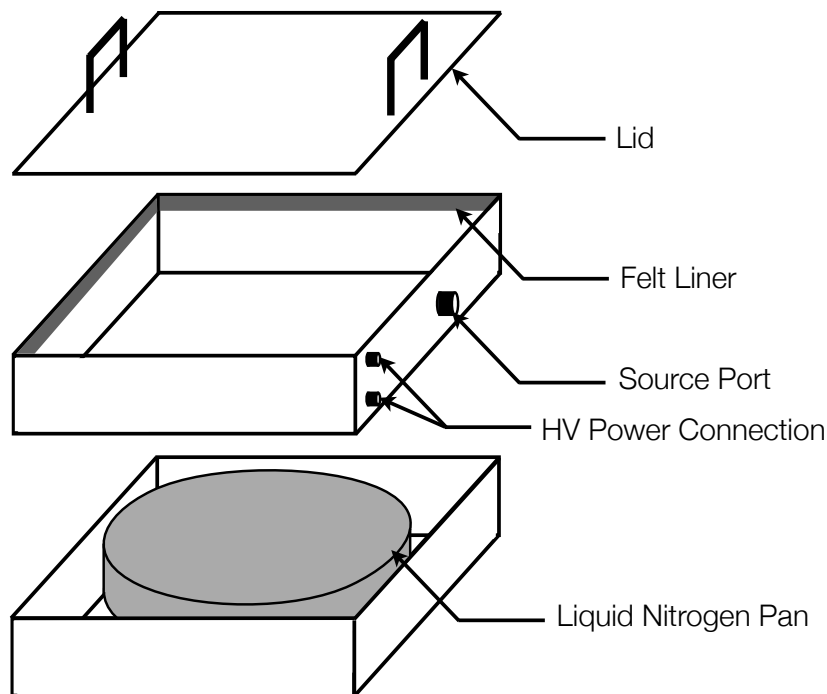


Figure 1: A sketch of the cloud chamber setup used in the laboratory.

In order to make the saturated atmosphere required inside the cloud chamber, there are

a few steps to take which are not entirely obvious. The first is to fill the liquid nitrogen pan with liquid nitrogen (that one is pretty basic). Filling this up to roughly the 2/3 or 3/4 mark will mean that the chamber should remain sensitive for at least a few hours.

When introducing the alcohol to make the saturated environment the best procedure is to apply a generous amount to the felt liner located around the top of the chamber (on which the lid sits when closed). Although “a generous amount” is somewhat ambiguous, operation of the chamber could require up to one half of the ethanol squeeze bottle, so ensure that enough is available. More ethanol can be procured from the Lab Technician’s office.

Alcohol can also be applied to the underside of the lid, allowing it to evaporate from that surface. Some will drip down to the surface below, which is fine. Once the alcohol has had the chance to evaporate into the chamber and mix with the air, tracks should start appearing along the bottom of the chamber. This process usually takes between 5 and 10 minutes. The sensitivity of the chamber can be tested by obtaining the thorium rod from the radioactive source cabinet and inserting it into the source port. If the environment on the inside of the chamber is “ready”, tracks should start to emanate from the rod almost immediately.

If desired, the high voltage can also be applied. The experimental setup includes a high voltage box which can be attached to the HV power connection shown in Figure 1. This will serve to change the sensitive layer depth by drawing the ionized tracks down into the more active area of the chamber, effectively increasing the number and density of the tracks. With only one power supply, this cannot be used simultaneously with the corona probe, however another supply could be obtained.

2 Theory overview

The first component of the theory to be discussed is the nature of the sensitive medium itself. As discussed in the previous section, it is necessary for the alcohol/air mixture to become supersaturated for the track from a charged particle to be visible. This is because there is a threshold level of saturation at which the deposit of energy from ionization will be sufficient to trigger the alcohol to condense around the produced ions.

The primary purpose of the cloud chamber is to provide a method of particle detection. Although most modern particle detectors look much different than this chamber, the majority operate on the same principle. As a charged particle travels through a material, it removes electrons from the atoms following collisions, a process called ionization. The governing equation for energy loss in matter is the Bethe-Bloch formula, a very good description of which is located in the Particle Data Group summary [3]. The equation for this energy loss is shown as Equation 1.

$$-\frac{dE}{dx} = \rho K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2m_e v^2}{I(1-\beta^2)} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (1)$$

In Equation 1, ρ is the density of the medium (ethanol saturated air), K is a constant defined as $4\pi N_A r_e^2 m_e c^2$, equal to $0.307075 \text{ MeV g}^{-1} \text{ cm}^2$, Z is the mean atomic number, A is the mean atomic mass, m_e is the electron mass, v is the velocity, β is the relativistic correction ($\beta = v/c$), I is the mean ionization energy and δ is the density correction. In the

case studied with this experiment, it will be assumed that δ is a negligible correction. You may want to determine whether this is true, and justify this assumption.

This equation governs the deposit of energy as a charged particle travels through the sensitive medium, which in turn gives rise to the formation of droplets. The mechanism behind this interaction is that the charged particle approaches close enough to an atom to free one of its electrons (ionization as described earlier). This electron will generally attach within a short period of time to an atom of either the gas or the alcohol vapor, resulting in two charged particles in the detector. More vapor will then condense on these ions, producing the tracks seen in the chamber. The theory behind this interaction is that the dipole nature of the molecule in saturation (alcohol in this case) results in these molecules being attracted to the ions. As these molecules build up on the original ion, they continue to be attractive to other polar molecules. Once the ion has built up enough molecules to exceed a critical threshold, the alcohol falls out of saturation and manifests as a droplet.

The theory behind the formation of these droplets may be too involved to detail in this overview, but could lead to an interesting experimental project. The start of this theory is outlined in the text “Physics of Atmospheres” [4], and relies primarily on Fick’s law of diffusion, as shown in Equation 2, to calculate the radius of the droplets created by the deposit of energy.

$$r \frac{dr}{dt} = \frac{S - 1}{[L^2 M_r \rho_L / \lambda R T^2] + [\rho_L R T / (\rho_{sat}(T_\infty) D M_r)]} \quad (2)$$

In Equation 2, r is the radius of the droplet, S is the saturation, L is the latent heat of vaporization, M_r is the molecular weight (in kg) of the alcohol, ρ_L is the density of the alcohol, λ is the thermal conductivity of the medium, R is the ideal gas constant, T is the temperature, and D is the diffusion constant. Equation 2 will only be necessary if the experiments chosen involve the determination of the characteristics of droplet formation.

One of the more obvious manifestations of the droplets is the fact that shortly after formation the track will fall quickly to the bottom plate of the chamber. This is because the condensed droplets are heavier than even the saturated air, and therefore fall under their own gravity. Upon contact with the cold bottom plate of the chamber the alcohol condenses and begins to produce large puddles of alcohol which will accumulate on the bottom of the chamber as the experiment continues.

3 Safety

Safety Rules

- Radiation safety rules must be strictly obeyed. Check with the supervising professor before using any radioactive material
- No food or drink is allowed in any radiation laboratory
- Radioactive sources should normally be shielded during use and storage and must never be left unattended in an open room. Do not subject the sources to heat, excessive pressure, or anything else that may damage them.
- When you are not using a source it is a good idea to keep it behind lead several metres away so that it doesn't irradiate you or produce unwanted effects in the detector
- If any radioactive source appears damaged, report it immediately to your supervising professor or the Advanced Lab Technician
- When using high voltage supplies, make sure that the connecting cables are of the correct type, namely SHV. Please ask the instructor if this is not clear.
- Extra care should be taken when handling the high voltage sources and supplies. After the High Voltage supply is turned off, wait for at least 2 minutes before handling the probe to allow any stray capacitance to discharge.
- Ethanol is flammable, so it should be kept away from any ignition sources, e.g. flames, heating elements, or electrical sparks.
- Ethanol fumes should not be breathed for extended periods, so keep the lid on the chamber except when introducing or removing sources, magnets, etc.
- This experiment uses liquid nitrogen, so all laboratory rules and precautions about handling cryogenic liquids must be observed.
- Eye protection, gloves, and proper footwear, e.g. no sandals, must be worn when working with cryogenic liquids or dewars.
- When pouring liquid nitrogen (LiN) into the cloud chamber tray, be careful not to splash it on your clothes that might absorb and hold it against your skin causing burns.
- Filling the the dewar with liquid nitrogen must be done by a Lab Technologist.
- Be careful not to drop the large glass lid; it could fracture and produce dangerous shards.

4 Possible Experiments

There are several possible experiments that one could do using the cloud chamber setup. It is suggested that you try at least a few of these, depending primarily on your interests. Many *many* additional experiments are possible and if you have a particular interest in any aspect of the chamber you should discuss this with the supervising professor. Generally they are very open to variations on the existing experiments, provided these are sufficiently challenging.

4.1 Active Region of the Detector

One of the interesting aspects of the cloud chamber is to attempt to define the active region of the detector itself. There is a great deal of theory concerning this, the majority of which can be found in several papers [2]. These papers present equations for both the level of supersaturation of the ethanol in the air and the critical saturation dependent on temperature.

As an example, the level of saturation of the air with ethanol as a function of the distance z from the cold plate can be described as shown in Equation 3.

$$S(z) = \frac{z}{h} \left(1 - \frac{z}{h}\right) (T_h - T_c)^2 \left[\frac{1}{2} \left(\frac{M_w L}{R \Delta T^2} - \frac{1}{\Delta T} \right)^2 - \frac{M_w L}{R \Delta T^3} + \frac{1}{2 \Delta T^2} \right] \quad (3)$$

In Equation 3, S is the level of saturation, z is the height in the chamber while h is the full height, T_h and T_c are the hot and cold temperatures, respectively, M_w is the molecular weight and L is the latent heat of condensation for ethanol, R is the gas constant, and ΔT is the temperature difference between the temperature at the top and bottom of the chamber.

The critical threshold for droplet formation can also be found in terms of the height in the chamber, making the assumption that the temperature increases linearly from the cold plate to the warm top.

$$\ln(S_{crit}) = LM_w \frac{T_h - T_c - \frac{z}{h} (T_h - T_c)}{RT_h^2} \quad (4)$$

Plotting Equations 3 and 4 together results in a plot which should look something like Figure 2. In the case of this plot, parameters have been chosen which are not the same as those used in your experiment.

In Figure 2, the sensitive area encompasses the height between the two intersections of the curves. You should attempt to calculate the curves for your cloud chamber and then measure them (likely using a radioactive source) to see if your calculations are correct.

Following this initial attempt to find the sensitive area, it may be interesting to evaluate some of the assumptions which were made when making the calculation of both the level of supersaturation and the critical saturation. For example, is the assumption that the temperature profile of the detector along the vertical axis a reasonable one? Can you verify this assumption and, if it is not valid, adjust the equations to account for this modification?

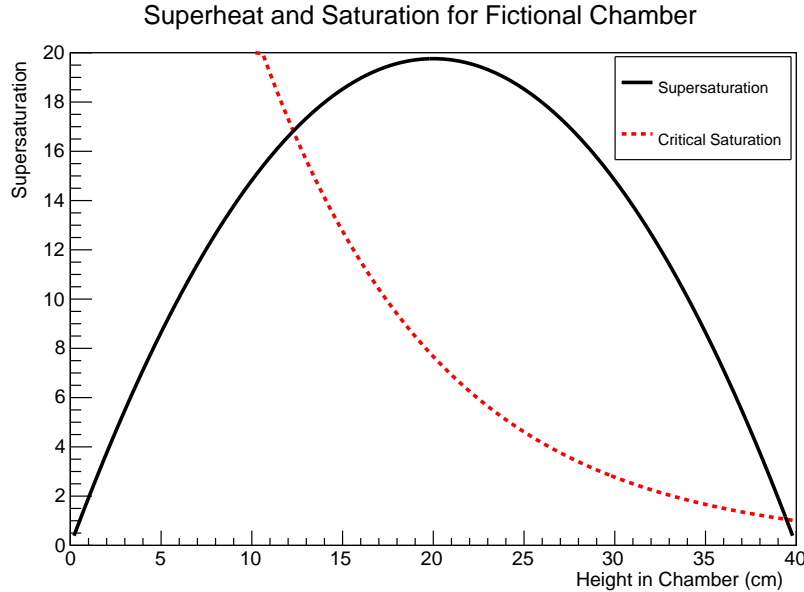


Figure 2: A typical plot showing the critical and supersaturation levels for a cloud chamber.

4.2 Radon Content of the Air

Radon is a radioactive element found in the air in almost all buildings in the world. It is a product of the decay of natural elements in the earth. The concentration of radon varies dramatically according to many factors such as the geographic location (primarily it is dependent on the makeup of the soil), the types of building materials and the amount of ventilation. In air, Radon is colorless, odorless and is mostly detected through monitoring its decay.

Radon found in the air is mostly ^{222}Rn , which alpha decays into ^{210}Po . As the name suggests, this involves the production of an alpha particle which can be detected using the cloud chamber. The goal is then to determine how many alpha decays are seen in a known volume and thereby determine the amount of ^{222}Rn in the air. For now it is safe to assume that all alpha decays are due to Radon and not any other elements.

In order to accomplish this you will pick an area inside the sensitive region of the detector and count the number of decays in a given length of time (probably on the order of five minutes). To determine the activity you will need to know the “sensitive volume” for that area, which obviously requires knowledge of the height from the cold surface at which alpha decays do not cause tracks. There are several ways to determine this, and you should feel free to be creative in your experimentation. The first potential experiment (detailed above) may provide some guidance.

The geometry of the sensitive area also provides a correction factor, as only those tracks which are within some small angle of being parallel to the cold plate create tracks long enough to be observed. You should make a correction for this geometrical effect by estimating the fraction of counts lost to this factor. In order to do this, you should assume that the alpha decays are isotropic, which is a good approximation of the true case.

Further extensions of this experiment could involve making a better approximation of the

geometrical effect by introducing a source into the chamber and counting the decays from that source, then comparing that value to the number expected based on the activity of the source. This will not account for a factor commonly referred to as the "efficiency" of the detector, which means that some of the tracks passing through the sensitive region may not cause droplet formation.

4.3 Bending of β Particles

One of the original uses of the cloud chamber was to study the bending of beta particles under the influence of a magnetic field. The cloud chamber allows this to be done in a very intuitive manner, since the particle bending can be seen in real time by examining the tracks.

The first step for this portion of the experiment is to observe and identify beta particles. You should get a beta source from the radioactive source cabinet (following all precautions) and place it in the cloud chamber. Once the system has reached equilibrium, the tracks from betas should be easy to see and visually separate from the alpha tracks sporadically seen in the sensitive area.

Once you are confident that you have seen betas, you can place the rare earth magnet into the chamber to see the effect it has on the particles. The equation governing the curvature is shown in Equation 5 for particles traveling in a perpendicular magnetic field.

$$F = qvB = m\frac{v^2}{R} \quad (5)$$

In Equation 5, F is the force on the particle, q is the charge, v is the velocity, and m is the mass of the particle. Finally, R is the radius of curvature of the track produced.

This experiment consists of inserting the magnet close to the source of betas and determining the effect that the magnetic field has on the particle tracks. The suggested mechanism for performing this experiment is to install a camera above the chamber with which you can record the path of the tracks. This should be set to take video, as your reaction time may not be sufficient to trigger when the bending occurs. The rare earth magnet can be placed within the chamber and its orientation can be changed from outside the chamber using another magnet. You should be able to see the changes in the paths with the magnetic field in different orientations, and using the recorded tracks, be able to determine the momentum of the beta particles.

4.4 Shielding of Radioactive Particles

Shielding the surroundings from radioactive particles is obviously big business and quite important to many industries. In this experiment, you should use Equation 1 with several materials to determine how much energy is lost by the particles produced from several sources. It is worth noting that alpha particles are stopped in a relatively short distance in air, and are definitely stopped by a sheet of paper. While this is interesting, it may be more appropriate to study the energy lost by betas as they travel through several different materials. It will be useful if you have made some determination between alphas and betas previously (identifying them through the nature of the track in the chamber) so this should be studied prior to undertaking the experiment.

The easiest way to conduct this experiment seems to be using some readily available shielding such as tin foil. The shielding can be placed in front of the beta source in layers of increasing thickness until the particles are completely stopped.

An extension of this experiment could be to study the path lengths of the particles themselves. If one were to place a mono-energetic source of either alpha or beta particles (it may be easier with alpha particles due to the increased visibility and reduced range) inside the chamber and record the track lengths produced from this source, a distribution should be produced which peaks at roughly the expected length. Using this distribution you should be able to not only verify the Bethe-Bloch equation for depositing energy in the detector, but also obtain a rough estimate of the sensitive height of the detector.

4.5 Scattering

There are several different types of scattering that one could see using the cloud chamber, and potentially even some famous experiments which could be reproduced.

The first experiment suggested follows the famous Rutherford gold foil experiment [5]. This is the famous experiment in which Rutherford used alpha particles which were incident on a gold foil to help illuminate the structure of the atom. In this test, Rutherford looked for the scattering of the alpha particles from the metal foil. You should be able to place an alpha source close to a metal foil and record the number of alphas which scatter “backwards” from the foil. By recording the angle at which the scattering happens (again, with a camera or some other source of recording the images) you should be able to draw conclusions much in the same way that Rutherford did.

Although you won’t be able to see gamma rays directly in the cloud chamber, you may be able to see the products of their interactions. One interesting way to observe the scattering of gammas is to place a gamma source close to an “absorber” which could be a foil of material in this case. By observing the distribution of particles which emerge from the absorber (and comparing to what is present without the gamma source) you should be able to draw many conclusions about the interactions of the gammas.

4.6 The Corona Electrode

Included with the cloud chamber apparatus is what is referred to as a “corona electrode”. In this case, that just consists of an electrode potted in a manner which allows for easy introduction into the chamber. This electrode can be electrically energized to a level which allows for conduction into the environment but is not strong enough to cause a breakdown-type discharge. When the conduction happens to the ethanol in the cloud chamber, these molecules will become ionized, and will react in the same manner as previously described, creating droplets which are visible.

The corona electrode should be found close to the cloud chamber, and fits snugly into the source port on the side of the chamber itself. You should connect this to a variable power supply and begin your investigations. Extra care should be used with the high voltage source, especially in the connection. Always power off the source before connecting or disconnecting the electrode, and always use the proper SHV connectors. Before inserting the electrode into the chamber you may want to inspect the end of the wire protruding from the potted

tube. The end of this wire will be the source of the ionized particles in the detector. Some questions to ask yourself include a) is the end of the wire smooth and does that matter? and b) is the wire itself in reasonable shape and does that matter?

Once the chamber is appropriately sensitive, the corona electrode can be powered up. It should be connected to the High Voltage power supply used to create the field inside the detector, with the ground lead attached to the grounding port on the side of the chamber. The supply can then be switched on and the bias to the electrode slowly increased.

As the voltage is increased you may (if you have very fine motor control) be able to create a situation in which the electrode produces intermittent “puffs” of droplets in the chamber. At this level the electrode is producing ionization in discrete batches, so how does this work? As the high voltage is increased, the intermittent puffing will be replaced by a constant stream of droplets towards the bottom of the chamber. If you leave the electrode in this configuration, you should observe sporadic events which cause the electrode to produce copious amounts of droplets. What is going on here? Can you predict roughly the time period of these events?

References

- [1] <http://hep.ucsb.edu/people/hnn/cloud/articles/rmp1949.pdf>
- [2] *A new instrument for measuring cloud condensation nuclei: Cloud condensation nucleus “remover”* Q. Ji, G.E. Shaw, and W. Cantrell, *Journal of Geophysical Research* 103, D21 pgs 28013-28019. <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/98JD01884>
- [3] <http://pdg.lbl.gov/2005/reviews/passagerpp.pdf>
- [4] **The Physics of Atmospheres** John T Houghton, 1977 (QC880.H68)
- [5] E. Rutherford, “The scattering of alpha and beta particles by matter and the structure of the atom,” *Phil. Mag. Ser. 6* **21** (1911) 669. doi:10.1080/14786440508637080; <https://www.physics.utoronto.ca/~phy326/cc/Rutherford1911.pdf>