Analysis of the Behavior of Alpha Particles emitted from Lead-210 Source

Lab Report #3

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Abstract

Our experiment was to analyze the behaviour of alpha particles emitted from a Lead-210 source through the use of a cloud chamber. Our experiments consisted of measuring the alpha particles range, comparing stopping power to droplet density, and observing the scattering effect of collisions. Our measured values were a range of 3.0 ± 0.5 cm and a scattering 2 standard deviations value of $17.66^{\circ} \pm 1.8^{\circ}$. For the correlation between stopping power and droplet density our results were inconclusive. Comparing the measured values to the expected results of 3.3 cm for alpha particle range in air and a 2 standard deviation angle of 19.05°, it can be seen that our data and analysis was accurate and our values for uncertainty overlap with the expected measurements.

Introduction

A cloud chamber is a type of particle detector that visualizes the paths of ionizing radiation. The cloud chamber works by creating a sealed environment of supersaturated alcohol vapor that allows passing ionizing radiation to create tracks. A diagram of a cloud chamber can be seen below in Figure 1.

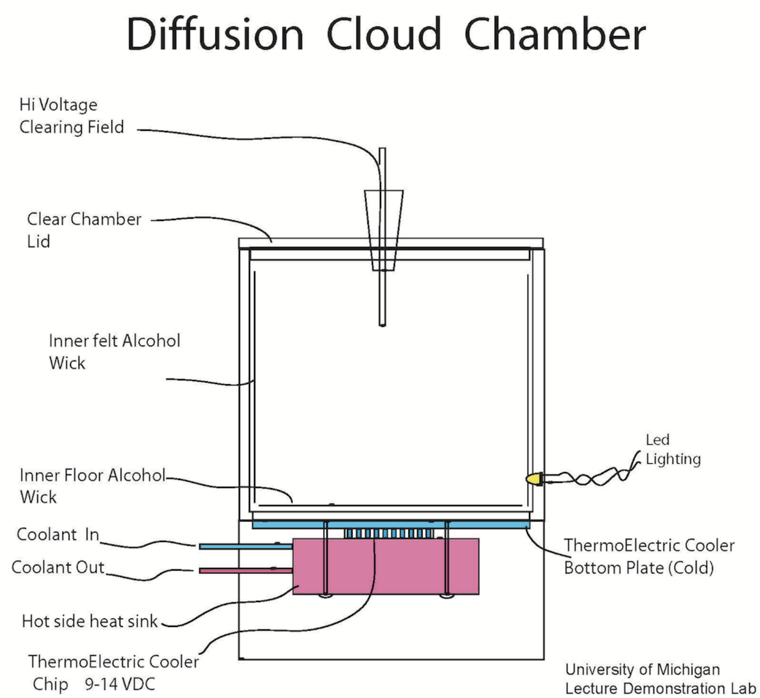

Figure 1: A diagram of the cloud chamber used in our experiment from the University of Michigan Physics department [1]

The supersaturated environment necessary to form tracks is created by a temperature gradient inside the cloud chamber. A peltier cooler reduces the bottom plate of the cloud chamber to -35°C while the top plate is allowed to remain at room temperature. When alcohol is added to the interior of the chamber it soaks up the wicks on the sides and evaporates near the top plate. This alcohol vapor then sinks towards the bottom of the cloud chamber where the air is colder. Under normal circumstances ions in the air would provide nucleation points and the alcohol vapor would easily condense into liquid droplets. However, the cloud chamber uses a high voltage field to deionize the chamber, so the alcohol vapor spends some time in a supersaturated state. Ionizing radiation that passes through this supersaturated region ionizes gas molecules near its path, which the alcohol vapor then condenses around. This results in a track of alcohol droplets being formed along the path of the radiation.

To provide a reliable source of ionizing radiation a radioactive source is placed into the cold region of the cloud chamber. The source used for our experiment was the radioactive isotope Lead-210, which was coated on the end of a needle. Lead-210 undergoes three decays, two beta decays and an alpha decay, before reaching the stable isotope Lead-206. The decay chain for Lead-210 is shown below in equations 1, 2, and 3.

$$^{210}\mathrm{Pb} \rightarrow {}^{210}\mathrm{Bi} + e^- + \bar{v}_e \tag{1}$$

$$^{210}\mathrm{Bi} \rightarrow {}^{210}\mathrm{Po} + e^- + \bar{v}_e \tag{2}$$

$$^{210}\mathrm{Po} \rightarrow {}^{206}\mathrm{Pb} + {}^{4}\mathrm{He} \tag{3}$$

The last decay, shown in equation 3 emits an alpha particle of energy 5.407 MeV. While the beta particles emitted from the first two decays also create tracks in the cloud chamber, our experiment focused on the tracks created by the alpha particles.

Alpha particles are electrically charged helium nuclei and have a 2+ charge. This charge is what ionizes nearby gas and creates the visible tracks of vapor. For each molecule the alpha particle ionizes it loses some energy and slows down. This causes the alpha particle to spend more time near gas molecules, ionizing more molecules, and losing more energy, until finally coming to rest in the gas. This loss of energy over distance, also known as the stopping power, is modelled via the Bethe Bloch energy loss formula seen below in equation 4. The equation is expressed in terms of a particle with speed v and charge z, travelling through a medium of electron density n and a mean excitation energy I.

$$-\frac{dE}{dx} = \frac{4\pi n z^2}{m_e v^2}\left(\frac{e^2}{4\pi\epsilon_0}\right)^2\left[\ln\left(\frac{2m_e v^2}{I}\right)\right] \tag{4}$$

From equation 4 it can be seen that the energy loss is proportional to v^{-2}, so as the particle slows down it loses more and more energy. The units of this equation is energy per distance, however because the stopping power for most materials and particles is very similar the most important factor is the density of the material. So in practice the units used are energy per mass areal density.

The last topic is that of alpha particle scattering. While travelling the alpha particle will collide with other molecules causing the alpha particle's momentum to change direction. These collisions occur randomly and create a deviation from straightness in the alpha particles tracks. The number of particles scattered to a given angle in a given medium can be modelled with the multiple scattering formula seen below in equation 5, where θ_0 is the total angle that two standard deviations of scattered particles will scatter to, βc is velocity ,p is momentum, z is charge number of alpha particle, and $\frac{x}{X_0}$ is the thickness of the medium.

$$\theta_0 = \frac{13.6\mathrm{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right) \tag{5}$$

Experimental Methods

From the topics described above our experiments on the alpha particles behaviors came in three sections. First to measure the range of the alpha particles in our cloud chamber. Second to compare the change in energy over distance of the alpha particles to the density of droplets formed in the track. And third to measure the deviation from straightness in the alpha particle tracks and compare to the Rutherford scattering equation.

To set up the cloud chamber properly first pour 10-20 cc of Isopropanol alcohol into the bottom of the cloud chamber and let it soak up the sponge wicks on the sides of the chamber. Next set the cooling pump to -10°C and let cool for 20 minutes or until it reaches -10°C. This cooling pump is external from the cloud chamber itself and serves to cool the chambers mechanisms before the peltier cooler is turned on to prevent damage. Next plug in the cloud chamber and allow to cool for a further 20 minutes. When the chamber is cooled a thick condensing fog of alcohol vapor should be visible near the bottom plate, indicating the cloud chamber is ready. After inserting the radioactive Lead-210 source into the chamber, connect the high voltage banana plug to the top of the Lead-210 needle and set the voltage to 400V. This will clear any ions from the chamber and should allow for thick vapor tracks from the alpha particles to be seen. Once finished turn off the cloud chamber and make sure to set the cooler to 5°C and let run for 15 minutes. This allows the cloud chamber to heat up more slowly and prevents damage to the chamber.

In order to analyze the tracks created by the cloud chamber we used a camera mounted directly above the cloud chamber to take a series of pictures of the tracks in the chamber. These sets of photos were then uploaded to a computer and analyzed with ImageJ. A diagram of this setup can be seen below in figure 2.

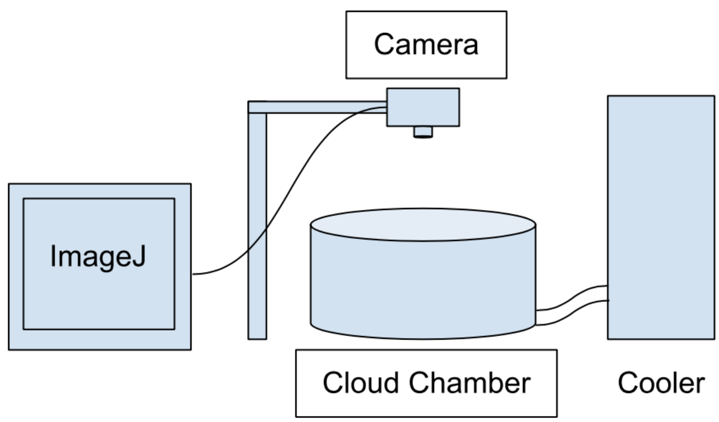

Figure 2: Diagram showing the mounting of the camera above the cloud chamber, allowing us to process images of the tracks in ImageJ.

In order to properly calibrate the images we needed to set the scale of the frame in ImageJ. To accomplish this we placed a ruler in the bottom of the cloud chamber and measured the know distance multiple times with ImageJ. This allowed us to find a value for pixels per centimeter, and by taking the standard deviation of our measurements of known length we were able to determine the uncertainty in our measurements of length. The scale used in our experiments is $0.0242\frac{\text{cm}}{\text{px}}$, and we found that we had an uncertainty of ± 0.1 cm in our measurements of length or about ± 4 pixels.

Raw Data

Alpha Particle Range

Measuring the distance travelled by 30 alpha particles emitted from the source with ImageJ we found the range distribution shown below in figure 3.

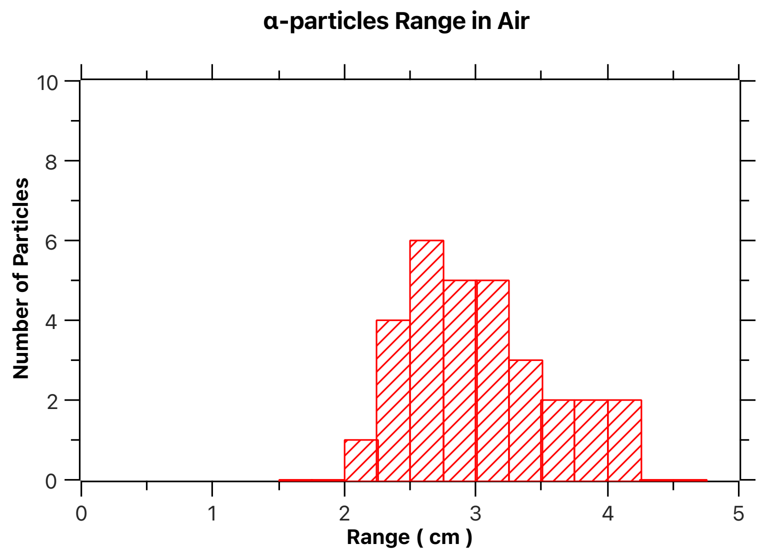

Figure 3: Histogram displaying the range of 30 alpha particles in air. The bins are 0.25 cm long and go from 2 cm to 4.24 cm.

Of the 30 particles measured we found a average range of 3.0 cm with a standard deviation of 0.5 cm. The value for the standard error is 0.1 cm which matches the uncertainty in the our measurement of length which was ± 0.1 cm.

Droplet Density vs Stopping Power

Measuring the tracks created by 10 alpha particles we collected the data seen below in table 1 for range and track area. As before the error in the range length measurement is $\delta x = \pm 0.1$ cm.

Particle Number	Range (cm)	Area (cm^2)
1	3.130	0.223
2	3.299	0.146
3	2.704	0.187
4	2.596	0.128
5	2.807	0.106
6	3.484	0.278
7	3.518	0.473
8	3.050	0.217
9	2.764	0.237
10	2.287	0.309

Table 1: Data collected for measurements of droplet density vs energy loss per distance. The range and area were both found using ImageJ analysis of particle tracks in the cloud chamber.

Scattering

Measuring the angles of 20 alpha particle tracks in the cloud chamber we collected the data seen in table 2 below. The uncertainty in the measurement of the angles was found by measuring the same given angle 10 times and finding the standard deviation from this calibration. Using this method we found $\delta\theta = \pm 0.9$.

Particle Number	Angle (°)
1	176.49
2	156.37
3	176.269
4	176.84
5	164.55
6	175.582
7	179.053
8	171.203
9	179.745
10	178.858
11	178.127
12	178.556
13	178.499
14	179.66
15	161.458
16	176.84
17	165.763
18	178.431
19	174.674
20	174.098

Table 2: Angle of the tracks created by 20 alpha particles in the cloud chamber. The angles were measured using analysis of the particle tracks in ImageJ.

The deviation of the angles in table 2 from straightness (180°) is 8.83°, meaning that one standard deviation of the tracks are within 8.83 ± 0.9 of a straight line.

Results

Alpha Particle Range

Our calculated value of alpha particle range of 3.0 ± 0.5 cm corresponds to a density adjusted range of $4.5 \times 10^{-3} \pm 8.0 \times 10^{-4} \frac{\mathrm{g}}{\mathrm{cm}^2}$, where the density of the air in the cloud chamber is $\rho = 0.001482 \frac{\mathrm{g}}{\mathrm{cm}^3}$ [2]. Using these values on the NIST ASTAR database [3] we find the correlating values of total stopping power and kinetic energy to be $749.9 \pm 62.25 \frac{\mathrm{MeV \cdot cm^2}}{\mathrm{g}}$ and 5.11 ± 0.60 MeV, respectively. The uncertainty in the values for stopping power and kinetic energy were found by comparing the values for the our maximum and minimum values of range in our uncertainty to the NIST database and using the range of the values as the uncertainty. Comparing to the expected values for range, stopping power and kinetic energy which are 3.3 cm, 720.7 $\frac{\mathrm{MeV \cdot cm^2}}{\mathrm{g}}$, and 5.407 MeV, the uncertainty in our measurements includes the expected values.

Droplet Density vs Stopping Power

From the 10 tracks analyzed for range and area, we used this data to find the droplet density and total stopping power as shown in table 3 below. The stopping power was found as before by using the NIST database and then converting to $\frac{\mathrm{MeV}}{\mathrm{cm}}$ with our value for medium density. The droplet density was first calculated by finding the number of droplets formed, by dividing the particle kinetic energy by 0.01015 MeV, the ionization energy for isopropanol vapor [4]. This value was then divided by the track area, as we assumed the track depth was approximately 1 cm.

Particle Number	Droplet Density ($\frac{\mathrm{Droplets}}{\mathrm{cm^3}}$)	Stopping power ($\frac{\mathrm{MeV}}{\mathrm{cm}}$)
1	2309.4	1.093
2	3650.7	1.067
3	2502.7	1.169
4	3554.7	1.191
5	4518.9	1.149
6	1989.2	1.041
7	1175.5	1.037
8	2336.4	1.106
9	2004.2	1.157
10	1352.8	1.263

Table 3: Calculated values of droplet density and total stopping power for 10 alpha particle tracks.

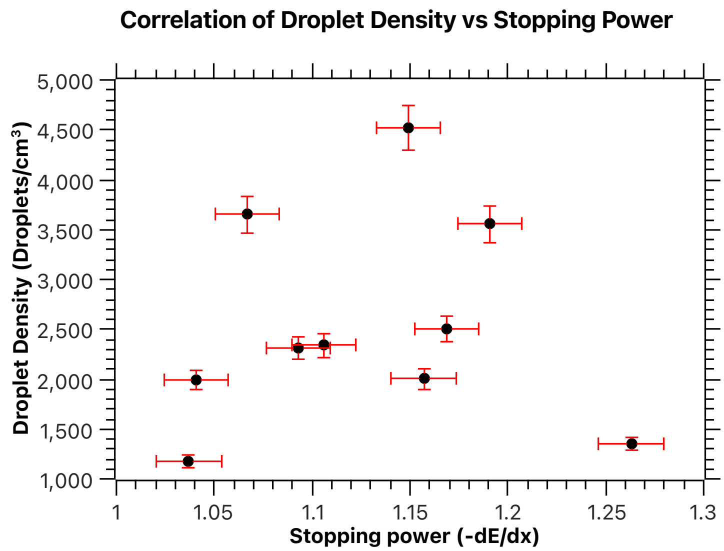

Figure 4: Plot displaying the correlation between droplet density and change in energy per unit distance (stopping power).

The uncertainty in our calculations comes from the range of stopping power and kinetic energy values associated with the extreme values of the particle range uncertainty. This uncertainty ended up being $\pm 1.6 \times 10^{-2} \frac{\text{MeV}}{\text{cm}}$ for the stopping power and $\frac{\delta\rho}{|\rho|} = \pm 5.08\%$ for the droplet density.

As seen in figure 4 there is a correlation between droplet density and stopping power. When the Energy loss per unit distance increases the droplet density also tends to increase. From the data it is not clear if the relation is linear or not.

Scattering

Using equation 5 to find θ_0 with the appropriate values for our alpha particle and medium we find a value of $\theta_0 = 19.05°$. This value implies that 95% of particles (2 standard deviations) should scatter in between this whole angle. Comparing to our value of 8.83°±0.9° for one standard deviation, we see that the uncertainty in our measurement overlaps with our calculated value. Comparing these to our data for track angle we see that 95% of the scattered angles do fall within both 19.05° and 17.66°±1.8° of a straight line.

Discussion

Overall the data we collected and analyzed matched with the values we expected to see. For the alpha particle range our result of 3.0 ± 0.5 cm matches the expected value for a 5.407 MeV alpha particle of 3.3 cm. This measurement could have been improved with more data points, allowing for a lower uncertainty. For measurements and calculations of the droplet density vs stopping power our results were ultimately inconclusive. The data indicated that there could be a correlation between the values as expected, but without more data points and lower values of uncertainty, the relationship between the two was difficult to visualize. Also instead of using the NIST database to find the associated values for stopping power, which introduced a lot of uncertainty, it might have been better to measure the particles velocity using a magnetic field and calculate it directly with the Bethe Bloch formula for energy loss. Lastly the results for the multiple scattering of the alpha particles matched well with the calculated value from the multiple scattering formula. The deviation of the particles from straightness was very close to the calculated total angle from 5. One way this experiment could have been improved is through the measurement of more particle tracks and compare their deviation the expected value θ_0.

References

[1] "Cloud chamber diagram." [Online]. Available: https://sharepoint.umich.edu/lsa/physics/demolab/SitePages/7D30.60%20-%20Cloud%20Chamber.aspx

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[4] "Isopropanol alcohol." [Online]. Available: https://webbook.nist.gov/cgi/cbook.cgi?ID=67-63-0