

Cloud Chamber Experiment

– See what you can't see –
Cosmic-ray and radioactive decays

October 18, 2021

Chapter 1

Introduction

There are particles around us we cannot see with our eyes nor feel with our hands. This is why we need particle detectors to see or - more generally - detect them. The cloud chamber is a particle detector which visualizes trajectories of charged particles in a super-saturated vapour layer. Developed in the early 20th century, it is one of the oldest particle detectors and has led to a number of discoveries in the history of particle physics.

The cloud chamber was originally invented by C. T. R. Wilson in 1896 in his studies of cloud formation. He developed a device to create a super-saturated state of (water) vapour and found that dust particles play an important role in the cloud making process. They behave as condensation nuclei, allowing droplets to form around them. However, Wilson found that even after he removed all the dusts from the chamber, still a little amount of droplets were formed. He came up with the idea that ions in the air could act as condensation nuclei. Shortly afterwards, this was proven by exposing the vapour to X-ray radiation, which had just been discovered. A large amount of droplets were generated by the X-ray. In 1910, Wilson reported the observation of alpha rays, beta rays and gamma rays. Seventeen years later, he was awarded the Nobel Prize for his work on the cloud chamber which makes the invisible particles visible. Since then, several discoveries were made with this detector, for example the discoveries of the positron (1931), muon (1936) and kaon (1947).

The cloud chamber is attractive in its feature to visualize particles in real-time and 3D. The observer would immediately understand that our world is full of particles. With this experiment, the students will learn about ionization processes, Coulomb scattering, bremsstrahlung, cosmic rays, radioactive decay, etc., but also about droplet formation in cloud physics.

Although the cloud chamber is nowadays not used at the frontier of particle physics any more due to its slow response speed, the idea of visualizing particle trajectories is still a fundamental subject in any kind of particle detectors. This experiment would give you a basis of experimental particle physics. I wish you to enjoy this experiment.

Chapter 2

Theory

The following section aims to give a brief overview of the theoretical basis needed for the subsequent analyses. Therefore, we introduce some important concepts and quantities of the particle interaction with matter, cosmic-ray, alpha particles and the working principle of cloud chamber.

2.1 Passage of charged particles in matter

Ionization loss of charged particles

When a charged particles passes through matter, it interacts with atomic electrons and nuclei via Coulomb force and transfer momentum to them, i.e. loses its energy. The electrons (or nuclei) who received the momentum is then no more bounded in an atom, therefore the atom is "ionized". The single process with a charged particle is illustrated in Figure 2.1.

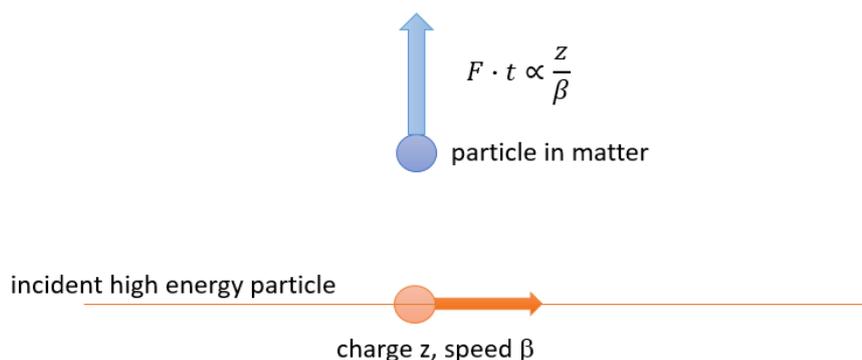


Figure 2.1: Schematic of momentum transfer in a single process.

The transferred momentum is equal to the impulse given by the incident particle, which is the force (F) times time (t),

$$P = \int F \cdot dt \propto \frac{zZ}{\beta}$$

Here, z is the charge of incoming particle and Z is that of the particle in matter. Lower the speed of incoming particle (smaller β), the momentum transfer is high. This is because lower the speed, the particle feels longer the force. The transferred kinetic energy is

$$K = \frac{1}{2} \frac{P^2}{m} \propto \frac{z^2 Z^2}{\beta^2 m} \propto \frac{z^2}{\beta^2}$$

They are proportional to z^2 and inverse proportional to β^2 . Note that the energy transfer to electrons is a dominant process due to the light mass of electron with respect to that of nucleus as its ratio is $(Z \cdot K_e) : K_N = Z \cdot 1/m_e : Z^2/m_N \simeq 1 : Z/2000$.

By integrating all atoms in a material, the energy loss ($-dE/dx$) is formulated. The complete formula taking the relativistic effect into account is following. This is so called the Bethe equation and applies in a range of $0.1 < \beta\gamma < 1000$ with a few % precision.

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 \right] \frac{\text{MeV}}{\text{g/cm}^2}$$

Here, K is a constant of $0.307 \text{ MeV mol}^{-1} \text{ cm}^2$. Z , A are the charge and atomic number of material, m_e electron mass. I^2 is the mean excitation energy. And W_{max} is the maximum energy transfer in a single collision, which is given,

$$W_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

M is a mass of incoming particle. The unit of $\frac{dE}{dx}$ is in $\frac{\text{MeV}}{\text{g/cm}^2}$. This means if you multiply the density of material (g/cm^3), you will get the energy loss in MeV/cm .

The dE/dx is high at low energy, there is a minimum around $\beta\gamma \simeq 3$, and then dE/dx slowly increases towards higher energy because of the relativistic effect (so-called relativistic rise).

Multiple Coulomb Scattering

The momentum transfer by single interaction might be small. But a charge particles passing through a matter faces many of them and deflected by many small angular scattering. Therefore the particle shows a zigzag trajectory in matter. Ignoring the less frequent "hard" scatters, we can assume the scattering angle after passing a thickness of material has a Gaussian distribution (due to central limit theorem). This is illustrated in Figure 2.2. A RMS of scattering angle θ (radian) before and after a material with a thickness of x is given,

$$\theta_0 = \theta_{plane}^{rms} = \frac{13.6 \text{ MeV}}{\beta p c} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln \left(\frac{x z^2}{X_0 \beta^2} \right) \right]$$

Here X_0 is a radiation length. X_0 has a strong dependence on the charge of material nuclei as $X_0 \propto 1/Z^2$. A high momentum particle goes straight and a low momentum one bends much.

For more detail, see *Review of Particle Physics*, Particle Data Group. *Passage of particles through matter*, <https://pdg.lbl.gov/2020/reviews/rpp2020-rev-passage-particles-matter.pdf> or Chapter 1 of the book: *Introduction to Elementary Particle Physics*, Alessandro Bettini, Cambridge University Press, doi:10.1017/CBO9780511809019, available online.

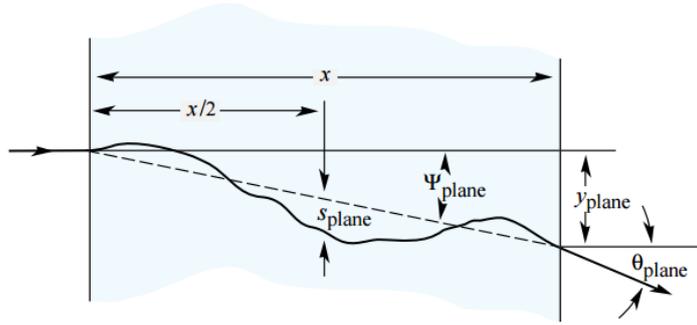


Figure 2.2: Multiple Coulomb scattering.

Exercise

1. Draw the ionization loss in nitrogen gas as a plot, for electron, muon, proton, alpha, and with a particle momentum as x-axis (1 MeV/c - 1 TeV/c) and an energy loss as y axis. And a same plot but with $\beta\gamma$ as x-axis ($0.1 < \beta\gamma < 1000$). Mean excitation energy, I , is 82 eV for nitrogen.
2. Calculate a mean scattering angle for 1 MeV/c electron and 1 GeV/c muon, after passing 5 cm of air. X_0 in air is 303.9 m.

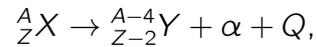
Table 2.1 summarises the used variables.

Table 2.1: Table of variables used in theory section.

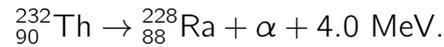
Symbol	Description	Value or units
c	speed of light in vacuum	$299\,792\,458\text{ m s}^{-1}$
m_e	electron mass	$0.510\,998\text{ MeV}/c^2$
r_e	classical electron radius $\frac{e^2}{4\pi\epsilon_0 m_e c^2}$	$2.817\,940\text{ fm}$
N_A	Avogadro's constant	$6.022\,141 \times 10^{23}\text{ mol}^{-1}$
K	$4\pi N_A r_e^2 m_e c^2$	$0.307\,075\text{ MeV cm}^2\text{ g}^{-1}$
z	charge number of incident particle	
Z	charge number of absorber	
A	atomic mass of absorber	g mol^{-1}
M	incident particle mass	MeV/c^2
p	incident particle momentum	MeV/c
β	incident particle velocity	c
γ	Lorentz factor $\frac{1}{\sqrt{1-\beta^2}}$	
E	incident particle energy $\gamma M c^2$	MeV
I	mean excitation energy	eV
W_{max}	maximum energy transfer to an electron in a single collision	MeV
	$\frac{2m_e c^2 \beta^2 \gamma^2}{1+2\gamma m_e/M+(m_e/M)^2}$	

2.2 Alpha decay

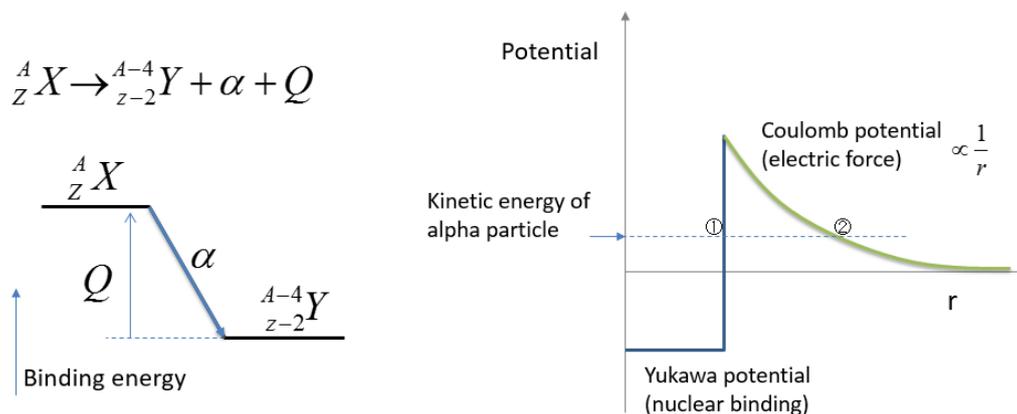
Alpha decay is a radioactive decay in which an atomic nuclei emits an alpha particle, a helium nucleus and consequently change to a different nuclei with 2 lower atomic number and 4 lower mass number, following the formula



and for example,



An atom X decay into an atom Y which has a lower binding energy as shown in the figure below on the left. Before the decay, the α particle is trapped in a potential well made by the nuclear force, so called the Yukawa potential. The emission of alpha does not mean that the alpha particle got enough energy to escape from the Yukawa potential. But the alpha particle goes through the potential wall by the quantum tunnelling. This is illustrated in the right figure. The alpha particle at ① with given kinetic energy goes through the potential wall made by the Yukawa potential and the Coulomb potential, and appear at ②, then accelerated following the Coulomb force.



The frequency of radioactive decay is proportional to the number of particle, namely,

$$\Delta N = -\lambda \cdot N_0 \cdot \Delta t$$

Here the ΔN is the number of decays in a short time Δt , when the initial number of particle is N_0 . λ is a coefficient. By integrating this formula, one can derive the following,

$$N(t) = N_0 \cdot e^{-\lambda t} = N_0 \cdot e^{-\frac{t}{\tau}}$$

The number of particles reduces exponentially by time with a time constant of $\tau = 1/\lambda$.

Be aware that there are two types of conventions that express time in particle decays. One is the "lifetime" which is exactly τ in the formula above. The other is the "half-life" ($T_{\frac{1}{2}}$) which means that a half of particles decays after this time. They have a relation,

$$T_{\frac{1}{2}} = \ln 2 \tau.$$

2.3 Cosmic ray

Cosmic rays are particles whose origins are related to particles from space, from the sun, from outside of the solar system and from distant galaxies. Origin of the high energy primary cosmic rays has been said supernovae. However, even with the state of the art knowledge we haven't understand fully the cosmic rays, especially its high energy spectrum or the matter-antimatter ratio. The cosmic ray is fundamental probe to understand our universe.

The high energy "primary cosmic rays", mainly protons, interact with the earth atmosphere and create numbers of particles via the strong interaction. The created particles (mesons) would then interact again and repeatedly. In such a way a single proton could make a cascade of hadron interactions, creating thousands of particles. This process grows at the height of around 10-30 km from the sea level. The created mesons decay via the weak interaction, for example, a pion decay into a muon and neutrino ($\pi \rightarrow \mu\nu_\mu$). All these mesons and leptons are called the "secondary cosmic rays". What we can observe at sea-level is these secondary cosmic rays. The majority of them are GeV-scale muons.

Exercise

1. Check the lifetime (τ) of pion and muon. Assuming classical physics, calculate how long these particles travels on average if they move at the speed of light, $c\tau$ (lifetime \times speed of light).
2. In Special relativity, a particle lives longer when seen from an observer at rest. Calculate the mean travel distance of pion and muon with their energies of 1GeV.

2.4 Cloud chamber

Most of the substances have three phases depending on its temperature and pressure, namely gaseous, liquid and solid phases (Figure 2.3). The evaporation and condensation process are always underway at the surface of liquid. In a sealed container, these processes are in equilibrium. The partial pressure of gaseous phase at this equilibrium state is called saturation vapour pressure, e_s . If the partial pressure e is bigger than e_s ($e > e_s$), the condensation process will overcome the evaporation. e_s as a function of temperature is given in the figure as a blue line between liquid and gaseous phase.

However, e_s is generally for a flat surface and the saturation vapour pressure for the curved surface, e_{sc} , is much larger (Kelvin Process or Curvature Process). The formation of droplet in a homogeneous gas is unlikely, as it requires $e_{sc} > 4e_s$ (i.e. relative humidity of 400 % for water). Therefore the droplet formation needs condensation nuclei which attracts molecules and effectively decreases e_{sc} . Dusts in air play the role of the condensation nuclei, and ions generated by high energy charged particles also do. For more reading concerning the droplet (cloud) formation, you might have a look into cloud physics, for example this site : <https://www.e-education.psu.edu/meteo300/>.

The cloud chamber in this experiment is called a "diffusion cloud chamber". We create a super-saturated vapour, where $e > e_s$, with ethanol by introducing a gradient of temperature. When a charged particles passes, orbital electrons of atoms in air are

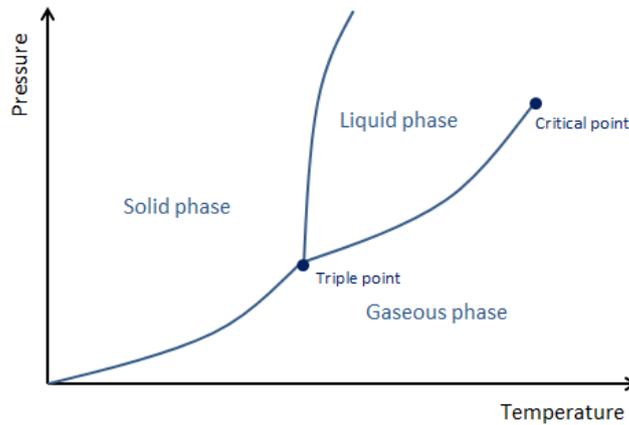


Figure 2.3: Phase diagram of a substance.

kicked out and positive ions remains. The positive ions attract molecules nearby and form droplets (Figure 2.4). The series of droplets shows the passage of particles like the vapour trail of airplane. Furthermore the number of droplets is a function of ionization energy loss by the particle, which differentiates alpha particles from high energy cosmic-ray muons.

The sensitive part of the chamber has a thickness of about 8 cm from the bottom. The trajectories can be seen clearly in this layer. While, any event above the sensitive layer might be seen burred. If you saw a big cloud like a mushroom, it is an alpha particle event above the sensitive layer.

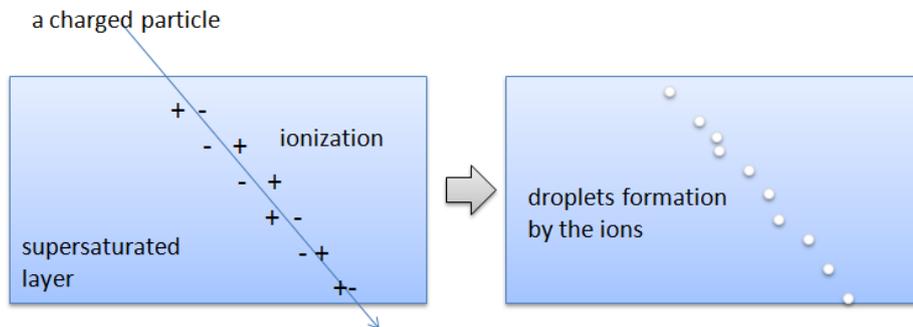


Figure 2.4: Working principle of cloud chamber.

Chapter 3

Experiments

3.1 Preparation

The experimental setup is shown in Figure 3.1.

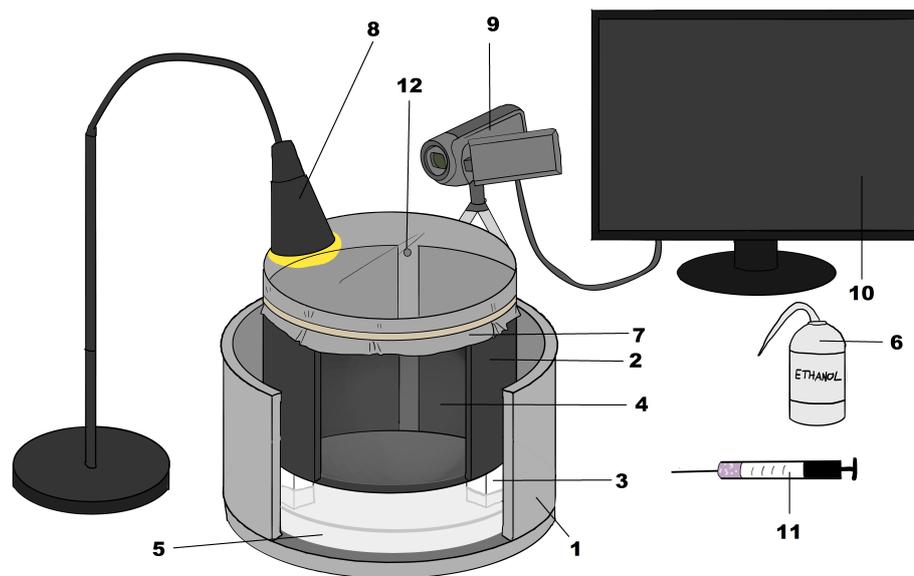


Figure 3.1: Setup of the experiment. **1** Liquid nitrogen buffer, **2** Black chamber, **3** Spacer, **4** Black paper, **5** Liquid nitrogen (N_2), **6** Ethanol (C_2H_5OH), **7** Plastic foil with rubber band, **8** Lamp, **9** Camcorder, **10** Monitor, **11** Syringe with Thorium (^{228}Th) and Radon (^{220}Rn), **12** Hole in the chamber. Figure by Hofmann & Kipfer 2019.

The procedure of preparation is following.

1. Put the plastic spacers in liquid nitrogen bath.
2. Put liquid nitrogen in the bath about 2 to 3 cm from bottom, or 1 cm below the top of teflon spacers.
3. Set the chamber on the spacers.

4. Soak the black paper in the ethanol bath in the stainless-steel container.
5. Put the black paper inside the chamber. Keep it wet (Splay ethanol if necessary). Do not cover the hole on the wall of the chamber.
6. Fill chamber with ethanol till about 3 mm height from bottom.
7. Close the chamber with the plastic wrap with the elastic band.
8. Set the light so that you can observe ethanol droplets.
9. Turn off the room light (One side of the room).
10. Wait for about 30 min for a stabilization.
11. Setup camcorder for observation.

After closing the chamber, you can see droplets of ethanol falling down to the bottom. Since the temperature at the top is high, the ethanol evaporates from the black paper. Then it is cooled down in the chamber and reached in a supersaturated state in the middle. The chamber is cooled down up to the height of the nitrogen bath. In the beginning the droplets are made due to the dusts in air. After the dusts in air go away, the droplet formation by ionization of particles will be dominant.

The light reflection by a droplet has a particular angle, which has maximum at 38 degree with respect to the light injection direction (similar discussion with rainbow. see Appendix B). Find an optimal lighting for you and the camera. See also the notes for the Sony camcorder below.

In case your chamber has a large amount of background (big clouds = alpha track above the supersaturation layer), replace the plastic wrap. This is because the plastic wrap may be negatively charged and absorbed polonium ions in air. The polonium atoms then decay emitting alpha. The background rate might change day by day, due to the radon accumulation in the laboratory (due to ventilation etc).

Notes for the Sony camcorder:

1. Recharge: The camcorder is rechargeable via the USB plug of camcorder. (Turn off the camera)
2. Manual focus: Push the button next to the objective lens to activate the manual focus. Rotate the ring to change focus.
3. Camera mode: The recommended camera setting is to be 50p, gray-scale.
4. Files: The high resolution movies are stored in "H:\AVCHD\BDMV\STREAM".
5. Delete file: Delete files in camcorder after the experiment to free disk space.

3.2 Observation of particle trajectories in cloud chamber

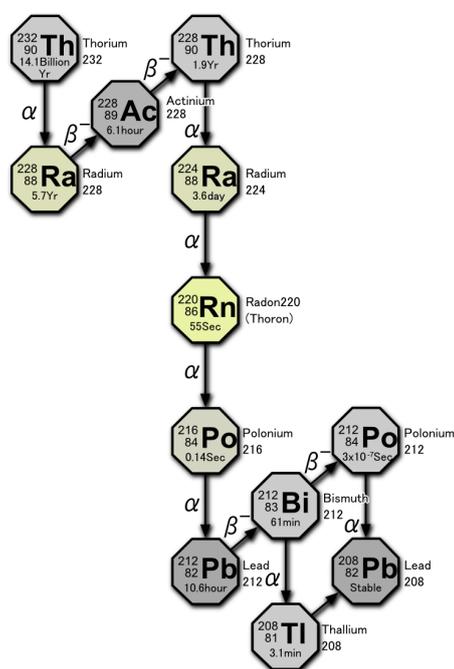
Once the setup is completed and the chamber is operational, you will see many phenomena in the chamber. You would see cosmic-ray muons, β -ray electrons, Compton scattering, alpha decays (Level 1). You may encounter some events like Rutherford scattering, electron-positron pair production by γ rays, electron-electron scattering, δ ray emission (Level 2), and further rare events like electromagnetic shower from high energy cosmic electrons, muon bundle from very high energy primary protons and others (Level 3).

ToDo:

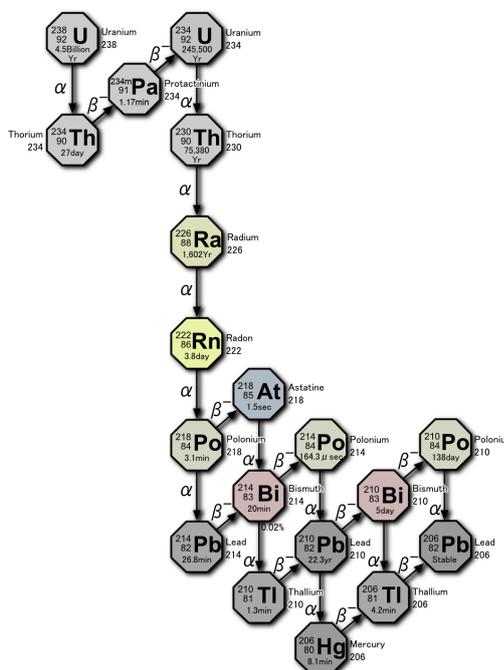
- Sketch what you saw and interpret them (several of them). You could also record a video and take pictures from it.
- Select a few trajectories and measure the angular difference before and after 5 cm of air. Calculate momenta by the multiple Coulomb scattering (for simplicity put $\beta = 1$).

3.3 Measurement of lifetime of radon

In nuclear decays, most of radioisotopes do not decay into a stable state directly, but more likely decay in series. Thorium series and Uranium series are one of the most common natural radioactive decay chains, which is shown in figures¹.



Thorium chain



Uranium chain

The radon in the intermediate step of chains is a gas. Therefore the radon created from series of decay can float in air and sucked in human lung, then decay emitting an alpha particle, followed by other chain decays. This is the biggest dose to human body from the environmental radiation. In this experiment, you measure the lifetime of radon in the thorium chain.

A weak ^{232}Th source is enclosed in a syringe. Consequently the syringe is filled with ^{220}Rn . Inject the gas in the syringe (1-2 cm^3) into the cloud chamber from a hole on the side wall. The supersaturation will be once broken, but it will recover in about 1 minute. Tips: Inject the gas to the bottom of the chamber. Otherwise the warm gas could stay at the top of chamber where is not sensitive to the particle. Take a few videos and analyse with PC.

¹Pictures from Wikipedia.

ToDo: Measure the lifetime of ^{220}Rn .

- Before the measurement, count background alpha particles for a few minutes and calculate the background alpha rate per 10 second (N_{BG}).
- Inject the gas (1-2 cm³), count the number of alpha particle every 10 sec and make a histogram. Use any software tools which you are familiar with. A sample code in ROOT (an analysis platform provided by CERN) is available in the Appendix.
- By fitting the histogram with a function (exponential + background), find the lifetime of ^{220}Rn . Note that a counting in a given period of time follows the Poisson distribution. Thus, the statistical uncertainty on a data point (N counts in 10 sec) should be $\sigma = \sqrt{N}$ (with an exception of $\sigma = 1$ if $N = 0$).

Postface

This experiment was firstly established in 2015 as a replacement of the former beta spectroscopy experiment. Since then, year by year improvements were made. The cloud chamber gives a visual evidence of the existence of particles and students can observe a number of particle physics phenomena. More importantly, the appearance of the trajectories is a beautiful art. The cloud formation by particles itself is also an interesting subject which has a deep connection with the earth climate and so with the history of life on the earth. There has been an idea to install a round coil to apply a magnetic field, which is still to be done in future. An automated track recognition/counting with a sophisticated image processing with GPUs was once considered, however, we concluded that we should not do because we do not want to make the experiment a black box to the students. It is more interesting to see the phenomena by eyes, and the process to interpret them is the most important. Yet, a synchronized image taking with two or more cameras would greatly help interpreting observations with 3D information. I hope future tutors further improve this experiment. I specially thank Nicolai Wenger for his major input to the text.

Bern 25.11.2020, PD Dr. Akitaka Ariga (akitaka.ariga@cern.ch).

Appendix A

Sample code in ROOT

For those who know ROOT and prefer to use it, the following sample code could be of help. Prepare a proper text file, copy and paste this code into "plot.C", and execute the macro.

```
void plot(){  
    /// Read data ///  
    // Read "data.txt" which has a format of  
    // time count err_of_time err_of_count  
    // such as,  
    // 5 17 5 4.1  
    // 15 15 5 3.9  
    // 25 13 5 3.6  
    // 35 14 5 3.7  
    // 45 14 5 3.7  
    // ...  
  
    TGraphErrors *gr = new TGraphErrors ("data.txt");  
    gr->GetXaxis()->SetTitle("sec");  
    gr->GetYaxis()->SetTitle("Counts / 10sec");  
    gr->SetTitle("Alpha track counts");  
  
    /// Fitting ///  
  
    // Specify the fitting region to fit (t0,t1).  
    // t0 should be the time when the chamber recovered an equilibrium.  
    double t0 = 80;  
    double t1 = 230;  
  
    // Measured background  
    double Nbg = 1.5;  
  
    // Define your fit function. A sum of an exponential function and background for example.  
    TF1 *fitfunc = new TF1("fitfunc",Form("[0]*exp(-x/[1])+%f",Nbg),t0,t1);  
    fitfunc->SetParLimits(1,10,200); // limit the parameter range for [1] from 10 to 200.  
    gr->Fit(fitfunc,""," ",t0,t1);  
  
    // Get the fitting results.  
    // ROOT fitting takes the errors of data points correctly.  
    double lifetime = fitfunc->GetParameter(1);  
    double lifetimeerror = fitfunc->GetParError(1);  
    printf("Lifetime is %4.1lf +- %4.1lf sec\n", lifetime, lifetimeerror);  
  
    /// Draw graph ///  
  
    gr->Draw("ap");  
  
    /// Print a figure ///  
    c1->Print("Rn220.lifetime.png");  
}
```

plot.C

Appendix B

Reflection angle at droplets

Light reflection at droplets has a particular angle. This problem has been well-known for a long time and was first solved by René Descartes, calculating the angle at which we see a rainbow. Let's look at Figure B.1-left. We want to calculate the angle $2\varphi_{max}$ which maximize the reflection.

From Snell's law we get

$$\frac{\sin(2\beta - \varphi)}{n_2} = \frac{\sin\beta}{n_1}, \quad (\text{B.1})$$

with n_1 and n_2 the refractive indices of air and the droplet liquid, respectively. Solving for φ , we get

$$\varphi = 2\beta - \arcsin\left(\frac{n_2}{n_1} \sin\beta\right). \quad (\text{B.2})$$

It can be shown that the intensity has its maximum where φ is maximum with respect to β , mathematically:

$$\frac{d\varphi}{d\beta} = 2 - \frac{\frac{n_2}{n_1} \cos\beta}{\sqrt{1 - \left(\frac{n_2}{n_1} \sin\beta\right)^2}} = 0. \quad (\text{B.3})$$

Inserting the refractive indices for air ($n_1 = 1$) and ethanol ($n_2 = 1.361$ @ 589.29 nm) we get $\beta_{max} = 38.4^\circ$ and $2\varphi_{max} = 38.2^\circ$. Figure B.1-right illustrates the above statement.

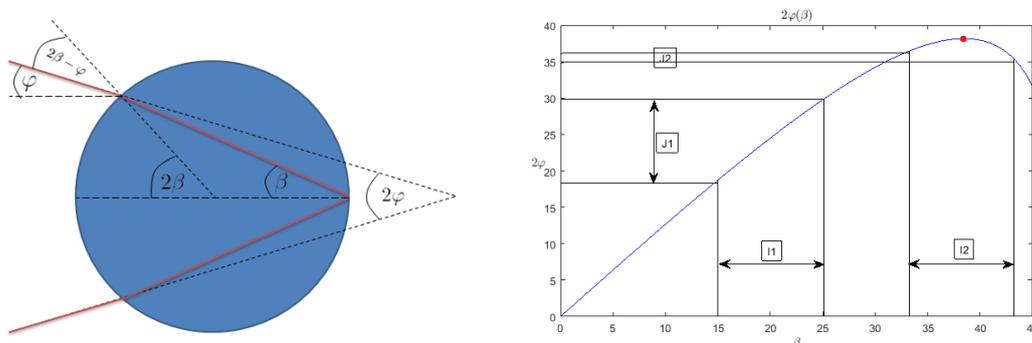


Figure B.1: Left: Schematic of the optics in a raindrop, completed with derived angles. Right: Figure used to illustrate that the intensity has its maximum where φ is maximum with respect to β . $J_2 < J_1$ for any interval I_2 closer to the maximum (red dot) than I_1 .