Cloud Chamber Prelab

May 23th, Partner: Jiabao. Xu.

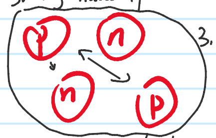
cloud chamber: α radioactive decay & magnetic spectroscopy

A. alpha decay

Strong Nuclei Force vs. Electromagnetic Force

liquid drop model $\;{}^{210}_{84}Po$ $\;A=210$ number of nucleons (protons & neutrons), $Z=84$ number of charges

1. strong nuclei force attraction



3. Surface tension

2. electric repulsion

Po element ${}^{210}Po$ nuclide & isotope

even the mass of proton and neutron are const. the mass of nuclei is not the sum of all nucleons

Since $E=mc^2$ the binding energy in nuclei show us extra mass

1. negative binding energy $\Rightarrow -A \times 15.8$ MeV
2. positive E&M repulsion energy $\Rightarrow Z^2/A^{1/3} \times 0.714$ MeV
3. positive surface tension $\Rightarrow A^{2/3} \times 18.3$ MeV
4. other quantum mechanical terms

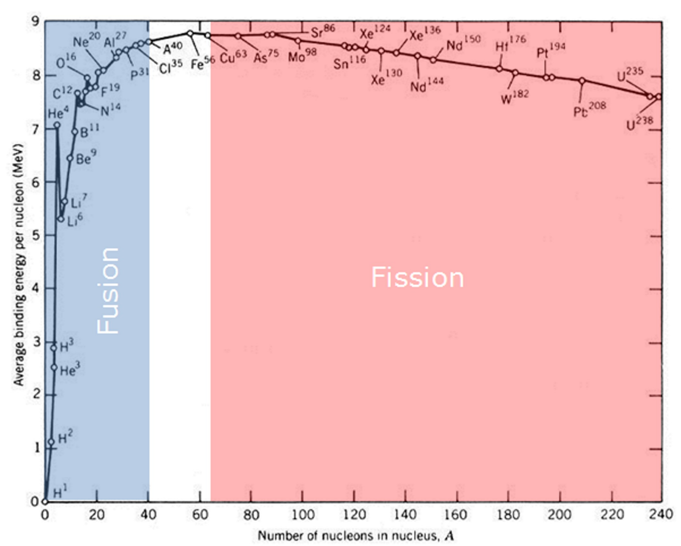
when E&M repulsion wins nuclei binding, fission and alpha decay happens

1) Fission

roughly even break up ${}^{252}Cf \rightarrow {}^{104}Zr + {}^{148}Ce$

2) alpha decay

emission ${}^4He$ nucleus



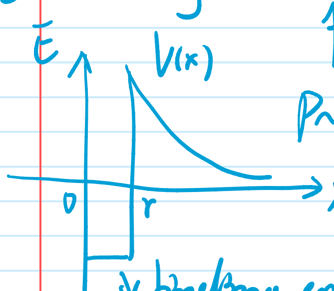
		half-life
${}^{210}Pb \rightarrow {}^{210}Bi + e^- + \bar{\nu}_e$		22-yr
${}^{210}Be \rightarrow {}^{210}Po + e^- + \bar{\nu}_e$		5-day
${}^{210}Po \rightarrow {}^{206}Pb + {}^4He$		138-day

$\Rightarrow$ 5.407 MeV of kinetic energy

2 beta decay - 1 alpha decay in equilibrium

B. Tunneling.

$$p(x) = \sqrt{2m(E-V)}$$

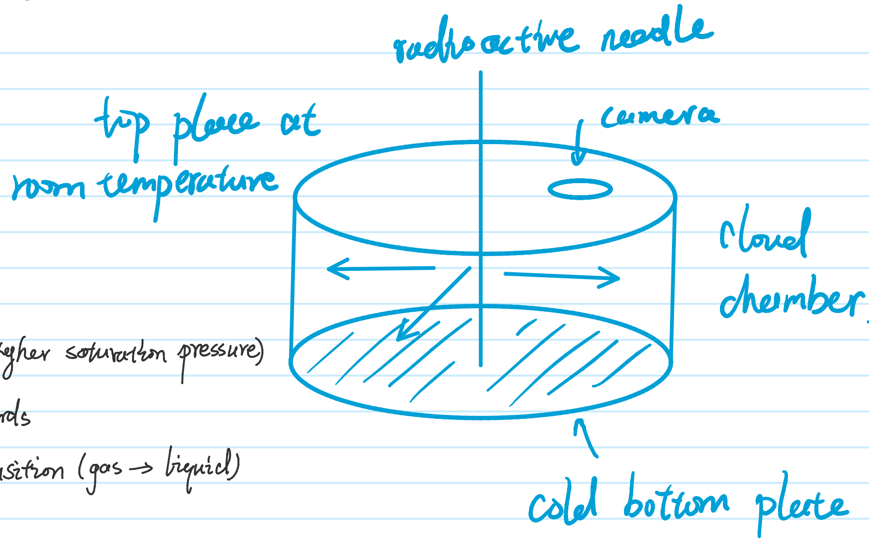


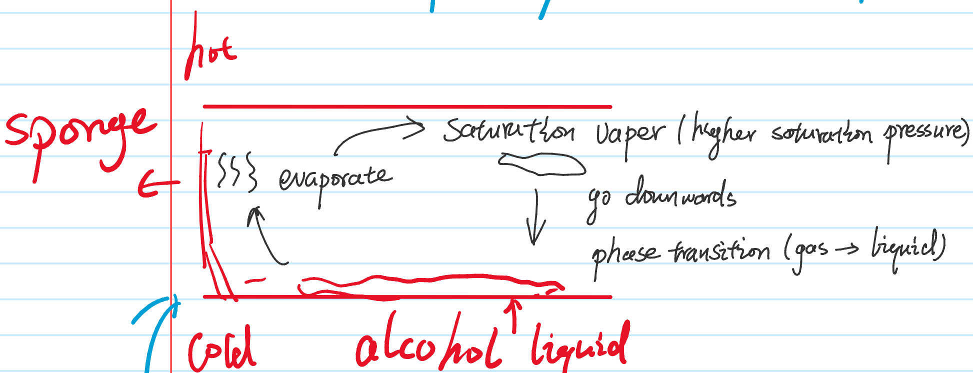
$$P \sim e^{-2\gamma}, \quad \gamma = \frac{1}{\hbar}\int_0^r |p(x)|\,dx$$

binding energy in nuclei

Cloud Chamber Prelab

C. The cloud chamber — detector of decay





use clear and deionized air to achieve super saturation

⇓

far-above-equilibrium vapor content

⇓

phase transition occurs easily in presense of free ions ("nucleation")

⇓

emitted α/β particle cause sudden droplets nucleation ("trajectory")

D. passage of particle through matter.

Bethe formula $-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2}\cdot\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right)-\beta^2\right]$

$\beta=\frac{v}{c}$, n: electron number density, excitation potential I

for high energy particle

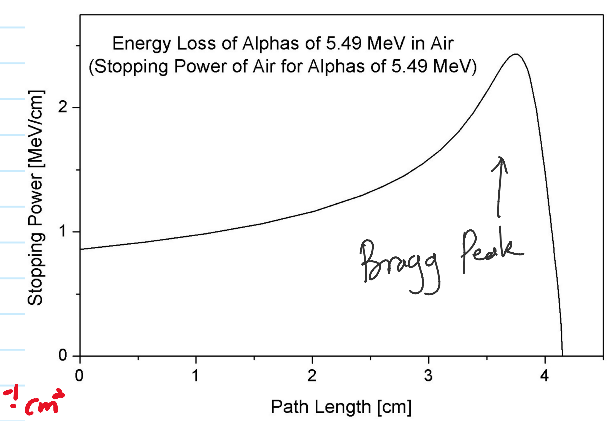
collisions ∝ density of gas ρ

a) ionize nearby molecules

b) give excited electron some kinetic energy

$\boxed{\left\langle \frac{dE}{dx} \right\rangle / \rho}$ $MeV\cdot g^{-1}\cdot cm^2$

↑ stopping power.



n is similar in difference materials $n \simeq 3\times10^{23}$

difference of CF_4 & Air is mainly ρ, medium density

$\beta \ll 1$, $E \simeq \frac{1}{2}mv^2$, $dE = mv\,dv$

$$-\frac{dE}{dx} = \frac{4\pi n z}{m_e v^2}\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \ln\left(\frac{2m_e v^2}{I}\right)$$

energy loss increase when v decrease

slow particle is more effective on ionizing them faster one

Differential Equation

Day 1 Lab Note

May 29th, 2:00 PM   Partner: Jiabao Xu.

Prepare cloud chamber set up

1. pour in prepared alcohol, (20cc, cover the bottom of chamber)
2. connect the table and tube of the refrigeration device, set the temperature of 10°C, wait for the chamber to cool down (~20 mins)
3. take out the radioactive lead needle, put it into the central hole on the chamber.
4. connect the needle with a high-voltage plug to remove free ions in the chamber
5. wait for the liquid in the chamber to cool down and evaporate

problem: Can't see any trajectories at first

in fact, it will take ~20 mins for the alcohol gas to reach a supersaturation state

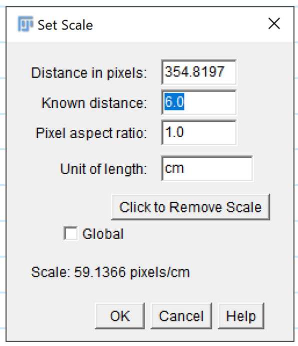
6. install the camera on the top plate of the chamber.
7. open ImageJ and use Webcam module to observe what happened in the chamber.
8. capture videos after "white trajectories" of particles begin to appear in a stable frequency

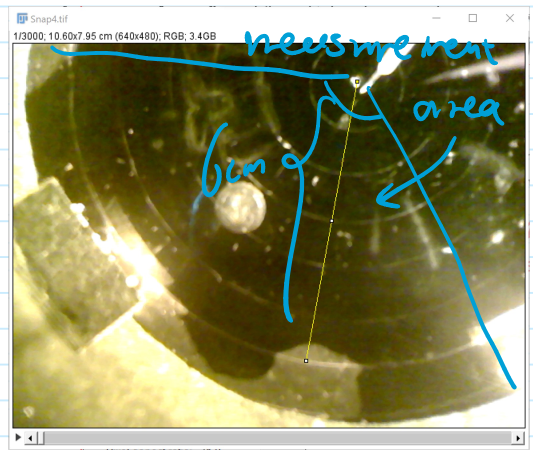
Safety: don't touch the radioactive part of the lead needle.

tips: wear gloves and adjust the plastic film on the bottom of the chamber to remove possible bubbles and reflective beads could achieve a better background with less noise in the video.

Process video and extract data with ImageJ.

1. Set scale for imageJ
2. Mark particle trajectories on screen and measure the length of mark line.
3. Repeat the measuring and count every trajectory in specific area





The difference between two kinds of decay is obvious

α: ${}^{4}_{2}He$ 3~3.5 cm   significant path, higher frequency

β: e^- 1.5~2.2 cm   weak trajectory, hard to observe. with much lower frequency

video format:
- resolution: 640×480
- frame rate: 10
- 3000 frams in total

systematic error:

pixel length 6cm/354.8 pix $\approx$ $\boxed{0.0169 \text{ cm/pix}}$

error caused by visual point marking ~ 5-6 pixels. $\approx$ 0.101 cm (δL)

(cm)	α decay	β decay
mean	3.244	
sdom	0.504	
uncertainty	0.102	

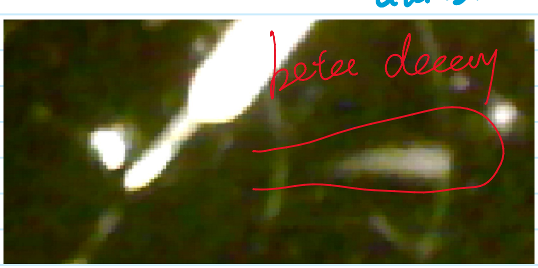
* β decay is less seen. ← problem

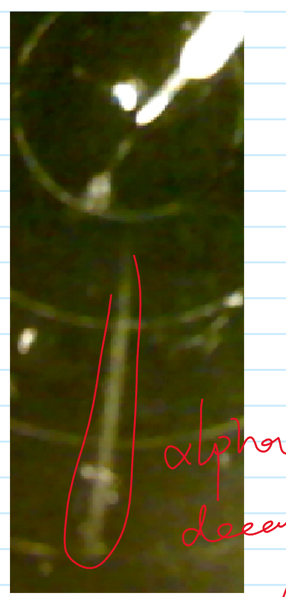
1. weak energy). 2. maybe absorped by ions, or atoms.

Results

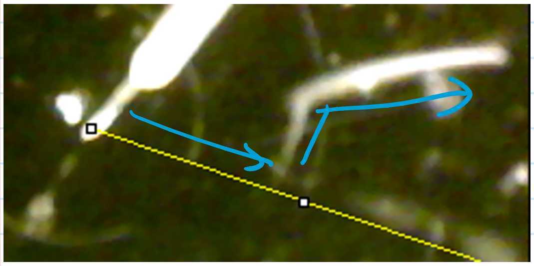
File Edit Font Results

	Area	Mean	Min	Max	Angle	Ler
1	0.083	81.225	20.891	252.854	-136.891	4.9
2	0.091	45.593	21.977	141.607	-103.360	5.4
3	0.043	29.146	13.649	70.701	10.871	2.5
4	0.054	61.056	24.016	143.920	-62.911	3.2
5	0.036	31.252	22.829	53.426	73.811	2.1



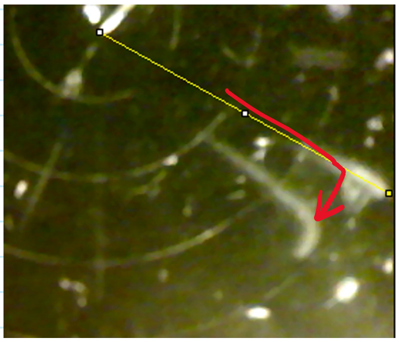


Day 1 Lab Note

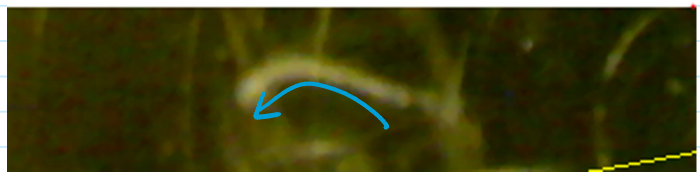


multiple scattering - Rutherford scattering

the events seems like emit from somewhere in the air instead from the radioactive needle, the reason is that the particle has collided with nuclei thus changed the direction

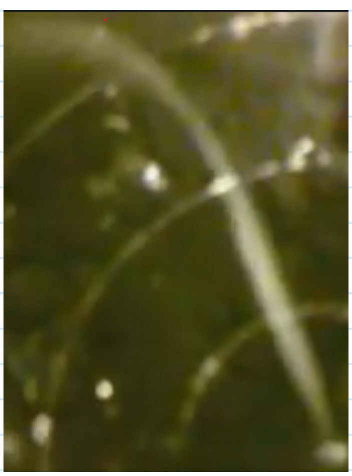


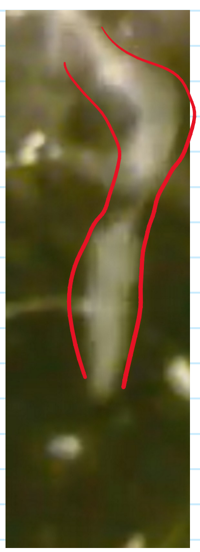
⇒ Bethe-Bloch energy loss is a random process with statistical nature, it's not smooth.



Observation with gamma ray on

1. Open the gamma ray source, put it near the cloud chamber.
2. Record what happened with gamma ray emitter on





the trajectory with gamma ray on is really amazing!

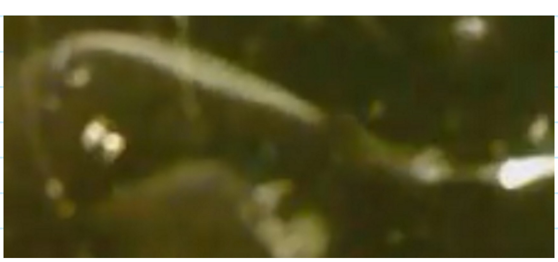
it's no more straight lines but wiggled like like ribbons fluttering in wind!

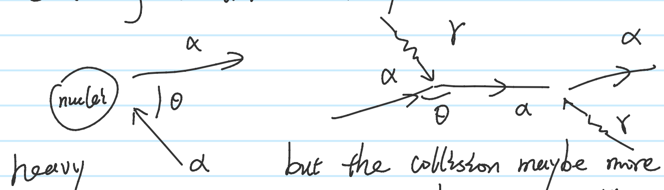
possible reason:

the probability that emitted α particles collide with high energy gamma photons is higher than colliding with nucleis of air molecules

but since the energy of photon is ~ 0.6617 MeV for Cs-137 γ-ray source and $E_\alpha \simeq 5.4$ MeV

Thus, the collisions between γ & α will not significantly change the momentum and direction of α. particles and there is no sharp angle scattering as collided with heavy nuclei





but the collision maybe more frequent, thus α seems like to wiggling constantly changing direction.

Day 2 Lab Note

May 29 th   Partner: Jinbao Xu.

use another kind of gas as medium (CF_4)

1. open the CF_4 cylinder. adjust the gas pressure
2. connect the gas tube the cloud chamber.
3. wait for 1~2 mins until the CF_4 gas fullfill the cloud chamber
4. repeat the steps in day 1, reassumbly the cloud chamber and install the web cam to start observation
5. wait for the alcohol to evaporate and reach supersaturated state.
6. capture videos and save them for latter analysis.

Properties	
Chemical formula	CF_4
Molar mass	88.0043 g/mol
Appearance	Colorless gas
Odor	odorless
Density	3.72 g/l, gas (15 °C)
Melting point	−183.6 °C (−298.5 °F; 89.5 K)
Boiling point	−127.8 °C (−198.0 °F; 145.3 K)
Solubility in water	0.005%$_V$ at 20 °C 0.0038%$_V$ at 25 °C
Solubility	soluble in benzene, chloroform
Vapor pressure	3.65 MPa at 15 °C 106.5 kPa at −127 °C

according to Bethe formula:

$$-\frac{dE}{dx} = \frac{4\pi n z^2}{m_e v^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e v^2}{I}\right)\right].$$

stopping power $\frac{dE}{dx}$ between different gas equals $\frac{n_1}{n_2}$. n is electron density

$$* \quad n = \frac{N_A\cdot Z\cdot\rho}{A\cdot M_u}$$

A: relative atomic mass
M_u: molar mass const.
Z: charge number.
ρ: gas density
N_A: Avodagro Constant

For air: compound of O_2 & N_2.

$$n_{air} = n_{O_2} + n_{N_2} = \frac{N_A}{M_u}\left(\frac{\overset{16}{Z_{O_2}}\rho_{O_2}}{\underset{31.99}{A_{O_2}}} + \frac{\overset{14}{Z_{N_2}}\rho_{N_2}}{\underset{28.014}{A_{N_2}}}\right)$$

$$n_{CF_4} = \frac{N_A}{M_u}\frac{Z_{CF_4}\rho_{CF_4}}{A_{CF_4}}$$

```
In[•]:= nair =
    NA / Mu
     (nitrogen CHEMICAL [density] * 14 / 28.014 + oxygen ELEMENT [density] * 16 / 31.998);
   nCF4 = NA / Mu Quantity[3.72, "g/L"] * 42 / 88.0043;

In[•]:= nair / nCF4
Out[•]= 0.754622
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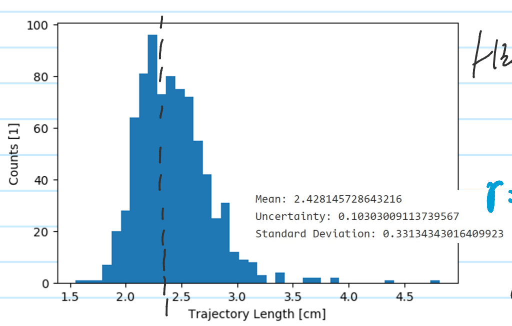
$$\boxed{\frac{n_{air}}{n_{CF_4}} \simeq 0.75.}$$



Histogram of measured trajectory length in CF_4

$$r = \frac{\Delta L_{CF_4}}{\Delta L_{air}} = \frac{2.428}{3.244} \simeq 0.748$$

$$\delta r / r = \sqrt{\left(\frac{\delta_{CF_4}}{\Delta L_{CF_4}}\right)^2 + \left(\frac{\delta_{air}}{\Delta L_{air}}\right)^2} \Rightarrow \delta r = 0.039$$

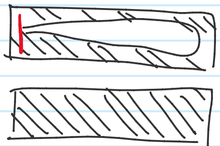
Day 3 Lab Note

find the relation between stopping power and droplet density

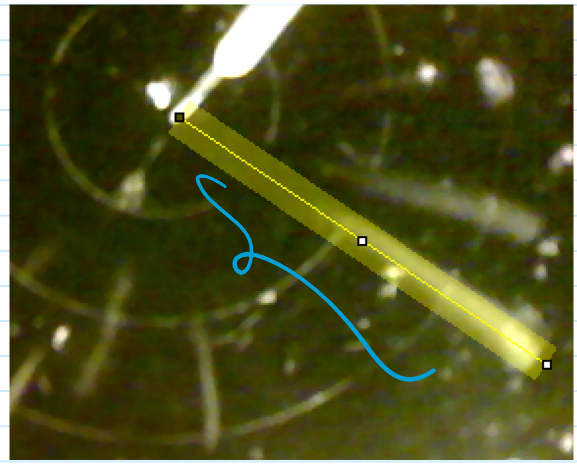
1. measure droplet density

use line drawing tool to cover trajectory

the width of line should be wider than width of the white path.

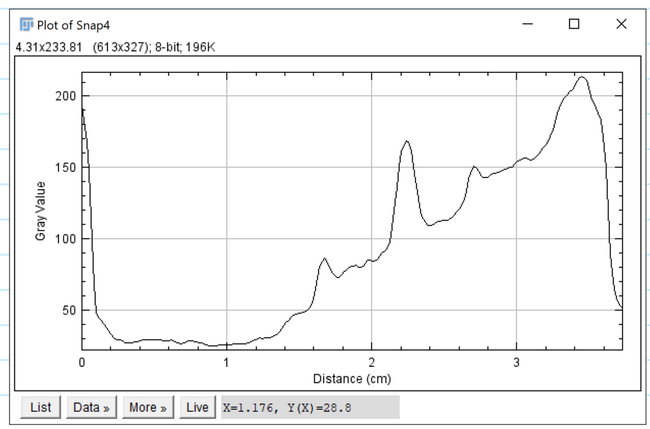


since the white droplets caused by nucleation is more brighter than the background, and the droplet density is proportional to the width of the trajectory, thus the brightness (gray value) can be used as a indicator of droplet density.



2. calculated the brightness average over the line, substract the background to eliminate the noise.

3. clustering lines into bins with different lengths

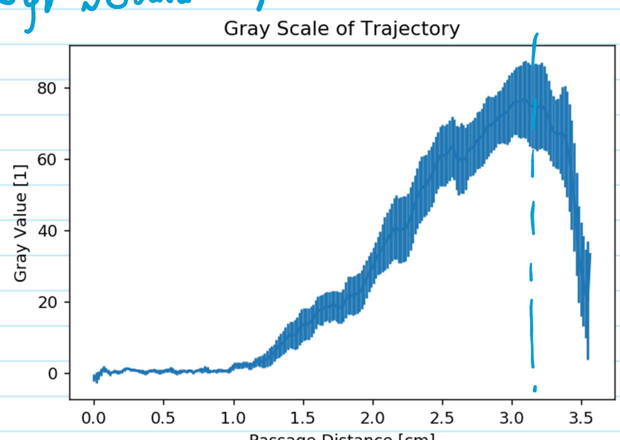


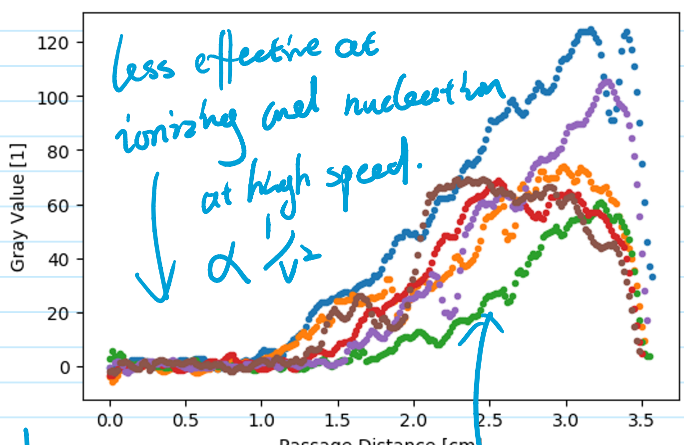
droplet density ∝ gray value

stopping power - length is shown

4. aggregate the result

$\delta_{gr} = \sqrt{\delta_{data}^2 + \delta_{sysm}^2}$





less effective at ionizing and nucleation at high speed.

$\propto \frac{1}{v^2}$

Bragg Peak.

particles lose more energy and cause more droplets when slowing down

As discussed in Pre-lab the droplet density show same shape as $-\frac{dE}{dx}$.

Day 4 Lab Note

ASTAR: Stopping Powers and Range Tables for Alpha Particles

AIR (dry, near sea level)

tricky

Kinetic Energy MeV	Total Stp. Pow. MeV cm2/g	CSDA Range g/cm2	Projected Range g/cm2
1.000E-03	2.215E+02	5.377E-06	2.025E-06
1.500E-03	2.342E+02	7.562E-06	3.034E-06
2.000E-03	2.444E+02	9.651E-06	4.073E-06
2.500E-03	2.536E+02	1.166E-05	5.129E-06
3.000E-03	2.622E+02	1.360E-05	6.198E-06
4.000E-03	2.784E+02	1.730E-05	8.355E-06
5.000E-03	2.937E+02	2.079E-05	1.052E-05
6.000E-03	3.084E+02	2.411E-05	1.267E-05
7.000E-03	3.225E+02	2.728E-05	1.481E-05
8.000E-03	3.362E+02	3.032E-05	1.692E-05
9.000E-03	3.495E+02	3.324E-05	1.900E-05
1.000E-02	3.625E+02	3.605E-05	2.106E-05
1.250E-02	3.933E+02	4.266E-05	2.606E-05
1.500E-02	4.225E+02	4.879E-05	3.087E-05
1.750E-02	4.501E+02	5.452E-05	3.550E-05
2.000E-02	4.765E+02	5.992E-05	3.996E-05
2.250E-02	5.018E+02	6.503E-05	4.427E-05
2.500E-02	5.260E+02	6.989E-05	4.843E-05

Determine decay energy $\bar{E}$.

1. NIST Database - ASTAR

https://physics.nist.gov/PhysRefData/Star/Text/ASTAR.html

projected length $\boxed{X = \int \rho\, dx}$ ρ: medium density

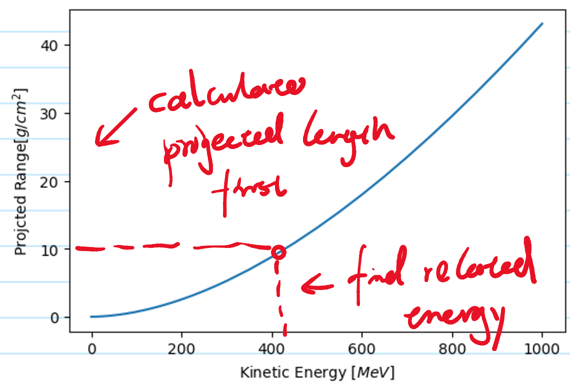
Stopping power $\langle \frac{dE}{dx} \rangle$

CSDA: continuous slow down approximation.

const $\left(\frac{dE}{dx}\right)$. density of ethanol vapor $\sim 1.59 \times 10^{-3}$ g/cm³

$X = \rho \cdot L$, fitting the curve

$\simeq 3.24 \times 1.59 \times 10^{-3} \simeq 5.151 \times 10^{-3}$ g/cm².



ignore the error of ρ. $\Rightarrow \delta X = \rho \cdot \delta L$.

curve fitting

Give estimation of decay energy by fitting. ← kinetic $\bar{E} = f(X)$

$E_\alpha = (5.5 \pm 0.1)$ MeV. Standard Value 5.407

* error about 1σ

Source of error

1. Use the data of air to approximate super saturated ethanol vaper.

2. use CSDA model, a kind of approximation.

3. the density of the gas in the chamber is not accurate. Since the evaporation of alcohol will absorb heat, we don't actually know the temperature, pressure or density of gas in the chamber.

4. the energy loss process is essentially statistical, there must be some random fluctuation

Advice and vision:

1. the chamber should be cleaned and the light should be a little brighter to reduce the background noise in video.
2. could use some device to measure the density of the gas so that we can use a CSDA model to roughly estimate the decay energy of α and β
3. once the background of the cloud chamber is cleaned, some image recognition program are easier to applied to automate the detection and measurement of the trajectory. It will be much easier to acquire data if we have some software.