Experiment 10: Absorption of β and γ Rays

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Office Hour: Mondays, 5:30PM-6:30PM @ Pupin 1216

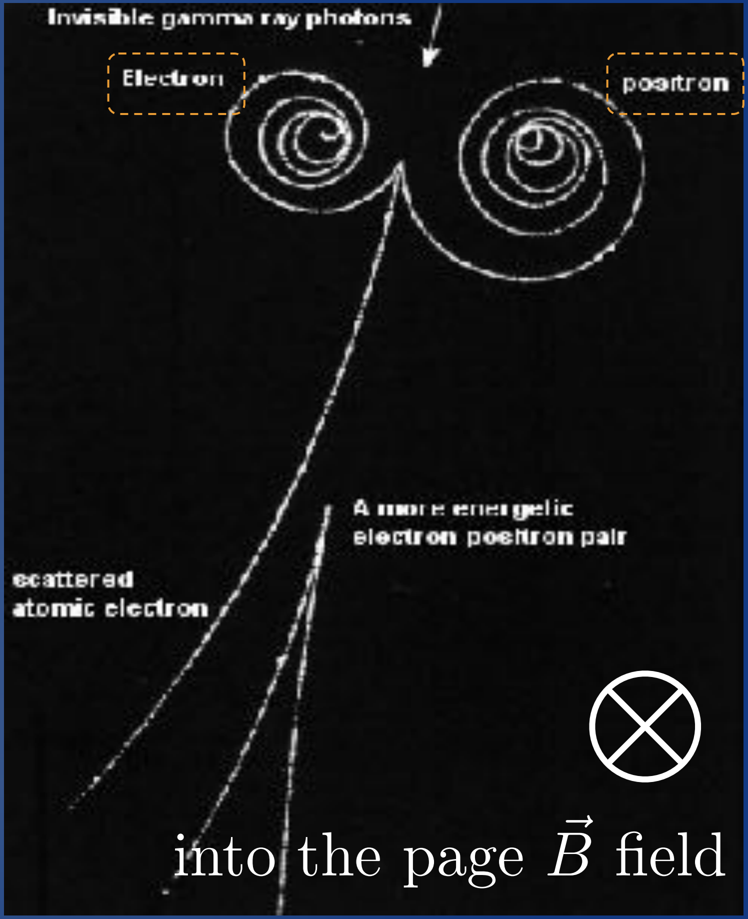
INTRO TO EXPERIMENTAL PHYS-LAB
1493/1494/2699

Introduction

- ***Background:***
  - Radioactivity and nuclear decay (α, β, γ)
- ***The experiment:***
  - Detecting β rays: the Geiger-Müller counter
  - Finding the plateau region (optimal voltage)
- ***Counting statistics:***
  - Poisson statistics
- ***Measurements:***
  - Estimating background
  - Determining β-rays *range* and *energy*
  - Determining γ-rays *absorption coefficient* and *energy*

Radioactivity

- Radioactivity is a purely quantum mechanical phenomenon
- **Radioactivity** = the tendency for nuclei to ***spontaneously*** split apart into several lower mass pieces
- By 1900's it was known that ***unstable*** particles can emit three types of particles:
  - α-particles: +2 electric charge, ~ 4 proton masses
  - β-particles: ±1 electric charge, 1/1800 mass of the proton
  - γ-rays: no electric charge, very energetic

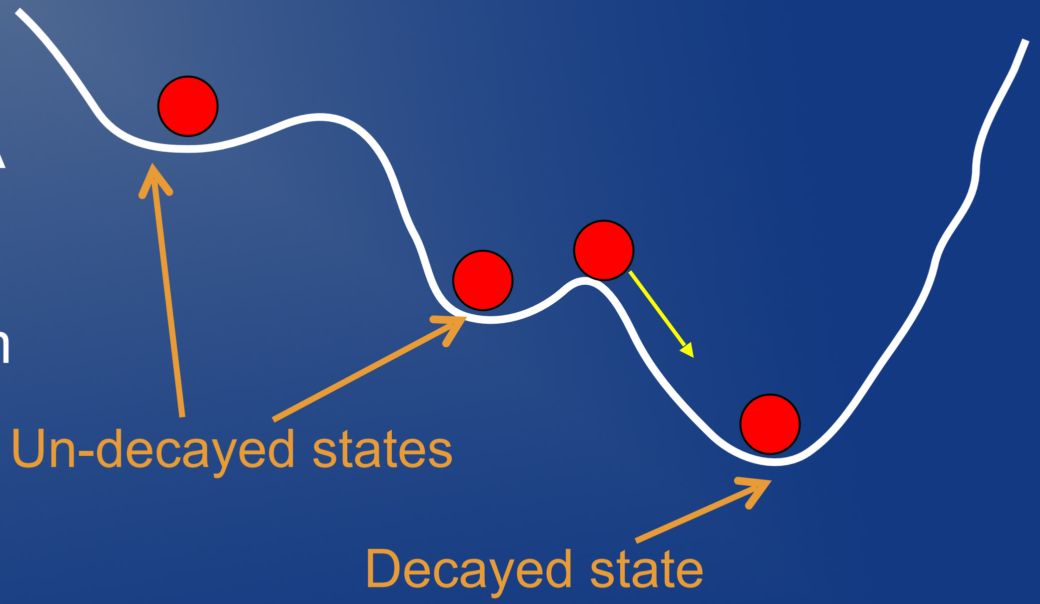


Recall that by placing the particles in magnetic fields, one can tell the sign of charge of particle.

Why does radioactive decay occur?

- ***Simplest picture:***
  - Like a ball rolling down the hill, an atom will go radioactive decay to *minimize its energy*

- But more complex…
  - There are many ***local minima.*** A nucleus might "sit" in a local minimum for quite some time before tunneling (due to quantum effects) to the global minimum of its energy



Un-decayed states

Decayed state

A new kind of interaction

- *How can you stick two protons together if they repel because of Coulomb force?*
- *How can a proton and a neutron stick together if only one of them is electrically charged?*
- *Why isn't the electron involved in the dynamics of a nucleus?*
- ***What makes nuclei stick together then?***

A new kind of interaction

- *How can you stick two protons together if they repel because of Coulomb force?*
  - *New force needs to be **attractive and stronger than Coulomb***
- *How can a proton and a neutron stick together if only one of them is electrically charged?*
  - *New force is **independent of electric charge***
- *Why isn't the electron involved in the dynamics of a nucleus?*
  - *New force is **short range** ~ size of the nucleus ~ 10^{-15} m*
- ***What makes nuclei stick together then?***

A new kind of interaction

- *How can you stick two protons together if they repel because of Coulomb force?*
  - *New force needs to be **attractive***
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  - *New force is **independent of electric charge***
- *Why isn't the electron involved in the dynamics of a nucleus?*
  - *New force is **short range** ~ size of the nucleus ~ 10^{-15} m*
- ***What makes nuclei stick together then?***
  - ***The Strong Nuclear Force***

Minimizing the potential: *α* decay

- Inside a nucleus there is a competition between the *repulsive electric force* (protons are likely charged) and the *attractive strong force*
- For light nuclei the strong interaction dominates, and the attractive force causes individual protons and neutrons to *bind*.
  - **Nuclear fusion:** *i.e.* 4H $\longrightarrow$ He + other stuff
  - Fusion occurs at high temperatures and densities, *i.e.* core of star
- For large nuclei with many protons, electromagnetic repulsion is large and can overcome the attractive strong force
  - **Nuclear fission:** nucleus fragments into smaller nuclei
  - ***Alpha decay:*** nucleus decay and ejects an He nucleus

Alpha decay (α)

- **Isotopes:**

$$\boxed{{}^{A}_{Z}X}$$

X = element
  (*e.g.* Pu, Au, C, etc..)

A = # neutrons + protons

Z = # of protons (atomic number)

- **Alpha particle:** It is nothing more than a bare Helium nucleus (2 protons + 2 neutrons):

$$\alpha = {}^{4}_{2}He$$

- **Example:** $${}^{240}_{94}Pu \rightarrow {}^{236}_{92}U + \alpha$$
- *Note that:*
  - (1) the number of nucleons is always conserved (*A=240* before and *A=236+4* after)
  - (2) charge is always conserved (*Z=94* before and *Z=92+2* after)

Minimizing the potential: *β* decay

- Special relativity tells us that mass is equivalent to energy:

$$E = mc^2$$

  - Can think of mass as type of potential energy. The nucleus will try to minimize it

- The masses of the proton and of the neutron are:

$$M_{\text{neutron}} = 939.56\ \text{MeV}/\text{c}^2$$

$$M_{\text{proton}} = 938.27\ \text{MeV}/\text{c}^2$$

- A neutron will minimize its energy by *decaying into a proton*, which has lower mass!

- Is it enough? Are we satisfying all the conservation laws?

$$n \longrightarrow p + ?$$

Minimizing the potential: *β* decay

$$n \longrightarrow p + ?$$

- *What conservation laws are needed to balance this reactions?*

- ***Charge conservation:*** *Q* = *0* on left and *Q* = +*1* on right
  - Conclusion: Need a ***negatively*** charged particle on right
- ***Energy conservation:*** $\Delta E = m_p c^2 - m_n c^2 = -1.29 \text{ MeV}$
  - Must be a light, charged particle.
- The best candidate to fulfill both requirements is clearly the electron!

$$n \longrightarrow p + e^- + ?$$

Minimizing the potential: *β* decay

- Is this what is observed in nature? $n \longrightarrow p + e^-$
- ***No!*** Experiments showed that only two particles in the final state are not enough to explain the data
- ***The missing brick was the neutrino / anti-neutrino:***

$$\boxed{n \longrightarrow p + e^- + \bar{\nu}_e}$$

- Today we know that neutrinos are required in β-decays to conserve the total *lepton number (L)*:
  - *L* = *+1* for electrons and neutrinos
  - *L* = *-1* for positrons and anti-neutrinos.
- Neutrinos are effectively massless and very weakly interacting.

Minimizing the potential: *β* decay

- For any given atomic mass (A), there is an "optimal" ratio of protons to neutrons:
    - About 1n:1p for light elements (*e.g.* C-12 has 6p, 6n)
    - About 3n:2p for heavier elements (*e.g.* U-238 has 92p, 146n)

- Too many neutrons ⟶ they will tend to decay into protons until the optimal ratio is achieved

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

- Too many protons ⟶ they will tend to decay into neutron until the optimal ratio is achieved

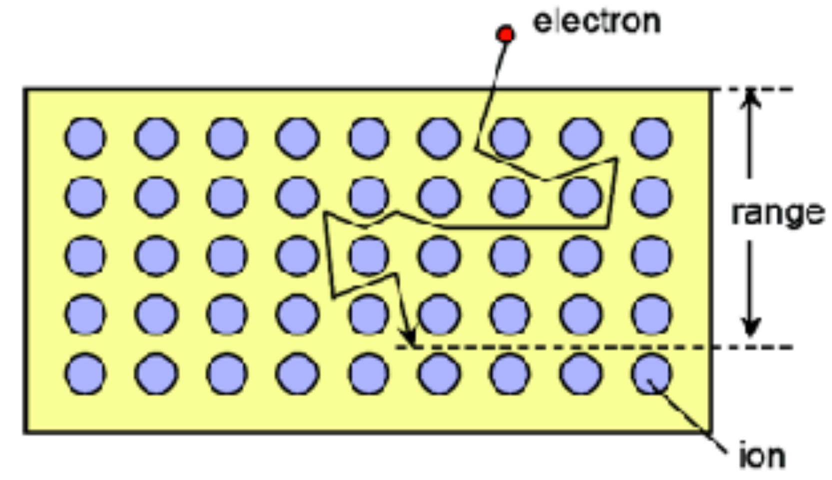
$$p \longrightarrow n + e^+ + \nu_e$$

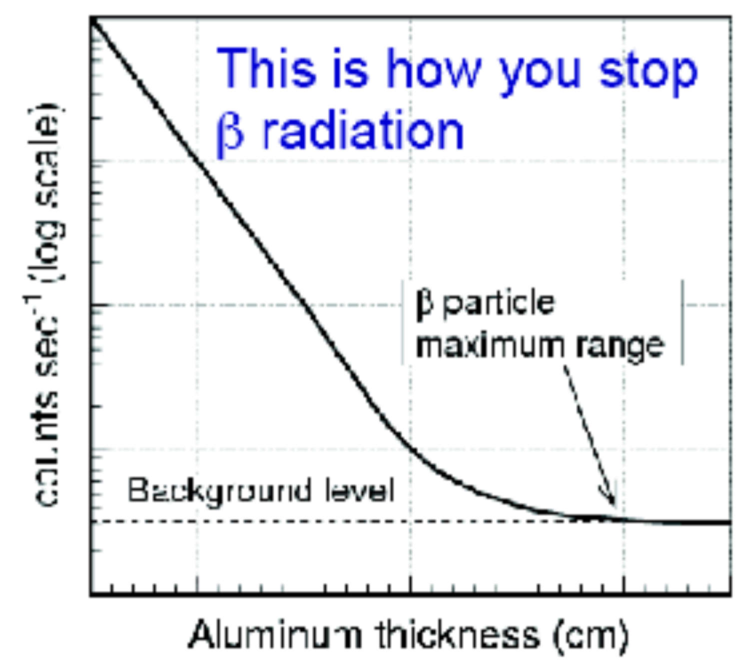
- **NOTE:** this last decay cannot happen in vacuum because the proton is lighter than the neutron!

Interaction of *β*'s with matter

- Possible ways for the *β*'s to lose energy are:
  1. Inside a material of density *ρ*, energetic *β*'s are deflected by ions (Coulomb repulsion)
  2. The *β* kicks one of the electrons of the material out (ionization) and hence undergo multiple scattering
- Because of this, the β's can travel through up to a *max range*. An empirical formula for it is:

$$r = \frac{0.412\ \mathrm{g}\cdot\mathrm{cm}^{-2}}{\rho}\left(\frac{E}{1\ \mathrm{MeV}}\right)^{1.29}$$





Minimizing potential: *γ* decay

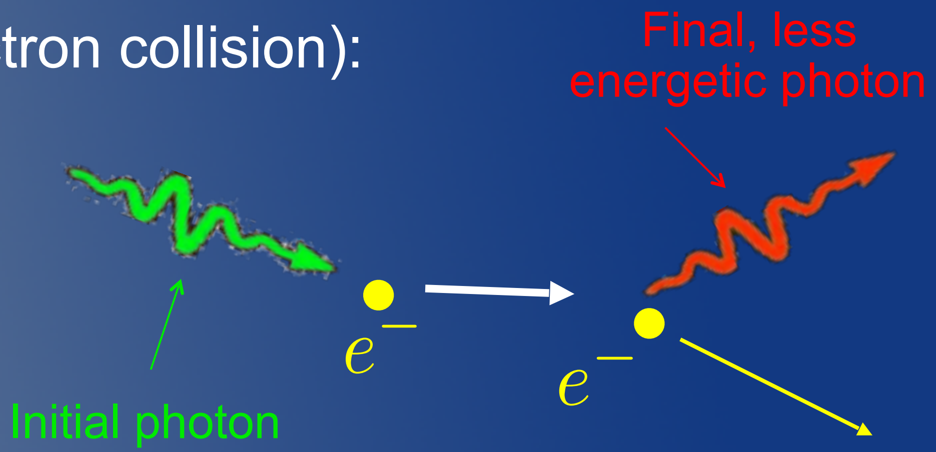
- Just like atoms, a nucleus has ***energy levels***
  - One ground state, many excited states. It can be found in any of them
- Transitions between nuclear states are precisely analogous to electronic transitions in atoms, just at much higher energy!
  - Atomic transitions in *e.g.* Hydrogen:
    - Distance between levels ~ size of atom ~ 10^{-9} m
    - Energy of emitted photons ~ visible light ~ few eV
  - Nuclear transitions:
    - Distance between levels ~ size of nucleus ~ 10^{-15} m
    - Energy of photons ~ gamma rays ~ around MeV
- Just like electronic transitions, nuclear transitions are characterized by sharp spectral lines corresponding to the emission of photons with well defined wavelengths

Interaction of *γ*'s with matter

- Interaction of gamma rays with matter is governed by <u>three processes:</u>

1. ***Compton scattering*** (photon-electron collision):

   Incoming photon transfers energy to electron. No minimum energy required for photon.



1. ***Photoelectric effect:*** photon hits an atom and kicks one of the electrons out. Minimum energy required (because atomic levels are quantized)

2. ***Pair production:*** The photon converts into a electron-positron pair. Minimum energy required (at lease two the mass of the electron ~ 1.022 MeV). Not of interest for this experiment

Interaction of γ's with matter

- The is no such a thing as a sharp range for *γ's*
- However, one can describe the number of photons (*dN*) absorbed while traveling a distance *dx* in material as:

\# of initial *γ*'s

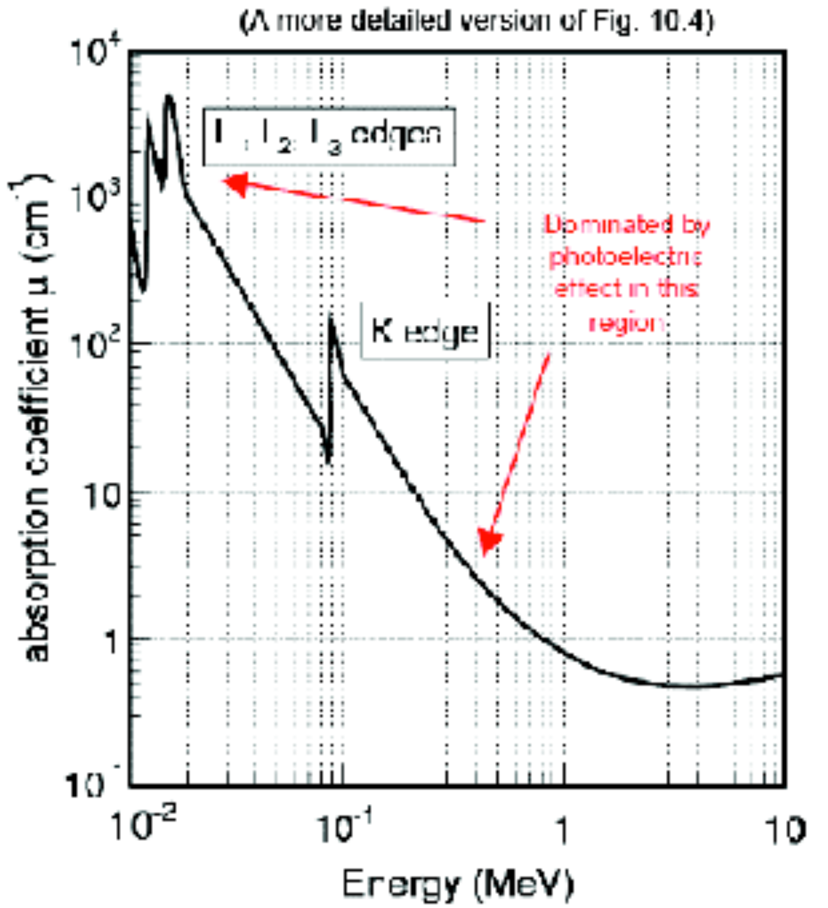
$$dN = -\mu N dx$$

\# of *γ*'s absorbed

Linear absorption coeff.

- The expected number of photons emerging from a material of thickness *x* then decreases exponentially with *x*:

$$\boxed{N(x) = N_0 e^{-\mu x}}$$

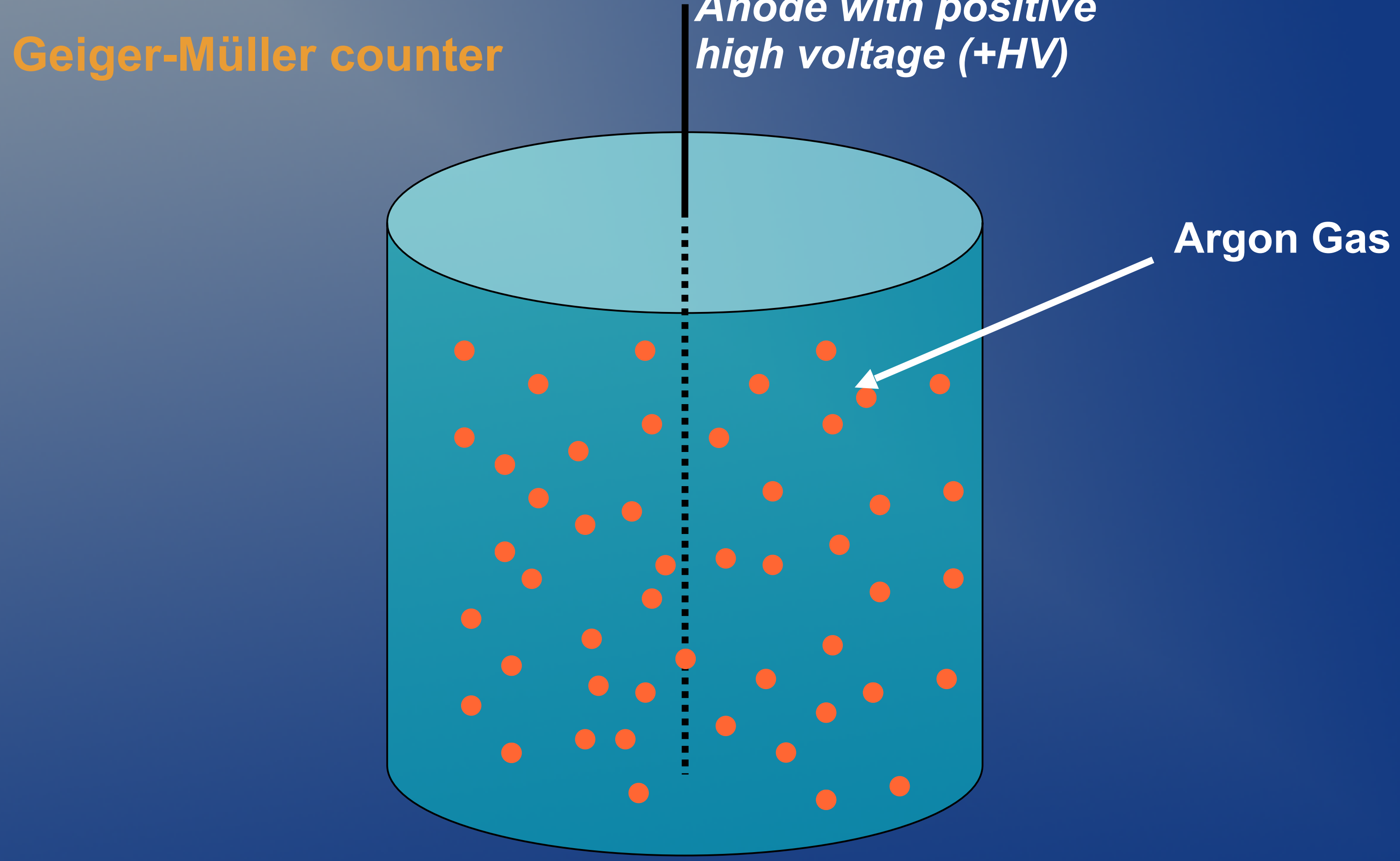


Linear absorption coefficient of gamma rays in lead. From J. Hubbell and S. Seltzer, Report NISTR 5632 (1995).

The Experiment

Detecting *β* rays: the Geiger-Müller

- **Question:** how can we detect β-rays?
- As mentioned they are nothing more than electrons emitted by a nucleus after a nuclear decay



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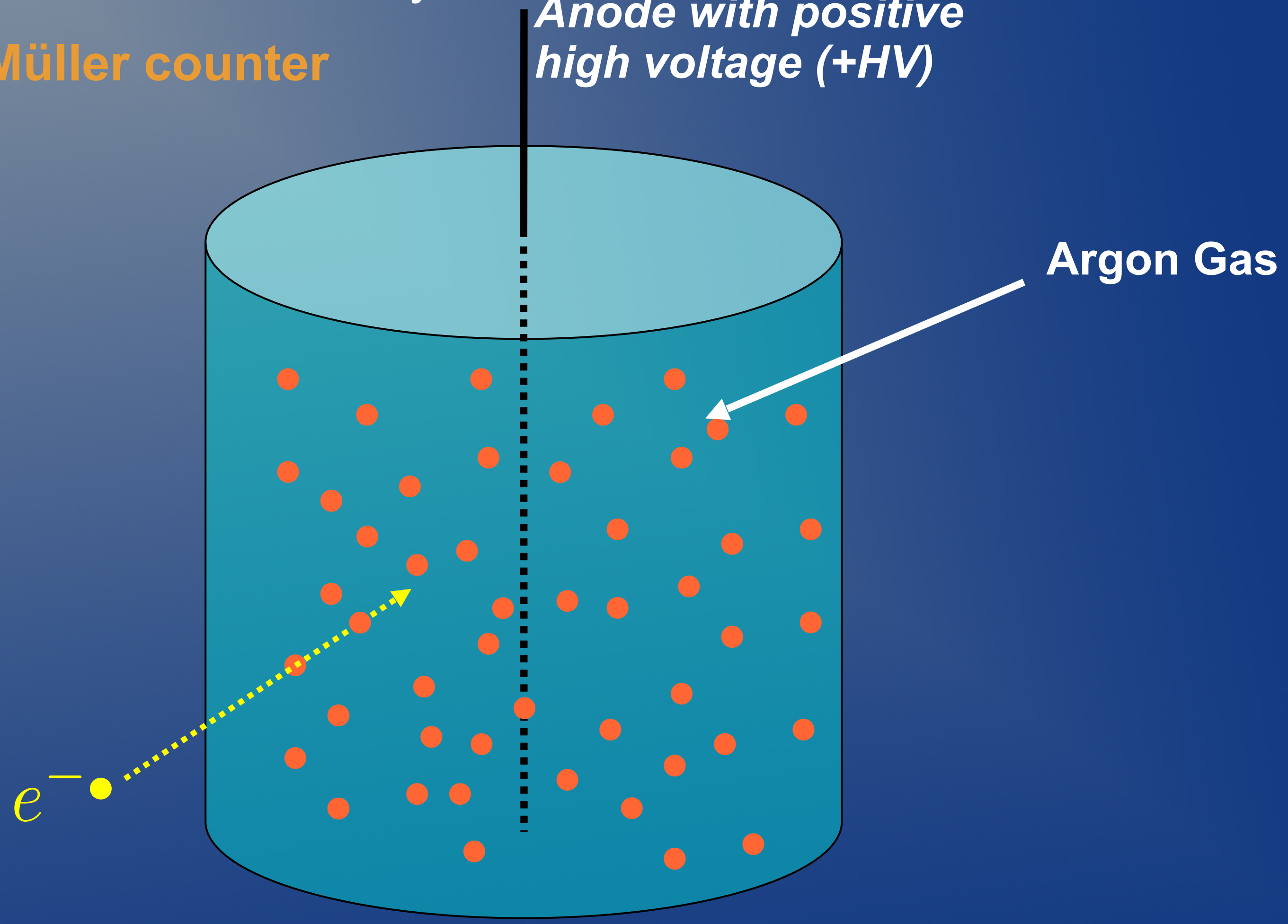

Detecting *β* rays: the Geiger-Müller

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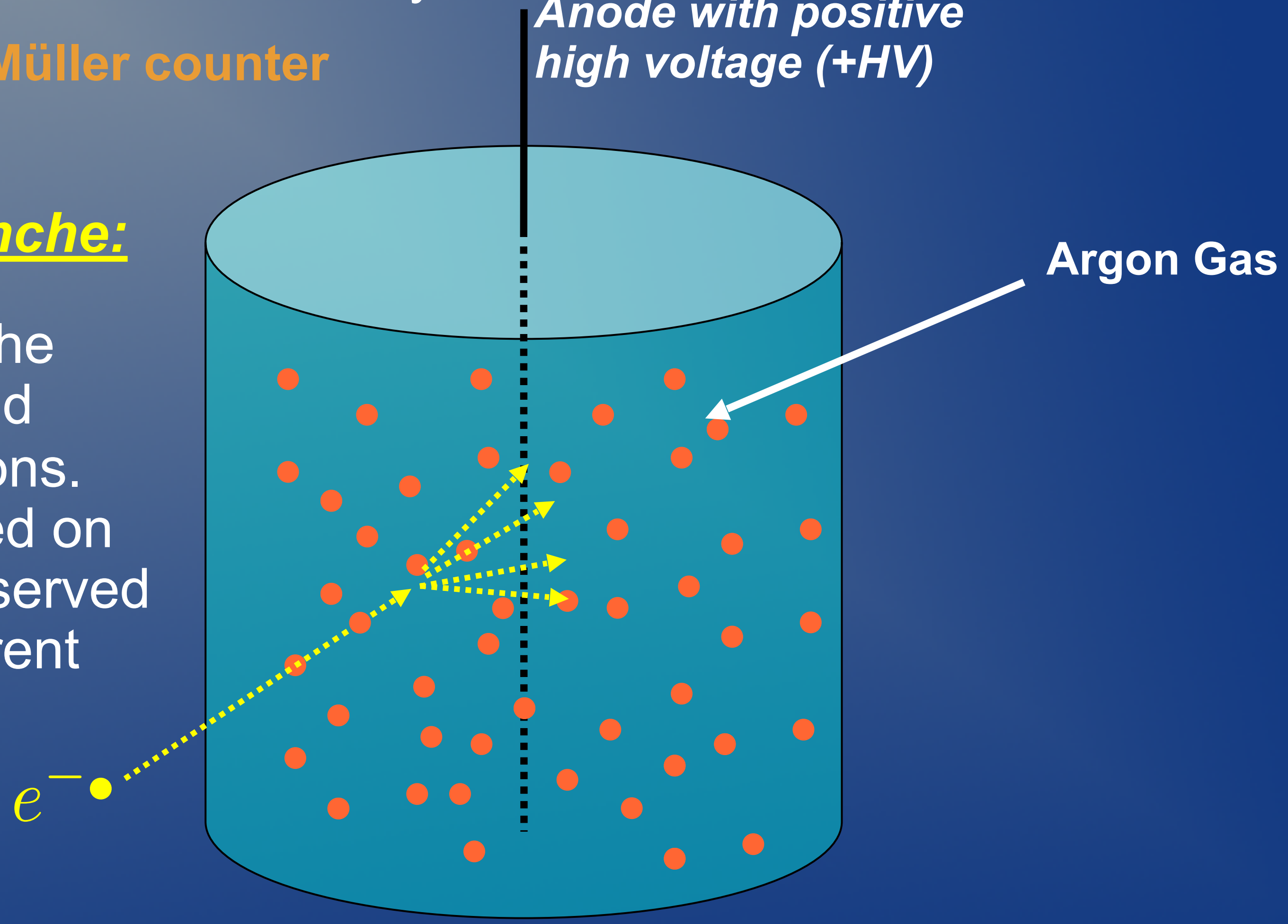
Geiger-Müller counter



Anode with positive high voltage (+HV)

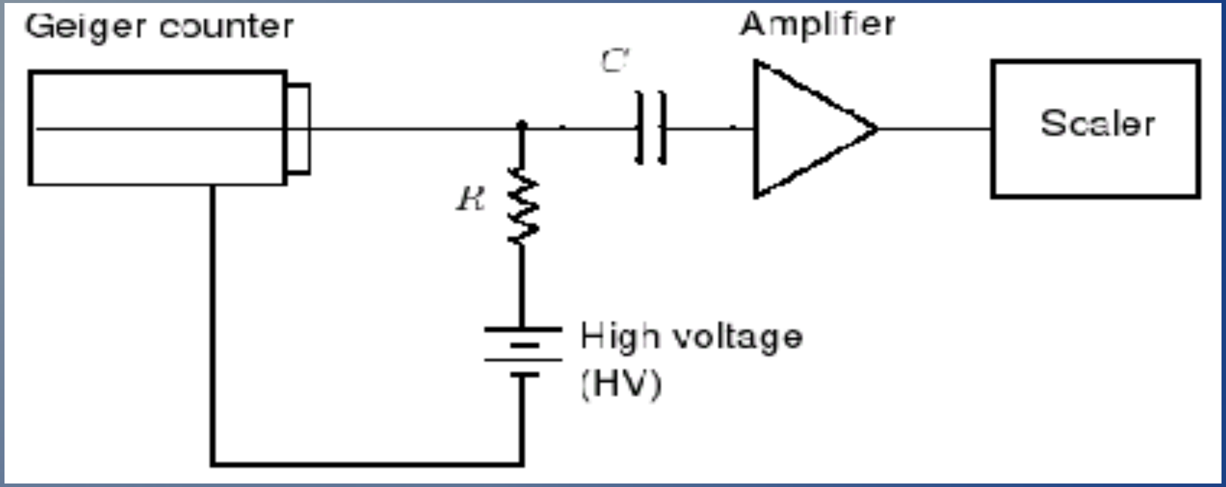
Argon Gas

e^-

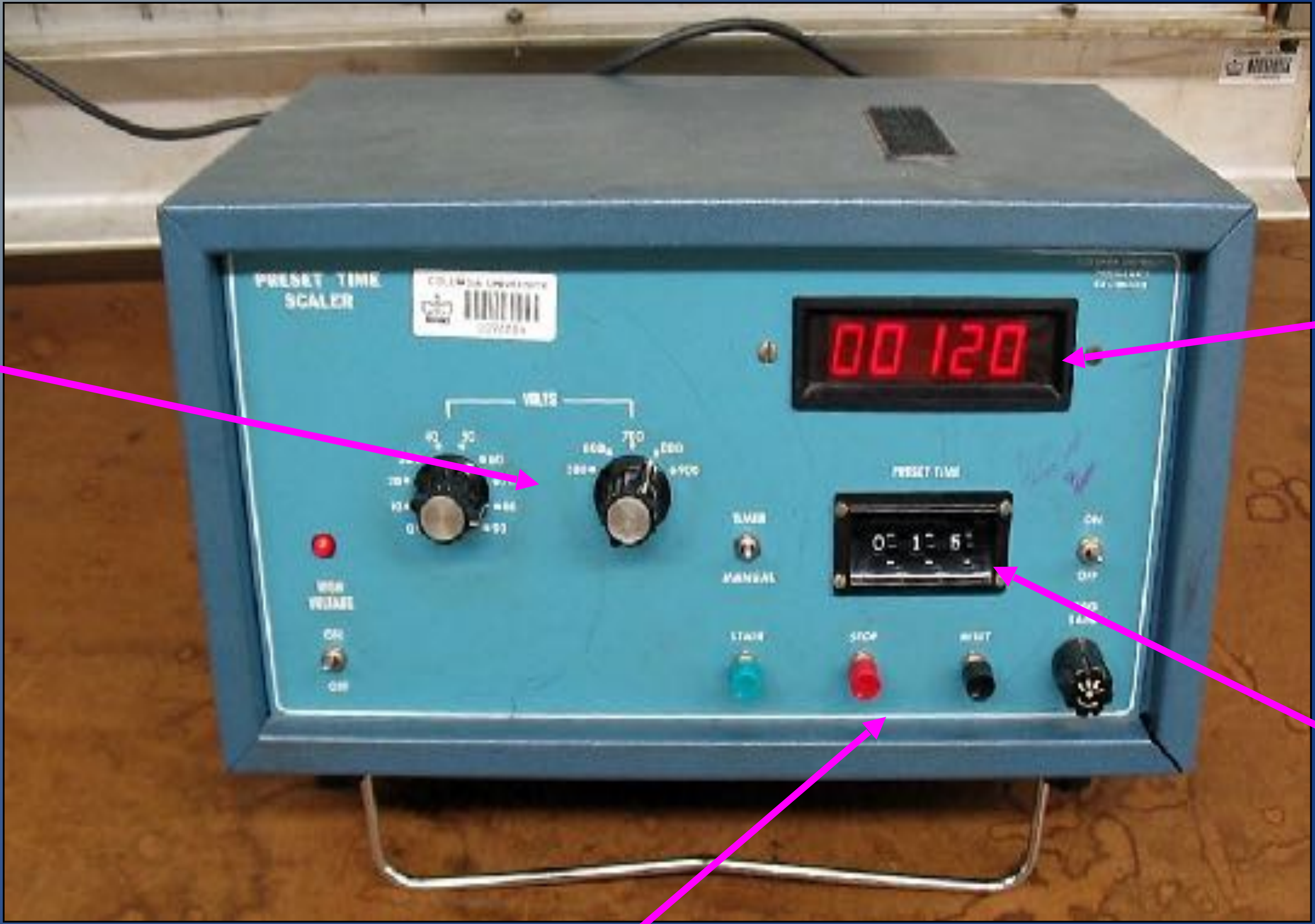
Townsend avalanche:

The electron hits the atoms of Argon and emits other electrons. These are collected on the anode and observed as a non-zero current

Experimental setup



Scaler and high voltage supply



Voltage control

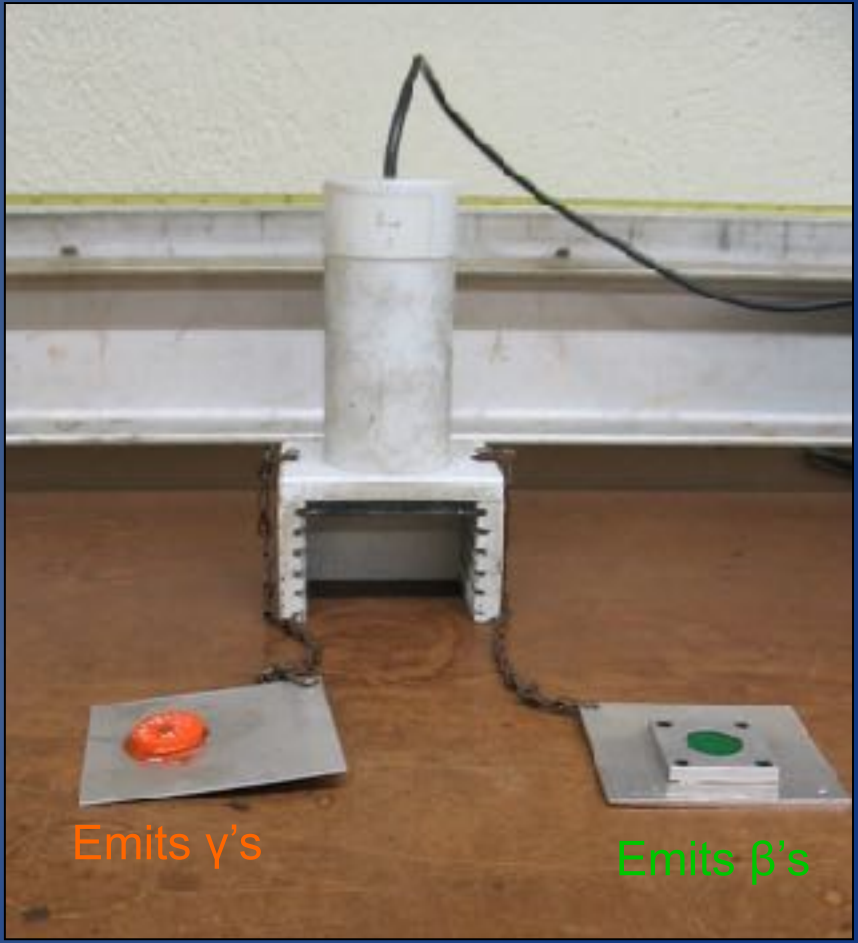
counter

Pre-set duration of the counting

Start, stop and reset

Geiger counter with sources

- Attached to the Geiger counter are two low radiation level sources
  - **Green**: source of β's (thallium – Tl)
  - **Orange**: source of γ's (Cesium – Cs)
- When not in use, cover sources with lead. This will prevent them from contributing to the background
- **SAFETY NOTE:** Please do not eat/drink during lab. Wash hands when you're finished.



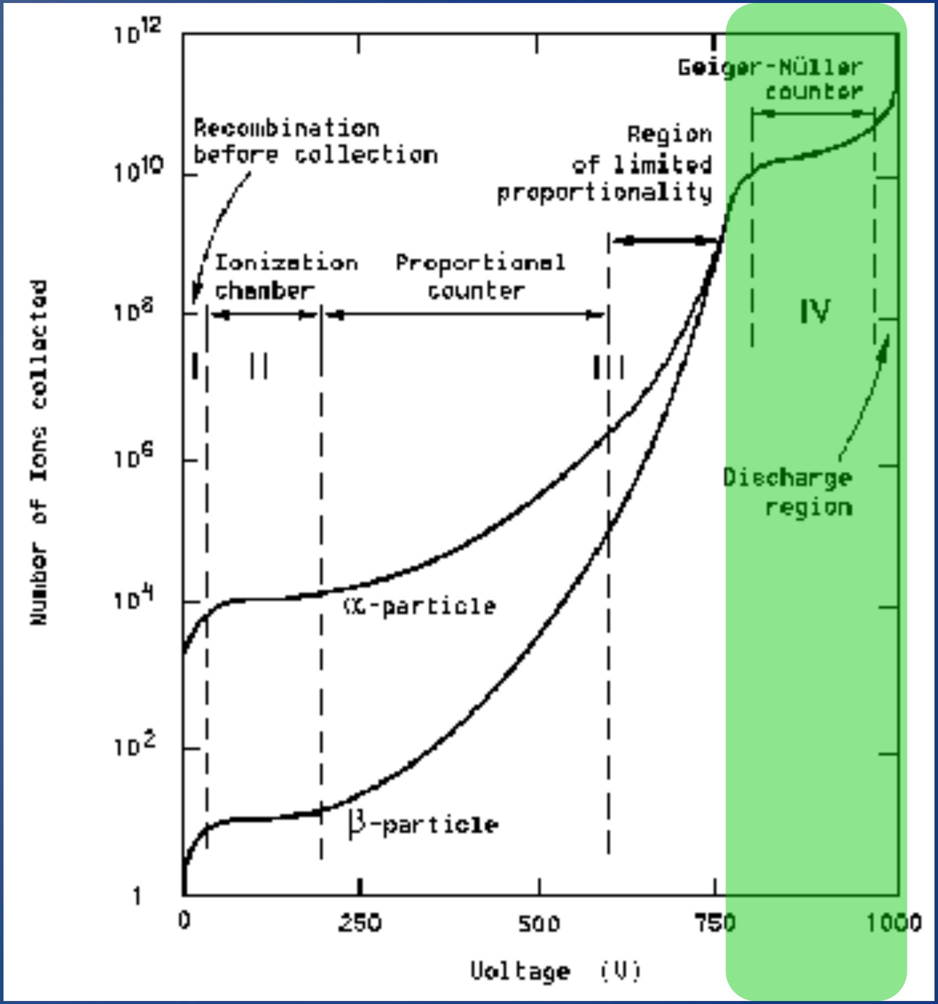
Main goals

- This week experiment can be divided in essentially three parts:
- **Part 1:** Preliminary set up
    - Determine the optimal working voltage for the Geiger counter
    - Determine the background counting
- **Part 2:** Thallium
    - Measure the range of the emitted β particles
    - Estimate their maximum energy
- **Part 3:** Cesium
    - Measure the linear absorption coefficient for the γ rays
    - Compute their energy and compare with expectation

Part 1: the plateau

- The first thing you need to do is to look for the value of the voltage (V) for which the Geiger-Müller is stable. This is called the *plateau*
- In this region the counter will be less affected by random fluctuation of the voltage generator
- Procedure:

1. Place the source under the tube and start increasing the voltage in steps of 20 V
2. At each step count for 15 seconds
3. When the counting changes by less than 10% over a range of 100 V you found the plateau



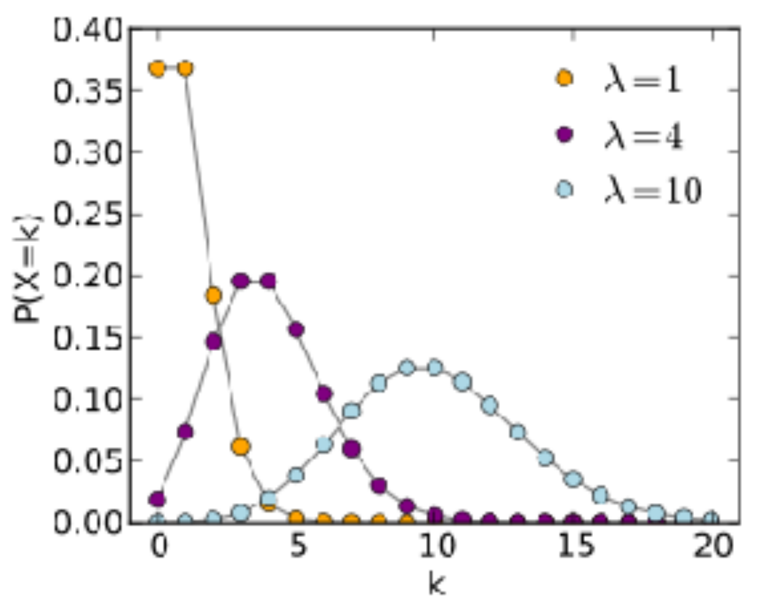
Counting statistics: Poisson distribution

- In this experiment you will "count stuff", *i.e.* number of β/γ passing through the counter
- Basic idea for parts 1 and 2:
  - Put source and some absorbing material under Geiger tube.
  - During some pre-set time interval count the number of particles emitted by the source
  - Plot count rate (counts/time) vs. absorber thickness
- **Complication**: Radioactive decay is a *genuinely random process*. Repeating a trial in the exact same conditions will result in slightly different counts.
- **Question:** How do we quantify the random fluctuations of the counting? What kind of distribution do they follow?

Counting statistics: Poisson distribution

- When the output of your measure is a count the fluctuations cannot follow a Gaussian distribution. In fact, for example, a count can never be a negative number
- It turns out that they follow the so-called ***Poisson distribution***:

$$\boxed{P_\lambda(N) = \frac{\lambda^N e^{-\lambda}}{N!}}$$



- The fluctuations from the mean value (λ) are given by:

$$\boxed{\sigma_N = \sqrt{N}}$$

- *This will be the error on each measure!*

Obtaining precise measurements

- We want to be as precise as possible, so **keep relative errors small**.
- Clearly to have small relative errors we need to have a high number of counts
- Examples:

$$N = 1000; \quad \sigma_N = \sqrt{1000} = 31.6;$$

Relative error: $\sigma_N/N = 0.03 = 3\%$ (Not too bad)

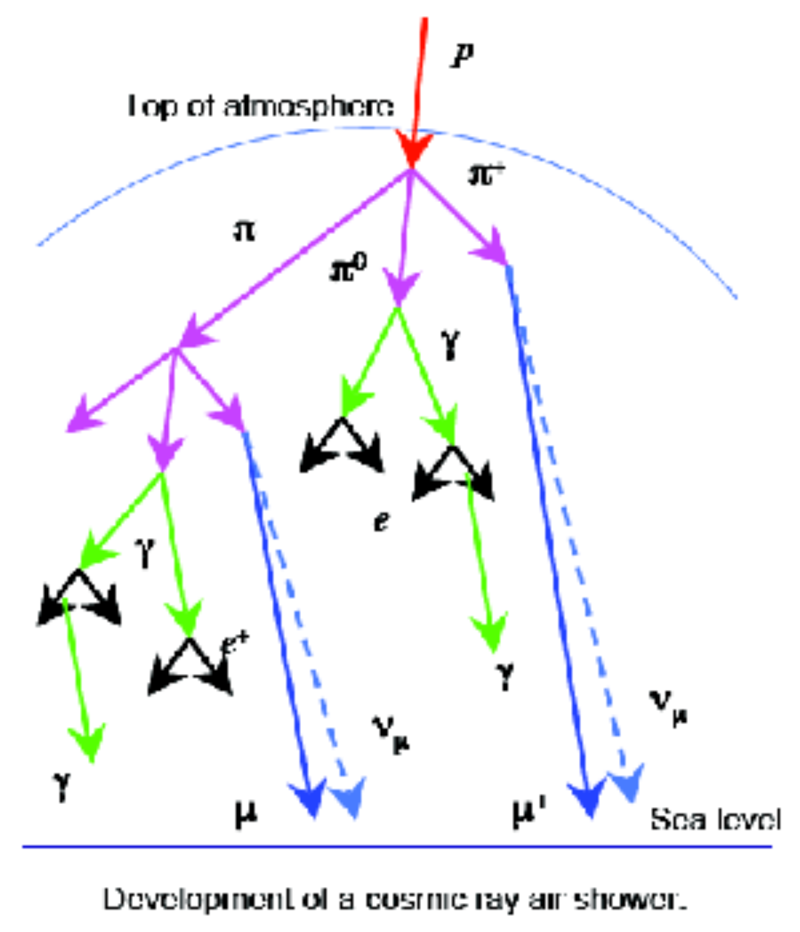
$$N = 10^6; \quad \sigma_N = \sqrt{10^6} = 1000;$$

Relative error: $\sigma_N/N = 0.001 = 0.1\%$ (Excellent)

- Therefore: longer count $\longrightarrow$ higher count $\longrightarrow$ smaller relative error
- You will have to find a compromise between small errors and reasonable counting time

Measurement of background

- When there are no sources, you will observe counts anyway! Why?
- Two main sources of background:
  - Cosmic ray showers from atmosphere
  - Sources nearby
- To estimate the background:
  - Place sources far from the counter and try to screen them with lead
  - Count for a certain amount of time
- Record the background count and its uncertainty



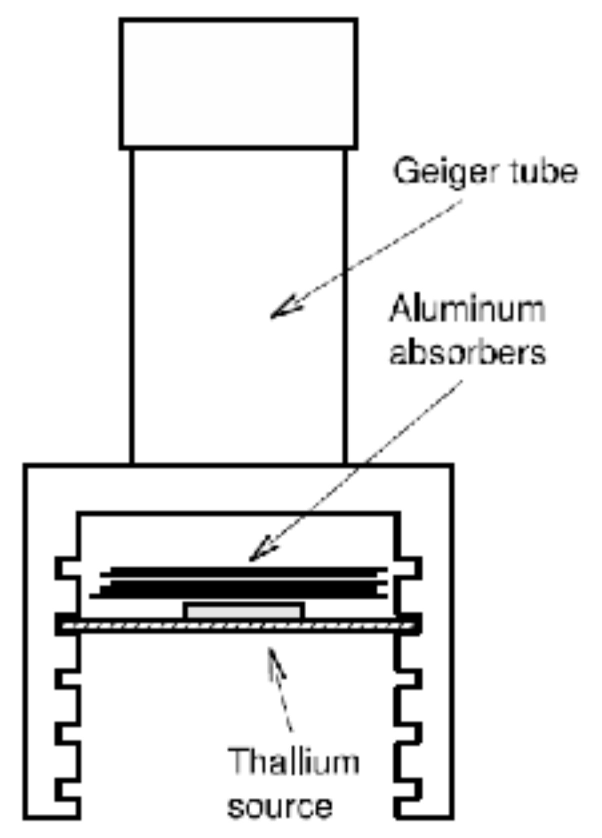
Development of a cosmic ray air shower.

Part 2: Thallium

- Use a unstable isotope of Thallium-204 to generate beta particles:

$$^{204}Tl \rightarrow \, ^{204}Pb + e^- + \bar{\nu}_e$$

- Place an Aluminum absorber between Thallium source and Geiger tube and take counts for a fixed amount of time (same as background!)
- Record the counts (with errors!) as a function of the number of Aluminum foils
- Given the thickness of each foil <u>record counts vs. total thickness</u>



Part 2: Thallium

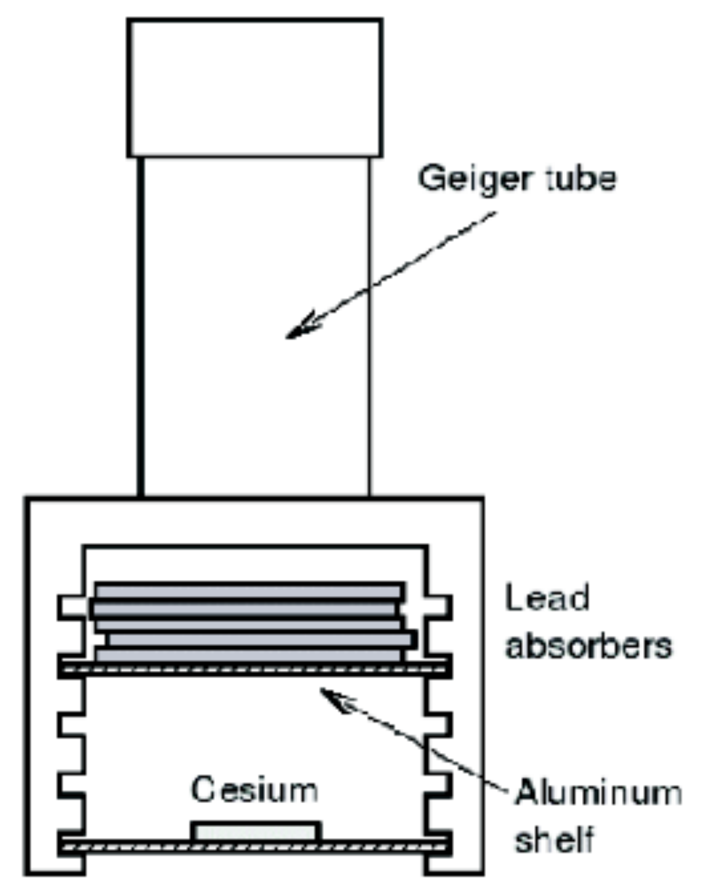
- Make a semi-log plot of your counts vs. thickness data
- On the same plot report also the background
- When the counts are ***statistically compatible*** with the background determine the range of the β particles
- Recall the equation for the range:

$$r = \frac{0.412\ \mathrm{g} \cdot \mathrm{cm}^{-2}}{\rho} \left(\frac{E}{1\ \mathrm{MeV}} \right)^{1.29}$$

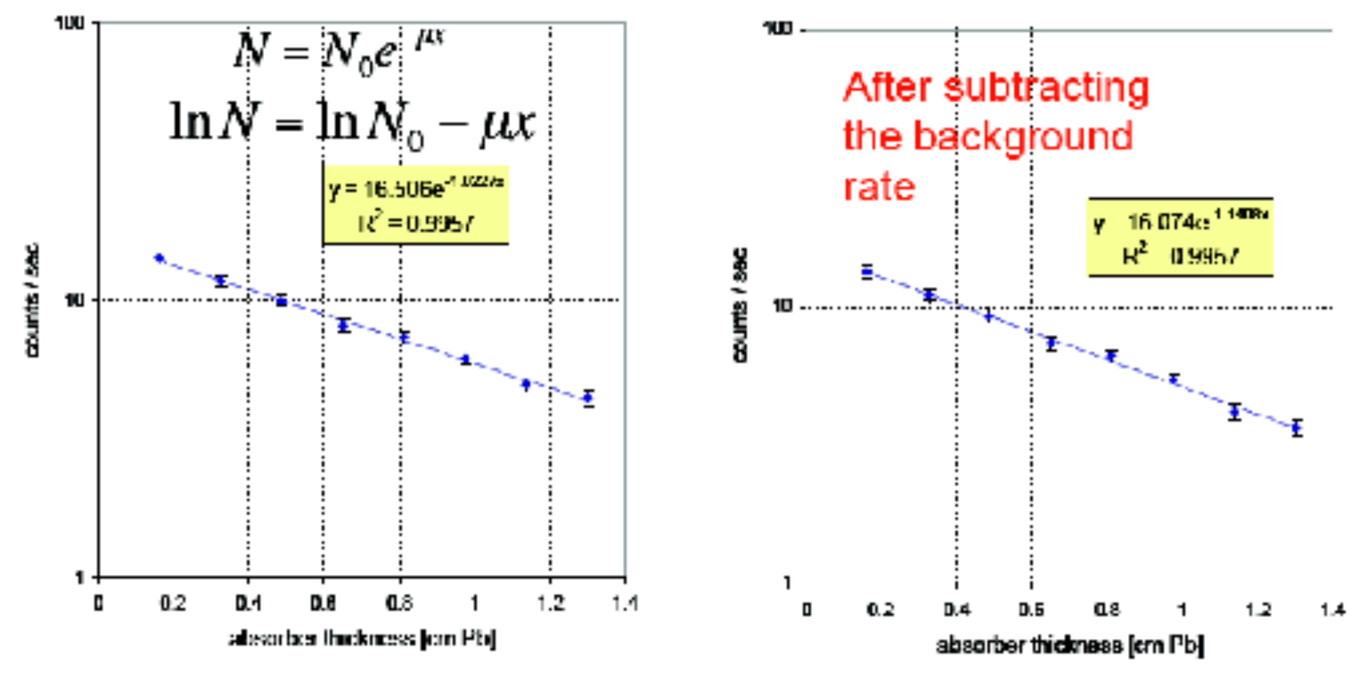
- Given the density of the Aluminum, $\rho = 2.702$ g cm^{-3}, and the experimental range find the energy of the β's
- Compare with expected $E = 0.765$ MeV

Part 3: Cesium

- Place the source of Cesium-137 on the last shelf of the Geiger
- Every time add one lead absorber (as far away as possible from the source) and record counts vs. thickness
- The thickness should be measured with a caliper
- Take a reasonable number of data
- **NOTE:** The counts will never go to zero!



Part 3: Cesium

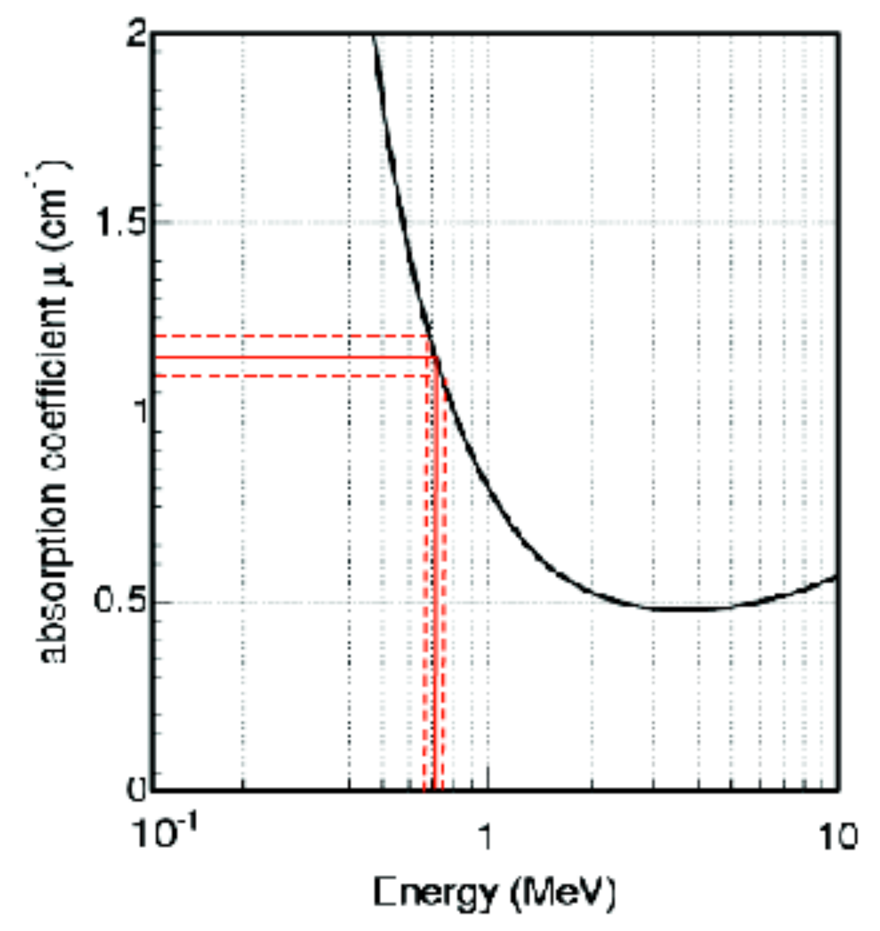


After subtracting the background rate

- From every count <u>subtract the background</u>
- Make again a semi-log plot and <u>compute the slope of the best fit line</u>
- This will be your coefficient of linear absorption, *μ*

Part 3: Cesium

- Figure 10.4 of the lab manual give the energy vs. *μ* curve for γ rays
- Given the experimental coefficient of absorption find the energy of the emitted photons
- Compare with the accepted value for photons emitted by Cs-137, $E_\gamma = 0.662$ MeV



Tips

- **<u>How to handle the radioactive sources:</u>** the levels of radiation emitted by these sources are extremely low, comparable to those that we experience every day. So do not be afraid! Just, please, do not eat the source…
- To make your life simpler it is better if, for a fixed source, you perform the counting always over the same time interval (including background count)
- **<u>REMEMBER:</u>** Do not wait for the counts of the Cesium to drop below the background. It will never happen!
- Re-measure the background often to make sure it does not fluctuate too much!