UNIT-28 PARTICLE PHYSICS

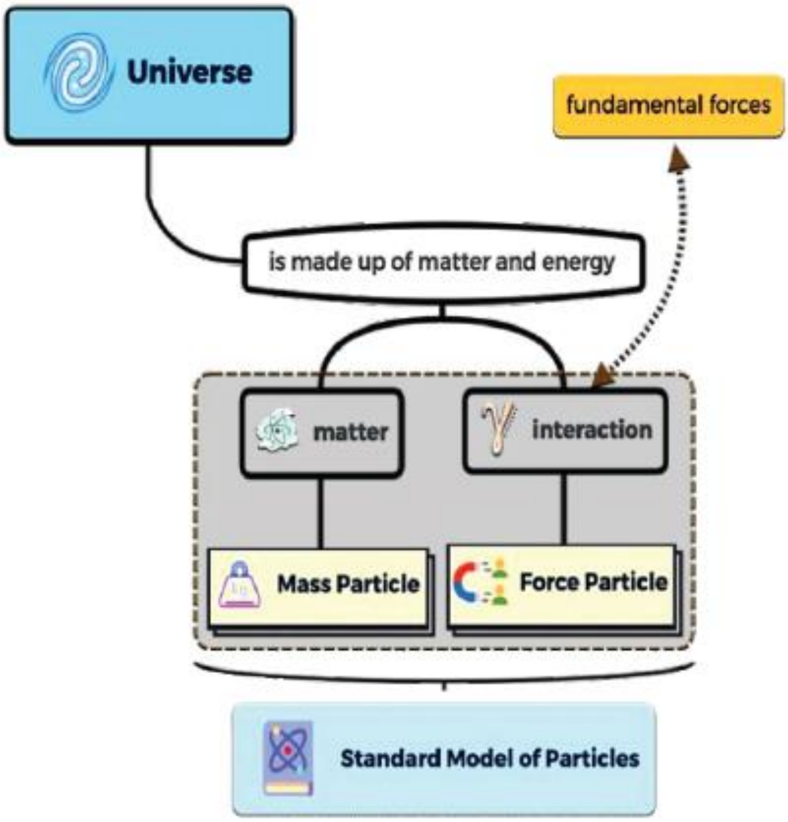
INTRODUCTION

Let's explore how our universe was formed and what holds everything together. People have been curious about these questions for a very long time. Originally, scientists believed that atoms were the smallest pieces that made up everything. But, in the 1800s, they discovered that atoms have smaller parts called electrons, protons, and neutrons. Today, physics tells us about even tinier pieces that make up everything. These super small pieces are called "elementary" or ": fundamental" particles; they're so simple that they don't have any smaller parts inside them. Molecules, atoms, protons, and neutrons are fundamental particles because these are made up of other particles, while electrons, quarks, and photons are particles. Studying all these elementary particles and understanding how they behave is the main goal of particle physics.

Standard Model.

Particle Physics is the branch of Modern Physics that deals with the study and search of the ultimate constituents of matter (elementary particles) and their interactions.

Our universe is made up of two things: matter and energy (radiation). To understand them better, scientists have divided particles into two main groups: matter particles and force particles. Scientists have identified many elementary particles belonging to these categories. These particles are categorized and explained in detail in the Standard Model of Particle Physics, which is the best- known theory to date. It is a framework that explains three of the four fundamental forces (electromagnetism, the weak nuclear force, and the strong nuclear force) and all known elementary particles. The Standard Model classifies all known elementary particles into two main classes:



Fermions:
These are the matter particles that make up everything in the universe.
Bosons:
These are the force-carrying particles that mediate the interactions between fermions.

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FUNDAMENTAL FORCES AND THEIR FIELD PARTICLES

1. GRAVITATIONAL FORCE:

It is the force that attracts two masses towards each other. It is the weakest of the four fundamental forces but acts over long distances. When considering massive objects, like the sun or giant planets, gravitational force is considered to be strong as the masses of these objects are also large. On an atomic level, this force is considered weak.

Field Particle: The hypothetical particle associated with gravity is the graviton, although it has not been observed yet. The Standard Model doesn't explain gravity.

2. WEAK NUCLEAR FORCE:

The weak force is responsible for radioactive decay, where unstable atomic nuclei break down into smaller, more stable nuclei. It's responsible for processes like beta decay and neutrino emission. This force is weaker than electromagnetic and strong nuclear forces but stronger than gravitational force.

Field Particle: There are three field particles associated with weak nuclear force. These are w+, w-, and Z bosons. These short-lived bosons carry the force over very small distances, explaining the limited range of the weak force.

3. ELECTROMAGNETIC FORCE:

This force is responsible for the interactions between charged particles, such as electrons and protons. It includes both electric and magnetic forces. Electromagnetic force is stronger than both gravitational and weak nuclear forces. It is also a long-range force, similar to the gravitational force.

Field Particle: The field particle of electromagnetic force is the photon. It is a massless and chargeless particle. Whenever charged particles interact, they exchange photons, causing the attractive or repulsive forces we observe.

4. STRONG NUCLEAR FORCE:

The strong force binds quarks together to form protons and neutrons, and it holds atomic nuclei together. It is the strongest force among all forces and acts at subatomic levels. This is the most dominant force in reactions and is so strong that it binds protons with similar charges with the nucleus. It is mostly attractive in nature. It has a very short range of just one femtometer.

Field Particle:

Gluons are the field particles that mediate the strong force between quarks.

PARTICLE ZOO

One way of studying elementary particles is to classify them into different categories based on certain behaviors and then to look for similarities or common characteristics among the classifications. We know that the Standard Model has classified all elementary particles and their interactions into two main groups according to their spins:

- ► Particles that carry force, called bosons, have a shaving spin in integer values such as 0 and 2.
- ► Particles that make up all matter, called fermions, have spin in odd half integer values such as ½. 3/2 etc.

BOSONS

The arrangement of all elementary particles in the Standard Model constitutes a particle zoo. All bosons can be classified into two types: Elementary Boson and Composite Bosons. Composite bosons consist of quark and anti-quark combinations, while elementary bosons are not made up of other elementary particles.

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ELEMENTORY BOSONS

Elementary bosons are the carriers of the fundamental forces in nature. For examples:

- Gluon
- W+, W- and Zº Bosons
- Photon
- Higgs Boson- gives mass to all particles.
- Graviton

The properties of elementary bosons are given in the table.

Force	Boson	Spin	Strength	Mass
Strong	Gluon	1	1	Massless
Electromagnetic	Photon	1	10^{-2}	Massless
Weak	W, Z	1	10^{-7}	80.91GeV
Gravity	Gravitation	2	10^{-39}	Massless

COMPOSITE BOSONS

Some bosons are formed when two or more particles join together to create an integer-spin particle, such as:

Mesons - Mesons are formed when two quarks bond together. Since quarks are fermions and have half-integer spins, if two of them are bonded together, then the spin of the resulting particle (which is the sum of the individual spins) would be an integer, making it a boson.

FERMIONS:

All material particles are made up of fermions. We can further divide fermions into two subclasses: elementary fermions and composite fermions.

Elementary Fermions:

Elementary fermions are the building blocks of all material particles. They are not made of any other particles. The fermions come in two types: leptons and quarks.

LEPTONS

Leptons are a group of elementary particles that do not experience the strong nuclear force. There are six types or flavors of leptons, which come in three pairs. The pairs are made up of three charged particles named electron, muon, and tau, along with their Partners called neutrinos (charge less). These all six leptons group into three generations: Generation I, Generation II and Generation III, as shown in the table. Each generation consists of one pair of leptons (for example, electron with electron neutrino).

PROPERTIES OF LEPTONS:

- Electron: Negatively charged; commonly found in atoms.
- Muon and Tau: Heavier counter parts of the electron.
- Neutrinos: Electrically neutral; they interact very weakly with matter.
- Leptons interact via weak and electromagnetic forces but not through the strong force.
- Leptons are stable particles and do not undergo decay under normal circumstances.
- Leptons exist alone and do not form groups.

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	Fermions			
	Charge	Generation I	Generation II	Generation III
Leptons	-1	electron (e)	muon (μ)	tau (τ)
	0	e-neutrino	μ-neutrino	τ-neutrino
Quarks	+2/3	up (u)	charm(c)	top(t)
	-1/3	down (d)	strange (s)	bottom(b)

QUARKS:

Quarks are elementary particles that experience all three fundamental forces: strong nuclear force, weak nuclear force, and electromagnetic force. Quarks come in six types, or flavors: up (u), down (d), charm (c), strange (s), top (t), and bottom (b). Quarks are a fundamental component of visible matter. All the matter around us, such as protons and neutrons, is made up of quarks. Similar to leptons, quarks also come in three generations, with each generation containing one pair of quarks. The up and down quarks are the only stable quarks in ordinary matter.

PROPERTIES OF QUARKS

- They carry fractional electric charges, either +2/3 or - -l/3
- Quarks interact strongly with the strong nuclear force, which is mediated by gluons. Quarks are never found as free particles in nature; they are always confined within larger particles called hadrons.
- Hadrons are particles made up of quarks held together by the strong nuclear force. Examples of hadrons include protons and neutrons.
- Quarks can undergo weak interactions, leading to processes such as beta decay. Weak interactions can change one type of quark into another. For example, a down quark can change into an up quark through weak decay processes.

Color Charge:

1. Electric charge comes in only one type: positive (with its opposite, negative). But strong charge (that deals with strong nuclear force) comes in three types: red, green, and blue. These color names are just labels and do not correspond to actual colors in the visual spectrum.
2. Quarks carry one of the three color charges, and they can change their colors during particle interactions. Quarks of different colors are attracted to one another due to the strong nuclear force; it means red attracts green, blue attracts red, and so on. On the other hand, quarks of the same color repel one another.
3. Quarks always combine in ways that result in "color-neutral" or "white-color" particles. For example, a proton consists of three quarks: one red, one green, and one blue, making it color-neutral. Only white color combinations are permitted. This is why isolated quarks do not exist in nature. This is known as quark confinement. Therefore, all free particles have a color charge of zero.

Composite Fermions:

Composite subatomic particles, such as protons, neutrons, alpha particles, etc., are composed of two or more elementary particles. All composite particles are massive. The composite particles that are made of quarks are called hadrons. The two main categories of hadrons are baryons and mesons.

(a) Baryons:

Baryons are a class of hadrons that consist of three quarks. For example, protons and neutrons are the most well-known baryons, each composed of three quarks:

Proton:

It consists of two up and one down quarks (uud). Up
(u) quark has +2/3 charge and down quark has -l/3charge.
Therefore, net charge on proton has +1 charge:

$$Proton = \bar{u}\bar{u}\bar{d} = \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$$

$$Neutron = \bar{u}\bar{d}\bar{d} = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} =$$

Neutron:

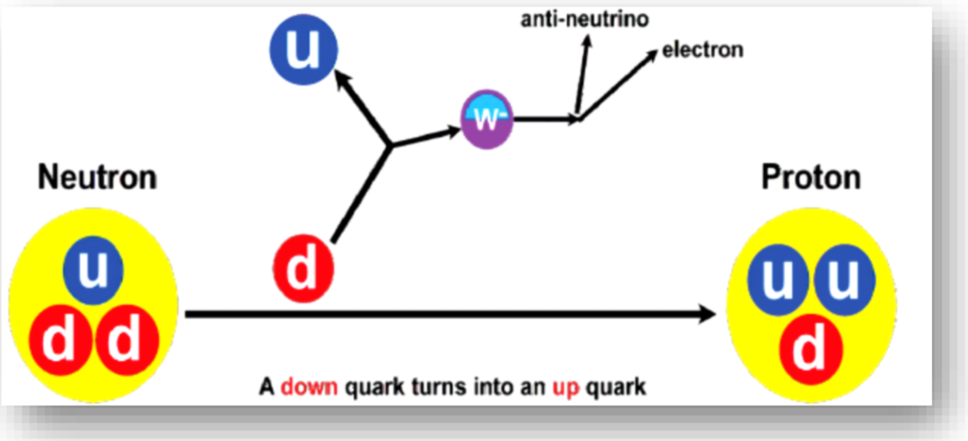
It consists of three quarks: one up and two down quarks (iidd). The net charge on neutron is zero:

(b) Mesons:

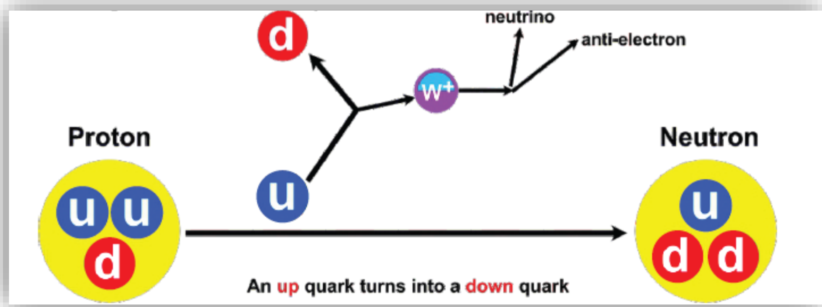
Mesons are another class of hadrons, but they consist of one quark and one anti quark. For example, pions (n) are common mesons. They carry the strong nuclear force, binding protons and neutrons together.

Quarks and Beta Decay:

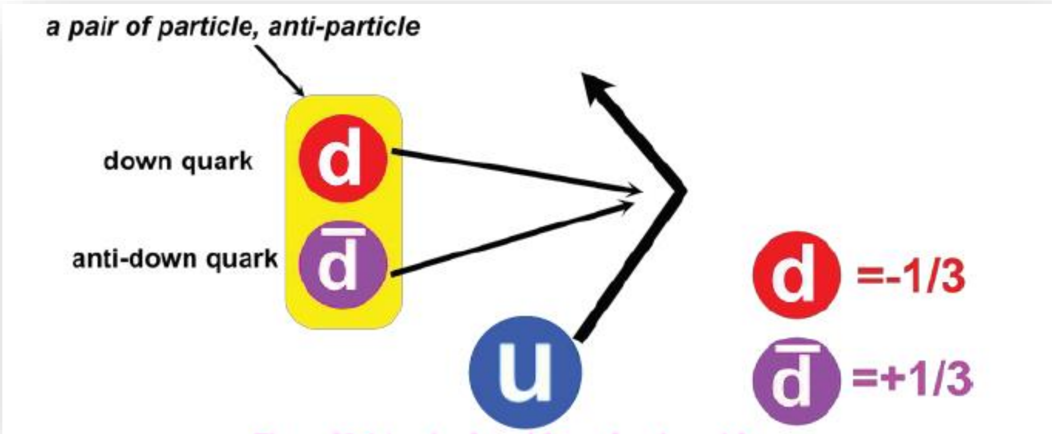
β^- decay is a type of radioactive decay process in which a neutron in an atomic nucleus is transformed into a proton. When a --decay occurs, a down quark emits a field particle called a W^- boson (a weak force-carrying particle) and transforms into an up quark. The W^- boson quickly breaks up into an electron and an antineutrino. The process is shown in Figure.



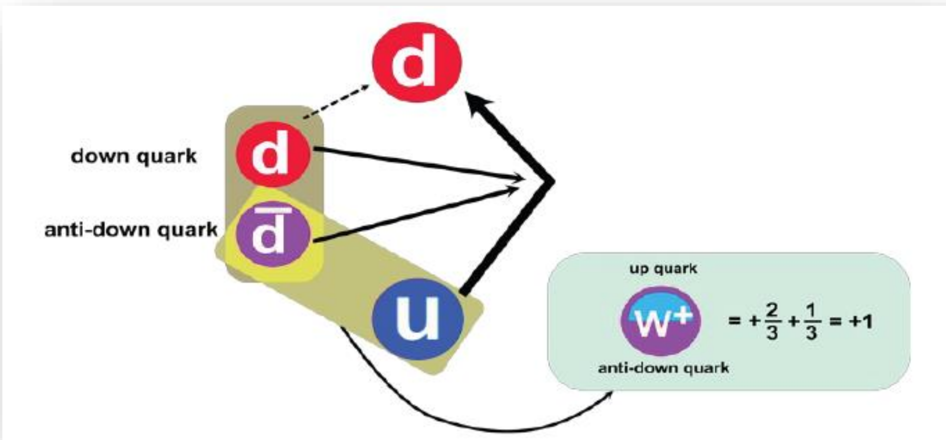
Electric charge is conserved during beta decay with the emission of an electron and an antineutrino. β^+Decay is a type of radioactive decay process in which a proton is transformed into a neutron. In W^-decay, an up quark emits a field particle called a W^+-boson and transforms into a down quark. The W^+- A boson quickly breaks up into an anti-electron (positron) and a neutrino. The process is shown in Figure.



The up quark can change into a down quark by emitting W+ weak particle. How could that trick be done? Explain. Nature can create short-lived particles, like particle-antiparticle pairs, out of nothing by borrowing energy permitted by the uncertainty principle. This principle allows for a fluctuation in energy levels at any given moment, making it possible for particles to briefly come into existence before annihilating each other. Imagine that there was created such a pair of particles: a down quark and an anti-down quark in the neighborhood of the up quark:



Anti-down quark is represented by a bar over the symbol d: $\bar{d}$. The charge on anti-down is +1/3. Therefore, net charge on the pair is zero. Next, imagine the down quark replacing the up quark. The up quark could then join up with the remaining anti-down quark to make the W particle:



The net charge on w+ is +1. The W boson can vary its constituents, and it can consist of a pair of positron-neutrino. The net charge is again +1. Now the w+ boson decays into a positron and a neutrino as shown in the diagram.

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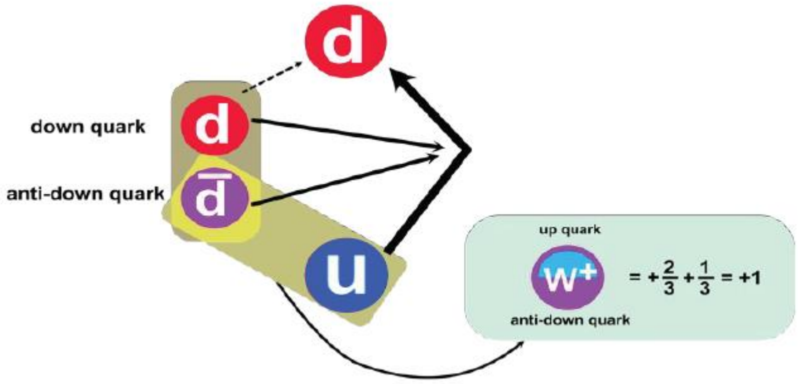
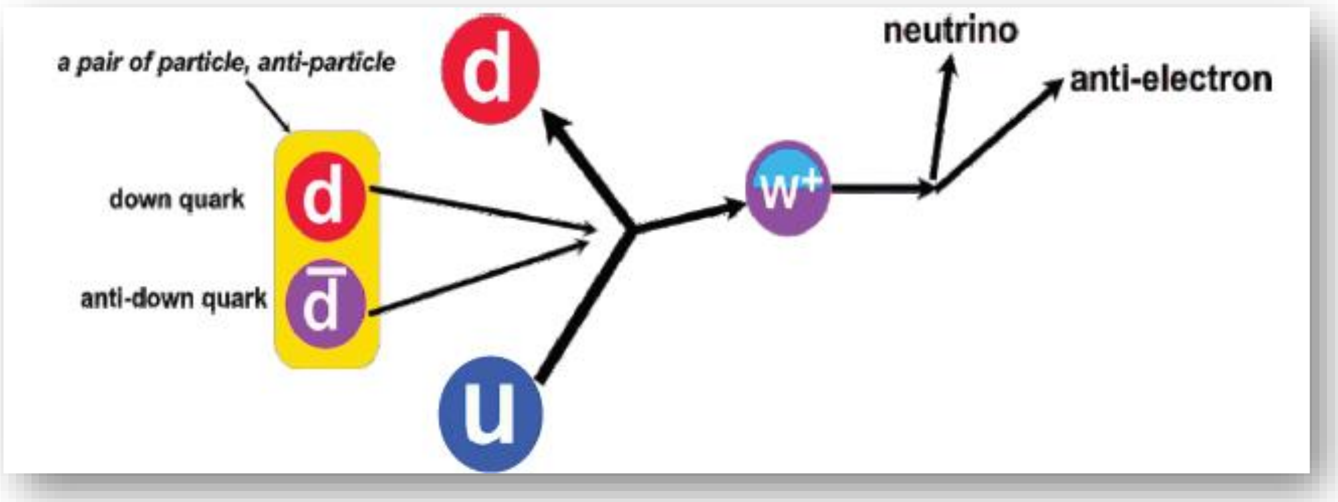


Radiation Detectors:

Radiation Detectors or Particle Detectors are devices that detect, track, and identify ionizing particles produced by nuclear decay, cosmic radiation, or particle accelerator reactions. In addition to reporting the presence of a particle, detectors can measure its energy and other properties such as momentum, spin, charge, and identify particle type. Particle detectors are classified into numerous types, including ionization detectors, scintillation detectors, Cherenkov light detectors, transition radiation detectors, and others.

Many particle detectors work by measuring the ionization produced when charged particles pass through a medium. The detectors based on the loss of energy caused by the ionization of atoms are called gaseous detectors, such as the Wilson cloud chamber and the GM counter.



Gaseous detectors are a crucial tool in detecting and analyzing electronic signals. They convert the ionization produced by a charged particle through a gas into an electronic signal, providing accurate measurements of a particle's position or trajectory, therefore, they are also known as tracking detectors. The Wilson cloud chamber is a type of tracking detector.

WILSON CLOUD CHAMBERS:

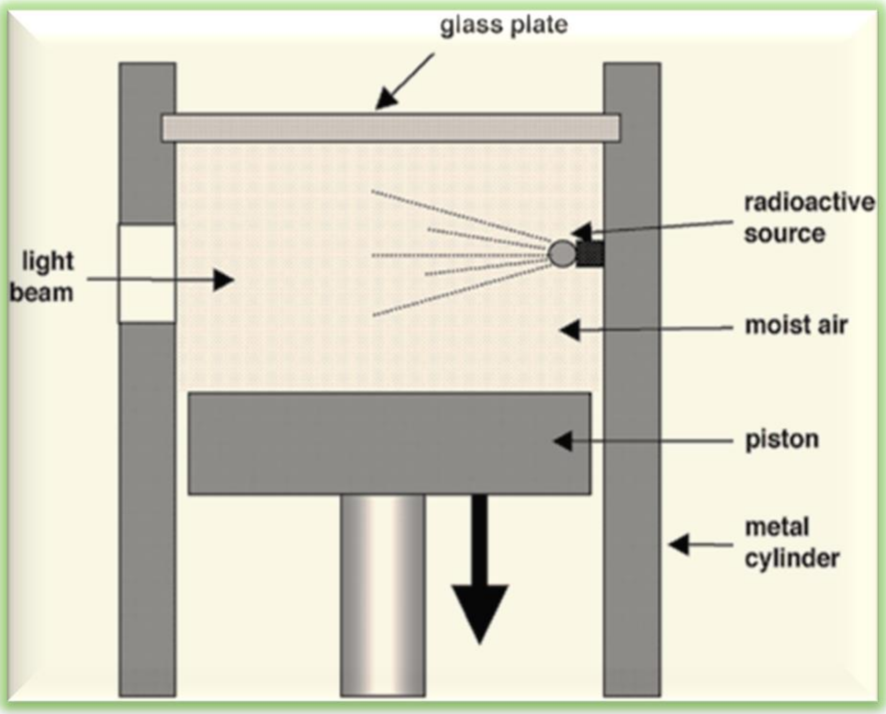
A Wilson cloud chamber is a type of tracking detector that works on the principle of ionization. It is a class of gas detectors that is used in particle physics and nuclear physics to visualize the tracks of subatomic particles such as electrons, positrons, alpha particles, and cosmic rays. It was invented by Scottish physicist Charles Thomson Rees Wilsoninl912 and played a crucial role in the early discoveries of subatomic particles.

Working Principle:

The Wilson Cloud Chamber consists of a sealed container filled with a supersaturated vapor, typically water or ethanol. When a particle passes through the chamber, it ionizes the vapor, creating a trail of droplets that condense around the ionized path. This creates a visible cloud-like track that can be photographed and analyzed.

CONSTRUCTION

It consists of a closed cylindrical chamber with a transparent glass top "I" and a movable piston on the bottom. On the sides near the top, the cylinder is provided with a glass window for light and the ionizing particles or radiation. A lever can move the piston up or down. Before making the enclosed space above the piston airtight, enough low-boiling-point liquid, such as water or alcohol, is introduced to produce its saturated vapors. A small quantity of the liquid remains.



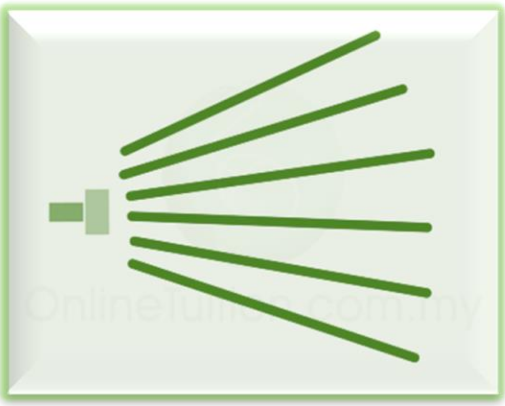
WORKING

When the piston moves down rapidly, adiabatic expansion of the air inside the chamber takes place. The piston is connected to a large evacuated vessel F through a valve V. When the valve is opened, the air under the piston rushes into the evacuated vessel F, thereby causing the piston to drop suddenly. The wooden blocks reduce the air space inside the piston. Water at the bottom of the apparatus ensures saturation in the chamber. The expansion ratio can be adjusted by altering the height of the piston.

As soon as the gas in the expansion chamber is subjected to sudden expansion, the ionizing particles are shot into the chamber through a side window. A large number of extremely fine droplets are formed on all the ions produced by the ionizing particles. These droplets form a track of the moving ionizing particles

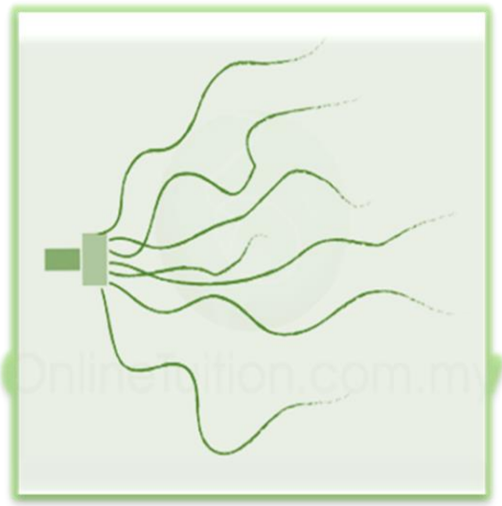
ALPHA PARTICLE TRACKS.

Tracks are straight and thick. This shows that alpha particles are very strongly ionizing. The tracks are of different lengths if the alpha particles have different amounts of kinetic energy



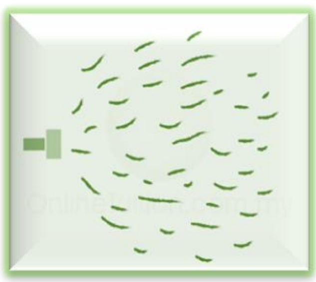
BETA PARTICLE TRACKS.

Tracks are twisted and thinner. The twisted tracks show that beta particles are easily deviated by collision with vapor molecules. The thinner tracks show beta particles less ionizing compared to the alpha particles.



GAMMA PARTICLE TRACKS.

Tracks are short, thinner, and irregular. This shows that gamma particles are the least ionizing



Use of Wilson Cloud Chambers:

- **Particle Identification**: Wilson cloud chambers were historically instrumental in the identification and study of subatomic particles. By observing the curvature of particle tracks in a magnetic field and the nature of the tracks themselves, scientists could identify and classify various particles.
- **Nuclear Physics Research**: Cloud chambers have been used to study the behavior of particles in nuclear reactions and to investigate the structure of atomic nuclei.
- Cosmic Ray Studies: Wilson cloud chambers are also used in cosmic ray research. These instruments can detect and track the passage of cosmic rays, which are high- energy particles originating from space.
- **Education and Outreach**: Cloud chambers are often used as educational tools in physics classrooms and science museums to help students and the general public visualize the behavior of subatomic particles.

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GEIGER–MÜLLER COUNTER

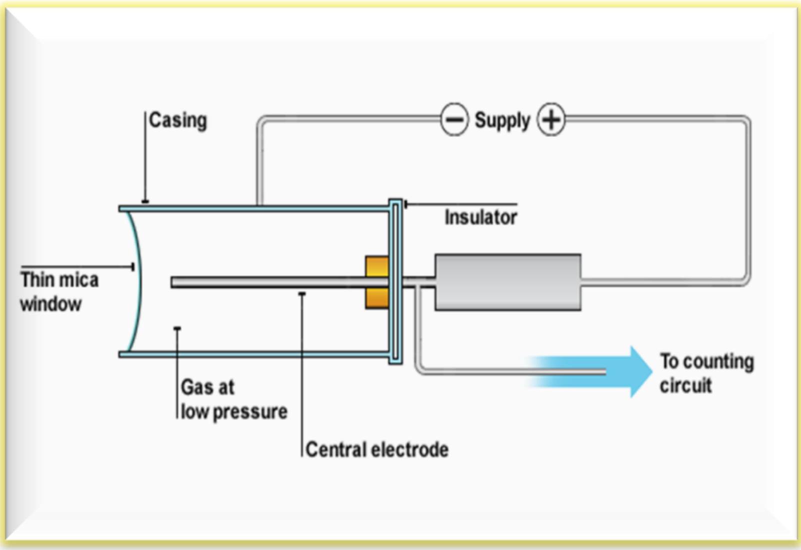
A Geiger–Müller counter (or GM tube) is the sensing element of a Geiger counter instrument that can detect a single particle of ionizing radiation, and typically produce an audible click for each. The Geiger-Muller (GM)counter was invented by two scientists Hans Geiger and Walther Muller, in 1908

CONSTRUCTION

The GM counter consists of a hollow metallic chamber, as shown in the figure, that acts as a cathode.

A thin wire anode is also placed along its axis. The chamber has a sealed window through which the radiation enters the chamber. The chamber is filled with an inert gas at low pressure.

There is a counter connected to this system to measure the radiation.

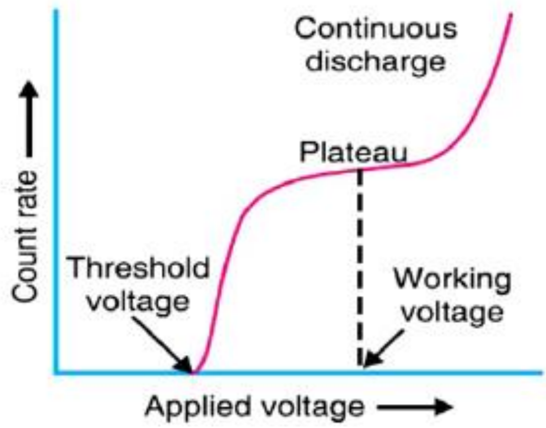


WORKING

The chamber is filled with an inert gas (helium, neon, or argon) at low pressure. A high voltage is Applied to this chamber. The metallic chamber will conduct electricity. When radiation enters the chamber through the window, the photons in the radiation will ionize the inert gas inside the chamber. This will make the gas conductive. The electrons produced due to ionization are accelerated due to the potential that we applied, and these electrons cause even more ionization. The ionized electrons travel towards the anode. The anode is connected to a counter. The counter counts the electrons reaching the anode. This is how we measure radiation.

Resultant Curve: Geiger Plateau

The performance of a GM counter is typically illustrated by the Geiger Plateau curve, which shows the count rate versus the applied voltage.



1. Initial Region:

At low voltages, no significant ionization occurs, so the count rate is very low.

2. Threshold Region:

As voltage increases, the counter starts to detect ionizing events. The count rate begins to rise sharply.

3. Geiger Plateau:

At a certain voltage range, the count rate levels off and remains relatively constant. This is the operational region of the GM counter. The plateau indicates that each ionizing event is creating a detectable pulse, and the counter is functioning reliably.

4. Continuous Discharge Region:

If the voltage is increased too much, continuous discharge occurs, where the counter no longer operates correctly, and the count rate rises rapidly again.

Use of GM Counter:

Geiger-Muller counters have a wide range of applications, including:

- **Radiation Monitoring:**
  They are commonly used for radiation monitoring in nuclear power plants, laboratories, and industrial settings to measure radiation levels and ensure the safety of workers and the environment."
- **Environmental Monitoring**:
  GM counters are employed for environmental radiation monitoring to assess the background radiation levels and detect any abnormal increases in radiation.
- **Health Physics**:
  Health physicists use GM counters to monitor the radiation exposure of individuals working with radioactive materials or in radiation-prone environments.
- **Education:**
  Health physicists use GM counters to monitor the radiation exposure of individuals working with radioactive materials or in radiation-prone environments.
- **Radiological Emergencies:**
  In the event of radiological emergencies or accidents involving radioactive materials, GM counters It can be used to assess radiation contamination levels.