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Elementary Particles

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Abstract:
Elementary-particle Physics deals with the fundamental constituents of matter and their interactions. In the past several decades an enormous amount of experimental information has been accumulated, and many patterns and systematic features have been observed. Highly successful mathematical theories of the electromagnetic, weak, and strong interactions have been devised and tested. These theories, which are collectively known as the standard model, are almost certainly the correct description of Nature, to first approximation, down to a distance scale 1/1000th the size of the atomic nucleus. There are also speculative but encouraging developments in the attempt to unify these interactions into a simple underlying framework, and even to incorporate quantum gravity in a parameter-free "theory of everything." In this article we shall attempt to highlight the ways in which information has been organized, and to sketch the outlines of the standard model and its possible extensions. Through this paper, we plan to look at ***Elementary Particles*** *in detail and address the following questions:*

- *What are elementary particles?*
- *How did we come to know of their existence?*
- *Discoveries behind the elementary particles in bubble chambers.*
- *Standard Model.*

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I. What are Elementary Particles

Elementary particles are the **smallest known building blocks of the universe.** They are thought to have no **internal structure**, meaning that researchers think about them as **zero-dimensional points that take up no space**. **Electrons** are probably the **most familiar elementary particles**, but the **Standard Model** of physics, which describes the interactions of particles and almost all forces, **recognizes 10 total elementary particles**.

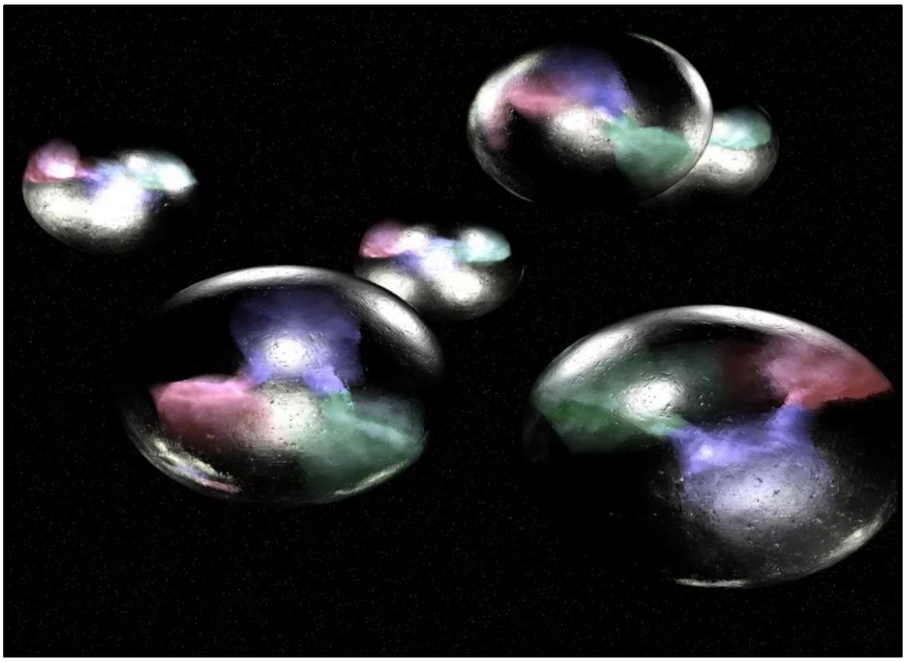


Image representing the different types of Quarks

Leptons(Electrons and Related Particles):

Electrons are the **negatively charged** components of atoms. While they are thought to be **zero-dimensional point particles**, electrons are surrounded by a cloud of other virtual particles constantly going in and out of existence, that essentially act as part of the electron itself. Some theories have predicted that the electron has a slightly positive pole and a slightly negative pole, meaning that this cloud of virtual particles surrounding it should therefore be a bit asymmetrical.

If this were the case, electrons might behave differently than their antimatter doubles, positrons, potentially explaining many mysteries about matter and antimatter. But physicists have repeatedly measured the shape of an electron and found it to be perfectly round to the best of their knowledge, leaving them without answers for antimatter conundrums.

Similar to the electron, there are two other particles called the muon and the tau. Muons can be created when high-energy cosmic rays from outer space hit the top of Earth's atmosphere, generating a shower of rare particles. Taus are even rarer and harder to produce, as they are more than 3,400 times heavier than electrons. Neutrinos, electrons, muons and taus make up a category of fundamental particles called leptons.

Quarks:

Quarks, which make up **protons** and **neutrons**, are another type of fundamental particle. Together with the leptons, quarks make up matter.

Quarks+Leptons=Matter

Once upon a time, scientists believed that atoms were the smallest possible objects; the word comes from the Greek "atomos," meaning "indivisible." Around the turn of the 20th century, atomic nuclei were shown to consist of protons and neutrons. Then, throughout the 1950s and '60s, particle accelerators kept revealing a bevy of exotic subatomic particles, such as pions and kaons.

In 1964, physicists Murray Gell-Mann and George Zweig independently proposed a model that could explain the inner workings of protons, neutrons and the rest of the particle zoo. Residing inside protons and neutrons are tiny particles called quarks, which come in six possible types: up, down, strange, charm, bottom, and top.

Protons are made from two up quarks and a down quark, while neutrons are composed of two downs and an up. The up and down quarks are the lightest varieties. Because more-massive particles tend to decay into smaller particles, the up and down quarks are also the most common in the universe; therefore, protons and neutrons make up most of the known matter.

By 1977, physicists had isolated five of the six quarks in the lab — up, down, strange, charm and bottom — but it wasn't until 1995 that researchers at Fermilab National Accelerator Laboratory in Illinois found the final quark, the top quark. Searching for it had been as intense as the later hunt for the Higgs boson. The top quark was so hard to produce because it's about 100 trillion times heavier than up quarks, meaning it required a lot more energy to make in particle accelerators.

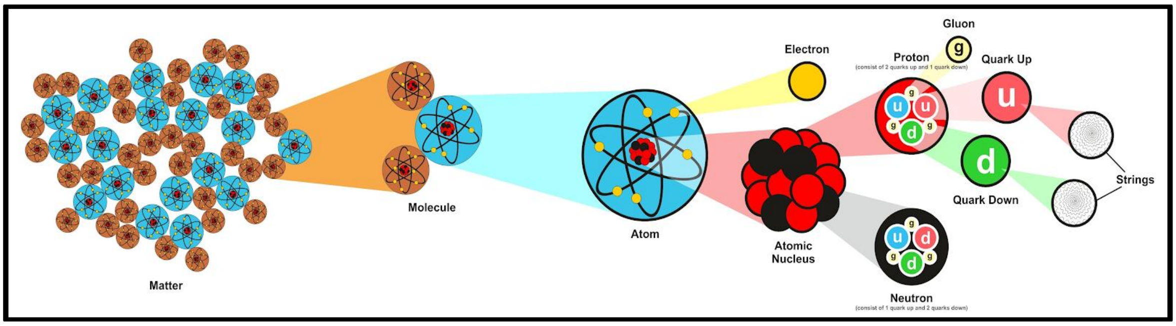


Diagram Representing how Quarks fit into our understanding of subatomic particles

Nature's Fundamental Particles:

There are the **four fundamental forces of nature: electromagnetic radiations, gravity, and the strong and weak nuclear forces.** Each of these has an associated fundamental particle.

Photons are the most well-known, and they carry the **electromagnetic force**. **Gluons** carry the **strong nuclear force** and **reside with quarks inside of protons and neutrons.** The **weak force**, which mediates certain nuclear reactions, is carried by two fundamental particles, the **W and Z bosons**. **Neutrinos**, which only feel the weak force and gravity, **interact with these bosons**, and so physicists were able to first provide evidence for their existence using neutrinos, according to CERN.

Gravity is an outsider here. It isn't incorporated into the Standard Model, though physicists suspect that it could have an associated fundamental particle, which would be called the **graviton**. If gravitons exist, it might be possible to create them at the Large Hadron Collider (LHC) in Geneva, Switzerland, but they would rapidly disappear into extra dimensions, leaving behind an empty zone where they would have been, according to CERN. So far, the LHC has seen no evidence of gravitons or extra dimensions.

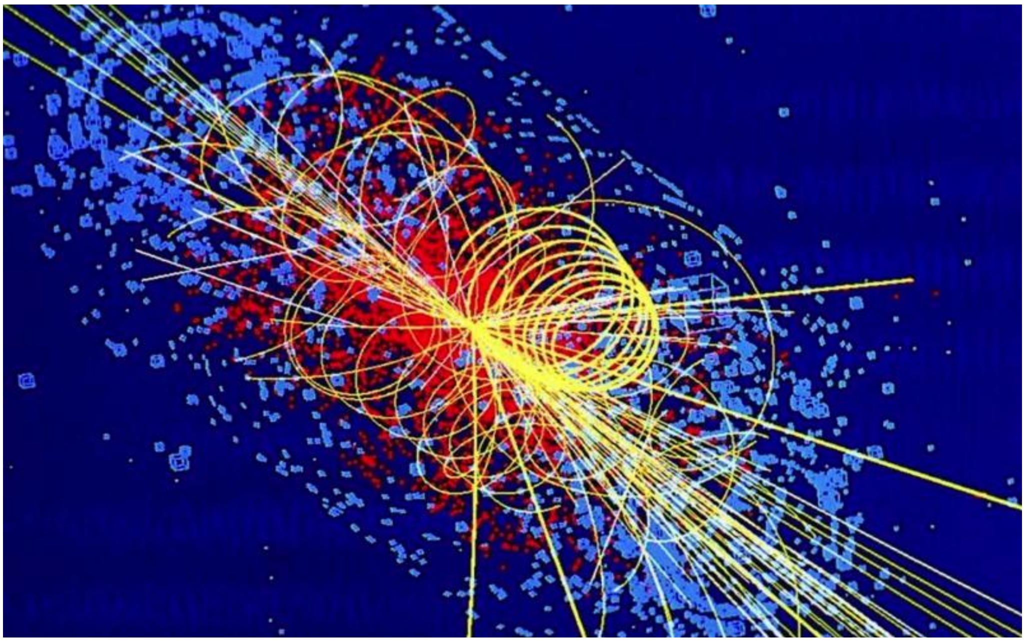
Table showing Fundamental Forces and their Associated Particle

Fundamental Force	**Associated Particle**
Electromagnetic Force	Photons
Strong Nuclear Force	Gluons
Weak Nuclear Force	W and Z Bosons
Gravitational Force	Graviton

Higgs Boson:

Higgs boson, the king of the elementary particles, is responsible for **giving all other particles their mass**. Hunting for the Higgs was a major endeavor for scientists striving to complete their catalog of the Standard Model. When the Higgs was finally spotted, in **2012**, physicists rejoiced, but the results have also left them in a difficult spot.

The Higgs looks pretty much exactly like it was predicted to look, but scientists were hoping for more. The Standard Model is known to be incomplete; for instance, it lacks a description of gravity, and researchers thought finding the Higgs would help point to other theories that could supersede the Standard Model. But so far, they have come up empty in that search.



Simulation showing the production of Higgs boson in the collision of 2 protons in the Large Hadron Collider,.

II. How did we come to know of the existence of Elementary Particles

Discovery of Leptons:

The first lepton identified was the **electron**, discovered by J.J. Thomson and his team of British physicists in 1897 in the famous **Cathode Ray Experiment**. Then in 1930, Wolfgang Pauli postulated the electron neutrino to preserve conservation of energy, conservation of momentum, and conservation of angular momentum in beta decay. Pauli theorized that an undetected particle was carrying away the difference between the energy, momentum, and angular momentum of the initial and observed final particles. The electron neutrino was simply called the neutrino, as it was not yet known that neutrinos came in different flavours/generations.

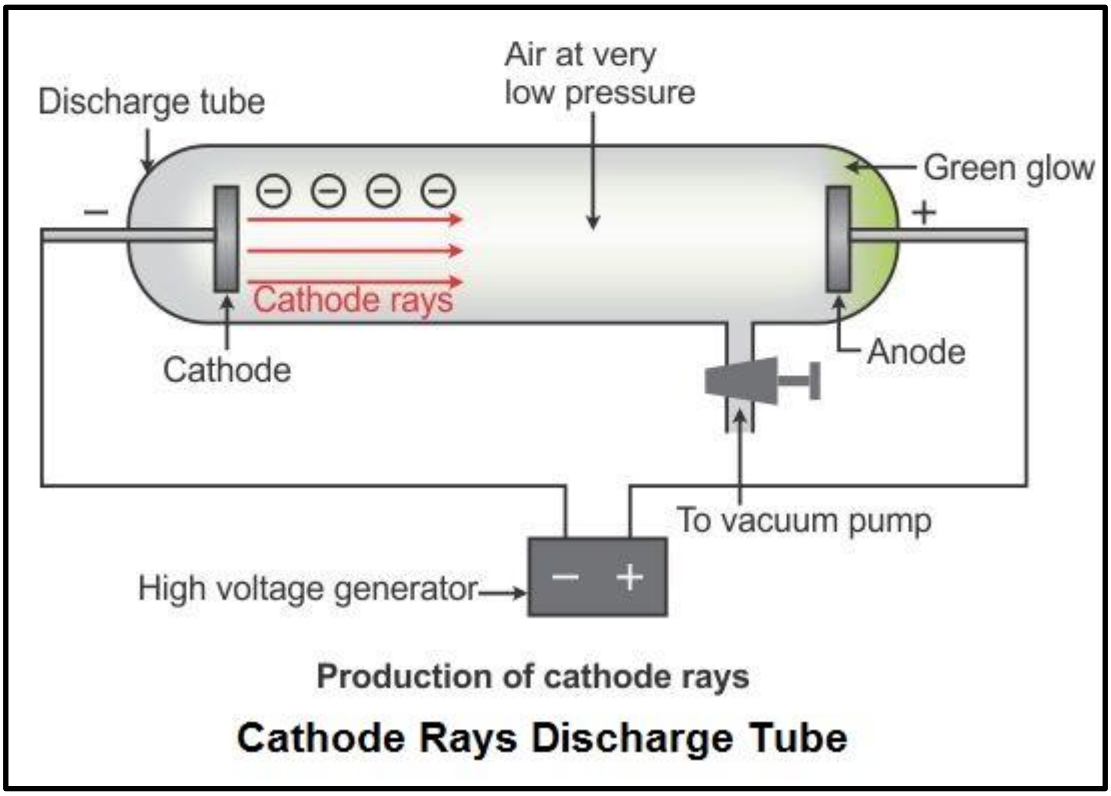


Diagram representing Cathode Ray Experiment for the discovery of Electron

Nearly 40 years after the discovery of the electron, the **muon** was discovered by Carl D. Anderson in 1936. Due to its mass, it was initially categorized as a meson rather than a lepton. It later became clear that the muon was much more similar to the electron than to mesons, as muons do not undergo the strong interaction, and thus the muon was reclassified: electrons, muons, and the (electron) neutrino were grouped into a new group of particles—the leptons. In 1962, Leon M. Lederman, Melvin Schwartz, and Jack Steinberger showed that more than one type of neutrino exists by first detecting interactions of the muon neutrino, which earned them the 1988 Nobel Prize, although by then the different flavours of neutrino had already been theorized.

The **tau** was first detected in a series of experiments between 1974 and 1977 by Martin Lewis Perl with his colleagues at the SLAC LBL group. Like the electron and the muon, it too was expected to have an associated neutrino. The first evidence for tau neutrinos came from the observation of "missing" energy and momentum in tau decay, analogous to the "missing" energy and momentum in beta decay leading to the discovery of the electron neutrino. The first detection of tau neutrino interactions was announced in 2000 by the DONUT collaboration at Fermilab, making it the second-to-latest particle of the Standard Model to have been directly observed, with Higgs boson being discovered in 2012.

Discovery of Quarks:

In 1964, two physicists independently proposed the existence of the subatomic particles known as quarks. Physicists Murray Gell-Mann and George Zweig were working independently on a theory for strong interaction symmetry in particle physics. Within this framework, they proposed that important properties of the strongly interacting particles – hadrons – could be explained if they were made up of constituent particles.

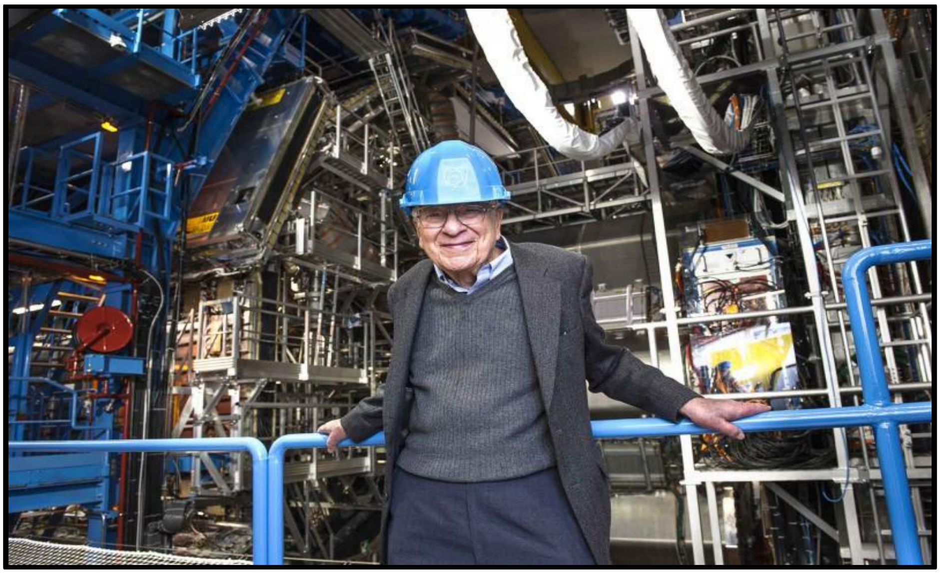


Image showing Murray Gell-Mann at CERN

In 1961 Gell-Mann had introduced a symmetry scheme he called the Eightfold Way, which was based on the mathematical symmetry known as SU(3). The scheme (for which he received the Nobel prize in physics in 1969) classified the hadrons into two main groups, rather as the Periodic Table classifies the chemical elements.

Gell-Mann built upon this work in a new model that could successfully describe – among other things – the magnetic properties of protons and neutrons. But Gell-Mann's model required the existence of three new elementary particles, which he called "quarks."

Gell-Mann says that he first came up with the sound "quork", and later chanced upon the phrase "Three quarks for Muster Mark" in James Joyce's Finnegans Wake. As Joyce presumably intended the word to rhyme with "Mark", people have been divided on the pronunciation ever since.

Physicist George Zweig made his contribution to the field while he was a visitor to CERN in a paper dated 17 January 1964, in which he proposed: "Both mesons and baryons are constructed from a set of three fundamental particles called aces." Though Zweig's name for the particles did not stick, he showed that some properties of hadrons could be explained by treating them as triplets of other constituent particles.

Image showing George Zweig at CERN

Both Gell-Mann's quarks and Zweig's aces had to have electrical charges equal to 1/3 or 2/3 that of an electron or proton, suggesting that an experimental search for these constituents would reveal whether or not they existed.

In 1968, a series of electron-proton scattering experiments by the MIT-SLAC collaboration at the Stanford Linear Accelerator Center (SLAC) in the US revealed the first signs that nucleons have an inner structure. The team fired electrons at protons and observed how the electrons bounced off. The scattering patterns were identified as being caused by point-like particles inside the protons. In the subsequent years, by combining these results with others from neutrino-scattering in the Gargamelle bubble chamber at CERN, it became clear that these constituents really do have charges of 1/3 and 2/3.

Quarks are now a key part of the Standard Model. In numerous experiments at CERN including those at the Large Hadron Collider (LHC), physicists are measuring the properties of Gell-Mann and Zweig's particles with ever-greater precision.

Discovery of Higgs boson:

In the 1970s, physicists realised that there are very close ties between two of the four fundamental forces – the weak force and the electromagnetic force. The two forces can be described within the same theory, which forms the basis of the Standard Model. This "unification" implies that electricity, magnetism, light and some types of radioactivity are all manifestations of a single underlying force known as the electroweak force.

The basic equations of the unified theory correctly describe the electroweak force and its associated force-carrying particles, namely the photon, and the W and Z bosons, except for a major glitch. All of these particles emerge without a mass. While this is true for the photon, we know that the W and Z have mass, nearly 100 times that of a proton. Fortunately, theorists Robert Brout, François Englert and Peter Higgs made a proposal that was to solve this problem. What we now call the Brout-Englert-Higgs mechanism gives a mass to the W and Z when they interact with an invisible field, now called the "Higgs field", which pervades the universe.

At CERN on 4 July 2012, the ATLAS and CMS collaborations present evidence in the LHC data for a particle consistent with a Higgs boson, the particle linked to the mechanism proposed in the 1960s to give mass to the W, Z and other particles.

Just after the big bang, the Higgs field was zero, but as the universe cooled and the temperature fell below a critical value, the field grew spontaneously so that any particle interacting with it acquired a mass. The more a particle interacts with this field, the heavier it is. Particles like the photon that do not interact with it are left with no mass at all. Like all fundamental fields, the Higgs field has an associated particle – the Higgs boson. The Higgs boson is the visible manifestation of the Higgs field, rather like a wave at the surface of the sea.

A problem for many years has been that no experiment has observed the Higgs boson to confirm the theory. On 4 July 2012, the ATLAS and CMS experiments at CERN's Large Hadron Collider announced they had each observed a new particle in the mass region around 125 GeV. This particle is consistent with the Higgs boson but it will take further work to determine whether or not it is the Higgs boson predicted by the Standard Model. The Higgs boson, as proposed within the Standard Model, is the simplest manifestation of the Brout-Englert-Higgs mechanism. Other types of Higgs bosons are predicted by other theories that go beyond the Standard Model.

On 8 October 2013 the Nobel prize in physics was awarded jointly to François Englert and Peter Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

III. Discoveries behind the Elementary Particles in Bubble Chambers

Bubble Chamber:

Bubble chamber is a **radiation detector** that uses a **superheated liquid that boils into tiny bubbles of vapour around the ions produced along the tracks of subatomic particles as the detecting medium**. The bubble chamber was **developed** in **1952** by the American physicist **Donald A. Glaser**.

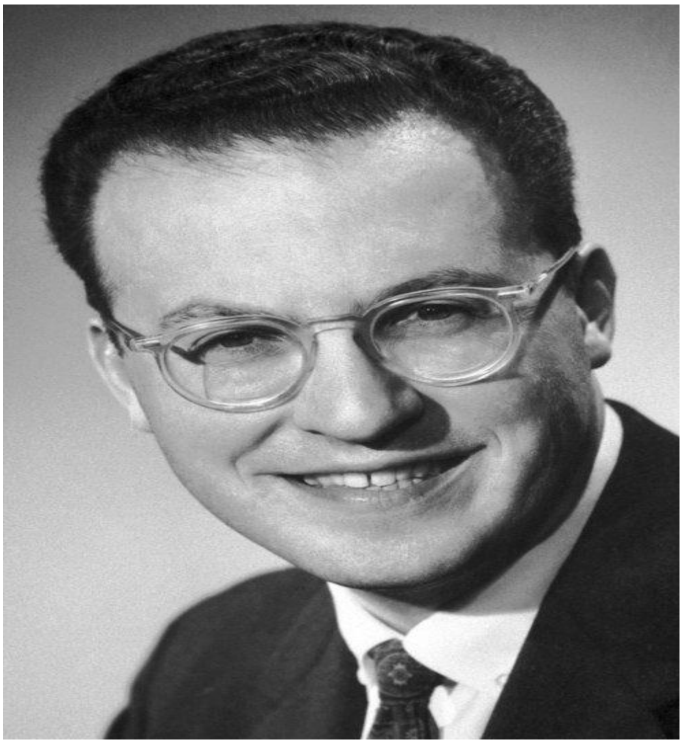


Image showing Donald Arthur Glasser

The Bubble Chamber makes use of the fact that a liquid's boiling point increases with pressure. It consists of a pressure-tight vessel containing liquid (often liquid hydrogen) that is maintained under high pressure but below its boiling point of that particular pressure. When the pressure on the liquid is suddenly reduced, the liquid becomes superheated;in other words, the liquid is above its normal boiling point at the reduced pressure. As charged particles travel through the liquid, tiny bubbles form along the particle tracks. By photographing the bubble trails it is possible to record the particle tracks, and the photographs can be analyzed to make precision measurements of the processes caused by the high-speed particles. Because of the relatively high density of the bubble-chamber liquid (as opposed to vapour-filled cloud chambers), collisions producing rare reactions are more frequent and are observable in fine detail. New collisions can be recorded every few seconds when the chamber is exposed to bursts of high-speed particles from particle accelerators. The bubble chamber proved very useful in the study of high-energy nuclear physics and subatomic particles, particularly during the 1960s.

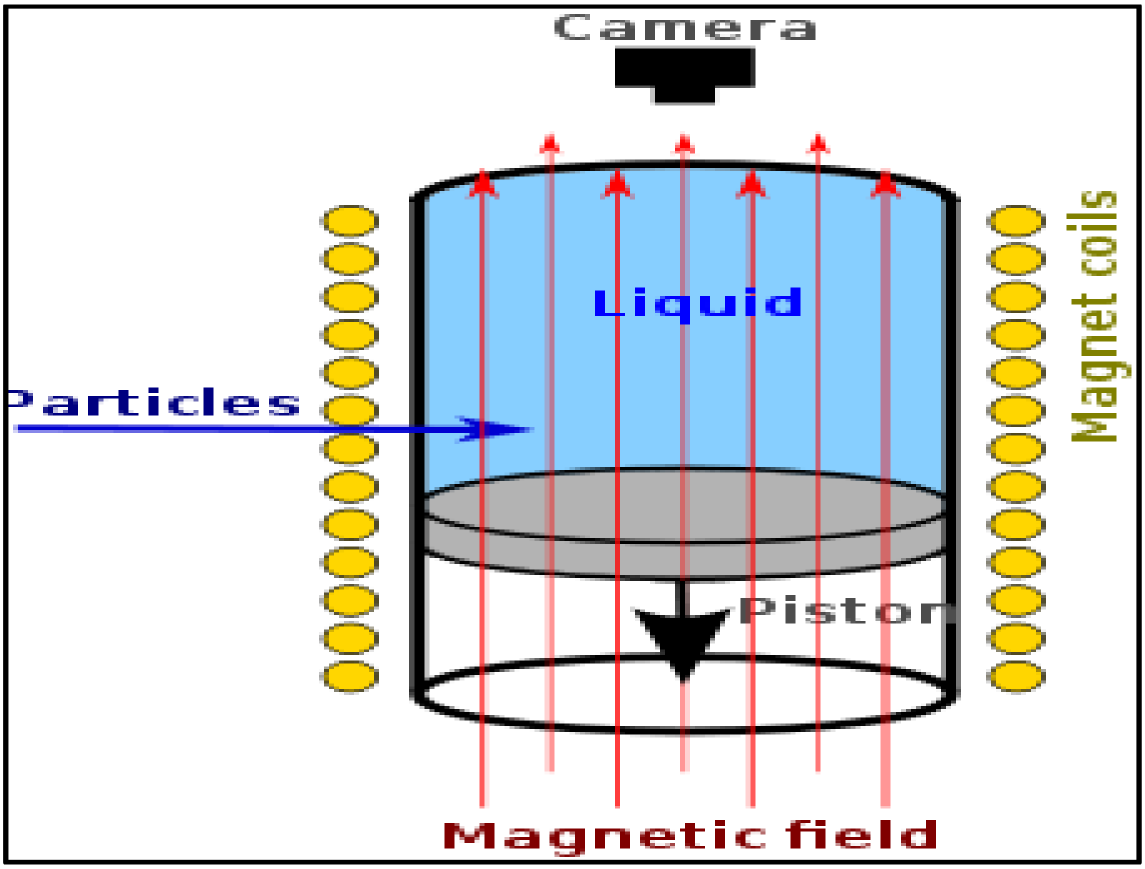


Diagram showing a simplified version of the Bubble Chamber

Discoveries in the Bubble Chamber:
The main scientific legacy of the Bubble Chamber towards our understanding of the microworld of physics particles forms an impressive list which includes:

- **Strange Particles**:are the members of a large family of elementary particles carrying the quantum number of strangeness, including several cases where the quantum number is hidden in strange/antistrange pairs. **Ex:Omega-Minus**
- **Meson and Hadron Resonances**
- **Hadron Spectrum**
- **Dynamical Quarks**
- Discovery of **Weak Neutral Currents** at Gargamelle in 1973, which established the soundness of the **Electroweak Theory** and led to the discovery of the **W and Z bosons in 1983.**
- Bubble Chambers are also being used to study **Weakly Interacting Massive Particles**, which are hypothetical particles that have been proposed as a candidate for **Dark Matter**.

IV. Standard Model

The theories and discoveries of thousands of physicists since the 1930s have resulted in a remarkable insight into the fundamental structure of matter: everything in the universe is found to be made from a few basic building blocks called fundamental particles, governed by four fundamental forces. Our best understanding of how these particles and three of the forces are related to each other is encapsulated in the Standard Model of particle physics. Developed in the early 1970s, it has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena. Over time and through many experiments, the Standard Model has become established as a well-tested physics theory.

Matter Particles:
All matter around us is made of elementary particles, the building blocks of matter. These particles occur in two basic types called quarks and leptons. Each group consists of six particles, which are related in pairs, or "generations". The lightest and most stable particles make up the first generation, whereas the heavier and less-stable particles belong to the second and third generations. All stable matter in the universe is made

from particles that belong to the first generation; any heavier particles quickly decay to more stable ones. The six quarks are paired in three generations – the "up quark" and the "down quark" form the first generation, followed by the "charm quark" and "strange quark", then the "top quark" and "bottom (or beauty) quark". Quarks also come in three different "colours" and only mix in such ways as to form colourless objects. The six leptons are similarly arranged in three generations – the "electron" and the "electron neutrino", the "muon" and the "muon neutrino", and the "tau" and the "tau neutrino". The electron, the muon and the tau all have an electric charge and a sizable mass, whereas the neutrinos are electrically neutral and have very little mass.

Forces and Carrier Particles:

There are four fundamental forces at work in the universe: the strong force, the weak force, the electromagnetic force, and the gravitational force. They work over different ranges and have different strengths. Gravity is the weakest but it has an infinite range. The electromagnetic force also has infinite range but it is many times stronger than gravity. The weak and strong forces are effective only over a very short range and dominate only at the level of subatomic particles. Despite its name, the weak force is much stronger than gravity but it is indeed the weakest of the other three. The strong force, as the name suggests, is the strongest of all four fundamental interactions.

Three of the fundamental forces result from the exchange of force-carrier particles, which belong to a broader group called "bosons". Particles of matter transfer discrete amounts of energy by exchanging bosons with each other. Each fundamental force has its own corresponding boson – the strong force is carried by the "gluon", the electromagnetic force is carried by the "photon", and the "W and Z bosons" are responsible for the weak force. Although not yet found, the "graviton" should be the corresponding force-carrying particle of gravity. The Standard Model includes the electromagnetic, strong and weak forces and all their carrier particles, and explains well how these forces act on all of the matter particles. However, the most familiar force in our everyday lives, gravity, is not part of the Standard Model, as fitting gravity comfortably into this framework has proved to be a difficult challenge. The quantum theory used to describe the micro world, and the general theory of relativity used to describe the macro world, are difficult to fit into a single framework. No one has managed to make the two mathematically compatible in the context of the Standard Model. But luckily for particle physics, when it comes to the minuscule scale of particles, the effect of gravity is so weak as to be negligible. Only when matter is in bulk, at the scale of the human body or of the planets for example, does the effect of gravity dominate. So the Standard Model still works well despite its reluctant exclusion of one of the fundamental forces.

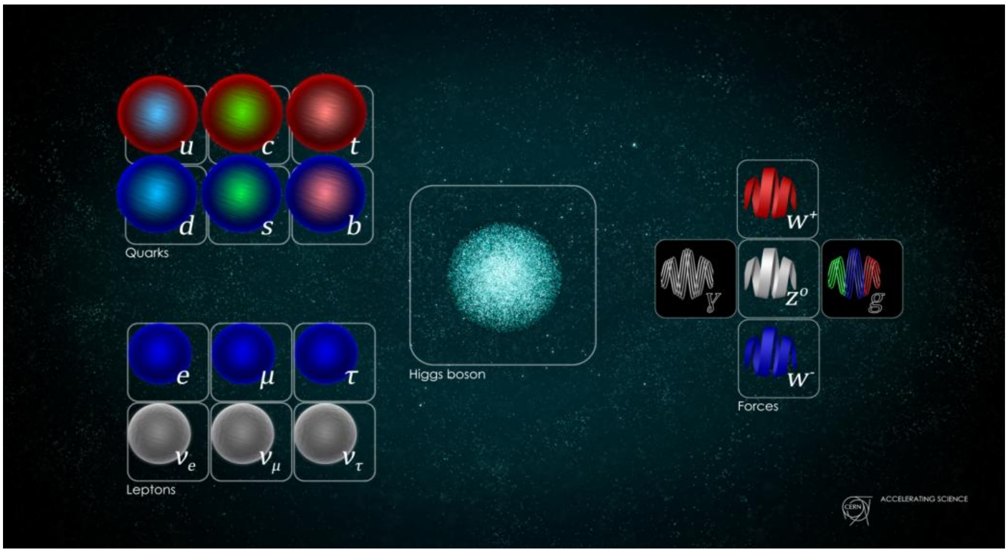


Image showing the different particles and forces of the Standard Model

Drawbacks of the Standard Model:

Even though the Standard Model is currently the best description there is of the subatomic world, it does not explain the complete picture. The theory incorporates only three out of the four fundamental forces, omitting gravity. There are also important questions that it does not answer, such as "What is dark matter?", or "What happened to the antimatter after the big bang?", "Why are there three generations of quarks and leptons with such a different mass scale?" and more. Last but not least is a particle called the Higgs boson, an essential component of the Standard Model.

So although the Standard Model accurately describes the phenomena within its domain, it is still incomplete. Perhaps it is only a part of a bigger picture that includes new physics hidden deep in the subatomic world or in the dark recesses of the universe. New information from experiments at the LHC will help us to find more of these missing pieces.

V. Conclusion

Through this paper, we got in depth information about elementary particles and their discoveries. The conclusions of this paper are:

I. Elementary particles are the smallest building blocks of matter. They consist of:

A. Leptons-electrons, mouns, taus, and their neutrinos

B. 6 flavours or types of Quarks-up, down, strange, charm, bottom, and top quarks-which combine to form protons and neutrons

C. Higgs boson

D. 4 fundamental forces of nature and their associated particles-Electromagnetic forces and photons, Strong Nuclear Forces and Gluons, Weak Nuclear Forces and W and Z bosons, and Gravity and Gravitons(yet to be discovered)

II. Leptons and Quarks together form Matter

III. The Bubble Chamber is a radiation detector developed by Donald Arthur Glaser and uses superheated liquids below their boiling point at high pressure to observe particles and ions. It was responsible for the ultimate discovery of W and Z bosons.

IV. The Standard Model utilises Leptons, Quarks, Higgs boson, and the 4 fundamental forces of nature to give the best description of the subatomic world which is consistent with most of the experimental results. However, it still has drawbacks such as the fact that it only incorporates 3 of the 4 fundamental forces of nature, omitting gravity, and even the discovery of the Higgs boson did not live upto the expectations of the scientists, and failed to provide them with a fundamental theory that supersedes all other theories. This leaves a lot of room for future studies and discoveries in the subatomic world as the hunt for a theory which accurately explains all subatomic phenomena.

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