Additional Advanced Particle Physics Concepts

Group 6, 11B

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1 Hideki Yukawa's Particle and the Heisenberg Uncertainty Principle

Hideki Yukawa was a Japanese theoretical Physicist who contributes for the understanding of strong nuclear force. He was interested in the strong nuclear force (force that binds protons and neutrons within the nucleus) and the interaction between neutrons and protons. He proposed a great idea about the existence of mesons (theory of mesons) to explain how neutron and proton interact. Also, he proposed that force is transmitted by **carrier particles**- particles that give rises to forces between other particles. In addition to this, Yukawa launched a field which is known as quantum chromodynamics. For this prediction, he won Noble Prize in 1949. These days, the meson theory seems to be a straightforward application of quantum field theory to the nuclear forces.

Yukawa's particles are called pi mesons or pions, are subatomic particle that are the lightest mesons and, more generally, the lightest hadrons. Pions feel strong nuclear force, weak nuclear force, electromagnetic force and gravity. Mainly they feel the strong nuclear force. Pions are not produced by radioactive decay, but pions are produced by natural processes when high-energy cosmic-ray protons and other hadronic cosmic-ray components interact with matter in Earth's atmosphere.

In fig 1, the strong nuclear force is transmitted within the nucleus between protons and neutrons. Force needs carrier particle to transfer. In this process,

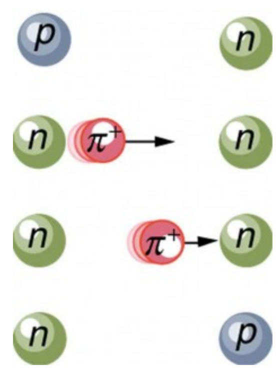


Figure 1: Transmission of strong force by the exchange of a pion.

pion is the carrier which is not directly observable but there effect can be observed and that's why it is called virtual carrier. Since the pion is created and exchanged, the conservation of mass- energy violated temporarily. This range of force is limited because pions (the force carriers) have finite mass. According to Heisenberg's uncertainty principle, if pions have finite mass, it will have limited lifetime and pions decay into other particles after a short distance.

Heisenberg's Uncertainty principle is formulated by a German Physicist Werner Heisenberg in 1927. It states that, it is impossible to determine the accurate value of pairs of quantum variables such as momentum and position, simultaneously. $\Delta x \Delta p \geq \frac{h}{4\pi}$

It explains why a scientist cannot measure multiple quantum variables simultaneously. It is also applied in energy and time.We cannot measure the precise energy of a system in a finite amount of time.

$\Delta t \Delta E \geq \frac{h}{4\pi}$

By using Heisenberg's uncertainty principle, Yukawa was able to calculate the mass of these carriers because pions occur for short period of time.

$$\Delta E \Delta t \geq \frac{h}{4\pi}, \Delta t \geq \frac{\hbar}{4\pi \Delta E}$$

The maximum distance is d$\approx c\Delta t$ where c is speed of light. For example, taking the range of the strong nuclear force to be about 1 fermi 10^{-15}, first we have to calculate the Δt.

$\Delta t \approx \frac{d}{c}, \Delta t \approx \frac{10^{-15}}{3 \times 10^8} \approx 3.3 \times 10^-24 sec$

Then, $\Delta E = \frac{h}{4\pi \Delta t}$

ΔE= 100 Mev, then mass $=\Delta E/\mathrm{c}^2 \approx 100 Mev/c^2$

The mass of this particle is between electron and nucleon. It is one-tenth of nucleon's mass and 200 times of electron's mass. That's why, the particle is given the name meson (means *medium mass*). The mass of muon is near to the calculated mass, which is 106 Mev/c^2, due to this, it was thought to be Yukawa's particle. However, muon do not feel the strong nuclear force and; therefore, it couldn't be Yukawa's particle.

In 1947, pions were observed in cosmic-ray experiments and they were created by accelerators of sufficient energy in the laboratory. Two charged (π^+, π^-)and one neutral pions (π^0) were discovered. The charged pions have the same mass, 139.6 Mev/ c^2 and the neutral one has a mass of 136 Mev/ c^2. Their masses are close to 100 Mev/ c^2 that we claculated above. They are unstable, with the charged pions and decaying after a mean lifetime of 26 nanoseconds, and the neutral pion decaying after a much shorter lifetime of 85 attoseconds. π^+ and π^- most often decay into muons and muon neutrinos, while π^0 decay into gamma rays.

2 Recap on the Four Basic Forces

Naturally, four fundamental forces exist in the universe-that are responsible for shaping the universe we inhabit and governs everything that happen in the universe: from the very small to the very large to those that we experience in our day-to-day lives. These forces are gravity, strong, electromagnetism, and weak nuclear forces. These all forces exchange a force carrier and affect all matter. These force are responsible for holding our feet on the ground, attach neutron and proton in order not to fly apart, chemical reaction of atoms and molecules, friction, light, keeping electron in its orbit, the interaction between fundamental particles like quarks, radio activity, movement of planets and galaxies and so on.

2.1 Gravity

Gravity is the most familiar force and weakest force that we experience in every second. It is responsible for keeping us on the ground as well as planets in their orbit. Gravity is an attractive force that draws two objects together. It acts on all particles including the mass less photon. The force carrier is **graviton**. It depends on object's mass and distance of separation, but it acts at infinity. Issac Newton was the first person to propose the idea of gravity. He described gravity is a literal attraction between objects. In present-days, the most accurate theory to explain gravitation is **General Theory of Relativity** interms of geometry of space-time. According to the theory of general relativity, gravity is the result of distortions in space-time created by mass and energy.

2.2 Electromagnetism

The electromagnetic force, given scientific definition by James Clerk Maxwell in the 19th century, acts on electrically charged particles such as quarks, leptons. It is responsible for the repulsion of like and the attraction of unlike electric charges. As the name indicates, it consists of electric and magnetic force. The force carrier particle is the mass less **photon**. Just like gravity, the magnitude of this force is inversely proportional to the square of the distance between charges. While electromagnetism is stronger than gravity, it is often balanced out in large objects by the equal numbers of positive and negative charges that form neutral atoms.

2.3 The Strong Nuclear Force

The strong nuclear force is an attractive force that exists with in all nucleons. It acts on quarks (color charged particles) but leptons can't feel. It holds quarks together to form hadrons. The strong nuclear force is the strongest of all forces;however, it exists at short range. At 10^{-15} m , the force become zero. The force carrier particle is Pi mesons or pions (now known as **gluons**). It explains the question how the nucleus is held together in the atom.

2.4 The Weak Nuclear Force

The Weak Nuclear Force is responsible for particle decay. This is the literal change of one type of subatomic particle into another. The Weak Nuclear Force acts on quarks and leptons. The force carriers are W^+, W^- and Z^0 bosons. When a quark or a lepton changes its type, it is said to be flavour change.

3 Cyclotrons

Cyclotron is particle accelerator introduced by E.O. Lawrence in 1931 and was awarded the 1939 Nobel prize in physics for this invention. This particle accelerator uses electromagnetic field to propel charged particles to very high speed and energies.Particle accelerators are devices used to accelerate and thus imparts high kinetic energy to charged particles and produces a beam of high-energy particles by using electrostatic or electrodynamics fields.

Cyclotron accelerates charged particles using fixed-frequency alternating electric fields. The particles accelerate in this type of machine due to the change in magnetic field, making increasingly large radius orbits during acceleration.

A cyclotron accelerates a charged particle beam using a high frequency alternating voltage which is applied between two hollow "D"-shaped sheet metal electrodes known as the "dees" inside a vacuum chamber. The dees are placed face to face with a narrow gap between them, creating a cylindrical space within them for particles to move. Particles are injected into the centre of this space.

Dees are located between the poles of electromagnet which applies a static magnetic field B perpendicular to the electrode plane. The magnetic field causes the path of the particle to bend in a circle due to the Lorentz force perpendicular to their direction of motion. An alternating voltage of several thousand volts is applied between the dees. The voltage creates an oscillating electric field in the gap between the dees that accelerates the particles. The frequency of the voltage is set so that particles make one circuit during a single cycle of the voltage. To achieve this condition, the frequency must be set to the particle's cyclotron frequency.

The centripetal force required to keep the particles in a curved path is F = mv^2/r

The force on the magnetic field B is $\mathrm{F}_B = qvB$

mv^2/r=qvB

v= qBr/m, then $E = q^2B^2R^2$ /2m

4 Matter, Antimatter, and All That Fuss

4.1 What is matter?

Matter :- is a substance made up of various types of particles that occupies physical space and has inertia.They are basically made up of atoms. According to the principles of modern physics, the various types of particles each have a specific mass and size. Basically atoms are the building blocks of matter. Atoms and/or molecules in two or more elements can join together to form a compound. This compound, which is the basis of matter. The most familiar examples of material particles are the electron, the proton and the neutron. Combinations of these particles form atoms.

4.2 What is antimatter?

Antimatter:- is defined as matter composed of the antiparticles of the corresponding particles in matter, and can be thought of as matter with reversed charge, parity, and time. A particle and its antiparticle (for example, a protons and an antiprotons) have the same , but opposite electric charge, and other differences in quantum numbers. Antiparticles bind with each other to form antimatter, just as ordinary particles bind to form normal matter. For example, a positron (the antiparticle of the electron) and an antiproton (the antiparticle of the proton) can form an anti hydrogen atom. The nuclei of anti helium have been artificially produced, albeit with difficulty, and are the most complex anti-nuclei so far observed. Physical principles indicate that complex antimatter atomic nuclei are possible, as well as anti-atoms corresponding to the known chemical elements.

Matter and antimatter particles are always produced as a pair and, if they come in contact, annihilate one another, leaving behind pure energy – annihilation. **Annihilation** is the process that occurs when a subatomic particle collides with its respective antiparticle to produce other particles, such as an electron colliding with a positron to produce two photons. A collision between any particle and its anti-particle partner leads to their mutual annihilation, giving rise to various proportions of intense photons (gamma rays), neutrinos, and sometimes less-massive particle–antiparticle pairs. The amount of energy released is usually proportional to the total mass of the collided matter and antimatter, in accordance with the notable mass–energy equivalence equation, E= m c^2.

But now days we don't see antimatters as we see matters in our day to day life even if, their contact transforms to energy. Some researchers have tried to identify why and they made a conclusion which they observed spontaneous transformations between particles and their antiparticles, occurring millions of times per second before they decay and these particles are mainly converting to matters rather than anti matters.

5 Quarks and matter - is that it all?

Deep within the atoms that make up our bodies and even within the protons and neutrons that make up atomic nuclei, are tiny particles called quarks. Quarks are the ultimate building blocks of visible matter in the universe. If we could zoom in on an atom in your body, we would see that it consists of electrons swarming in orbits around a nucleus of protons and neutrons. And if we could zoom in on one of those protons or neutrons, we'd find that they themselves are made up of a trio of particles that are so small that they have almost no size at all, and are little more than points. These point-like particles are the quarks. Quarks are elementary particles. Like the electron, they are not made up of any other particles. You could say that they are on the ground floor of the Standard Model of particle physics.

Quark theory explained everything that physicists were observing, leading to the Standard Model that by some arcane means explains the entire structure of the universe. The Standard Model predicted 6 types of quarks: up, down, top, bottom, charm, and strange. They are differentiated based on properties such as mass and charge. The last to be experimentally confirmed was the heaviest, the top quark.
Quarks pop in and out of existence since quarks are particles that create matter. Thus, the antimatter and matter pop into existence and then pop out after gaining the pairs of electron-positron and quark-antiquark within the quantum level. The idea of quarks was proposed in 1964, and evidence of their existence was seen in experiments in 1968 at the Stanford Linear Accelerator Center (SLAC). The heaviest and last discovered quark was first observed at Fermilab in 1995.

6 Grand Unified Theories - the Unification of Forces, Quantum Chromodynamics

Grand Unified Theory (GUT) is a theory in particle physics that merges the electromagnetic, weak, and strong forces into a single force at high energies. It is a model that attempts to describe the fundamental forces and the relation ship between elementary particles interms of a single theory. In 19th century, physicists realized that electric and magnetic forces are connected and now called electromagnetic force. Later at high energies, it was realized that the electromagnetic and weak forces are identical and called electroweak force. In the electroweak force theory, physicists predicted the existence of the two opposite W bosons (W^+, W^-)and Z^0 with their mass to be 81 GeV/c^2 and 90 Gev/c^2 respectively. Then the particles were observed at CERN with the predicted character with the predicted characters.

The forces are definitely distinct under most circumstances. Even the electroweak theory's prediction of the carrier was assumed that at extremely small distances, the two forces are identical. These three forces aren't completely independent of one another. There are similarities on the way the carrier transmit the force. Some particles, like the quarks, can experience all three of these interactions. Other particles, like the electron, muon, and tau, can only experience the electromagnetic and weak nuclear forces. Still others, like the neutrinos, can only experience the weak force, while the photon can only experience the electromagnetic force.

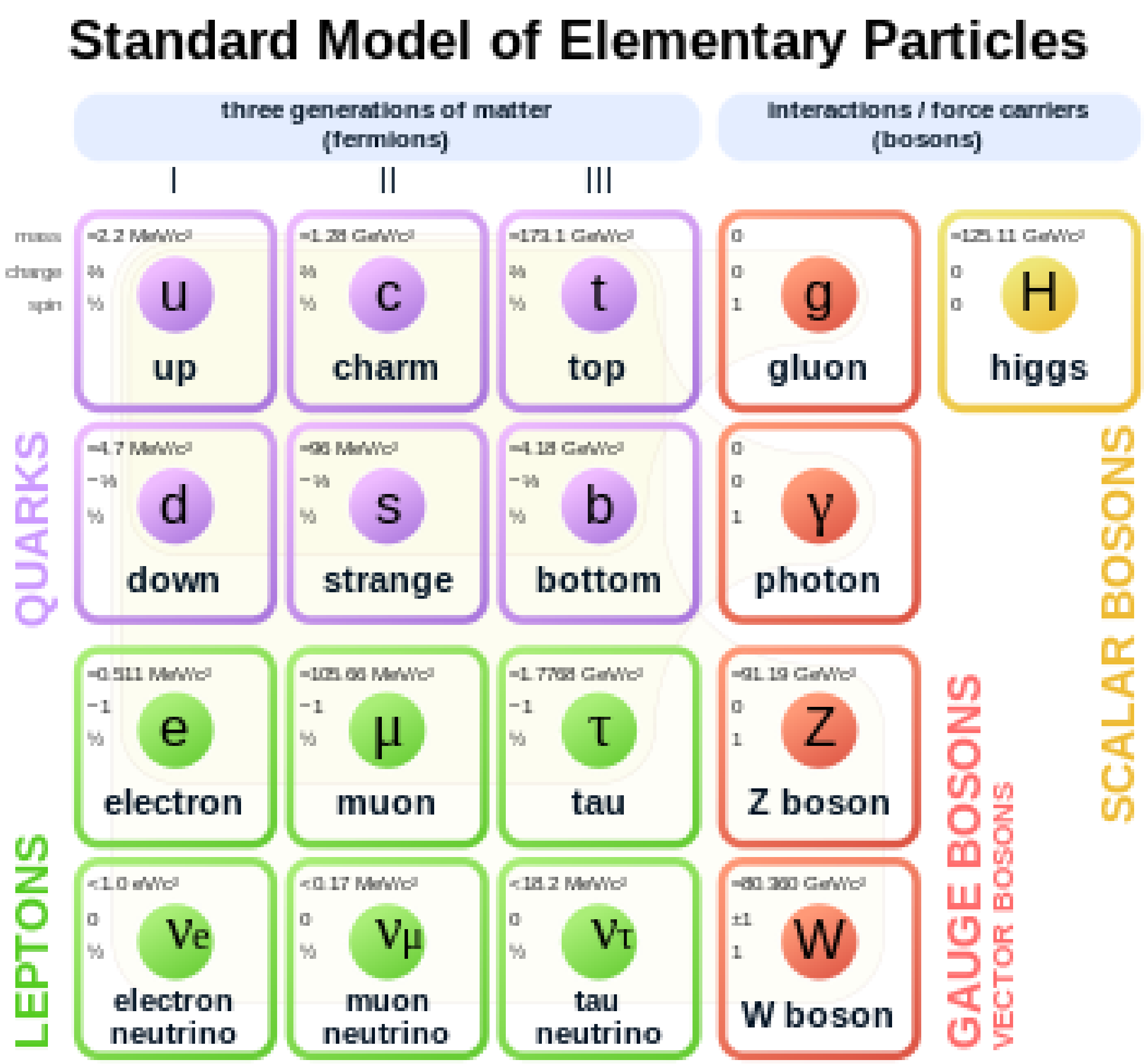
In 1960s, the existence of quarks and leptons was discovered. During the 1970s quantum field theory dedicated to the strong force known as quantum chromodynamics (QCD) was developed. **Quantum chromodynamics** (chromo means color) is the quantum field theory that studies the strong interaction between quarks takes place through the exchange of particles known as gluons. Physicists further proceeded to find if strong force can be unified with the electroweak force in a grand unified theory (GUT). A grand unified theory still did not include gravity and is not a successful field theory.

7 The Standard Model

The standard model is a model of particle physics that describes three of the four fundamental forces including elementary (fundamental) particles-particles that is not composed of other particles. This theory describes strong, weak, electromagnetic forces but gravity. It tells us about how elementary particles join to form large particles and how they respond to the fundamental forces.

In the standard model, there are three families which are leptons, quarks and bosons. The leptons and quarks are fermions, since they have a half-integer spin. However, bosons have a whole-integer spin. Leptons include elelctrons, muons, tau and their neutrinos. Neutrinos are the most abundant particles that have mass in the universe. Quarks are tiny particles that carry color charge and can't exist alone but when joined, they form hadrons. Bosons are force carriers that are helping for the transmission of fundamental forces. There are two kinds of bosons: gauge and scalar bosons. Gauge bosons are responsible for mediating the fundamental interactions. The Higgs boson (scalar boson) plays a unique role in the Standard Model, by explaining why the other elementary particles, except the photon and gluon are massive. The types of the particles are listed below.

In the standard model, several elementary particles are included. They can be summarized as:


Standard Model of Elementary Particles
three generations of matter (fermions)
interactions / force carriers (bosons)
I
II
III
mass
charge
spin
u
up
c
charm
t
top
g
gluon
H
higgs
d
down
s
strange
b
bottom
γ
photon
e
electron
μ
muon
τ
tau
Z
Z boson
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS