An Introduction to the Standard Model

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Elementary Particle Physics is the study of the subatomic particles which are themselves the building blocks of all matter and energy present in the universe. It addresses to the most elementary question ‘What is matter made of?’ at the most fundamental level. As the study reveals, these elementary particles if of the same kind are indistinguishable. We cannot differentiate between one electron and another. This makes our life easier since now we could formulate a common mathematical structure for all these identical particles. Another important goal particle physics hopes to achieve is to guess a force law which describes the particles’ behavior.

One of the recent grand successes of the Physics society is the development of the Standard Model. This model is a set of theories that describe the elementary particles(quarks and leptons, I shall explain what they are later on) and their interactions very accurately. A complete study on Standard Model would include the study of a general principle called local Gauge Invariance.

Introduction

For an experimental physicist, working with these teeny-tiny particles and performing measurements of their unimaginably minuscule physical properties is pretty impossible. Therefore they developed some macroscopic techniques to do the same

- Scattering experiments; wherein one type of particles are shot on another and their angle of deflection recorded reveals some information about the particles and their nature.
- Decay; In a decay experiment, one leaves an ensemble of a particle to decay over time and reveals certain properties like stability of the particle, rate of conversion, different scattering particles combinations and also, as we will see later, may disclose the presence of any previous unobserved particles.
- Bound states; if any multiple particle system combines to form a more stable state.

I choose to take a historical perspective of how the mankind, though first failed on multiple occasions, but ultimately emerged victorious (and even more curious) in this grand study of the smallest. But before that:-

Production of Elementary Particles

Electrons can be produced easily by thermally or electrically exciting any object and then placing a positively charged plate that attracts the free electrons to form an electron gun.

Other particles cannot be produced this easily. So one relies on natural sources for them. There are three main sources:-

- Cosmic rays; primarily a source of muons and neutrinos cosmic rays fall with enormously high energies.
- Decay processes, protons, neutrons, neutrinos, beta rays(electrons or positrons) and alpha rays may be produced by nuclear disintegration.
- Particle accelerator; Starting with an electron and/or protons, accelerating them to near light speeds and smashing them into a target leads to disintegration of the constituents. If surrounded by certain particle detectors, the disintegrated debris can be detected and be used.

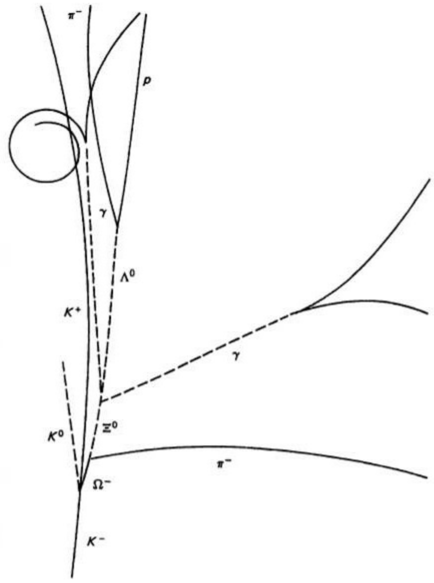

Figure 1: A typical particle decay(leading to many more). Dashed lines show neutral particles which did not leave a trajectory.[Photo by Brookhaven National Laboratory]

Detection of Elementary Particles

There are many small particle detectors like Bubble chamber, Cloud chamber, Spark chamber, Geiger counters, etc. But today a typical particle detector is made of a combination of the smaller ones and uses computer techniques to show the final trajectory of the particles passing through the mass. Such a detector is usually filled with some ionizable substance and when a charged particle passes by, it ionizes the matter surrounding it, and later these ions can be observed easily. Further there is a constant magnetic field subjected in a particular direction so that any charged particle performs a circular motion. Direction and radius of this motion helps determine the charge by mass ratio and the sign of charge of the particle.

One may notice (on Figure 1) there being vertices where a charged particle appears and seems to not obey conservation of momentum when it deflects to one direction rather than going straight. This is where one can predict a neutral particle was also born and keep conservation of momentum undisturbed. The only drawback in all this is neutral particles are not directly detected this way.

Elementary Particles

I would like to start from after the discover of electrons, protons and neutrons, together forming the classical period in elementary particle physics. By late 1920s Einstein's explanation of Photoelectric effect and de Broglie's wave-particle duality hypothesis were well accepted. It was further understood that any noncontact force called for 'mediator', an exchange particle(a quanta of the field). Photons were recognized as mediators of electromagnetic force, gravitons for gravity, W and Z bosons for Weak forces and Gluons for Strong forces.

Within the next 20 years Yukawa proposed meson's the mediators for strong force and it's search lead to the discovery of μ (muon)(Isidor Rabi asked "Who ordered them?") and the actual Yukawa mesons π (pion). Neutrinos(ν) were also discovered within this time.

Meanwhile, solutions to the Dirac equation, due to Paul Dirac, implied every particle should have an oppositely charged and otherwise identical antiparticle. So one would ask why don't we see any anti particles; the answer to that would be that during the formation of the universe, it happened to separate large chunks of particles from antiparticles in space, and wherever we had any little bits of pairs they got annihilated leaving only one amongst particle and antiparticle, the majority ones. Also naming something 'particle' and it's counter particle as 'anti-particle' is just a matter of convention, we could have as well called our electrons as 'anti-electrons' and the anti-electrons as 'electrons'.

Crossing Symmetry

In Particle physics, if we know a decay of the form occurs in nature

$$A + B \to C + D$$

then reactions like

$$\bar{C} + \bar{D} \to \bar{A} + \bar{B}$$
$$A + \bar{C} \to \bar{B} + D$$

Or any other combination of the particle-antiparticle is possible (if only the energies in the left and the right permit energy conservation).
for example

$$\pi \to \mu + \nu$$
$$and, \pi + \bar{\nu} \to \mu$$

are basically the same reaction, involving the same set of forces.

More particles!

Following this different types of neutrinos, namely electron-neutrinosν_e and muon-neutrinosν_μ and their anti particles were discovered. To make sense of the reactions that were being observed physicists formulated conservation of electron number and muon number. These quantities arise due to invariance of interaction under certain internal symmetry groups.

Soon much heavier particles (Hadron) particles started being discovered. Particles like $K, \eta, \sigma, p, \Lambda, \Sigma, \Xi, \Delta,$ and so on were quickly revealed. Their production time, which is on a time scale of about 10^{-23} and decay time, which is on a time scale of about 10^{-10} suggested that their production and decay occurred via different mechanisms. The two mechanisms are understood as a Strong force driven formation and a Weak force driven disintegration. Very soon Murray Gell-Mann proposed another property property 'Strangeness' which was conserved in the Strong force interactions and not conserved in Weak force interactions

Eightfold Way, Isospins and Quarks

When we see a classical kinematic or dynamic system, we always tend to look for symmetries in them so that the solution could be found out without too much effort. Symmetry in nature in general always leads to simplification of any system. But how does this happen? How does a symmetry suddenly make a problem easier? Emmy Noether, in 1917, published the answer to it:- "Every symmetry implies a conservation law". For example, in classical mechanics, a linear space translation invariance implies 'conservation of Momentum' whereas translation in time implies 'conservation of Energy'.

Gell-Mann notices there existed a symmetry in Baryon and mesons; the Eightfold way. This manifestation primarily dealt with spins and charges of hadrons and this also leads to the approximate 'Isospin symmetry' (which may appear to be somehow related to the Spin states of a hadrons).

All leptons, quarks, protons and neutrons are spin 1/2 particles, i.e, a measurement of their spin angular momentum along the direction of their axis gives either $m_s = \frac{1}{2}$ or $m_s = -\frac{1}{2}$. Therefore we can represent these two states as $\uparrow$ and $\downarrow$. A spin 1/2 particle can be in either one the two states or generally a superposition state of the two. This can be easily seen with a vectorial notation called spinors. Let: $|\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $|\downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$
Therefore a general particle may be depicted as

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \alpha \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \beta \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Where α and β correspond to the probability(Square-root actually) of observing the respective state. Under this framework, the operators for spin angular momentum along the three axes are proportional to the Pauli' s matrices.

Now, this is all just playing with representations. We could use this type of representation to depict different states of what are called Isospin particles. Physicists back in 1930s observed that protons and neutrons have remarkably close masses(938.3 Mev/c^2 and 938.5Mev/c^2 respectively) and on applying electromagnetic energy correction to a proton their energy could come even more closer. Was it possible that these were two states of fundamentally the same particle and that they both interact with strong forces identically? If so, we could represent them as $p = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $n = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$, and any common mixed state would be $N = \begin{pmatrix} p \\ n \end{pmatrix}$. If this was so, any rotation in the isospin space of the two particles, i.e. changing the values of n or p would result in no change in the Strong force experienced. This is called an Internal symmetry because this symmetry purely exist in an imaginary isospin space. Therefore by Noether's theorem we can say that isospin remains invariant under a reaction caused by strong forces.

If we now go see the table of masses of all baryons we would easily notice there being similarity in masses of many particles, which we could formulate to be different states of the same isospin state. For example, Σ^+, Σ^0 and Σ^{-1} are 1189.37, 1192.64 and 1197.45 respectively. Therefore these can be thought of as different states of the same isospin state.

Gell-Mann soon proposed that even these Hadrons are fundamentally composed of even elementary particles called Quarks which did not exist individually (Why? Nobody knows. This is called Quark Confinement and can be considered as God's statement for now) but only in combined states. Quarks were proposed to be of three types(or 'flavors') Up(u), Down(d) and Strange(s) and said that Baryons are composed of three quarks(any combination of quark or antiquark) whereas Mesons were of one quark and one antiquark. Further, since quarks were spin $\frac{1}{2}$ certain particles which had same quark multiple times seemed to disobey Pauli's exclusion principle. So in order to keep up with the Quark model another property, Color, of quarks was proposed. Each quark was then assumed to be coming in Red, Blue and Green colors and a proposal that all naturally occuring free particles are Colorless, in the sense any baryon has one quark of each color making it colorless and any meson has one particle of a

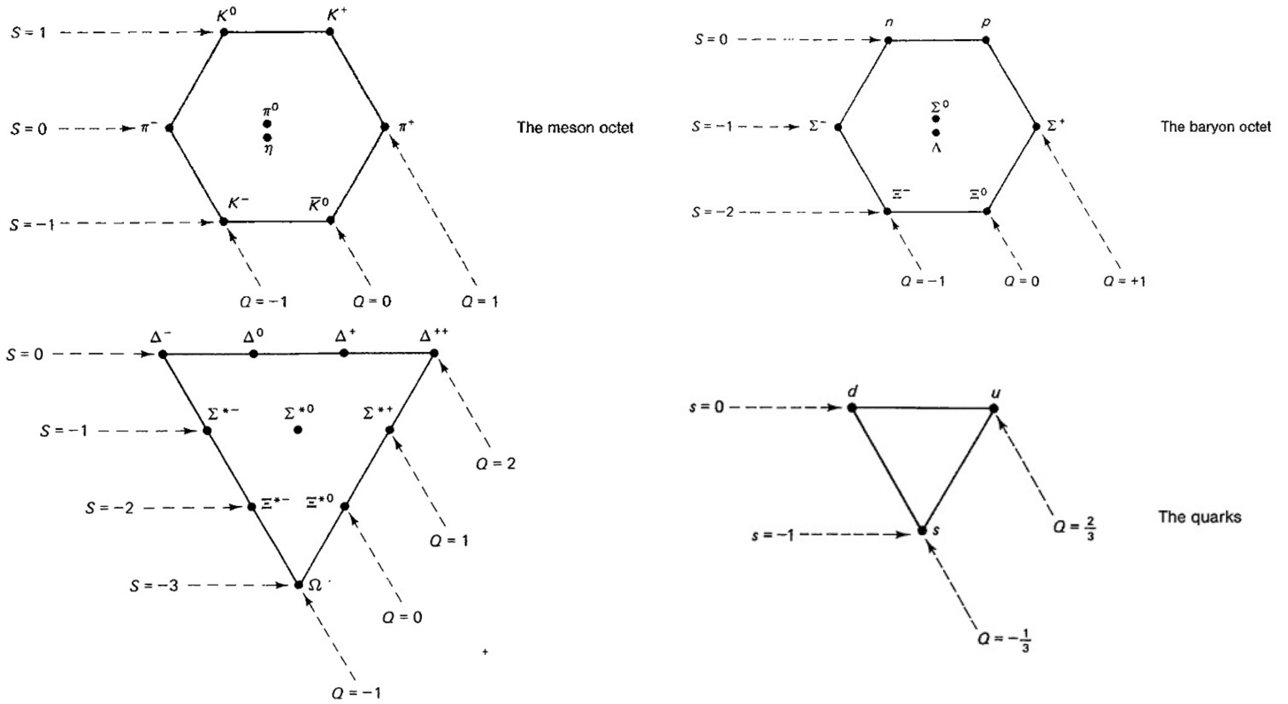

Figure 2: Top: Eightfold Way for (Pseudo-scalar)Mesons and (Spin $\frac{1}{2}$)Baryons. Bottom: Baryon decuplet for all Spin $\frac{3}{2}$ baryons and Triangular Eightfold Quark symmetry[Picture taken from Griffith's book]

color and an anti-particle of the same color.

Very soon many more Quarks and Leptons which finally stopped to a point giving us what we have now as the Standard Model. In the current view all matter and energy comes in the form of Leptons, Quarks and Mediators.

Leptons

	l	Q	L_e	L_μ	L_τ
$1^{st}Gen$	e	-1	1	0	0
	ν_e	0	1	0	0
$2^{nd}Gen$	μ	-1	0	1	0
	ν_μ	0	0	1	0
$3^{rd}Gen$	τ	-1	0	0	1
	ν_τ	0	0	0	1

L_e, L_μ and L_τ are corresponding lepton numbers.

Each lepton has a corresponding anti-lepton.

Quarks

	q	Q	D	U	S	C	B	T
$1^{st}Gen$	d	-1/3	-1	0	0	0	0	0
	u	2/3	0	1	0	0	0	0
$2^{nd}Gen$	s	-1/3	0	0	-1	0	0	0
	c	2/3	0	0	0	1	0	0
$3^{rd}Gen$	b	-1/3	0	0	0	0	-1	0
	t	2/3	0	0	0	0	0	1

Down(d),Up(u),Strange(s),Charm(c),Bottom(b),Top(t).

Each quark flavor is of three colors and each of these flavor-color combination has an anti quark.

So this makes it 12 leptons plus 36 quarks along with 12 mediators as a total particles of the Standard Model.

Masses

lepton	mass	quark	mass
ν_e	$2x10^{-6}$	u	2
ν_u	0.2	d	5
ν_τ	18	s	100
e	0.511	c	1200
μ	106	b	4200
τ	1777	t	174000

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