First Week Report

Abhishek Daniel

On week 1, A lecture on quantum chromodynamics(QCD). Among the known fundamental forces of nature strong nuclear force is responsible for holding the protons and neutrons inside the nucleus of the atom and also responsible for the interaction between them. But protons and neutrons are not the fundamental particles. In fact they are composite particles made up of **quarks and gluons**. They also interact via strong nuclear force which is governed by theory of Quantum Chromodynamics. This is the fundamental theory of strong The branch of physics which studies these interactions is called the Nuclear Physics.

Studying the quantum chromodynamics will allow us to understand the hadron and nuclear structure of the atom, hadron spectroscopy, stellar evolution and so on. Like Quantum electrodynamics, QED(quantum theory of Electromagnetism) posses electric charge, QCD have another conserved quantity like electric charge called the **'colour charge'**. Note that the QCD has nothing to do with actual colour. Every quarks and gluons carry this colour charge. There are three types of colour charge, **Red, Blue and Green**. Like QED, these colour charges have their counter charges (Anti-Red, Anti-Blue, Anti-Green).

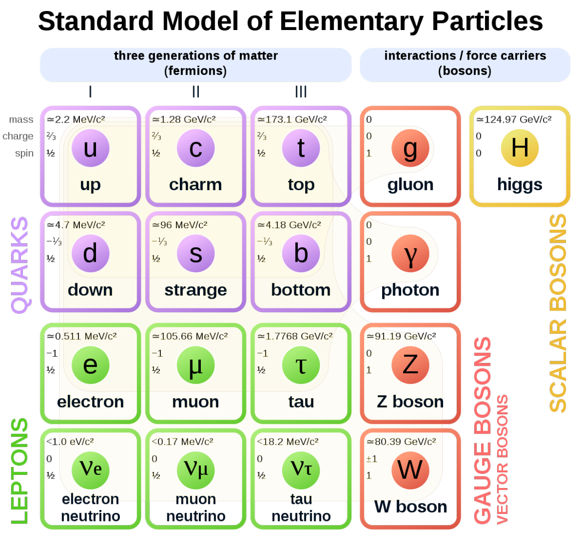

Figure 1: Standard Model of Particle Physics

Also, The quarks have another characteristic called the **'flavour'**. They have six different flavours. They are up, down, charm, strange, top and bottom. Every flavours of quark have different masses. For example, the top quark is the heaviest quark of mass approximately 173 GeV(in natural units). Another similarity between QED and QCD is like photon(the force carrying particle for electromagnetic force), gluons(the force carrying particle for strong nuclear force) have no mass.

But there are certain properties which make the quantum chromodynamics peculiar from quantum electrodynamics. They are as follows:

1. **Confinement:** The quarks always connected/bounded with another quarks via gluons. They always bound in such a way that the colour of the group of quarks is colour neutral.

For example, a proton is the collection of two up quarks and one down quark having colours are Red, Blue and Green. Thus the combination of them results in colour neutral(White). According to confinement, these quarks are always confined with other quarks. Thus it impossible to detect an individual quark, a lone quark. Consider a meson, a collection of a quark and an anti-quark connected via gluon. If we try to stretch them apart, the energy will stored in the gluon which acts like a spring. With enough energy the gluon spring will be broken and the energy will get released. The energy is so high which results in the pair production of quark and anti-quark and will get attached to the broken ends of the gluon.

2. Unlike QED where the photons won't interact with themselves. The QCD permits the gluons to interact with themselves making the theory of QCD, non-perturbative at low energies.

$$\mathcal{L}_{QCD} = \bar{\psi_f}\left(i\gamma^{\mu} D_{\mu} - m_f\right)\psi_f - \frac{1}{2} tr\left(F_{\mu\nu}F^{\mu\nu}\right)$$

is the Lagrangian density of QCD. Here the second term $\frac{1}{2}tr\left(F_{\mu\nu}F^{\mu\nu}\right)$ is responsible for the gluons with themselves. This results in mathematical difficulties and also some hypothetical composite particles like Glueball, made entirely with gluons and no quarks. The mathematical difficulties can be overcome by performing lattice QCD on the powerful supercomputers.

3. QCD Spectroscopy is quite tedious when we compare to the Hydrogen spectrum. One of the reason for this is they decay rapidly on their excited state creating many by products. This process of decay happen faster in the order of 10^{-23} seconds. They are one of the shortest lived phenomenon we know.

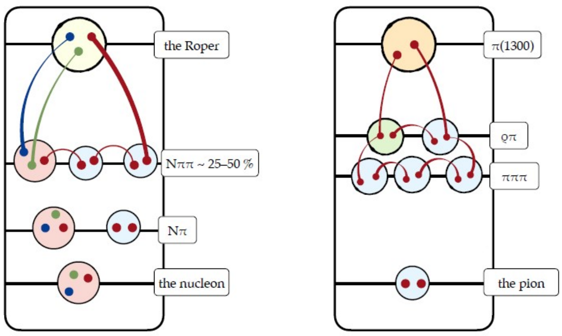

Figure 2: Spectrum of a Nucleon and a pion

One of the main difficulties in QCD is understanding the interaction between three particle ie. three body forces. The interactions between 2 nucleons are well established and easy to understand. If we have 2 nucleons, there is only one way of interaction is possible either AB or BA. But when we 3 nucleons together we not only have pair wise interactions AB, BC and AC but also there must be a three way interaction ie. three body interaction. Also there are many experiment shows the there must be three body interactions when we compared it theoretical models. If we ignore these interactions, the theoretical model will get shifted from 10% to 20% from the experimental result.

But verifying these theories and carrying it into experiment is not easy. In fact most of them require huge particle accelerator where some trillions of collisions happen per second and the data is accumulated for many years. Thus discoveries require a detailed analysis on the data.

Thus it is important to know how particle accelerators work. First from the theory of interest make a prediction and have to build particle accelerator apt for that task. A particle accelerator accelerate the particles closer to the speed of light and allow them to smash each other. The energy released from the collision may create a plethora of particles. Detectors will detect the individual type of particles. Thus isolate the individual particles. Then we can compare the outcome with the theory. This helps us to deduce what could happen in the collision. During this collisions, it seems like the particles appear as resonances in experiment ie. as an amplification of the probability of incoming particles to interact. Remember if the particles do not interact then the would left undetected by the detectors. But if two particles are sufficiently attracted to make a bound state then the probability of them interacting with each will increases.

After the lecture, on the following days I revisited my Quantum Mechanics course. I have gone through the solution of Schrödinger equation for different potentials, the Hydrogen atom and studied its spectrum. After that I have gone through Complex Analysis like find the nth root of a complex number, Cauchy-Riemann theorem, Möbius transformations, Mapping complex functions, Riemann mapping theorem, Inverse of Analytic functions, Complex differentiation and integration, Cauchy's theorem and integral formula, infinite series of complex numbers, Taylor series, Laurent series, Isolated singularities, Residue theorem and using Residue theorem to calculate improper integration. No programming was done in this week. But hoping that we will do a lot of programming in the coming weeks and learn new skills and have deeper understanding in the field.