60th Compton Lectures
The Origin of Mass in Particle Physics

Ambreesh Gupta

Lecture VI: Symmetry Breaking

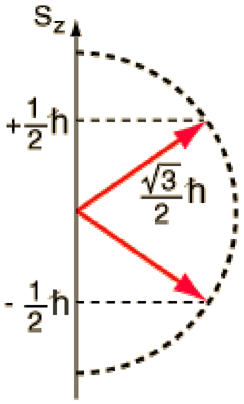
> The most incomprehensible thing about nature is that it is comprehensible. – Albert Einstein.

1. Mathematics in Physics

In the last few lectures we have been developing some of the concepts related with the mathematical structure of the Standard Model of particle physics. This is the world of the small and the fast where the laws of physics are somewhat different than what we experience in our daily lives. With mathematical constraints of the physical law and the experimental observations/falsification we can attempt to understand the nature of the Universe around us. Why does mathematics work in describing the physical laws of nature is a fundamental question in itself. It is argued that Murphy’s Law, which states - if something can go wrong, will – will sooner or later catch up with mathematics. That is yet to be seen, and one can always question, why should Murphy’s Law not go wrong sometimes for its own sake?

We saw that Newton introduced the concept of mass in physical equations as a relationship between force and acceleration (F=ma). Along with space and time, mass plays a pivotal role in physical laws. In the case of fields, for example the electron field, a disturbance in the field produces an electron. The mass of the electron or the electron field is defined through the energy and momentum of the disturbance through the relation $E^2 = m^2 + p^2$ (speed of light c is taken one in the system of units).

As we have seen, quantum mechanical particles have the property of spin, which can be related with angular momentum of a spinning body in the case of classical physics, although not entirely. For one, the spin of a particle is always equal to $s(h/2\pi)$, where $s=0,1/2,1,3/2$ etc., and h is Planck’s constant. If we measure the spin of a quantum mechanical particle we will find it to be in one of the $2s+1$ spin state. A spin-0 particle has one state, spin-1/2 has two states, spin-1 has three states etc. The integral spin particles are called Boson and half integral spin particles are called fermions. Pictorially, a spin 1/2 particle can be found in only two states as shown below and not in every possible orientation.



One interesting fact is that the photon, which is mass less spin-1 particle, can have only two spin state one in the direction of its motion and one opposite to that and it does not have a transverse spin state. If it did have a transverse polarization, it would seem the photon was moving with two velocities looking from two different sides of its motion. That is not possible, since the photon has one velocity – the velocity of light. A mass less spin-1 particle traveling at the speed of light will always have only two spin states that it can be found in.

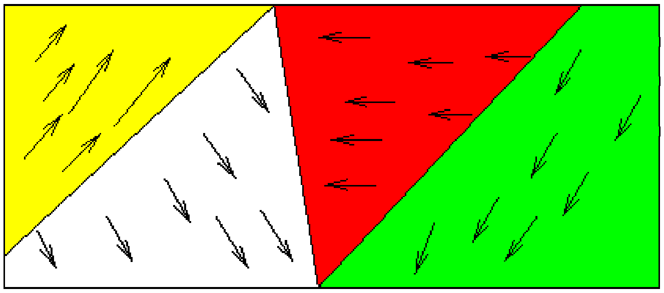
Since the particle (or the corresponding wave) is just an aspect of the underlying field (the corresponding wave), a filed should encode this property of spin. As we have defined in the past, the field is just a set of numbers at each space-time point, and the way these numbers are grouped, encode various properties of the field.

2. Revisiting Higgs Mechanism: Spontaneous Symmetry Breaking

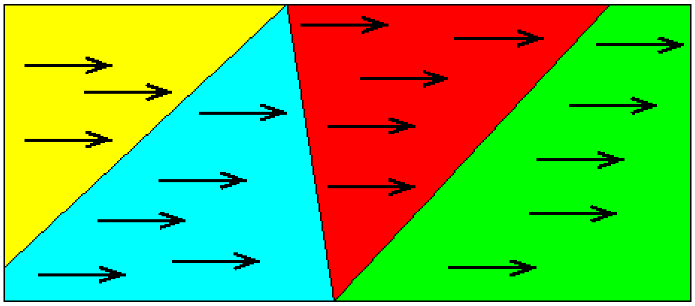
We have seen how the use of using local gauge symmetry (i.e., the impossibility of physically measuring the phase of a field) has required one to add new fields. The first example was for electron field, where symmetry arguments led one to predict the existence of the photon. Except, the photon was already known to exist. But, similar strategy in other cases has led to discovery of new particles. The second, example we chose was the seeming symmetry between a proton and neutron since they have equal (almost) masses. When demanded local invariance with respect to this symmetry, six new fields appeared. But the particles associated with these fields were mass less spin one particles like a photon except two of them were charged. Although, the proton-neutron symmetry model is not very realistic, the problem of mass less charged vector boson can be resolved if they are massive. The introduction of mass has to be done such that the gauge symmetry is not broken.

Why is it important to preserve the gauge symmetry? We saw in the case of quantum electrodynamics (QED) how in the early stages of its development the theory was plagued by appearance of infinities in the calculations making it hard to make prediction. The renormalizability of the theory i.e., cure from infinities was shown and attributed to the gauge symmetric nature of QED. So, it is important to maintain the gauge symmetry of the Yang-Mills theory discussed above in order to keep in renormalizable.

The mechanism for providing mass to the vector bosons generated by the Yang-Mills theory is called the Higgs Mechanism. The Higgs Mechanism is an example of the phenomenon called Spontaneous Symmetry Breaking. The phenomenon was known long before the development of the Higgs mechanism in the case of condensed matter physics. A piece of iron, which is a ferromagnet, when raised above the certain temperature called the Curie temperature, losses all it its magnetism. In the picture below the magnetic dipoles in each triangle are randomly oriented. There is no preferred direction, there for a rotational symmetry is manifest.



When the iron is cooled below the Curie temperature, out all possible direction the magnetization will point in one particular direction out all possible choices. The symmetry is said to be spontaneously broken.



When symmetry is spontaneously broken, in either in geometrical space or in some abstract space, one can think of the implication of this is the existence of ‘waves’. For example in the above case, if one of the elementary magnets inside the material were to be moved away from the preferred direction of magnetization, a spin wave will be setup. In the case of abstract space of fields, the spin wave is replaced particle properties. Goldstone theorem says that every symmetry of the laws of nature that not is also a symmetry of the ground state implies existence of an elementary particle.

As discussed in the last lecture, the idea of spontaneous symmetry breaking, when applied to local gauge symmetries, via the existence of Higgs field, results in providing mass to the mass less vector bosons.

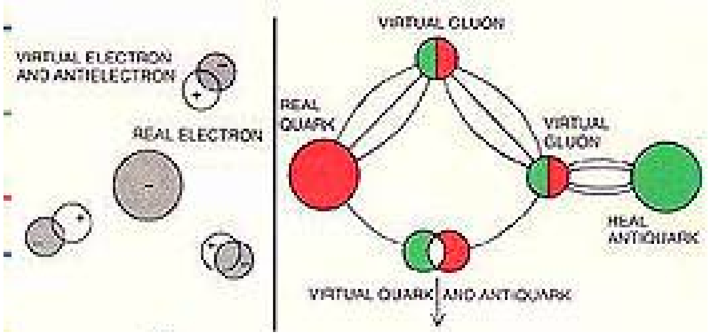
3. Strong Forces

The attempt of Yang and Mills to develop a gauge theory for strong interaction using isotopic spin symmetry led to unrealistic predictions. Further development could happen only after the basic facts about hadrons were realized: They are not elementary particles. A model of proton and neutron, and other hadrons, as a composite objects was proposed in 1963 by Murray Gell-Mann. About the same time Yuval Ne'eman and George Zweig I independently introduced similar idea. In this model hadrons are made up of smaller particles Gell-Mann named as quarks. A hadron can be built out of quarks either by combining three quarks, which gives rise to baryons, or combining a quark and an anti-quark, which gives rise to mesons.

Analogous to the electric charge property responsible the electric force; quarks have a property called color charge which is responsible for the strong force. To explain how three quarks can be bound, one has to have a property such that the three charges attract. The quarks are assigned three primary colors – red, green and blue. The anti-quarks are assigned 'anti-colors' cyan, magenta and yellow. Each quark flavor comes in all three colors. The term 'color' is chosen so that the rules of forming hadrons can be expressed by requiring all allowed combination of quarks to be "white". With these rules of color, there are two ways of producing "white" (hadrons): by mixing three primary colors (baryons) or by mixing one primary color and one anti-color (mesons). The theory of interaction of quarks, based on the symmetry of invariance with respect to local transformation of colors, is called quantum chromodynamics.

The quark color, like isotopic spin, can be thought of as an arrow pointing outward in a circle. Three colors charge can be represented by three arrows at equal angels apart and pointing outward from the center of the circle. Successive rotation of a third transforms a quark from red to green to blue and back to red again. In a baryon, which has three quarks with total color white, a global rotation of each quark color, will change the individual quark colors, but leave the total hadron color to be "white". When the color invariance in quantum chromodynamics is demanded locally, it would change the color of just one quark. To restore the symmetry eight new fileds have to be introduced. These are the fields that give rise to strong force. The quanta of color fields are called gluons. Similar to quanta of electric force, photons, gluons are mass less and have a spin angular momentum of one unit. But, unlike the photons, gluons carry color charge, and hence they can interact with each other. Each gluon carries, one color and one anti-color charge. All hadrons, baryons and mesons have to remain color neutral, and the strong forces are a system of interaction that maintains that condition. Isolated quarks and gluons have not been observed in experiments. Unlike electromagnetic force, the strong force increases when the separation between quarks increase like stretching of an elastic band. When the quarks are close, the elastic band flops and the quarks move freely inside the hadron and they don't notice their confinement. If 'enough' energy is given, the elastic band can be broken, but enough in this case means, enough to produce a new quark pair. So, the broken pair will immediately get attached with the new quarks forming hadrons. This is the reason that isolated quarks are never observed.

The picture below depicts the difference between the force laws of quantum electrodynamics and quantum chromodynamics. In the case of electric charge, the appearance of virtual pair has the effect of screening the charge at the center. Similarly, pair of virtual quarks diminishes the strength of forces between quark and anti-quark. But, in QCD, the gluons are color charged, unlike the photons, so, gluons also have an influence on the magnitude of color force between quarks. The gluons do not reduce the magnitude of color force, but enhance it. This produces the rubber band effect mentioned in the previous paragraph.



The Higgs mechanism that is used to provide mass to the W/Z Boson in the electroweak theory is also sufficient to give mass to the leptons and quarks. But, the theory predicts only the relationship between mass and other parameters of the Standard Model. All the masses are parameters that are measured in experiments and the input to the theory.