

# 60<sup>th</sup> Compton Lectures

## The Origin of Mass in Particle Physics

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### Lecture IV: Electroweak Physics

“Emptiness of an Atom: An atom is basically empty with a small nucleus with all the mass and a large room for the electrons to roam. For example, in a hydrogen atom if the nucleus was of size 2.5 inch the electron orbit would be 4 miles.”

#### 1. Weak interaction

In 1896 Becquerel discovered radioactivity decays in which the nucleus transforms. There are three kinds of radioactive decays: the alpha, beta and gamma. In these decays of the nucleus, the alpha decay involves emission of a helium atom, beta decay involves emission of an electron and the gamma decay involves emission of a photon. The beta decay of nucleus was a puzzle.

The underlying process was involved the decay of the neutron in to a proton, an electron and an anti-electron-neutrino ( $n \rightarrow p + e + \bar{\nu}_e$ ). Similarly the decay of the muon ( $\mu \rightarrow e + \nu_e + \bar{\nu}_\mu$ ) in to electron, anti-electron neutrino and muon neutrino, also happens under the influence of weak forces. The puzzle was there because the decay of a neutron or of a muon was too slow compared to what would be expected from electromagnetic interaction. When a particle decays, the decay rate can be shown to be proportional to the strength of the force/interaction. The smallness of the rate in above cases suggests a force other than the electromagnetic force to be responsible. This is now known as the weak force. The weak force is unique in the sense that they are responsible for changing one particle into another. This is different from the usual perception of force in terms of how strongly or weakly a force makes two objects attract or repel. All of the quarks and leptons feel weak force, but due to their weakness compared to electromagnetic and strong interaction, they are not readily observed. They are observed in process that happen where the other two reactions are strongly suppressed.

It is interesting that in 1930, neither the neutron nor the neutrino were discovered. The reactions were written in term of one nucleus transforming into another with emission of an electron. If the neutrino is removed from the above reaction, the experimentally observed distribution of electron energy in beta decay was hard to explain. This was precisely the reason that led Pauli to hypothesize the existence of a neutrino. It was the “silent” accomplice in the reaction, which carried some fraction energy. Since neutrinos interact only via the weak force, they hence go unobserved in detectors. The neutrino was discovered in 1956 by Rein and Cowan.

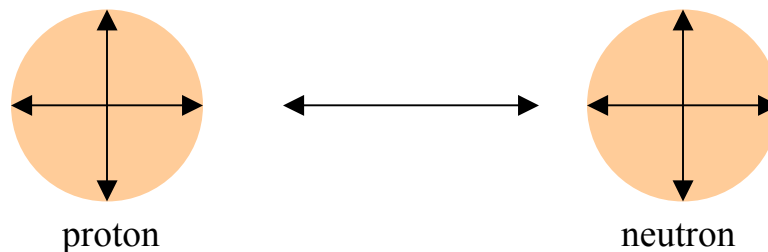
In 1934 Fermi developed a theory for weak interaction in beta decays that incorporated Pauli’s neutrino and proved to be brilliantly successful. Fermi’s theory was inspired by the structure of electromagnetic reaction, which involves the exchange of an intermediate

photon between charged particles. But, in its original formulation the theory did not have any exchange boson. This was a problem, as this formulation would break down at high energies, as the probability of the reaction would be predicted to be unrealistic i.e., the theory was not renormalizable. In the lecture we saw how similar renormalization problem was solved for quantum electrodynamics (QED). But, those ideas did not work very well for weak interactions.

We know now that there is a massive intermediate vector boson involved in the reaction. Another way to think about the weakness of weak interaction is due to the fact that the strength of weak interaction is suppressed due to the heavy boson. At high enough energies they become comparable to electromagnetic interaction. In 1956, Lee and Yang discovered another interesting property of the weak interactions. Weak interactions do not conserve parity. The discovery these and other properties of the weak interaction and attempts to put them in a mathematical structure finally resulted in the electroweak theory formulated by Glashow, Salam and Weinberg in 1967.

## 2. Yang Mills-Theory

Inspired by the success of gauge theoretical ideas in QED, Yang and Mills developed a theory for ‘isotopic-spin symmetry’, the rule stating that the strong interaction remained invariant when identities of proton and neutron are interchanged. In the picture below the arrows in the circle represent the proton and the neutron component of a particle. Depending whether the proton or the neutron arrow is pointing up the particle will behave like a proton or a neutron. Intermediate states are quantum mechanical superpositions i.e., unless a measurement is performed the particle is both a neutron and a proton. If this were an exact symmetry, no experiment would be able to discern the difference between the two states. Which, we know is not exactly true.



Although the Yang-Mills theory, which was being developed for strong interaction, was not very successful in describing/predicting real world, the ideas used in the development of this kind of theory were of fundamental importance in the development of the Standard Model. The main theme was to start with established global symmetry and ask what the consequence would be if the theory was made local. We have seen that answer to such questions in the case of electric and electron field resulted in the presence of new fields (for example photon field in case of gauge invariance of electron field) if

the considered symmetry was to be preserved locally. Since the Yang-Mills theory is more complicated, it turns out that more than one field has to be added in order for the theory to be locally invariant. Examining the nature of these fields, it seemed to require a photon field that was charged!

In the last lecture we saw that in QED, the symmetry operation is local change in the electron field and each such phase shift being accompanied by an interaction with the electromagnetic field i.e., exchange of a photon. If an electron goes through two phase shift in succession, one by emitting and the next by absorbing a photon, the end result remains the same if the process was reversed i.e., the electron absorbs first and emits next. This form of transformation is called abelian transformation. If the act of absorption is denoted by A and act of emission by B, then mathematically, the fact that these acts (transformations) are abelian implies  $AB=BA$ .

In the Yang-Mills theory, where the symmetry operation (gauge transformation) is local rotation of isotopic spin arrow, the result of multiple transformations can be quite different. If the particle is subjected to a gauge transformation A, followed by a second transformation B; the end result could be that the particle is in proton state. If the sequence of transformation is reversed i.e., first B and then A, then it is not necessary that the particle end up in the same state i.e., a proton. The particle could end up being in a neutron state. Mathematically, due to the fact that  $AB \neq BA$ , the transformations A and B are said to be non-Abelian. QED is an example of an abelian gauge theory where Yang-Mills theory is a non-Abelian gauge theory.

The existence of an electrically charged photon, which has a mass zero and infinite interaction range, would change the world beyond recognition. Of course, no such particle has been seen experimentally. One way to fix the problem was by giving these so-called 'charged photons' a mass, which would confine the associated forces to finite range. As the long-range effects of photon like fields are removed, the results from experiments can be reconciled. But, introduction of mass in this fashion resulted in destroying the gauge invariance. Also, introducing the mass by hand resulted in much more severe problems of infinities than in the case of QED. The theory was not 'renormalizable'. It was F. Englert, Robert H. Brout and Peter Higgs who discovered a way to endow some of the Yang-Mills field with mass while retaining the exact symmetry. This was called as the Higgs Mechanism.

### 3. Higgs Mechanism

The fundamental idea of the Higgs Mechanism is to endow the theory an extra field, one having a special property that it does not vanish in vacuum. In physics, the vacuum is defined as the state in which all fields have their lowest possible energy. For most fields this energy is minimized when the field is set to zero. For example the electron field has minimum energy when there are no electrons. The construction of Higgs field is unusual in this respect. It has to have smallest energy when the field has some uniform value greater than zero.

The inclusion of Higgs field does not destroy the Gauge symmetry but merely conceals it. It retains the renormalizable quality of mass-less Yang-Mills theory. But, it also provides mass to the 'charged photon' field discussed earlier. The Higgs field is a scalar

quantity, having only magnitude, and so the quantum of the field must have a spin of zero. The mass-less vector bosons, generated by the requirement of local gauge invariance discussed earlier, have only two spin state (instead of the normal three spin state of a vector particle). If they are to acquire mass, they will have to have all the three spin states. Since in quantum mechanics, the spin states are strictly accounted, the extra spin state has to come from some place. It comes from the Higgs field. Each of the mass less vector boson from the Yang-Mills theory acquires mass and spin by coalescing with one Higgs particle. One-way to think about this is that the Yang-Mills particles eat Higgs particle and gain weight, while the Higgs particle become ghosts.

#### 4. Weinberg-Salam-Ward model of Electroweak Physics

One of the important properties we saw earlier about the weak interaction is that it is short range i.e., it has significant influence only at short distances of the order of  $10^{-15}$  centi meters. This short range implied that the virtual particles exchanged were very massive, about eighty to hundred time more massive than a proton. Developing on these ideas of Yang-Mills theory and Higgs Mechanism in 1967, Weinberg, Salam and Glashow build a theory of weak interaction, which also embraced electromagnetism. The requirement of the local gauge invariance leads the prediction of four mass less photon-like fields, which are infinite in range with one carrying positive electric charge, one negative and the other two are neutral. The spontaneous symmetry breaking via the Higgs-Mechanism introduces four Higgs fields. Each of the field is represented by a scalar particle. Three of these fields are swallowed by the three mass less photons, and hence acquire large mass. The fourth photon-like particle is actually the photon and it remains mass less. The prediction of heavy intermediate vector boson was confirmed in 1983 with discovery of the W and the Z bosons at CERN. Carlo Rubbia and Simon van der Meer were awarded the Nobel Prize for this discovery in 1984. The electroweak theory was shown to be renormalizable by G. t'hooft and M. Veltman in 1971. They were awarded the Nobel Prize for this in 1999. Of the four Higgs field generated via spontaneous symmetry breaking remained unused and should be observable in experiment. But, so far it has eluded intense experimental searches.

The picture below shows the display of first Z event seen at CERN.

