60th Compton Lectures
The Origin of Mass in Particle Physics

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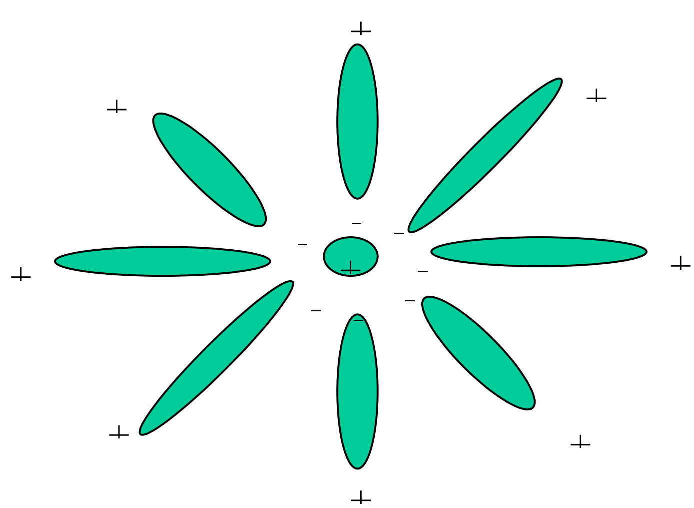
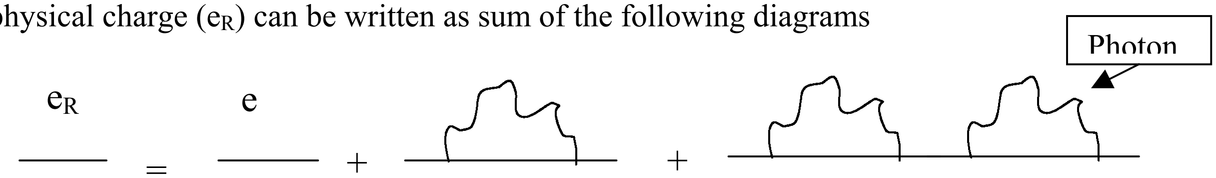
Lecture IV: Symmetry in Physics and the Standard Model

1. Infinities

In the previous lecture we saw that when two particles interact, the various possibilities (that happen in the bubble of ignorance introduced in a previous lecture) can be written down using the pictorial Feynman diagrams. Virtual photons and electrons of certain energies can be produced for small enough time and then destroyed in accordance to the Heisenberg's time-energy uncertainty relation. Numerous diagrams can be drawn to create more and more complex possibilities. But, Not all diagrams contribute equally to the combined probability. In the theory interaction of electron and photon, the probability at each vertex, the point where electron and photon lines meet, is proportional to the fine structure constant ($\alpha \sim 1/137$). As the complexity of the diagrams and number of vertex increase, the contributions from them become smaller and smaller. Taking all possible diagrams will form an infinite series. When this series is summed together, depending on what is being studied, the summation can be either finite of infinite. The magnetic moment of the electron is an example where the summation of the series does not become infinite. But, as can be imagined, the production and decay of the virtual particles will affect the observed charge and mass of the electrons. For example the net charge at the center for the diagram below, observed from outside, will be affected by the dipoles surrounding the central charge.



Since vacuum is a bubbling sea of virtual particle being created and destroyed, the charge and mass of an electron will get an observable effect from its surrounding. If the effect of the diagrams on charge and mass of electron is estimated, the resulting calculation by including all diagrams becomes infinite. Infinities like these plagued the development of quantum electrodynamics for sometime. The solution to the problem lies in realizing that the observed charge in experiments is the physical quantity. In terms of the diagrams the physical charge (e_R) can be written as sum of the following diagrams



Even though partially or independently the diagrams on the right might lead to infinite contribution their sums at different orders cancel such that the total sum does not become infinity. In any interaction involving an electron the same complete set of diagrams occur and hence it can be interpreted to be the physical value (e_R), which is measured in experiments.

2. The idea of Gauge Symmetry

<u>Note:</u> In the following discussion Gauge and Phase are used interchangeably. For our purposes, they are the same.

Symmetry can be defined as the invariance in the pattern that is observed when some transformation is applied to it. Normally, we associate symmetry with geometrical forms. For example in the picture of snowflake below, the symmetry in the pattern can be detected at a glance.

Although the concept of symmetry had its origin in geometry, it is general enough to embrace invariance with respect to transformation of other kinds. An example would be the magnitude of electric forces between a configuration of positive and negative charges. If the positive and negative charges are interchanged the force remain unchanged. This invariance is a symmetry that is not of geometrical kind. Symmetries in the laws of nature have played a part in construction of physical theories for a long time. The examples of symmetry above are of global symmetry. The changes happen at every space point at the same time. There can also be local symmetries where the convention for invariance can be defined at every space-time point independently of other points. It turns out that the requirement of local symmetry places much more stringent constraint in the construction of a theory. For local symmetry to be observed the laws of physics must retain validity even when a different transformation is applied at each point in space and time. In order to make a theory invariant with respect to local transformation something new must be added - a force. We have seen an example of how this happens in earlier lecture. Using special relativity and electric field and demanding invariance of physical laws in transformation between reference frames, we could infer the presence of magnetic field.

The electron has a spin of one-half and so has two spin states. Therefore the associated field must have two components. Each component is represented by a complex number, i.e., a number that has both real and imaginary part, which includes as a factor the square root of -1. The electron field is a moving packet of waves, which are oscillations in the amplitudes of the real and imaginary components of the fields. The field defines the probability of finding an electron in a specified spin state at a given point and at a given time. The probability is given by the sum of the squares of the real and the imaginary parts of the field. The oscillation can be defined in terms of three quantities, the wavelength that is proportional to the momentum, the frequency that is proportional to the energy and the phase. The phase measures the displacement of the wave with respect to some arbitrary origin. In general the imaginary part of the amplitude is ninety degree out of phase from the real part. The absolute value of the phase cannot be determined. The only thing that can be measured is the difference between two phases at two points of two times.

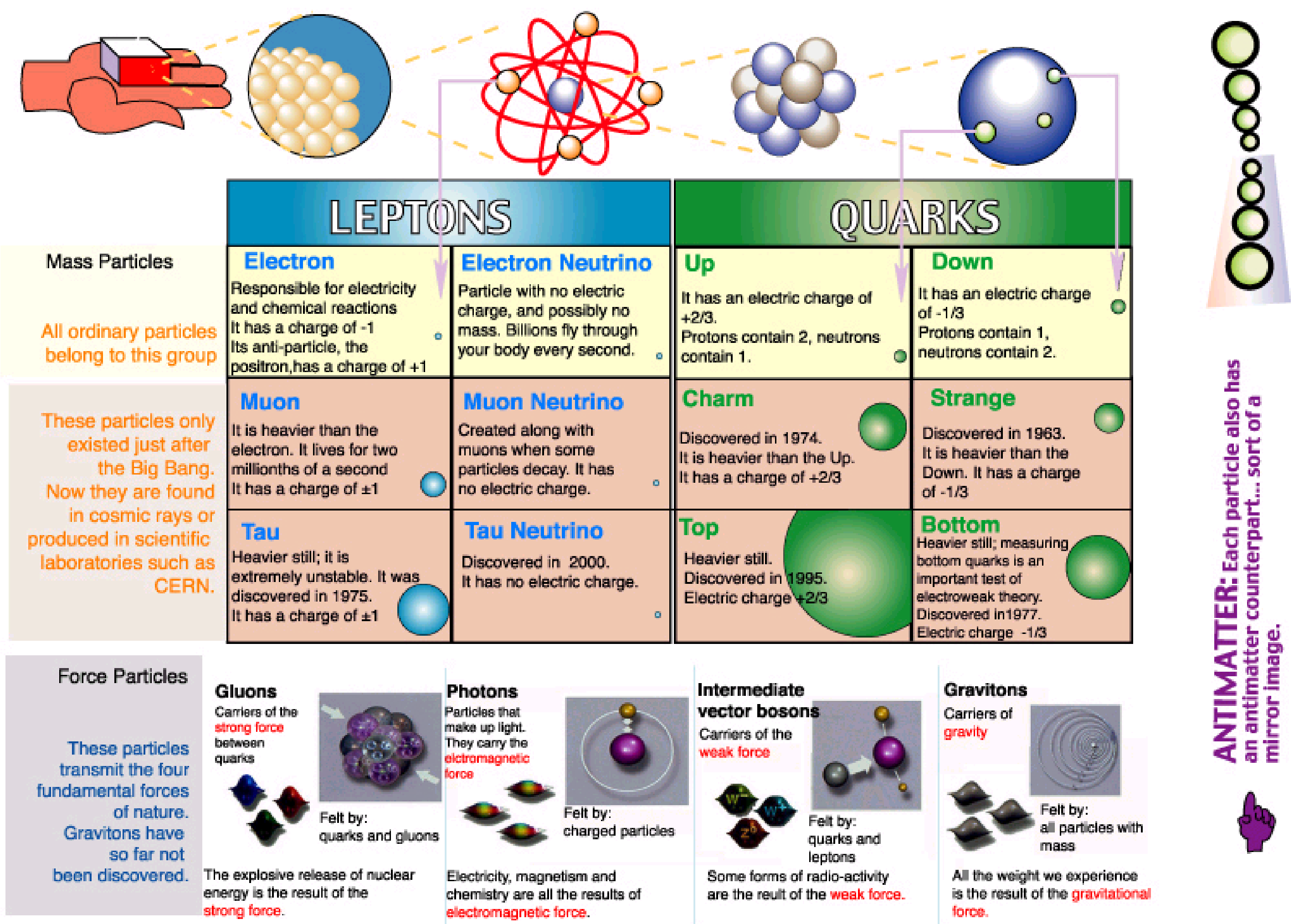
The fact that the phase of electron wave is inaccessible implies phase cannot have influence on any possible experiment. Hence an electron field exhibits symmetry with respect to arbitrary changes of phase. Any phase angle can be added and subtracted from the electron field and the result of all experiments will remain invariant.

Getting back to double slit experiments with electrons, the interference pattern formed on the screen can be attributed to the wave nature of the electron and it is only the phase difference that determines the peaks and valleys in the pattern. This is of course example of a global symmetry. It can be demonstrated that theory of electron fields alone, with no other form of field, is not invariant with respect to a corresponding local gauge transformation. In the above double slit experiment example if a device that shifts the electron phase by 180 degrees is placed in front of one slit the peak and valley of the interference pattern will shift. If the theory is to be made invariant with respect to local gauge symmetry such that the interference pattern does not shift, a new field has to be added that would compensate for changes in the electron phase. It turns out that the required field is a vector field with infinite range. The need for infinite field implies the field quantum must be massless. These are properties of and electromagnetic field, whose quantum is the photon. Therefore by requiring the local gauge invariance of electron field, existence of electromagnetic field can be inferred.

Apart from the electromagnetic force and gravitational force there are two other forces - the strong and the weak forces. The strong forces are the ones responsible for holding the nucleus together. The weak forces cannot be categorized as being attractive or repulsive like the other three forces. They change one particle into another. For quantum electrodynamics, the two fields required in the theory, electron and photon, where already known at the time it was being developed. But, the situation was very different for the strong and the weak interaction. It took a long time before the strong and the weak forces could start making sense. The reason was that the necessary local gauge theory was not understood. The development of these gauge theories required introduction of new particles and force, which conformed to the necessary gauge symmetry and also made the theories sensible in terms of making them finite (i.e., they are Renormalizable).

3. The Standard Model of Particle Physics: Constituents

The Standard Model describes the world in terms of fundamental particles and their interactions. According to the standard model the entire material world is composed of leptons and quarks; all other particles are composite made from these fundamental building blocks. There are forces that operate between particles – the color force between quarks, the weak nuclear force, electromagnetic force and gravity. Gravity, because of its feebleness, is not included in the picture of Standard Model. Both particles and forces are manifestation of fields and the mathematical structure that describes them is that of gauge field theories. The force field can be thought of as vector boson particles, the W/Z, gluons and photon. All the particles and forces and some of their particles are listed in the chart below.



4. Particle Creation and Detection

The simplified view of particle physics experiment, introduced earlier, can be described in three stages

- Preparation of the particle type and the energy at which the interaction will be studied.
- Colliding the particle at a certain pre-defined point and forcing and interaction.
- Particles produced in the interaction have to be detected and identified and their energy and momentum measured if the interaction is to be reconstructed.

The three stages are almost independent of each other. They pose different problems and have forced technology to be improved in specific ways so the particle physics experiments can function.