Lecture 27: April 29, 2021

PHYSICS 419 - Spring 2021

1 Expansion Redux

Hubble proved that the universe is expanding. The cosmic microwave background is the remnant of the embryonic universe that was produced from the big bang. Consequently, we have the notion that the universe started from a dot and expanded outward, graduating from a radiation dominated period to the matter dominated phase in which we now live. The question arises into what did the universe expand? That is, if everything is the universe, how can it expand into anything. There is really no good non-mathematical answer to this question. But there are two approaches that can be taken. First, we have learned from relativity that laws of physics do not change if we alter our vantage point. Hence, we could easily have taken the view that the universe is not expanding but rather that everything in it is contracting. As a consequence, it appears that everything is receding. In acutality, we cannot know that this is not the correct view. But we do have the intuitive notion that everything really is not the size of a dot. Another approach is to assume that the universe (vacuum) stretched off to infinity at the beginning. The nice thing about infinity is that if we add something to infinity we still have infinity. Hence, if a tiny dot on the vacuum started to expand, the question of what it was expanding into does not arise if we assume the vacuum already stretched off to infinity. We really cannot know that the universe is not infinite. Hence, this seems to be a reasonable alternative to the expansion dilemma.

2 Unification of forces

There are four known forces: gravity, strong nuclear (QCD), electromagnetism (QED), and weak nuclear. Other than gravity, ALL the forces involved in elementary physics problems (sliding friction, static friction, normal, spring, string, etc) are manifestations of electromagnetism. The strong nuclear force binds the nucleons together; the weak nuclear force produces radioactive decay.

Electricity and Magnetism

The Northwestern FI is the top in the field. Appointments there are tough to come by. 2 of the possible appointments are on Wednesday.

From 500 BCE to 1700 CE, electricity and magnetism seemed quite different. But links between them started to show up. For example, moving electric charges exert forces on magnets. Equivalently, moving magnets exerted forces on electrical charges. Maxwell unified them both. The unification predicted a new phenomenon: light, a transverse wave composed of electrical and magnetic fields. The properties of that wave (speed, polarization, energy density, momentum) all are DERIVED from the theory unifying the forces. While light was not a new phenomenon, in most cases unification does lead to new particles and fields that must be verified by new experimentation. Unification is an example of emergence: the whole is not equal to the sum of its parts. Remember what happened when we put quantum mechanics and special relativity together. We obtained both spin and antimatter. Neither theory by itself has either of these properties. Spin and antimatter are emergent properties resulting from the unification of QM and SR. This appears to be ontological emergence, I think.

In atoms, electrical forces are much stronger than magnetic forces. At very high temperature (high enough so that relative velocities on the order of the speed of light) magnetic and electrical effects are about the same size. In a world of charged particles flying around near speed c, it would not make sense to have separate treatments of "magnetic" and "electric" forces, since these would obviously be manifestations of the same effects. Remember that these fields transform into each other via Lorentz transformations.

Magnetic and electric forces become separable only if you pick a particular reference frame in which most things aren't moving fast. That is, if the local environment strongly breaks the Lorentz symmetry of relativity, the forces look different. In the full symmetry environment, they obviously belong to a unified theory.

All forces are the result of particle exchange. For example, the EM force results from the exchange of photons. A typical picture is shown in Fig. (1). For example, when one electron bounces off another one, one can draw this picture: There are two key properties of the EM interaction: 1) the incoming and outgoing particles are the same and 2) the interaction between the particles is mediated by a massless particle, namely the photon. Because the photon is massless, it can travel a large distance. Consequently, the forces it can mediate are long-range. This intuitive notion will always be true in physics, namely the less massive the mediator of the particle interaction is, the more long range the resultant interaction is.

Electroweak Interaction

The EW interaction is mediated by two particles that are massive, the W and Z particles. The mass of these particles is $80GeV/c^2$ and $91GeV/c^2$, respectively. All leptons experience the weak interaction. Leptons come in pairs where one member of the pair is the neutral counterpart of the other: (e, ν_e), (μ, ν_μ),

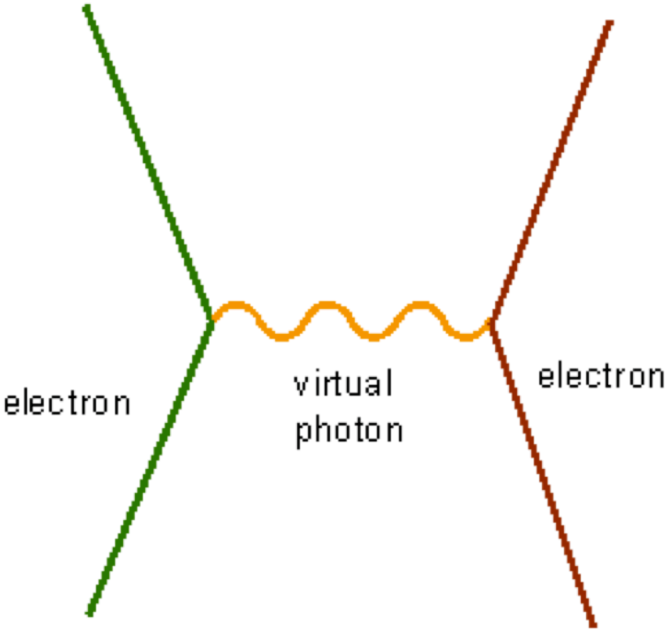

Figure 1: Example of the processes that lead to interactions between electrons. The red and green lines represent electrons while the squiggly line a photon. Light is the messenger of electricity and magnetism.

(τ, ν_τ) where μ is a muon and ν_μ is the muon neutrino, τ is the tau particle and ν_τ the tau neutrino, e is the electron and ν_e the electron neutrino. Aside from being mediated by a massive particle, the weak interaction can also change the incoming and outgoing particles. For example an electron can be changed into its neutrino. For example a typical interaction mediated by the weak interaction is (e, μ) interacting with the W particle and giving rise to (ν_e, ν_μ). Photons cannot mediate this reaction. In fact, it was as a result of reactions of this sort that it was deduced that the weak interaction had to exist. In all instances, the weak interaction does not always result in a changing of the particle type. The Z particle can mediate an interaction involving neutrinos only. Here is a summary of the similarities and differences between the EW and EM forces. EM interactions depend on the electric charge, a conserved quantity. Weak interactions depend on another property (called weak isospin) which isn't conserved.

1.) EM interactions are long range $(1/r^2)$.

2.) Weak interactions are short range $(10^{-18}m)$, decreasing exponentially).

3.) Some particles (e.g., quarks) participate in EM, but not weak interactions. Some (e.g., neutrinos) have the opposite behavior.

It is general rule of thumb that if a force is long ranged, it must be mediated by a massless particle.

3 Origin of Mass

There is a fundamental difference between mass and charge. All particles have a well defined value of both but we do not worry about where charge comes from. We do worry about why particles have the masses they seem to have. The reason is that charge originates from a symmetry principle and hence is related to a conservation law. Mass, on the other hand, has no such origin. It just appears. Hence, the question of where mass comes from is real. The origin of mass is related to the Higgs particle that we invoked in the context of inflationary cosmology.

Suppose the vacuum is full of Higgs particles. Let's also assume that as the universe cools (after the initial expansion) the Higgs field acquires a particular value, thereby breaking the symmetry of the vacuum. This is an example of spontaneous symmetry breaking. If this happens then (as in the case of magnetism), there has to be some measurable consequence of the symmetry breaking in analogy with the magnetisation. Here is what Glashow, Weinberg and Salam proposed in the 1960s.

1.) The photon doesn't interact with the Higgs field and so it remains massless.

2.) The W and Z particles become massive, and the weak force becomes short-range. This explains the observed differences between the EW and EM interactions.

3.) The masses of all particles (quarks, electrons, etc.) result from the interaction with the vacuum.

The whole story is the standard model of particle physics. The Higgs particle was announced July 4, 2012, thereby confirming much of what was pure conjecture as to the origin of where mass came from. Note, mass is no longer an intrinsic property of isolated objects. If we could change the properties of the vacuum or of the interactions with it, we could change the masses. Indirect evidence exists that this is true. So mass is not intrinsic. This goes along with the fact that mass is not a conserved quantity. It can be converted into energy. Another consequence of the unification of EW and EM is weak neutral currents which were actually observed before the theory was formulated but had no real explanation.

4 Grand Unification

The next unification would be that of the electroweak force and the strong nuclear force, which is described by QCD (quantum chromodynamics). The strong interaction is fundamentally different from all other forces: Its strength increases as the distance increases. Hence, the ground state of particles experiencing the strong interaction is a tightly bound state. Quarks are the only particles that experience the strong interaction. It is for this reason that there are not free quarks found in nature. There are a variety of different proposals for this unification. Each involves distinct experimental predictions for new particles, how the strengths of the interactions depends on the length scale, etc. Other than the search for the Higgs particle, high-energy accelerator physics is primarily concerned with sorting out these effects, and finding the proper form of the GUT. One of the earliest proposals was due to Georgi and Glashow. However, this theory predicted that the proton was unstable. This turned out not to be true. However, it seems that super symmetry has saved the theory of Georgi and Glashow.

What about Gravity?

The first of the fundamental forces to be found is the hardest to integrate into the unified framework.

Finding some deeper theory than GR is NOT just an optional whim on the part of people who like unified theories. The present form of GR and QM are NOT CONSISTENT, so there must be some deeper form which applies in the realm where quantum effects become important (very short times/distances, high energies).

So far the only proposals that look like they have a chance to give GR in the usual regime without making contradictions in the high-energy regime are proposals involving more space-time dimensions: string theory and its relatives.

Assuming that the effort to unify QM and GR is successful, our view of the universe will have become one in which all forces (fields) and particles are the same kind of entity. This includes the geometry of the universe, which GR has made into a dynamical entity. Gravity (at long wavelengths, low energies) is thought to be mediated by a massless particle called the graviton. Note, the graviton can interact with itself, unlike the photon. This means that gravity is non-linear. This is another consequence of lack of conservation of mass.

The structure of the universe, and of spacetime itself, is determined by the interactions between the various particles. This may lead to an issue of uniqueness and self-consistency. For a given general form of a theory, is there only one set of particles and interactions that might be found, or are there possible ranges of coupling constants, etc.? If the form of the theory doesn't specify all those numbers, what does?