

Symmetry and Unification Summary/Review

Spring 2009 Compton Lecture Series:
From Quantum Mechanics to the String
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- The weak force is different from the strong and electromagnetic forces
 - Some processes among the particles we’ve discussed cannot be explained by either the strong force or the electromagnetic force. These forces do not account for quarks changing flavor, or for neutrinos (which carry neither charge nor color) interacting at all.
 - Processes that involve neutrino interactions or quark flavor change tend to be much less likely than those that do not (for example a particle that decays via this type of interaction has a much longer lifetime than one that decays via a strong or an electromagnetic interactions.) This leads us to call this new force the “weak” force.
 - The weak mediator particles are massive, spin-1 bosons called W^+ , W^- , Z^0 . The weak mediators are the only fundamental force mediators that are massive, and the only ones that are charged under another force.
- Particles are disturbances in fields
 - If you think of the field as a rubber sheet, then particles are bumps in the sheet that move along, carrying momentum and energy.
 - The elasticity in the sheet means there is some potential energy associated with a disturbance that causes a bump. We associate this potential energy with the mass of the particle.
 - The potential energy density in the field V depends on the amount the field has been displaced from zero ϕ . If the function $V(\phi)$ gives some increasing positive amount of energy density for ϕ away from zero, this we associate with a normal mass. If non-zero ϕ (a disturbance in the field) leads to negative energy, we call this a “tachyonic” mass.
 - A tachyonic mass is really an instability in the field: it is as if we have taken the whole rubber sheet and pulled it away from where it wants to rest. If the potential V just gets more and more negative as the disturbance height ϕ grows, then we can’t make sense of the theory. But sometimes V has some stable minimum for a certain amount of disturbance ϕ_0 . This is as if we have pulled the whole rubber sheet away from its natural resting place by exactly the amount ϕ_0 . The system makes perfect sense so long as we redefine what we mean by the “vacuum” (where there are no particles) to be this stable natural resting place.
- A spontaneously broken symmetry is a symmetry of the laws of nature that isn’t realized in the world around us
 - A symmetry is an action you can perform on a system that ends up leaving the system unchanged. For example a 90 degree rotation of a square ends up leaving the square exactly the same, meaning this is a symmetry of the square. On the other hand, a 90 degree rotation of a rectangle will not usually leave the rectangle unchanged: this is not a symmetry of the rectangle (but a 180 degree rotation is). A circle can be rotated by any amount and it is unchanged: this is a continuous rotation symmetry.
 - Translations in space are one example of a spontaneously broken symmetry.
 - * The laws of nature, for example Newton’s law $F = ma$ are the same at all points in space. Moving to another city or country will not mean you have to live where $F = ma$ isn’t true.
 - * However, the world around us is not the same after a spatial translation. New York is not indistinguishable from Chicago, and certainly it is different from the center of the sun, or some random point in empty space.

- * Far back in the history of the universe, space was essentially uniform, but slight quantum perturbations eventually resulted in regions where there was a slightly higher density of matter. These regions tended to attract more matter, and this led to the development of galaxies and solar systems. At this point the translational symmetry was *spontaneously broken*.
- A second example of a spontaneously broken symmetry is a marble that moves on a roller-coaster track with two identical valleys separated by a hill.
 - * The track itself has a symmetry of reflection: it looks the same on either side of the central hill.
 - * When the marble is at rest, it settles into one of the two valleys, breaking the symmetry.
 - * For small movements about this stable point, the symmetry remains broken.
 - * But if you give the marble enough energy, its motion will restore the symmetry.
- The Higgs field has a “double well” potential energy and when it settles into one of the natural resting places spontaneously breaks a symmetry
 - The Higgs field interacts with the electro-weak mediators, and when it settles into the physical vacuum, it breaks the symmetry between the four mediators.
 - At high enough energies, the Higgs field is experiencing so much perturbation that it is no longer really in either natural resting place; here the symmetry is restored.
 - At these energies, the different masses of the four weak and electromagnetic mediators can be ignored, and they all look the same again.
 - During the history of the universe it has been continuously expanding, and as it has expanded, it has cooled down (so there is less energy in a given volume of space). Far back in the past it was hot enough that there was symmetry between the weak and electromagnetic forces, and then it cooled off and spontaneously broke this symmetry, with the Higgs field settling down into one of the minimum energy configurations.
- Interactions with the constant Higgs field cause particles to have effective masses
 - In what we call the vacuum, the Higgs field actually has some constant value ϕ_0 .
 - Particles that interact with the Higgs field are thus moving through a medium with which they are constantly interacting.
 - The energy associated with these interactions we interpret as mass energy for that particle.
 - This is somewhat analogous to the motion of light through a medium. Light travels slightly slower than the speed c when it moves through a medium. In this way, it is behaving as if it has some effective mass. In this case, if we zoom in on the light we see a photon that travels at speed c until it is absorbed by an air molecule, and then later emitted. It is the decay between absorption and re-emission that makes it seem like it is moving slower than c over a long distance. But with particles interacting with the Higgs, no matter how much you zoom in, you can never resolve into vacuum and Higgs molecules, because the whole field is just at a constant value; this makes the particles truly behave as if they have mass.
 - This allows quarks and the weak mediators to obtain mass. The photon stays massless because in truth, the symmetry being broken is a *continuous* symmetry, and whenever you break a continuous symmetry there is a massless particle associated with this called a “Nambu-Goldstone Boson”.