## Structure of matter, 7

*More about the matter with mass*

To repeat, the basic premise of QED is that the physical world doesn't care about the *phase* of the electron wavefunction; calculations and observations strongly support that idea. The basic premise of QCD is that the physical world doesn't care about the *color* of the quark wavefunction; calculations and observations strongly support that idea. The basic premise of QFD is that the physical world doesn't care about the flavor (isospin) of the quark or lepton wavefunctions. **But that's not true!** For example, a "free" $d$ quark can certainly emit a (virtual) $W$ particle and become a $u$ quark, but a "free" $u$ will never emit a $W$ and become a $d$. The mass of the $d$ is greater than the $u$ so the latter process cannot conserve energy and momentum. The fact that the two members of each lepton and quark family have very different masses makes it impossible to pretend that they can be interchanged at will while interacting weakly.

The observation that neutrinos are always left-handed and antineutrinos are always right-handed (Wu's parity violation experiment) suggests that the weak interactions also involve only left-handed massive leptons and quarks—i.e., particles that are right-handed can't interact weakly. This can be accomplished by declaring that left-handed particles carry isospin = $\pm 1/2$, while right-handed particles carry isospin = 0, *and* that $W$ s only interact with particles carrying $\pm 1/2$ isospin. **But that's not true, either!** The reason is that you can go faster than a particle with mass. Therefore, a right-handed particle with its spin in the same direction as its momentum will be a left-handed particle in a frame of reference traveling in the same direction but faster than the particle. (The particle's spin direction will be the same, in that frame, but its momentum will be reversed.) Massive particles don't have intrinsic handedness—*although massless particles do* (because you can't catch up to them because they travel at the speed of light).

Finally, local gauge theory predicts massless photons for QED, massless gluons for QCD, and massless weak force carriers for QFD. **But the latter is certainly not true!** The observed $W^+$ and $W^-$ have mass of about 80 GeV/c$^2$ (roughly 80 protons worth) while the $Z^0$ mass is about 90 GeV/c$^2$. If we take the field equations obtained from local gauge theory and simply put a mass term into the "Maxwell" equations for the potential fields, the theory is *not* renormalizable, making it automatically suspect. Worse, that term causes the theory to *not* be invariant under isospin transformations, which was the basic assumption for using local gauge theory in the first place. Mass "infects" the weak interaction at every turn and makes its theory seemingly very sick.

*Quantum Flavor Dynamics (QFD), II*

Rather than give up on the very compelling formalism of local gauge theory, QFD "explains" the infection of mass by introducing a new field, the *Higgs field*. The explanation starts out at high energy densities (i.e., where all particles are highly relativistic). In this scenario, under these conditions particles have no mass; the mass terms like $mc^2\psi$ in the fermion Dirac equations are ignorable at high energies. The leptons and/or quarks in the system supposedly interact directly with the Higgs field, so there *are* terms like $g_H H\psi$, where $H$ is the value of the Higgs field and $g_H$ is the dimensionless strength of the interaction. Although there are quantum fluctuations in the Higgs field, because of the way it interacts with itself these fluctuations cancel at high energy densities and the average value of the Higgs field is zero; in this "perfect vacuum" state leptons and/or quarks do not interact with the Higgs field. The world is totally symmetric under local isospin and hypercharge transformations. To ensure this, the Dirac equation for spin-1/2 particles carrying isospin and hypercharge includes isospin and hypercharge potential fields. At high energy densities mass terms in the Maxwell equations for the potential fields are negligible. The quanta of these fields are the massless spin-1 bosons corresponding to the fields $W_1, W_2, W_3, W_4$. To incorporate the weird handedness effects of the weak interactions, the "massless" fermions are defined as left-handed with isospin $\pm 1/2$ and right-handed with isospin 0. The $W_1, W_2, W_3$ only interact with left-handed fermions, while the isospin singlet $W_4$ doesn't care at all about isospin. In this scenario, the $W_4$ interacts with fermions in proportion to their hypercharge. In SM 6 it was noted that the weak hypercharge is –1 for the leptons. But, if right-handed leptons have 0 weak isospin then the electrically charged ones must have weak hypercharge equal to –2; the $W_4$ field will therefore interact twice as strongly with right-handed leptons as with left-handed ones. (Note that the neutral right-handed neutrinos would have both isospin and hypercharge equal to zero, so if they existed they wouldn't have any interactions *except gravity*! Might they therefore be dark matter? Intense searches for right-handed neutrinos have so far not yielding unambiguous confirmation.)

The scenario continues: As the energy density is lowered below some critical value, the Higgs field undergoes a "phase transition" and its average value ($V$) everywhere becomes nonzero, even without excitations. A useful analogy to this putative phenomenon is ferromagnetism, where above the Curie temperature electron spins are all randomly arrayed with zero net magnetization, while below it the electrons, via their ("exchange") interaction, spontaneously align, producing a large net magnetization. Before the alignment transition, the collection of randomly oriented spins looks the same from all perspectives: it has perfect rotational symmetry. After alignment there is a preferred direction in space: the original perfect symmetry has been "broken." And because this direction is not imposed externally (if there is no external magnetic field)—it arises from random interactions between groups of neighboring electrons—the transition is an example of "spontaneous symmetry breaking."

The spontaneous symmetry breaking of the Higgs vacuum (in the scenario) has several immediate consequences. First, the direct interaction between fermions and the Higgs field becomes approximately $g_H V\psi$, so $g_H V$ acts like $mc^2$ for that $\psi$ (with presumably a different value for different particles because $g_H$ is different—we don't know why this might be true nor how to calculate the values). In addition, interactions between the Higgs field and the isospin and hypercharge potential fields produce terms in their Maxwell equations of the form $V^2 \times (\text{mixture of potential fields})$. Disentangling these mixtures leads to the interpretation that the (negatively charged) quanta of the fields $W_1, W_2$ get equal masses (proportional to $V$) due to their interaction with the Higgs vacuum, while the (electrically neutral) particles of a mixture of the zero isospin fields consisting of mostly $W_3$ and less $W_4$ gets a different mass (also proportional to $V$). Finally, the particles of a second mixture of mostly $W_4$ and less $W_3$ (also electrically neutral) does not interact with the Higgs field at all and therefore gets no mass.

Now, in the real world of massive fermions, observed interactions of $W^+, W^-$ particles involve only left-handed particles. Thus, it is natural to interpret the first set of quanta as the actual $W^+, W^-$ particles (both with Higgs-conferred mass of about 80 GeV). On the other hand, observed interactions involving $Z^0$ particles favor left-handedness but also include right-handedness. The first, electrically neutral, massive mixture of $W_3$ and $W_4$ has all the necessary characteristics to be the actual $Z^0$ particle (with Higgs-conferred mass of 90 GeV). Finally, the second, electrically neutral, but *massless* mixture of $W_3$ and $W_4$ treats left- and right-handed electrons, for example, equally. Moreover, the strength of the interaction of this mixture with a fermion carrying weak isospin $I$ and weak hypercharge $Y$ is found to be proportional to $I+Y/2$, which is exactly the Gell-Mann-Nishijima formula for the fermion's electric charge (in units of *e*). All of this is very compelling evidence that the second mixture of $W_3$ and $W_4$ *must be the photon!*

In other words, the hypothetical Higgs mechanism for conferring particles with mass reveals to us that quantum electrodynamics is actually an intrinsic part of QFD. The resulting unification of electromagnetic and weak phenomena is called the "electroweak interaction." (Whew, some scenario!)

*The Higgs boson*

Proof of the pudding (or at least strong corroboration) of the spontaneous symmetry breaking produced by the putative Higgs field requires exciting the Higgs vacuum somehow to produce an "observable" particle. In the simplest Higgs scenario such a particle should have zero electric charge and zero angular momentum: an electrically neutral spin-0 boson. Because the masses of all particles are related to the average Higgs vacuum value, it is possible to place limits on what the mass of this "Higgs boson" should be. Rigorous searches (prior to mid 2011) for excess activity at different energies in collision experiments at the Fermilab Tevatron and at CERN limited the range of masses to between 115 GeV and 130 GeV. In December 2011, two groups working at independent detectors at the LHC at CERN—where counter-circulating beams of 3.5 TeV protons collided—both reported excess activity in particle channels expected for Higgs production and decay at about 125 GeV. The excesses reported at that time were small but detailed analysis of additional data since then (in March 2013) indicate that the excess activities are likely not to be explainable by experimental variability to a confidence level of over 99.9999%. In addition, the particle's spin is almost certainly zero; thus what has been discovered at the LHC appears to carry all of the predicted properties of the long sought after Higgs boson.