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Neutrino mass and family mixing

Neutrinos are products of radioactive decay in many stellar fusion processes, primarily starting with the reaction $p+p \to {}^2He^* \to {}^2H + e^+ + \nu_e$. The nucleus ${}^2He^*$ is a highly unstable (that's what the * represents) isotope of helium consisting of four primary u quarks and two primary d quarks. For years (since 1962 or so), various groups have been measuring the solar electron-neutrino flux, invariably observing it to be lower than theoretical predictions. Moreover, neutrinos are generated in the upper atmosphere, via collisions of cosmic ray particles with atmospheric atoms, and in nuclear reactors and some accelerator reactions. Attempts to measure one or other type of neutrino in these circumstances, when the evidence is clean, typically show deficits from expectation. "Explanations" for these neutrino deficits have been plentiful, but, in the end, only one appears to be generally applicable: *neutrino oscillations*. The idea is that a u quark in the short-lived ${}^2He^*$ nucleus converts into a d quark by emitting a W^+ that, in turn, decays into the positron and the electron-neutrino. Doing so presumably reduces the electric repulsion in the nucleus sufficiently that the otherwise forbidden reaction $u \to d + e^+ + \nu_e$ actually occurs. (The reaction doesn't reduce the electric repulsion enough in a single proton, so it doesn't occur in protons by themselves; that's good for us!)

If the p,p collision is sufficiently energetic, the W^+ actually can decay into any one of three possible pairs: $(e^+,\nu_e),(\mu^+,\nu_\mu),(\tau^+,\nu_\tau)$. As is always the case in quantum mechanics, the best one can say about the state of the neutrino so produced *before* measuring its flavor (somehow) is that it is an admixture of all three flavors. As time goes on, the coefficients of this mixture cycle in time, and the rate of cycling depends on the mass of the component flavor. If all three neutrino flavors have the same mass (including zero), then the probabilities of detecting any of the flavors is independent of time. If they have different masses, however, the probabilities change with time. Apparently, this explains the neutrino deficit experiments. By the time a neutrino from the Sun arrives at Earth, for example, its probability of being an electron-neutrino (as opposed to one of the other flavors) at the site of the detector will probably be less than 1. Though this kind of oscillation has been convincingly demonstrated in a variety of experiments, the actual masses of the neutrinos have yet to be determined.

Neutrino oscillations have an important consequence: *weak interactions apparently permit family change as well as flavor change*. Family switching is accomplished for neutrinos by mixing neutrinos from the different families together. Perhaps a similar effect is found in quark phenomena as well. Indeed, there are many examples. One of the most important is the decay of the neutral K-meson, thought to be a mixture of $d\bar{s}$ and $s\bar{d}$ quarks. There are two possible mixtures: $d\bar{s} - s\bar{d}$ and $d\bar{s} + s\bar{d}$. Both of these mixtures are found in collision debris. The first, K_1, decays into two pions, the second, K_2, decays into three pions. Pions are states of $u\bar{u}, d\bar{d}$, $u\bar{d}$, $d\bar{u}$; that is, the decay of the neutral K switches an s into a d or a u, and an $\bar{s}$ into a $\bar{d}$ or a $\bar{u}$. Note that the mass difference between the neutral K (either 1 or 2) and two pions is larger than that between the K and three pions. As a result, the K_1 decays faster than the K_2. As discussed below, these decays harbor a potentially profound consequence for the structure of the universe.

CP violation

The weak decay of the positive pion, $\pi^+ \to \mu^+ + \nu_\mu$, violates parity transformation symmetry because the neutrino is always left-handed. A parity, or P, transformation would change the direction of the neutrino's momentum without changing its spin direction and therefore would require that the neutrino switch to right-handed, but that is never observed. Similarly, the weak decay $\pi^- \to \mu^- + \bar{\nu}_\mu$ always produces a right-handed antineutrino. This also violates P symmetry. But, the particles on the left sides of both reactions are antiparticles of one another as are the particles on the right sides. Denoting the transformation "switch to antiparticle" by C leads to the result $CP(\pi^+ \to \mu^+ + \nu_\mu) = (\pi^- \to \mu^- + \bar{\nu}_\mu)$. The latter expression means that each process is possible and both occur at the same rate and with all the same dynamic properties. In other words, the decay of the pion (and most other particle processes) is invariant under the combined transformation CP. Note that *CP symmetry requires that every particle has an antiparticle and that each occurs equally likely in all processes*.

If the world were perfectly CP symmetric there would always be equal amounts of matter and antimatter and the universe would not look like the overwhelmingly matter-filled world we live in. To make this world there has to be CP violation. It turns out that the weak interaction allows for some CP violation. This is most famously observed in the neutral K-meson decay. As mentioned previously, the short-lived K_1 decays into two pions, while the long-lived K_2 decays into three. This implies that the two Ks have different CP properties. High-energy collisions that produce neutral Ks produce some of both K_1 and K_2. Monitoring pion production along the length of a long beam of Ks shows lots of two pion decays at first and fewer—but *not zero*—farther down the beam. In fact, the rate of two-pion decay far down the beam is too high to be accounted for by surviving K_1s. It must be that K_2 can decay sometimes into two pions as well as three pions. The decay of the K_2 is *not* CP invariant!

Alas, this one process is not sufficiently abundant to account for the current amount of matter, and lack of antimatter, in the universe. Other small CP violating weak decays have been observed (involving mesons carrying b quarks) but none can lead to the present universe. A more promising setting is neutrino and antineutrino oscillations. Recent studies by the "T2K" collaboration in Japan suggest there is a large difference in the rates of neutrino versus antineutrino oscillations and that implies a significant CP violation. Whether it is enough to explain the predominance of matter over antimatter is still unclear. Where all the antimatter went in the early universe remains one of most challenging unanswered questions facing the Standard Model of Particle Physics.

Summary of the Standard Model

The Standard Model contains the following fermions. (1) Six spin-1/2 quark flavors, grouped in three generations of two members each. Each quark flavor has a different mass, the range of which spans a factor of about 10^5. Each quark has one of three possible colors, as well as a weak isospin and a weak hypercharge value. Three quark flavors are electrically charged +2/3 e, the other three –1/3 e. (2) Six spin-1/2 lepton flavors, grouped in three generations of two members each. Each lepton has a different mass, the range of which spans a factor of about 10^9. Each lepton has a weak isospin and a weak hypercharge value, but no color. Three leptons are electrically neutral, three have electric charge –1 e.

In addition the Model contains the following bosons. (1) Eight spin-1 gluons, which "mediate" the color interaction. They are massless, electrically neutral, but carry color. Gluons carry no weak isospin or hypercharge. (2) Four spin-1 electroweak bosons, which mediate the electroweak force. The $W^{\pm}$ carry weak isospin, but no hypercharge or color. They are electrically charged ($\pm 1\,e$) and massive. The Z^0 is electrically neutral, carries weak isospin, and is massive, but carries no hypercharge or color. The photon is electrically neutral and massless, and carries no weak isospin, hypercharge, or color. (3) One spin-0 Higgs boson. The Higgs boson carries weak isospin and hypercharge, but no color. It is massive, but electrically neutral.

Gluons arise from conservation of color charge. Their dynamical description is a "local gauge theory." The electroweak bosons arise from conservation of weak isospin and hypercharge. Their dynamical description is a local gauge theory. The Higgs boson interacts with all particles carrying weak isospin and hypercharge (including itself) and as a result imbues elementary particles (but not composite systems) with the property of mass.

Quantitative predictions of the Standard Model agree to within a small uncertainty with observations and, therefore, it is believed to be an excellent approximation for fundamental processes. On the other hand, the Standard Model also contains a number of unresolved problems. The Standard Model is mute about the origin of the many parameters of the particles it includes. It does not explain why there is a handedness preference in the weak interaction. The Standard Model has no good candidate for a dark matter particle nor does it tell us anything about why the density of dark energy is so small. Of course, gravity does not appear anywhere in the Standard Model. In fact, Einstein's theory of general relativity is at variance with quantum field theory (upon which the Standard Model is based). Quantum field theory is predicated on the assumption that interactions occur at a point in spacetime: interactions are *local* in quantum field theory. But general relativity (plus the Heisenberg Uncertainty Principle) says that distances less than the Planck length (see, SM 2) are inside a black hole, so nothing can be said about such interactions! Finding answers to these problems appears to require a theoretical structure beyond the Standard Model, of which there are many candidates but as yet no experimental support.