Neutrinos

For our final regular lecture of the semester (not counting the review in the next class, which will be entirely driven by your questions), we will talk about neutrinos. As you know, these are ghostly particles that barely interact with matter in normal circumstances. That means that these allow us an unobscured glimpse of what happens in the interior of the Sun, but also means that detection is very difficult indeed! We'll begin with a little about the history of the idea of neutrinos and their initial detection, and then circle back to their applications and importance in stellar astrophysics.

The original idea for neutrinos goes back to 1930, when Wolfgang Pauli proposed the existence of a new particle to save energy and momentum conservation in beta decay. Beta decay is a process by which a neutron or proton is converted into the other, often (but not always) in an atomic nucleus. A good example involves the decay of carbon-14 (famous for radiocarbon dating):

$$^{14}_{6}\mathrm{C} \rightarrow ^{14}_{7}\mathrm{N} + e^- + \bar{\nu}_e \ , \tag{1}$$

where here the bar above the ν means that this is an antineutrino, and the subscript "e" on the ν means that this is an electron (anti)neutrino. But consider 1930, when it wasn't yet possible to detect neutrinos at all. Then the reaction looked like

$$^{14}_{6}\mathrm{C} \rightarrow ^{14}_{7}\mathrm{N} + e^- \ , \tag{2}$$

and that was a problem because the sum of the energies of the nitrogen and the electron didn't equal the energy of the original carbon, nor did the sum of the momenta of the nitrogen and the electron equal the momentum of the original carbon.

So how should we explain that? When we explore a new realm experimentally or observationally, there is no guarantee that the "laws" that worked previously work in the new realm. For example, it used to be thought that mass on its own, and energy on its own, were conserved, but it's actually mass-energy that is conserved in local interactions. Thus although it seems strange to us, it was reasonable and even creative of Niels Bohr to suggest that perhaps energy and momentum are only conserved in a statistical way. But Pauli proposed instead that there was a particle that was emitted that saved energy and momentum conservation. He originally called this the "neutron", but when Chadwick discovered what is now called the neutron (and is a completely different particle), Pauli's suggested particle became called a "neutrino" (Italian for "little neutral one") following a joking suggestion by Edoardo Amaldi that was then popularized by Enrico Fermi.

One problem: it quickly became clear that the little neutral one really didn't want to interact, so experimental physics couldn't be in the game (an outstanding paper by Fermi on neutrinos was rejected by Nature because it was "too remote from reality"!). Only in 1956 was the neutrino finally detected directly in a laboratory, and in 1965 the first natural neutrinos were detected in a mine in South Africa.

For stellar astronomy, neutrinos enter our story in a way that we mentioned before but will now discuss in more detail. Starting in the 1960s, Ray Davis used a detector in the Homestake gold mine in Lead, South Dakota to detect neutrinos from the Sun that would be produced by fusion processes. The theorist on the project was John Bahcall, who calculated the expected rate at which these would be detected. When the rate turned out to be 1/3 of the expected value, this was ultimately determined to be because of what are called flavor oscillations... but let's back up and give some details first.

Their approach to detection was to use cleaning fluid containing chlorine (600 tons of it!) and every once in a while clean it out to see if they detected argon, which should be produced by:

$$\nu_e +^{37} \mathrm{Cl} \longrightarrow e^- +^{37} \mathrm{Ar}\ . \tag{3}$$

The neutrino must have an energy of at least 0.81 MeV. That's a little inconvenient, because neutrinos from the p-p chain have energies only up to 0.42 MeV. These are the most common neutrinos produced in the Sun (>90% in the standard model). Thus it is necessary to rely on neutrinos from the CNO cycle instead. The rates are expected to be mighty tiny: if a "target" is defined as an individual chlorine atom (in this example), then a typical rate of detection is 10^{-36} captures s^{-1} target^{-1}, which is called a "solar neutrino unit" or SNU.

The net result, which has been confirmed by many experiments since the original Davis and Bahcall work, is that we see only 1/3 of the expected rate. One obvious but not very interesting possibility was that Davis' experimental setup was less efficient than thought at collecting argon atoms. However, careful checks by Davis and support by later experiments ruled that out. Another obvious and slightly more interesting possibility was that the temperature, density, or composition structure of the Sun is slightly different than was assumed in Bahcall's standard solar model. Since some of these reactions (especially the CNO reactions!) are very temperature-sensitive, this seems promising (indeed, getting the right answer to a factor of 2 or 3 is impressive in its own right!). However, specific solutions ran into great difficulty, because of the huge number of observational constraints (most substantially from helioseismology). What else could it be?

The now-accepted solution is exciting because it represents a deviation from the model of electroweak interactions (remember that in the 1960s and 1970s, the electromagnetic and weak forces were unified). To explain this, we recall that in the standard model of particle physics, we have three types of leptons: electrons, muons, and tau particles. Muons and taus are the heavier cousins of electrons, with the same electric charge, but are unstable. These are the three "flavors" of leptons. To each of these, there is an associated neutrino: the electron neutrino, the muon neutrino, and the tau neutrino.

Suppose that you produce an electron neutrino, or a muon neutrino, or a tau neutrino, of some energy and let it propagate in free space. What do you expect to happen? What people *had* expected is that your neutrino would maintain its identity indefinitely.

To put this in a quantum mechanical context and remind ourselves of some principles of quantum mechanics, you remember that for a given potential, a given operator has eigenfunctions. Eigenfunctions are wavefunctions such that when you apply the operator to the wavefunction, you get a constant multiple of the original wavefunction; that multiple is called the eigenvalue. In general, different operators will have different eigenfunctions. That is, if you measure the momentum of a particle, you are (in the math of quantum mechanics) applying the momentum operator to the wavefunction. The original wavefunction did not have to be an eigenfunction of the momentum operator. However, you can express any wavefunction as the sum of the eigenfunctions of any given operator, with coefficients. When you measure the momentum (in this case), you have to obtain a value that is the eigenvalue of one of the momentum eigenfunctions in your sum. The probability of that value (as opposed to other values) is related to the coefficients in the sum. Right after your measurement, the wavefunction is the momentum eigenfunction that you measured.

What if you just let the particle alone, allowing it to travel through free space? Then the evolution of the wavefunction is as follows. You can break the wavefunction into a sum of coefficients times energy eigenfunctions. If you consider eigenfunction i, with energy eigenvalue E_i, then the complex phase of the eigenfunction evolves with time t as $e^{-iE_it/\hbar}$. If the original wavefunction was the sum of more than one energy eigenfunction with different E_i values, then the phases evolve at different rates, and thus the whole wavefunction evolves as well. If instead the original wavefunction was a single energy eigenfunction then the spatial part doesn't change, and only the phase of the wavefunction evolves. Since the probability of finding a particle at a given location $\mathbf{r}$ depends on the complex square of the wavefunction, the $e^{-iE_it/\hbar}$ factor cancels out and thus the waveform is *stationary* and does not evolve meaningfully in time.

Circling back to our neutrinos, the expectation of many was that the flavor eigenstates (i.e., electron, muon, or tau) *were* the energy (or equivalently, mass) eigenstates. If that were the case, then a neutrino that started out in one flavor (say, the electron flavor) would continue in that flavor in vacuum indefinitely. But it turns out that this is *not* the case. Flavor eigenstates area actually the sum of energy (or mass) eigenstates. Thus, again quantum mechanically, if you measured the original neutrino to be an electron neutrino, then right after the measurement, that's the wavefunction. But that wavefunction contains elements of three energy eigenstates. They evolve at different rates, which means that later, the wavefunction is not just the electron flavor. Thus if you measure the flavor later, it could be a muon or a tau neutrino even if it started as an electron neutrino.

This wasn't expected in the standard model, and what it means is that neutrinos have mass (but not much; although measurements of the flavors aren't yet possible individually, the sum of the masses of the three flavors is less than one millionth of the mass of an electron). It also turns out that when neutrinos propagate through matter (e.g., in the core of the Sun or in a core-collapse supernova), the probability of flavor change is enhanced. This is a big deal. That's why, once the solar model had been tightly verified using helioseismology, the discovery of a neutrino deficit was judged worthy of a Nobel Prize.

Neutrinos are fermions, and their intrinsic angular momentum is $\hbar/2$. A weird thing about them, though, is that, relative to their motion, they can only spin one way: their effective angular momentum is antiparallel to their direction of motion. That contrasts with, say, photons, which can have an intrinsic angular momentum that is parallel or antiparallel to their direction of motion. That makes neutrinos "left-handed", and in the same way, antineutrinos are "right-handed".

Could right-handed neutrinos (and left-handed antineutrinos) exist? Maybe or maybe not. This gets into the realm of speculative particle physics. Maybe they don't exist. Maybe they exist and have very large masses (explaining their lack of detection in particle colliders). Maybe they exist and don't even interact via the weak force (making them "sterile neutrinos", although the low interaction cross section of ordinary neutrinos makes them pretty sterile already!). Sterile neutrinos are one of the list of candidates for dark matter and occasionally there will be some excitement in astronomy about a possible signal... but nothing yet has withstood close scrutiny.

When we think about how neutrinos interact with matter, the simplest process is scattering, e.g.,

$$\nu_e + e^- \rightarrow \nu_e + e^- \ . \tag{4}$$

This is akin to Thomson scattering of a photon off of an electron *but* the cross section for scattering off of an electron is

$$\sigma_\nu \approx 10^{-44} \left(\frac{E_\nu}{m_e c^2}\right)^2 \ \mathrm{cm}^2 \ . \tag{5}$$

This is what is technically known as an itsy bitsy cross section. Now, particle physicists have a lot of time and a fondness for alcohol, leading to interesting terminology and names for units. In this case, they've dubbed 10^{-24} cm^2 a "barn" and 10^{-48} cm^2 a "shed", so a typical neutrino cross section is some ten thousand sheds! This compares with the Thomson cross section, which is close to one barn; indeed, hitting an electron with a photon is like hitting the broad side of a barn compared to hitting an electron with a neutrino. For people without a sense of humor, 10^{-44} cm^2=10^{-48} m^2 is one square yoctometer. Pretty small, no matter how you slice it.

Despite the extremely weak interactions of neutrinos, as we discussed earlier in the course there are an enormous number produced in core-collapse supernovae (because when the core collapses to a protoneutron star the production of all those neutrons from protons and electrons also makes neutrinos). Indeed, in a typical supernova perhaps 99% of all of the $\sim 10^{53}$ erg of energy eventually escapes in the form of neutrinos. Perhaps $\sim 1\%$ of them interact on the way out, which is enough to cause the explosion that we see. This is yet another example of competing extremes in astronomy: a very large number of weakly-interacting particles has a big impact! Some ~ 20 neutrinos with energies of tens of MeV were seen from SN 1987A (February 24, 1987, from a star in the Large Magellanic Cloud) from a few detectors, and that gave valuable information about the explosion process. Much larger detectors exist now, and the Magellanic Clouds are tens of kiloparsecs away; if a supernova occurred today within the Galaxy, we would expect tens to hundreds of thousands of neutrinos and would thus get an unprecedented view of the core collapse process (particularly if the explosion were close enough that we could also see gravitational waves...).

Another thing that you notice about the neutrino scattering cross section formula is that, unlike with Thomson scattering, the cross section depends on neutrino energy. The $\sigma \propto E^2$ scaling goes up to the rest mass of the thing off of which the neutrino scatters, so at higher energies it is actually scattering primarily off of nuclei rather than electrons. At higher energies than the rest mass, σ is $\propto E$, and then it levels off at even higher energies. What all of this means is that you can try to detect really high-energy neutrinos because their interactions become stronger. However, very high energy neutrinos are uncommon, so you need a detector with a huge volume to have a good chance to catch them.

Huge volume means water in some form, but early attempts ran into unexpected levels of noise. For example, the DUMAND experiment (Deep Undersea Muon and Neutrino Detector) had a substantial background from luminous deep-sea fishes! The IceCube detector, near the South Pole (lots of UMd people work on that detector), has had better success. It strings detectors, sparsely, through about a cubic kilometer of ice. The idea is that if a neutrino hits something, at energies of typically a TeV or greater, then it gives enough momentum to the electron or nucleus that the particle hit by the neutrino then travels faster than light can in the ice (remember that the speed limit of the universe is the speed of light in a *vacuum*, not the speed of light in any given medium). This produces Cerenkov light, which can be detected using photomultipliers.

Very high-energy neutrinos, up to a few PeV, have been seen using IceCube. Their origin is still debated, with blazars and other high-energy sources being good candidates. Stars, unfortunately, are not such good candidates. For example, given the energy dependence of the scattering cross section, can you speculate about what would happen if PeV neutrinos were to be produced in a core-collapse supernova? Would we see them?