Neutrinos

In our continued pursuit of the early universe, we will now investigate neutrinos. These ghostly particles, which would typically sail through a light year of lead without interacting, have a significant enough effect in the early universe that nucleosynthetic calculations were able to limit their number of flavors (an impressive achievement, given that particle physics experiments couldn't constrain the number of flavors at the time), and have sometimes been suggested as good candidates for dark matter. We will start with the prediction and discovery of neutrinos, then talk about their properties, evolution in the universe, and recent observations suggesting that they have mass.

Prediction and Discovery

Beta decay is a process by which a neutron decays and produces a proton and an electron, $n \rightarrow p + e^-$. This can happen for neutrons in a nucleus, and thus this effect was known even before neutrons were discovered by Chadwick in 1932. It was shown, however that the process did not conserve energy or linear momentum.

How should this be resolved? From our perspective it might seem obvious that energy and momentum must of course be conserved. However, every time a new physical realm is explored, we must be prepared for our current knowledge to be challenged or expanded. An example is that it used to be thought that energy by itself, and mass by itself, were conserved. In reality, it is mass-energy as an entity that is conserved.

With this in mind, it actually took some guts for Wolfgang Pauli to predict in 1930 that there was another particle involved in the decay. In modern notation,

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{1}$$

where the $\bar{\nu}_e$ is an electron antineutrino. Note that $\bar{\nu}_e$ has to be neutral, for charge conservation. Pauli showed that such a particle could rescue energy and momentum conservation. It also enforces lepton number conservation: leptons are particles that do not contain quarks, and hence do not participate in interactions involving the strong nuclear force. Here, antiparticles count as -1 particles, so the electron and antineutrino add up to be $1 - 1 = 0$ leptons, consistent with the absence of leptons on the left hand side.

The interactions, however are remarkably weak (see below). As a result, it took until 1956 for Cowen et al. to detect them. Since that point, it has been shown that neutrinos come in three different "flavors", called electron, mu, and tau (after the electron and its two heavier [and unstable] counterparts the muon and tau). Each also has an antiparticle. But how can these interact?

Electron-neutrino interactions

See http://www.sns.ias.edu/∼jnb/ (John Bahcall's home page) for many details about neutrino astrophysics.

Neutrinos interact very weakly; in fact, their existence is the hallmark of the weak force. Typically, a neutrino of energy E_ν has an electron scattering cross section of

$$\sigma_\nu \approx 10^{-48}\left(\frac{E_\nu}{m_e c^2}\right)^2\ \mathrm{m}^2\ . \tag{2}$$

This is what is technically known as an itsy bitsy cross section; for comparison, the electron-photon scattering cross section is $6.65\times10^{-29}\ \mathrm{m}^2$, some twenty orders of magnitude larger. 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 $10^{-28}\ \mathrm{m}^2$ a "barn" and $10^{-52}\ \mathrm{m}^2$ 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, $10^{-48}\ \mathrm{m}^2$ is one square yoctometer. Pretty small, no matter how you slice it.

Let's figure out the fraction of neutrinos interacting in certain circumstances. First, the Sun. **Ask class:** to order of magnitude, what is the density of the Sun? About 1000 kg m^{-3}. That means that the number density is about $10^{30}\ \mathrm{m}^{-3}$. **Ask class:** so, what is the mean free path of ~ 1 MeV neutrinos? About 10^{18} m. The Sun is about 10^9 m in radius, so only about 10^{-9} of the neutrinos interact.

Stated this way, it may appear that neutrinos would be irrelevant for practically any purpose. However, this is not the case. In particular, let's think about the dense core in the center of a star just prior to a supernova. **Ask class:** if you crush the Sun down to a radius 1000 times less than it actually has, what happens to the optical depth to neutrinos? Density is $1000^3 = 10^9$ times greater, but the length traveled is 1000 times less, so optical depth is 10^6 times greater. That suggests an optical depth of about 10^{-3}. The neutrinos in supernova are actually somewhat more energetic as well, about 3–5 MeV, so a fraction $\sim 10^{-2}$ of the energy is absorbed. This seems to be enough to be the crucial driver of the supernova, since a good 10^{53} erg is released in neutrinos.

The Solar Neutrino Problem

In the past few decades, however, it is the neutrinos themselves (rather than their effects) that has captured the attention of most of the physics community. The reason for this is the so-called solar neutrino problem.

The point is that nuclear fusion of hydrogen to helium in the Sun must produce copious amounts of neutrinos, because $4\text{H}\rightarrow{}^{4}\text{He}$ requires the conversion of two protons to neutrons. This can happen in a few different specific ways (it isn't just a super-rare collision of four hydrogen atoms). Starting in the 1960s, however, experiments led by Ray Davis and later by the Kamiokande collaboration in Japan detected only about a third of the predicted neutrinos. One obvious possibility is that the detectors weren't as sensitive as expected, and another is that the solar predictions were incorrect. However, repeated tests of the experiments (and new and different techniques) ruled out experimental error. More recently, exquisitely precise probes of the solar interior using helioseismology (i.e., solar oscillations) constrained the solar model to such a degree that there was negligible astrophysical wiggle room.

The currently accepted resolution is that as the neutrinos propagate from the dense stellar interior, their flavor can change. Since they all start out as electron neutrinos, and since the experiments were unable to detect mu or tau neutrinos, a factor of 1/3 was perfectly consistent with the standard solar model. The flavor oscillation suggests, as it turns out, that neutrinos have mass. We will explore the consequences below, after talking about detection of neutrinos.

Neutrino Detection

How do you detect something that passes through even the densest things like they weren't there? You use a big honking mass of stuff and hope there are a few interactions!

The classic Davis approach took advantage of chemical changes. He used hundreds of tons of cleaning fluid (containing chlorine). If a neutron in a chlorine nucleus absorbs an electron neutrino, it converts into a proton and an electron, thus transforming the nucleus into one of argon. Argon is a noble gas, so it isn't produced naturally and is easy to pry from the cleaning fluid by processing. Davis swept his cleaning fluid for argon every month or so for decades to accumulate evidence of an electron neutrino shortfall. Currently, some detectors look for a change of gallium to germanium, but it's the same basic principle.

Another approach looks for fast-moving electrons that have been scattered by electron neutrinos. If the electrons move faster than the speed of light in the surrounding medium (which is water, due to its clarity and cheapness) they give off blue Cerenkov light that is detected by surrounding scintillators. This was the method used by the Kamiokande group. This group, along with the Irvine-Michigan-Brookhaven water Cerenkov group, detected neutrinos from Supernova 1987A, the closest supernova in centuries. See Figure 1. Similar methods are being used to look for dark matter interactions as well. It should go without saying that the backgrounds and possibility of interference are substantial, requiring great care.

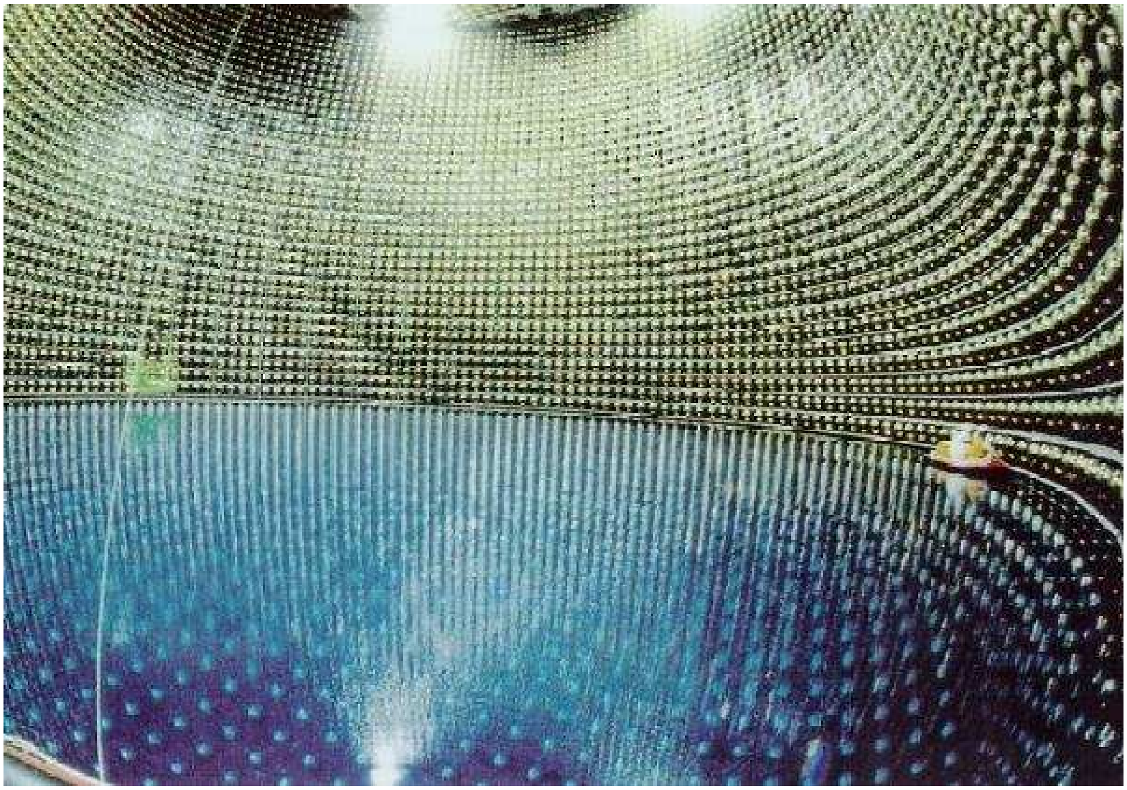

Fig. 1.— The Super-Kamiokande neutrino detector in Japan, before all 9000 phototubes exploded in series and turned this into a lake of broken glass. See the people in the boat on the right for scale. From http://www.aip.org/png/images/deth20.jpg

As an example of this, there has been an ambitious attempt to put detectors at the bottom of the ocean, figuring that if some water is good, more is better. However, the DUMAND (Deep Underwater Muon And Neutrino Detector) group ran into an unexpected problem: luminescent deep-sea fish kept coming over to investigate the scintillators, raising the false positive rate to an unacceptable level! Similar large-scale detection arrays exist in Antarctica, where people have put long strings of scintillators hundreds of meters down in the ice, with an eye towards detecting ultra-high energy neutrinos. There are no fish in the ice, but the ice does have greater roughness than expected. Still, the experiments are proceeding well.

Neutrino Background

At redshifts so high that the temperature of the universe is $T = 2.7(1+z)$ K$\gg m_e c^2$, the number density of electrons, positrons, photons, neutrinos, and antineutrinos (electron flavor in both cases) are about equal, and in thermodynamic equilibrium. **Ask class:** how would we use this to compute, to within a factor of 2, the redshift at which neutrinos decouple from the electrons and positrons, with the criterion that the mean free path is equal to the horizon radius?. Note that everything is ionized, and that the total number of electrons is dominated by electron-positron pairs, rather than by the small number of electrons we have today. The total number density of blackbody photons at temperature T is $n \sim 2\times 10^7 T^3$ m^{-3}, where T is in Kelvin. When integrating over the blackbody spectrum the electron-neutrino scattering cross section is roughly $\langle\sigma\rangle = 4\times 10^{-48}(T/10^{10}\text{ K})^2$ m^2. In addition, since this was the radiation-dominated part of the evolution of the universe, the age at redshift z was approximately $t(z) \approx 0.3(z/10^{10})^{-2}$ s.

Answer:

We want $L(z) = R(z)$, where $L(z) = 1/(n\sigma)$ and $R(z) = ct(z) \approx 10^8(z/10^{10})^{-2}$ m. Since $T = 2.725\times 10^{10}(z/10^{10})$ K, we know that $n \approx 4\times 10^{32}(z/10^{10})^3$ and $\langle\sigma\rangle \approx 3\times 10^{-47}(z/10^{10})^2$. Therefore,

$$L(z) \approx 8\times 10^7(z/10^{10})^{-5} = R(z)\ . \tag{3}$$

Solving gives $z \approx 10^{10}$. As we said above, because the electrons and positrons annihilate later and thus add to the energy reservoir in photons, if we were to observe a neutrino background it would be slightly cooler than the photon background, about 1.9 K instead of 2.7 K.

Ask class: how tough would this background be to detect? Bloody difficult, that's how tough! Such low-energy neutrinos would in fact be undetectable by the methods we discussed (the speed given to a recoiling electron would be much below the speed of light in water, hence no Cerenkov, and chemical changes would also not be possible). Even if we somehow managed to detect the recoil of electrons in free space due to neutrinos, note that the cross section would be on the order of 10^{-67} m^2. That makes the previous smallness of the cross section look huge by comparison!

Undaunted, however, we can investigate whether the neutrinos that are left behind are nonetheless decent candidates for dark matter. If their total energy density is comparable to that required for dark matter, and if the neutrinos are nonrelativistic at this epoch, they might work.

The number density is around 1.4×10^8 m^{-3}, and the dark matter density is about 2.7×10^{-27} kg m^{-3}, or about 1.5×10^9 eV m^{-3}, so the required mass-energy per neutrino is about 10 eV. The electron mass-energy is 511 keV, so 10 eV doesn't sound like much. What do experiments say?

Unfortunately for this hypothesis, the experiments indicate that the masses are likely to be far below this. The flavor-changing data actually indicate the difference in squared mass-energy. The difference in squared mass between the first and second neutrino eigenstate is 0.000079 eV^2, and between the second and third is 0.0031 eV^2. In addition, analysis of data from the CMB and elsewhere suggests that the sum of all three masses is less than about 0.3 eV. Neutrinos are not the cold dark matter.

This means that the dark matter must be a currently undetected particle: not a single particle in the entire Standard Model zoo can account for the inferred properties. This is scary, because we are appealing rather strongly to the unknown, but at the same time it is very exciting because it suggests that there is an important world out there we have yet to detect.

Intuition Builder

How many neutrinos pass through your body each second? Are there more from the Sun or from the cosmic background?