“Like Dustmaids Down a Drafty Hall”: Neutrinos at the Sudbury Neutrino Observatory

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Even with my office door partly closed, I can hear my colleagues down the hall arguing. Each is criticizing the other’s latest theory of the microscopic Universe. Backing his opponent into a corner, one accuses the other of trying to create a theory which violates a fundamental symmetry of Nature. I smile to myself, because I know what the response will be: in this theory, there is a new particle which ensures that this symmetry is preserved. Not a bad week, I think—that will make three new particles predicted, and it is still only Tuesday.

In 1930, the situation was very different. The Universe was made up of just a handful of particles whose interactions with one another were almost entirely understood. Physicists believed there were only a few details left to understand before we had a complete theory describing the fundamental makeup of the Universe—the field of particle physics was nearing its end. One of these details was the surprising behavior of the electrons emitted when a radioactive nucleus underwent β decay. In these decays, a heavy nucleus became lighter by emitting an electron (a ‘β particle’). When a nucleus decays into two particles (in this case, the lighter nucleus and the electron) the energy available is the same each time—some of the mass of the nucleus was converted into the kinetic energy of both the electron and the recoiling lighter nucleus (as described by Einstein’s famous formula $E = mc^2$). With just two particles in the final state, conservation of momentum and energy requires that they each have the same energy every time. The problem was that measurements showed the electrons had energies all the way from zero to the total energy they should have had.

The problem of the ‘missing energy’ in β decay was so serious, physicists as prominent as Niels Bohr were making radical suggestions, such as a violation of energy conservation in quantum mechanical processes. In 1929, the physicist Wolfgang Pauli came up with his own radical idea. Calling it a 'desperate way out' of the β decay crisis, Pauli wrote to colleagues attending a conference (addressing it to his 'Dear Radioactive Ladies and Gentlemen') postulating the existence of a third particle involved in β decay. If a third particle did participate in the reaction, then the energy could be shared between it, the electron, and the recoiling nucleus so that the electron could have a different energy each time. In cases where Pauli's third particle and the nucleus took up all the available kinetic energy, the electron would have zero.

Pauli was very worried about his idea—unlike today, postulating the existence of a new particle was a rare event. Pauli knew, too, that the obvious criticism of his theory was that no one had ever observed a third particle in β decay—just the electron and the leftover nucleus. So Pauli cleverly endowed his particle with properties which would make it nearly undetectable. Unlike the electron or the proton, Pauli's new particle had no charge, so that it would not produce ionization tracks in the detectors of his experimentalist colleagues. Of course, even a neutral particle might scatter a charged particle like an electron as it left the detector, and that electron would be seen, so Pauli also predicted his new particle interacted with matter only very weakly (if at all). His particle was so pentrating, it could pass through a light year's thickness of lead without interacting.

There was one more way, however, that a missing particle might be seen in a detector looking at β decay. Not all of the energy available in the decay turns into kinetic energy—some of it provides the mass of the electron (in the inverse of Einstein's mass-energy relationship). So Pauli's third particle would also remove some of the energy in the reaction, and therefore the maximum energy the electron could have would be reduced. Knowing that experimentalists had not seen any evidence of missing mass in the reaction, Pauli proposed that in addition to being chargeless and weakly interacting, his new particle had little or no mass at all. Pauli named his particle the 'neutron', but when Chadwick discovered heavy massive particles in the nucleus (clearly not Pauli's particle) and gave them the name 'neutron', Enrico Fermi gave Pauli's particle the name 'neutrino', which means 'little neutral one'.

Predicting the existence of a particle which could not be detected doesn't earn a theorist too many friends amongst experimentalists, and Pauli worried that the neutrino would never be observed. However, even a particle like the neutrino will still interact occasionally—just by good luck (or bad luck, depending on your perspective) a neutrino may scatter an electron or be absorbed by a nucleus. To increase the likelihood that this happens, experimentilists would need either a lot of matter (a big detector) or a high flux of neutrinos. Luckily there are many sources which produce neutrinos in large quantities—nuclear weapons and reactors, cosmic rays interacting in the atmosphere, or particle accelerators.

However, even with many neutrinos and a large detector, there are many other processes which can look like neutrinos and overwhelm the signal—a typical neutrino detector may only detect a handful of neutrinos a day. By comparison, there are enough cosmic ray muons showering the Earth that if they were raindrops there would be an inch of rain or so every three hours. So neutrino detectors need to avoid cosmic rays, and the only way to do this is to shield the detector, often by placing it deep underground.

In addition to cosmic rays, within any given piece of matter there are small amounts of radioactive nuclei. Although their numbers may be tiny (one part in a trillion or less) and their decays rare, a typical piece of matter will have many thousands of decays each day—far more than the few neutrinos expected. So the materials needed to build neutrino detectors also need to far cleaner than normal, to ensure as few radioactive contaminants are present as possible.

In 1956, using a large detector sitting next to a nuclear reactor (which put out enormous numbers of neutrinos), the physicists Fred Reines and Clyde Cowan were able to make the first direct observations of neutrinos. Pauli's fears that he had predicted the existence of an undetectable particle were therefore luckily not borne out.

Further experiments determined that neutrinos came in three distinct types or 'flavors', each corresponding to a different charged particle: the electron-neutrino (ν_e) to the electron, the muon-neutrino ν_μ to the muon, and the tau-neutrino τ the tau lepton. In addition, they were (as Pauli predicted) very weakly interacting. And lastly, as far as experiment could determine, the neutrino had no mass at all.

These neutrino properties were incorporated into physicists' best theory of the way the microscopic Universe worked, the unimaginatively named Standard Model of Particle Physics. The Standard Model describes more than just neutrinos, however, it predicts the way in which particles decay and scatter off of one another and even how things behaved in the very early Universe. In over twenty years of experiments testing the predictions of the Standard Model, no confirmed deviations from its predictions were ever found. Like the early part of the twentieth century, it had begun to look like physicists understood everything which could be measured. The Standard Model appeared to be a complete description of Nature at the microscopic level.

The unusual properties of neutrinos were summarized by the writer John Updike in 1960, in his poem 'Cosmic Gall' which begins:

> *NEUTRINOS, they are very small.*
> *They have no charge and have no mass*
> *And do not interact at all.*
> *The earth is just a silly ball*
> *To them, through which they simply pass,*
> *Like dustmaids down a drafty hall*
> *Or photons through a sheet of glass...*

Physicists, being somewhat more pedantic than poets, tend to point out Updike's mistake—the neutrino *does* interact occasionally, so the third line should perhaps be '*And barely interact at all*'. However, as we will see, even some of Updike's second line has turned out to be wrong.

During the time that neutrino properties were being discovered and understood, a completely different branch of physics was beginning to see the uses neutrinos had as tools to understand new phenomena. As neutral particles able to pass through enormous amounts of matter, neutrinos could be used to examine even the centers of dense astrophysical objects.

One particularly interesting possibility was that neutrinos could be used to prove the theory that the Sun's power was produced by nuclear fusion going on in its core. In these fusion reactions, four hydrogen nuclei (just protons) were combined into one helium nucleus, made of two protons and two neutrons. The chain of nuclear reactions which converts the four protons into helium has two important by-products: the energy which ultimately becomes sunlight, and neutrinos. But unlike the photons of sunlight which may scatter off of the atoms in the solar envelope for tens of thousands of years, neutrinos born in the core of the Sun take just two seconds to travel to its surface, and then another eight minutes to get to the Earth.

In the mid-1960's, Raymond Davis, Jr., a Brookhaven chemist, set up the first large-scale experiment to look for neutrinos from the Sun. Like all solar neutrino detectors, Davis's experiment was big (about 500 tons), deep (about a mile underground in the Homestake gold mine) and kept as clean of radioactivity as was then possible in an active mine. His detector was essentially a large vat of dry cleaning fluid, which contained the element Chlorine. When a solar ν_e was absorbed by a Chlorine atom, it would be tansformed into a radioactive form of the element Argon. Argon has a relatively long half-life (many days) and so an Argon atom created by a neutrino interaction could be removed from the detector sometime later, and then observed by looking for its radioactive decay.

The model of how the Sun produced energy predicted that Davis should see about five Argon atoms every couple of days or so. The detection of these neutrinos was expected to be a triumphant confirmation of solar astrophysics, but unfortunately for theorists like John Bahcall who had worked hard on the solar models, Davis's measurements fell short of the predition. Far short, in fact—Davis saw only 1/3 of the expected flux of neutrinos from the Sun.

At the time, and for years afterward, most physicists weren't too concerned by the discrepancy between Davis's measurements and Bahcall's predictions. After all, the experiment itself was very difficult—Davis was trying to see just a handful of atoms each day, and couldn't even tell whether those atoms really came from the Sun or perhaps some unexpected source of radioactivity. On top of this, trying to model the goings-on at the center of the Sun was also very hard—the number of neutrinos was sensitive to the internal density and temperature, which themselves were model predictions based upon observations of the solar surface.

The situation began to change when other experiments were built to look for the solar neutrinos. One of these experiments—the Kamiokande experiment—used the phenomenon of Cerenkov radiation to detect the neutrinos in real time, and to show conclusively that the neutrinos were coming from the Sun. Cerenkov radiation is created whenever a charged particle—like an electron—travels through a medium faster than light itself does. While nothing can travel faster than light through vacuum, photons actually slow down quite a bit when they travel through transparent materials, while a high energy particle does not. When a charged particle exceeds the local speed of light, it creates a 'shock wave' similar to that produced by an airplane exceeding the local speed of sound. However, instead of a 'sonic boom', the shock wave created by the charged particle creates light, light which actually looks somewhat blue to the eye.

The typical number of detectable photons created when a low energy particle produces Cerenkov radiation is only about 50, which is a tiny number (a lightbulb will typically produce more than 10^{20} photons every second). However, single photons can be detected using photomultiplier tubes (PMTs), which work via the photoelectric effect. A photon striking the front face of a PMT will produce an electron, and inside the PMT the electron is accelerated by voltage applied to the tube, until it hits a piece of material from which it liberates two electrons. These two electrons are themselves accelerated toward another piece of material, where they each liberate more electrons. This process is repeated in several 'stages' until there are enough electrons to be measured by electronics (usually built by the physicists working on the experiment).

The Kamiokande experiment used roughly 1000 tons of clean water as the Cerenkov medium, and about 1000 PMTs to measure the Cerenkov light. A neutrino entering the Kamiokande detector could (with very good luck) scatter an electron out of one of the water molecules, and if the neutrino energy was high enough, the electron would create Cerenkov light. One big advantage of this method over experiments like Davis's was that the electron would travel along the same direction that the neutrino had been travelling. By showing that the electrons were typically traveling in the direction away from the Sun, Kamiokande was able to show that the neutrinos Davis had been seeing were, in fact, coming from the Sun. The strange thing was that while Davis saw only 1/3 of the expected solar neutrino flux, Kamiokande saw about 1/2.

Other solar neutrino experiments followed these, and each one saw a deficit. Experiments which used methods like Davis's but looked at lower energy neutrinos saw 2/3 of the expected flux, while Super-Kamiokande, a much larger version of Kamiokande, confirmed the Kamiokande result of 1/2 for the high end of the neutrino energy spectrum. Figure 1 shows the data for the three different classes of experiment, and we can see that in all cases there is a deficit, though it does vary from one type of experiment to another (actually, from one neutrino energy regime to another).

At the same time, the model of the Sun improved as well, and tests of the model using

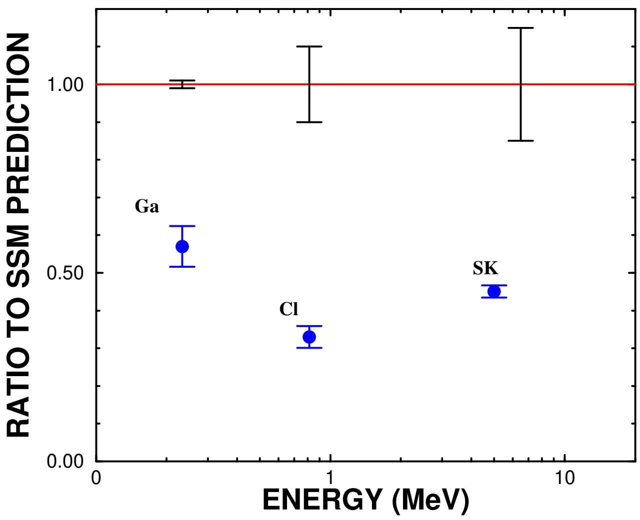

Figure 1: Comparison of experimental measurements of the solar neutrino flux to the predictions of the Standard Solar Model

measurements of the oscillations of the solar surface (helioseismology) confirmed many of the predictions of the model (those which did not involve neutrinos). Physicists slowly began to believe that there really was something very strange going on with the solar neutrinos, and the discrepancy became known as the 'Solar Neutrino Problem'.

The are three ways in which neutrinos from the Sun could appear to be missing. The first is simply that all the experiments were somehow wrong. Although the experiments are difficult, the fact that they all saw a deficit using very different methods argued that the deficit was real—it was hard to see how they could have a common error. The second possibility was that the model of the Sun was wrong. Trying to make a precision astrophysical prediction is notoriously difficult—without being able to travel to the objects being studied, many assumptions have to be made. However, the solar model was tested with many different input assumptions, and the positive results of the helioseismology measurements argued that the model could not be seriously in error. The final possibility was that both the model and the measurements were correct, but that the reason too few neutrinos were being seen by the experiments is that neutrinos were behaving in a way not predicted by the Standard Model of Particle Physics.

As described above, the Standard Model incorporates neutrinos as three distinct, massless particles. But if the Standard Model picture of neutrinos were incomplete, and the three flavors of neutrinos are not separate but are allowed to change from one type to another, it could explain the Solar Neutrino Problem. The Sun can only produce ν_e's, there is not enough energy in its nuclear fusion processes to produce the other two neutrino types, and so experiments like Davis's looked exclusively for this single flavor. If the ν_e's born in the center of the Sun change into one of the other types on their way to the Earth, then the experiments will have seen fewer neutrinos than they had expected—the others would sail right through the detectors without being noticed.

The changing of neutrinos back and forth from one flavor to another is usually referred to as neutrino 'oscillations'. Neutrino oscillations are a quantum mechanical effect: each neutrino is actually a superposition of other neutrinos (in the way a chord on the piano is a superposition of other notes), and the change in the relative phase of the neutrinos causes the superposition (the thing we measure in experiments) to change. If instead of being massless, each neutrino had a small (but different) mass, then they would each move at different speeds and their superposition could change. So a neutrino born as a ν_e (a particular superposition of a ν_1 and a ν_2, for example) could, after it travelled some distance, be a different superposition of a ν_1 and a ν_2 which happened to look (to us) like a ν_μ.

Strong evidence that neutrinos *can* oscillate from one flavor to another was reported in 1998 by the Super-Kamiokande experiment which looked at muon flavor neutrinos that were produced in the Earth's upper atmosphere by cosmic rays. What Super-Kamiokande observed was that the number of ν_μ's they measured depended on where the ν_μ's were produced—*above* the detector where they needed to travel only 100 km or so before observation or *below* it all the way on the other side of the Earth where they would need to travel thousands of kilometers. If ν_μ's can oscillate, they would produce exactly the type of distance-dependent difference in the number of neutrinos seen by Super-Kamiokande.

Unfortunately, for solar neutrinos, the distance from the production point (the Sun) to the detection point (the Earth) does not vary enough to allow the type of measurements made with Super-Kamiokande's 'atmospheric' ν_μ's. Proving that neutrino oscillations were the solution to the Solar Neutrino Problem was therefore going to take an entirely different approach.

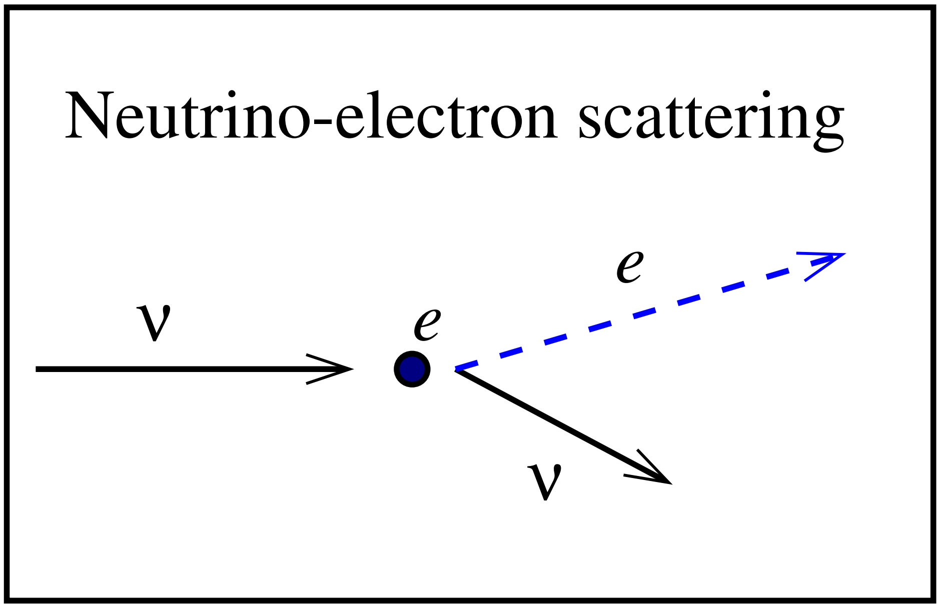

Figure 2: The elastic scattering of an electron by a neutrino. This reaction is sensitive primarily to ν_e's, but has some sensitivity to other flavors.

In 1984, University of California at Irvine physicist Herb Chen suggested a possible way to resolve the issue. Rather than look for distance-dependent effects, Chen realized that the way to prove that the ν_e's produced in the Sun are oscillating into ν_μ's or ν_τ's is to directly look for ν_μ's or ν_τ's. Chen's idea was to build a water Cerenkov detector which used heavy water, rather than ordinary water. Heavy water is water in which the hydrogen (H) has been replaced by its heavier isotope deuterium (D) (making D_2O instead of H_2O). The Deuterium nucleus (called a deuteron) contains one proton and one neutron, and it is the neutron which makes all the difference.

In heavy water, neutrinos can interact in one of three ways. The first is simply by scattering electrons, a process which happens in ordinary ('light') water and was used by Kamiokande and Super-Kamiokande to see solar neutrinos (see Figure 2). In heavy water as in light water, these electrons would produce detectable Cerenkov light. This elastic scattering process occurs for ν_e's about 6.5 times more often than it can happen for ν_μ's or ν_τ's. The second reaction is the absorption of a neutrino by the neutron in the deuteron, shown in Figure 3. In this process the neutron is changed into a proton and a high energy

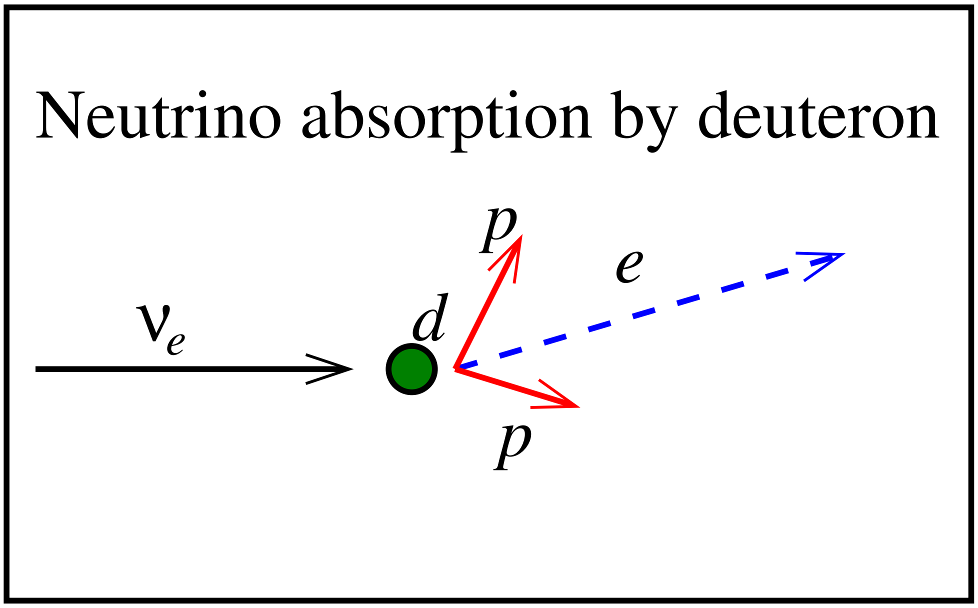

Figure 3: The neutrino absorption reaction. This reaction is sensitive only to ν_e's.

electron is emitted, producing Cerenkov light. Because there is an electron created, this process happens only for ν_e's. The final process is the breakup of the deuteron—a neutrino simply splits the neutron from the proton, as shown in Figure 4. Because no new charged particles are produced in this reaction, it can happen for any neutrino flavor—equally as often for ν_μ's or ν_τ's as for ν_e's.

With heavy water, then, the idea was that the solar neutrino problem could be solved directly: simply comparing the number of all neutrino types coming from the Sun (measured by the deuteron breakup reaction) to the number of ν_e's (measured by the neutrino absorption reaction) could tell whether neutrinos which were born as ν_e's changed into one of the two other types. No longer would there be any question whether the model of the Sun was in error (because the total flux would be measured, not predicted) and by doing the three measurements with one detector, nearly all the potential experimental errors would cancel because they would be common to both reactions.

The only problem with Chen's idea was that it required a lot of heavy water (which is very hard to make and therefore very expensive) and, like all solar neutrino experiments, the detector would have to be underground somewhere and built in a very clean environment.

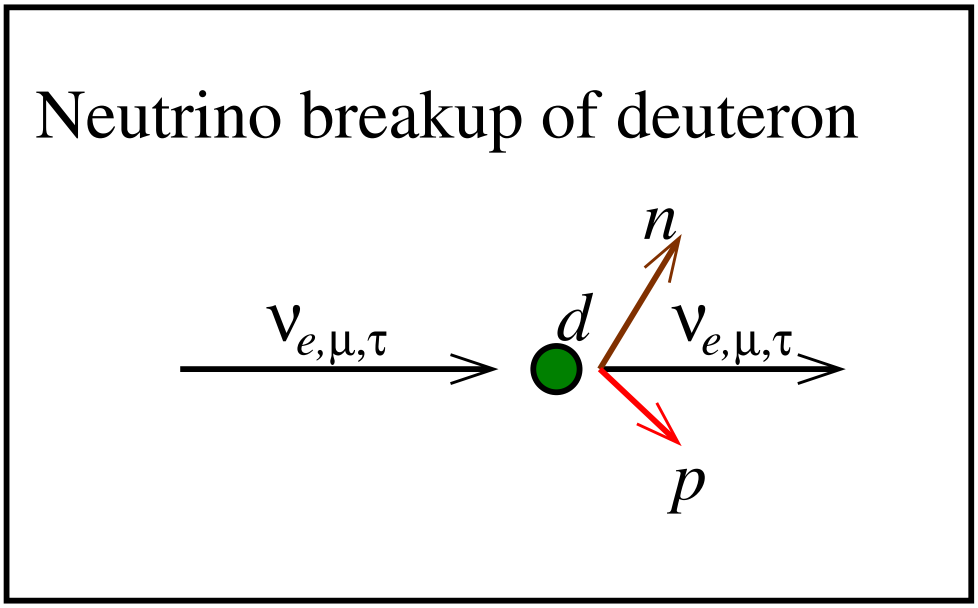

Figure 4: The deuteron breakup reaction. This reaction is sensitive to all flavors of neutrinos equally.

Remarkably, there was a place where such a detector could be built—the Creighton Mine in Sudbury, Ontario. In addition to being able to carve a large cavity out of the rock over 2 km underground—deep enough to do solar neutrino measurements—the Canadian nuclear power industry had large reserves of heavy water, because heavy water is used as a moderator in their particular design of nuclear reactors (the CANDU reactor). Ultimately, Sudbury was chosen as the site for the detector, and an Ontario power company agreed to lend $200 million worth of heavy water to create the Sudbury Neutrino Observatory.

As shown in Figure 5, SNO's heavy water (a total of 1000 tons) is held in a transparent acrylic vessel 12 m in diameter. Outside the heavy water volume is 6000 tons of light water. The cavity for SNO is 22 m wide by 34 m high, carved out of rock 6800 feet beneath the surface of INCO Ltd.'s Creighton Mine in At SNO's depth—deeper than any other solar neutrino experiment—there are only three cosmic rays passing through the detector each hour. The Cerenkov light created by the neutrino interactions is detected by an array of 9500 photomultiplier tubes. The PMTs are supported by a stainless steel geodesic sphere 17.8 m in diameter, as shown in Figure 5. In addition to having very small backgrounds from

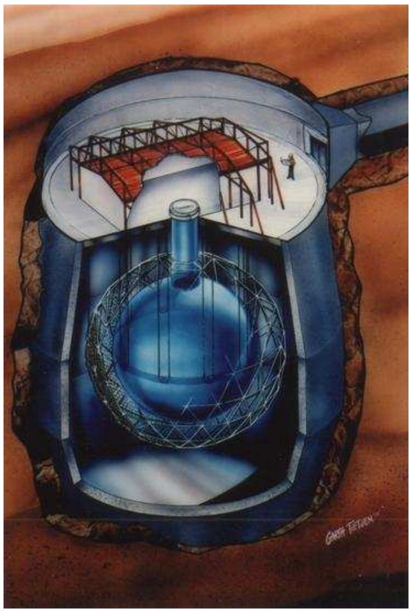

Figure 5: Diagram of the SNO Detector

cosmic rays, SNO also was built (and is maintained) in a clean room environment, making it perhaps the point of lowest radioactivity in the world.

Just building the detector of course, is not enough—the SNO collaboration (made up of over 100 physicists from 12 different institutions in Canada, the United Kingdom, and the United States) had to determine how to remove the backgrounds that were in the data, and how to figure out how a neutrino interaction in the detector would look. From the time that data taking began, the process of calibrating the detector and analyzing the data took almost two years. Of the 400 million or so events that the detector recorded, fewer than 3000 were left at the end of the analysis process.

By measuring the differences in the way neutron events from the deuteron breakup reaction and electrons from the neutrino absorption reaction and elastic scattering reaction looked, the SNO collaboration was able to determine how many of the 3000 or so events in the final sample came from each reaction. With knowledge of how many neutrinos it took to produce the events from each of the reactions, SNO could finally decide how many ν_e's came from the Sun (using the number of events from the neutrino absorption reaction), and how many total neutrinos came from the Sun (using the deuteron breakup reaction). If the second number was much bigger than the first, then it was direct proof that neutrinos were changing from ν_e's into one or both of the other two types on their way from the Sun to the Earth.

The data analysis found that of the 2928 events in the final data set, 1967 were found to come from the neutrino absorption reaction, and 576 from the deuteron breakup reaction. The probability of observing the neutrino absorption reaction is actually much higher than observing events from the deuteron breakup reaction (for example, the probability to detect the electron produced in the neutrino absorption reaction is greater than 50%, while the probability of detecting the neutron is just 14%), and so the 1967 events correspond to 1.76×10^6 ν_e's$/cm^2s$, while the 576 events correspond to almost three times as many total neutrinos: 5.06×10^6 ν/cm^2s! In other words, when SNO measures the flux of all neutrino types using the deuteron breakup reaction, it finds there are three times as many neutrinos coming from the Sun than is seen if one just looks for the electron neutrinos.

The only conclusion possible from this is that 2/3 of the ν_e's born in the center of the Sun are changing into neutrinos of other types before arriving to the Earth. The most natural mechanism for this transformation is neutrino oscillations, which require that neutrinos have mass. In the Standard Model, neutrinos are distinct, massless particles, and so for the first time—in over twenty years—the predictions of the Standard Model have fallen short. Our best model of the microscopic Universe has thus turned out to be incomplete and, perhaps ironically, the model of how the Sun generates power which had been thought to be incomplete has been found to be correct.

Must the Standard Model be completely cast aside on the basis of these new observations? Not quite. The Standard Model can be altered to accommodate neutrino masses and 'mixing', as long as we add new parameters to the theory—something like adding more epicycles to the geocentric theory of the solar system. We are left wondering whether there is a more fundamental theory than the Standard Model which we are just begining to glimpse through our studies of neutrinos.

Despite the discoveries, SNO is not yet done. For the past two years, SNO has been running with NaCl—essentially table salt—added to the heavy water to enhance the sensitivity to the deuteron breakup reaction (Chlorine is better at capturing neutrons than deuterium is). The hope is that this greater sensitivity will lead to better precision in the measurements of how neutrinos mix with one another. After the NaCl phase, new detectors will be added to SNO, which will be able to detect individual neutrons directly, providing even greater precision.

From Pauli's prediction of the neutrino, to Davis and Bahcall's first apparent failure to understand the Sun's neutrinos, to SNO's final solution to the Solar Neutrino Problem, neutrinos have turned out to be more puzzling—and interesting—than we (or even John Updike) had imagined. What will happen with future measurements by SNO and other neutrino experiments is difficult to predict, but it is likely to include even more suprises.