

Week 2

April 7, 2018

Lost and Found: Solar Neutrinos and Oscillations

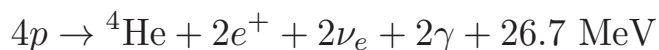


Nuclear fusion reactions occurring deep within the Sun produce an abundance of neutrinos, along with many photons. The photons bounce around, losing information about their origins. In contrast, the neutrinos, owing to their rare interactions with matter, reach us directly from their point of production, which makes them an invaluable tool for understanding processes inside the Sun. But unexpected results in early searches for solar neutrinos led us to completely rethink how neutrinos work.

This week, we will cover the fundamentals of solar neutrino production and detection, and the so-called Solar Neutrino Problem — the resolution of which played a key role in our understanding of neutrinos.

I. Standard Solar Models

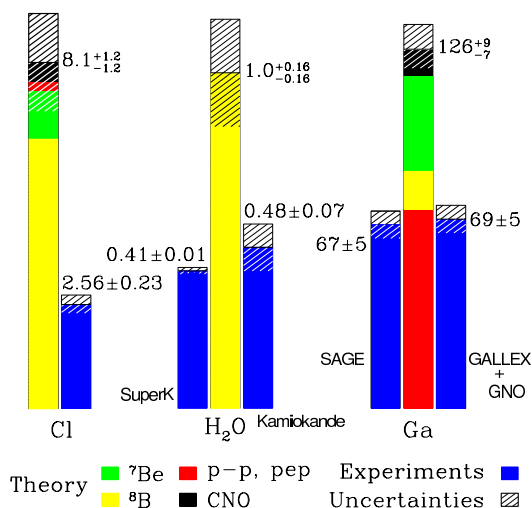
The pp Fusion Chain: In the mid-20th century, nuclear physics has just undergone a revolution with the development of atomic energy. This knowledge is put to use to construct the first mathematical models of the nuclear processes that fuel the Sun. In particular, physicists calculate the fusion chain reaction, which converts four protons into a helium nucleus, producing two electron-type neutrinos (ν_e):



Standard Solar Model: This nuclear physics is combined with observational measurements of the Sun (the size, age, brightness, etc.) in order to compute the rate at which the various reactions within the pp chain occur. This provides a prediction for how many neutrinos from each reaction should be arriving on Earth.

II. The Solar Neutrino Problem

Homestake, 1960s: Raymond Davis, Jr. builds an experiment to detect the neutrinos from the Sun. Deep underground in the Homestake gold mine in South Dakota, Davis' experiment counts the number of electron-type neutrinos interacting



<http://www.sns.ias.edu/~jnb>

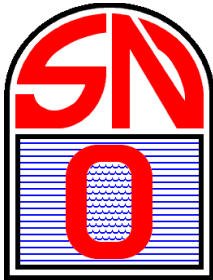
over a given period of time. He finds only about 1/3 the expected number.

Confirmations: Two additional observatories, GALLEX/GNO in Italy and SAGE in Russia, perform similar experiments and find the same results. The Kamiokande-II experiment (and later, the larger Super-Kamiokande) in Japan is capable of seeing neutrino interactions in real time, and confirms that the neutrinos are coming from the Sun and have the correct energy, but are still too few in number. (Meanwhile, the Kamiokande experiments are noticing a similar deficit in neutrinos produced in the Earth's atmosphere by cosmic rays, the "atmospheric neutrino anomaly.")

III. Neutrino Oscillations

Neutrino Mass and Mixing: The neutrinos created in weak interactions — ν_e , ν_μ , and ν_τ — do not have well-defined masses. Instead, they are constructed from neutrinos that do have specific masses, called ν_1 , ν_2 , and ν_3 , in a quantum superposition. These components travel at different velocities, causing the composition of a neutrino to change over time. In this way, a ν_e created in the Sun has a chance of arriving on Earth as a ν_μ or ν_τ , which would not be detected in an experiment searching only for ν_e . These "oscillations" of solar neutrinos are further complicated by their journey through the matter comprising the Sun, through the so-called MSW effect.

The Sudbury Neutrino Observatory (SNO): The SNO experiment, a large underground detector in Canada filled with heavy water ($^2\text{H}_2\text{O}$), provides a real-time measurement of both of ν_e individually, and of all neutrino types, at the same time. About 1/3 of the expected ν_e are seen (consistent with previous experiments) but the measurement of ν_e , ν_μ , and ν_τ together matches the prediction. This provides overwhelming evidence that the neutrinos are changing type en route to Earth, and therefore must have non-zero mass.



III. Solar Neutrinos Today

Experimental efforts are ongoing to detect neutrinos from every fusion reaction, in order to fully validate the solar model. Additionally, searches for neutrinos from a second fusion chain (the CNO cycle) could address a long-standing discrepancy in the chemical composition of the Sun (the Solar Metallicity Problem). Finally, there is hope that higher-precision experiments could uncover entirely new kinds of interactions beyond the current Standard Model of Particle Physics, which might affect neutrinos' propagation in the very dense Sun.