

# The Solar Neutrino Problem

Nat Hawkins

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## Abstract

**Background:** The solar neutrino problem can be described as the discrepancy between the predicted production of electron neutrinos in the sun and what was being observed on Earth in various detectors. Some interaction rates were observed to be as low as a factor of one-third. **Purpose:** Work needed to be done to understand the various deficits in different energy ranges for neutrinos produced in the nuclear reactions in the sun. **Methods:** Detectors of various designs and sensitivity were constructed over the course of nearly four decades to better understand the behavior and Physics of neutrinos. **Results:** It was discovered that neutrinos can oscillate between different types of neutrinos. No neutrinos were in fact ever missing. Neutrino oscillations lead to a transformation to types that detectors were not designed to measure. **Conclusion:** The Standard Model lacks proper explanation as it describes the neutrino as massless [1]. For neutrino oscillations to occur, neutrinos would need to have some quantifiable mass. While this problem led to technological advances in our understanding of neutrinos and our ability to measure sensitive occurrences, work still needs to be done to better understand neutrino behavior as well as expand upon current assumptions of the Standard Model.

# 1 Introduction

## 1.1 What Is The Solar Neutrino Problem?

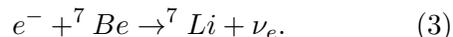
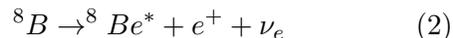
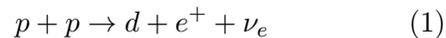
The solar neutrino problem was first observed in 1964, when Raymond David Jr. and John Bahcall proposed an experiment to test whether converting hydrogen nuclei to helium in the sun is the source of sunlight. Through the use of computer modeling, the number of neutrinos of different energies that the sun produces was approximated. The experiment was set up to measure the number of radioactive  $^{37}\text{Ar}$  atoms that neutrinos would produce when they interacted with a tank of cleaning fluid ( $\text{C}_2\text{Cl}_4$ ) approximately the size of a swimming pool. In 1968, the results of the experiment were announced. Through extrapolation, it was determined that only approximately one third of the predicted number of neutrinos were measured. This begged the question of what happened to the other neutrinos? [1]

The solar neutrino problem, put simply, is the discrepancy that exists between the flux of neutrinos that we predict the sun to emit based on luminosity and energy, versus what we have detected on Earth. Once this issue came to light, Physicists realized that there was some piece missing in their understanding of neutrinos and how they behave and interact.

Before beginning the discussion of the solar neutrino problem itself in greater detail and the efforts of accurate neutrino detection, I will take some time to discuss the source of these “problem” neutrinos, which is the sun.

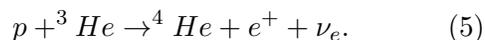
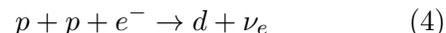
## 1.2 Source of Neutrinos In The Sun

From the perspective of Earth, the most intense source of stellar neutrinos is our Sun, as it is the closest star. Fusion reactions in the sun produce neutrinos of varying degrees of energy. We often summarize the reactions of the sun in what are called PP-chains. When discussing the PP-chains and solar neutrinos, we discuss the reactions,[3]



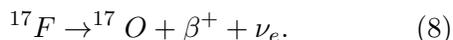
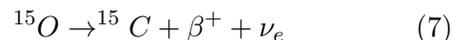
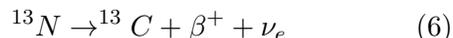
The important reaction to focus on is the one give in Eq 1. This demonstrates that one neutrino is produced per each  ${}^4\text{He}$  nucleus made.

In addition to these dominant modes, two more reactions are critical for understanding the production of neutrinos in the sun, which are [3]



Eq. 4 details the “pep” process. This is similar in nature to the pp process (Eq. 1.) except the electron capture replaces the  $\beta^+$  decay. The width of energy distribution for the pep process is on the order of keV’s and do not contribute largely to the total overall energy output of the sun, but do contribute to the production of neutrinos in the sun. The “hep” process in Eq. 5 produces the highest energy neutrinos in the sun with upward bounds of 18.7 Mev.

Further neutrino production occurs in the CNO cycle (Carbon-Nitrogen-Oxygen Cycle) in the reactions



There are a few things to note definitively prior to moving forward with this paper. First, with all neutrino production reactions, only electron neutrinos are formed. Two other flavors of neutrinos exist, muon and tau neutrinos, but they are typically observed in laboratory accelerators and in exploding stars. Second, according to the standard model of particle Physics, neutrinos are massless [2]. This will be a key consideration moving forward with our discussion. Finally, neutrinos rarely interact with solid matter. Neutrinos easily escape the sun and reach the Earth (as well as the energy associated with fusion reactions that we see in the form of sunlight and

feel as warmth), but for every 100 billion neutrinos that reach Earth, only about 1 interact with anything[1]. Since neutrinos rarely associate with solid matter, the science of detecting neutrinos complex.

## 2 Detecting Neutrinos

### 2.1 Kamiokande

In 1989, a Japanese-American collaboration attempted to solve this problem of neutrino detection discrepancy. Kamiokande was the name given to the experimental group. The experimental setup was simple by design in that the apparatus was a large silo filled with pure water. Countless detectors were set up inside of this silo to measure the rate at which electrons scattered the highest energy neutrinos with extreme sensitivity. The experiment produced empirical evidence supporting the work done in 1964 done by Raymond Dave Jr. The data indicated that they observed fewer neutrinos than the models predicted, but not quite as low of a percent as the Chlorine detector [5].

In 1996, the Super-Kamiokande experiment began operation. Figure 1 shows the design of the detector. Due to its sensitivity for detecting Cherenkov radiation, more precise measurements of high energy neutrinos were possible. However, these measurements only confirmed the original deficit found in the Chlorine experiment. Although it was sensitive to other neutrino types besides electron neutrinos, it detected about 50 % the predicted neutrinos [5].

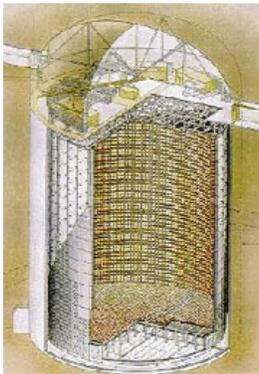
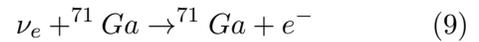


Figure 1: The Super-Kamiokande detector. Located 1,000 meters below ground to shield the detector. Containing 50,000 tons of pure water. The radiation detected when a neutrino interacts with an electron is known as Cherenkov radiation. [4].

### 2.2 GALLEX and SAGE

GALLEX and SAGE were two additional neutrino detectors that came about in the following decade.

GALLEX was a radiochemical neutrino detector in operation between 1991 and 1997 in Heidelberg, Germany. Similar in nature, the GALLEX detector, shown in Figure 2, was filled with approximately 101 tons of Gallium trichloride hydrochloric acid. The Gallium in the solution acted as the target for the neutrino interaction. The reaction is summarized by the following equation:



The goal of the experiment was to measure the low end energy spectrum neutrino interactions of order 200 keV. Prior to this detector, most energy thresholds were on the order of MeV, so now there were measurements of pp chain neutrino actions, which we know to be the lowest endpoint energy [1]. It was again observed the flux of neutrinos was less than what the standard model predicted.

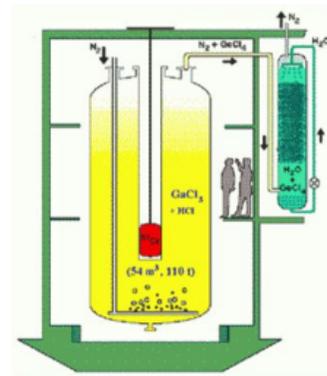


Figure 2: Design of the GALLEX apparatus. [6]

SAGE was constructed in Moscow, Russia and conducted its experiment along the same

timeline. SAGE used  $^{51}\text{Cr}$  for detecting neutrino interactions instead of  $^{71}\text{Ga}$ . The same results followed with lower neutrino absorption than predicted. See Figure 3 for diagram of SAGE experiment.

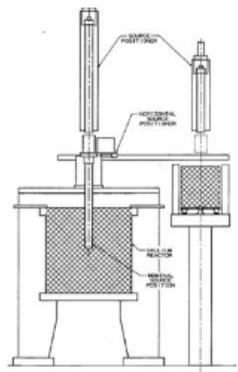


Figure 3: The SAGE detector. The apparatus was designed to house similar reactions as GALLEX, but with Chromium-51. [5]

Both of these detectors were integral in the discussion of this issue because it highlighted that up until now, not only had scientists been trying to measure high energy neutrinos, but it also showed that both high and low energy neutrinos were “missing”, although not in the same proportions. [4]

### 3 Brief Quantitative Results Summary

While quantitative data analysis is not a focus of this paper, I feel that it is important to make mention of it. While discussing these various experiments and the consistent result of measuring below-expected neutrino interaction rates, it can be helpful to see just how off of the theoretical mark these experiments were.

Bahcall gives a nice summary of the quantitative results of the various detectors and experiments [4]. The table is shown in Figure 1. The table summarizes the neutrino interaction rates. When discussing the “missing” neutrinos, the fourth column can serve most helpful. As Table 1 shows, these ratios vary between 34.5 %

and 62 %. As discussed previously, too, these detectors were looking in varying energy ranges, meaning that this fractional observance was seen across the neutrino energy spectrum.

## 4 Solution

The solar neutrino problem was solved on June 18, 2001 [1] by a team of collaborative Canadian, American, and British scientists. The results came from an experiment in a detector full of 1,000 tons of heavy water ( $D_2O$ , or water composed of deuterium in place of hydrogen). The Solar Neutrino Observatory (SNO), seen in Figure 4, in its first experiments, was set up to detect sensitive to electron neutrinos. The detector observed approximately one-third as many electron neutrinos as the standard computer model of the sun predicted were created in solar reactions [1].

It then became apparent that the issue was with the Standard Model. If the Standard Model is correct then the SNO and the Super-Kamiokande should be off by the same fraction as the predicted number of neutrinos [2]. The missing neutrinos were discovered shortly thereafter. The total number of neutrinos of all type predicted by computer models were present, but only some of the neutrinos in question remained electron neutrinos after formation. In June of 2001, the SNO conducted experiments which measured the total number of high energy neutrinos of all types. The results concluded that while all neutrinos produced in the sun are electron neutrinos, most of the neutrinos become muon neutrinos and tau neutrinos in the vacuum of space between the sun and the Earth.

The lack of sensitivity to the muon and tau neutrinos is the reason that early experiments measured such a deficit of neutrinos. Only the water Cherenkov detectors are capable of measuring these other neutrino types, and until the construction of SNO and Super-Kamiokande, this detection was not plausible.

Neutrinos are now known to undergo the quantum process of neutrino oscillations [5]. Low energy solar neutrinos can switch types as they travel in a vacuum. The number of changes it can make and the frequency of changes depends on the energy of the neutrino in question [1].

#### 4.1 The Issue With The Standard Model

The issue was now posed that the Standard Model describes neutrinos as being massless particles. For neutrino oscillations to occur, some neutrinos must have mass. Revisions are needed to include this in the standard model.

Simple calculations and fitting suggests that the mass of a neutrino is approximately 100 million times smaller than the mass of an electron [1]. Although these are approximations. Further work is being done in determining neutrino masses and association between neutrinos and the particles with which neutrinos are associated (electrons, muons, and tau particles for the associated neutrinos).



Figure 4: Solar Neutrino Observatory (SNO). [7]

## 5 Future Work

Although the solar neutrino problem is considered to be all but solved, there remains a lot to investigate. The sun provides a plentiful source

for neutrinos, serving as an ideal source studying the behavior of neutrinos.

The limitation is currently the capabilities of our detectors. Chlorine and Gallium detectors, such as those conducted in the early stages of the investigation, are incapable of measuring energy of neutrino events. The Cherenkov water detectors such as Kamiokande and SNO are capable of measuring the energy of events, but they are only sensitive to higher energy neutrinos ( $\approx > 5MeV$ ), which accounts for about 0.01 % of the neutrinos that the Sun emits according to current day, computer-modeled calculations [1].

Observing the remaining 99.99% of solar neutrinos in the lower energy thresholds is important in order to test more precisely the theory of stellar evolution. It is expected that the number of low energy neutrinos can be predicted and measured more accurately. The reasoning for this is discussed in many texts and I will not discuss it in depth here, see [1], [2], and [4]. As a result of this assumption of our capabilities, an accurate measurement of the number of low energy neutrinos will be a critical test of the degree of accuracy of our solar theory.

Solving the solar neutrino problem lead to the discovery of neutrino oscillations. Further work could shed more light on the phenomenon of neutrino oscillations.

The avenue for future work I propose here is the development of more detectors capable of measuring lower energy threshold neutrinos. Alimonti et al. discussed the construction of the Borexino detector at the underground laboratories at Gran Sasso, Italy (LNGS). This detector was built with the intention of measuring neutrino events in the low energy threshold. While the desired sensitivity to low energy neutrino events was not achieved, this paper helped to set up the theoretical and experimental framework for low energy sensitivity experiments [8].

This remains a prevalent topic in Nuclear Physics today. Continuing work in the development of more sensitive detectors and improving our methods of measurement could open the door to new discoveries in the realm of neutrinos.

## 6 Conclusions

The solar neutrino problem was discovered to be an issue of understanding the Physics behind and behavior of neutrinos. After nearly four decades of work, science had uncovered that the neutrinos were never missing, just in a form that no one thought to look for.

From a nuclear science perspective, this issue opened the door expanding the understanding of the complex nature of neutrinos and refine the technology needed for careful measurement and detection. It also added additional terms for consideration when discussing the Standard Model of particle Physics.

While a lot of work has gone into developing detectors for neutrinos, there is still a need for apparatuses sensitive to low energy events. Future work is needed in improving our abilities to measure neutrino events at all energy levels in order to get a more complete picture the behavior of neutrinos.

## References

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- [7] Image of the SNO. [http://newscenter.lbl.gov/wp-content/uploads/sites/2/2015/10/SNO\\_SNO\\_xy-3363335\\_1-t\\_A9zSIX0i.jpg](http://newscenter.lbl.gov/wp-content/uploads/sites/2/2015/10/SNO_SNO_xy-3363335_1-t_A9zSIX0i.jpg)
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Experiment	Theoretical	Measured	Measured/Theoretical
Chlorine	$7.6 \pm 0.16$	$2.56 \pm 0.088$	$0.337 \pm 0.030$
Kamiokande	$5.05 \pm 0.18$	$2.80 \pm 0.136$	$0.554 \pm 0.075$
SAGE	$128 \pm 0.06$	$77.0 \pm 0.087$	$0.62 \pm 0.052$
GALLEX	$128 \pm 0.06$	$74.1 \pm 0.092$	$0.579 \pm 0.053$
Super-Kamiokande	$5.05 \pm 0.18$	$2.32 \pm 0.037$	$0.459 \pm 0.017$
SNO	$5.05 \pm 0.18$	$1.75 \pm 0.084$	$0.3465 \pm 0.029$

Table 1: Summary table from Bahcall (2001). Columns two and three are the theoretically predicted and measured neutrino interaction rates (respectively) in units of SNU ( $10^{-36}$  interactions per target atom per second). Note that the fractional comparison between the measured and theoretical predictions is significantly smaller than 1 in some cases.