

The Solar Neutrino Problem

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Introduction

The Sun emits electron-neutrinos due to the β^+ decay occurring in the Sun's core. However, the number of electron-neutrinos detected on the earth is far lower than predicted by the current model of the Sun. This is The Solar Neutrino Problem. In this essay, we shall look at the problem in depth, as well as its solution, and then begin to look at the implications of this solution on the rest of theoretical and particle physics.

The Problem

The Sun is fuelled by nuclear fusion reactions. In stars like our Sun, protons (or hydrogen nuclei) are fused into alpha-particles (or helium nuclei). There are a few mechanisms through which this can occur¹ but as the fusion is *neutron-less*, β^+ decay² is required to produce the neutrons present in helium nuclei from protons. The process can therefore be summarised as:



Where, ' H ' is hydrogen, ' He ' is helium, ' e^+ ' is a positron (an anti-electron) and ' ν_e ' is an electron neutrino.

Notice the two electron-neutrinos, ' ν_e ', produced. Neutrinos rarely interact with anything and so these neutrinos escape the Sun, and we are able to detect some of them on the Earth.

¹These are *the CNO cycle* and *the proton-proton chain*. See [1] and [2] for details. The greatest understanding is probably gained from reading section IV 'Understanding the process' of [1] and the first page of [2] whilst referring to the diagrams found in the appendices of [1].

²This is when a proton is turned into a neutron through the emission of a positron (an anti-electron) and an electron-neutrino.

Usually, detection involves using the neutrino to spark a form of β^- decay³. A neutrino ‘reacts’ with the neutron, changing it into a proton and emitting an electron, but unlike normal β^- decay an anti-neutrino is not produced. For example:



Where, ‘ d ’ is a deuteron (nucleus of deuterium - an isotope of hydrogen), ‘ ν_e ’ is an electron-neutrino, ‘ p ’ is a proton and ‘ e^- ’ is an electron.

The light produced from fusion in the core of the Sun is unable to escape directly, therefore the light we receive only provides us with information about the outer regions of the Sun. Neutrinos therefore allow us to ‘see’ into the Sun’s core.

In 1968 John Bahcall and Raymond Davis, Jr. attempted to prove that the Sun generated its energy via nuclear fusion of protons. They did so by trying to detect some of the neutrinos emitted by the Sun (so called, *solar neutrinos*). To detect the neutrinos they built a large tank in a mine in Lead, South Dakota, USA and filled it with cleaning fluid (C_2Cl_4). They then measured the Ar^{37} produced by interactions between the electron-neutrinos and the chlorine, ie.



Where, ‘ Cl ’ is chlorine, ‘ ν_e ’ is an electron-neutrino, ‘ Ar ’ is argon ‘ e^- ’ is an electron.

They did indeed detect the solar neutrinos, and thus prove that the Sun was powered by nuclear fusion. However they detected only around one third of the neutrinos they expected to. The discrepancy was so large that it couldn’t be explained as a result of the error on the experiment. Was it their experiment or current theory that was flawed? *The Solar Neutrino Problem* or *The Mystery of the Missing Neutrinos* was born.

The Solution

After the chlorine experiment in 1968, the scientific community tried to explain what had happened to the missing neutrinos. The main suggested solutions were, that the chlorine experiment was flawed in some way, that the predicted number of neutrinos was wrong (and so the standard solar model

³This is when a neutron is turned into a proton through the emission of an electron and an anti-neutrino.

was also wrong), or finally that the predicted number of argon atoms that would be produced by the neutrinos was wrong. There was, however, another suggestion. In the year after the chlorine experiment, Bruno Pontecorvo and Vladimir Gribov suggested that the neutrinos could be changing type (ie. from electron-neutrinos to muon-neutrinos) due to a non-conservation of lepton charge⁴. However the idea of so called ‘neutrino oscillations’ was not taken very seriously at the time.

In the aftermath of the original results of the chlorine experiment, the theoretical calculations used were checked by many scientists, and the experiment itself was refined and the accuracy improved. The missing neutrinos could still not be accounted for, putting weight behind arguments such as Pontecorvo and Gribov’s. Building on their ideas, Lincoln Wolfenstein (in 1978)⁵ and later, Stanislav Mikheyev and Alexei Smirnov (in 1985)⁶ showed that neutrinos might be able to oscillate, if neutrinos have non-zero masses.

In 1989, 21 years after the chlorine experiment, a new experiment based in the Japanese alps called ‘Kamiokande’, led by Masatoshi Koshiba and Yoji Totsuka, confirmed the discrepancy between theory and experimental results. Many more experiments followed worldwide, detecting between one third and half of the neutrinos predicted by the standard solar model. These experiments were SAGE in Russia, led by V. Gavrin, GALLEX in Italy led by T. Kirsten, GNO also in Italy led by E. Belotti, and finally Super-Kamiokande in Japan which was led by Y. Totsuka and Y. Suzuki.

The new experiments that had detected solar neutrinos, combined with progress in other areas that gave scientists new faith in the standard solar model, meant that the idea of ‘new’ physics causing neutrino oscillations was taken increasingly seriously.

In 2001 SNO collaboration published results⁷ from their detector in Sudbury, Ontario, Canada. For the results, their detector used heavy water in a way that was sensitive only to electron-neutrinos and only the high energy ones that had previously been studied by the Super-Kamiokande experiment. They had detected approximately one third of the neutrinos predicted by theory.

The Super-Kamiokande experiment had been able to detect not just electron-neutrinos but also some of the other types, and they had detected half of the neutrinos predicted by theory. If the standard model of particle physics was correct (and neutrinos couldn’t change their type) then the two experiments’ results should have been consistent. They were not. The

⁴As explained in their joint paper [3].

⁵See his paper [4] on the subject.

⁶See their extremely long paper [5] where they build further on Wolfenstein’s ideas.

⁷See [6] which is the paper in which they first declared these initial results.

mystery of the missing neutrinos had been solved.

The SNO collaboration went on to calculate the total number of neutrinos (regardless of type); this number was consistent with the prediction for the standard solar model. They then performed new experiments with their detector to find the numbers of all the different types of neutrinos.

When solar neutrinos are created from the β^+ decay in the Sun's core they are created as electron-neutrinos, but on their journey to the Earth they oscillate between neutrino type, ie. between electron-neutrinos (ν_e), muon-neutrinos (ν_μ) and tau-neutrinos (ν_τ). The neutrinos seemed to be missing as most of the experiments as those experiments were only sensitive to electron-neutrinos. However when all the neutrino types are detected then the number of neutrinos we detect is in accordance with the standard solar model.

The Implications

The standard model says neutrinos are massless and that neutrinos cannot change their type. However the solar neutrino experiments have proven that neutrinos can oscillate between different types, ie. $\nu_e \Rightarrow \nu_\mu$, $\nu_e \Rightarrow \nu_\tau$ etc...

In the face of this evidence, the standard model must be revised. Not only are neutrinos able to change their type, but in order for this to be possible neutrinos must have some mass.

For particle physics, the next step is to investigate the nature of neutrino oscillations and the ideas of Pontecorvo and Gribov, as well as those of Mikheyev, Smirnov and Wolfenstein. Whilst for astrophysics, neutrinos may be useful in learning more about both our Sun and other stars. In both of these areas further investigation into low energy neutrinos may be useful, as so far most research has been on high energy neutrinos, which are created by a rare process in the Sun involving the decay of the Boron isotope, B^8 .

Conclusion

Solar neutrinos were investigated in order to prove that the Sun is powered by nuclear fusion. In 1968, John Bahcall and Raymond Davis, Jr. successfully detected solar neutrinos; however, they detected fewer than they had expected to. The problem was eventually solved in 2001 with the discovery that the neutrinos had changed their type on their journey to the Earth, and thus evaded detection. This has shown that neutrinos can change their type and so the standard model of particle physics is flawed and must be revised.

The Solar Neutrino Problem has been a great example of how different areas of science tie in with one another, and how strange results in one field can lead to huge breakthroughs in another.

Bibliography

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