Project work:  
The solar neutrino Problem

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1 Introduction

1.1 What is the SNP?

In the early 1960s first calculations were made concerning the flux of solar neutrinos (see section 2.1 on p. 2). These predictions were made to prepare an experiment by R. Davis, jr. that should measure this flux. The first results of the experiment were a factor 2.5 smaller than expected from the theory of the standard solar model, although the uncertainties in the calculations were big enough to suspect that there wasn’t a big problem with the whole theory. Over the next years however the input parameters of the theory were improved thus reducing the error of the calculation, but still there were around one third of the predicted neutrinos missing. This problem between the theory of the solar model (and the weak interaction) and the experiment became known as the "problem of the missing neutrinos" or the "solar neutrino problem" (SNP).

2 General Information

2.1 A history of the SNP

It took roughly 40 years to solve the solar neutrino Problem. Here I want to give an overview of these years:

1962 R. Davis and J. Bahcall begin to discuss a solar neutrino experiment using electron capture in chlorine (see section 3.1.1). It soon becomes obvious that they would need a detailed solar model to calculate the flux of solar neutrinos on earth. First calculation suggest that the detection rate of the neutrinos would be too small in any practicable experiment.

1963 After an error in the calculation was found the detection rate is high in enough to be measured. In the following years the calculations are improved using better input parameters (e.g. reaction rates in the pp-chain)

1968 The first results from the Homestake experiment are presented: The measured flux is lower by a factor of 2.5 than the theoretical calculation had predicted. But the uncertainties in the solar model are too big to cause agitation among physicists.

1969 V. Gribov and B. Pontecorvo propose an explanation for the SNP using neutrino oscillation. Most particle physicists don’t believe in the solution, as it involves rather big mixing angles (the common point of view was that flavour oscillations in the neutrino sector should have small mixing angles like the oscillation in the quark sector.)

1968–1986 During this time only the Homestake experiment is able to detect solar neutrinos. The measurement techniques are refined and the input data to the solar models get better and better. The discrepancy between theory and experiment remains.

1985 S. Mikheyev and A. Smirnov showed that resonance phenomena could convert enough electron neutrinos into $\tau$- and $\mu$-neutrinos (MSW-effect). As these neutrinos are harder to detect this would explain the missing neutrinos. Due to the fact that this theory worked for small and large mixing angles it was meet with more sympathy from particle physicists. However this theory needed neutrinos with a mass greater than zero and distributed over a wide range.

1986 The Kamiokande experiment in Japan is revised to detect solar neutrinos. Although there are fewer neutrinos detected than was predicted the discrepancy is not as big as in other neutrino detectors (around half of the predicted neutrino flux is detected).

1988 J. Bahcall and R. Ulrich use their solar models to simulate soundwaves in the sun and compare the results to recent helioseismological data. Measurement and calculation agreed to an accuracy of about 0.5%. This showed quite clearly that the solar models used to predict the solar neutrino flux were good enough to describe the behaviour of the sun. New parts (like element diffusion) are included in the simulation of the solar model.

1990–1997 The GALLEX (1991–1997) and SAGE (1990–1994) detectors confirm the missing neutrinos. They were the first detectors to be sensitive to lower energy pp-neutrinos from the initial reaction.
1995 New helioseismological data is in excellent agreement with the simulation of J.Bahcall. As the data this time stretches over the whole interior of the sun there is a strong implication that the standard solar model describes the processes in the core of the sun quite accurate. At this point the solar model was more precise than it needed to be to produce the correct results for the neutrino flux. As the solar model was in good agreement with the measurement that meant that the explanation had to be found in new neutrino physics.

1996 The Super-Kamiokande experiment starts.

1998 The Super-Kamiokande finds evidence for neutrino oscillation

1999 SNO (Subury Neutrino Observatory) experiment starts

2001 SNO publishes evidence that solar neutrinos oscillate on their way from the sun to earth.

The data we got today about the neutrino oscillation is not only from solar neutrinos. There are many other experiments using neutrinos created in reactors or neutrinos created in the atmosphere by cosmic radiation. All this data can only be explained if the mixing angles of the neutrinos are large.

2.2 How are solar neutrinos created?

The sun produces its energy through nuclear fusion. Usually this process is divided into several steps, forming an reaction chain. There are several of these chains in the sun. The two most important are the pp-chain and the CNO-cycle, where the pp-chain is by far the dominant process in our sun.

2.2.1 pp-chain

The overall reaction of the pp-chain is the fusion of 4 protons to a Helium nucleus.

\[ 4 \cdot \frac{1}{1}H \rightarrow \frac{4}{2}He + 2 \cdot e^+ + 2 \cdot \nu_e + 2\gamma \]

This is equation might lead to the wrong conclusion that the fusion is done in one reaction. In fact there are several ways of completing the pp-cycle, as shown in figure 2.2.1.

Figure 1: the primary processes in the pp-chain

Figure 2: The energy spectrum of the solar neutrinos [10, p.3]

The neutrinos created in the pp-chain have different energies, depending on where and by what reaction they were created. Thus the energy spectrum (see fig. 2) of the solar neutrinos is a good way to determine which reactions are currently going on in the core of the sun and what the ratio of the individual processes is. The

2.2.2 the CNO cycle

In the CNO-cycle heavier elements like \( ^{13}_7N \), \( ^{15}_8O \) and \( ^{17}_9F \) are produced. These are all \( \beta^+ \) radia-
tors and their decay yields an electron neutrino. The CNO-cycle is only dominant in stars with masses larger than the mass of the sun and is therefore “not expected to play a discernible role in any of the planned or in progress solar neutrino experiments” [9, p.6]

3 Measurement of solar neutrinos

As neutrinos are only participating in the weak interaction it is very hard to detect them at all. The only possible way of doing this is to watch for the traces of nuclear reactions that involve neutrinos. Additionally there are many other particles that also create reactions in matter (often even more then the neutrinos themselves). These reactions create a constant background noise, so that it is very important for all the neutrino experiments to have a good shield against external radiation (like cosmic radiation) and as few radioactive material inside the experimental hall as possible.

The shielding against outside radiation is usually done by placing the experiment under the surface of earth and putting a shield (metall + water layer) around the tank with the detection substance.

The filtering of nuclear reactions in the liquid is much harder to realize and can’t be eliminated totally.

As the background noise can’t be sufficiently suppressed it is furthermore important that the measurement technique is as good as possible, so that the few signals created by neutrinos are not lost in the background noise.

There are nowadays two major ways to detect solar neutrinos and both have yielded important results for the SNP.

3.1 Radiochemical detectors

The radio-chemical detectors were the first neutrino detectors\(^1\) to be developed. A radio chemical detector usually has a large tank filled with a chemical substance that is likely to interact with a neutrino through weak interaction.

This interaction induces a nuclear process that changes the nucleus. As the created atoms are not stable their decay can be studied. To study this decay the radioactive isotopes are filtered from the substance in the tank and measured with a proportional counter.

The so determined number of created isotopes combined with the cross-section of the neutrino reaction can be converted into a neutrino flux that can be compared to theoretical calculations.

The disadvantage of the radiochemical detectors is that they are only sensitive to electron neutrinos and have usually a relative high energy threshold.

3.1.1 Homestake

The Homestake experiment of R. Davis, Jr. was the first neutrino detector ever to be build. As mentioned in section 2.1 it was build in the early 1960’s in the Homestake mine, USA. As detection substance Davis et al used a cleaning fluid that contained tetrachloroethylene. The chlorine contained in it can capture a neutrino and react to Argon:

\[
{^{37}}_{17}Cl + \nu_e \rightarrow {^{37}}_{18}Ar + e^{-} \tag{1}
\]

As mentioned early only the solar neutrinos from the ppII and ppIII reaction have enough energy to cause this reaction. This is a disadvantage of the Homestake experiment: Its detector reaction has an energy threshold of 0.81MeV [28] and is therefore not sensitive to most of the solar neutrinos which lowers the expected rates of created \(^{37}Ar\) and makes the neutrinos even harder to detect. (This disadvantage can be compensated if gallium is used instead of chlorine, but that was too expensive at that time)

The created argon was taken approximately every two month out of the tank (which corresponds to the half-life of Ar)

The Homestake experiment ran until 1994 which was longer than all other neutrino detectors. In the decades of its research several improvements have been made and only 2200 Ar atoms have been created (from which 1997 were extracted)[28, p.3]

3.1.2 GALLEX

The GALLEX experiment uses a Gallium Solution instead of a Chlorine solution. The use of Gallium has the big advantage of a low energy threshold for the neutrino-capture reaction (\(\approx 233\)keV [20]). Through this low threshold GALLEX is able to detect not only the high energetic neutrinos from the ppII and

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\(^1\)neutrino detectors refers in the following to detectors for solar neutrinos
ppIII branch, but also neutrinos form the initial pp and pep reaction (see section 2.2). This is important because a measurement, especially of the pp-neutrino flux, is needed to prove that the pp-cycle really is the main energy source of the sun.

The GALLEX experiment used 30t of Gallium in a $GaCl_3 - HCl$ solution. If exposed to neutrinos the reaction

$$^{71}_{31}Ga + \nu_e \rightarrow^{71}_{32}Ge + e^-$$  \hspace{1cm} (2)

takes place. (The tank with the solution was exposed to the neutrino flux for 3-4 weeks) After that several filtering processes took place to extract the Ge from the solution and the decay of it was monitored.

### 3.2 Čerenkov detectors

#### 3.2.1 Čerenkov effect & working principle

The Čerenkov effect describes the emitting of radiation if a charged particle in a medium (an insulater) moves faster than the speed of light in that medium. The light emitted by the particle is forming a cone with an accurate angle to the particle velocity. This angle depends on the velocity of the particle.

This effect can be used to detect particles. As the particles travel through a medium they produce characteristic Čerenkov light that can be detected with photomultiplier arrays. As the Čerenkov light depend on the particle that is causing them (e.g. sharpnes of the rings) it is possible to identify the particles. Knowing the particle and its speed one can calculate the energy of the particle.

This observation method has the advantage of allowing real time measurement.

#### 3.2.2 KamiokaNDE and Super-KamiokaNDE

The Kamiokande detector (designed by Masatoshi Koshiba) was originally built to detect the decay of protons but was later modified to be also sensible to neutrinos. It is located 1000m underground in the Kamiokamine. The whole experiment was later updated to the SuperKamiokande Experiment which uses 5000t of water as detector substance. To avoid a large background the walls of the mine are encased with a special substance to prevent radon from getting into the experimental hall. Additionally the detector tank is divided into an inner and outer tank, where the outer acts as a filter and warning system (if there are energetic particles entering the system they will cause a signal in the outer as well as in the inner tank).

As neutrinos have no electrical charge they produce no Čerenkov light. The Kamiokande experiment therefore looks for a scattering process of a neutrino and an electron:

$$\nu_e/\mu/\tau + e^- \rightarrow \nu_e/\mu/\tau + e^-$$

The scattered electrons then have a energy high enough to produce Čerenkov light. As the electrons are scattered in the direction of the neutrino it is possible to see where the neutrino came from. In addition to that the produced Čerenkov light yields information about the energy of the electron which is directly related to the neutrino energy.

As with the Kamiokande experiment the direction of the incoming neutrinos could be determined, it proofed that these neutrinos were really coming from the sun.

As mentioned in section 2.1 the Kamiokande experiment yielded a smaller difference between the measured and the predicted flux. This is due to the fact that there are no nuclear reactions involved in the detection process, so that it is not important which flavour ($e, \nu, \tau$) the neutrino has (In nuclear reactions the number of leptons from a certain family is conserved so that only electron neutrinos can be used for the reactions mentioned in sec. 3.1.1 and 3.1.2).

#### 3.2.3 Sudbury Neutrino Observatory

The Sudbury Neutrino Observatory (SNO) was constructed during 1990-1999 in the Creighton mine near Subury, Canada. The long construction time is due to the fact that the cave for the SNO was build specially for this purpose (which alone took 3 years). After the cave was build and the walls were isolated (simillar to the kmiokande experiment) the detector was constructed under clean room conditions. The detector was spherical and it also had a shield of light water and a waterpurification system to keep the percentage of radioactive isotopes low. In contrast to the kamiokande experiments however the SNO used heavy water as detector medium.
which enables nuclear reaction involving neutrinos in addition to the neutrino scattering described above. These reactions are:

1. **Charged current reaction**
   
   In this process an electron neutrino and the neutron from the deuterium nucleus interact (weak interaction) to form a proton and an electron:
   
   \[
   ^2D + \nu_e \longrightarrow p + p + e^-
   \]
   
   As the electron gets a big part of the neutrino energy it will be fast enough to create Čerenkov light.

2. **Neutral current reaction**
   
   This reaction uses also the weak interaction between neutrinos and the neutron in the deuterium, but in this reaction the deuterium is merely split up:
   
   \[
   \nu_{e/\mu/\tau} + ^2D \longrightarrow p + n + \nu_{e/\mu/\tau}
   \]
   
   The free neutron is then moderated to thermal speed and finally captured. This process emits \(\gamma\)-rays which can be detected and assigned to corresponding neutrino interactions.

   As the crosssection for neutron capture of deuterium is low there are methods to improve this process, e.g. adding NaCl into the detector (as chlorine has a high crosssection for neutron capture) or using \(^3\)He proportional counters.

The second reaction plays an important role for the SNP: As the reaction is sensitive to all types of neutrinos the total neutrino flux can be measured and compared with the theory. This was done and it was found that there were no neutrinos missing. This result meant that the electron neutrinos created in the sun somehow change into \(\mu\)- and \(\tau\)-neutrinos on their way to earth.

### 3.3 How to decide where the neutrinos came from?

As the neutrino flux from the sun isn’t the only source of neutrinos on earth (e.g. neutrinos created in the upper atmosphere or in \(\beta\)-decay) it is not obvious where the neutrinos came from, but it can be calculated what energies the neutrinos should have depending on where they came from.

#### 3.3.1 In radiochemical detectors

In the Homestake experiment it was easy to count the events contributed by solar neutrinos, because those were the only ones with energies high enough to activate the necessary reaction. [27, p.2]

In other radiochemical detectors it is possible to measure the energy of Auger-electrons created by the decay of the detector substance. This gives information about the energy of the neutrino which is a good indication to where the neutrino came from.

#### 3.3.2 In Čerenkov detectors

The Čerenkov detectors have the possibility of detecting not only the energy of a neutrino but also the direction where it came from. In this case it is easy to see if a neutrino came from the direction of the sun or not (as neutrinos rarely interact the scattering of a neutrino, e.g. in the upper atmosphere, so that it looks like it came from the sun can therefore be neglected). Is the direction correct a analysis of the shape of the Čerenkov ring can give information about the energy and therefore the position of creation of the neutrino.

### 4 Solution of the SNP – \(\nu\)-oscillation

As mentioned before only neutrino oscillation can really explain all the experimental data available today (Not only from solar neutrino experiments, but also from experiments with reactor neutrinos e.g. KAMLand).

The point of neutrino oscillation is that neutrinos have a mass \(m \neq 0\). If the neutrinos have this mass it is possible that their mass eigenstates are not the same as their flavour eigenstates (in fact this is necessary for neutrino oscillation).

This means that a neutrino created in a weak interaction reaction has a flavour eigenstate that is a superposition of different mass eigenstates (it is assumed that the neutrino is only a superposition of 3 or less mass eigenstates, because otherwise it can be shown that the result is a sterile neutrino, that has no interaction in the
Standard model:  

$$|\nu_\alpha\rangle = \sum_{i=1,2,3} U_{\alpha i} |\nu_i\rangle$$

Where $\nu_\alpha$ is a flavour eigenstate and $\nu_i$ is a mass eigenstate and $U^*$ is the lepton mixing matrix (Maki-Nakagawa-Schoti-Matrix). Applying a quantum mechanical time evolution operator on this superposition and expressing the mass eigenstates in terms of flavour eigenstates we get:

$$|\nu_\alpha(t)\rangle = \sum_{i=1,2,3} \sum_{\delta=e,\mu,\tau} U_{\alpha i} U_{\delta i}^T e^{-iE_\delta t} |\nu_\delta\rangle$$

From this equation we see that the probability for a neutrino of flavour $\alpha$ to change into a neutrino with flavour $\beta$ is not always zero but time dependent:

$$\langle \nu_\beta | \nu_\alpha(t) \rangle \propto \sum_{i=1,2,3} U_{\alpha i} U_{\beta i}^T e^{-iE_i t}$$

Looking at the $e^{-iE_i t}$ term we see that the probability oscillates and that the neutrino therefore is constantly changing its flavour.

This oscillatory behaviour gave the name “neutrino-oscillation” for the phenomenon.

5 Future Prospect

Although the solar neutrino problem has been solved the interest in neutrino and solar neutrino research is still high, which is shown by the fact that the USA plans to give up their leading role in accelerator physics to concentrate on neutrino physics [15, p.14]. Included in this plans is a large new neutrino detector in the Homestake mine.

But the US are not the only ones interested in neutrinos, large collaboration all over the world are currently palnning or running neutrino telescopes like AMANDA/ICECUBE at the south pole or ANTARES in the mediteranian sea.

The important point for space physics is that the new detectors should be sensitive to low energy neutrinos. This is important because most of the solar neutrinos are created in the pp-reaction and have only energies around 0.42MeV. A good measurement of the low energy neutrino fluxes can so provide information about the current core temperature of the sun and the reactions (a good way to test if the sun is in a quasi steady state of energy creation in the core and radiation losses at the surface). Furthermore the observation of low energy neutrinos may yield completely new phenomena.

Other neutrino experiments are currently running (or are planned) to investigate the particle physics of neutrinos (like the mass and their mixing angles) but I won’t go into to details of them.

Summary

Summarizing we can say that after over 4 decades of solar neutrino research the problem of the missing neutrinos has been solved but the neutrino itself stays a mysterious particle with many properties yet to be determined. In these years great steps have been taken in improving the experiments to detect neutrinos, as well as in the standard model and the standard solar model.
A bibliography

In the following bibliography the used resources are ordered according to the topic for which I used them. However, some articles and websites have been used for more than one topic. These are only mentioned once.

References

A.1 Neutrino creation in the sun


A.2 History of SNP


A.3 Neutrino Oscillation & Neutrino physics

A.4 Detectors


[27] Brookhaven National Laboratory - “SOLAR ENERGY GENERATION THEORY BEING TESTED IN BROOKHAVEN NEUTRINO EXPERIMENT”, News from Brookhaven National Laboratory 1967


[29] http://www.sno.phy.queensu.ca/

A.5 Čerenkov effect