The Problem of the Missing Neutrinos

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1. Introduction

The existence of the particles that where later called Neutrinos, was first suggested by Wolfgang Pauli in 1930. He came up with the idea of a new elementary particle in the desperate attempt to find an explanation for the continuous energy spectrum of the electron and the violation of energy conservation in the nuclear β-decay. If the atomic core was split up not only in electron and proton but three particles, the so far undetected neutrino could possess the missing energy[1]. Although Pauli's idea was basically right, it took almost 30 years before Reines and Cowan succeeded to detect neutrinos for the first time, in 1959 [2].
The reason why these particles are so hard to "see" lies in their properties. According to the standard model of particle physics there are three different kinds of them: electron-, myon- and tauneutrinos. Like the electron, the myon and the tauon, they are Leptons which means that they don't succumb to the strong force as the quarks do, which are the second sort of elementary particles. Neutrinos don't have an electric charge and they are supposed to be massless, therefore they move with the speed of light. Finally all these properties taken together lead to the fact that they very rarely interact with any matter.
But while this physical model has proven to describe a lot of experimental results astonishingly precise, there have also been some inconsistencies. They have led to a long debate if this model has to be corrected concerning the neutrino mass. One of those inconsistencies is the "The Problem of the Missing Neutrinos".
The following report gives a review of the origin, the development and the solution of this "Solar Neutrino Problem" as it is also called in a more scientific way, as well as its implications on particle physics.

2. Solar model and solar neutrinos

Solar neutrinos are generated in the core of the sun by nuclear fusion, where hydrogen is converted to helium, which causes the sun to shine. The most common process is the so called p-p chain reaction that can be summed up as

$$4\,\mathbf{p} \;\rightarrow\; {}^{\mathbf{4}}\mathbf{He}^{\,\mathbf{2+}} \;+\; \mathbf{2e^{+}} \;+\; \mathbf{2}\nu_{\mathbf{e}} \;+\; \mathbf{2}\gamma$$

The multiple reactions that are included in this line are shown in Figure 1.

In addition to the chain reaction there is also the CNO-cycle, but with a considerable lower reaction rate.
All solar neutrinos are electron neutrinos and they have characteristic energies according to the reaction they were involved in. The neutrino energy spectra of the p-p start reaction and the third branch as well as the CNO-cycle are continuous. All other produced neutrinos have one specific energy. The number of produced neutrinos depends on the reaction rates. In other words: The brighter the sun shines, the more neutrinos are generated. The quantity and the energy spectrum of the solar neutrinos therefore depend on thermal conditions like temperature and density in the sun's interior.
This data can not be taken directly, of course. The solar model has to be based on observations from a great distance because of the incredible heat. The first logical choice was to observe the

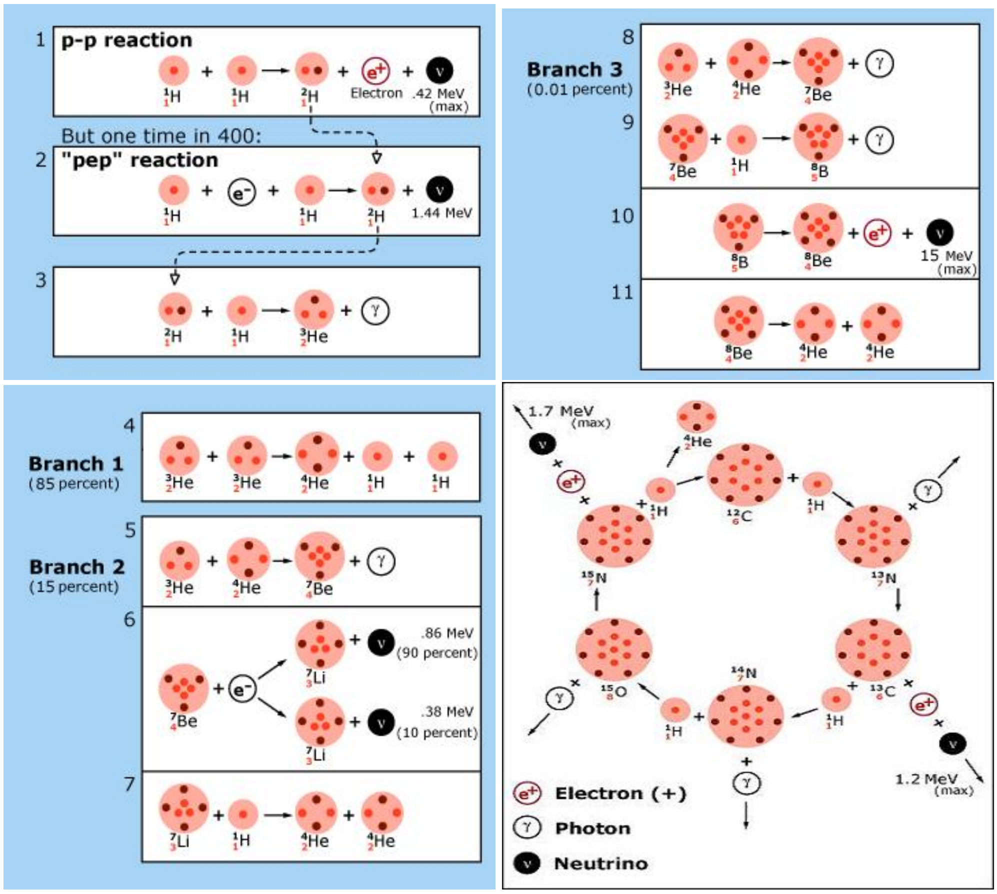

Figure 1: The p-p reaction chain [3a] and the CNO-circle reaction proceeding in the core of the sun [3b]

emitted light. But the photons that reach the earth are not the same ones that were produced at the core. Due to multiple scattering, the wavelength of the radiation changes many times on the zigzag way to the surface and takes several million years to finish this way even on the speed of light. Therefore, they do not provide detailed information about the fusion process in the core of the sun.

Almost all the solar neutrinos, however, advance from the core to the surface of the sun and further through interplanetary and interstellar space without any deflection. John Bahcall, who started the first theoretical calculations of a solar neutrino flux in 1962 [5], described this attitude in a very impressive way. In [4] he states:

> ”About 100 billion neutrinos from the sun pass through your thumbnail every second, but you do not feel them because they interact so rarely and so weakly with matter.”

All of them carry precise information about their reaction of origin in the sun's core.
In 1964 Bahcall summarised the situation as follows.

> The principle energy source for [...] the sun is believed to be the fusion of four protons to form an alpha particle. No direct evidence for the existence of nuclear reactions in the interiors of stars has yet been obtained, because the mean free path for photons emitted in the center of a star is typically less then 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars." [6]

3. The Solar Neutrino Problem

3.1 The first experiment and its result

The small interaction cross section that makes it possible for the neutrinos to fly through the sun and to the earth unhindered, becomes a big problem when measuring them, because interaction with matter is the only trace of neutrinos. Otherwise they would just go on straight through the earth, without anyone noticing them. Therefore the task of measuring solar neutrinos is a very difficult one.
The first one to engage this challenge was Ray Davis. During the 1960s, he came up with an experimental setup that uses chlorine to capture electron neutrinos through the reaction

$$^{37}\mathbf{Cl} + \nu_\mathbf{e} \rightarrow \mathbf{^{37}Ar} + \mathbf{e}^-$$

where the neutrinos must have at least 0.814 MeV [7]. This reduces the detectable solar neutrinos to about 12%, because only the reactions 2, 6 and 10 from the pp-chain reaction (Figure 1) produce neutrinos with energies over this threshold. And the CNO-cycle was not considered, because it was not yet known that it actually takes place in the sun.
Under this circumstances, the theoretically predicted number of produced argon atoms was 4 to 11 per day, assuming a volume of $100,000$ gallons (378,000 liters) of tetrachloroethylene (C_2Cl_4). Such a big tank was indeed built. More precisely, it was built in Homestake mine (USA), about 1500m deep. The soil around the tank was needed to shield it from particle showers produced by cosmic rays that could simulate the reaction and thus falsify the measurement. For the same reason, the tank had to be thoroughly cleaned and the used chemical had to be free of impurities. The produced argon atoms were taken out of the tank by bubbling helium through the tetrachloroethylene [7,8].
The first measurement of solar neutrinos was successfully taken in 1967. It was proved that the sun shines due to nuclear fusion. But the result was also a little disappointing: The determined neutrino flux did not fit the prediction based on the existing solar model. Only one third of the expected number was observed. The "Problem of the Missing Neutrinos" was born [8].

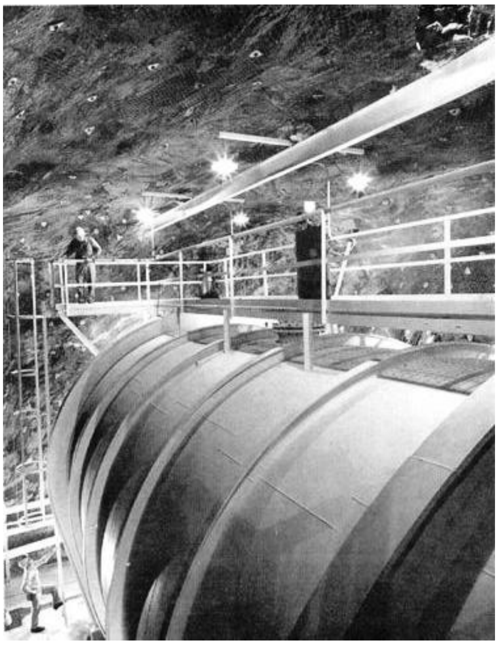

Figure 2: The neutrino detector in the Homestake mine [8]

3.2 Development of theory and experiments

As far as it was known at the time, either the theoretical or the experimental value had to be wrong. During the next two decades, Davis (Experiment) and Bahcall (Theory) worked closely together to find the answer. They refined the data by narrowing the existing error margins considerable, but both values were confirmed [5].
From 1989 on, several other solar neutrino experiments contributed new data. The detectors GALLEX (1991 - 1997)[9] and SAGE (1991 -2002)[10] worked in principle in the same way as the Homestake detector, but used gallium instead of chloride. The induced reaction had a lower threshold energy and could therefore capture more neutrinos (Figure 4). The result, however, was the same: Two thirds of the predicted neutrinos were missing. The KamiokaNDE (1988)[11] detector was placed under the earth in a mine, too. But it contained water and its walls were fitted with photomultipliers. If a neutrino (with a certain minimum energy) interacts with an electron in a scattering process, it generates a highly energetic electron that travels through the water with a higher velocity than light ($c_{water} = 2.3 \cdot 10^9 \frac{m}{s}$) (Figure 3). Similar to a jet that creates a sonic shockwave by exceeding the speed of sound, the electron produces a cone of blue light, the Cherenkov radiation. The photomultipliers then detect this light. This time, a higher rate of neutrinos was detected, but still only about half of the theoretical expected value. Later, the huge Super-KamiokaNDE [12] that worked the same way but on a bigger scale, once again confirmed this result.
Simultaneously, the solar model turned out to describe the processes in the sun quite accurately,

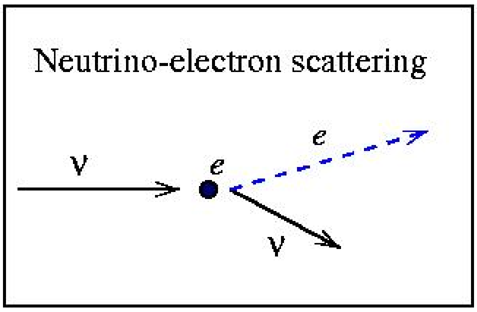

Figure 3: Neutrino electron scattering in a water detector [15]

when it was compared to the data that was gathered via helioseismology. This newly developed field of research studies the propagation of pressure waves in the sun. The values of the sound speed, for example, agreed better than 0.1 % in the interior of the sun. Therefore, the solar model could not explain the missing neutrinos either.

3.3 The solution of the Solar Neutrino Problem - neutrino oscillation

Since the solar model gives a correct description of the sun's interior and the experimental results still did not fit the expectation this model provides, the neutrinos themselves had to cause the aberration. Somehow the description of the neutrino properties by the standard model of particle physics was wrong. This possibility was discussed since the first experimental results were published, but very few physicists considered it seriously. It just seemed more likely that the conditions inside the sun were not known accurately enough. Especially the temperature dependance of the calculated flux was a convincing argument: It is a dependance of T^{25} [5]! Therefore, an error of only 1% in the assumption for the temperature in the core causes roughly a 30% error in the neutrino flux. Still, some people came up with other explanations for the missing neutrinos. And as it finally turned out, one of them actually gave the right answer.
Already in 1968, only one year after the first measurement, Vladimir Gribov and Bruno Pontecorvo have proposed that the electron neutrinos from the sun could become muon neutrinos which were discovered in 1962. Back then the existence of the tau neutrino was still unknown [8,13]. In 1985, Stanislav Mikheyev and Alexei Smirnov built upon the earlier work of Gribov and Pontecorvo and showed that neutrino oscillations are theoretically possible, if neutrinos have masses [13]. Neutrino oscillation basically means the change of one species of neutrino into another. Today, it is more common to speak of different states so called ”flavor” of one and the same particle species.
The experimental prove that this theory solves the Solar Neutrino Problem was adduced in 2002 with the SNO, another Cherenkov water detector. This detector, however, consists of heavy wa-

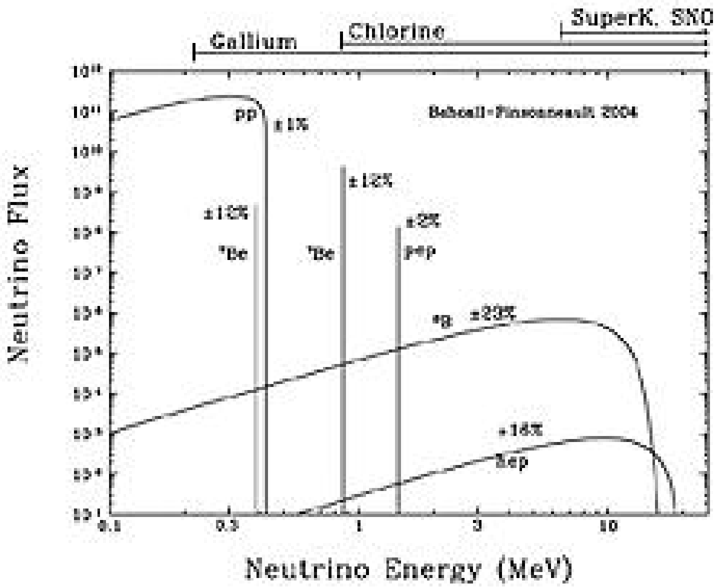

Figure 4: The predicted solar neutrino energy spectrum and the detection range for different detector mediums - the neutrino fluxes are given in number of neutrinos $cm^{-2}s^{-1}$ MeV^{-1} (continuum) and number of neutrinos $cm^{-2}s^{-1}$ (line sources) at the Earth's surface.[16]

ter, because neutrinos interact with it in two additional ways apart from electron scattering in ordinary $\mathbf{H_2O}$ described in Figure 4. The first one is the reaction

$$^2\,\mathbf{D}\ + \nu_{\mathrm{e}}\ \rightarrow\ \mathbf{2\,p}\ + \mathbf{e}^- \tag{1}$$

It is also detected via Cherenkov radiation due to high kinetic energy of the electron. The second possibility is

$$^2\,\mathbf{D}\ + \nu\ \rightarrow\ \mathbf{p} + \mathbf{n}\ + \nu \tag{2}$$

The produced neutron is then slowed down in scattering processes until it is eventually captured by an other nucleus. The capture frees energy in form of photons that scatter electrons in turn. And these electrons can again be detected due to Cherenkov radiation. To enhance the probability of the neutron capture, $\mathbf{NaCl}$ is added to the water. Both reactions are summed up in Figure 5. Here, it is very important to notice that reaction (1) only works for electron neutrinos but all three flavors can initiate reaction (2). Therefore, the detector can be used in two modes: first without and then with $\mathbf{NaCl}$. One time, only electron neutrinos will be observed, and then ALL neutrinos are detected. [14,15]
The measured value of mode one confirmed once again the mystery: Only one third of the electron neutrinos that are produced in the sun's core reach the earth. But the result of mode

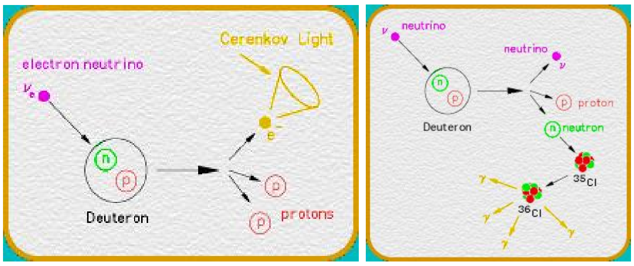

Figure 5: Neutrino interaction with heavy water - reaction 1 and 2

two fitted the theoretical flux prediction based on the solar model. Finally, the missing neutrinos have been found. They just change state and arrive at the earth as far more difficult to detect muon and tau neutrinos. In retrospect, there have already been strong hints to the solution of the problem. The higher detection rate of the Kamiokande experiments, for example, can be understood because it is known that the electron-neutrino scattering process is also possible with muon and tau neutrinos, but with a smaller interaction cross probability.

4. Summary and prospect on further neutrino research

What was supposed to be a verification of the theory that nuclear fusion heats the sun by detecting solar neutrinos, turned out to reveal new knowledge about neutrinos themselves. It was finally discovered that neutrinos change their state while propagating. The theoretical description of neutrino oscillations implies that they are indeed not massless. This means the fundamental description of the world's elementary particles, the standard model of particle physics, is not yet complete.
Today, the research on and with neutrinos is a very active field. On the one hand, the shortly discovered oscillations are "new" physics that have never been observed before. On the other hand, neutrinos hold the ability to carry information about astronomical occurrences straight to earth without any deflection. This is why huge detectors were built or are planned to observe cosmic neutrinos,too. Most of these detectors use a natural supply of water, like ANTARES in the Mediterranean, or ice, like AMANDA in the Arctic, to detect the neutrinos through Cherenkov radiation.

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