PROCEEDINGS OF SCIENCE

Solar neutrinos: from their production to their detection

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Nuclear fusion reactions take place in the core of the Sun. On our neighborhood star, hydrogen is being fused into helium in the proton-proton chain reaction in which four protons are fused and two of them undergo a beta decay to become neutrons, releasing positrons and neutrinos. More than 40 years ago it was suggested to detect solar neutrinos to test the validity of solar models. The first measurement of the neutrino flux took place in the Homestake mine in South Dakota in 1968. The experiment detected only one third of the expected flux value, giving birth to the Solar Neutrino Problem. Since then different experiments were built in order to understand the origin of this discrepancy. Now we know that neutrinos undergo oscillation phenomena and change their nature while travelling from the core of the Sun to Earth. Thanks to neutrinos detection it is possible to infer and to prove how the Sun shines.
This paper introduces solar neutrino physics from a historical point of view from its beginning to our days.

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1. ”Our” star: the Sun

The Sun is is a medium-sized star and by far the biggest celestial body in the solar system. Its distance from the Earth is about 150 million kilometers. With a diameter of 1392000 kilometers, that corresponds to 109 Earth diameters, it appears to have an angular size of about 0.5 degrees. All planets orbit around the Sun because of its enormous gravity. It has a mass of about $2 \cdot 10^{30} kg$ (accounting for about 99.86% of the total mass of the solar system) that corresponds to about 333000 times the Earth’s mass. The effective surface temperature is 5780 Kelvin (putting it in the G2 spectral class). The characteristics of the Sun are summarized in table 1.

Characteristics of the Sun.	
Mass (Earth=1)	332,800
Mean diameter ($10^6 m$)	1392
Rotation period	26-37 d
Mean distance to Earth ($10^6 km$)	149
Density	1.41
Surface gravity m/s^2	274

Table 1: Characteristics of the Sun.

Spectroscopy measurements show that hydrogen makes up about 94% of the Sun, while helium makes up about 6% of the solar material, and all the other elements make up just 0.13%, 0.11% of this quantity is composed by oxygen, carbon, and nitrogen that are the three most abundant "metals"[1]. In the Sun there are also traces of neon, sodium, magnesium, aluminum, silicon, phosphorus, sulfur, potassium, and iron. The previous quoted percentages are by relative number of atoms. If one uses the percentage by mass, one finds that hydrogen makes up 78.5% of the mass of the Sun, helium 19.7%, oxygen 0.86%, carbon 0.4%, iron 0.14%, and the other elements are 0.54%.

Starting from the center of the Sun and moving outwards we can distinguish a core, a radiative zone and a convective zone. The core accounts for about 10% of the mass of the Sun and is where energy, from nuclear fusion, is generated. Due to the enormous amount of gravity compression the core is very hot and dense. At these high temperatures and densities nuclear fusion takes place. The Sun’s core is at about 15.5 million K and it is about 150 times denser than water. The radiative zone is where the energy is transported from the core to the colder outer layers by photons. The radiative zone includes approximately 85% of the Sun’s radius. The convective zone is where energy in the outer 15% of the Sun’s radius is transported by the bulk motion of gas in a process called convection.

2. How the Sun shines

As we said, the core of the Sun reaches temperatures of $\approx 15.5 \cdot 10^6 K$; at these temperatures nuclear fusion can occur transforming 4 hydrogen nuclei into 1 helium nucleus [1], [2]. One

[1] In astronomy any atom heavier than helium is called a "metal" atom

helium nucleus has a mass that is smaller than the combined masses of the four hydrogen nuclei. This *missing mass* is converted into the energy which is released by Sun.

The net reaction is:

$$4 \cdot {}^1H \rightarrow {}^4He + energy \tag{2.1}$$

The combined mass of of 4 ^1H is $6.6943 \cdot 10^{-27} kg$, which is heavier than the mass of 1 ^4He at $6.6466 \cdot 10^{-27} kg$. The difference is $0.0477 \cdot 10^{-27} kg$ ($\approx 0.7\%$). Using Einstein's equation $E = mc^2$, we find that each fusion releases $0.0477 \cdot 10^{-27} kg \cdot (3 \cdot 10^8 m/s)^2 = 4.3 \cdot 10^{-12} J$ that is 26.7 MeV [2]

Each second about 600 million tons of hydrogen are converted into about 596 million tons of helium-4. The remaining 4 million tons (actually 4.26 million tons) are converted into energy including radiation in the form of light. The current luminosity of the Sun is $3.846 \cdot 10^{26} W$.

3. What about neutrinos?

In the previous reaction (2.1) we started with 4 protons and ended up with 1 He nucleus which is composed of 2 protons and 2 neutrons. This means we had to transform 2 protons into 2 neutrons; in this inverse beta decay a proton (see eq. 3.1) becomes a neutron emitting a positron and an electron neutrino ν_e.

$$p \rightarrow n + e^+ + \nu_e \tag{3.1}$$

According to the Standard Model of particle physics, there are 3 types of neutrinos but in this reaction only an electron neutrino is emitted.

3.1 From protons to helium nucleus: The ppI chain

By far the most important reaction in the Sun is the proton-proton chain reaction. The first step involves the fusion of two hydrogen nuclei ^1H (protons) into deuterium ^2H, releasing a positron as one proton changes into a neutron and a neutrino: $^1H + {}^1H \rightarrow {}^2H + e^+ + \nu_e + 0.42 MeV$.[3] After this first reaction the deuterium produced can fuse with another hydrogen to produce a light isotope of helium, ^3He: $^2H + {}^1H \rightarrow {}^3He + \gamma + 5.49\ MeV$. Finally, after millions of years, two of the helium nuclei ^3He produced can fuse together to make the common helium isotope ^4He, releasing two hydrogen nuclei; this last fusion happens in $\approx 85\%$ of the case $^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H + 12.86\ MeV$ and is named PPI chain.

The 5.5 MeV gamma rays are absorbed by only a few millimeters of solar plasma and then re-emitted again in random directions and at slightly lower energy. The gamma rays take 10000 to 170000 years to reach the surface of the Sun. Each gamma ray created in the core of the Sun is converted into several million of visible light photons (some eV) before escaping into space. The photons escape as visible light.

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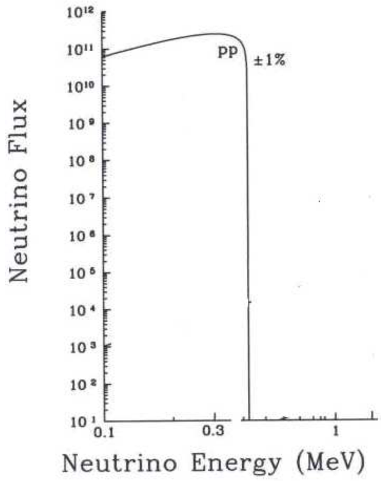

Figure 1: Neutrino energy spectrum emitted in the $^1H + ^1H$ reaction. Neutrinos emitted in this reaction have energy extending from 0 MeV to 0.42 MeV.

Figure 1 shows the spectrum of neutrinos emitted in the $^1H + ^1H$ reaction. In this reaction we have 3 bodies in the final state; this means that the emitted neutrino (like the electron) has a continuous spectrum extending from 0 MeV to the Q-value of the reaction, that is 0.42 MeV.

3.2 From protons to helium nucleus: The ppII and ppIII chains

The PPI chain just described is not the only one in which protons fuse in order to form helium nuclei. For instance, once ^3He is produced it can capture a proton (this happens with a very small probability) and directly create a ^4He emitting a positron and an electron neutrino. Or, with a much higher probability, ($\approx$ 15%) ^3He can interact with a ^4He and form ^7Be; this last can capture an e^- ($\approx$ 99.9%) or a ^1H ($\approx$ 0.1%) in order to form ^7Li or ^8B respectively. The ^7Li captures a proton and creates two ^4He; $^7Li + ^1H \rightarrow ^4He + ^4He$; this chain is named PPII chain. The ^8B decays beta $^8B^* \rightarrow ^8Be + e^+ + \nu_e$ and $^8Be \rightarrow ^4He + ^4He$ this chain is named PPIII chain.

At the beginning of the proton-proton chain, the reaction $^1H + ^1H \rightarrow ^2H + e^+ + \nu_e + 0.42\,MeV$ happens with a probability of $\approx$ 99.77%, in the remnent $\approx$ 0.23% the three body reaction can occur $^1H + e^- + ^1H \rightarrow ^2H + \nu_e$. Figure 2 summarizes the different paths of the pp chain. The figure also shows the different neutrino contributions [4]. Figure 3 shows the neutrino energy spectrum as

[2] $1eV \approx 1.6 \cdot 10^{-19} J$

[3] The positron immediately annihilates with one of the hydrogen's electrons, and their mass energy is carried off by two gamma ray photons $e^+ + e^- \rightarrow 2\gamma + 1.022\,MeV$.

[4] Solar neutrinos are labeled according to the reaction in which they are emitted: *pp* neutrinos are the ones emitted in the *pp* fusion, *pep* neutrinos the ones emitted in the three bodies fusion *pep*, *hep* neutrinos in the proton capture of ^3He, ^7Be neutrinos in the electron capture of ^7Be and ^8B neutrinos emitted in the decay of $^8B^*$. While neutrinos emitted

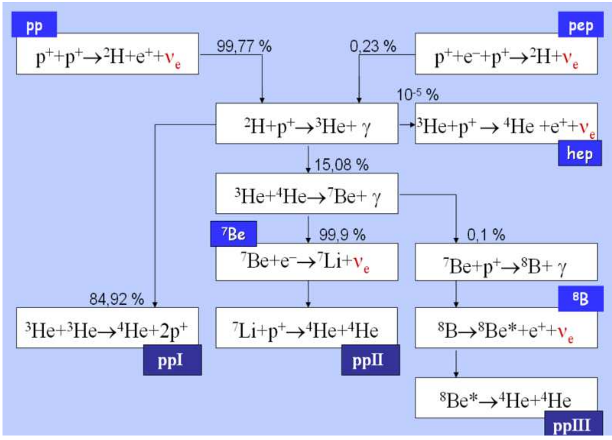

Figure 2: Th efigure shows the different paths with the different neutrino contribution of the pp chain (see text).

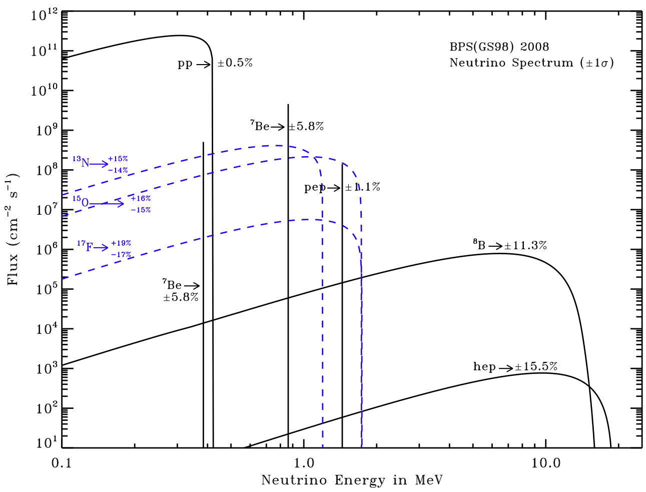

Figure 3: Neutrino energy spectrum as predicted by the Solar Standard Model (SSM).

predicted by the Solar Standard Model (SSM).

3.3 From protons to helium nucleus: The CNO cycle

The pp chain is not the only reaction that transforms protons into helium. In a star like the Sun about 98% of the energy is created in pp chain; the remaining 1-2% of the created energy is given by the CNO cycle. The CNO cycle becomes the dominant source of energy in stars heavier than the Sun. In this cycle there is also an emission of neutrinos (dashed line in figure 3).

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in reactions that have three bodies in the final state have a continuous spectrum ranging from 0 to the Q-value of the reaction (*pp*, ^{8}B and *hep*); neutrinos emitted in reactions that have two bodies in the final state are monocrhomatic (*pep* and ^{7}Be), see figure 2.

4. How to detect Solar Neutrinos?

There are two possible ways to detect solar neutrinos: radiochemical experiments and real time experiments.

In radiochemical experiments the reactions involve isotopes which interacting electron neutrinos produce other radioactive isotopes and an electron.

$$\nu_e +^A_Z X \rightarrow^A_{Z+1} Y + e^- \tag{4.1}$$

The production rate of the daughter nucleus is given by

$$N \int \Phi(E)\sigma(E)dE \tag{4.2}$$

where $\Phi(E)$ is the solar neutrino flux, $\sigma(E)$ is the cross section of solar neutrinos and N is the number of target atoms.

With a typical neutrino flux of $10^{10} \nu cm^{-2} s^{-1}$ and a cross section of about $10^{-45} cm^2$ we need about 10^{30} target atoms (that correspond to ktons of matter) to produce one event per day.

5. Homestake: The first solar neutrino detector

The first solar neutrino experiment took place in the Homestake gold mine in South Dakota [3]. The detector consisted in a large tank containing 615 tons of liquid perchloroethylene, which was chosen because it is rich in chlorine.The experiment operated continuously from 1970 until 1994.

Neutrinos were detected via the reaction:

$$\nu_e +^{37} Cl \rightarrow^{37} Ar + e^- \tag{5.1}$$

The energy threshold of this reaction is $E_{th} = 814\, keV$ allowing the detection of ^7Be and ^8B but not pp neutrinos which, as we said, have a maximum energy of 0.42 MeV.

The ^{37}Ar isotopes are radioactive and decay by electron capture with a $\tau_{1/2}$ of about 35 days into $^{37}Cl^*$:

$$^{37}Ar + e^- \rightarrow^{37} Cl^* + \nu_e \tag{5.2}$$

Once a month, after bubbling helium through the tank, the ^{37}Ar atoms were extracted and counted. The number of atoms created was only about 5 atoms of ^{37}Ar per month in 615 tons C_2Cl_4.

The number of detected neutrinos was about 1/3 lower than expected by the Solar Standard Model. This discrepancy is the essence of the Solar Neutrino Problem (SNP) which has been for many years an important problem among physicists.

6. Possible explanations to the SNP

There are three possible explanations to the Solar Neutrino Problem. The first one is to consider that the Standard Solar Model is not correct; but solar models have been tested independently by helioseismology (that is the science that studies the interior of the Sun by looking at its vibration modes), and the standard solar model has passed all tests so far. Indeed, non-standard solar models seem very unlikely. The second one is to consider that Homestake could be wrong, i.e. the Homestake detector could be inefficient its reactions would not have been predicted correctly. After all, to detect a handful of atoms per week in more than 600 tons of material is not an easy task. The third one, and the strangest hypothesis, is to consider that something happens to the neutrinos while travelling from the core of the Sun to the Earth.

7. Kamiokande and SuperKamiokande: Real time detection

The first real time solar neutrino detector, Kamiokande, was built in JapanIn 1982-83 [4]. It consisted in a large water Cherenkov[5] detector for a total mass of 3000 tons of pure water. In real time neutrino experiments scientists study the bluish light produced by the electrons scattered by an impinging neutrino 7.1. In the Kamiokande the light is recorded by 1000 photomultiplier tubes (PMT).

$$\nu_x + e^- \to \nu_x + e^- \tag{7.1}$$

The energy threshold of the reaction in Kamiokande is $E_{th} = 7.5\ MeV$ so only ^8B neutrinos and *hep* neutrinos are detected. At the beginning of '90s a much bigger detector was built, the SuperKamiokande, where the active mass was of 50000 tons of pure water viewed by 11200 PMTs. In the SuperKamiokande the energy threshold was lowered to $E_{th} = 5.5\ MeV$ [5].

As we have seen radiochemical experiments integrate in time and in energy because they are slow and need time to produce measurable results. This causes the loss of information about single individual energy values. However, unlike radiochemical experiments, in real time experiments it is possible to obtain single values and therefore a spectrum energy to distinguish the different neutrino contributions. Furthermore, given that the scattered electron maintains the same direction of the impinging neutrino, it is possible to infer the direction of the origin of the incoming neutrino and so to point at its source. This proved that neutrinos actually come from the Sun.

The number of detected neutrinos was about 1/2 lower than the number of expected neutrinos, aggravating the Solar Neutrino Problem.

8. Looking for pp neutrinos: Gallex and SAGE

Until 1990 there were no observations of the initial reaction in the nuclear fusion chain (i.e. the detection of *pp* neutrinos). *pp* neutrinos are less model-dependent and hence more robust to

[5]Cherenkov radiation is an electromagnetic radiation emitted when a charged particle passes through matter at a speed greater than the speed of light in that medium. The charged particles polarize the molecules of that medium, which then turn back rapidly to their ground state, emitting radiation in the near ultraviolet. The radiation is emitted under a cone shaped zone; its angle depends on the velocity of the charged particle and the refraction index of the medium.

prove the validity of the Solar Standard Model. Two radiochemical experiments were built in order to detect solar pp neutrinos; both employing the reaction:

$$\nu_e + ^{71}Ga \rightarrow ^{71}Ge + e^- \tag{8.1}$$

The energy threshold of this reaction is $E_{th} = 233\, keV$.

In the Gallex experiment, located at the Gran Sasso underground laboratory in Italy, 30 tonnes of natural gallium were employed [6] [7], while in the soviet-american experiment, located in the Baksan underground laboratory, there were 50 tons of metallic gallium [8].

Calibration tests with an artificial neutrino source ^{51}Cr confirmed the efficiency of both detectors. Once again the measured neutrino signal was smaller than predicted by the standard solar model ($\approx$ 60%).

All experiments detected fewer neutrinos than expected from the SSM! Table 2 and figure 5 summarizes the observed vs expected ratio for all experiments.

Homestake	0.34 ± 0.03
Super-K	0.46 ± 0.02
SAGE	0.59 ± 0.06
Gallex and GNO	0.58 ± 0.05

Table 2: observed vs expected ratio in the four experiment (before SNO, see later).

9. What happens to neutrinos?

9.1 neutrino oscillations

Neutrinos have the peculiar property that their flavour eigenstates do not coincide with their mass eigenstates. Flavor eigenstates ν_e, ν_μ, ν_τ are different from mass eigenstates ν_1, ν_2, ν_3 [9]. Flavour eigenstates can be expressed in terms of mass eigenstate system and vice versa.

The neutrino flavour states ν_e, ν_μ, ν_τ are related to the mass states ν_1, ν_2, ν_3 by linear combination:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{9.1}$$

U is the Pontecorvo-Maki-Nakagawa-Sakata matrix and is the analog of the CKM matrix in the hadronic sector of the Standard Model. This effect is known as neutrino oscillations.

There are three mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$; but since one of the three mixing angles is very small (i.e. θ_{13}), and because two of the mass states are very close in mass compared to the third, for solar neutrinos we can restrict the six neutrino cases to only 2 cases and consider the oscillation between $\nu_e \longleftrightarrow \nu_\mu, \nu_\tau$.

The probability of an electron neutrino produced at $t = 0$ to be detected as a muon or tau neutrino is:

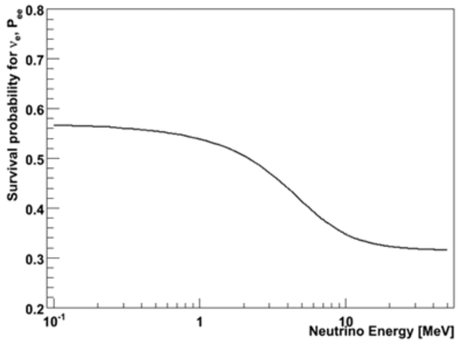

Figure 4: Survival probability vs energy of an electron neutrino at t=0 to be detected as a muon or tau neutrino.

$$P(\nu_e \to \nu_{\mu,\tau}) = \sin^2 2\theta \ \sin^2 \frac{\Delta m^2}{4E} L \tag{9.2}$$

This probability depends upon two experimental parameters that are the distance from the neutrino source to detector L (in km) and the energy of the neutrinos E (in GeV) and two fundamental parameters that are $\Delta m^2 = m_1^2 - m_2^2 \ (eV^2)$ and $\sin^2 2\theta$.

So, for a given energy E and a detector at distance L it is possible to determine the two fundamental parameters θ and Δm^2.

9.2 The Mikheyev Smirnov Wolfenstein Effect (MSW) or Matter Effect

Neutrino oscillations can be enhanced by traveling through dense matter [6]. The Sun is made of up/down quarks and electrons; all neutrinos ν_e, ν_μ, ν_τ can interact through neutral current (NC) equally, but only electron neutrinos ν_e can interact through charge current (CC) scattering $\nu_x + e^- \to \nu_x + e^-$. This means that the interaction of ν_e is different from ν_μ and ν_τ [10] [11].

9.3 Neutrino survival probability

As we have already pointed out, the probability of an electron neutrino produced at $t = 0$ to be detected as a muon or tau neutrino after a certain distance depends on its energy. For high energy neutrinos flavour change is dominated by matter oscillations, while for low energy neutrinos flavour change is dominated by vacuum oscillations. The regime transition between vacuum oscillations and matter driven oscillations is expected between $1 - 2\ MeV$. See figure 4.

10. Detecting all neutrino types: The Sudbury Neutrino Observatory

The Sudbury Neutrino Observatory (SNO) is a neutrino observatory located in Creighton Mine in Sudbury, Canada. It was turned on in May 1999 to detect solar neutrinos through their interactions with 1000 tons of heavy water viewed by 9600 photomultiplier tubes.

The advantage of this detector is to detect CC and NC fluxes independently [12].

[6] The core of the Sun has a density of about 150 gcm^{-3}.

In the charged current interaction, the impinging neutrino converts the neutron of the heavy water deuteron into a proton (eq. 10.1). This reaction is possible only for electron neutrinos.

$$\nu_e + d \rightarrow p + p + e^- \tag{10.1}$$

In the neutral current interaction, the neutrino dissociates the deuteron, breaking it into its constituent neutron and proton (eq. 10.2). This reaction is possible for all neutrino flavour types.

$$\nu_x + d \rightarrow p + n + \nu_x \tag{10.2}$$

As we can see in equation 10.3 ϕ_{CC} is given only from ϕ_{ν_e} while for ϕ_{NC} is given of all neutrino types $\phi_{\nu_e}, \phi_{\nu_\mu}, \phi_{\nu_\tau}$.

$$\begin{cases} \phi_{CC} = \phi_{\nu_e} \\ \phi_{NC} = \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} \end{cases} \tag{10.3}$$

In equation 10.4 we reporte the measured flux and in equation 10.5 we reporte the total flux calculated with the solar standard model (BPS07).

$$\begin{aligned} \phi_{CC} &= 1.68^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.}) \cdot 10^6\ cm^{-2}s^{-1} \\ \phi_{NC} &= 4.94^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.}) \cdot 10^6\ cm^{-2}s^{-1} \end{aligned} \tag{10.4}$$

$$(4.7 \pm 0.5) \cdot 10^6\ cm^{-2}s^{-1} \tag{10.5}$$

The measured flux via NC reaction is comparable with the one expected from theory; while the ratio between the measured flux via ϕ_{CC} and via ϕ_{NC} is: $\frac{\phi_{CC}}{\phi_{NC}} = \frac{1.68}{4.94} \sim \frac{1}{3}$ confirming that actually ν_e are converted into ν_μ and ν_τ during their voyage from the core of the Sun to the surface of the Earth where they are detected.

Figure 5 reports the summary of all solar neutrino experiments. All experiments "see" fewer neutrinos than expected by SSM except for the Sandbury Neutrino Observatory experiment in case of neutral currents.

Electron neutrinos ν_e oscillate into non-electron neutrino ν_μ and ν_τ with parameters $\Delta m^2_{12} = 7.6 \cdot 10^{-5} eV^2$ and $\sin^2 2\vartheta_{12} = 0.87$ corresponding to the Large Mixing Angle (LMA) of the Mikheyev Smirnov Wolfenstein effect.

If we plot the survival probability vs energy (see figure 4) we can recognize two regions, as we said in the previous paragraph. For high energy neutrinos flavuor change is dominated by matter oscillations, while for low energy neutrinos flavour change is dominated by vacuum oscillations. The regime transition is expected between 1-2 MeV.

11. To measure in real time below 1 MeV: The Borexino detector

As we have pointed out in previous paragraphs, real time experiments allow us to reconstruct the complete spectrum and hence to disentangle the different electron neutrino contributions.

Borexino is able to measure neutrino coming from the Sun in real time with low energy ($\approx$ 200 keV) and high statistic [13]. The detection principle is based on elastic scattering (ES) on

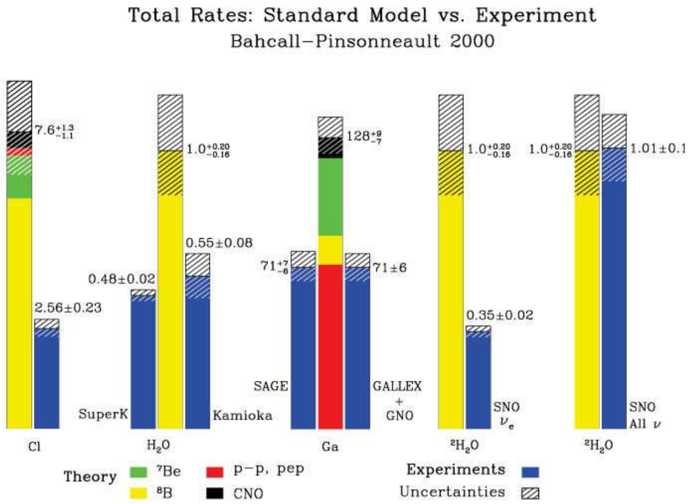

Figure 5: Summary of all Solar neutrino experiments.

electrons in very high purity liquid scintillator contained in a nylon balloon surrounded by different shielding media of decreasing radiopurity. The active fiducial mass is $\approx 100\, tons$ [7].

The main goal of Borexino is to obtain a direct measure in the low energy region of the neutrino spectrum and in particular ^7Be neutrinos. Beside this, it will be able to measure for the first time the neutrinos coming from CNO cycle therefore trying to solve the solar model chemical controversy. One fundamental input of the Standard Solar Model is the metallicity of the Sun. A lower metallicity implies a variation in the neutrino flux with reduction of $\approx 40\%$ for CNO neutrino flux. A direct measurement of the CNO neutrinos rate could help to solve this controversy giving a direct indication of metallicity in the core of the Sun. Furthermore, Borexino is able to measure the survival probability for both low energy and high energy neutrinos with the same detector.

12. Conclusion

More than 40 years have passed since the first detection of neutrinos coming from the Sun took place. The lack of neutrinos compared with the ones expected from the theory raised the solar neutrino problem. Since then different experiments were built, all over the world, to solve this mystery. Now we know that neutrinos undergo oscillations changing their nature during their voyage from the core of the Sun to our detectors. Thanks to their nature, neutrinos can bring

[7]The ν induced events cannot be distinguished from other $\beta - \gamma$ events due to natural radioactivity. The neutrino signal is on the order of some tens of events/day/100 tons above threshold. In order to have a signal to noise ratio on the order of 1 the ^{238}U and ^{232}Th intrinsic contamination cannot exceed $10^{-16} g/g$. This corresponds to a radioactivity 9-10 orders of magnitude lower than anything on Earth.

information about the engine that powers our star telling us how stars shine. This long race is not over yet end and some open questions remain to be solved.

13. Acknowledgements

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