SOLAR NEUTRINO EXPERIMENTS; A REVIEW

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ABSTRACT

The status of the running and planned experiments devoted to solar neutrino detection is shortly reviewed. Superkamiokande and SNO have been presented in devoted papers; therefore they will be only mentioned in the introduction. More details will be given on the two gallium based experiments (GALLEX-GNO and SAGE) and the results they obtain will be given. The two new detectors - BOREXINO and KamLAND - aimed to the detection of ^{7}Be ν and reactor antineutrinos (to investigate the so called Large Mixing Angle solution) will be described. Also a few details on projects, in different stage of construction or R&D - ICARUS, LENS, MOON...- will be given. Finally, searches for antineutrinos of solar origin will be mentioned.

1. Introduction

The physics of solar neutrino is well known; however, for sake of completeness and readibility of the paper, we shortly summarise the present status of models and of running experiments.

The flux of solar neutrinos as a function of energy has been computed by many authors; in the following we will assume as a reference model, the version of J. Bachall and *coll.* [1] of the Standard Solar Model, but we will mention also other standard models which give, at least for some components of the neutrino flux, different predictions. It has to be noted that the selected model is in good agreement with the helioseismological results and gives the time evolution of the ν production.
The predictions of the model on the energy spectrum are summarised in Fig.1 and Table 1. The major components in the flux are those due to p-p (and p-e-p) neutrinos, produced in the fusion of two protons, to the ^{7}Be E.C. and to the decay of ^{8}B; all these processes occur in the hydrogen cycle which is responsible for the 98% of the energy produced by the Sun. Also the CNO cycle, which is marginal for energy production, contributes to the ν flux, as shown in Fig.1. It is important to observe that these components cover different part of the energy spectrum: p-p neutrinos, by far the most numerous, are confined at very low energy, which makes their detection very difficult, while the ^{8}B neutrinos, much more scarce, having a much larger energy, are of easier detection and they have been detected first. The estimated accuracy of predictions is very different from component to component: the p-p neutrinos flux is essentially independent on the details of the model, being constrained by the total luminosity (for that reason this flux is considered "model independent", although this

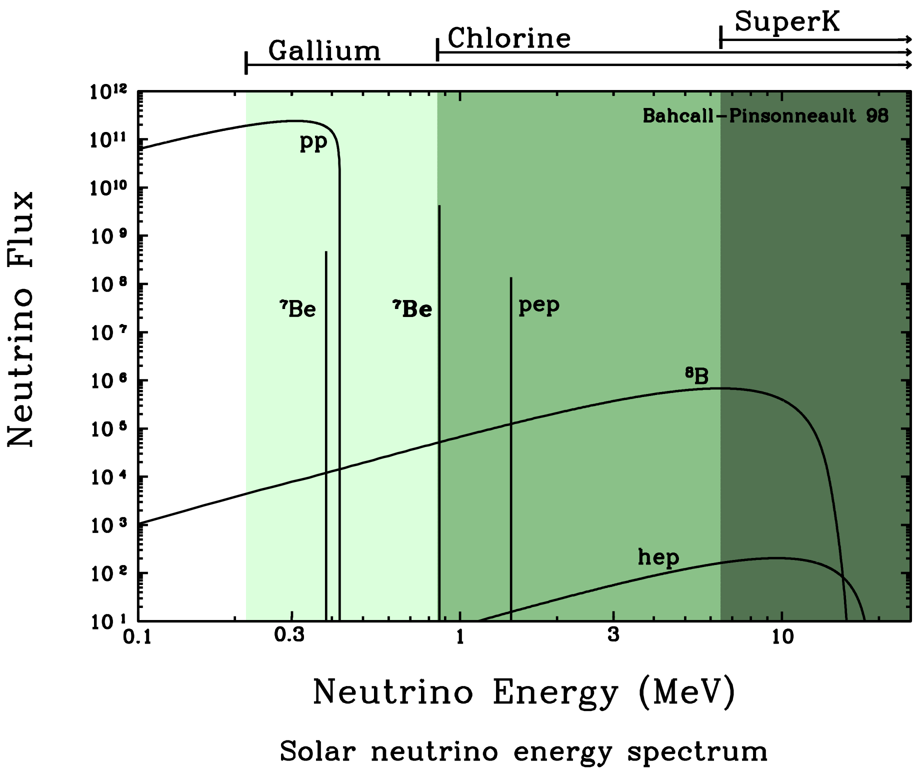

Figure 1: Solar neutrino energy spectrum.

statement is true only in the frame of this special class of models), while the accuracy on the ^{8}B flux is about 20% at 1 sigma level.

Knowing the flux, it is possible to compute the response of detectors. Detectors based on the use of gallium (see sect.2) are sensitive to all the electron ν with energy larger than 233 keV, therefore also to the p-p ν; the expected rate in ^{71}Ge is 130 SNU (1 SNU corresponds to 1 interaction/second in a target of 10^{36} nuclei); ^{37}Cl is sensitive to ν_e with energy larger than 814 keV, i.e. ^{7}Be and ^{8}B ν; the expected rate is 7.7 SNU, mainly due to reactions leading to excited states of ^{37}Ar; in the water cherenkov experiments, the neutrino scattering off electrons is detected, therefore they are sensitive to neutrinos and antineutrinos of any flavour; however, the cross section for ν_e is about 6 time larger than for other types of ν; in this experiments, the energy threshold is quite high, for instrumental reasons, therefore they are sensitive only to ^{8}B ν.

The measured values of the total rate, in the assumption that the flux is constant in time and that only ν_e are present, is reported in table 2. Historically, the first discrepancy observed was that of the chlorine experiment; this large deficit (more than 3 sigmas) stimulated many studies on the model in order to understand the discrepancy; this deficit was confirmed by the Kamiokande and Superkamiokande experiments[4)]. It was observed that the two experimental results, from the Cl and

Table 1: Predicted fluxes according to three different models.

Type	Energy MeV	BAH00[1] $10^9\nu$ cm^{-2}s^{-1}	BRU99[2] $10^9\nu$ cm^{-2}s^{-1}	DAR98[3] $10^9\nu$ cm^{-2}s^{-1}
p-p	$\leq$ .420	59.6 $\pm$1%	59.8	61.0
p-e-p	1.44	.140$\pm$1.5%	.141	.143
^{7}Be	.86/.38	4.82 $\pm$10%	4.7	61.0
^{8}B	$\leq$ 14.06	0.0515^{+20}_{16}%	.005	61.0
^{13}N	$\leq$ 1.20	.556 $\pm$19%	.466	61.0
^{15}O	$\leq$ 1.74	.488 $\pm$22%	.397	.374
^{17}F	$\leq$ 1.74	.006 $\pm$25%	-	.00453

Table 2: Predicted and measured solar neutrino fluxes

	Predicted rate	Measured rate
Ga	129 $^{+8}_{-7}$ SNU	74.1 $\pm$ 6.7 (Gallex+GNO)
		77.0 $\pm$ 7.0 (SAGE)
Cl	7.7 $^{+1.2}_{-1.0}$ SNU	2.56 $\pm$ 0.16 $\pm$ 0.15
$\nu_e e^-$	$5.15 \cdot 10^6$ cm $^{-2}$ s^{-1} $^{+20\%}_{-16\%}$	$(2.32\ ^{0.09}_{-0.08}) \cdot 10^6$ cm^{-2} s^{-1} $^{+20\%}_{-16\%}$

from the water, are in contrast, in the sense that the expected rate in Cl is lower than that one can compute, assuming the energy spectrum is that deduced from standard hypothesis, and the flux is that measured by SK. After the results from GALLEX and SAGE , the disagreement became even worse; the face value of the interaction rate is practically equal to that predicted for the p-p neutrinos only: therefore no room is left for ^{7}Be , whose flux is predicted with a reasonable accuracy. Moreover, while the Cl experiment has been not calibrated, and therefore one has to rely on computed ν-Cl cross-sections, both GALLEX and SAGE have been checked in many experimental ways (see sect.2). In conclusion, as it appears from table , the measured interaction rates (and the deduced fluxes) are significantly lower, at a level of many sigmas, than the predicted ones; that is especially true for the gallium experiments because the predicted rate for the different models (see below) ranges $\approx 120 - 140$ SNU, in all the cases much higher than the measured one.

Although it does'nt appear impossible to accomodate the present result on ^{8}B neutrinos with the SSM predictions, even if that requires some extreme hypothesis that need to be further checked, the gallium predicted rate, essentially independent from changes in the input parameters, shows a very significant disagreement with data in all the cases considered.

To reconcile the measured and predicted values, it was quite natural to introduce the phenomenon of neutrino oscillations. The literature on this subject is very reach and also at this conference the subject is discussed (see f.i.[5)]). Finally, let us mention that unconventional ideas has been proposed as, f.i. deviation from the pure Maxweel-Boltzmann distribution which can affect very significantly the interaction rate(see f.i [6,7,8)]).

While the rates strongly suggest the existence of neutrino oscillations, up to now no other clear manifestations,(energy spectrum distortions, time variations) of the phenomenon has been detected. This fact is not against the hypothesis of neutrino oscillations (large portions of the oscillation parameter space don't require these effects) but the observation of one of these effects would be a completely model independent proof of non standard neutrino physics. In that sense, the search of these deviations from the standard expectations, which are carefully investigate by SK, is of primary importance (see f.i.[4)]).

In this context, the results of SNO are of the greatest relevance. In a dedicated paper, H. Robertson[9)] will describe the progress of SNO; here let only stress a few point that, in my opinion, are important: i) SNO will measure the neutrino scattering off electron as SK , although with much less statistics, in a background environment (muon flux) much better than in SK; from a purely experimental point of view, this will provide an important cross check between the two experiments; ii) SNO will measure at the same time the semileptonic charge current interaction on neutron, providing the pure electron neutrino ^{8}B flux; the two measurements (on electrons and on neutrons) can allow the determination of the flux of neutrinos of different flavor than the electronic one; iii) finally the measurement of the interaction rate via neutral charge reactions will allow, for the first time, a measure of the flux of neutrinos, indepedently of their flavor; allowing a stringent test of the oscillation in non sterile ν hypothesys; note that such a result will also constrain the solar models.

The role of the other experiments will be discussed in next sections.

2. Gallium experiments

The most numerous neutrinos are those produced in the p-p fusion;their flux is also much less dependent on the details of standard solar models, as it has been mentioned in the introduction. Therefore, the detection of a significant deficit of these neutrinos would be a strong proof of non standard physics. For that reason, many years ago two experiments, GALLEX, now GNO, in operation at Gran Sasso, and SAGE, at Baksan, were designed to be sensitive to the p-p neutrinos. They are based on the detection of the radioactive ^{71}Ge produced in the reaction:

$$^{71}Ga(\nu_e, e^-)^{71}Ge$$

which has an energy threshold of 233 keV, well below the maximum energy (420 keV)

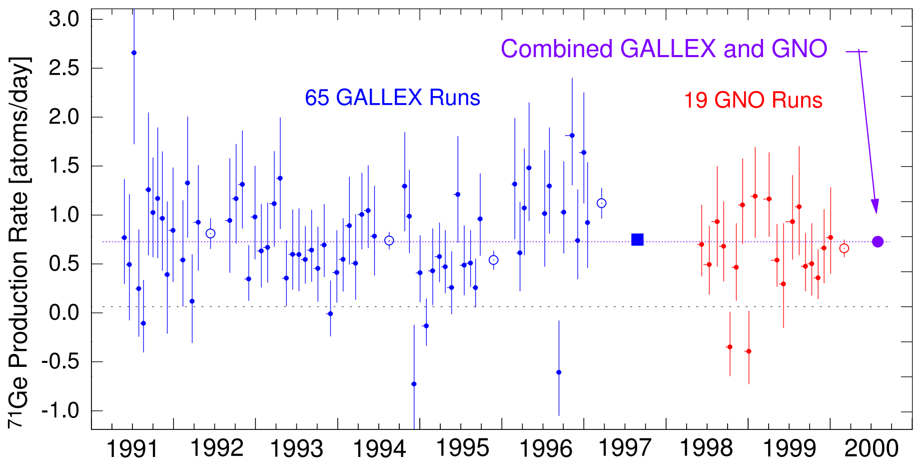

Figure 2: Measured solar neutrino capture rate (atoms/day) in the single 65 GALLEX solar runs, and in GNO solar runs SR1-SR19 (GNO-I). A signal of 100 SNU corresponds to a production rate of 0.90 ^{71}Ge atoms per day inside the 30 tons gallium tank.

of the p-p- neutrinos.

A few data about the gallium -germanium system. Gallium is a metal melting at 39 C; its isotopic composition is: ^{69}Ga with 60% i.a. and ^{71}Ga with 40% i.a.; ^{71}Ge transform back in ^{71}Ga via E.C. with a half-life of 11.4 days emitting Auger electrons and X rays at 10 (K capture) KeV, 1.2 (L capture) and .5 (M capture) keV. X rays and Auger electrons are detected in specially designed proportional counters. The target mass is: 55 tons of metallic gallium and 30 tons of gallium in hydrochloric solution for SAGE and GNO respectively; therefore the two experiments use a different extraction technique and also are affected by different backgrounds. The results are the followings:
GALLEX-GNO[10)] 74.1 ±6.8 SNU (statiscal+systematic errors added)
SAGE 67.2 $\pm 7.1_{stat.} \pm 3.2_{syst.}$ SNU pubblished in [11)];
after a revaluation of efficiencies, the result is[12)]

$$75^{+7}_{-6}\, SNU$$

and, finally[13)] 77^{+7}_{-6} SNU.
These values, must be compared with the predicted rate of 129+9-7 SNU; it is important to stress the fact that the contribution of pp and pep neutrinos is 73 SNU; taking into account the small contribution of ^{8}B neutrinos, very small room is left to ^{7}Be and CNO neutrinos, in quite an evident contradiction with any reasonable standard solar model. Fig.2 shows the single run results for GALLEX-GNO; the experiment took data without interruptions, except for the time needed to expose the solution to a ν from a ^{51}Cr source and for the so called As test(1997-98), when also significant improvements on the electronics and other aspects of the experimental system were done.

The future program of GNO can be summarized as follows: i) to continue the data taking with 30 ton of gallium; owing the above mentioned improvements, we expect to reach a result on the mean rate of the same accuracy as that of GALLEX, but in a shorter time; ii)to improve our knowledge, and therefore reduce them, on systematic errors (radon background, counter efficiencies) iii) to analyze data with different statistical methods (neural network or other similar more powerful procedures than that presently used); iv) to interpret the data also in view of possible time variations; v) to expose, for the third time, the gallium solution to an artificial source of neutrinos, in order to check the satus of the experiment and to increase the accuracy on our knowledge of ν-Ga cross sections; vi) to develop new types of ^{71}Ge detectors, to improve the signal/background ratio; vii) and finally to explore the possibilities for a substantial increase of the target mass, as planned in the GNO proposal.

Point v) merits some more comments. GALLEX and GNO have been exposed to a Cr source; the results demonstrated that no unknown systematic errors, at the level of 10%, were present in the experimental procedure[14)]. After the ^{71}As experiment[15)], which demonstrated that the extraction and synthesys efficiency was known with 1% accuracy, the Cr results can be used to determine the ν-Ga cross section at an energy very close to that of of ^{7}Be lines. The two previous GALLEX exposures gave two results which, while statistically compatible, are not in perfect agreement. Therefore, after five years from the last exposure to the Cr source, is highly desirable to repeat such a calibration both to check the status of the detector and to improve the accuracy on the cross section. In conclusion, the gallium experiments are, at present and probably for many years, the only expriments providing a 10% (or better) accuracy measurement of solar neutrino interaction rate with a sufficiently low energy threshold to detect the p-p neutrinos.

3. Borexino and KamLAND

One of the topical problems in experimental solar ν physics is the direct detection and measurement of the ^{7}Be solar ν. From the present data, a strong reduction of the flux of these ν is expected; their measurement could address the solution in term of oscillation, of the solar neutrino problem. Borexino [16)]is a low background real time experiment; its main experimental goal is the detection of the .862 MeV ^{7}Be ν component through the $\nu e^- \rightarrow \nu e^-$ electroweak scattering reaction. The maximum energy of the recoling electron is 664 keV; therefore the detector has been designed in order to have a very low (250 keV) energy theshold. Boerexino is an unsegmented liquid detector featuring 300 tons of well shielded ultrapure scintillator, viewed by 2200 PMT's. The detector core consist of 300 tonnes of scintillator enclosed in a nylon transparent spherical vessel; it is surrounded by 1000 tons of high purit buffer liquid and finally by 2400 tons of pure water. In past years, a big effort has been directed to achieve the needed purity of the different component of the detector (liquids, PMT's, supporting structure); a Counting Test Facility was runned since 1994 to identifie and measure the background sources, allowing significant reduction in the background level. The expected nuber of events in a 100 fiducial mass of liquid scintillator is 40/day, according to the full S.S.M. predictions. The expected statistics is large enough for an accurate determination of the interaction rate andof its (if any) time variations, therefore largely improving our knowledge on productionand propagations of neutrino in matter and in vacuum. Having mentioned the importance of this measurement, it must also stress the difficulties of such an experiments, difficulties that fully justify the time required for the construction of the detector. The experiment will start to take data in 2002.

KamLAND. The detector design of KamLAND is very similar to that of Borexino, but its mass is larger, totalling 600 tons of fiducial mass. It is installed in the cave previously filled by the Kamiokande water Cerenkov detector. The original aim of KamLAND is the detection of $\bar{\nu}_e$ emitted by the japanese power reactors, to study the region of the so called LMA solution[18,19]. The $\bar{\nu}$ will be detected by the inverse beta decay reaction, which is much more constrained than the simple ν elastic scattering off electrons, moreover the energy of the interacting neutrinos is much larger. Therefore, KamLAND is less demanding than Borexino in terms of radiopurity of the set-up. However, if the detector will be sufficently "clean" , it will be also useful to study solar neutrinos. In that positive case, in a few years from now, two experiments, located at different depths and in different background environment, will provide very important data on the ^{7}Be ν. The detector is supposed to enter in operation at the end of 2001.

4. New experiments

In this section we will shortly review some of the planned experiments in the field. For HELLAZ we refer to the paper presented at this Conference.

4.1. ICARUS

The ICARUS project for the construction of a large (ktonnes) liquid argon time projection chamber, started many years ago. In 1990, a 3 tons prototype was constructed at CERN; it was operated for four years for preliminary studies on various technical aspects of this kind of technique; later, a 50 litres chamber was succesfully exposed to a neutrino beam and also to other test beams. More recently, a 10 m^3 module was constructed at LNGS and runned for a few monthes.This module showed an excellent crygenic stability; the measured half-life of electrons in the liquid was close to the designe figure of 2 ms. In parallel, the construction of a 600 tonnes module, approved in 1997 [20], started in Pavia. The detector is made by two equal submodules, one of them completely instrumented. The module has been filled and now is in operation; beautyful cosmic ray events have been observed, demostrating the high quality of the detector(June, 2001). ICARUS can be applied to study a large variety of phenomena; among them, since the original proposal of the project, the study of solar neutrinos was planned. Solar neutrinos produce two type on events: elastic scattering off electrons and semileptonic interactions on Ar, leading to excited states of ^{40}K. The expected rate, according to the SSM and assuming an energy threshold of 5 MeV is 800 elastic events and more than 2000 interaction on Ar per kton and per year. Further experimental tests, namely long lasting measurements in a protected environment, will allow to evaluate the real potentialities of such a detector for solar neutrino studies; in any case, it will be of great interest, from a purely experimental point of view, to measure the flux of ^{8}B ν with a completely different technique than the water Cerenkov one.

4.2. LENS

The region of subMeV solar ν is of major interest; the aim of LENS [21]is the real time observation of p-p and ^{7}Be ν through the reaction:

$$^{176}Yb(\nu_e, e^-)^{176}Lu^*$$

followed by the de-excitation of Lu^* with an energy threshold of 300 keV. A strong reduction of the background is obtained thank to the delayed coincidence between the electron emission in the ν interaction and the decay of one of the Lu excited states. According to the present design, a target mass of 20 tons of Yb will be diluted in about 200 tons of liquid scintillator. The expected number of events is about 500 (300 due to p-p and 200 due to ^{7}Be) events per year (SSM). The activity of the collaboration is mainly concentrated on the problem of dilution, light output, stability of the loaded scintillator and on background problems. Two remarks must be done: i)the detector require an accurate calibration with a ν source, because cross sections on Yb can be estimated only theoretically, making use of p-n reactions; ii) the predicted statistics is not very large. In any case, the development of the dilution technique of rare earth elements, and probably of other unusual elements, in liquid scintillator is of noticeable interest.

4.3. MOON and other projects

It is well known that Molibdenum 100 is a very interesting nucleus for double beta decay search, but it is interesting for solar ν interaction, having a low energy threshold (168 keV) and a quite high interaction rate, close to 1000 SNU. For that reasons, an experiment has been proposed Ejiri and *coll.*[22,23].
The use of other double beta active nuclei has been proposed, namely of ^{136}Xe [24]and[25] and of ^{76} [26]. Note that in these cases, one source of background is the 2ν double beta

decay! Finally, let us recall proposal like MUNU, Iodine, Heron, which have been already discussed since many years at many neutrino conferences.

The field of solar ν has stimulated the conception of many new detectors, some of them unconvential. We simply list some of them and apologize for the incompletness of the description.

5. Solar antineutrinos

The Sun is probably a very weak source of electrons antineutrinos, practically undetectable; low energy ($\leq$3 MeV) $\overline{\nu}_e$ are produced in the decay of heavy nuclei; the corresponding flux is estimated to be [35] 200 $\overline{\nu}_e$ cm^{-2} s^{-1} However, a mechanism that can produce a measurable flux of $\overline{\nu}_e$ has been proposed many years ago; if neutrinos are Majorana particles and their magnetic moment is of the order of 10^{-11} mB, the following chain of transitions can occur:

$$\nu_{eL} \longrightarrow RSFP \longrightarrow \bar{\nu}_{\mu R} \longrightarrow FlavorOscillation \longrightarrow \bar{\nu}_{eR}.$$
$$\nu_{eL} \longrightarrow FlavorOscillation \longrightarrow \nu_{\mu L} \longrightarrow RSFP \longrightarrow \bar{\nu}_{eR}.$$

(see, f.i. [27][28][29][30]). Many of the running or proposed experiments on solar neutrinos are suitable to search for antineutrinos; at present , limits on the flux, of the order of few % of the neutrino flux, have been provided by Kamiokande [31] and Superkamiokande[32], LSD[33], LVD[34], see Table. The two last experiments, the first one installed at M.nt Blanc and the second one, a very huge liquid scintillator detector, in operation at Gran Sasso, are mainly devoted to the detection of supernovae and were specially designed to detect $\bar{\nu}$ interaction. The result of LVD is very preliminar, the collected statistics being one order of magnitude larger than that used to deduce the quoted limit; therefore, a much more interesting limit, in term of energy threshlod and statistics, will be given in a short time. When a more rich set of data, from the above quoted experiments and from SNO, Borexino and Kamland will be available, it will be possible to better constrain (or proof) this quite special pattern of neutrino transformation.

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