Novel results on low energy neutrino physics

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Abstract Many progresses have been achieved in the study of low energy neutrinos from Sun and Earth. In the solar neutrinos the flux from $^7$Be has been measured with a total error <5% (introducing strong constraints also on the pp flux), while the day/night effect in that energy region has been determined at 1%. The $^8$B neutrinos have been detected with a threshold down to 3 MeV, while the solar neutrinos flux from pep reaction has been measured together with a stringent limit on CNO. These results give the experimental proof of the neutrino oscillation in vacuum and the validation of the MSW-LMA model in that region, while the day/night allows the isolation of the LMA solution by means of the solar neutrinos only, without the assumption of CPT symmetry. The evidence of the antineutrinos produced within the Earth by radioactive decays is now very robust, but more statistics is needed to clearly estimate the radiogenic contribution to the terrestrial caloric energy.

1. A few open problems in the neutrino physics.

First of all I would like recall three open problems in the solar neutrino physics.

One of them concerns the so called “metallicity”: metallicity refers to the presence in the Sun of nuclei as Carbon, Nitrogen, Oxygen, Neon and Argon. A modeling of the solar atmosphere has to meet the abundances determined via atomic and molecular spectral lines in the photosphere. This modeling has been done some years ago in one dimension in a time-independent hydrostatic analysis that incorporates convection (GS98-[1]). It showed a good agreement with the helioseismology, which studies the propagation speed of mechanic waves in the Sun, in connection with turbulences. A more refined modeling of the solar surface in 3D has been done more recently resulting in a reduced metallicity with respect GS98, but the results are in disagreement with the helioseismology (AGS09-[1]). The puzzle has not been solved yet.

The different metallicities have influence also on the solar neutrino fluxes, even if in some cases the differences are small. In the second and third column of table 1 the model previsions are displayed [1]. The highest difference is shown by the CNO fluxes; $^7$Be and $^8$B differ of ~10 and 20%, respectively, but the model uncertainties are large.

A second problem concerns the study of the paradigmatic MSW-LMA oscillation model in the vacuum regime and of the region between vacuum and matter oscillation (the so called transition region). We can refer to the figure 1, where the survival probability of $\nu_e$ is displayed with the experimental points obtained before the Borexino experiment: only the oscillation in matter at high energy has been measured, while at lower energy only two points with very large errors are provided by the radiochemical experiments[2]. Then it was necessary to study experimentally the oscillation in vacuum and to check the MSW-LMA model in the vacuum and transition regions. It has to be
reminded that the shape of the transition region can show discrepancies with respect to the model previsions in presence of hypothetical non-standard neutrino interactions [3].

Table 1. Comparison between the Standard Solar Model previsions and the experimental results. GS98 and AGS09 refer to high and low metallicity, respectively (see text).

| ν flux | GS98      | AGS09      | cm$^2$s$^{-1}$ | Experimental results          |
|--------|-----------|------------|---------------|-------------------------------|
| pep    | 1.44±0.012| 1.47±0.012 | x 10$^8$      | 1.6±0.3 Borexino              |
| $^7$Be | 5.00±0.07 | 4.56±0.07  | x 10$^9$      | 4.87±0.24 Borexino            |
| $^8$B  | 5.58±0.14 | 4.59±0.14  | x 10$^6$      | 5.2±0.3 SNO+SK+Borexino+Kamland|
|        |           |            |               | 5.25±0.16+0.011-0.013 SNO-LETA |
| $^{13}$N | 2.96±0.14 | 2.17±0.14  |               | < 7.4 Borexino (total CNO)    |
| $^{15}$O | 2.23±0.15 | 1.56±0.15  | x 10$^8$      |                               |
| $^{17}$F | 5.52±0.17 | 3.40±0.16  |               |                               |

Figure 1. Experimental measurements of the $\nu_e$ survival probability before Borexino.

Finally the best fits of the oscillation parameters, and in particular $\Delta m^2$, obtained from the global fit on the solar data only ($5.37^{+1.55}_{-1.07} \times 10^{-5}$ eV$^2$), is different from the global fit on solar plus Kamland antineutrino data. The tension between the two results could be explained either with a not zero $\theta_{13}$ or with the existence of a sterile neutrino. In addition the LMA region cannot be isolated by the fit on only solar, because the probability of a LOW region (at $\Delta m^2 \sim 1.15 \times 10^{-7}$ eV$^2$) is not zero.

2. New results on solar neutrinos

New data on solar neutrinos have been provided in the last two years by Borexino, Kamland, SNO and Superkamiokande.

Borexino has recently released: a precise measurement of the solar neutrinos from the reaction involving $^7$Be (flux and day/night), the first determination of the flux from the pep reaction, an upper limit for the CNO flux, a measurement of the $^8$B with a lower threshold down to 3.0 MeV ($E_{\nu}=3.2$ MeV).
The other experiments have measured the $^8$B flux with various lower thresholds: Kamland over 5.5 MeV ($E_{\nu} = 5.8$ MeV); SNO-LETA (Low Energy Threshold Analysis) with a threshold at 3.5 MeV ($E_{\nu} = 3.8$ or 4.5 MeV depending on the reaction taken into consideration); Superkamiokande III over 5.0 MeV ($E_{\nu} = 5.3$ MeV).

2.1. The study of the solar neutrinos below 2 MeV.
Borexino uses 300 m$^3$ of liquid scintillator with a fiducial volume for solar neutrinos of 86 m$^3$. Due to its world record radiopurity, Borexino takes data with a hardware threshold at 60 keV and a software one at ~200 keV. The detected $\nu$ interaction is the elastic scattering on electron.

In figure 2 the row spectrum of the data collected by Borexino in the fiducial volume, once subtracted the muons and the events muon induced.

![Energy spectrum of the events detected by Borexino in the fiducial volume, once subtracted the muons and the events muon induced.](image)

Figure 2. Energy spectrum of the events detected by Borexino in the fiducial volume, once subtracted the muons and the events muon induced.

Two important aspects can be emphasized: A) The energy spectra of the recoiled electrons for the mono-energetic neutrinos from $^7$Be and pep show a shoulder (Compton edge), very useful for their identification; B) despite the unprecedented radio-purity of Borexino some contaminants are still present: $^{210}$Po, which is an $\alpha$ emitter with a lifetime $\tau = 200$ days; $^{85}$Kr, a beta-gamma emitter, which contaminates just the $^7$Be energy region; $^{11}$C which is generated by the cosmic muons crossing the Gran Sasso overburden (1.2 $\mu$/m$^2$h): it is a $\beta^+$ emitter with $\tau = 29.4$ minutes; $^{210}$Bi, beta emitter with a continuous spectrum up to $\sim 1150$ keV.

The identification of this residual background carried out by the Borexino collaboration is based upon various tools. i) $\alpha$s can be rejected with good efficiency exploiting the scintillator slower response for $\alpha$ particles with respect to electrons and photons; this property is very useful because $\alpha$s are emitted only by the radioactive contaminants, as it is the case of $^{210}$Po. ii) $^{11}$C (and other cosmogenic nuclides) can be identified via a threefold coincidence which involves: incident muon track, the positron emitted in the $^{11}$C which produces a prompt signal due to its annihilation, a neutron produced in the muon interaction which is thermalized after a travel $\sim 240$ $\mu$s long and is captured emitting a 2.2 MeV. iii) $^{85}$Kr energy distribution is measured leaving it as free parameter in the fit, but it can be checked also directly through its decay to the excited $^{85}$Rb with a 173 keV $\beta$ emission, followed, after a lifetime of 1.464 $\mu$s, by the decay to $^{85}$Rb ground state with a 514 keV gamma emission. Unfortunately this $^{85}$Kr decay has only a 0.46% branching ratio: then the statistics is not very high.
2.1.1. \(^7\)Be flux and day/night. The fit on the neutrino energy spectrum, obtained in 740.6 live days of data taking, is shown in figure 3. The free parameters are: \(^7\)Be, \(^85\)Kr, \(^210\)Bi, \(^11\)C, \(^210\)Po, while pp, pep and CNO are fixed according to the MSW-LMA model with high metallicity.

The fitted plot is the same as in figure 2, but once the \(\alpha\) subtracted. Two fits are performed, a first using the Montecarlo code and a second one with an analytical algorithm: the obtained results are fully compatible in the two cases [4].

The total 862 keV \(^7\)Be rate is: 46±1.5 (stat.) ±1.5 (syst.) counts per day/100 tons. Assuming the MSW-LMA expectations we can calculate the \(^7\)Be flux: \(\Phi(\ ^7\text{Be}) = (4.87 \pm 0.24) \times 10^{-9} \text{cm}^{-2} \text{s}^{-1}\). The ratio to the Solar Standard Model (SSM) prevision is \(f_{\text{Be}} = 0.97 \pm 0.05\) (stat) ±0.07 (syst).

In the \(^7\)Be energy range (550-715) keV the possible day/night rate difference has been also measured searching for a possible re-conversion of \(\nu_\mu\) and \(\nu_\tau\) to \(\nu_e\) during the night travel through the Earth. The day and night spectra, normalized to the same number of live data taking days, are subtracted each other and a search on the so obtained plot for a residual component having the shape of the electron recoil spectrum due to the \(^7\)Be neutrinos is performed. Using the asymmetry parameter

\[
A_{dn} = 2 \frac{R_n^{\ ^7\text{Be}} - R_d^{\ ^7\text{Be}}}{R_n^{\ ^7\text{Be}} + R_d^{\ ^7\text{Be}}} = \frac{R_{\text{diff}}}{R} \text{ it has been obtained } A_{dn} = -0.001\pm0.012\text{(stat)}\pm0.007\text{(syst)} [5].
\]

![Figure 3. Same plot as in figure 2, but once alphas subtracted.](image)

2.1.2. pep and CNO. The Compton edge of the pep neutrinos scattering on electrons, which tags their energy spectrum, falls just in the energy range of the positrons (plus the two gammas produced by their annihilation) emitted in the \(^11\)C decay. Then the first problem is the identification of the cosmogenic \(^11\)C via the three fold coincidence (TFC), as explained in the point ii) of the subsection 2.1. This method implies that a space and time veto would be performed after the coincidences between the signals from the muon and neutrons: in this way exposure, that is more likely to contain \(^11\)C due to the correlation between the parent muon, the neutron and the subsequent \(^11\)C decay, is discarded.. An optimal compromise between \(^11\)C rejection and preservation of the fiducial exposure has been found reducing the \(^11\)C to 9.1% with a 48.5% of residual exposure [6].

But 9.1% of \(^11\)C is still a significant background. The difference between \(e^-\) and \(e^+\) interactions in the scintillator can be exploited to perform a discrimination on the pulse shapes between the \(^11\)C \(\beta\) decays and the neutrino induced \(e^-\) recoil. A difference in the time distribution arises from the formation of ortho-positronium (in 50% of the cases) between the positron and one electron of the scintillator; the ortho-positronium has a lifetime \(\tau=140\) ns, reduced in the scintillator to 3 ns. In addition the two gammas emitted in the positron annihilation produce a more distributed multi-site topology than in the case of the electron. An optimized pulse shape parameter, constructed via a boosted-decision-tree algorithm (BDT), has been developed.
The external background, more important in this energy range than in the $^7$Be window, is studied with an external ~ 5MBq $^{228}$Th source positioned close to the core of the detector.

The fitting strategy makes use of a binned maximum likelihood multidimensional fit on the events surviving the TFC selection. The fit is performed simultaneously on the energy spectrum, the radial distribution and the pulse shape BDT parameter, with different fitting ranges. In addition the fit is performed in the same time on the events surviving the TFC vetoes and on the energy spectrum of the rejected events, constraining the non-cosmogenic species to be the same, because uncorrelated with the vetoes.

The more important species left free in the fit are: $^{210}$Bi, $^{11}$C, $^{85}$Kr as internal background, $^{208}$Tl, $^{214}$Bi, $^{40}$K as external background, and finally $^7$Be, pep, CNO as signals. pp is fixed at the prediction of the Solar Standard model, while for $^8$B the mean value of the experimental results is assumed.

In a second step the pep neutrino flux has been fixed at the SSM expectation to improve the CNO limit.

In figure 4 the fit on the energy spectrum for pep and CNO is shown: the fitted distributions for pep, $^{210}$Bi, the residue $^{11}$C survived to the TFC and the external background are displayed. In fig.5 the pep, once the background subtracted, is also shown: the Compton edge of the electron recoils is well visible.

The pep rate is: $3.13\pm0.23$ (stat.)$\pm0.23$ (syst.) counts per day/100 tons; the CNO upper limit: $<7.6$ cpd/100 tons. Assuming the MSW-LMA parameters $\Phi$(pep)$= 1.6\pm0.3 \times 10^8 \text{cm}^2 \text{s}^{-1}$ and $\Phi$(CNO)$= 1.674 \times 10^8 \text{cm}^2 \text{s}^{-1}$; the ratios to the SSM expectations with high metallicity are: $f_{\text{pep}}=1.1\pm0.2$ and $f_{\text{CNO}}<1.4$.

3. New data on the $^8$B neutrino flux.
Borexino has released the result on the $^8$B flux measurement in the range 3.0-16.3 MeV with the lowest threshold used until now [5] and a statistics collected during 688 live days. In the energy range: 3.0-5.0 MeV additional background is introduced by the $^{208}$Tl, an electron and gamma emitter, and by cosmogenic isotopes. The $^{208}$Tl contribution can be subtracted because it is a daughter of $^{212}$Bi, which either can decay with $\beta$ emission to $^{210}$Po with 64% B.R. and $\tau=431$ ns, or can decay to $^{208}$Tl with $\alpha$ emission and with 36% B.R. and $\tau=4.47$ min. The decay coincidence $^{212}$Bi-$^{210}$Po can be easily identified in Borexino. The cosmogenic isotopes can be rejected either with proper vetoes after each crossing muons or with threefold coincidences.

KamLAND succeeded to measure the $^8$B flux reducing the fiducial volume to 176.4 m$^3$ (to reject external gammas) and to define a threshold at 5.5 MeV (to avoid the background due to the natural radioactivity)[8].
Superkamiokande III has performed a $^8\text{B}$ study with higher precision with respect to the previous one [9]. This result has been achieved by discarding part of the fiducial exposure, when the detector suffered higher background, and reducing the fiducial volume. For the data falling in the energy range 5.-6.5 MeV the data taking has been reduced to 298.2 live days, while for the interval 6.5-20. the statistics corresponds to 547.9 days. Similarly the fiducial volume of 22.5 ktons used for the energy range 5.5-20. MeV has been reduced to 13.3 ktons for 5.0-5.5 MeV. External and internal radioactivity, muon spallation and cosmogenics are the main background.

A summary of these results obtained via the detection of the $\nu-e$ elastic scattering are summarized in figure 6, where the $^8\text{B}$ oscillated fluxes are displayed (see [8]). The SNO-LETA results have not been taken into account in this plot. The weighted average of the plotted data is $\Phi(^8\text{B}) = 2.33 \pm 0.05 \times 10^6$ cm$^{-2}$ s$^{-1}$.

\begin{figure}[ht]
\centering
\includegraphics[width=0.5\textwidth]{figure6}
\caption{The $^8\text{B}$ flux measured via $\nu-e$ elastic scattering [8]}
\end{figure}

The SNO-LETA analysis concerns 668.8 live days with a threshold at 3.5 MeV, which corresponds to 3.8 MeV for the elastic scattering (ES) and to $\sim 4.5$ MeV for the charged currents (CC) data [10]. The fit is done on the data of all three phases and of ES, CC (induced only by $\nu_e$) and neutral current (NC) (induced by all neutrino species), using as measured parameters the energy spectrum, the radial position, the angle with respect to the Sun direction and the isotropy of the PMT patterns. The simultaneous fit on the three reactions detected in SNO (and on 17 background types) gives in the same time the $^8\text{B}$ flux and the survival probability. The sources of physics related background are mainly the internal, bulk and external $^{214}\text{Bi}$ and $^{208}\text{Tl}$, the external $\beta-\gamma$s, the surface ($\alpha,n$).

The best fit of the $\Phi(^8\text{B})$ is $5.25 \pm 0.16$(stat.)$^{+0.013}_{-0.013}$(syst.) cm$^{-2}$ s$^{-1}$.

4. Impact of the new result on open problems.
I am referring to the section 1 and I would discuss, after the results of the sections 2 and 3, the situation of the three open aspects of the neutrino physics mentioned there.

The fluxes measured are summarized in the last column of table 1. Unfortunately no conclusion can be obtained by comparing them with the SSM predictions, due to the experimental and SSM uncertainties and to the fact that the experimental results fall just in between the high and low metallicity, except for the pep case.

The $\nu_e$ survival probability is much improved with respect to figure 1. The $^7\text{Be}$ measured by Borexino and the strong constraints to pp, introduced by the Borexino and Gallex data, fix the survival probability for the oscillation in vacuum (see figure 7), validate the MSW-LMA model in that region, and allow to obtain the ratio $\frac{P_{\nu_e}^{\text{Vac}}}{P_{\nu_e}^{\text{Matter}}} = 1.63 \pm 0.26$. At high energy, for the Borexino (threshold 3.0 MeV) and SNO-LETA (threshold at 3.5 MeV) results the average value is plotted due to the limited statistics of both. We can note that in both cases the data tend to decrease when the energy decreases.
and then to be lower with respect to the MSW-LMA expectation. But in both cases the spread is within 1σ.

Finally the result obtained by Borexino on ⁷Be day/night succeeds in ruling out the LOW region at >8.5σ C.L.; then due to the Borexino results now it is possible to isolate the LMA solution with the solar data only, without the reactor antineutrinos and then no need to assume CPT conservation.

5. Geo-neutrinos.
The geo-neutrinos are antineutrinos emitted by the radioactive decays, which take place in the Earth interior. The instable nuclides belong to the ²³⁸U and ²³²Th natural families; in addition also ⁴⁰K is present.

While the chemical composition of the Earth Crust can be investigated by means drill holes, the geo-neutrinos are the only way to study the Earth Mantle; on the other hand the radioactive elements are supposed do not be present in the Core, due to affinity problems with the Ni-Fe alloy, which constitutes the region around the Earth centre.

![Figure 7](image-url)

**Figure 7.** The experimental measurements of the νₑ survival after Borexino.

The radioactive decays produce also heat: the ²³⁸U family emits in total 6 antineutrinos and 51.7 MeV caloric energy; the ²³²Th family, 4 antineutrinos and 42.8 MeV; and finally the ⁴⁰K, 1 antineutrino and 1.32 MeV. Then the question arises: how much of the terrestrial heat is due to the radioactive decays? The only way to answer to this question is to measure the flux of antineutrinos from the Earth.

An estimation of the total Earth heat, evaluated via geo-thermal gradient calculations, brings to 40-47 TW, but also a global power of ~30 TW is not excluded. The canonical geological model, the *Bulk Silicate Earth* (BSE) gives a prevision of ~19 TW, based upon chondritic meteorite and volcanic rock analysis. The distribution of the caloric energy in the mantle produces convective turbulences, which are connected with the tectonic plate movements and the volcanic activities.

The geo-neutrinos have been detected and can be detected by only two experiments: Borexino and KamLAND. The antineutrino interactions in the scintillator are very well tagged via the inverse β decay with a prompt signal (e⁺) and a delayed signal (n thermalization and capture). Then, despite their low energy (up to ~ 2.8 MeV), the geo-antineutrinos can be detected also if the internal radioactivity level of the detector is not very small, as it is the case of KamLAND.
The main backgrounds in the geo-neutrinos study are due to the reactor antineutrinos and the internal radioactivity. The Gran Sasso site is favored having a reactor antineutrino flux ~1/7 with respect to Kamioka one.

Borexino data are collected in 537.2 live days [11]. The reactor antineutrino flux has been calculated using the IAEA and EDF data bases, taking into account all reactors in the world. The expected flux in Borexino and in the fiducial exposure is 9.4±0.6 events; the internal background due to possible fake events produced by (α, n) reactions, accidental coincidences, radioactive cosmogenic nuclides, is 0.42±0.56.

KamLAND statistics corresponds to 2135 live days [12]. The reactor flux, following the Japan electric power companies, produces in the detector, during the exposure, 284.7±26.5 events. The fake events due to the internal background are 484.7±26.5.

The best fits on the experimental data give for the geo-neutrino fluxes: 9.9$^{+3.4}_{-1.3}$ events for Borexino and 111$^{+45}_{-33}$ in the KamLAND case. The null hypothesis is disfavored with 4.2σ C.L. in both cases. The uncertainties of these results do not allow a firm conclusion; nevertheless, analyzing together the KamLAND and Borexino data, the BSE prevision seems slightly favored. But more statistics in needed. Borexino has large room to improve its sensitivity with more statistics because the Signal/Noise is 3/1 in the geoneutrino window.

6. Conclusions.
1. $^7$Be and $^8$B flux measurements are now very robust.
2. The first measurement of the pep flux, a first stringent limit on CNO and strong constraints on pp flux are now achieved.
3. The MSW-LMA model is now validated also in the vacuum oscillation region; on the other hand the experimental measurements corresponding to the transition region need more statistics, especially if we want to check possible contributions from the hypothetical Non Standard neutrino Interactions. The LMA solution now can be isolated using the solar data only.
4. Good determination of the ratio Vacuum/Matter survival probabilities has been achieved.
5. The experimental results obtained until now are not yet useful in solving the SSM metallicity puzzle.
6. The evidence of geo-neutrinos is very robust. More statistics is needed to clearly evaluate the radiogenic contribution to the terrestrial calorific energy.
7. Borexino is doing on these months a new purification campaign, which until now is very promising. The goal is a precise measurement of the pep flux and a direct determination of the CNO flux. A measurements of the CNO flux is very important mainly for two reasons: 1) the CNO cycle is considered dominant in the massive stars but its experimental direct evidence has not been reached yet; 2) the CNO flux shows the highest difference between high and low metallicity in the Standard Solar Model.

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