Solar and Atmospheric Neutrino Oscillations

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Abstract

I review the status of neutrino masses and mixings in the light of the solar and atmospheric neutrino data in the framework of two-, three- and four-neutrino mixing.

1. Indications for neutrino mass: two-neutrino analysis

I first review the present experimental status for solar and atmospheric neutrinos and the results of the different analysis in the framework of two-neutrino oscillations.

1.1. Solar neutrinos

The sun is a source of νe’s which are produced in the different nuclear reactions taking place in its interior. Along this talk I will use the νe fluxes from Bahcall–Pinsonneault calculations [1] which I refer to as the solar standard model (SSM). These neutrinos have been detected at the Earth by seven experiments which use different detection techniques [2,3]: The chlorine experiment at Homestake, the water cerenkov experiments Kamiokande and Super-Kamiokande (SK) and the radiochemical Gallex, GNO and Sage experiments. Due to the different energy threshold for the detection reactions, these experiments are sensitive to different parts of the solar neutrino spectrum. They all observe a deficit between 30 and 60% which seems to be energy dependent mainly due to the lower Chlorine rate.

To the measurements of these six experiments we have to add also the new results from SNO. They are however still not in the form of definite measured rates which could be included in this analysis.

SK has also presented their results after 1117 days of data taking on [3]:

The recoil electron energy spectrum: SK has measured the dependence of the even rates on the recoil electron energy spectrum divided in 18 bins starting at 5.5 MeV.

They have also reported the results of a lower energy bin 5 MeV < E_e < 5.5 MeV, but its systematic errors are still under study and it is not included in their nor our analysis. The spectrum shows no clear distortion with \( \chi^2_{\text{dat}} = 13/(17 \text{ dof}) \).

The Zenith Angle Distribution (Day/Night Effect) which measures the effect of the Earth Matter in the neutrino propagation. SK finds few more events at night than during the day but the corresponding Day-Night asymmetry \( A_{D/N} = -0.034 \pm 0.022 \pm 0.013 \) is only 1.3σ away from zero.

In order to combine both the Day-Night information and the spectral data SK has also presented separately the measured recoil energy spectrum during the day and during the night. This will be referred in the following as the day–night spectra data which contains 2 × 18 data bins.

The most generic and popular explanation of the solar neutrino anomaly is in terms of neutrino masses and mixing leading to oscillations of νe into an active (νμ and/or ντ) or sterile neutrino, νs. In Fig. 1 I show the allowed two–neutrino oscillation regions obtained in our updated global analysis of the solar neutrino data [4]. We show the possible solutions in the full parameter space for oscillations including both MSW and vacuum, as well as quasi-vacuum oscillations (QVO) and matter effects for mixing angles in the second octant (the so called dark side).

These results have been obtained using the general expression for the survival probability found by numerically solving the evolution equation in the Sun and the Earth matter valid in the full oscillation plane.

\[ P_{\nu_e \rightarrow \nu_x} = \sum_{l=1}^{3} \Delta_{ll}^2 \sin^2 2 \theta_{ll} \cos 2 \Delta m^2_{ll} L/4E \]

\[ \Delta m^2_{ll} = (m_{l+1}^2 - m_l^2) / 2E \]

\[ \sin^2 2 \theta_{ll} = (1 - \cos^2 2 \theta_{lm}) (1 - \cos^2 2 \theta_{lk}) \]

\[ L = \text{distance to the Sun} \]

\[ E = \text{energy of the neutrino} \]

\[ m_l = \text{rest mass of the neutrino} \]

\[ m_{l+1} = \text{rest mass of the next heavier neutrino} \]

\[ \Delta m^2_{ll} = (m_{l+1}^2 - m_l^2) / 2E \]

\[ \sin^2 2 \theta_{ll} = (1 - \cos^2 2 \theta_{lm}) (1 - \cos^2 2 \theta_{lk}) \]

Fig. 1. Presently allowed solar neutrino parameters for two-neutrino oscillations by the global analysis from Ref. [4]. The plotted regions are 90, 95 and 99% CL.
In the case of active–active neutrino oscillations we find three allowed regions for the global fit: the SMA solution, the LMA and LOW-QVO solution. For sterile neutrinos only the SMA solution is allowed. For oscillations into an sterile neutrino there are differences partly due to the fact that now the survival probability depends both on the electron and neutron density in the Sun but mainly due to the lack of neutral current contribution to the water cerenkov experiments. In Table I, I give the values of the parameters in these minima as well as the GOF corresponding to each solution.

There are some points concerning these results that I would like to stress:

(a) Despite giving a worse fit to the observed total rates, once the day–night spectra data is included the LMA gives the best fit. This is mainly driven by the flatness of the spectrum and it was already the case with the last year data.

(b) The GOF of the LOW solution has increased considerably as it describes the spectrum data very well despite it gives a very bad fit to the global rates. Notice also that LOW and QVO regions are connected at the 99% CL and they extend into the second octant so maximal mixing is allowed at 99% CL for $\Delta m^2$ in the LOW-QVO region.

(c) As for the SMA the result from the correct statistically combined analysis shown in Fig. 1 and in Table I indicates that the SMA can describe the full data set with a probability of 34% but it is now shifted to smaller mixing angles to account for the flatter spectrum.

(d) Similar statement holds for the SMA solution for sterile neutrinos.

Thus the conclusion is that from the statistical point of view all solutions are acceptable since they all provide a reasonable GOF to the full data set. LMA and LOW-QVO solutions for oscillations into active neutrino seem slightly favoured over SMA solutions for oscillations into active or sterile neutrinos but these last two are not ruled out.

### 1.2. Atmospheric neutrinos

Atmospheric showers are initiated when primary cosmic rays hit the Earth’s atmosphere. Secondary mesons produced in this collision, mostly pions and kaons, decay and give rise to electron and muon neutrino and anti-neutrinos fluxes. Atmospheric neutrinos can be detected in underground detectors by direct observation of their charged current interaction inside the detector. These are the so called contained events. SK has divided their contained data sample into sub-GeV events with visible energy below 1.2 GeV and multi-GeV above such cutoff. On average, sub-GeV events arise from neutrinos of several hundreds of MeV while multi-GeV events are originated by neutrinos with energies of the order of several GeV. Higher energy muon neutrinos and antineutrinos can also be detected indirectly by observing the muons produced in their charged current interactions in the vicinity of the detector. These are the so called upgoing muons. Should the muon stop inside the detector, it will be classified as a “stopping” muon, (which arises from neutrinos of energies around ten GeV) while if the muon track crosses the full detector the event is classified as a “through-going” muon which is originated by neutrinos with energies of the order of hundred GeV.

At present the atmospheric neutrino anomaly (ANA) can be summarized in three observations:

- There has been a long-standing deficit of about 60% between the predicted and observed $v_e/v_\mu$ ratio of the contained events [5] now strengthened by the high statistics sample collected at the SK experiment [3].
- The most important feature of the atmospheric neutrino data at SK is that it exhibits a zenith-angle-dependent deficit of muon neutrinos which indicates that the deficit is larger for muon neutrinos coming from below the horizon which have traveled longer distances before reaching the detector.
- The deficit for throughgoing muons is smaller that for stopping muons, i.e. the deficit decreases as the neutrino energy grows.

The most likely solution of the ANA involves neutrino oscillations. In principle we can invoke various neutrino oscillation channels, involving the conversion of $v_\mu$ into either $v_e$ or $v_\tau$ (active-active transitions) or the oscillation of $v_\mu$ into a sterile neutrino $v_s$ (active-sterile transitions) [6]. Oscillations into electron neutrinos are nowadays ruled out since they cannot describe the measured angular dependence of muon-like contained events [6]. Moreover the most favoured range of masses and mixings for this channel have been excluded by the negative results from the CHOOZ reactor experiment [7].

In Fig. 2 I show the allowed neutrino oscillation parameters obtained in our global fit [6] of the full data set of atmospheric neutrino data on vertex contained events at IMB, NUSEX, Frejus, Soudan, Kamiokande [5] and SK experiments [3] as well as upward going muon data from...
where $R_{ij}$ is a rotation matrix in the plane $ij$. With this the parameter set relevant for the joint study of solar and atmospheric conversions becomes five-dimensional:

$$\Delta m^2_\odot \equiv \Delta m^2_{12}, \qquad \Delta m^2_{\text{atm}} \equiv \Delta m^2_{23}, \qquad \theta^\odot_{12} = \theta_{12}, \quad \theta^\odot_{\text{atm}} = \theta_{\text{atm}}, \quad \theta^\odot_{\text{reac}} = \theta_{13},$$

where all mixing angles are assumed to lie in the full range from $0, \pi/2$.

In general the transition probabilities will present an oscillatory behaviour with two oscillation lengths. However from the required hierarchy in the splittings $\Delta m^2_{\text{atm}} \gg \Delta m^2_\odot$ indicated by the solutions to the solar and atmospheric neutrino anomalies it follows that:

- For solar neutrinos the oscillations with the atmospheric oscillation length are averaged out and the survival probability takes the form:

$$p_{\nu_e, MSW}^{\nu_e} = \sin^4 \theta_{13} + \cos^4 \theta_{13} p_{\nu_e, MSW}^{\nu_e}$$

where $p_{\nu_e, MSW}^{\nu_e}$ is obtained with the modified sun density $N_e \rightarrow \cos^2 \theta_{13} N_e$. So the analyses of solar data constrain three of the five independent oscillation parameters: $\Delta m^2_{12}, \theta_{12}$ and $\theta_{13}$.

- Conversely for atmospheric neutrinos, the solar wavelength is too long and the corresponding oscillating phase is negligible. As a consequence the atmospheric data analysis restricts $\Delta m^2_{23}, \theta_{23}$ and $\theta_{13}$, the latter being the only parameter common to both solar and atmospheric neutrino oscillations and which may potentially allow for some mutual influence.

Therefore solar and atmospheric neutrino oscillations decouple in the limit $\theta_{13} = 0$. In this case the values of allowed parameters can be obtained directly from the results of the analysis in terms of two-neutrino oscillations presented in the first section. Deviations from the two-neutrino scenario are then determined by the size of the mixing $\theta_{13}$. This angle is constrained by the CHOOZ reactor experiment which imposes an strong lower limit on the probability

$$p_{\nu_e, CHOOZ} = 1 - \sin^2 (2\theta_{13}) \sin^2 \left( \frac{\Delta m^2_{23} L}{4E_r} \right)$$

> 0.91 at 90% CL for $\Delta m^2_{23} > 10^{-3}$ eV$^2$.

The first question to answer is how the presence of this new angle affects the analysis of the solar and atmospheric neutrino data [8]. In Fig. 3 I show the allowed regions for the oscillation parameters $\Delta m^2_{23}$ and $\tan^2 \theta_{13}$ from our global analysis of the solar neutrino data in the framework of three-neutrino oscillations for different values of the angle $\theta_{13}$. The allowed regions for a given CL are defined as the set of points satisfying the condition

$$\chi^2(\Delta m^2_{23}, \tan^2 \theta_{12}, \tan^2 \theta_{13}) \leq \chi^2_{\text{min}} = \Delta \chi^2(\text{CL, 3 dof})$$

where, for instance, $\Delta \chi^2(\text{CL, 3 dof}) = 6.25, 7.83$, and 11.36 for CL = 90, 95, and 99% respectively. The global minimum used in the construction of the regions lays in the LMA region and corresponds to $\tan^2 \theta_{13} = 0$, this is, for the “decoupled” scenario. Notice that the only difference between the first panel in Fig. 3 and the active oscillations solution in Fig. 3 is due to the different numbers of dof used in the definition of the regions. The behaviour of the regions illustrate the “tension” between the data on the total event

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2. Three-neutrino oscillations

In the previous section I have discussed the evidences for neutrino masses and mixings as usually formulated in the two-neutrino oscillation scenario. Let us now fit all the different evidences in a common three-neutrino framework and see what is our present knowledge of the neutrino mixing and masses. Here I present a brief summary of such analysis performed in Ref. [8] and I refer to that publication for further details and references.

The evolution equation for the three neutrino flavours can be written as:

$$-i\frac{d\nu}{dt} = \left[ U M_\nu \frac{1}{2E} U^\dagger + H_{\text{int}} \right] \nu,$$

(1)

where $M_\nu$ is the diagonal mass matrix for the three neutrinos and $U$ is the unitary matrix relating the flavour and the mass basis. $H_{\text{int}}$ is the Hamiltonian describing the neutrino interactions. In general $U$ contains 3 mixing angles and 1 or 3 CP violating phases depending on whether the neutrinos are Dirac or Majorana. I will neglect the CP violating phases as they are not accessible by the existing experiments. In this case the mixing matrix can be conveniently chosen in the form

$$U = R_{23}(\theta_{23}) \times R_{13}(\theta_{13}) \times R_{12}(\theta_{12}).$$

(2)
rates which favour smaller $\theta_{13}$ values and the day–night spectra which allow larger values. It can also be understood as the "tension" between the energy dependent and constant pieces of the electron survival probability in Eq. (4).

As seen in the figure the effect is small unless large values of $\theta_{13}$ are involved. From Fig. 3 we find that as $\tan^2 \theta_{13}$ increases all the allowed regions disappear, leading to an upper bound on $\tan^2 \theta_{13}$ for any value of $\Delta m^2_{31}$, independently of the values taken by the other parameters in the three–neutrino mixing matrix. The corresponding 90 and 99% CL bounds are tabulated in Table II.

As for the atmospheric neutrino data in Fig. 4 I show the $(\tan^2 \theta_{23}, \Delta m^2_{31})$ allowed regions, for different values of $\tan^2 \theta_{13}$ from the global analysis of the atmospheric neutrino data. The upper-left panel, $\tan^2 \theta_{13} = 0$, corresponds to pure $\nu_\mu \rightarrow \nu_e$ oscillations, and one can note the exact symmetry of the contour regions under the transformation $\theta_{23} \rightarrow \pi/4 - \theta_{23}$. This symmetry follows from the fact that in the pure $\nu_\mu \rightarrow \nu_e$ channel matter effects cancel out and the oscillation probability depends on $\theta_{23}$ only through the double–valued function $\sin^2(2\theta_{23})$. For non-vanishing values of $\theta_{13}$ this symmetry breaks due to the three-neutrino mixing structure even if matter effects are neglected. We see that the analysis of the full atmospheric neutrino data in the framework of three–neutrino oscillations clearly favours the $\nu_\mu \rightarrow \nu_e$ oscillation hypothesis. As a matter of fact the best fit corresponds to a small value of $\theta_{13} = 9^\circ$.

With our sign assignment we find that for non-zero values of $\theta_{13}$ the allowed regions become larger in the second octant of $\theta_{23}$. No region of parameter space is allowed (even at 99% CL) for $\tan^2 \theta_{13} > 0.6$. Larger values of $\tan^2 \theta_{13}$ would imply a too large contribution of $\nu_\mu \rightarrow \nu_\tau$ and would spoil the description of the angular distribution of contained events. The mass difference relevant for the atmospheric analysis is restricted to lay in the interval: $1.25 \times 10^{-3} < \Delta m^2_{31}/eV^2 < 8 \times 10^{-3}$ at 99% CL. Thus it is within the range of sensitivity of the CHOOZ experiment and as a consequence the angle $\theta_{13}$ is further constrained when we include in the analysis the results from this reactor experiment. This is illustrated in Table II where one sees that the limit on $\tan^2 \theta_{13}$ is strengthen when the CHOOZ data is combined with the atmospheric neutrino results.

One can finally perform a global analysis in the five dimensional parameter space combining the full set of solar, atmospheric and reactor data. As an illustration of such

| Data Set         | $\tan^2 \theta_{13}$ | min | limit 99% |
|------------------|-----------------------|-----|-----------|
| Solar            | 0.0                   | 3.5 (62') |
| Atmos            | 0.026                 | 0.57 (37') |
| Atm + CHOOZ      | 0.005                 | 0.08 (16') |
| Atm + Solar      | 0.015                 | 0.52 (36') |
| Atm + Solar + Chooz | 0.005 | 0.085 (16') |

Fig. 4. 90, 65 and 99% CL three-neutrino allowed regions in ($\tan^2 \theta_{13}$, $\Delta m^2_{31}$) for different $\tan^2 \theta_{13}$ values, for the combination of global analysis of atmospheric neutrino data from Ref. [8]. The best-fit point is denoted as a star.
analysis I present in Table II the resulting bounds on $\theta_{13}$. The final results from the joint solar, atmospheric, and reactor neutrino data analysis lead to the following allowed ranges of parameters at 99% CL.

$$1.1 \times 10^{-3} < \Delta m_{s2}^2 / eV^2 < 7.3 \times 10^{-3}$$

$$0.33 < \tan^2 \theta_{33} < 3.8$$

$$\tan^2 \theta_{13} < 0.085 \quad \text{(if solar LMA)}$$

$$\tan^2 \theta_{13} < 0.135 \quad \text{(if solar SMA)}$$

\[(6)\]

In conclusion we see that from our statistical analysis of the solar data it emerges that the status of the large mixing-type solutions has been further improved with respect to the previous SK data sample, due mainly to the substantially flatter recoil electron energy spectrum. In contrast, there has been no fundamental change, other than further improvement due to statistics, on the status of the atmospheric data. For the latter the oscillation picture clearly favours large mixing, while for the solar case the preference is still not overwhelming. Both solar and atmospheric data favour small values of the additional $\theta_{13}$ mixing and this behaviour is strengthened by the inclusion of the reactor limit.

3. Four-neutrino oscillations

Together with the results from the solar and atmospheric neutrino experiments we have one more evidence pointing out towards the existence of neutrino masses and mixing: the LSND results. These three evidences can be accommodated in a single neutrino oscillation framework only if there are at least three different scales of neutrino mass-squared differences which requires the existence of a light sterile neutrino. Here I present a brief update of the analysis performed in Ref. [9] of solar neutrino data in such framework of four-neutrino mixing and I refer to that publication for further as well as for the relevant references.

In four-neutrino schemes the rotation $U$ relating the flavor neutrino fields to the mass eigenstates fields is a $4 \times 4$ unitary mixing matrix, which contains, in general 6 mixing angles (I neglect here the CP phases). Existing bounds from negative searches for neutrino oscillations performed at collider as well as reactor experiments impose severe constrains on the possible mass hierarchies as well as mixing structures for the four-neutrino scenario. In particular they imply:

(a) Four-neutrino schemes with two pairs of close masses separated by a gap of about 1 eV which gives the mass-squared difference responsible for the oscillations observed in the LSND experiment, can accommodate better the results of all neutrino oscillation experiments.

(b) In the study of solar and atmospheric neutrino oscillations only four mixing angles are relevant and the $U$ matrix can be written as $U = R_{34} R_{24} R_{23} R_{12}$ We choose solar neutrino oscillations to be generated by the mass-square difference between $\nu_2$ and $\nu_1$. With this choice the survival of solar $\nu_e$’s mainly depends on the mixing angle $\theta_{12}$ and it is independent of $\theta_{34}$. The mixing $\theta_{23}$ and $\theta_{34}$ determine the relative amount of transitions into sterile $\nu_s$ or active $\nu_3$ and $\nu_\tau$ only through the combination $\cos \theta_{23} \cos \theta_{34} (c_{23}^2 s_{24}^2)$. We distinguish the following limiting cases:

- $c_{23}^2 s_{24}^2 = 0$ corresponding to the limit of pure two-generation $\nu_e \rightarrow \nu_s$ transitions.
- $s_{23}^2 c_{24}^2 = 1$ for which we have the limit of pure two-generation $\nu_e \rightarrow \nu_s$ transitions. If $c_{23}^2 s_{24}^2 \neq 1$, solar $\nu_e$’s can transform in the linear combination $\nu_\nu$ of active $\nu_\nu$ and $\nu_s$.

In the general case of simultaneous $\nu_e \rightarrow \nu_x$ and $\nu_\nu \rightarrow \nu_x$ oscillations the corresponding probabilities are given by

\[ P_{\nu_e \rightarrow \nu_x} = c_{23}^2 s_{24}^2 (1 - P_{\nu_e \rightarrow \nu_s}) \]  \[ (7) \]

\[ P_{\nu_\nu \rightarrow \nu_x} = (1 - c_{23}^2 s_{24}^2) (1 - P_{\nu_\nu \rightarrow \nu_s}) \]  \[ (8) \]

where $P_{\nu_e \rightarrow \nu_s}$ takes the standard two-neutrino oscillation for $\Delta m_{s21}^2$ and $\theta_{12}$ but computed for the modified matter potential $A = A_{CC} + c_{23}^2 s_{24}^2 A_{NC}$. Thus the analysis of the solar neutrino data in the four-neutrino mixing schemes is equivalent to the two-neutrino analysis but taking into account that the parameter space is now three-dimensional ($\Delta m_{s12}^2$, \[ tan^2 \theta_{12}, c_{23}^2 s_{24}^2 \]).

I first present the results of the allowed regions in the three-parameter space for the global combination of observables. In Fig. 5 I show the sections of the three-

Fig. 5. Results of the global analysis for the allowed regions in $\Delta m_{s12}^2$ and $sin^2 \theta_{12}$, for the four-neutrino oscillations. The different panels represent the allowed regions at 99% (darker) and 90% CL (lighter). The best-fit point in the three parameter space is plotted at a star.
Table III. Maximum allowed value of $c_{23}^2c_{24}^2$ for the different solutions to the solar neutrino problem.

| CL | SMA | LMA | LOW | QVO |
|----|-----|-----|-----|-----|
| 90 | 0.9 | 0.44 | 0.3 | forbidden |
| 95 | all | 0.53 | 0.44 | 0.28 |
| 99 | all | 0.72 | 0.77 | 0.88 |

dimensional allowed volume in the plane ($\Delta m^2_{12}, \tan^2(\theta_{12})$) for different values of $c_{23}^2c_{24}^2$. The global minimum used in the construction of the regions lies in the LMA region and for pure active oscillations value of $c_{23}^2c_{24}^2 = 0$. As seen in Fig. 5 the SMA region is always a valid solution for any value of $c_{23}^2c_{24}^2$. This is expected as in the two–neutrino oscillation picture this solution holds both for pure active–active and pure active–sterile oscillations. Notice, however, that the statistical analysis is different in the two–neutrino picture the pure active–active and active–sterile cases are analyzed separately, whereas in the four–neutrino picture they are taken into account simultaneously in a consistent scheme. We see that in this “unified” framework, since the GOF of the SMA solution for pure sterile oscillations is worse than for SMA pure active oscillations (as discussed in the first section), the corresponding allowed region is smaller as they are now defined with respect to a common minimum.

On the other hand, the LMA, LOW and QVO solutions disappear for increasing values of the mixing $c_{23}^2c_{24}^2$. I list in Table III the maximum allowed values of $c_{23}^2c_{24}^2$ for which each of the solutions is allowed at a given CL. We see that at 95% CL the LMA solution is allowed for maximal active-sterile mixing $c_{23}^2c_{24}^2 = 0.5$ while at 99% CL all solutions are possible for this maximal mixing case.

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