The discovery of neutrino mass establishes the need for physics beyond the Standard Model. I summarize the status of two- and three-neutrino oscillation parameters from current solar, atmospheric, reactor and accelerator data. Future neutrinoless double beta decay experiments will probe the nature of neutrinos, as well as the absolute scale of neutrino mass, also tested by tritium beta decay spectra and cosmological observations. Sterile neutrinos do not provide a good way to account for the LSND hint, which needs further confirmation. Finally I sketch the main theoretical ideas for generating neutrino mass.

1 Two–Neutrino Parameters

In conjunction with the most recent SNO data with enhanced neutral current sensitivity (salt phase) and the KamLAND reactor data, solar neutrino experiments have now established the oscillation phenomenon. This closes the solar neutrino problem and opens an era of opportunity for learning more about the Sun or about beyond–oscillations properties of neutrinos, such as magnetic moments and non-standard interactions. Although well-motivated by theory, such mechanisms can no longer account for the data and may only be present at a sub–leading level. Similarly, the solid oscillation interpretation of the atmospheric neutrino data leaves little room for beyond-oscillation non-standard physics.

Neutrino masses have finally been discovered. A complete analysis of recent solar, atmospheric, accelerator and reactor neutrino data has been given in Ref. This paper presents an updated determination of the neutrino oscillation parameters taking into account all data (see Ref. for details) including the new solar neutrino data from the SNO–salt phase. The resulting 90%, 95%, 99%, and 3σ 2 d.o.f. C.L. regions in sin^2 θ sol and Δm^2 sol allowed by all solar neutrino data before (lines) and after (shaded regions) the inclusion of the SNO–salt data are shown in Fig. Also shown in this figure is Δχ^2 as a function of sin^2 θ sol and Δm^2 sol, minimized with respect to the undisplayed parameter. One finds that especially the upper part of the

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See Refs. for extensive list of experimental solar and atmospheric neutrino references. For a discussion of other neutrino data analyses see Table 2 in and the reviews in.
LMA–MSW region and large mixing angles are strongly constrained by the new data, with $\sin^2 \theta_{\text{sol}} = 0.5$ excluded at more than 5σ. This rules out all bi–maximal models of neutrino mass [19].

The first 145.1 days of KamLAND data have important implications on the determination of the solar neutrino parameters, as discussed, for example, in Ref. 21, 22. Fig. 2 shows the projections of the allowed regions from all solar neutrino and KamLAND data at 90%, 95%, 99%, and 3σ C.L. for 2 d.o.f. onto the plane of $\sin^2 \theta_{\text{sol}}$ and $\Delta m^2_{\text{sol}}$ before (lines) and after (shaded regions) the inclusion of the SNO–salt data. Also shown is $\Delta \chi^2$ as a function of $\sin^2 \theta_{\text{sol}}$ and $\Delta m^2_{\text{sol}}$, minimized with respect to the undisplayed parameter. One sees that the SNO–salt results reject the previously allowed high-mass branch of $\Delta m^2_{\text{sol}}$ at about 3σ. Moreover, for the first time it is possible to obtain meaningful bounds on solar neutrino parameters at the 5σ level, showing that neutrino physics has just entered the precision age.

Turning to the atmospheric neutrino parameters, we show in Fig. 3 the projection of the allowed regions from the global fit of all atmospheric data (details in Ref. 20) 23, onto the plane of the atmospheric neutrino parameters. The regions displayed correspond to 90%, 95%, 99%, and 3σ C.L. for 2 d.o.f. implied by the atmospheric+solar+CHOOZ data, while for the shaded regions also the K2K and KamLAND data are added. Also shown is the $\Delta \chi^2$ as a function of $\sin^2 \theta_{\text{atm}}$ and $\Delta m^2_{\text{atm}}$, minimized with respect to undisplayed parameters. One sees that the first 29 events from K2K 23 included here already constrain the upper region of $\Delta m^2_{\text{atm}}$. This should be contrasted with the lowering of $\Delta m^2_{\text{atm}}$ indicated by a recent preliminary reanalysis of
Figure 2. Two-neutrino solar+KamLAND neutrino oscillation parameters, from Ref. 20.

Figure 3. Two-neutrino atmospheric neutrino oscillation parameters from Ref. 20.

the atmospheric data by the Super–Kamiokande collaboration presented at the Aachen EPS conference[24]. While the two analyses differ, the value for $\Delta m^2_{\text{ATM}}$ quoted in[24] is statistically compatible with the result shown above. For $\Delta m^2_{\text{ATM}} = 2 \times 10^{-3} \text{eV}^2$ and maximal mixing Ref. 20 obtains a $\Delta \chi^2 = 1.3.$
2 Three–Neutrino Parameters

We now summarize the results of a global analysis combining all current solar, atmospheric, reactor and accelerator data in order to obtain the allowed three-neutrino oscillation parameters\(^\text{20}\). The simplest three–neutrino lepton mixing matrix is parameterized as a product of three complex rotations

\[
K = \omega_{12} \omega_{13} \omega_{23}, \quad \omega_{ij} \text{ being a rotation in the } ij \text{ sector.}
\]

This involves three mixing angles and three CP-violating phases\(^\text{15}\), one of which is the analogue of the quark CP phase, whose effect in oscillations we neglect, while the two Majorana phases\(^\text{15}\) do not show up in oscillations but appear in lepton number violating processes\(^\text{25,26}\). This way one is left with just the three angles in the neutrino oscillation analysis:

- \(\theta_{12} \equiv \theta_{\text{sol}}\) which governs solar neutrino oscillations,
- \(\theta_{23} \equiv \theta_{\text{atm}}\) which characterizes atmospheric neutrino oscillations,
- and \(\theta_{13}\) which couples these two analyses.

Oscillations also involve the neutrino mass-squared differences

\[
\Delta m_{21}^2 \equiv m_2^2 - m_1^2, \quad \Delta m_{31}^2 \equiv m_3^2 - m_1^2.
\]

Because of the hierarchy \(\Delta m_{21}^2 \ll \Delta m_{31}^2\) it is a good approximation to set \(\Delta m_{21}^2 = 0\) in the analysis of atmospheric and K2K data, and to set \(\Delta m_{31}^2\) to infinity for the analysis of solar and KamLAND data. The global fit to the data then involves five oscillation parameters \(\sin^2 \theta_{12}, \sin^2 \theta_{23}, \sin^2 \theta_{13}, \Delta m_{21}^2, \Delta m_{31}^2\). The results of such three–neutrino analysis are summarized in Fig. 4 taken from Ref.\(^\text{20}\) showing the allowed regions and \(\chi^2\) projections for the above five oscillation parameters. The regions are at 90\%, 95\%, 99\%, and 3\(\sigma\) C.L. for 2 d.o.f. for various parameter combinations. Also shown is \(\Delta \chi^2\) as a function of the five oscillation parameters, minimized with respect to all undisplayed parameters. Finally, the best-fit values, 2\(\sigma\), 3\(\sigma\) and 5\(\sigma\) intervals (1 d.o.f.) for the three-flavour neutrino oscillation parameters derived from current solar, atmospheric, reactor (KamLAND and CHOOZ) and accelerator (K2K) experiments are given in Table 1 of Ref.\(^\text{20}\). It is remarkable that, for the first time, one can determine solar neutrino parameters at the 5\(\sigma\) level, showing that neutrino physics has now entered the precision phase.

3 Future agenda

So far all CP phases are neglected in all current neutrino oscillation analyses. This is justified because the CP violating effects are suppressed...
due to the stringent limits on $\theta_{13}$ following mainly from reactor data, shown in Fig. 4. On the left panel one can see the 90%, 95%, 99%, and 3$\sigma$ allowed ($\sin^2\theta_{13}, \Delta m^2_{\text{sol}}$) regions from CHOOZ data alone (lines) and CHOOZ+solar+KamLAND data (shaded regions). Moreover leptonic CP violating effects are suppressed by the small mass splitting indicated by the solar neutrino data analysis. Indeed, in the 3-neutrino limit, CP violation disappears as two neutrinos become degenerate \cite{28}. Current data determine the ratio $\alpha \equiv \Delta m^2_{\text{sol}}/\Delta m^2_{\text{atm}}$ as shown in the right panel of Fig. 4.

**Figure 4.** Three-neutrino oscillation parameters from Ref. \cite{20}.

**Figure 5.** $\sin^2\theta_{13}$ and $\alpha \equiv \Delta m^2_{\text{sol}}/\Delta m^2_{\text{atm}}$ from current neutrino data, from Ref. \cite{20}. 
Now that the neutrino oscillation phenomenon has been confirmed, one may try to go a step further and test for the phenomenon of leptonic CP violation, either induced by the Dirac phase (oscillations) or by the Majorana phases through L-and-CP violating processes. Let us start with oscillations. One sees that the value for $\alpha$ inferred from the global neutrino oscillation analysis and the reactor bound on $\sin^2 \theta_{13}$ both limit the prospects for probing CP violating effects at future neutrino oscillation experiments with superbeams or neutrino factories. It will be challenge to probe such small effects, and this will require a near–detector in order to reject against the presence of non–standard neutrino interactions.

On the other hand, now that neutrino masses have been established, it is natural to check whether neutrinos are Majorana particles, as expected from theory. Neutrinoless double beta decay provides the most sensitive probe into the nature of neutrinos, irrespective of its theoretical origin. There is indeed a new generation of proposed experiments aimed at detecting $\beta\beta_0$ with improved sensitivity.

Although potentially sensitive to the Majorana CP phases present in the lepton mixing matrix, current nuclear physics uncertainties still preclude a realistic way to test Majorana phases using this process, even if several isotopes are combined. As for other lepton number violating processes, these are strongly suppressed by the small masses of neutrinos and/or the V-A nature of the weak interaction. For example the L-violating neutrino oscillation probability involved in the “thought-experiment” proposed in Ref. is suppressed by $(m_\nu/E)^2$, while transition Majorana neutrino magnetic moments also vanish in the massless neutrino limit.

Let us now turn to another issue, namely, the number of light neutrinos. Are there more than three light neutrinos?

The LSND collaboration has claimed evidence for oscillations, which would strongly suggest the existence of a fourth (singlet) neutrino species at the electron-volt range, as could arise, say, due to some protecting global symmetry such as lepton number. However, a combined global four–neutrino study including also the solar, atmospheric and negative short–baseline oscillation searches, such as Karmen, Bugey and CDHS, strongly prefer the minimal three light–neutrino hypothesis. The data rule out the possibility of symmetric (2+2) schemes, because in this case sterile neutrinos take part in both solar and atmospheric oscillations. Though strongly disfavoured by short-baseline experiments, the presence of a light

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6Depending on the model, leptogenesis may involve both Dirac and Majorana phases.
sterile neutrino in a (3+1) scheme may still be allowed, since it can be chosen to decouple from solar and atmospheric oscillations. Data from cosmology, including CMB data from WMAP \cite{48,49,50,51} and the 2dFGRS large scale structure surveys \cite{52} lead to further restrictions, especially on large $\Delta m^2_{\text{SND}}$ values.

4 Neutrino Theory: Top-Down versus Bottom-Up

The theoretical setting involved in the description of current neutrino oscillation experiments was laid out long ago \cite{15}, including the two-component quantum description of massive Majorana neutrinos and the gauge theoretic characterization of the lepton mixing matrix. The other crucial ingredient was the formulation of neutrino oscillations in the presence of matter \cite{5,6}.

The origin of neutrino mass remains as much of a mystery today as it was back in the eighties. Much of the early theoretical effort was motivated in part by the idea of unification which introduced the seesaw mechanism \cite{13,14}. Although first formulated in the context of the $SO(10)$ group, it was soon realized that the seesaw idea can be applied to left-right symmetric theories \cite{16}, or the simplest effective Standard Model gauge framework \cite{15,17,18}. While the $SO(10)$ or $SU(2)_L \otimes SU(2)_R \otimes U(1)$ seesaw formulations have the virtue of relating the small neutrino mass to the dynamics of parity (gauged B-L) violation, the effective $SU(2) \otimes U(1)$ description is more general and applies to any theory, for example with ungauged B-L \cite{17,18}. It is also worth–noting that the general seesaw scheme implies a Higgs triplet contribution to neutrino masses, from an induced tadpole or an elementary scalar vacuum expectation value \cite{15,16,53}.

However, it is worth stressing that the seesaw is just one way of generating the fundamental dimension–five neutrino mass operator \cite{54}. Such may also arise from physics “just around the corner”. One example is provided by certain super-string-inspired models \cite{55}. Indeed in such “anti-seesaw” models neutrino masses vanish as the B-L scale goes to zero, rather than infinity.

An alternative origin for neutrino mass is provided by the idea of low energy supersymmetry \cite{50,57,58} in schemes that break R parity through a sneutrino vacuum expectation value \cite{59,60}. These lead effectively to bilinear R parity violation \cite{61}. The novelty here is that neutrino mixing angles can be tested at accelerator experiments \cite{62,63,64}. Hybrid alternatives involving triplet Higgs bosons and supersymmetry are possible \cite{65}.

In summary there is no “road–map” for the ultimate theory of neutrino
mass, a wide variety of pathways remains open. In this context one expects small residual effects associated to non-standard weak interaction properties of neutrinos. These may follow from the particular structure of the charged and neutral currents expected in theories where neutrino masses follow from the existence of isosinglet leptons 15 or from alternative low energy radiative mechanisms for neutrino mass generation 66 and their variants.

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