Neutrinos : summary of new results

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After a short presentation of the neutrino mass-mixing parameters, the core of the paper will be devoted to the recent experimental results from SNO, KamLAND and K2K. As a conclusion, I will discuss possible CP violation measurements with neutrinos.

1 Neutrino Oscillations Physics

Neutrino oscillations in vacuum would arise if neutrinos were massive and mixed [1] similar to what happen in the quark sector. If neutrinos have masses, the weak eigenstates, ν_α ($\alpha = e, \mu, \tau, ...$), produced in a weak interaction are, in general, linear combinations of the mass eigenstates ν_i ($i = 1, 2, 3, ...$).

In the simpler case of two-family mixing, one has:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}. \tag{1}$$

Starting from a flavor eigenstate $|\nu_\alpha\rangle$, the probability for detecting a state $\langle\nu_\beta|$ at a distance L is given by:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \frac{(p_1 - p_2)L}{2} \simeq \sin^2 2\theta \sin^2 \left(\kappa \frac{\Delta m_{12}^2 L}{E}\right). \tag{2}$$

In (2) κ is 1/4 in natural units ($\hbar = c = 1$) or 1.27 in practical units : energy in GeV, the distance in km and the mass difference squared in eV^2.

In the three-family scenario, the general relation between the flavor eigenstates ν_α and the mass eigenstates ν_i is given by the 3x3 mixing matrix $V = UA$, where the matrix A contains the Majorana phases

$$A = \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

that are not observable in oscillation experiments, and U is the PMNS matrix [1, 2], which is usually parameterized by [3]

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \tag{4}$$

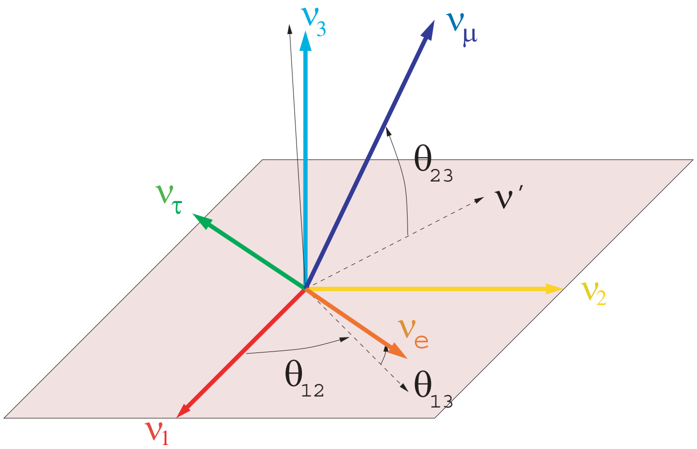

Figure 1: *Representation of the rotation between the flavor and mass neutrino eigenstates.*

where, for the sake of brevity, we write $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$. The relations between mass and flavor eigenstates can be visualized as rotations in a three-dimensional space, with the angles defined as in Fig. 1. With a derivation analogous to the two-family case, the oscillation probability for neutrinos reads

$$P(\nu_\alpha \to \nu_\beta) = \sum_{jk} J_{\alpha\beta jk} e^{-i\Delta m^2_{jk} L/2E} \quad (5)$$

where $J_{\alpha\beta jk} = U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}$.

For anti-neutrinos, the probability is obtained with the substitution $J_{\alpha\beta jk} \to J^*_{\alpha\beta jk}$. As $J_{\alpha\beta jk}$ is not real in general, due to the phase δ, neutrino and anti-neutrino oscillation probabilities are different, and therefore CP is violated in the neutrino mixing sector.

As an example, the full oscillation probability for the oscillation $\nu_\mu \to \nu_e$ is:

$$\begin{aligned} P(\nu_e \to \nu_\mu) = P(\overline{\nu}_\mu \to \overline{\nu}_e) &= \\ 4c^2_{13}[\sin^2\Delta_{23} s^2_{12} s^2_{13} s^2_{23} &+ c^2_{12}(\sin^2\Delta_{13} s^2_{13} s^2_{23} + \sin^2\Delta_{12} s^2_{12}(1 - (1 + s^2_{13}) s^2_{23}))] \\ &+ \frac{1}{4}|\tilde{J}|\cos\delta[\cos 2\Delta_{13} - \cos 2\Delta_{23} - 2\cos 2\theta_{12}\sin^2\Delta_{12}] \\ &- \frac{1}{4}|\tilde{J}|\sin\delta[\sin 2\Delta_{12} - \sin 2\Delta_{13} + \sin 2\Delta_{23}], \end{aligned} \quad (6)$$

where we have used the notation $\Delta_{jk} \equiv \Delta m^2_{jk} L/4E$ and the complex Jarlskog determinant $\tilde{J}$ [4]

$$\tilde{J} = c_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} e^{i\delta}.$$

Oscillations in a three-generation scenario are consequently described by six independent parameters: two mass differences (Δm^2_{12} and Δm^2_{23}), three Euler angles (θ_{12}, θ_{23} and θ_{13}) and one CP-violating phase δ. The present experimental knowledge on neutrino oscillation parameters indicates $\Delta m^2_{12} \equiv \Delta m^2_{sol} \ll \Delta m^2_{23} \equiv \Delta m^2_{atm}$ and small values for θ_{13} [5], so that ν_e or ν_μ disappearance experiments can be safely analyzed in the two families formalism.

This formalism has to be modified for neutrino propagation through matter. Because matter contains electrons and no μ or τ, the electron neutrino is singled out, having charged-current interactions with electrons in addition to the neutral-current interactions. This is the so-called MSW matter effect [6].

2 New results in solar neutrinos

Electron neutrino are produced in the sun through fusion reactions, leading to the production of ^4He, $4p \rightarrow^4 He + 2e^+ + 2\nu_e + 27MeV$. Expected solar neutrino fluxes are given on fig. 2 according to the Standard Solar Model (SSM) [7] for the various branches of the production mechanism.

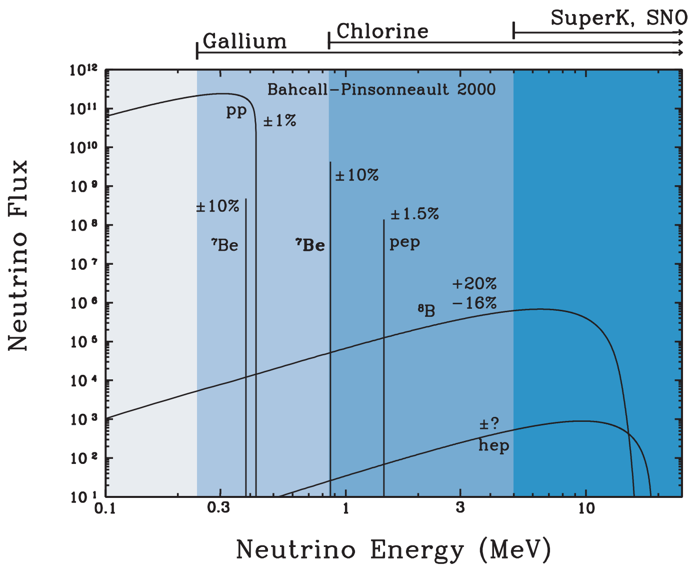

Figure 2: *Solar neutrino fluxes from the SSM.*

	Flux$\times 10^{-10}$ $(cm^{-2}s^{-1})$	Error
pp	5.96	$\pm$ 1%
pep	1.410^{-2}	$\pm$ 1.5%
hep	9.310^{-7}	$\pm$?%
^{7}Be	4.8210^{-1}	$\pm$ 10%
^{8}B	5.0510^{-4}	$^{+20}_{-16}$ %

Above 5 MeV, which is the threshold for water Cerenkov detectors, like SuperK or SNO, one expects $\approx 5 \times 10^6 cm^{-2}s^{-1}$ ν_e (mainly ^{8}B) from the sun.

The so-called solar neutrino problem (SNP) is summarized on fig. 3 where neutrino fluxes measured by the pre-SNO solar neutrino experiments are compared with the SSM predictions [8]. All experiments (radiochemical [9],[10],[11] for which the neutrino fluxes are expressed in Solar Neutrino Units ($1SNU \equiv 10^{-36}$ neutrino captures target atoms^{-1}s^{-1}), or water Cerenkov [12, 13], fluxes normalized to the SSM prediction) see a clear deficit of solar neutrinos.

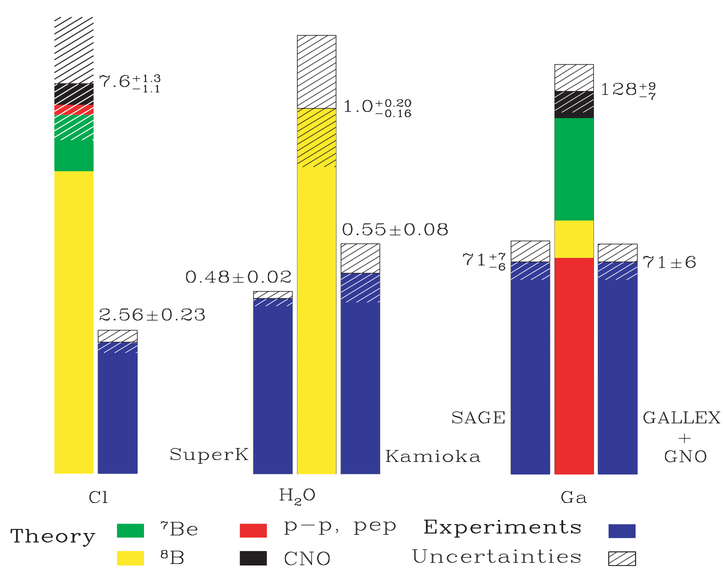

Figure 3: *The solar neutrino problem [8].*

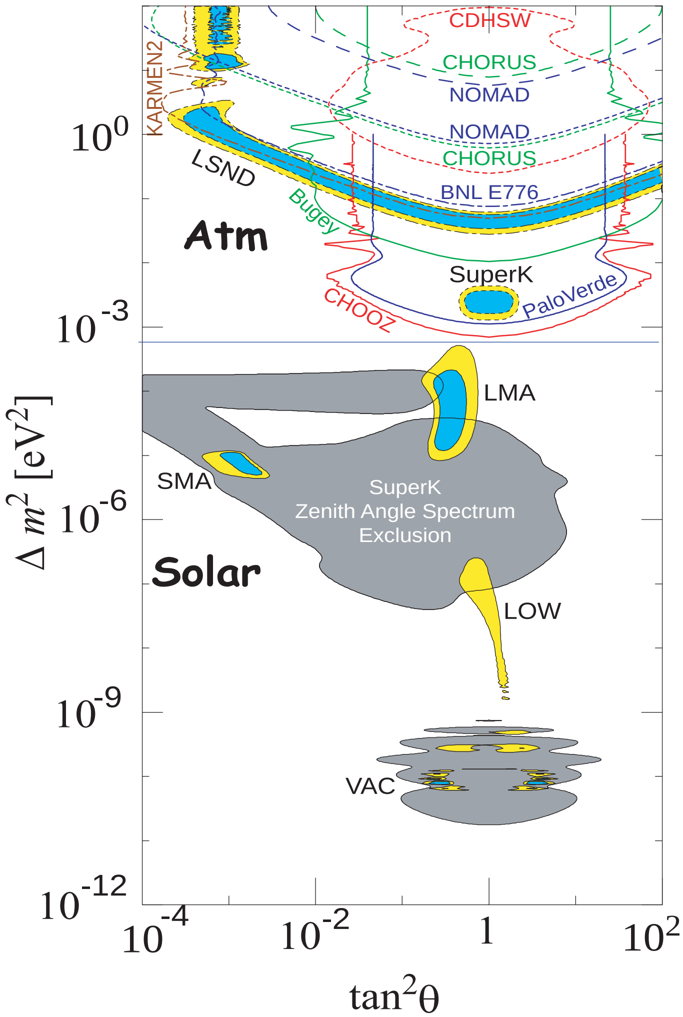

Figure 4: *Oscillation parameters allowed regions before SNO and KamLAND [14].*

Interpreting these results in terms of oscillation of ν_e to $\nu_\mu - \nu_\tau$ defines four regions in the plane $\Delta m^2 - \tan^2\theta$ (fig. 4, "solar" part.):

- three regions obtained by analyzing these data including matter effects [6] : small mixing angle (SMA), large mixing angle (LMA), and low (LOW) Δm^2;
- and one for pure oscillation in vacuum (VAC).

Note however that those pre-SNO experiments were almost only sensitive to ν_e.

Experiment	reaction	sensitivity
Homestake	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	ν_e
Gallex & Sage	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	ν_e
SuperK	$\nu_x + e- \rightarrow \nu_x + e-$	$\nu_e + 0.15\ (\nu_\mu + \nu_\tau)$

2.1 The SNO experiment

The SNO detector [15] was indeed designed to be equally sensitive to the three neutrino flavors and check if the solar neutrino deficit could be explained by ν_e transformation into ν_μ,ν_τ. SNO is a one kt D_2O Cerenkov detector located at Sudbury (Canada). Thanks to the presence of deuterium, this detector can measure

- the Neutral Current (NC) reaction $\nu_x + d \rightarrow \nu_x + p + n$, followed by a neutron capture $n + d \rightarrow t + \gamma(6.3MeV)$, this reaction has precisely the same cross-section for ν_e, ν_μ, ν_τ;
- the Charged Current (CC) reaction $\nu_e + d \rightarrow \nu_e + p + p$, in addition to
- the elastic scattering (ES) reaction $\nu_e + e^- \rightarrow \nu_e + e^-$, the "standard" process used by SuperK to detect solar neutrinos.

With 306 live days (11-1999 to 5-2001), SNO [15] has recorded $\approx$ 2800 neutrino events. Assuming that the neutrino spectrum shape follows the SSM prediction, the NC, CC and ES events can be separated (fig. 5). The SNO collaboration has measured $1967.7^{+61.9}_{-60.9}$ CC events, $263.6^{+26.4}_{-25.6}$ ES events, and $576.5^{+49.5}_{-48.9}$ NC events. Translated into fluxes, these events yield to

$$
\begin{aligned}
\Phi_{CC} &= (1.76 \pm 0.05 \pm 0.09) \times 10^6 cm^{-2} s^{-1} = \Phi_{\nu_e}, \\
\Phi_{ES} &= (2.39 \ ^{+0.24}_{-0.23} \pm 0.12) \times 10^6 cm^{-2} s^{-1} = \Phi_{\nu_e} + 0.15 \left(\Phi_{\nu_\mu} + \Phi_{\nu_\tau} \right), \\
\Phi_{NC} &= (5.09 \ ^{+0.44}_{-0.43} \ ^{+0.46}_{-0.43}) \times 10^6 cm^{-2} s^{-1} = \Phi_{\nu_e} + \Phi_{\nu_\mu} + \Phi_{\nu_\tau},
\end{aligned}
$$

from which it easy to extract the ν_e and ν_μ-ν_τ fluxes

$$
\begin{aligned}
\Phi_{\nu_e} &= (1.76 \pm 0.05 \pm 0.09) \times 10^6 cm^{-2} s^{-1}; \\
\Phi_{\nu_e - \nu_\tau} &= (3.41 \pm 0.45 \ ^{+0.48}_{-0.45}) \times 10^6 cm^{-2} s^{-1}.
\end{aligned}
$$

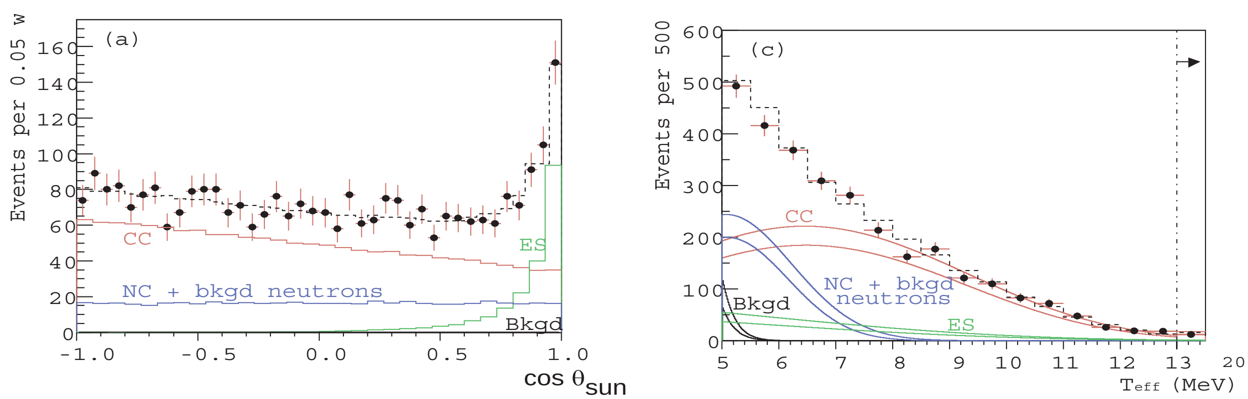

Figure 5: *Distribution of* $\cos\theta_{sun}$ *and electron kinetic energy, compared with NC, ES, CC Monte Carlo predictions assuming SSM neutrino spectrum shape.*

One can thus conclude that

- SNO is an appearance experiment, their data yield a $\nu_e - \nu_\tau$ flux 5.3 σ above zero;
- the total neutrino flux measured by SNO, $\Phi_{\nu_e} + \Phi_{\nu_\mu} + \Phi_{\nu_\tau} = (5.09 \ ^{+0.44}_{-0.43} \ ^{+0.46}_{-0.43}) \times 10^6 cm^{-2} s^{-1}$, is in good agreement with the SSM prediction, $\Phi^{8B}_{SSM} = (5.05 \ ^{+1.01}_{-0.81}) \times 10^6 cm^{-2} s^{-1}$.

The impact of these data on the neutrino parameters allowed region (fig. 4, "solar" part.) is simple, only the LMA solution remains at 95%CL :

$$
\left(2 \times 10^{-5} \leq \Delta m^2 (eV^2) \leq 2 \times 10^{-4} \right); \left(0.2 \leq \tan^2 \theta \leq 0.7 \right).
$$

The collaboration is now analyzing the data taken since may 2001 with two tons of salt added to the heavy water in order to raise the NC neutron capture efficiency : $n +^{35} Cl \rightarrow^{36} Cl + \Sigma\gamma(8.6 MeV)$. Preliminary results are expected during the summer. This fall, ^3He proportional counters will be deployed in the heavy water tank allowing the detection of the NC breakup of the deuteron on an event by event basis.

2.2 The KamLAND experiment

KamLAND [17] is a nuclear reactor anti-neutrino disappearance experiment designed to study the Solar Neutrino Problem with "man" made (anti-)neutrinos. Located in the former Kamiokande site in the Kamioka mine, it consists of one kt (again) of liquid scintillator contained in a 13 meters diameter balloon. Anti-neutrinos are detected via the coincidence of the prompt signal from the positron annihilation produced by the CC reaction $\overline{\nu}+p \rightarrow e^{+}+n$, and a delayed signal from the neutron capture on hydrogen $n+p \rightarrow d+\gamma(2.2MeV)$. The $\overline{\nu}_e$ flux seen by the KamLAND detector is dominated by a few reactors located at a mean distance of 180 km. 79% of the flux arises from 26 reactors within a distance range 138-214 km, opening the possibility to measure, for some sub-regions of the LMA parameters (typically $10^{-5} \leq \Delta m^2(eV^2) \leq 4\times10^{-5}$), an energy spectrum distorsion of the $\overline{\nu}_e$, in addition to a flux reduction.

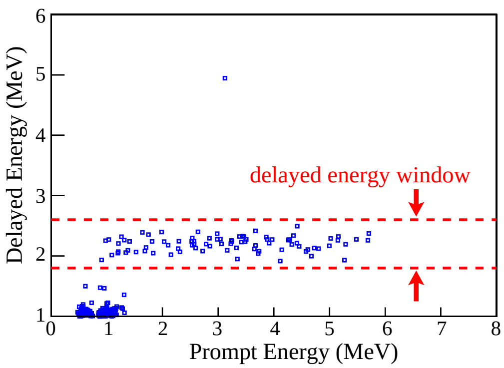

Figure 6: *Prompt and delayed energy distribution.*

The published data correspond to 7 months of data taking (03-2002 to 09-2000). Defining a window around the 2.2 MeV delayed signal (see fig. 6) and setting the prompt energy threshold at 2.6 MeV to get rid of the geo-neutrinos, result in $N_{obs} = 54$ observed $\overline{\nu}_e$ candidates. The background is estimated to be $N_{BG} = 0.95 \pm 0.99$ events, mainly originating from radioactive spallation products that are (β+delayed neutron) emitters, like ^8He and ^9Li. The corresponding reactor $\overline{\nu}_e$ events expected without oscillation is $N_{exp} = 86.8 \pm 5.6$.

There is thus a clear deficit of $\overline{\nu}_e$ events, $\frac{N_{obs}-N_{BG}}{N_{exp}} = 0.611 \pm 0.085 \pm 0.041$. The probability that this result be compatible with a no disappearance hypothesis is only 0.05% (4.1 σ).

The positron energy, $E_e = E_{prompt} - m_e$, obtained from the measured prompt signal, allows the estimation of the anti-neutrino energy via

$$E_{\overline{\nu}_e} = (E_e + \Delta)\left[1 + \frac{E_e}{M_p}\right] + \frac{\Delta^2 - m_e^2}{2M_p},$$

where Δ is the neutron-proton mass difference. The corresponding E_{prompt} spectrum is plotted on fig. 7. For comparison, the expected spectrum without oscillation, including contribution from the ^{238}U and ^{232}Th geo-neutrinos, is also given. This spectrum is consistent at the 93 % C.L with a distorted shape with oscillation parameters $\sin^2 2\theta = 1$ and $\Delta m^2 = 6.9\times10^{-5}eV^2$, but a renormalized no-oscillation shape also agrees with the data at 53 % CL.

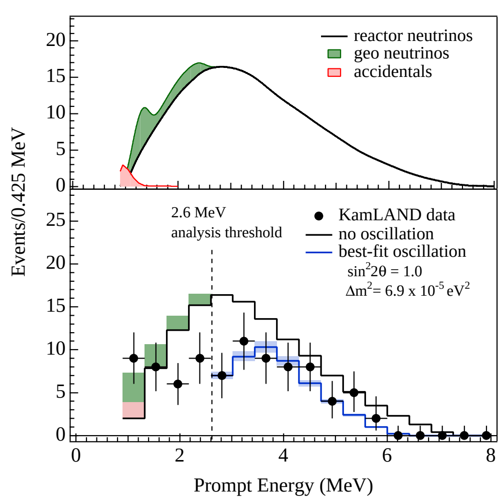

Figure 7: E_{prompt} *of the* $\overline{\nu}_e$ *events.*

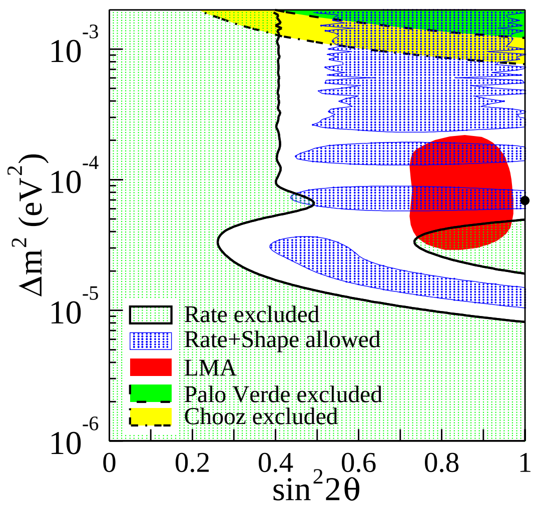

Figure 8: *Solar ν mass-mixing parameters after KamLAND first results.*

The KamLAND data define at 95 % CL two sub-regions in the LMA sector (fig. 8)

$$5.8 \times 10^{-5} \leq \Delta m^2(eV^2) \leq 9.1 \times 10^{-5} \ (I),$$

$$6.4 \times 10^{-4} \leq \Delta m^2(eV^2) \leq 2.0 \times 10^{-4} \ (II),$$

with a best fit point at $\Delta m^2 = 6.9 \times 10^{-5} eV^2$. KamLAND is currently accumulating more statistics. After 5 years of data taking they expect to constrain the LMA sub-regions within (at 95 % CL.)

$$6.4 \times 10^{-5} \leq \Delta m^2(eV^2) \leq 7.2 \times 10^{-5} \ (I)$$

$$1.3 \times 10^{-4} \leq \Delta m^2(eV^2) \leq 1.5 \times 10^{-4} \ (II)$$

2.3 Solar neutrino conclusions

SNO and Kamland have demonstrated that neutrino oscillation with LMA parameters is likely to be the solution to the solar neutrino problem. We are entering the precision era in the determination of the parameters governing the neutrino flavor evolution, and more data are expected from SNO (soon), KamLAND and SuperK-II. To conclude this section, let me quote what was writing G. Fogli [18] in a recent paper, published soon after the Nobel prize was awarded to Davis and Koshiba : *"The year 2002 is likely to be remembered as the annus mirabilis of solar neutrino physics."*

3 New results in atmospheric neutrinos

The allowed parameter region for $\nu_\mu \to \nu_x$ oscillation (fig. 4, "atmospheric" part.) is mainly constrained by the SuperK atmospherics neutrinos zenith distribution data [19], which have established in 1998 that neutrinos are massive [1]. The new results in this sector comes from the K2K experiment [22], a long (250 km) baseline (LBL) ν_μ disappearance experiment between KeK and SuperK [23]. Again, K2K was designed with the goal of testing the oscillation of atmospheric neutrinos with "human" made neutrinos. Taking the central value of the allowed SuperK parameter region, $\Delta m^2 = 2.6 \times 10^{-3} eV^2$, the disappearance would be maximum for 1 GeV ν_μ at a distance of 374 km, not so far from the actual KeK-SuperK distance. The K2K collaboration has put a lot of effort on the prediction of the neutrino spectrum that would be measured at SuperK without oscillation.

[1] Waiting that the Miniboone [21] experiment cross-checks the LSND results [20], I will forget the LSND claim of evidence of neutrino oscillation at high $\Delta m^2 \approx 0.2 - 10 eV^2$

A 1 kt (again !) water Cerenkov detector (KT), a "mini" SuperK, located 280 meters after the end of the decay tunnel, allows the measurement of the ν_μ flux before any significant oscillation has started. In SuperK the energy of the ν_μ is extracted for single ring μ-like events from the muon angle and momentum measurements assuming CC quasi-elastic (QE) scattering :

$$E^\nu_{rec} = \frac{M_N E_\nu - m^2_\mu/2}{M_N - (E_\nu - p_\mu \cos\theta_\mu)}.$$

The ratio between QE and non QE CC neutrino cross sections in H_2O has thus to be constrained as precisely as possible.

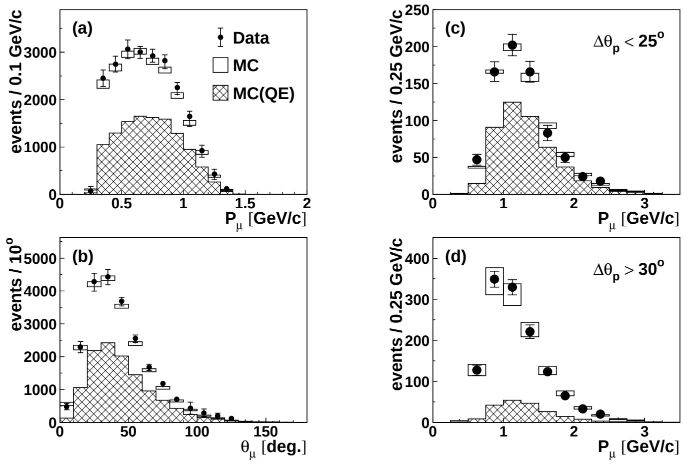

Figure 9: *muon momentum and angle distribution from ν_μ events as measured by the K2K front detectors: KT and FGD, compared to the MC prediction. The shaded area represents the MC predicted QE fraction.*

A 6 tons fine grained detector (FGD) consisting of scintillating fibers layers interleaving water target tanks and located just downstream the KT detector allows to measure the QE/nonQE ratio and to determine the neutrino energy spectrum for high energy events ($p_\mu \leq 1GeV$). The low energy part of the spectrum is measured by the KT detector (fig. 9). The expected neutrino energy spectrum at SuperK, without oscillation, $\left[\frac{dN}{dE^\nu_{rec}}\right]^{SK}$ is thus computed from the neutrino energy spectrum measured by the near detectors $\left[\frac{dN}{dE^\nu_{rec}}\right]^{ND}$ extrapolated to SuperK via a "Far-Near" transfer function $\frac{F}{N}$, determined from a full Monte Carlo simulation, including the QE/nonQE ratio measured by the FGD:

$$\left[\frac{dN}{dE^\nu_{rec}}\right]^{SK} = \frac{F}{N}\left[\frac{dN}{dE^\nu_{rec}}\right]^{ND}.$$

The published data were taken from June 1999 to July 2001, just before the SuperK accident and corresponds to ($5 \times 10^{19} POT$). $N_{obs} = 56$ ν_μ events have been measured in SK with an accidental background estimated to be $N_{BG} < 10^{-3}$ events. The expected ν_μ events without oscillation is $N_{exp} = 80.1\ ^{+6.2}_{-5.4}$. Again, there is a clear deficit of ν_μ events

$$\frac{N_{obs} - N_{BG}}{N_{exp}} = 0.70 \pm 0.09\ ^{+0.054}_{-0.047}.$$

The probability that this result be compatible with a no disappearance hypothesis is 1% (2.8 σ).

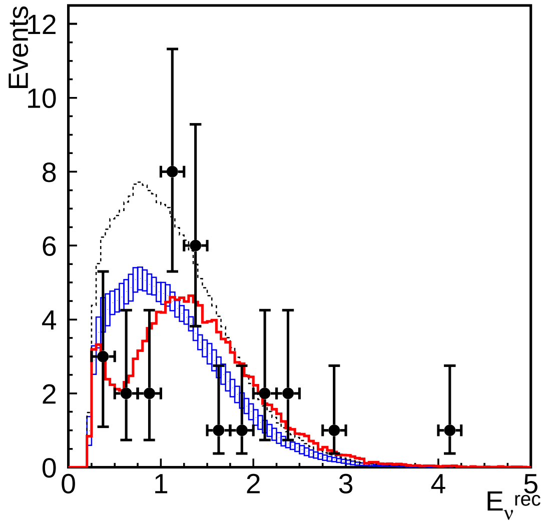

Figure 10: *Reconstructed neutrino energy for the 29 1-ring μ-like events measured by K2K; compared with a no-oscillation spectrum, Blue Box histogram (resp. dashed curve) normalized to the observed (resp. expected) number of events and the best fit oscillation analysis (red curve).*

The energy spectrum for the 29 single ring μ-like events of the 56 ν_μ events seen in SuperK is plotted on fig. 10. The data are compatible (KS test at 79% CL) with an oscillation hypothesis with

$$\left(\Delta m^2 = 2.8 \times 10^{-3} eV^2; \sin^2 2\theta = 1\right).$$

The impact of K2K on the neutrino mass-mixing parameters has been analyzed in a recent paper by Fogli [24]. At 90% CL, the mass bounds evolve from $\Delta m^2 = (2.6\,^{+1.2}_{-0.7}) \times 10^{-3} eV^2$, without K2K to $\Delta m^2 = (2.6\,^{+0.7}_{-0.7}) \times 10^{-3} eV^2$; whereas the bounds on $\sin^2 2\theta$ are entirely dominated by SuperK.
K2K is thus confirming the atmospheric neutrinos oscillation with man made neutrinos.
The experiment has resumed data taking early this year after the partial SuperK reconstruction and should reach the 3.5σ level in 2005 ($10 \times 10^{19} POT$).

The atmospheric precision era should start with the launching of the US LBL MINOS [25] experiment early 2005.

4 Opening the road toward a measurement of neutrino CP violation ?

After these exciting results, several neutrino properties are still to be determined :

1. What is the mass hierarchy ?
2. What is the mass of the lightest neutrino ?
3. Are neutrinos Majorana particles ? and in case of a positive answer, what are the values of the Majorana CP phases ?
4. What is the value of the Dirac CP phase δ ?

There are numerous projects to improve our knowledge on all these questions, but since this talk was given at a conference devoted to CP physics, I will, as a conclusion, focus on the experimental paths to determine the Dirac CP phase.

The golden experiment to measure the Dirac CP phase would be an asymmetry measurement between the appearance probability $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu}_\mu \to \overline{\nu}_e)$ or reciprocally between the appearance probability $P(\nu_e \to \nu_\mu)$ and $P(\overline{\nu}_e \to \overline{\nu}_\mu)$.

For example in the $\nu_\mu \to \nu_e$ case, at the atmospheric oscillation maximum ($\Delta_{23} = \pi/2$) this asymmetry reads (using Eq. 6 with $\theta_{23} = \pi/4$ and $\theta_{13} \ll 1$)

$$A_{CP} \approx \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \approx \sin\delta \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \sin\Delta_{12}.$$

This type of experiment could in principle be performed with a neutrino factory [26], a neutrino superbeam [27] or a neutrino beta beam [28]. But the number of events being proportional to $\sin^2 2\theta_{13}$ and $A_{CP} \propto 1/\sin\theta_{13}$, it is important first to better constrain the value of θ_{13}, for which only the CHOOZ [5] upper limit $\theta_{13} < 10^o$ is available. In practice, it is considered that such an experiment would be possible for $\theta_{13} > 0.5^o$.

The JHF-ν [29] collaboration is currently designing a third generation LBL experiment to improve this limit at the 2.3^o level after 5 years of running. The experiment will use the 50 GeV, 0.75 MW proton synchrotron JPARC (140$\times$ KeK PS) under construction in Japan on the JAERI site at Tokai. Like K2K, SuperK will be used as the far detector, and the experiment is expected to start data taking early 2008. A few years later[2], we will know if the road toward a measurement of neutrino CP violation is practicable or not...

Acknowledgments

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