News on Neutrino Oscillations and Neutrino Masses

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Abstract
Recent results on neutrino oscillations and neutrino masses are presented. The most exciting news are the Super-Kamiokande measurements of atmospheric neutrinos, which show evidence for the neutrinos being massive. Various possible schemes for the neutrino masses are discussed.

1 Introduction
This report has been given at the request of the organizers of the Delphi symposium. It summarizes the most exciting news on neutrino oscillations and neutrino masses, as they were presented at the Neutrino '98 Conference (ν'98) at Takayama (Japan) in June 1998, at the Ringberg Euroconference (New Trends in Neutrino Physics) in May 1998, and in various recent publications.

One of the fundamental questions in particle physics is as to whether neutrinos have a mass ($m_\nu > 0$, massive neutrinos) or are exactly massless (like the photon). For the following reason this question is directly related to the more general problem whether there is new physics beyond the Standard Model (SM): In the minimal SM neutrinos have a fixed helicity, always $H(\nu) = -1$ and $H(\bar{\nu}) = +1$. This implies $m_\nu = 0$, since only massless particles can be eigenstates of the helicity operator. $m_\nu > 0$ would therefore transcend the simple SM.

Direct kinematic measurements of neutrino masses have so far yielded only rather loose upper limits, the present best values being [1]:

\[
\begin{align*}
m(\nu_e) &< 15 \text{ eV} \quad \text{(from tritium $\beta$-decay)} \\
m(\nu_\mu) &< 170 \text{ keV (90\% CL)} \quad \text{(from $\pi^+$ decay)} \\
m(\nu_\tau) &< 18.2 \text{ MeV (95\% CL)} \quad \text{(from $\tau$ decays).}
\end{align*}
\]

\[1\]

*Invited talk at the XXVIII International Symposium on Multiparticle Dynamics, Delphi, Greece, September 1998; MPI Preprint MPI-PhE/98-15
Figure 1: Scheme of a neutrino oscillation experiment.

These limits will very likely not be improved considerably in the future. Access to much smaller mass values is provided by neutrino oscillations. They allow, however, to measure only differences of masses squared, $\delta m^2_{ij} \equiv m_i^2 - m_j^2$, rather than masses directly. For completeness we summarize briefly the most relevant formulae for neutrino oscillations in the vacuum, considering for simplicity only two neutrino flavours ($\nu_a, \nu_b$), e.g. ($\nu_e, \nu_\mu$) (two-flavour formalism). The generalisation to three or more flavours is straightforward in principle, but somewhat more involved in practice.

The two flavour eigenstates ($\nu_a, \nu_b$) are in general related to the two mass eigenstates ($\nu_1, \nu_2$) with masses ($m_1, m_2$) by a unitary transformation:

$$
\begin{pmatrix}
\nu_a \\
\nu_b
\end{pmatrix}
\rightarrow
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
$$

where $\theta$ is the mixing angle. If $m_1 \neq m_2$, the two eigenstates ($\nu_1, \nu_2$) evolve differently in time, so that for $\theta \neq 0$ a given original linear superposition of $\nu_1$ and $\nu_2$ changes with time into a different superposition. This means that flavour transitions (oscillations) $\nu_a \rightarrow \nu_b$ and $\nu_b \rightarrow \nu_a$ can occur with certain time-dependent oscillatory probabilities. In other words (Fig. 1): If a neutrino is produced (or detected) at A as a flavour eigenstate $\nu_a$ (e.g. $\nu_\mu$ from $\pi^+ \rightarrow \mu^+ + \nu_\mu$), it is detected, after travelling a distance (baseline) $L$, at B with a probability $P(\nu_a \rightarrow \nu_b)$ = $P(\nu_\mu \rightarrow \nu_e)$. The probability $P(\nu_a \rightarrow \nu_b)$ = $P(\bar{\nu}_a \rightarrow \bar{\nu}_b)$ = $P(\nu_b \rightarrow \nu_a)$ is given by

$$
P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \cdot \sin^2 \left( \frac{\delta m^2 \cdot L}{4 \cdot E} \right)
$$

for $\nu_a \neq \nu_b$

$P(\nu_a \rightarrow \nu_a) = 1 - P(\nu_a \rightarrow \nu_b)$ (survival of $\nu_a$)

where $\delta m^2 = m_2^2 - m_1^2$ and $E =$ neutrino energy. Thus the probability oscillates when varying $L/E$, with $\theta$ determining the amplitude ($\sin^2 2\theta$) and $\delta m^2$ the frequency of the oscillation. The smaller $\delta m^2$, the larger $L/E$ values are needed to see oscillations, i.e. significant deviations of $P(\nu_a \rightarrow \nu_b)$ from zero.
and of $P(\nu_a \rightarrow \nu_a)$ from unity. Notice the two necessary conditions for $\nu$ oscillations: (a) $m_1 \neq m_2$ implying that not all neutrinos are massless, and (b) non-conservation of the lepton-flavour numbers.

The masses $m(\nu_a)$ and $m(\nu_b)$ of the flavour eigenstates are expectation values of the mass operator, i.e. linear combinations of $m_1$ and $m_2$:

$$m(\nu_a) = \cos^2 \theta \cdot m_1 + \sin^2 \theta \cdot m_2$$
$$m(\nu_b) = \sin^2 \theta \cdot m_1 + \cos^2 \theta \cdot m_2$$

For a small mixing angle: $m(\nu_a) \approx m_1$, $m(\nu_b) \approx m_2$. For maximum mixing ($\theta = 45^\circ$): $m(\nu_a) = m(\nu_b) = (m_1 + m_2)/2$.

2 Atmospheric neutrinos

The most exciting new results presented at $\nu'98$ come from Super-Kamiokande on atmospheric neutrinos; they show convincing evidence for neutrino oscillations and thus for massive neutrinos.

Atmospheric neutrinos are created when a high-energy cosmic-ray proton (or nucleus) from outer space collides with a nucleus in the earth’s atmosphere, leading to an extensive air shower (EAS) by cascades of secondary interactions. Such a shower contains many $\pi^{\pm}$ (and $K^{\pm}$) mesons (part of) which decay according to

$$\pi^+, K^+ \rightarrow \mu^+ \nu_\mu, \quad \pi^-, K^- \rightarrow \mu^- \bar{\nu}_\mu,$$

yielding atmospheric neutrinos. From (4) one would expect in an underground neutrino detector a number ratio of

$$\frac{\mu}{e} = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} = 2,$$

if all $\mu^{\pm}$ decayed before reaching the detector. This is the case only at rather low shower energies whereas with increasing energy more and more $\mu^{\pm}$ survive due to relativistic time dilation (atmospheric $\mu$). Consequently the expected $\mu/e$ ratio rises above 2 (fewer and fewer $\nu_\mu$, $\bar{\nu}_\mu$) with increasing $\nu$ energy. For quantitative predictions Monte Carlo (MC) simulations, which include also other (small) $\nu$ sources, have been performed modelling the air showers in detail and yielding the fluxes of the various neutrino species ($\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$) as a function of the $\nu$ energy (5). The various calculations agree on the absolute $\nu$ fluxes only within $\sim 30\%$ whereas the agreement on the flux ratio $\mu/e$ is much better, namely within $\sim 5\%$.

Atmospheric neutrinos reaching the underground Super-Kamiokande detector can be registered by neutrino reactions inside the detector, the simplest and most frequent reactions being CC quasi-elastic scatterings:

(a) $\nu_e n \rightarrow p e^- \quad (b) \nu_\mu n \rightarrow p \mu^- \bar{\nu}_\mu p \rightarrow n \mu^+$. 

3
Super-Kamiokande (Fig. 2) is a big water-Cherenkov detector in the Kamioka Mine (Japan) at a depth of $\sim 1000$ m. It consists of 50 ktoms ($50 000 \text{ m}^3$) of ultrapurified water in a cylindrical tank (diameter = 39 m, height = 41 m). The inner detector volume of 32 ktoms is watched by 11 146 photomultiplier tubes (PMTs, diameter = 20$''$) mounted on the volume’s surface and providing a 40% surface coverage. The outer detector, which vetos entering particles and tags exiting particles, is a 2.5 m thick water layer surrounding the inner volume and looked at by 1885 smaller PMTs (diameter = 8$''$). A high-velocity charged particle passing through the water produces a cone of Cherenkov light which is registered by the PMTs. The Cherenkov image of a particle starting and ending inside the inner detector is a ring, the image of a particle starting inside and leaving the inner detector is a disk. A distinction between an $e^{\pm}$-like event (7a) and a $\mu^{\pm}$-like event (7b) is possible (with an efficiency of $\geq 98\%$) from the appearance of the image: an $e^{\pm}$ has an image with a diffuse, fuzzy boundary whereas the boundary of a $\mu^{\pm}$ image is sharp. The observed numbers of $\mu$-like and $e$-like events give directly the observed ratio $(\mu/e)_{\text{obs}}$ which is to be compared with the MC-predicted ratio $(\mu/e)_{\text{MC}}$ (for no $\nu$ oscillations) by
computing the double ratio

$$R = \frac{(\mu/e)_{\text{obs}}}{(\mu/e)_{\text{MC}}}.$$  \hfill (8)

Agreement between observation and expectation implies $R = 1$.

The events are separated into fully contained events (FC, no track leaving the inner volume) and partially contained events (PC, one or more tracks leaving the inner volume). For FC events the visible energy $E_{\text{vis}}$, which is obtained from the pulse heights in the PMTs, is close to the $\nu$ energy. With this in mind, the FC sample is subdivided into sub-GeV events ($E_{\text{vis}} < 1.33$ GeV) and multi-GeV events ($E_{\text{vis}} > 1.33$ GeV). In the multi-GeV range the $\nu$ direction is determined as the direction of the Cherenkov-light cone, since at higher energies the directions of the incoming $\nu$ and the outgoing charged lepton are close to each other.

The double ratio $R$ has been measured previously by Kamiokande, the smaller predecessor of Super-Kamiokande with 3.0 ktons of water, yielding $R = 0.60 \pm 0.06$ (stat.) $\pm 0.05$ (syst.) from 482 sub-GeV events and $R = 0.57 \pm 0.08$ (stat.) $\pm 0.07$ (syst.) from 233 multi-GeV events. \hfill (9)

The new Super-Kamiokande result, based on larger statistics, is $R = 0.63 \pm 0.03$ (stat.) $\pm 0.05$ (syst.) from 2389 FC sub-GeV events and $R = 0.65 \pm 0.05$ (stat.) $\pm 0.08$ (syst.) from 520 FC multi-GeV events and 301 PC events. \hfill (10)

In all cases $R$ is significantly smaller than unity (atmospheric $\nu$ anomaly) which is due, as it turns out (see below), to a deficit of $\nu_\mu, \bar{\nu}_\mu$ and not to an excess of $\nu_e, \bar{\nu}_e$ in $(\mu/e)_{\text{obs}}$. A natural explanation of this deficit is that some $\nu_\mu, \bar{\nu}_\mu$ have oscillated into $(\nu_e, \bar{\nu}_e)$ or $(\nu_\tau, \bar{\nu}_\tau)$ according to (3) before reaching the detector. However, the solution $\nu_\mu \to \nu_e$ of Kamiokande (not of Super-Kamiokande) is ruled out by the CHOOZ experiment (see below) so that probably only $\nu_\mu \to \nu_\tau$ remains.

This explanation has been evidenced by a study of the $\nu$ fluxes and of $R$ as a function of the zenith angle $\Theta$ between the vertical (zenith) and the $\nu$ direction. A $\nu$ with $\Theta \approx 0^\circ$ comes from above (down-going $\nu$) after travelling a distance of $L \approx 20$ km (effective thickness of the atmosphere); a $\nu$ with $\Theta \approx 180^\circ$ reaches the detector from below (up-going $\nu$) after traversing the whole earth with $L \approx 13000$ km.

Fig. 3 shows for multi-GeV events (for which the $\nu$ direction can be determined) the dependence of $R$ on cos $\Theta$ as measured by Kamiokande. Up-$\nu_\mu$ are seen to be missing ($R < 1$) whereas down-$\nu_\mu$ appear in the expected frequency ($R \approx 1$). In terms of $\nu$ oscillations this means that part of the up-$\nu_\mu$ have changed their flavour on their long way through the earth whereas for down-$\nu_\mu$ $L$ is so small that $P(\nu_\mu \to \nu_e, \nu_\tau)$, eq. (3), is practically zero. The $\nu_\mu$ deficit in
Figure 3: Dependence of the ratio $R$, eq. (8), on the zenith angle $\Theta$ for multi-GeV events from Kamiokande. The dotted histogram shows the MC prediction including $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with the parameters (11). The dashed histogram is for $\nu_\mu \leftrightarrow \nu_e$ oscillations.

Fig. 3 is the larger, the larger $\Theta$ and thereby $L$ is. A quantitative oscillation analysis yielded as the best-fit parameters:

$$\delta m^2 = 1.6 \times 10^{-2} \text{eV}^2, \quad \sin^2 2\theta = 1.0 \quad \text{for } \nu_\mu \leftrightarrow \nu_\tau. \quad (11)$$

The fit (dotted histogram in Fig. 3) describes the data points rather well.

Super-Kamiokande [6, 7] has measured the $\cos \Theta$ dependence not only of $R$, but also of the $\nu_e$ and $\nu_\mu$ fluxes separately: Fig. 4 shows the $\cos \Theta$ distributions (crosses) of (a) FC $e$-like and (b) FC $\mu$-like + PC events in the multi-GeV range. (The PC events turned out to be practically all $\nu_\mu$ events). The rectangles show the MC predictions for no oscillations. An up-down asymmetry is defined as

$$A = (U - D)/(U + D)$$

where $U(D)$ is the number of events with $-1 < \cos \Theta < -0.2$ ($0.2 < \cos \Theta < 1$). For no oscillations, $A \approx 0$ is expected for $E_\nu > 1$ GeV, independently of the MC model. From the data in Fig. 4 the following experimental values were obtained [6, 7]:

$$A_e = -0.036 \pm 0.070, \quad A_\mu = -0.296 \pm 0.049. \quad (12)$$

Whereas there is no asymmetry for $\nu_e$, $A_e$ being compatible with zero, a clear asymmetry with a 6$\sigma$ significance is observed for $\nu_\mu$. Moreover, whereas for $e$-like events the data agree reasonably well with the MC prediction, for $\mu$-like events a deficit is found at larger $\Theta$. No explanation other than $\nu$ oscillations could be found for this deficit. An oscillation analysis yielded a much better fit for $\nu_\mu \leftrightarrow \nu_\tau$ ($\chi^2/NDF = 65/67$) than for $\nu_\mu \leftrightarrow \nu_e$ ($\chi^2/NDF = 88/67$). The best-fit parameters are

$$\delta m^2 = 2.2 \times 10^{-3} \text{eV}^2, \quad \sin^2 2\theta = 1.0 \quad \text{for } \nu_\mu \leftrightarrow \nu_\tau, \quad (13)$$

to be compared with (11). Fig. 5 shows in the $(\sin^2 2\theta, \delta m^2)$ plane the allowed regions from Kamiokande (90% CL) and from Super-Kamiokande (68, 90, 99% CL). The Kamiokande and Super-Kamiokande 90% CL regions have only a small overlap around $\delta m^2 \approx 0.5 \times 10^{-2} \text{eV}^2$. With this $\delta m^2$ value, the distance $L_{osc}$...
Figure 4: Zenith-angle distribution of (a) FC $e$-like and (b) FC $\mu$-like + PC events in the multi-GeV range from Super-Kamiokande. The points show the data, the rectangles show the MC prediction for no oscillations [6].

Figure 5: Allowed regions in the $(\sin^2 2\theta, \delta m^2)$ plane for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations from Kamiokande (90% CL) and Super-Kamiokande (68%, 90%, 99% CL) [7].

for a full oscillation (oscillation length $L_{\text{osc}} = 4\pi \hbar c E/\delta m^2$) is $L_{\text{osc}} \approx 500$ km according to eq. (3) for $E = 1$ GeV.

In conclusion: Evidence has been found by Kamiokande and more significantly by Super-Kamiokande for $\nu$ oscillations $\nu_\mu \leftrightarrow \nu_\tau$ with $\delta m^2 \sim 0.5 \times 10^{-2}$ eV$^2$ and maximal mixing. For a hierarchical mass scenario $m_1 \ll m_2 \ll m_3$ this implies $m_3 \approx \sqrt{\delta m^2} \sim 0.07$ eV. More generally, this value can be regarded as a lower limit of $m_3$ ($m_3 = \sqrt{\delta m^2 + m_2^2} \geq \sqrt{\delta m^2}$).

For completeness we mention two experiments, Kamiokande [8] and MACRO [9], that have recently measured up-going ($\Theta > 90^\circ$) muons which pass through the detector from outside. Owing to their large zenith angle $\Theta$ they cannot be atmospheric muons – those would not range so far into the earth –, but are rather produced in CC reactions by energetic ($\langle E_\nu \rangle \sim 100$ GeV) up-going $\nu_\mu$, $\bar{\nu_\mu}$ in the rock surrounding the detector. In both experiments a deficit, although not very significant because of large errors, is observed in the flux of upward through-going muons as compared to the theoretical expectation:
Figure 6: Survival probability $P(\nu_e \rightarrow \nu_e)$ vs. $\nu$ energy $E_\nu$ for $\delta m^2 \approx 6 \cdot 10^{-6}$ eV$^2$, $\sin^2 2\theta \approx 0.007$ (small-angle solution). The dashed lines show (with arbitrary scale) the flux spectra of the pp, Be$^7$, pep and B$^8$ neutrinos.

$\mu_{\text{obs}}/\mu_{\text{MC}} = 0.79 \pm 0.18$ from Kamiokande and 0.74 $\pm$ 0.14 from MACRO; the errors are mainly due to the relatively large theoretical flux uncertainty. Using the zenith angular distribution of the upward through-going muons for an oscillation analysis, Kamiokande obtains the following best-fit parameters in the physical region (to be compared with the values (11) and (13)):

$$\delta m^2 = 3.2 \cdot 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta = 1.0 \quad \text{for } \nu_\mu \leftrightarrow \nu_\tau \,. \quad (14)$$

However, the 90% CL allowed region in the ($\sin^2 2\theta, \delta m^2$) plane (not shown) is much larger than the allowed Kamiokande region in Fig. 5, which shows that the through-going muon data are much less restrictive than the data with $\nu$ interactions taking place in the detector. Similarly, MACRO obtains an allowed region around the values

$$\delta m^2 = 2.5 \cdot 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta = 1.0 \quad \text{for } \nu_\mu \leftrightarrow \nu_\tau \,. \quad (15)$$

3 Solar neutrinos

Solar neutrinos come from the fusion reaction

$$4p \rightarrow \text{He}^4 + 2e^+ + 2\nu_e \quad (16)$$

inside the sun with a total energy release of 26.7 MeV after two $e^+e^-$ annihilations. The $\nu$ energy spectrum extends up to about 15 MeV with an average of $\langle E_\nu \rangle = 0.59$ MeV. The total $\nu$ flux from the sun is $\phi_\nu = 1.87 \cdot 10^{38}$ sec$^{-1}$.

Reaction (16) proceeds in various steps in the pp chain or CNO cycle, the
Table 1: The five solar $\nu$ experiments and their results (using a recent compilation\(^{(12)}\)). The SSM is BP95.

| Experiment | Reaction | Threshold [MeV] | Result (Result/SSM) |
|------------|----------|-----------------|----------------------|
| Homestake  | Cl\(^{37}\)(\(\nu_e, e^−\))Ar\(^{37}\) | $E_\nu > 0.814$ | $2.56 \pm 0.22 \text{ SNU}$ (0.28 ±0.04) |
| GALLEX     | Ga\(^{71}\)(\(\nu_e, e^−\))Ge\(^{71}\) | $E_\nu > 0.233$ | $78 \pm 8 \text{ SNU}$ (0.57 ± 0.05) |
| SAGE       | Ga\(^{71}\)(\(\nu_e, e^−\))Ge\(^{71}\) | $E_\nu > 0.233$ | $67 \pm 8 \text{ SNU}$ (0.49 ± 0.07) |
| Kamiokande | $\nu e \rightarrow \nu e$ | $E_\nu > 7.5$ | $(2.80 \pm 0.38) \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ (0.42 ± 0.09) |
| Super-Kam  | $\nu e \rightarrow \nu e$ | $E_\nu > 6.5$ | $(2.44^{+0.10}_{−0.09}) \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ (0.37 ± 0.07) |

1 SNU (Solar Neutrino Unit) = 1 $\nu_e$ capture per $10^{36}$ target nuclei per sec

most relevant $\nu_e$ sources being

\[
\begin{align*}
pp &: p + p \rightarrow D + e^+ + \nu_e \quad (E_\nu < 0.42 \text{ MeV}) \\
Be^7 &: Be^7 + e^- \rightarrow Li^7 + \nu_e \quad (E_\nu = 0.86 \text{ MeV}) \\
B^8 &: B^8 \rightarrow Be^8 + e^+ + \nu_e \quad (E_\nu < 14.6 \text{ MeV})
\end{align*}
\]

$\nu_e$ fluxes from the various sources and rates for the various detection reactions have been predicted in the framework of the Standard Solar Model (SSM)\(^{(10, 11)}\). With respect to these predictions a $\nu_e$ deficit from the sun has been observed by the various experiments as listed in Tab. 1 (see ratios Result/SSM). In particular, the Be\(^7\)-$\nu$ are apparently not registered by the chlorine and gallium experiments. These deficits, the well-known solar neutrino problem, could be explained by $\nu$ oscillations $\nu_e \rightarrow \nu_X$ into another flavour $X$ ($\nu_e$ disappearance) either inside the sun (matter oscillations, Mikheyev-Smirnov-Wolfenstein (MSW) effect\(^{(13)}\)) with the two possible solutions\(^{(14)}\)

\[
\begin{align*}
\delta m^2 &\approx 5.1 \cdot 10^{-6} \text{ eV}^2, \quad \sin^2 2\theta \approx 0.0082 \quad \text{(small-angle solution)} \\
\delta m^2 &\approx 1.6 \cdot 10^{-5} \text{ eV}^2, \quad \sin^2 2\theta \approx 0.63 \quad \text{(large-angle solution)},
\end{align*}
\]

or on their way from Sun to Earth (vacuum oscillations, $L \approx 1.5 \cdot 10^8$ km) with the solution\(^{(14)}\)

\[
0.5 \cdot 10^{-10} < \delta m^2 < 0.8 \cdot 10^{-10} \text{ eV}^2, \quad \sin^2 2\theta \gtrsim 0.65.
\]

As an example, Fig. 6 shows the survival probability $P(\nu_e \rightarrow \nu_e)$ for the small-angle solution\(^{(18)}\) as a function of the $\nu$ energy $E_\nu$, together with the $\nu$ spectra.
Figure 8: Time variation of the flux of $B^8$ neutrinos from Super-Kamiokande. The line shows the seasonal flux variation expected from the eccentricity of the earth’s orbit around the sun [18].

According to this plot the gallium experiments see essentially only the pp neutrinos whereas Homestake and Kamiokande/Super-Kamiokande see within their sensitive energy ranges only part of the $B^8$ neutrinos; the $Be^7$ neutrinos cannot be seen at all by the gallium and chlorine experiments since they have practically all changed to another flavour, $P(\nu_e \rightarrow \nu_e) \approx 0$.

After this very brief introduction we report some selected new results on solar $\nu$ from $\nu'98$. The GALLEX experiment [15] has been terminated. The final result from four running periods I to IV with a total of 65 runs is a $\nu_e$-capture rate of $(78 \pm 8)$ SNU [16] (Tab. 1). The successor of GALLEX is GNO (= Gallium Neutrino Observatory) [16, 17] in the Gran Sasso Underground Laboratory (Italy). GNO has started data taking in April 1998 with 30 tons of Ga. The experiment aims at $\sim 60$ tons of Ga by the year 2000 and at $\sim 100$ tons by 2002. It intends to monitor the solar $\nu$ flux over at least one solar cycle (11 years) achieving a total error of less than 5% ($\sim 4$ SNU) whereas the present GALLEX errors are 8% (stat.) and 6% (syst.).

Super-Kamiokande [18] with an energy threshold of 6.5 MeV has measured the $B^8$-$\nu$ flux from the sun via the reaction $\nu + e \rightarrow \nu + e$ with a rate of 13.5 solar $\nu$ events per day. For $E_e \gg 1$ MeV the reaction is strongly forward peaked, $E_e \theta_e^2 < 1$ MeV, where $E_e$ ($\theta_e$) is the total energy (scattering angle in rad) of the recoil electron. Fig. 8 shows the cos $\theta_{\text{sun}}$ distribution where $\theta_{\text{sun}}$ is the angle between the direction of the recoil electron and the direction to the sun. A strong forward peak which is due to solar $\nu$, is observed above a flat background (coming mainly from $\beta$ decays of spallation products induced by cosmic-ray muons). From the number of events in the peak ($\sim 6800$ at $\nu'98$) a total $B^8$-$\nu$ flux (after correcting for the full SSM $B^8$-$\nu$ spectrum) of

$$\phi^{\text{tot}}(B^8) = \left(2.44 \pm 0.05 \text{ stat. } \pm 0.09 \text{ syst.}\right) \cdot 10^6 \text{ cm}^{-2} \text{ sec}^{-1}$$

is obtained which amounts to $(36.8 \pm 6.5)$% of the SSM (Tab. 1). No seasonal dependence of the solar $\nu$ flux was observed (Fig. 8), apart from the expected 6.7% variation due to the eccentricity of the earth’s orbit around the sun ($\varepsilon = 0.0167$, curve in Fig. 8, $\chi^2/NDF = 10/8$). Likewise, no significant day-night effect was found, $(D - N)/(D + N) = -0.023 \pm 0.024$. Such a variation could come from a $\nu_e$ regeneration by the MSW effect in the earth [10, 19]. Finally, first results
were presented on the $E_e$ spectrum for which the absolute energy scale of Super-Kamiokande was calibrated using electrons of known energy between 5 and 16 MeV from a nearby electron linac \[20\]. A precise measurement of the energy spectrum is of great interest since a distortion of the spectral shape with respect to the SSM-predicted shape can be caused by $\nu$ oscillations via their energy dependence, see eq. (3). From a preliminary analysis vacuum oscillations \[21\] seem to be favoured over matter oscillations. However, more statistics is needed.

The next forthcoming new solar $\nu$ detectors are SNO (= Sudbury Neutrino Observatory, Canada) \[22\] and Borexino \[23\]. SNO (start 1999), a heavy-water Cherenkov detector (1 kton of $\text{D}_2\text{O}$), will measure the reactions

$$\begin{align*}
\nu_e + D &\rightarrow e^- + p + p \quad (\text{CC}) \quad E_{\text{thresh}} = 1.442 \text{ MeV} \\
\nu_a + D &\rightarrow \nu_a + p + n \quad (\text{NC}) \quad E_{\text{thresh}} = 2.226 \text{ MeV}
\end{align*}$$

(a = $e, \mu, \tau$) above $\sim 5$ MeV. Whereas the charged-current (CC) reaction is sensitive only to $\nu_e$, the neutral-current (NC) reaction is sensitive to all three $\nu$ flavours. Thus by comparing the $\nu$ fluxes obtained from the CC and NC event rates one will find out directly whether or not the solar $\nu$ deficit is due to $\nu$ oscillations $\nu_e \rightarrow \nu_X$, while the total solar $\nu$ flux (independent of flavour) agrees with the SSM prediction. Borexino (start 2000), an organic liquid scintillator detector (300 tons) in the Gran Sasso laboratory, will measure the reaction $\nu_e + e \rightarrow \nu_e + e$ with a very low threshold of $\sim 0.25$ MeV, thus covering a large part of the $E_e$ spectrum from the so far unseen Be$^7$-$\nu$e. Since the reaction is sensitive to all three $\nu$ flavours (although with different cross sections for $\nu_e$ and for $\nu_\mu e$, $\nu_\tau e$ scattering) Borexino will allow to decide whether the original Be$^7$-$\nu_e$ have only changed their flavour or whether Be$^7$-$\nu$ are missing from the very beginning which would be in conflict with the SSM.

### 4 LSND and KARMEN

The LSND experiment at Los Alamos (LSND = Liquid Scintillator Neutrino Detector) has previously observed \[24\] events of the type $\bar{\nu}_e p \rightarrow n e^+$ in connection with $\pi^+$ decays at rest and subsequent $\mu^+$ decays at rest ($\pi^+ \rightarrow \mu^+ \nu_\mu$, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$) from which no $\nu_e$ are expected. The occurrence of $17.4 \pm 4.7 \bar{\nu}_e p$ events ($\bar{\nu}_e$ appearance) above background with $36 < E_e < 60$ MeV was attributed to flavour transitions $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, of $\bar{\nu}_\mu$ from $\mu^+$ decays. The allowed regions in the ($\sin^2 2\theta, \delta m^2$) plane from an oscillation analysis are shown by the shaded areas in Fig. 3. In the meantime the signal above background has gone up from 17.4 to $20.8 \pm 5.4$ excess events \[25\] (1993-1997 data), yielding an oscillation probability of $(0.31 \pm 0.09 \pm 0.05)\%$ (preliminary). The evidence for $\nu$ oscillations is strengthened by observing \[26, 27\] in the same experiment also an excess of $18 \nu_\mu$ events ($\nu_\mu + C \rightarrow e^- + X$) above the expected $\nu_e$ background from $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ and $\pi^+ \rightarrow e^+ \nu_e$. These excess events are attributed to $\nu_\mu \rightarrow \nu_e$ transitions, the $\nu_\mu$ coming from $\pi^+ \rightarrow \mu^+ \nu_\mu$ decays in flight, and lead to the same allowed regions in the ($\sin^2 2\theta, \delta m^2$) plane as the $\bar{\nu}_e p$ events.
The KARMEN Collaboration (= KArlsruhe-Rutherford Medium Energy Neutrino experiment) is carrying out with an upgraded detector (KARMEN 2) an experiment with stopped $\pi^+$ and $\mu^+$, similar to LSND and using the same reactions for detecting $\bar{\nu}_e$ or $\nu_e$. So far no $\bar{\nu}_e$ event has been found where $2.88 \pm 0.13$ background events are expected. The $(\sin^2 2\theta, \delta m^2)$ region which is excluded by KARMEN at 90% CL (full curve in Fig. 9), covers almost the total allowed region of LSND. So the two experiments are hardly compatible. KARMEN is taking more data to increase their sensitivity (dotted curve in Fig. 9).

An experiment (BOONE = BOOster Neutrino Experiment) is forthcoming at the booster accelerator of Fermilab to definitely verify or refute the LSND result and to measure the oscillation parameters. The experiment has been approved and is foreseen to start by 2001.

### 5 Possible neutrino mass schemes

Table 2 summarizes the results on $\delta m_{ij}^2$ obtained from various oscillation analyses, considering only those experiments that have apparently observed a positive oscillation signal. All reactor and accelerator experiments, except LSND, have so far found no indications for $\nu$ oscillations thus yielding only limits on $\delta m^2$ and $\sin^2 2\theta$. The table includes the prediction for the sum of the light $\nu$ masses which comes from a cosmological model with non-baryonic cold and hot dark matter (CHDM), both needed to explain the observed structure and density in the universe at all distance scales: Assuming a flat universe without cosmological constant ($\Omega = 1$, $\Lambda = 0$) one obtains with 20% hot dark matter in the
Table 2: Allowed ranges for $\delta m^2_{ij}$ from the various oscillation analyses and constraint on the $\nu$ masses from a cold-hot dark matter model

| Measurement                  | $|\delta m^2_{ij}|$ (eV$^2$) | Oscillation                  |
|------------------------------|------------------------------|------------------------------|
| atmospheric $\nu$            | $(0.4 - 7) \cdot 10^{-3}$   | $\nu_\mu \leftrightarrow \nu_\tau$ |
| solar $\nu$                  |                              | $\nu_e \leftrightarrow \nu_\mu, \nu_s$ |
| - matter                     | $(0.5 - 1.6) \cdot 10^{-5}$ |                              |
| - vacuum                     | $(0.5 - 0.8) \cdot 10^{-10}$|                              |
| LSND                         | $0.2 - 10$                   | $\nu_\mu \leftrightarrow \nu_e$ |
| hot dark matter              | $\sum_{\nu} m_\nu \approx 5$ eV |                              |

form of light relic neutrinos ($\sum_{\nu} \Omega_\nu = 0.2$):

$$\sum_{\nu} m_\nu = 94 \cdot \sum_{\nu} \Omega_\nu h_0^2 \text{eV} \approx 4.7 \text{ eV},$$

where $h_0 \approx 0.5$ is the normalized Hubble constant ($H_0 = 100 h_0 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

From Tab. 2 it seems evident that there are three independent $\delta m^2_{ij}$ values. This requires a minimum of four different $\nu$ species since for three $\nu$ flavours the three possible $\delta m^2_{ij}$ are not independent: $\delta m^2_{12} + \delta m^2_{23} + \delta m^2_{31} = 0$. The fourth $\nu$ must be a sterile (inactive) neutrino ($\nu_s$), which does not participate in the weak interaction (e.g. a right-handed $\nu$), since from the LEP experiments the number of light active neutrinos, coupling to $Z^0$, is known to be 3 ($2.993 \pm 0.011$) [29].

An alternative, leaving it at three $\nu$ species, is of course that one of the measurements in Tab. 2 is wrong. We now discuss, step by step, some possible mass assignments in a qualitative way (Fig. 10): we simplify the presentation somewhat by assuming – against large-mixing angle solutions – that the mixing angles $\theta_{e\mu}, \theta_{\mu\tau}, \theta_{\tau e}$ are small. In this case $\nu_1, \nu_2, \nu_3$ are the dominant states in $\nu_e, \nu_\mu, \nu_\tau$, respectively, such that $m(\nu_e) \approx m(\nu_\mu) \approx m(\nu_\tau)$ according to eq. (4), i.e. the measured $\delta m^2_{ij}$ for the mass eigenstates hold approximately also for the flavour eigenstates. Quantitative treatments can be found elsewhere [30, 31].

The atmospheric and solar results alone can be accommodated in two ways (Fig. 10):

- Three $\nu$ with a hierarchical mass pattern, $m(\nu_e) \ll m(\nu_\mu) \ll m(\nu_\tau)$, as predicted by the seesaw mechanism. Using the $\delta m^2$ values in Tab. 2, this pattern implies $m(\nu_e) \approx 0$, $m(\nu_\mu) \approx 3 \cdot 10^{-3}$ or $10^{-5}$ eV (from solar $\nu$) and $m(\nu_\tau) \approx 7 \cdot 10^{-2}$ eV (from atmospheric $\nu$). In this scenario there is no room for e.g. the $\nu_\tau$ being the hot dark matter particle.

- Three $\nu$ with a democratic (nearly degenerate) mass pattern, $m(\nu_e) \approx m(\nu_\mu) \approx m(\nu_\tau)$, with relatively small mass differences such that they yield
Figure 10: Sketches showing qualitatively some possible $\nu$ mass assignments in order to accommodate (a) the solar $\nu$ and atmospheric $\nu$ results, (b) the solar $\nu$, atmospheric $\nu$ results and hot dark matter (HDM), and (c) the solar $\nu$, atmospheric $\nu$, LSND results and HDM.

the experimental $\delta m^2$ values from solar and atmospheric $\nu$ oscillations respectively.

This latter mass pattern is still satisfactory if we add the CHDM prediction (22) as a further constraint. In this case (Fig. 10b) $m(\nu_e) \approx m(\nu_\mu) \approx m(\nu_\tau) \approx 1.6 \text{ eV}$ such that $\sum_\nu m_\nu \approx 4.8 \text{ eV}$.

Finally, if also the LSND result is added, a fourth, sterile $\nu$ ($\nu_s$) is needed, as explained above. A possible mass pattern is shown in Fig. 10c: Two rather light, nearly degenerate neutrinos, $\nu_e$ and $\nu_s$, and two somewhat heavier, also nearly degenerate neutrinos, $\nu_\mu$ and $\nu_\tau$, as hot dark matter particles with $m(\nu_\mu) \approx m(\nu_\tau) \approx 2.4 \text{ eV}$ so that constraint (22) is fulfilled. In this scheme the solar $\nu_e$ deficit comes from $\nu_e \leftrightarrow \nu_s$ oscillations, the atmospheric $\nu_\mu$ deficit from $\nu_\mu \leftrightarrow \nu_\tau$ oscillations and the LSND result from $\nu_e \leftrightarrow \nu_\mu$ oscillations with a relatively large $\delta m^2 \approx (2.4 \text{ eV})^2 = 5.8 \text{ eV}^2$. An alternative mass arrangement is to interchange $\nu_s$ and $\nu_\tau$ in Fig. 10c.

It has been claimed that the present atmospheric, solar and LSND results can
also be described by three \( \nu \) flavours, i.e. by two independent \( \delta m^2 \) values, if one applies the three-flavour oscillation formalism to all three experimental results simultaneously, instead of employing the two-flavour formalism, eq. (3), for each result separately. See however ref. [33] where the consequences of the CHOOZ result (see below) are analyzed.

6 Some further results and future plans

Two short-baseline (SBL) accelerator experiments, CHORUS [34] and NOMAD [35], have been searching for \( \nu_\mu \rightarrow \nu_\tau \) transitions in a wide-band \( \nu_\mu \) beam at the CERN SPS (\( \langle E_\nu \rangle \approx 27 \text{ GeV}, L \sim 800 \text{ m}, \text{i.e. } \langle E_\nu \rangle/L \sim 7 \text{ eV}^2 \)) by looking for events \( \nu_\tau N \rightarrow \tau^- X \). No \( \nu_\tau \) event was found so far in either experiment from which the following 90% CL upper limits on the mixing angle at large \( \delta m^2 \) were deduced: \( \sin^2 2\theta_{\mu\tau} < 1.8 \cdot 10^{-3} \) (CHORUS), \( < 4.2 \cdot 10^{-3} \) (NOMAD).

Long-baseline (LBL) experiments (large \( L/E \)) are according to eq. (4) sensitive to smaller \( \delta m^2 \). The first LBL reactor experiment has been carried out by the CHOOZ collaboration [36] at a nuclear power station near Chooz in France (\( \langle E_\nu \rangle \sim 3 \text{ MeV}, L = 1 \text{ km}, \text{i.e. } \langle E_\nu \rangle/L \sim 6 \cdot 10^{-4} \text{ eV}^2 \)), searching for \( \nu_e \rightarrow \nu_X \) disappearance. No evidence for \( \nu \) oscillations was found, the two-flavour analysis yielding the exclusion plot shown in Fig. 11. The \( (\sin^2 2\theta, \delta m^2) \) region to the right of the CHOOZ curve is excluded at 90% CL. In particular the following upper limits were obtained from the plot: \( \delta m^2 < 0.9 \cdot 10^{-3} \text{ eV}^2 \) for \( \sin^2 2\theta = 1 \) (maximum mixing), \( \sin^2 2\theta < 0.18 \) for large \( \delta m^2 \). The \( \delta m^2 \) limit improves the limits obtained from previous SBL reactor experiments, included
in Fig. 11 by about an order of magnitude. The figure also shows that the CHOOZ result excludes the allowed region which Kamiokande has obtained for $\nu_\mu \leftrightarrow \nu_e$ oscillations from their atmospheric $\nu$ measurements. The corresponding allowed region of Super-Kamiokande is excluded by CHOOZ to a large part.

With accelerators the following three LBL experiments are being prepared for the near future [37]:

- In Japan a beam from KEK to Super-Kamiokande (K2K [38]) with $\langle E_\nu \rangle \sim 1$ GeV and $L = 250$ km, i.e. $\langle E_\nu \rangle / L \sim 10^{-3}$ eV$^2$. The experiment will look for $\nu_\mu$ disappearance and $\nu_e$ appearance. K2K is expected to start data taking in 1999.

- In USA a $\nu_\mu$ beam from Fermilab to Soudan 2 (E875/MINOS [39]) with $\langle E_\nu \rangle \approx 11$ GeV and $L = 730$ km, i.e. $\langle E_\nu \rangle / L \sim 7 \cdot 10^{-3}$ eV$^2$. MINOS is expected to start data taking in 2002.

- In Europe a $\nu_\mu$ beam [40] from CERN to the Gran Sasso laboratory with $\langle E_\nu \rangle \sim 25$ GeV and $L = 730$ km, i.e. $\langle E_\nu \rangle / L \sim 3 \cdot 10^{-3}$ eV$^2$. Three detectors are planned: Two detectors, ICARUS [11], a liquid-argon drift chamber, and OPERA [12], employing a target with emulsion sheets (similar to CHORUS), will search for $\nu_\tau$ appearance; the third detector, NOE [43], a fine-grained massive calorimeter based on scintillating fiber technique, will search for $\nu_\mu$ disappearance as well as for $\nu_e$, $\nu_\tau$ appearance.

In all these experiments, given the baseline $L$, $E_\nu$ should be on the one hand as small as possible in order to reach low $\delta m^2$. On the other hand the event rate in the detector decreases with decreasing $E_\nu$ for two reasons: (a) the cross section is proportional to $E_\nu$, and (b) the divergence of the $\nu$ beam gets larger with smaller $E_\nu$. The beam divergence is a severe limitation at large distances $L$ and calls for a correspondingly large detector mass and/or high $\nu$ beam intensity. The latter could be achieved by using neutrinos not, as usually, from charged $\pi$ and $K$ decays, but from $\mu$ decays in future high-luminosity muon storage rings with long straight sections pointing in the desired direction [14].

Two new direct measurements of upper limits to the $\nu_e$ mass from tritium $\beta$-decay, $^3$H$^3 \rightarrow ^3$He$^3 + e^- + \bar{\nu}_e$, were presented at $\nu$'98:

Mainz experiment [45] : $m^2_{\nu} = (-9 \pm 8 \pm 2)$ eV$^2 \Rightarrow m_\nu < 3.4$ eV

Troitsk experiment [46] : $m^2_{\nu} = (-2.1 \pm 3.7 \pm 2.3)$ eV$^2 \Rightarrow m_\nu < 2.7$ eV,

where the upper $m_\nu$ limits are at 95% CL.

Finally, the Heidelberg-Moscow collaboration [17], searching in the Gran Sasso laboratory with a germanium detector for the neutrinoless double $\beta$-decay (0$\nu$2$\beta$ decay) of $^{76}$Ge, $^{76}$Ge$^7 \rightarrow ^{76}$Se$^7 + 2e^-$, has determined the following new 90% CL limits for the half-life and the (average) $\nu$ mass (provided that the $\nu_e$ is a Majorana neutrino, i.e. $\nu^M \equiv \bar{\nu}^M$):

$$T_{0\nu}^{2\beta}(^{76}\text{Ge}) > 1.1 \cdot 10^{25} \text{ years} \Rightarrow \langle m^M_{\nu} \rangle < 0.46 \text{ eV}.$$ (24)
For the longer range future a detector consisting eventually of $\sim 1$ ton of Ge (GENIUS) is envisaged which is to be realized in several steps.

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