Part 10

Non-Photon Astrophysics and the Future

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Neutrino Masses and Mixing

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Abstract. Recent results on neutrino masses and mixing are presented. There is convincing evidence for nonzero but tiny masses of at least two flavor neutrinos, based on two types of neutrino oscillations, solar and atmospheric neutrinos. The large mixing angle between first and second flavors and also the one between the second and third flavors were found, quite contrary to small mixing angles among quark flavors, and pose a new mystery.

1. Introduction

The Standard Model of elementary particles assumes neutrino masses to be identically zero and hence their mixing to be also zero. However, it is well known that there are no fundamental symmetries that prevent neutrinos from acquiring masses. Mixing among the neutrino flavors implies that the eigenstates for weak interactions are not identical with those for free moving, or mass eigenstates. The two eigenstates are connected by a unitary transformation, whose unitary matrix is called the MNS [1] matrix. It consists of three independent angles $\theta_{12}, \theta_{23}, \theta_{31}$ and a complex phase δ called the CP phase. If the neutrinos indeed possess finite masses, their mixing may well be finite, too, and especially the CP phase δ might be large. Quark mixing angles have been measured with reasonable precisions. Comparison of the quark mixing angles with those of the leptons may shed new light on the generation problem: why there are three generations of quarks and leptons.

One second after the Big Bang, neutrinos of all flavors ($\nu_e, \nu_\mu,$ and ν_τ) decoupled from the thermal equilibrium. As the Universe expanded, their energies were redshifted and their number densities diluted. These so-called Big Bang neutrinos should be, in the present epoch, in a thin gaseous state with the mean temperature, 1.9K and the density, $n_\nu = 110(\nu_i + \bar{\nu_i})\ cm^{-3}, i = e, \mu, \tau$. Energies corresponding to the mean temperature are so small that the Big Bang neutrinos would travel without single interactions through the entire Universe. There is at present no way to detect these neutrinos.

If neutrinos are massive, they may constitute a significant fraction of the energy density in the Universe and control the fate of the Universe, namely expanding forever or contracting eventually. The density factor of neutrinos is

[1] Maki-Nakagawa-Sakata

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given by

$$\Omega_\nu = \sum m_\nu n_\nu/\rho_c = 0.015 h_0^{-2} \sum m_{\nu,eV} = 0.021(1 \pm 0.2) \sum m_{\nu,eV}$$

where $\rho_c = (3/8\pi)H_0^2/G_N$ is the critical density of the Universe,

$$H_0 = 100 h_0 \ km/s/Mpc = 72 \pm 7 \ km/s/Mpc$$

is the Hubble constant, and the neutrino mass is in the unit of eV. If $m_\nu \geq 1 \ eV$, neutrinos are a non-negligible component of the possible hot dark matter.

The Universe lacks anti-matter though physical principles do not discriminate between particle and antiparticle to a high accuracy. A plausible theory to explain this is that in the very early Universe the lepton number non-conservation and the CP violation in the leptonic sector induced an asymmetry between leptons and antileptons. This leptonic asymmetry was then converted to the quark asymmetry during the electroweak phase transition, resulting in the matter-antimatter asymmetry. The CP violation of the leptonic sector is closely related to the complex CP phase δ given above. Neutrino masses and mixing are not only important in particle physics but also closely related to the fundamental quests in cosmology.

Recently precise observations of atmospheric and solar neutrinos revealed convincing evidence for two types of neutrino oscillations, $\nu_\mu \to \nu_\tau$ and $\nu_e \to \nu_\mu$. These discoveries then indicate finite neutrino masses of at least two flavors, m_2 and m_3 and also finite mixing angles, θ_{23} and θ_{12}.

In the following sections we will first briefly review the neutrino oscillation, and then present the results on atmospheric and solar neutrinos.

2. Atmospheric Neutrinos

Atmospheric neutrinos are decay products of hadronic showers produced by cosmic ray interactions in the atmosphere. The flavor ratio of the atmospheric neutrino flux $(\nu_\mu + \bar{\nu_\mu})/(\nu_e + \bar{\nu_e})$ has been calculated to an accuracy of better than 5 % in the range from 0.1 GeV to higher than 10 GeV (Barr et al. 1998; Honda et al. 1990). It has a value of about two for energy $\leq 1 \, GeV$ and increases with increasing neutrino energy. For neutrino energy higher than a few GeV, the fluxes of upward and downward going neutrinos are expected to be nearly equal due to the spherical nature of Earth. The effect of the geomagnetic field is expected to be small in this energy regime, because the primary cosmic rays that produce these neutrinos have rigidities exceeding the geomagnetic cutoff rigidity ($\sim 10 \, GeV/Ze$).

The Super-Kamiokande experiment has played a dominant role in studying atmospheric neutrinos and in discovering their oscillations. It employs a 50,000 ton imaging water Cherenkov detector, which is shown in Fig. 1.

The detector consists of two sub-detectors. The inner detector has 32,000 tons of water viewed by 11,146 50 cm ϕ phtomultiplier tubes (PMTs) corresponding to a 40 % photo-coverage of the inner surface. It is actually used for physics analyses. The 18,000 ton outer detector completely surrounds the inner part and serves as a shield against neutrons and gamma rays emanated from the rock. It is

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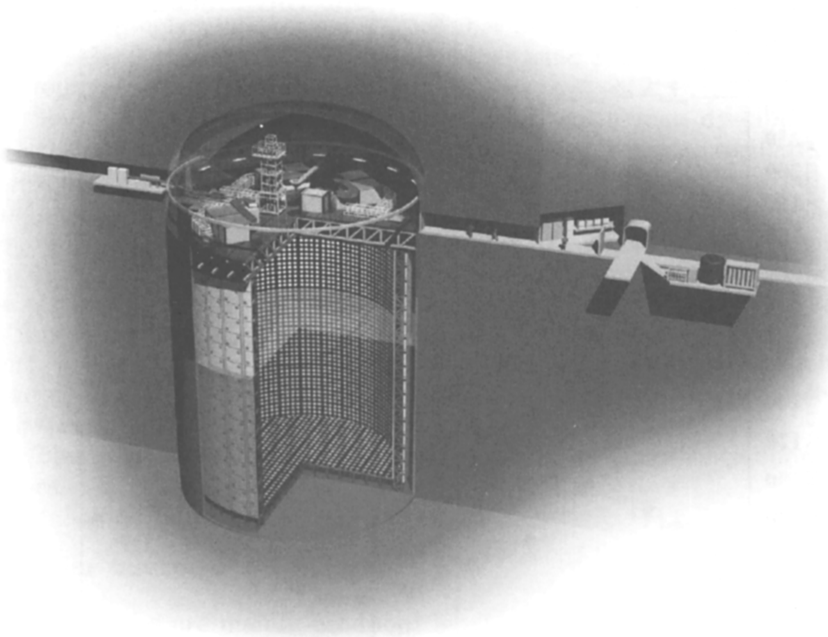

Figure 1. A computer graphic of the Super-Kamiokande detector

equipped with 1885 20 cm ϕ PMTs to tag incoming cosmic-ray muons and muons coming out of the inner detector. Thanks to the high photo-coverage, the trigger threshold is 3.5 MeV (visible energy and electron equivalent) at 50 % efficiency. The so-called fiducial volume is the inner most 22,500 tons in which atmospheric and solar neutrinos are allowed to interact and produce charged particles which then emit Cherenkov light. The absolute energy scale of the inner detector has been calibrated with stopping and though-going cosmic-ray muons, their decay electrons, and electrons with energies between 5 MeV and 16 MeV produced with an electron LINAC. The estimated uncertainty is $\pm 2.4\%$. Momentum resolutions for electrons and muons are estimated to be $2.5/\sqrt{E(GeV)} + 0.5\%$ and 3%, respectively.

ν_e and ν_μ are identified by their secondary particles, $e^\pm$ and $\mu^\pm$, respectively. Identification of $e^\pm$ and $\mu^\pm$ in the Super-K detector is achieved by quantifying the diffuseness of Cherenkov ring edges; electrons generate cascade showers in water and many low-energy electron/positron pairs in the showers then produce diffuse rings, while muons do not suffer multiple Coulomb scattering and produce sharp Cherenkov rings. Emission angles (θ_c) of Cherenkov light become small for slow particles from the relation $\cos\theta_c = c/nv$, n being the refractive index of water ~ 1.33. Measured θ_c provide supplementary information to identify muons at low energies.

Super-K has achieved very low misidentification probabilities for single-ring muons and electrons which are $0.5 \pm 0.1\,\%$ and $0.7 \pm 0.1\,\%$, respectively. They

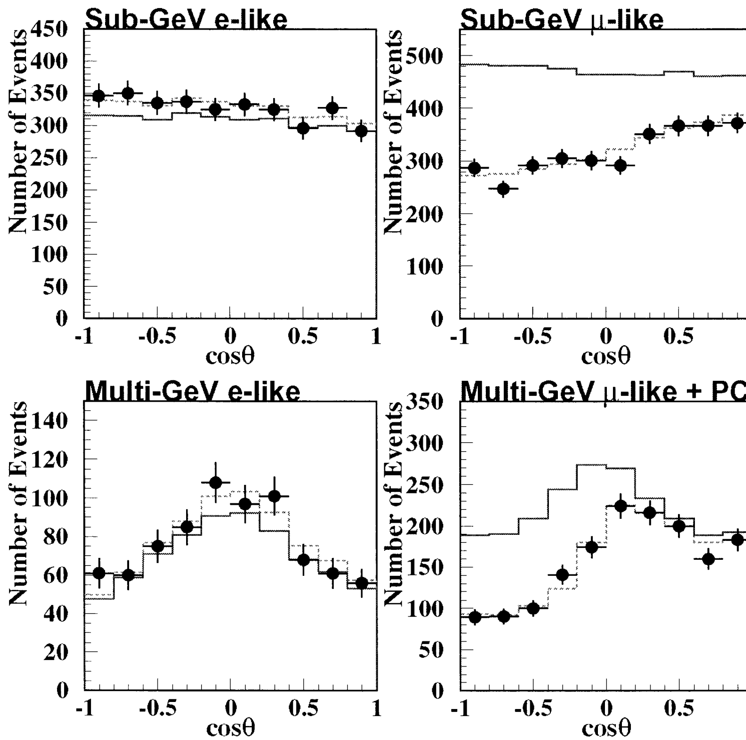

Figure 2. Zenith angle distributions of e-like and μ-like events for sub-GeV and multi-GeV data sets. The partially-contained data set is combined with the multi-GeV μ-like sample. Upward-going particles have $\cos\theta < 0$ and downward-going particles have $\cos\theta > 0$. The solid histogram shows the MC expectation for no oscillation normalized to the data live time. The dotted histogram is the best fit expectation for $\nu_\mu \to \mu_\tau$ oscillations with the overall normalization fitted as a free parameter.

were estimated based on simulated charged-current neutrino events and verified by a test beam experiment (Kasuga et al. 1996).

Super-K has already accumulated data for 1498 live days. The results are shown in Fig. 2 (Super-K 1998).

Events are selected by requiring that only single Cherenkov rings are seen and produced particles are fully contained within the inner detector. They are mostly produced by charged-current interactions. Events are classified as electron-like and muon-like, and are further divided in sub-GeV and multi-GeV samples, respectively, with their momenta larger or smaller than 1.33 GeV/c. The data samples contain 3266, 3181, 772 and 664 events for sub-GeV e-like, sub-GeV μ-like, multi-GeV e-like and multi-GeV μ-like, respectively. The multi-GeV muon sample is combined with partially contained events (913 events) in which one of the secondary particles goes out of the inner detector and is detected in the outer one. The exiting particles are most likely muons (estimated probability,

$98 \pm 0.3\,\%$) and energetic. Figure 2 shows that the up-down symmetry of μ-like events is strongly violated and the number of upward-going μ-like events are almost half of what is expected. On the other hand e-like events are normal and well represented by the Monte Carlo (MC) simulation.

Since the number of e-like events and their zenith-angle distributions agree with the expected ones, it is natural to assume a two neutrino oscillation model, $\nu_\mu \to \nu_\tau$. The quantitative fit was performed with the relevant parameters, Δm^2_{23} and $\sin^2 2\theta_{23}$ and by taking into account several systematic uncertainties. The expected numbers for e-like and μ-like events have large uncertainties due to uncertainties in the primary cosmic-ray flux, nuclear interactions in the atmosphere, and cross sections of ν-nucleus interactions. Hence the overall flux normalization was left as a free parameter. The best fitted values are $\Delta m^2_{23} = 2.5 \times 10^{-3}\ eV^2$, and $\sin^2 2\theta_{23} = 1.0$. The corresponding zenith-angle distributions are shown by dotted histograms in Fig. 2. Figure 3 shows the allowed region.

This is the first evidence for neutrino oscillations and hence finite neutrino masses.

3. solar neutrinos

Solar neutrinos are mainly produced by the following nuclear reactions in the solar core;

$$
\begin{array}{llll}
p + p & \to & {}^2H + e^+ + \nu_e & (pp) \\
p + e^- + p & \to & {}^2H + \nu_e & (pep) \\
{}^7Be + e^- & \to & {}^7Li + \nu_e & ({}^7Be) \\
{}^8B & \to & {}^8Be^* + e^+ + \nu_e & ({}^8B)
\end{array}
$$

The fluxes on Earth of pp, pep, ${}^7Be$, and ${}^8B$ neutrinos are widely different: $5.95(1.00 \pm 0.01) \times 10^{10}$, $1.40(1.00 \pm 0.015) \times 10^8$, $4.77(1.00 \pm 0.10) \times 10^9$, and $5.05(1.00^{+0.20}_{-0.17}) \times 10^6$, all in units of $cm^{-2}s^{-1}$, according to the Standard Solar Model (SSM) calculation (Bahcall, Pinsonneault, & Basu 2001). pp neutrinos have a continuous energy spectrum with the end point energy of 0.233 MeV. ${}^7Be$ neutrinos are mono-energetic, and their energies (branching ratios) are $0.861 MeV(90\%)$ and $0.383 MeV(10\%)$, respectively. The continuous energy spectrum of ${}^8B$ neutrinos are somewhat broadened by a broad decay width of ${}^8Be^*$. Their energies extend up to about $15 MeV$.

The solar neutrino problem, namely the deficit of observed event rates by $50 \sim 70\,\%$, has persisted for more than 30 years. Recently, precise measurements of ${}^8B$ neutrinos by Super-Kamiokande and in particular by SNO revealed that the solar neutrino problem is indeed caused by the neutrino oscillation of a second type, $\nu_e \to \nu_\mu$. The SNO result also indicates that the sum of the ν_e and $\nu_{\mu,\tau}$ fluxes agrees with the ${}^8B$ neutrino flux from the SSM calculation; namely the Sun works fine.

3.1. Super-K results

Super-K uses a reaction, $\nu_i + e^- \to \nu_i + e^-$ and detects Cherenkov light emitted by the recoil electrons. The total uncertainty in the absolute energy scale dominates the systematic uncertainties. With the help of an electron LINAC, it was

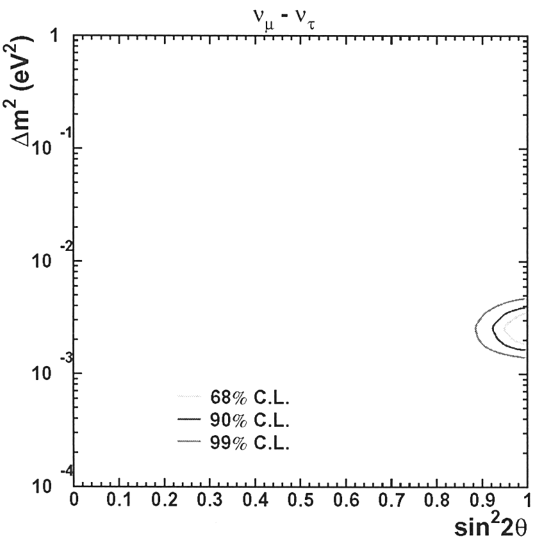

Figure 3. The 68%, 90%, and 99% confidence intervals for Δm^2_{23} and $\sin^2 2\theta_{23}$ for $\nu_\mu \to \nu_\tau$ two neutrino oscillations.

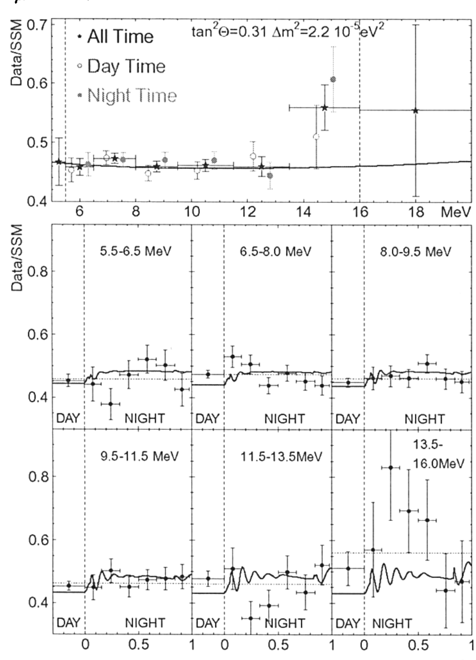

Figure 4. Detailed spectra obtained by the Super-K experiment. Data are binned in energy and day and night times. The curves correspond to what is expected for the two component neutrino oscillation of $\Delta m^2_{12} = 2.2 \times 10^{-5}\ eV^2$ and $\tan^2\theta_{12} = 0.31$ which is in the LMA solution and excluded at 95 % C.L.

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estimated to be ± 0.6 %, including possible long term variation and direction dependence.@ The energy resolution for electrons is also determined simultaneously. It is reproduced well by the MC simulation. Recoil electrons follow directions of the parent neutrinos with a high accuracy. However, due to large multiple Coulomb scattering, electron directions are poorly determined, about 27 deg at 10 MeV. The angular resolution is also calibrated with the LINAC and the resolution function is well reproduced by the MC simulation.

Super-K has accumulated $22385 \pm 226^{+783}_{-716}$ solar neutrino events for electron energies of $5 \sim 20$ MeV, which corresponds to the flux, $2.35 \pm 0.02 \pm 0.08 \times 10^6\ cm^{-2}s^{-1}$ (Super-K 2001). This measured value should be compared with the SSM prediction, $5.05^{+1.05}_{-0.8} \times 10^6\ cm^{-2}s^{-1}$. The electron data are divided to six data sets in energy ranging from 5.5 MeV to 16.0 MeV. Possible day/night flux variation is studied in each data set, as shown in Fig. 4.

These distributions are subject to oscillation analyses which will be presented later.

3.2. SNO results

SNO is an imaging *heavy* water Cherenkov detector. A spherical acrylic vessel contains 1000 tons of *heavy* water, and is surrounded by a shield of light water in a 34 m high barrel shaped cavity of maximum diameter 22 m. 9456 20 cm ϕ PMTs with Winstone-cone mirrors are supported on a spherical structure of 17.8 m diameter and view the inner region. The absolute energy scale and uncertainties are established with a triggered ^{16}N source. A ^{252}Cf neutron source, which provides 6.25 MeV γ rays from neutron capture, and a $^3H(p,\gamma)^4He$ source with 19.8 MeV γ rays are also used. The uncertainty in the energy scale is ± 1.4 %. The analysis threshold is $T_{eff} \geq 5\ MeV$, where T_{eff} is a most probable kinetic energy.

The unique feature of the SNO experiment is that a variety of reactions can be used to detect solar neutrinos thanks to quasi-free neutrons in heavy water:

$$\begin{array}{lcll} \nu_e + d & \rightarrow & e^- + p + p & \text{(CC)} \\ \nu_i + e^- & \rightarrow & \nu_i + e^- & \text{(ES)} \\ \nu_i + d & \rightarrow & \nu_i + p + n & \text{(NC)} \end{array}$$

One can measure the ν_e flux from the first reaction (CC), the sum of the ν_e, ν_μ, and ν_τ fluxes from the third reaction (NC), and the $\nu_e + \alpha(\nu_\mu + \nu_\tau)$ fluxes with $\alpha \sim 0.154$ from the second reaction (ES). The NC reactions are identified by detecting γ-rays from the capture reaction $d(n,\gamma)t$ with $E_\gamma = 6.25\ MeV$. Note that Super-K uses the ES reaction only.

The flux of ^8B neutrinos was derived from each reaction assuming the standard spectrum shape:

$$\phi_(CC) = 1.76^{+0.06}_{-0.05} \pm 0.09 \tag{1}$$

$$\phi_(ES) = 2.39^{+0.24}_{-0.23} \pm 0.12 \tag{2}$$

$$\phi_(NC) = 5.09^{+0.44}_{-0.43}\ {}^{+0.46}_{-0.43} \tag{3}$$

where the units are $10^6\ cm^{-2}s^{-1}$ (SNO 2002). The ES results agrees with the more precise result from Super-K. Figure 5 shows the flux of $\nu_\mu + \nu_\tau$ vs. that of ν_e.

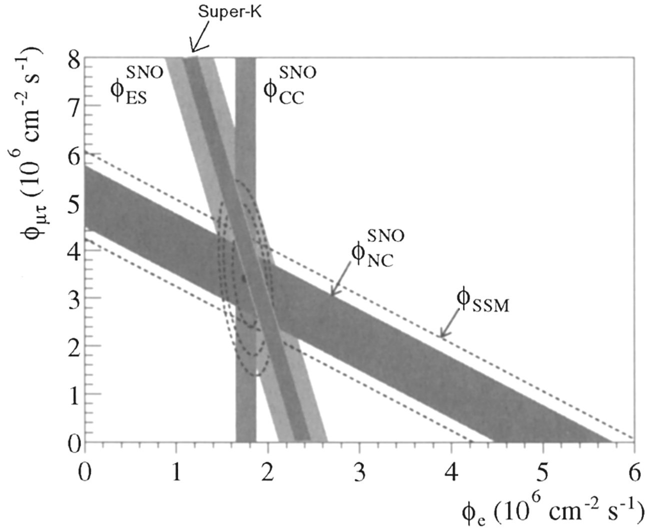

Figure 5. $\nu_{\mu,\,\tau}$ flux vs ν_e flux obtained from the three neutrino reactions from SNO. The ES result from Super-K is also shown. The SSM ^8B flux prediction is shown by dotted bands. The error ellipses represent the 68%, 95%, and 99% probability contours for the fluxes of ν_e and $\nu_{\mu,\,\tau}$ obtained from the SNO results. (The Super-K result was added to the figure provided by the courtesy of the SNO collaboration.)

This is clear evidence for the existence of non-ν_e flavor in solar neutrinos on Earth and hence for the neutrino oscillation, $\nu_e \to \nu_\mu$.

3.3. LMA Solution

The relevant parameters, Δm^2_{12} and θ_{12}, have been determined by several authors using all the existing experimental results. The SNO result is shown in Fig. 6, as an example (SNO 2002a).

Fit was performed with the following procedure:

- The two parameters to be determined are Δm^2_{12} and $\tan^2\theta_{12}$.
- The ^8B flux is treated as a free parameter as the corresponding flux is observationally contrained from the NC reaction.
- The matter effect is taken into account.
- Fitted are the SNO results on the fluxes obtained from the CC, NC and ES reactions (SNO 2002) and day and night spectra (SNO 2002a), the Super-K day and night spectra (Super-K 2001), the flux results from Homestake (Cleveland et al. 1998), GALLEX (Altmann et al. 200), and SAGE (Abdurashitov et al. 2002) experiments.

SNO and Super-K results contribute dominantly to constraining the allowed region.

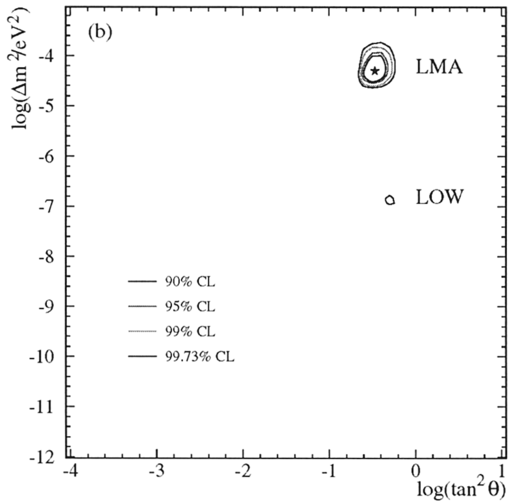

Figure 6. Allowed region of Δm^2_{12} and $\tan^2\theta_{12}$ obtained by leaving the total ^8B flux free. The data are the SNO day and night spectra and CC + NC + ES event rates together with the Super-K day and night spectra, the event rates obtained by Homestake, GALLEX and SAGE, and the SSM predictions for the more robust *pp*, *pep*, and ^7Be fluxes. (Courtecy of the SNO Collaboration)

The best fit values are; $\Delta m^2_{12} = 5.0 \times 10^{-5}\ eV^2$, $\tan^2\theta_{12} = 0.34$, and the flux value is $\phi_{^8B} = 5.86 \times 10^6\ cm^{-2}s^{-1}$. The corresponding χ^2/dof is 57.0/72. The large-mixing-angle (LMA) region is left as the only viable solution to the solar neutrino problem.

4. Discussion and Conclusion

Two kinds of neutrino oscillations are now established; $\nu_\mu \to \nu_\tau$, and $\nu_e \to \nu_\mu$ from precise observations of atmospheric and solar neutrinos, respectively. The results are summarized as follows;

$$\Delta m^2_{23} = 1.6 - 3.9 \times 10^{-3} \quad (4)$$
$$\Delta m^2_{12} = 3 - 20 \times 10^{-5} \quad (5)$$
$$\sin^2 2\theta_{23} = 0.92 - 1.0 \quad (6)$$
$$\sin^2 2\theta_{12} = 0.6 - 0.9 \quad (7)$$

where the units of Δm^2 are eV^2, and the intervals correspond to the 90 % CL. Theoretical prejudice is that the three masses should hierarchical, namely $m_3 \gg m_2 \gg m_1$. Then by taking the square root of the above Δm^2, the neutrino masses of the second and the third flavors are $m_3 = 0.04 - 0.06\ eV$, and $m_2 = 0.005 - 0.01\ eV$, respectively. These values are too small to close the Universe. Another model is the degenerate mass scheme, $m_3 \sim m_2 \sim m_1$, which is not

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ruled out. There is an upper limit of the ν_e mass from Tritium beta-decay experiments, $m_e < 2.2\ eV$, $(95\,\%CL)$. Hence $\sum m_i < 6.6\,eV$. In both cases the total sum of the neutrino masses is much less than what is required to close the Universe. The maximum of Ω_ν is 1.4% and 15%, for hierarchical and degenerate mass schemes, respectively.

The mixing angles, θ_{23} and θ_{12}, are, to our great surprise, almost maximal and quite contrary to those in the quark sector; $\sin^2 2\theta_{23} = 0.0064 \pm 0.0010$, and $\sin^2 2\theta_{12} = 0.188 \pm 0.007$. Why quarks and leptons have different mixing angles is still a puzzle. It is not known how much the large mixing among the neutrinos might affect the Universe.

In conclusion, much progress has been made in neutrino physics. Finite neutrino masses and surprisingly large mixing angles have been discovered. These findings were obtained by observations of neutrinos generated by the Sun and cosmic rays.

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