Physics Related to the Atmospheric Neutrino Anomaly

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Preface

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Organization of the research project:

Head investigator	Osamu Yasuda	TMU,Dept. of Physics, Assit. Prof.
Investigator	Hisakazu Minakata	TMU, Dept. of Physics, Prof.
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Expenditure of the research project:

fiscal year 1998	1,200,000 yen
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fiscal year 2000	900,000 yen

1 Current status of study on neutrino oscillations

1.1 Neutrino oscillations [1, 2] between two flavors

The propagation of neutrinos in vacuum can be described by a Schrödinger equation

$$i\frac{d}{dx}\left(\begin{array}{c}\nu_\alpha(x)\\ \nu_\beta(x)\end{array}\right) = U\mathrm{diag}\left(0, \frac{\Delta m^2}{2E}\right)U^{-1}\left(\begin{array}{c}\nu_\alpha(x)\\ \nu_\beta(x)\end{array}\right),$$

where

$$U \equiv \left(\begin{array}{cc}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{array}\right)$$

is the MNS mixing matrix [2], and $\Delta m^2 \equiv m_2^2 - m_1^2$ is the mass squared difference between the two mass eigenstates. By a straightforward calculation we have the oscillation probability

$$P(\nu_\alpha \to \nu_\beta; L) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right).$$

On the other hand, neutrino oscillations in matter are modified because of the charged current interaction between electrons and electron neutrinos [3], and oscillations between ν_e and ν_μ are described by

$$i\frac{d}{dx}\left(\begin{array}{c}\nu_e(x)\\ \nu_\mu(x)\end{array}\right) = \left[U\mathrm{diag}\left(0, \frac{\Delta m^2}{2E}\right)U^{-1} + \mathrm{diag}\left(A(x), 0\right)\right]\left(\begin{array}{c}\nu_e(x)\\ \nu_\mu(x)\end{array}\right),$$

where $A(x) \equiv \sqrt{2}G_F N_e(x)$, $N_e(x)$ stands for the electron density. Assuming constant density, the oscillation probability in this case is given by

$$P(\nu_e \to \nu_\mu; L) = \sin^2 2\theta_M \sin^2\left(\frac{BL}{2}\right),$$

where $\theta_M$is the effective mixing angle in matter defined by

$$\tan 2\theta_M \equiv \frac{\Delta m^2 \sin 2\theta/2E}{\Delta m^2 \cos 2\theta/2E - A}$$

and

$$B \equiv \sqrt{\left(\Delta m^2 \cos 2\theta/2E - A\right)^2 + \left(\Delta m^2 \sin 2\theta/2E\right)^2}.$$

1.2 Solar neutrino problem

Solar neutrinos are electron neutrinos produced in several reactions in the Sun and they have been observed by experiments with targets such as gallium (SAGE [4] · GALLEX [5] · GNO [6]), chlorine (Homestake [7]) and water (Kamiokande [8] · Superkamiokande [9]). All the experiments have seen a deficit of solar neutrinos [10]:

Experiment	measured flux	ratio exp/BP98	threshold energy	years of running
Homestake	$2.56\pm0.16\pm0.16$	$0.33\pm0.03\pm0.05$	0.814 MeV	1970-1995
Kamiokande	$2.80\pm 0.19\pm 0.33$	$0.54\pm 0.08 \quad ^{+0.10}_{-0.07}$	7.5 MeV	1986-1995
SAGE	$75\pm7\pm3$	$0.58\pm0.06\pm0.03$	0.233 MeV	1990-2006
Gallex	$78\pm 6\pm5$	$0.60\pm 0.06\pm 0.04$	0.233 MeV	1991-1996
Superkamiokande	$2.40\pm 0.03\pm 0.08$	$0.465\pm 0.005\pm0.015$	5.5 MeV	1996-
GNO	$66\pm 10\pm3$	$0.51\pm 0.08\pm 0.03$	0.233 MeV	1998-

In this table Bahcall-Pinsonneault, 1998 (BP98) [11] is used as a theoretical model. The solar neutrino problem is twofold: a) All the experiments obtained smaller numbers of events than theory predicts; b) The ratio of (experimental value)/(theoretical prediction) depends on the threshold energy of the experiment. The most promising explanation for this phenomena at present is neutrino oscillations. Until June 2000 there were three solutions, all of which gave a good fit to the data. These are the small mixing angle (SMA) MSW solution ($\Delta m^2 \simeq 10^{-5}$eV^2, $\sin^2 2\theta_\odot \sim 10^{-2}$), the large mixing angle (LMA) MSW solution ($\Delta m^2 \simeq 10^{-5}$eV^2, $\sin^2 2\theta_\odot \sim 1$) and the vacuum oscillation (VO) solution ($\Delta m^2 \simeq 10^{-10}$eV^2, $\sin^2 2\theta_\odot \sim 1$). At the Neutrino 2000 Conference the Superkamiokande group updated the data on solar neutrinos [12] and they reported that the LMA MSW solution gives the best fit and the LOW solution ($\sin^2 2\theta_\odot \sim 1$, $\Delta m^2_\odot \sim 10^{-7}$eV^2) the second best fit to the data because the energy spectrum is flat and the effect of day-night difference is small. However, the SMA MSW solution and the quasi-vacuum solution ($\sin^2 2\theta_\odot \sim 1$, $\Delta m^2_\odot \sim 10^{-9} - 10^{-8}$eV^2) are still allowed at 99%CL (See Fig. 1 for the result of updated analysis on solar neutrinos) and the situation is still unclear. We may have to wait for data from other experiments such as SNO, BOREXINO, etc., to single out a correct solution.

1.3 Atmospheric neutrino problem

Atmospheric neutrinos are $\nu_\mu+\bar{\nu}_\mu$ and $\nu_e+\bar{\nu}_e$ which are decay products from the secondary particles such as $\mu^\pm$ and $\pi^\pm$ which are produced in collisions of primary cosmic rays and nucleons in the atmosphere, and we expect from a naive argument that the ratio of the fluxes of two kinds of neutrinos is approximately 2. So far several experiments such as Baksan, NUSEX [17], IMB [18], Kamiokande [19], Frejus [20], Soudan2 [21], Superkamiokande [22], MACRO [23] have been performed. NUSEX and Frejus concluded that the ratio was the same as the theoretical prediction, but IMB, Kamiokande, Soudan2, Superkamiokande have reported that the double ratio $R \equiv [\#(\nu_\mu + \bar{\nu}_\mu)_{\rm data}/\#(\nu_\mu + \bar{\nu}_\mu)_{\rm MC}][\#(\nu_e + \bar{\nu}_e)_{\rm data}/\#(\nu_e + \bar{\nu}_e)_{\rm MC}]^{-1}$ is smaller than 1 (See the table on page 4 which is taken from [10]). It is not so clear how to interpret the results of NUSEX and Frejus, but as far as the other experiments are concerned, there is a difference between observations and theory, and this is called the atmospheric neutrino problem.

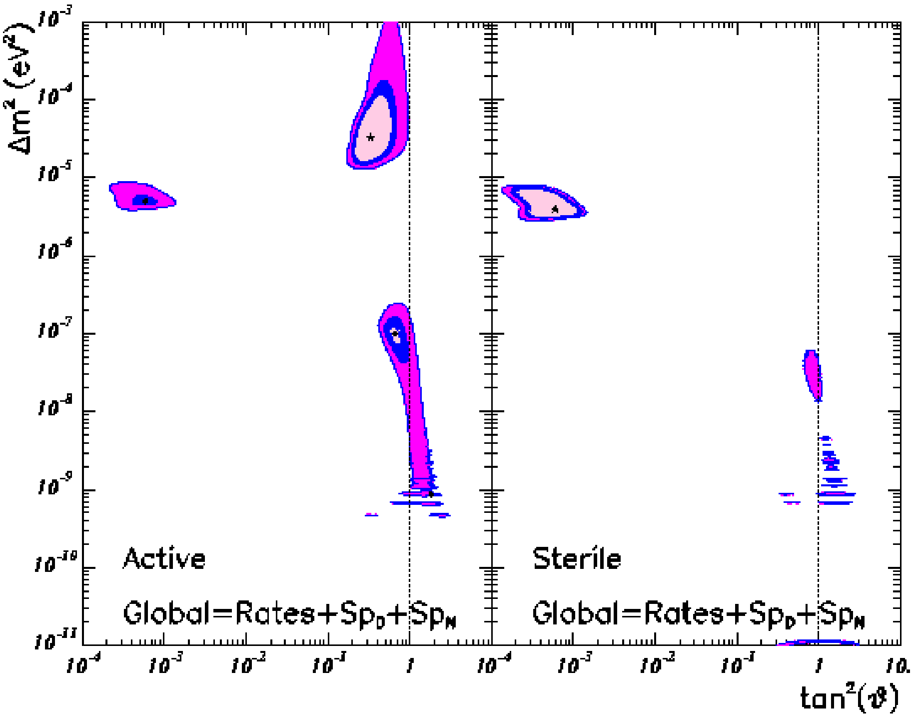

Figure 1: Results of recent analysis on solar neutrinos [13], which almost agrees with [14] and [15].

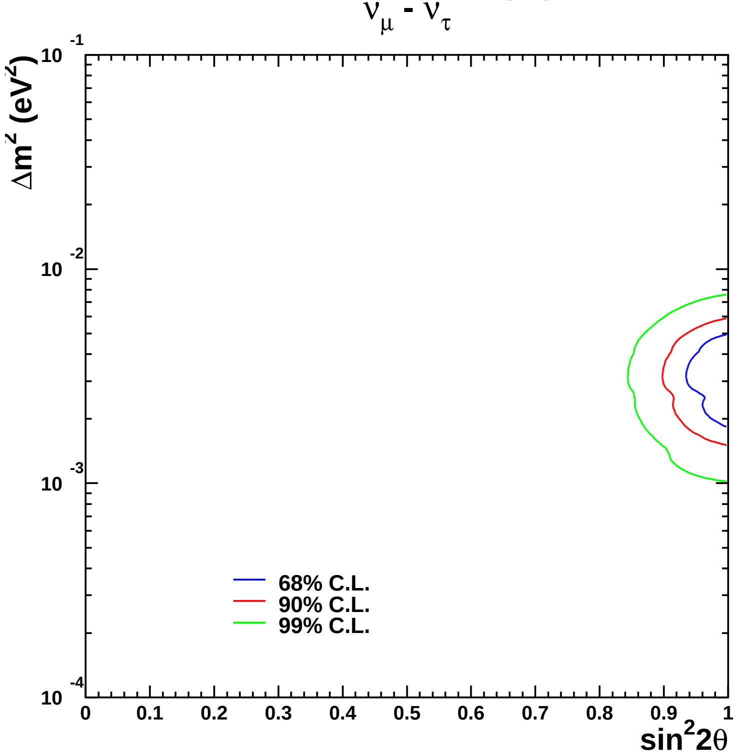

Figure 2: Allowed region from Superkamiokande contained and partially contained event for $\nu_\mu - \nu_\tau$ oscillations [16].

Experiment	technique	double ratio R	years of running
IMB	water Cherenkov	0.54±0.05±0.07	1982-1991
Kamiokande	water Cherenkov	0.60±0.06	1983-1995
Soudan 2	iron calorimeter	0.68±0.11±0.06	1989-1993-
Frejus	iron calorimeter	0.99±0.13±0.08	1984-1988
Baksan	liquid scintillator	0.85±0.03±0.05	1978-
Nusex	calorimeter	1.0±0.3	1982-1988
SuperKamiokande	water Cherenkov	(sub-GeV) 0.65±0.02±0.05 (multi-GeV) 0.67±0.03±0.08	1996-

In particular, in the so-called multi-GeV data (1 GeV$\lesssim E_\nu \lesssim$ 100GeV) of Kamiokande and Superkamiokande, while the value of the double ratio R is close to 1 for neutrinos which travel for a short length after their production above the detector, R is significantly smaller than 1 for neutrinos which travel across the Earth (zenith angle dependence). This phenomenon can be interpreted in terms of neutrino oscillations and it has been reported that the best fit value is $\Delta m^2 \simeq 3\times10^{-3}$eV^2 (See Fig. 2 for the allowed region of oscillation parameters from updated data). The zenith angle dependence of the double ratio is so remarkable that the atmospheric neutrino data can be regarded as evidence for neutrino oscillations.

1.4 Reactor and accelerator experiments

Reactor experiments are disappearance experiments of $\bar{\nu}_e$ produced in reactors, where people measure how many neutrinos are converted from $\bar{\nu}_e$ into something else at a given distance. So far all the reactor experiments have given negative results. Bugey[24] gave the strongest bound on $\sin^2 2\theta$, and CHOOZ[25] did on Δm^2 (See Fig. 3 for the excluded region).

Among all the accelerator experiments on neutrino oscillations, LSND[26], which looks at the channel $\bar{\nu}_\mu \to \bar{\nu}_e$, is the only experiment which reports an affirmative result (See Fig. 4 for the allowed region). If one combines this result with all other experiments, one gets 0.3 eV$^2 \lesssim \Delta m^2 \lesssim$ 2.3eV^2 at 90%CL. Until conclusive results are obtained by the new experiment MiniBooNE, which is starting from the end of the year 2000, it will remain unclear whether the LSND result is correct or not. If the LSND result is confirmed, then it becomes necessary to introduce so-called sterile neutrinos in order to explain the solar neutrino deficit, the atmospheric neutrino anomaly and the LSND result within the framework of neutrino oscillations.

1.5 Three flavor neutrino oscillations

We know that there are at least three kinds of light neutrinos so it is in principle necessary to discuss neutrino oscillations among three flavors. The flavor eigenstates are related to the mass eigenstates by the 3×3 MNS matrix:

$$\left(\begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array}\right) = \left(\begin{array}{ccc} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{array}\right) \left(\begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array}\right),$$

and without loss of generality we assume $|\Delta m^2_{21}| < |\Delta m^2_{32}| < |\Delta m^2_{31}|$ where $\Delta m^2_{ij} \equiv m^2_i - m^2_j$, $m^2_j(j = 1, 2, 3)$ are the mass squared for the mass eigenstates. If there are

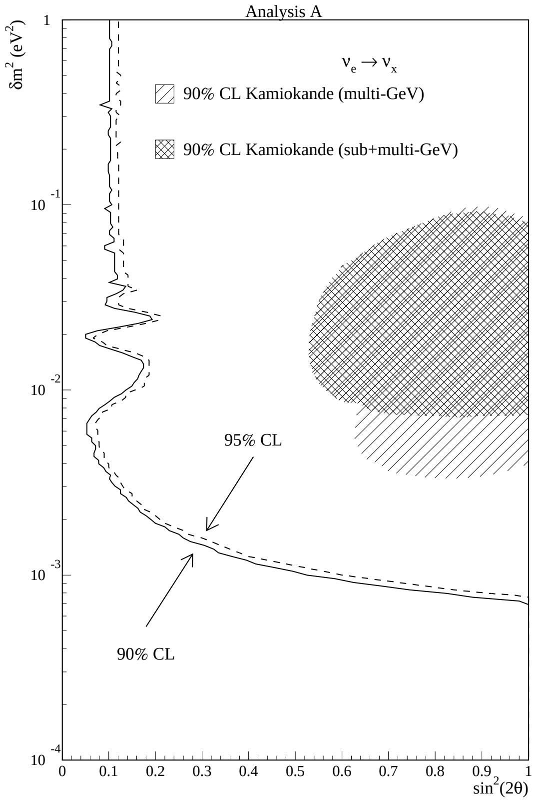

Figure 3: CHOOZ excluded region [25].

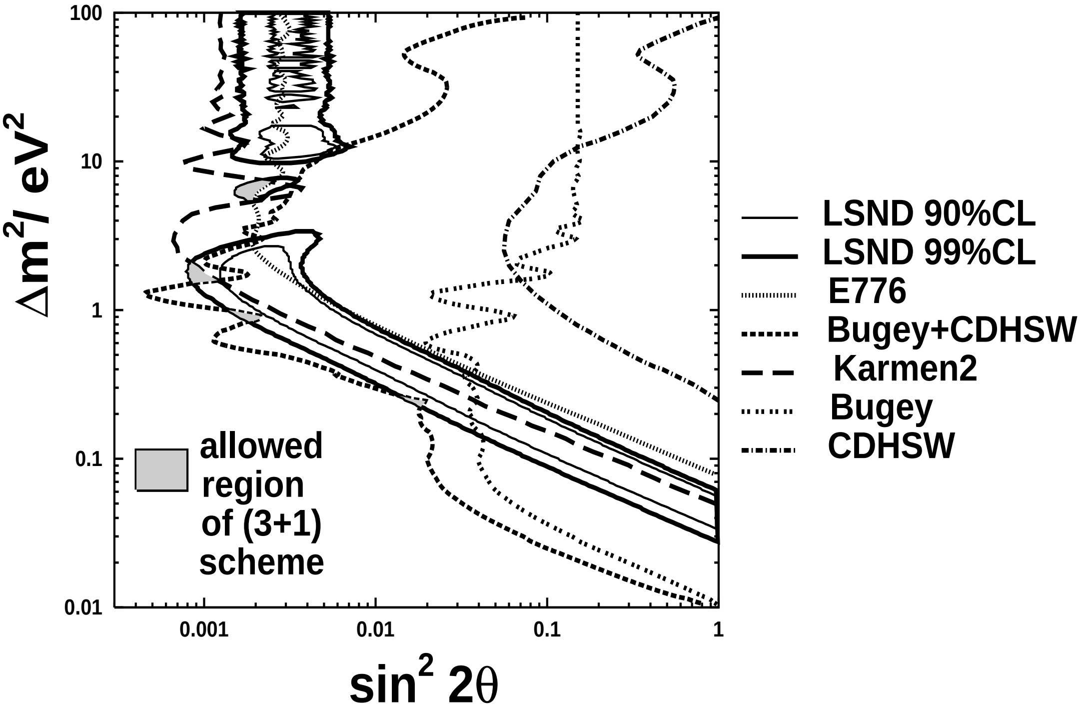

Figure 4: LSND allowed region from the the final result [26]. The inside of the thin and thick solid lines stand for 90%CL, 99%CL. All other experiments exclude the right side of each line.

only three kinds of neutrinos, then there are only two independent Δm^2_{ij} since $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$. In this case it is impossible to account for the solar neutrino deficit, the atmospheric neutrino anomaly and LSND (the only nontrivial possibility is to take the smaller Δm^2_{ij} as the scale of atmospheric and the larger as that of LSND and to try to explain the solar neutrino problem with the energy independent solution; It turns out, however, that the main oscillation channel in the atmospheric neutrinos is $\nu_\mu \leftrightarrow \nu_e$ in this case and therefore the zenith angle dependence of the atmospheric neutrino data cannot be explained). So we have to give up any efforts to explain LSND and we have to take the smaller Δm^2_{ij} as the scale $\Delta m^2_\odot$ of the solar neutrino problem and the larger as $\Delta m^2_{\rm atm}$ of the atmospheric neutrino anomaly. Under the present assumption it follows $\Delta m^2_{\rm atm} = \Delta m^2_{32} \gg \Delta m^2_{21} = \Delta m^2_\odot$ and we have a large hierarchy between Δm^2_{21} and Δm^2_{32}. If $|\Delta m^2_\odot L/4E| \ll 1$ then from a hierarchical condition we have the oscillation probability

$$P(\bar{\nu_e} \to \bar{\nu_e}) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right),$$

so if $\Delta m^2_{\rm atm} > 2 \times 10^{-3}{\rm eV}^2$ then the CHOOZ data force us to have either $\theta_{13} \simeq 0$ or $\theta_{13} \simeq \pi/2$. On the other hand, the solar oscillation probability in the three flavor framework is related to the one in the two flavor case by [27]

$$P^{(3)}(\nu_e \to \nu_e; A(x)) = c^4_{13} P^{(2)}(\nu_e \to \nu_e; c^2_{13} A(x)) + s^4_{13},$$

where $A(x)$ stands for the matter effect. To account for the solar neutrino deficit, therefore, $|s_{13}|$ cannot be too large, and it follows that $|\theta_{13}| \ll 1$, and the MNS mixing matrix U becomes

$$U \simeq \left(\begin{array}{ccc} c_\odot & s_\odot & \epsilon \\ -s_\odot/\sqrt{2} - c_\odot/\sqrt{2} & c_\odot/\sqrt{2} - s_\odot/\sqrt{2} & 1/\sqrt{2} \\ s_\odot/\sqrt{2} - c_\odot/\sqrt{2} & -c_\odot/\sqrt{2} - s_\odot/\sqrt{2} & 1/\sqrt{2} \end{array} \right),$$

which indicates that the solar neutrino problem is explained by oscillations, half of which are $\nu_e \to \nu_\mu$ and the other of which are $\nu_e \to \nu_\tau$, and that the atmospheric neutrino anomaly is accounted for by oscillations of almost 100% $\nu_\mu \to \nu_\tau$ ($|\epsilon| \equiv |\theta_{13}| \ll 1$).

On the other hand, if $\Delta m^2_{\rm atm} < 2\times 10^{-3}{\rm eV}^2$, then θ_{13} can be fairly large (This possibility gives a bad fit to the atmospheric neutrino data but is not excluded at 4σCL yet). From the combined three flavor analysis of the Superkamiokande atmospheric neutrino data with the CHOOZ data, it has been shown [28, 29] that $\theta_{13} \lesssim \pi/12$ is allowed at 99%CL. Hence the probability

$$P(\nu_\mu \to \nu_e) = s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

of appearance of ν_e can be relatively large and there is a chance in long baseline experiments to observe ν_e in this case.

1.6 Sterile neutrino ν_s

ν_s is a particle with spin 1/2 which is singlet with respect to the standard model gauge group, and it interacts with other neutrinos (active neutrinos) only through mass terms.

The difference of neutrino oscillations with and without ν_s is that ν_s has neither charged current nor neutral current interactions in matter. ν_e has both charged current and neutral current interactions, ν_μ and ν_τ have neutral current interactions, and ν_s has no interaction, so neutrino oscillations in matter can be described in this case by a Schrödinger equation

$$i\frac{d}{dx}\left(\begin{array}{c}\nu_\mu(x)\\ \nu_s(x)\end{array}\right) = \left[U\mathrm{diag}\left(0,\frac{\Delta m^2}{2E}\right)U^{-1}+\mathrm{diag}\left(A(x),0\right)\right]\left(\begin{array}{c}\nu_\mu(x)\\ \nu_s(x)\end{array}\right),$$

where

$$A(x) = -\frac{1}{\sqrt{2}}G_F N_n(x)$$

is the potential between ν_μ (or ν_τ) and ν_s, and $N_n(x)$ stand for the density of neutrons. Note the difference with the potential $A(x) = \sqrt{2}G_F N_e(x)$ for $\nu_e \leftrightarrow \nu_\mu$ (or $\nu_e \leftrightarrow \nu_\tau$). Therefore, there is a difference between neutrino oscillations $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ in the atmospheric neutrinos, due to the matter effect in the Earth. One of the reasons that ν_s have often been discussed since 1998 was because Liu et al.[30] claimed that the zenith angle dependence of the upward going μ data by the MACRO group is consistent with a theoretical prediction based on $\nu_\mu \leftrightarrow \nu_s$. Up until then people had believed that $\nu_\mu \leftrightarrow \nu_s$ cannot be used for the atmospheric neutrino anomaly, because $\Delta m^2 \sim 10^{-2}\mathrm{eV}^2$, $\sin^2\theta \sim 1$ contradicts the constraint from the Big Bang Nucleosynthesis (BBN), which tells us that $\Delta m^2 \sin^4 2\theta \lesssim 10^{-3}\mathrm{eV}^2$ has to be satisfied in order for the theoretical prediction of ^{4}He abundance to reproduce the observational value (in other words the effective number N_ν of light neutrinos which have been in thermal equilibrium has to be less than four) [31]. In the mean time it was pointed out by Foot and Volkas [32] that for a certain range of the oscillation parameters neutrino oscillations themselves create asymmetry between ν and $\bar{\nu}$, and the asymmetry prevents ν_s from oscillating into active neutrinos so that ν_s would not have been brought into equilibrium. That was how people started serious investigation of $\nu_\mu \leftrightarrow \nu_s$ as a scenario to account for the atmospheric neutrino anomaly. Furthermore, as of the year 2000, the estimate for N_ν is milder than before and $N_\nu = 4$ is allowed. In fact it has been shown recently [33] that the combined analysis of BBN and the recent data by BOOMERanG [34] and MAXIMA-1 [35] of the Cosmic Microwave Background prefers a higher value of N_ν: $4 \le N_\nu \le 13$. So $\nu_\mu \leftrightarrow \nu_s$ is acceptable for atmospheric neutrino oscillations, as far as cosmological constraints are concerned. However, it has been shown by the Superkamiokande group [36] that the high energy atmospheric neutrino events, such as upward going μ data and neutral current enriched multi-ring events, disfavor the scenario $\nu_\mu \leftrightarrow \nu_s$ at 99%CL.

On the other hand, the possibility of sterile neutrino oscillations $\nu_e \leftrightarrow \nu_s$ in solar neutrinos has also been explored. The main difference between active and sterile oscillations in the case of solar neutrinos lies in the prediction for rates of water Cherenkov experiments which would also measure ν_μ and ν_τ due to neutral current interactions in the case of active oscillations. For sterile oscillations rates of water Cherenkov experiments are smaller than those for the active case, so the only possible scenario is the SMA MSW solution which can create large difference between water Cherenkov and chlorine experiments because of its non-flat energy spectrum. By looking for a possible day-night asymmetry of the flux, the Superkamiokande group concluded at Neutrino 2000 that the $\nu_e \leftrightarrow \nu_s$ is disfavored at 95%CL. Thus pure sterile oscillations are disfavored both in atmospheric and solar neutrino oscillations.

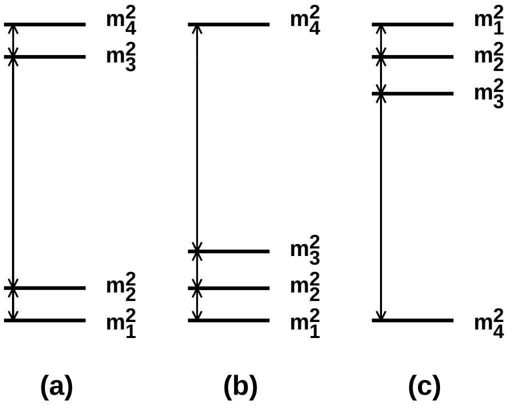

Figure 5: Mass patterns of four neutrino schemes. (a) corresponds to (2+2)-scheme, where either ($|\Delta m^2_{21}| = \Delta m^2_\odot$, $|\Delta m^2_{43}| = \Delta m^2_{\rm atm}$) or ($|\Delta m^2_{43}| = \Delta m^2_\odot$, $|\Delta m^2_{21}| = \Delta m^2_{\rm atm}$). (b) and (c) are (3+1)-scheme, where $|\Delta m^2_{41}| = \Delta m^2_{\rm LSND}$ and either ($|\Delta m^2_{21}| = \Delta m^2_\odot$, $|\Delta m^2_{32}| = \Delta m^2_{\rm atm}$) or ($|\Delta m^2_{32}| = \Delta m^2_\odot$, $|\Delta m^2_{21}| = \Delta m^2_{\rm atm}$) is satisfied.

1.7 Neutrino oscillations among (3+1) neutrinos

If the solar neutrino deficit, the atmospheric neutrino anomaly and the LSND result turn out to be all due to neutrino oscillations, then we have to introduce sterile neutrinos to account for all the three anomalies. In the case of four neutrino schemes there are two distinct types of mass patterns. One is the so-called (2+2)-scheme (Fig. 5(a)) and the other is the (3+1)-scheme (Fig. 5(b) or (c)). Depending on the type of the two schemes, the phenomenology is different.

It has been shown in Refs. [40, 41] using the older data of LSND [26] that the (3+1)-scheme is inconsistent with the Bugey reactor data[24] and the CDHSW disappearance experiment[42] of ν_μ. However, in the final result the allowed region has shifted to the lower value of $\sin^2 2\theta$ and it was shown [43] that there are four isolated regions $\Delta m^2_{\rm LSND} \simeq$0.3, 0.9, 1.7, 6.0 eV^2 which satisfy the constraints of Bugey and CDHSW and the LSND data at 99%CL. The case with $\Delta m^2_{\rm LSND}$=0.3 eV^2 turns out to be excluded by the Superkamiokande atmospheric neutrino data. In the case of the (3+1)-scheme with $\Delta m^2_{\rm LSND} \simeq$0.9, 1.7, 6.0 eV^2, if the contribution of sterile neutrino oscillations to the atmospheric neutrino is small, then the phenomenology is basically the same as that of the ordinary three flavor scenario, and it would be naively difficult to distinguish it from the ordinary one with three flavors, except in precise long baseline experiments [37, 38] or in high energy cosmic neutrino experiments which might be able to see an enhancement due to matter effects of the Earth [39].

In the case of the (2+2)-scheme, it was shown [40, 44] that if we postulate all the constraints of the reactor and accelerator experiments and the BBN constraint without asymmetry in ν and $\bar{\nu}$, then it follows that $\nu_e \leftrightarrow \nu_s$ accounts for the solar neutrino problem with the SMA MSW solution, while $\nu_\mu \leftrightarrow \nu_\tau$ explains the atmospheric anomaly, and the small mixing between ν_e and ν_μ does the LSND result. However, pure sterile oscillations in the solar neutrino data are excluded by the Neutrino 2000 Superkamiokande data, so this argument has to be given up. Since the constraint on the effective number N_ν of the light neutrinos became less stringent, people have started investigating the possibility of hybrid oscillations with active and sterile neutrinos. Giunti et al. [45] worked on the solar neutrino data and Yasuda [46] on the atmospheric neutrino data. Both data sets allow hybrid oscillations and by combining these two results it can be shown that the only possibility which is consistent with the up-to-date Superkamiokande data on solar and atmospheric neutrinos as well as all other reactor and accelerator experiments is a hybrid scenario in which the solar neutrino deficit is accounted for by $\nu_e \leftrightarrow \nu_{\rm active}$ and $\nu_e \leftrightarrow \nu_s$ while the atmospheric neutrino anomaly is explained by $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$, with weight of the same order, respectively. This scenario predicts phenomenology which is quite different from the ordinary three flavor scheme and it can be tested in the near future long baseline experiments.

1.8 Hot dark matter and $\beta\beta_0$ decay experiments

Hot dark matter (HDM) is not a subject directly related to neutrino oscillations, but HDM is one of the objects which might suggest neutrino mass. It has been suggested that a mixed dark matter scenario, which consists of both cold dark matter (CDM) components (heavy particles such as axions) and HDM components (neutrinos), accounts for the spectrum of density fluctuations in the structure formation of the universe. If this assertion is established, then it follows that neutrinos have mass of order a few eV. On the other hand, recent observations suggest a fairly large contribution of cosmological constant to the mean mass density of the universe and it has been claimed that there is not much room for neutrino masses ($\sum_j m_{\nu_j} <$ 4eV at 95%CL [47]), contrary to what has been suggested for HDM before. Due to large systematic errors in cosmological observations, however, it may be premature to give a conclusion on neutrino masses by cosmological arguments only.

If neutrinos have masses which are of order 1eV (in this case the mass pattern has to be that of almost degenerate type since the mass squared differences suggested by the solar and atmospheric neutrino data are much smaller than 1eV^2), then there is a good chance for neutrinoless double β decay experiments to see positive signals in the near future [48]. On the other hand, if the largest mass of neutrinos is of order $(\Delta m^2_{\rm atm})^{1/2}$ then it is a challenging problem for the future projects of neutrinoless double β decay experiments (See [49] and references therein).

1.9 Exotic solutions

Apart from ordinary oscillations due to masses, several possibilities have been proposed which predict different behaviors of the oscillation probability as a function of the neutrino energy. Those include violation of the equivalence principle [50], violation of the Lorentz invariance [51], presence of torsion [52], flavor changing neutral current interactions [53], neutrino decays [54, 55], decoherence of the neutrino beam [56], large extra dimensions [57], etc. As in the case of test of sterile oscillations, the zenith angle dependence (or the up-down asymmetry) of the high energy atmospheric neutrino data give strong constraints on these exotic scenarios. In the case of violation of the equivalence principle or the Lorentz invariance, the ν_μ disappearance probability $P_{\mu\mu} \equiv P(\nu_\mu \to \nu_\mu; L)$ is given by

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2 ({\rm const} \cdot EL)$$

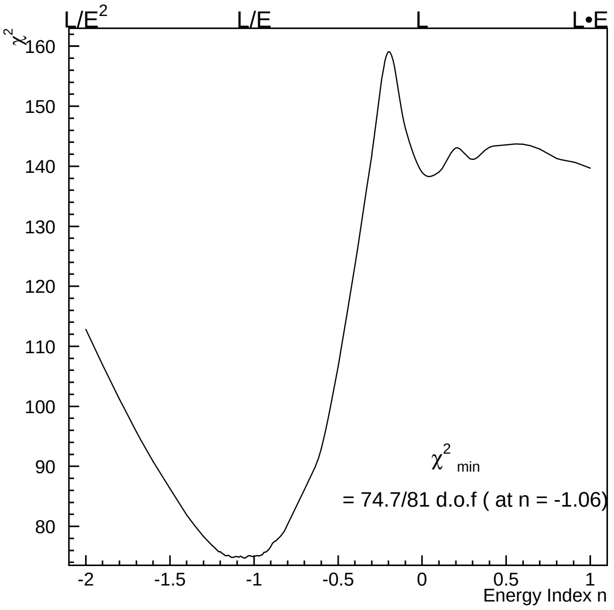

Figure 6: χ^2 of the SK atmospheric neutrino data as a function of index n ($1 - P_{\mu\mu} = \sin^2 2\theta \sin^2(\mathrm{const}E^n L)$) [16]. $n = -1$ corresponds to ordinary oscillations due to masses.

and in the case of flavor changing neutral current interactions

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2 (\mathrm{const} \cdot L)\,.$$

Both possibilities are strongly disfavored (See Fig. 6). In the case of neutrino decays, which were originally introduced to try to explain the solar, atmospheric neutrinos and the LSND within the three flavor framework with two oscillation parameters Δm^2_{21}, Δm^2_{32} and one neutrino decay constant α, the disappearance probability is

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta \exp(-\alpha L/E) + \frac{1}{2}\sin^2 2\theta \exp(-\alpha L/2E) \cos\left(\Delta m^2 L/2E\right)$$

which has the following two extreme cases:

$$\begin{array}{lcll} P_{\mu\mu} & = & \sin^4\theta + \cos^4\theta \exp(-\alpha L/E) & \Delta m^2 \to \infty \quad \text{(case A)}, \\ P_{\mu\mu} & = & \left[\sin^2\theta + \cos^2\theta \exp(-\alpha L/2E)\right]^2 & \Delta m^2 \to 0 \quad \text{(case B)}. \end{array}$$

If the case A gave a good fit to the data then it would be possible to account for the solar neutrino deficit, the atmospheric neutrino anomaly and the LSND data within the three flavor framework by putting $\Delta m^2_{21} = \Delta m^2_{\odot}$, $\Delta m^2_{32} = \Delta m^2_{\rm LSND}$, $\alpha = \Delta m^2_{\rm atm}$, but unfortunately it is not the case. It has been shown that the case A gives a bad fit [54] but the case B gives a good fit to the data [55]. Similarly, decoherence of the neutrino beam predicts

$$P_{\mu\mu} = 1 - \sin^2 2\theta \left(1 - e^{-\gamma L}\right),$$

and this scenario has been shown to give a good fit to the data. Before the announcement against sterile oscillations in both solar and atmospheric neutrino data by the Superkamiokande group in June 2000, several groups claimed [57] that scenarios of large extra dimension give a good fit to the data of solar neutrinos or atmospheric neutrinos. However, oscillations predicted by those scenarios are basically sterile oscillations and they may no longer give a good fit to the data.

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2 Summary of research results

One of the main subjects Yasuda has been working on is examination of a hypothesis that the atmospheric neutrino anomaly is explained by neutrino oscillations. By numerical calculations which almost simulate the Monte Carlo results by Super-Kamiokande, various aspects of the atmospheric neutrino data were worked out. The atmospheric neutrino data of Super-Kamiokande were analyzed in the frameworks of two, three and four flavors. In the case of two flavors, the contained event data were analyzed under the hypothesis of $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ (sterile neutrinos) oscillations and both scenarios turned out to be acceptable [2, 7]. Also exotic possibilities, such as violation of the equivalence principle or flavor changing neutral current interactions were examined [6], and all these scenarios turned out to be acceptable as far as the contained events are concerned. In the case of three flavors, it was shown that a relatively large value of θ_{13} is allowed without the CHOOZ constraint [3, 4, 5]. In the case of four flavors, it was found that a large class of the hybrid oscillations with $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ is still allowed despite the zenith angle dependence of the upward going mu data by Super-Kamiokande [12, 14]. Combining this result and that by Gonzalez-Garcia et al. on the solar neutrino data, it was concluded that the only solutions consistent with the data of solar and atmospheric neutrinos are hybrid of active and sterile oscillations in both solar and atmospheric neutrinos and some implications to long baseline experiments were discussed [16].

Yasuda has also worked on the implications of neutrino oscillations for high energy cosmic neutrinos in the three and four flavor framework [10, 11]. It was shown that AMANDA-type experiments would not be able to gain any information in the three flavor case while some information on the mixing matrix may be obtained in the four flavor case.

Since the end of 1999 Yasuda has been mainly working on the phenomenology of long baseline experiments and neutrino factories. It was shown that the effects of CP violation can be enhanced due to matter effects if one looks at T violation at very low energy, even if the solar neutrino oscillation is described by the small mixing MSW solution [9]. Optimization of signals of CP violation at neutrino factories with respect to the baseline and the muon energy was also discussed and the conclusion was that the signal is optimized for the baseline approximately 3000km and the muon energy 50 GeV [13].

Minakata and Yasuda have worked on implications of massive neutrinos to neutrinoless double beta decay experiments [1, 8, 30]. By imposing constraints from both solar and atmospheric neutrino data possible consequences to neutrinoless double beta decay experiments were discussed, particularly in the case where all three neutrinos have masses of a few eV. It was found that a scheme with almost degenerate massive neutrinos which is suggested by the mixed dark matter scenario inevitably implies a positive signal in neutrinoless double beta decay experiments.

Minakata has worked on analyses of solar neutrino data with Nunokawa. By performing an updated model-independent analysis, it was found that astrophysical solutions to the solar neutrino problem are disfavored at more than 5σ and a new way of illuminating the suppression pattern of various solar neutrino fluxes was proposed [23, 24]. The possibility of observing CP violation in measurements of solar neutrinos was also examined and it was shown that the CP phase disappears in the survival probability of ν_e [25].

Minakata has also studied systematically with Nunokawa how to measure CP violation in long baseline neutrino experiments. In [21] CP violation and matter effects in neutrino oscillations were discussed in detail using perturbation theory in matter effects and it was shown that the genuine CP violating effect is small. In [26, 28] a phenomenon of "vacuum mimicking" was utilized in the context of the low-energy option and it preceded the proposal by B. Richter. Though the concrete experiment described in the work using 100 MeV neutrino beam is not completely feasible under the present technology, it can be a useful starting point toward searching for the optimal parameters.

Minakata also worked on supernova neutrinos in the three flavor framework of neutrino oscillations and it was shown that inverted and normal hierarchy patterns can be distinguished under a certain condition by neutrino conversion from supernovae [29]. Data of SN1987A were analyzed and a strong indication was obtained that the inverted mass hierarchy is disfavored unless θ_{13} is extremely small.

Kajita has been working on experiments of atmospheric and solar neutrinos as a leader in the Superkamiokande (SK) collaboration.

In February and May 1998 the SK group published papers on the sub-GeV [32] and the multi-GeV [33] data of atmospheric neutrinos for 25.5 kt·yr, and they have shown that the double ratios from both data give values which are significantly smaller than 1. Subsequently they published a paper [36, 37, 38] on the analysis of the contained and partially contained even data for 33.0 kt·yr, and from the zenith angle dependent deficit of mu-like events it was concluded that their data can be interpreted as evidence of neutrino oscillation. This work has caught a lot of attention not only from physicists but also from the media. The SK group has published its results on the upward through going μ data [41] and the upward stopping μ data [44]. Again their results are perfectly consistent with an oscillation hypothesis, although the allowed regions obtained were wider than that of the contained event data. They also published a paper on the East-West anisotropy of the atmospheric neutrino data [42] and they have shown that the azimuthal angle dependence of the data agrees with the prediction of the Monte Carlo simulations. Since the azimuthal angle dependence is supposed to be free from neutrino oscillations this result indicates that our knowledge on the atmospheric neutrino flux is correct. In [48] they have examined a hypothesis of sterile neutrino oscillations in the atmospheric neutrino data. By looking at the zenith angle dependence of the upward going μ data and the enriched neutral current multi-ring events, they excluded the $\nu_\mu \leftrightarrow \nu_s$ scenario at 95%CL. This work has given strong constraints on various models.

In the mean time the SK group has worked on solar neutrino experiments. In April 1998 they published the first paper on the solar neutrino data for 297 days from the SK experiments [34]. With the threshold energy 6.5 MeV they have observed the solar neutrino flux which is significantly smaller than the theoretical prediction and is consistent with the older results by Kamiokande. In October 1998 they published the result on the day-night asymmetry of the solar neutrino flux using their data for 504 days and they obtained the exclusion region in the oscillation parameter space [39]. In December 1998 they published a paper on the energy spectrum of solar neutrinos, again with their data for 504 days [40]. The energy spectrum turned out to be rather flat except for the high energy region ~ 14 MeV, where theory gives a poorer prediction due to the uncertainty on the hep neutrino flux. Measurement of radon concentration in the SK detector was performed using the radon monitoring system [43]. The radioactivity from radon, which is a major background for observing solar neutrinos, turned out to be quite small.

3 List of papers

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4 Oral presentations

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2. O. Yasuda
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5. O. Yasuda
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6. O. Yasuda
Phenomenology of Neutrino Oscillations at a Neutrino Factory, *KEK International Workshop on High Intensity Muon Sources (HIMUS 99)*, Tsukuba, Japan, 1 – 4 December 1999.

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5 Book edited

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