CITATION: R.M. Barnett *et al.* Physical Review D54, 1 (1996) and 1997 off-year partial update for the 1998 edition (URL: http://pdg.lbl.gov)

Massive Neutrinos and Lepton Mixing
THIS IS PART 4 OF 5

To reduce the size of this section's PostScript file, we have divided it into five PostScript files. We present the following index:

(E) Solar ν Experiments

SOLAR NEUTRINOS

(by K. Nakamura, KEK, National Laboratory for High-Energy Physics, Japan)

The Sun is a main-sequence star at a stage of stable hydrogen burning. It produces an intense flux of electron neutrinos as a consequence of nuclear fusion reactions which generate solar energy, and whose combined effect is

$$4p + 2e^- \rightarrow {}^4\text{He} \; + 2\nu_e + 26.73 \text{ MeV} - E_\nu \; , \tag{1}$$

where E_ν represents the energy taken away by neutrinos, with an average value being $\langle E_\nu \rangle \sim 0.6$ MeV. Each neutrino-producing reaction and the resulting flux predicted by the two recent standard solar model (SSM) calculations [1,2] are listed in Table 1. Figure 1 shows the energy spectra of solar neutrinos from these reactions quoted from the SSM calculation by Bahcall and Ulrich [3]. All SSM calculations give essentially the same results for the same input parameters and physics. The Bahcall and Pinsonneault model [1] and the Turck-Chièze and Lopes model [2] listed in Table 1 differ primarily in that Bahcall and Pinsonneault include helium diffusion [4].

Observations of solar neutrinos directly addresses the SSM and, more generally, the theory of stellar structure and evolution which is the basis of the SSM. The Sun as a well defined neutrino source also provides extremely important opportunities to investigate nontrivial neutrino properties such as nonzero mass and mixing, because of the wide range of matter density and the very long distance from the Sun to the Earth. In fact, the currently available solar-neutrino data seem to require such neutrino properties, if one tries to understand them consistently.

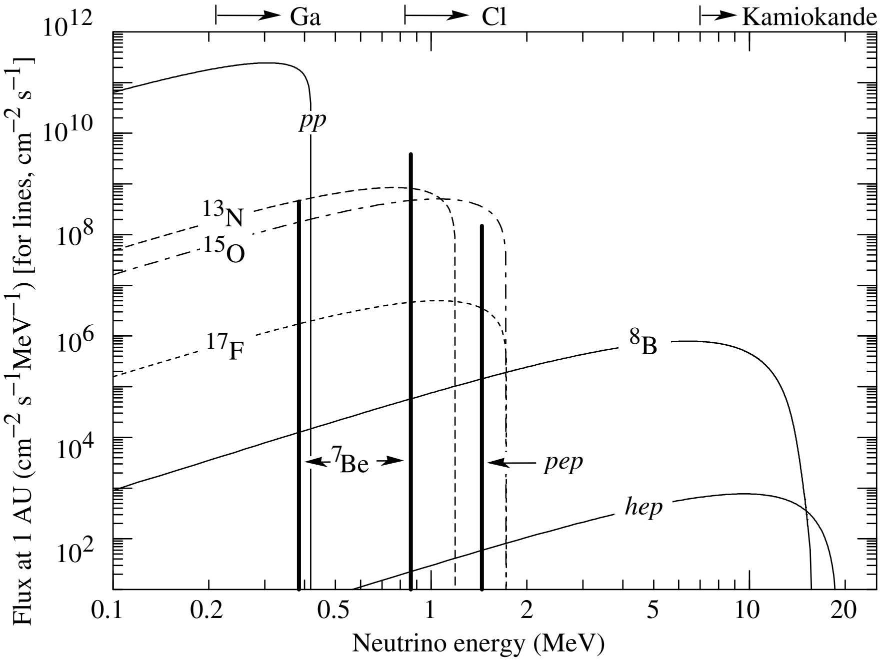

Figure 1: The solar neutrino spectrum predicted by the standard solar model. The neutrino fluxes from continuum sources are given in units of number $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{MeV}^{-1}$ at one astronomical unit, and the line fluxes are given in number $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Spectra for the *pp* chain are shown by solid lines, and those for the CNO chain by dotted or dashed lines. (Courtesy of J.N. Bahcall, 1995.)

At present, four solar-neutrino experiments are taking data. Three of them are radiochemical experiments using ^{37}Cl (Homestake in USA) or ^{71}Ga (GALLEX at Gran Sasso in Italy and SAGE at Baksan in Russia) to capture neutrinos:

Table 1: Neutrino-producing reactions in the Sun (the first column) and their abbreviations (second column). The neutrino fluxes predicted by Bahcall and Pinsonneault (B-P) [1] and by Turck-Chièze and Lopes (T-C-L) [2] are listed in the third and fourth columns, respectively. The errors associated with the B-P calculation are "theoretical" 3 standard deviations according to the authors.

Reaction	Abbr.	B-P	T-C-L
$pp \to d\, e^+\, \nu$	pp	$6.00(1 \pm 0.02)$E10	6.02E10
$pe^- p \to d\, \nu$	pep	$1.43(1 \pm 0.04)$E8	1.3E8
$^3\mathrm{He}\, p \to ^4\mathrm{He}\; e^+\nu$	hep	1.23E3	
$^7\mathrm{Be}\; e^- \to ^7\mathrm{Li}\; \nu + (\gamma)$	^{7}Be	$4.89(1 \pm 0.18)$E9	4.33E9
$^8\mathrm{B} \to {}^8\mathrm{B}^*\; e^+\nu$	^{8}B	$5.69(1 \pm 0.43)$E6	4.43E9
$^{13}\mathrm{N} \to {}^{13}\mathrm{C}\; e^+\nu$	^{13}N	$4.92(1 \pm 0.51)$E8	3.83E8
$^{15}\mathrm{O} \to {}^{15}\mathrm{N}\; e^+\nu$	^{15}O	$4.26(1 \pm 0.58)$E8	3.15E8
$^{17}\mathrm{F} \to {}^{17}\mathrm{O}\; e^+\nu$	^{17}F	$5.39(1 \pm 0.48)$E6	

$^{37}\mathrm{Cl}\ \nu_e \to {}^{37}\mathrm{Ar}\ e^-$ (threshold 814 keV) or $^{71}\mathrm{Ga}\ \nu_e \to {}^{71}\mathrm{Ge}\ e^-$ (threshold 233 keV). The produced ^{37}Ar and ^{71}Ge are both radioactive nuclei with half lives ($\tau_{1/2}$) of 34.8 days and 11.43 days, respectively. After an exposure of the detector for two to three times $\tau_{1/2}$, the reaction products are extracted and introduced into a low-background proportional counter, and are counted for a sufficiently long period to determine the exponentially decaying signal and a constant background. In the chlorine experiment, the dominant contribution comes from ^{8}B neutrinos, but ^{7}Be, *pep*, ^{13}N, and ^{15}O neutrinos also contribute. At present, the most abundant *pp* neutrinos can be detected only in gallium experiments. Even so, almost half of the capture rate in these experiments is due to other solar neutrinos.

The fourth is a real-time experiment utilizing νe scattering in a large water-Čerenkov detector (Kamiokande in Japan). This experiment takes advantage of the directional correlation between the incoming neutrino and the recoil electron. This feature greatly helps the clear separation of the solar-neutrino signal from the background. Due to its high threshold (7 MeV at present), Kamiokande observes pure ^{8}B solar neutrinos (*hep* neutrinos have too small a flux to be observed in the present generation of solar neutrino experiments.)

Solar neutrinos were first observed in the Homestake chlorine experiment around 1970. From the very beginning, it was recognized that the observed capture rate was significantly smaller than the SSM prediction. This deficit has been called "the solar-neutrino problem." The Kamiokande-II Collaboration started observing the ^{8}B solar neutrinos at the beginning of 1987. Because of the strong directional correlation of νe scattering, this result gave the first direct evidence that the Sun emits neutrinos (no directional information is available in radiochemical solar-neutrino experiments.) The observed solar-neutrino flux was also significantly less than the SSM prediction. In addition, Kamiokande-II obtained the energy spectrum of recoil electrons and the fluxes separately measured in the day time and nighttime. GALLEX presented the first evidence of *pp* solar-neutrino observation in 1992. Here also, the observed capture rate is significantly less than the SSM prediction. SAGE, after initial confusion which is ascribed to statistics by the group, observes a similar capture rate to that of GALLEX. The most recent results on the average capture rates or flux from these experiments [5–8] are compared with the recent SSM calculations [1,2] in Table 2.

There was a controversy concerning whether the ^{37}Cl capture rate showed time variation, anticorrelated with the sunspot numbers which represent the 11-year solar-activity cycle. However, more than 7 years of the Kamiokande-II solar-neutrino observation does not show evidence for a statistically significant

Table 2: Recent results from the four solar-neutrino experiments. For Homestake [5], GALLEX [6], and SAGE [7], the data are capture rates given in SNU (Solar Neutrino Units; 1 SNU = 10^{-36} capture per atom per second). For Kamiokande [8], the datum is ^{8}B solar-neutrino flux given in units of 10^6 cm^{-2} s^{-1}. The first errors are statistical and the second errors are systematic. The SSM predictions by Bahcall and Pinsonneault (B-P) [1] and by Turck-Chièze and Lopes (T-C-L) [2] are listed in the third and fourth columns, respectively. The errors associated with the B-P calculation are "theoretical" 3 standard deviations according to the authors.

Experiment	Data	B-P	T-C-L
Homestake	$2.55 \pm 0.17 \pm 0.18$	8.0 ± 3.0	6.4
GALLEX	$79 \pm 10 \pm 6$	131.5^{+21}_{-17}	122.5
SAGE	73^{+18+5}_{-16-7}	131.5^{+21}_{-17}	122.5
Kamiokande	$2.89^{+0.22}_{-0.21} \pm 0.35$	5.7 ± 2.4	4.4

correlation or anticorrelation between the solar-neutrino flux and sunspot number.

All results from the present solar-neutrino experiments indicate significantly less flux than expected from the SSM calculations. Is there any possible consistent explanation of all the results of solar-neutrino observations in the framework of the standard solar model? This is difficult because the Homestake result and the Kamiokande result, taken at face value, are mutually inconsistent if one assumes standard neutrino spectra. That is, with the reduction factor of the ^{8}B solar-neutrino flux as determined from the Kamiokande result, the Homestake ^{37}Cl capture rate would be oversaturated, and there would be no room to accommodate the ^{7}Be solar neutrinos. Several authors made more elaborate analyses using the constraint of observed solar luminosity, and found that not only the SSM but also nonstandard solar models are incompatible with the observed data. Now it is a common understanding that the solar-neutrino problem is not only the deficit of the ^{8}B solar-neutrino flux, but also the deficit of ^{7}Be solar-neutrino flux. The latter problem stems from the incompatibility between the Homestake and Kamiokande results and this makes astrophysical solutions untenable. There is another solar-neutrino problem concerning the low gallium capture rate observed by GALLEX and SAGE.

In view of the above situation, it is attractive to invoke nontrivial neutrino properties. Neutrino oscillation in matter (MSW mechanism) is particularly attractive in explaining all the experimental data on the average solar-neutrino flux consistently, without any a priori assumptions or fine tuning. Several authors made extensive MSW analyses using all the existing data and ended up with similar results. For example, Hata and Langacker [9] analyzed the solar-neutrino data as of mid-1993. They obtained solutions for various standard and nonstandard solar models taking the Earth effect and the Kamiokande day-night data into account. Assuming the Bahcall-Pinsonneault SSM [1], the small-mixing solution ($\Delta m^2 \sim 6 \times 10^{-6}$ eV^2 and $\sin^2 2\theta \sim 7 \times 10^{-3}$) gives an excellent fit to the data, but the large-mixing solution ($\Delta m^2 \sim 9 \times 10^{-6}$ eV^2 and $\sin^2 2\theta \sim 0.6$) is marginally allowed at 90% confidence level.

Assuming that the solution to the solar-neutrino problem be provided by some nontrivial neutrino properties, how can one discriminate various scenarios? There are at least two very important things to do experimentally. One is the measurement of energy spectrum of the solar neutrinos and the other is the measurement of the solar-neutrino flux by utilizing neutral-current reactions. Two high-statistics solar-neutrino experiments which are under construction, SuperKamiokande and Sudbury Neutrino Observatory (SNO) are expected to provide such results within a few years. A 50 kton water-Čerenkov detector, SuperKamiokande is sensitive to the solar-neutrino spectrum through measurement of recoil electron energy. SNO will use 1,000 tons of heavy water (D_2O) to measure solar neutrinos through both inverse beta decay ($\nu_e d \to e^- pp$) and neutral current interactions ($\nu_x d \to \nu_x pn$). In addition, νe scattering events will also be measured. The Borexino experiment with 300 tons of ultra-pure liquid scintillator is approved for the Gran Sasso. The primary purpose of this experiment is the measurement of the ^{7}Be solar neutrino flux, where possible deficit is now a key question, by lowering the detection threshold for the recoil electrons to 250 keV. It is hoped that these experiments will finally provide the key to solving the solar-neutrino problem.

References

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VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$77.1 \pm 8.5^{+4.4}_{-5.4}$ SNU	[98] ANSELMANN	95B	GALX	^{71}Ga → ^{71}Ge
$73^{+18}_{-16}{}^{+5}_{-7}$ SNU	[99] ABDURASHI...	94	SAGE	^{71}Ga → ^{71}Ge
$(0.46 \pm 0.05 \pm 0.06) \times$SSM	[100] HIRATA	90	KAM2	Water Cerenkov
2.33 ± 0.25 SNU	[101] DAVIS	89	HOME	^{37}CL radiochemical

• • • We do not use the following data for averages, fits, limits, etc. • • •

	[102] ACKER	94	THEO	Solar ν decay
	[103] BAHCALL	94	THEO	
	[104] BAHCALL	93		
	[105] HAMPEL	93	RVUE	
6.4 ± 1.4 SNU	[106] TURCK-CHI...	93B	THEO	^{37}CL radiochemical
$(4.4 \pm 1.1) \times 10^{-6}$ cm^{-2}s^{-1}	[106] TURCK-CHI...	93B	THEO	Water Cerenkov, $E \geq 7.5$ MeV
123 ± 7 SNU	[106] TURCK-CHI...	93B	THEO	^{71}Ga $\rightarrow$ ^{71}Ge
8.0 ± 3.0 SNU	[107] BAHCALL	92		^{37}Cl prediction
132^{+21}_{-17} SNU	[107] BAHCALL	92		^{71}Ga prediction
	[108] GARCIA	91	CNTR	Nuclear physics
	[109] HIRATA	91	KAM2	
	[110] FILIPPONE	90	THY	
	[111] HIRATA	90B	KAM2	
7.9 ± 2.6 SNU	[112] BAHCALL	88	THEO	^{37}Cl prediction; total theor. range
132^{+20}_{-17} SNU	[112] BAHCALL	88	THEO	^{71}Ga prediction; total theor. range
5.8 ± 1.3 SNU	TURCK-CHI...	88	THEO	^{37}Cl prediction
125 ± 5 SNU	TURCK-CHI...	88	THEO	^{71}Ga prediction
5.6 SNU	[110] FILIPPONE	83	THEO	^{37}Cl prediction
7.6 ± 3.3 SNU	[113] BAHCALL	82		^{37}Cl prediction
$106^{+13}_{-\ 8}$ SNU	[113] BAHCALL	82		^{71}Ga prediction
7.0 ± 3.0 SNU	FILIPPONE	82	THEO	^{37}Cl prediction
6.9 ± 1.0 SNU	FOWLER	82	THEO	^{37}Cl prediction
7.3 SNU	BAHCALL	80	THEO	^{37}CL prediction

See also the reviews by BAHCALL 92, DAVIS 89, and ACKER 94. The latter rules out neutrino decay as a solution to the solar neutrino problem at better than 98% using the existing solar neutrino as of mid-1993.

[98] ANSELMANN 95B result is for a total of 39 completed runs (GALLEX I and GALLEX II combined), which updates the ANSELMANN 94 result. The total run data, covering the period 14 May 1991 through 22 June 1994, are consistent with a ^{71}Ge production rate constant in time. The results are strengthened by a calibration run using a strong ^{51}Cr source (ANSELMANN 95), where the (measured)/(expected) Cr-induced ^{71}Ge rate was found to be 1.04 ± 0.12.

[99] ABDURASHITOV 94 result is for a total of 15 runs from January 1990 through May 1992, using 30 tons of metallic gallium for the first 7 runs, increased to 57 tons for the rest of 8 runs. The first 5 runs in 1990 yielded $40^{+31}_{-38}{}^{+5}_{-7}$ SNU which updates the ABAZOV 91B result.

[100] HIRATA 90 data consists of 1040 days with threshold $E_e > 9.3$ MeV (first 450 days) or $E_e > 7.5$ MeV. "The total data sample is also analyzed for short-term variations; within the statistical error, no significant variation is observed." The flux is scaled by the value relative to the standard solar model (SSM) prediction. A theoretical flux of $(5.8 \pm 2.1) \times 10^6$ cm^{-2} s^{-1} is cited, with the central value corresponding to 7.9 SNU for ^{37}Cl experiment (but see TURCK-CHIEZE 93B and other theoretical calculations.) The analysis is more fully reported in HIRATA 91B. Earlier analyses were reported by HIRATA 91 and HIRATA 90B.

[101] DAVIS 89 is the average from the ^{37}CL experiment at the Homestake Mine (HOME) from 1970–1988. Earlier averages are given in the references therein.

[102] ACKER 94 rules out neutrino decay as a solution to the solar neutrino problem at better than 98% CL, using the existing solar neutrino data as of mid-1993.

[103] BAHCALL 94 argues that there are really two solar neutrino problems: (1) incompatibility of the chlorine (Homestake) and Kamiokande experiments, (2) deficiency of the observed solar neutrino flux in the gallium experiments.

[104] BAHCALL 93 is a study of 1000 solar models in which each input parameter is chosen from a normal distribution with the appropriate mean and error. It is concluded that "Even if one abuses the solar models by artifically imposing consistency with the Kamiokande experiment, the resulting predictions of all 1000 of the 'fudged' solar models are inconsistent with the result of the chlorine experiment."

[105] HAMPEL 93, by a member of the GALLEX collaboration, is a discussion of possible scenarios to explain the combined solar neutrino experimental data.

[106] TURCK-CHIEZE 93B proposes new results on the solar neutrino predictions and acoustic mode frequencies. See also TURCK-CHIEZE 93 for an extensive review (233 pages, 524 references) concerning the solar interior. Table 17 provides a particularly useful comparison of experiment and theory as of mid-1993.

[107] BAHCALL 92 is an extensive discussion of theoretical neutrino flux calculations with predicted event rates for various different solar neutrino detectors. "The quoted errors represent the total theoretical range and include the effects on the model predictions of 3σ errors in measured input parameters."

[108] GARCIA 91 reports a new study of ^{37}Caβ decays, with the result that the BAHCALL 88 SSM prediction for ^{37}Cl should be increased from 7.9 to 8.1 SNU.

[109] HIRATA 91 reports a search for day-night and semi-annual variations in the solar neutrino flux observed in the Kamiokande II Detector. The sample is the same 1040 day counting period used for HIRATA 90 and HIRATA 90B. "Within statistical error, no such short-time variations were observed." This result was used to constrain neutrino oscillation parameters, in the framework of oscillations between two mass eigenstates. "A region defined by $\sin^2 2\theta >$ 0.02 and 2×10^{-6} eV^2 $< \Delta(m^2) < 1 \times 10^{-5}$ eV^2 is excluded at the 90% CL without any assumptions on the absolute value of the expected solar neutrino flux."

[110] In a later unbiased analysis, FILIPPONE 90 show that the hypothesis of a time-independent ^{37}Cl neutrino capture rate is marginally rejected, having only 2% probability. However, it is disturbing that we are not able to find a simple hypothesis of time variation that would describe the data well. A capture rate anticorrelated with sunspot number, although more probable than the constant rate hypothesis, has a probablity of only 6%. One possible explanation of these results is simply the poor statistics of the ^{37}Cl experiment."

[111] HIRATA 90B gives an analysis of the implications of these data for allowed values of $\Delta(m^2)$ and $\sin^2 2\theta$ describing neutrino mixing between two mass eigenstates, in the model of resonant (MSW) neutrino oscillations. The possibility of regeneration as the neutrinos pass through the earth is neglected. Two limits are given, the first from the measured event rate alone, and the second from the combination of the measured event rate and the recoil electron energy spectrum. The latter "disfavor the region of adiabatic solutions $\Delta(m^2) \sim 1.3 \times 10^{-4}$ eV^2 and $7.2 \times 10^{-4} < \sin^2 2\theta < 6.3 \times 10^{-3}$ at 90%CL." The allowed regions in $\sin^2 2\theta$ vs. $\Delta(m^2)$ are given graphically; see Figs. 2(a) and 2(b) in the paper.

[112] BAHCALL 88 "total theoretical range is calculated by evaluating the 3σ uncertainties for all measured input parameters and using the full spread in calculated values for input quantitites that cannot be measured; the uncertainties from different quantities are combined quadratically." (Quotation from BAHCALL 89, p. 301.)

[113] BAHCALL 82 quotes "effective 3σ errors." First extensive discussion of formal uncertainties in the problem.

(F) Astrophysical neutrino observations

Neutrinos and antineutrinos produced in the atmosphere induce μ-like and e-like events in underground detectors. The ratio of the numbers of the two kinds of events is defined as μ/e. It has the advantage that that systematic effects, such as flux uncertainty, tend to cancel, for both experimental and theoretical values of the ratio. The "ratio of the ratios" of experimental to theoretical μ/e, $R(\mu/e)$, is reported below. If the actual value is not unity, the value obtained in a given experiment may depend on the experimental conditions.

R(μ/e) = (Measured Ratio μ/e) / (Expected Ratio μ/e)

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.00 \pm 0.15 \pm 0.08$	[114] DAUM	95	FREJ	Calorimeter
$0.60^{+0.06}_{-0.05} \pm 0.05$	[115] FUKUDA	94	KAM2	sub-GeV
$0.57^{+0.08}_{-0.07} \pm 0.07$	[116] FUKUDA	94	KAM2	multi-Gev
	[117] BECKER-SZ...	92B	IMB	Water Cerenkov

[114] DAUM 95 results are based on an exposure of 2.0 kton yr which includes the data used by BERGER 90B. This ratio is for the contained and semicontained events. DAUM 95 also report $R(\mu/e) = 0.99 \pm 0.13 \pm 0.08$ for the total neutrino induced data sample which includes upward going stopping muons and horizontal muons in addition to the contained and semicontained events.

[115] FUKUDA 94 result is based on an exposure of 7.7 kton yr and updates the HIRATA 92 result. The analyzed data sample consists of fully contained e-like events with $0.1 < p_e < 1.33$ GeV/c and fully-contained μ-like events with $0.2 < p_\mu < 1.5$ GeV/c.

[116] FUKUDA 94 analyzed the data sample consisting of fully contained events with visible energy > 1.33 GeV and partially contained μ-like events.

[117] BECKER-SZENDY 92B reports the fraction of nonshowering events (mostly muons from atomospheric neutrinos) as $0.36 \pm 0.02 \pm 0.02$, as compared with expected fraction $0.51 \pm 0.01 \pm 0.05$. After cutting the energy range to the KAM2 limits, BEIER 92 finds $R(\mu/e)$ very close to the KAM2 value.

R(ν_μ) = (Measured Flux of ν_μ) / (Expected Flux of ν_μ)

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.73 \pm 0.09 \pm 0.06$	[118] AHLEN	95	MCRO	Streamer tubes
	[119] CASPER	91	IMB	Water Cherenkov
	[120] AGLIETTA	89	NUSX	
0.95 ± 0.22	[121] BOLIEV	81		Baksan
0.62 ± 0.17	CROUCH	78		Case Western/UCI

[118] AHLEN 95 result is for all nadir angles. The lower cutoff on the muon energy is 1 GeV. The errors are statistical / systematic. The Monte Carlo flux error is ± 0.12.

[119] CASPER 91 correlates showering/nonshowering signature of single-ring events with parent atmospheric-neutrino flavor. They find nonshowering ($\approx \nu_\mu$ induced) fraction is $0.41 \pm 0.03 \pm 0.02$, as compared with expected 0.51 ± 0.05 (syst).

[120] AGLIETTA 89 finds no evidence for any anomaly in the neutrino flux. They define ρ = (measured number of ν_e's)/(measured number of ν_μ's). They report ρ(measured)=ρ(expected) $= 0.96^{+0.32}_{-0.28}$.

[121] From this data BOLIEV 81 obtain the limit $\Delta(m^2) \leq 6 \times 10^{-3}$ eV^2 for maximal mixing, $\nu_\mu \not\to \nu_\mu$ type oscillation.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\nu_e \leftrightarrow \nu_\mu$)

For a review see BAHCALL 89.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.55	90	[122] FUKUDA	94	KAM2	$\Delta(m^2)$ = 0.007–0.08 ev^2
>0.33	90	[123] HIRATA	92	KAM2	$\Delta(m^2) > 0.004$ eV^2
<0.47	90	[124] BERGER	90B	FREJ	$\Delta(m^2) > 1$ eV^2
<0.14	90	LOSECCO	87	IMB	$\Delta(m^2)$= 0.00011 eV^2

[122] FUKUDA 94 obtained this result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande.

[123] HIRATA 92 states that the allowed region for $\nu_e \leftrightarrow \nu_\mu$ conflicts with the constraints from the solar neutrino data (HIRATA 90B).

[124] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_e \leftrightarrow \nu_\mu$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$700 < \Delta(m^2) < 7000$	90	[125] FUKUDA	94	KAM2
<150	90	[126] BERGER	90B	FREJ

[125] FUKUDA 94 obtained this result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande.

[126] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\overline{\nu}_e \leftrightarrow \overline{\nu}_\mu$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.9	99	[127] SMIRNOV	94	THEO	$\Delta(m^2) > 3 \times 10^{-4}$ eV^2
<0.7	99	[127] SMIRNOV	94	THEO	$\Delta(m^2) < 10^{-11}$ eV^2

[127] SMIRNOV 94 analyzed the data from SN 1987A using stellar-collapse models. They also give less stringent upper limits on $\sin^2 2\theta$ for $10^{-11} < \Delta(m^2) < 3 \times 10^{-7}$ eV^2 and $10^{-5} < \Delta(m^2) < 3 \times 10^{-4}$ eV^2. The same results apply to $\overline{\nu}_e \leftrightarrow \overline{\nu}_\tau$, ν_μ, and ν_τ.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.65	90	[128] FUKUDA	94	KAM2	$\Delta(m^2)$ = 0.005–0.03 ev^2
>0.5	90	[129] BECKER-SZ...	92	IMB	$\Delta(m^2)$= 1–2 $\times 10^{-4}$ eV^2
<0.6	90	[130] BERGER	90B	FREJ	$\Delta(m^2) > 1$ eV^2

[128] FUKUDA 94 obtained this result by a combined analysis of sub-and multi-GeV atmospheric neutrino events in Kamiokande.

[129] BECKER-SZENDY 92 uses upward-going muons to search for atomospheric ν_μ oscillations. The fraction of muons which stop in the detector is used to search for deviations in the expected spectrum. No evidence for oscillations is found.

[130] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE (10^{-5} eV^2)	*CL%*	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$500 < \Delta(m^2) < 2500$	90	[131] FUKUDA	94	KAM2
<350	90	[132] BERGER	90B	FREJ

[131] FUKUDA 94 obtained this result by a combined analysis of sub-and multi-GeV atmospheric neutrino events in Kamiokande.

[132] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \rightarrow \nu_s$)

ν_s means ν_τ or any sterile (noninteracting) ν.

VALUE (10^{-5} eV^2)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3000 (or <550)	90	[133] OYAMA	89		Kamiokande II
< 4.2 or $> 54.$	90	BIONTA	88	IMB	Flux has ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$

[133] OYAMA 89 gives a range of limits, depending on assumptions in their analysis. They argue that the region $\Delta(m^2) = (100\text{–}1000) \times 10^{-5}$ eV^2 is not ruled out by any data for large mixing.