# Neutrino Mixing

With the exception of a few possible anomalies such as LSND, current neutrino data can be described within the framework of a 3×3 mixing matrix between the flavor eigenstates $\nu_e$, $\nu_\mu$, and $\nu_\tau$ and the mass eigenstates $\nu_1$, $\nu_2$, and $\nu_3$. (See Eq. (14.6) of the review "Neutrino Mass, Mixing, and Oscillations" by K. Nakamura and S.T. Petcov.) The Listings are divided into the following sections:

**(A) Neutrino fluxes and event ratios:** shows measurements which correspond to various oscillation tests for Accelerator, Reactor, Atmospheric, and Solar neutrino experiments. Typically ratios involve a measurement in a realm sensitive to oscillations compared to one for which no oscillation effect is expected.

**(B) Three neutrino mixing parameters:** shows measurements of $\sin^2(2\theta_{12})$, $\sin^2(2\theta_{23})$, $\Delta m^2_{21}$, $\Delta m^2_{32}$, and $\sin^2(2\theta_{13})$ which are all interpretations of data based on the three neutrino mixing scheme described in the review "Neutrino Mass, Mixing, and Oscillations." by K. Nakamura and S.T. Petcov. Many parameters have been calculated in the two-neutrino approximation.

**(C) Other neutrino mixing results:** shows measurements and limits for the probability of oscillation for experiments which might be relevant to the LSND oscillation claim. Included are experiments which are sensitive to $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, sterile neutrinos, and CPT tests.

## (A) Neutrino fluxes and event ratios

### Events (observed/expected) from accelerator $\nu_\mu$ experiments.

Some neutrino oscillation experiments compare the flux in two or more detectors. This is usually quoted as the ratio of the event rate in the far detector to the expected rate based on an extrapolation from the near detector in the absence of oscillations.

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $1.01 \pm 0.10$ | [1] ABE | 14B | T2K | $\nu_e$ rate in T2K near detect. |
| $0.71 \pm 0.08$ | [2] AHN | 06A | K2K | K2K to Super-K |
| $0.64 \pm 0.05$ | [3] MICHAEL | 06 | MINS | All charged current events |
| $0.71^{+0.08}_{-0.09}$ | [4] ALIU | 05 | K2K | KEK to Super-K |
| $0.70^{+0.10}_{-0.11}$ | [5] AHN | 03 | K2K | KEK to Super-K |

[1] The rate of $\nu_e$ from $\mu$ decay was measured to be $0.68 \pm 0.30$ compared to the predicted flux. From $K$ decay $1.10 \pm 0.14$ compared to the predicted flux.

[2] Based on the observation of 112 events when $158.1^{+9.2}_{-8.6}$ were expected without oscillations. Including not only the number of events but also the shape of the energy distribution, the evidence for oscillation is at the level of about 4.3 $\sigma$. Supersedes ALIU 05.

[3] This ratio is based on the observation of 215 events compared to an expectation of $336 \pm 14$ without oscillations. See also ADAMSON 08.

[4] This ratio is based on the observation of 107 events at the far detector 250 km away from KEK, and an expectation of $151^{+12}_{-10}$.

[5] This ratio is based on the observation of 56 events with an expectation of $80.1^{+6.2}_{-5.4}$.

## Events (observed/expected) from reactor $\overline{\nu}_e$ experiments.

The quoted values are the ratios of the measured reactor $\overline{\nu}_e$ event rate at the quoted distances, and the rate expected without oscillations. The expected rate is based on the experimental data for the most significant reactor fuels ($^{235}$U, $^{239}$Pu, $^{241}$Pu) and on calculations for $^{238}$U.

A recent re-evaluation of the spectral conversion of electron to $\overline{\nu}_e$ in MUELLER 11 results in an upward shift of the reactor $\overline{\nu}_e$ spectrum by 3% and, thus, might require revisions to the ratios listed in this table.

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **$0.944 \pm 0.007 \pm 0.003$** | [1] AN | 13 | DAYA | DayaBay, LIng Ao/Ao II reactors |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $0.944 \pm 0.016 \pm 0.040$ | [2] ABE | 12 | DCHZ | Chooz reactors |
| $0.920 \pm 0.009 \pm 0.014$ | [3] AHN | 12 | RENO | Yonggwang reactors |
| $0.940 \pm 0.011 \pm 0.004$ | [4] AN | 12 | DAYA | DayaBay, LIng Ao/Ao II reactors |
| $1.08 \pm 0.21 \pm 0.16$ | [5] DENIZ | 10 | TEXO | Kuo-Sheng reactor, 28 m |
| $0.658 \pm 0.044 \pm 0.047$ | [6] ARAKI | 05 | KLND | Japanese react. $\sim 180$ km |
| $0.611 \pm 0.085 \pm 0.041$ | [7] EGUCHI | 03 | KLND | Japanese react. $\sim 180$ km |
| $1.01 \pm 0.024 \pm 0.053$ | [8] BOEHM | 01 | | Palo Verde react. 0.75–0.89 km |
| $1.01 \pm 0.028 \pm 0.027$ | [9] APOLLONIO | 99 | CHOZ | Chooz reactors 1 km |
| $0.987 \pm 0.006 \pm 0.037$ | [10] GREENWOOD | 96 | | Savannah River, 18.2 m |
| $0.988 \pm 0.004 \pm 0.05$ | ACHKAR | 95 | CNTR | Bugey reactor, 15 m |
| $0.994 \pm 0.010 \pm 0.05$ | ACHKAR | 95 | CNTR | Bugey reactor, 40 m |
| $0.915 \pm 0.132 \pm 0.05$ | ACHKAR | 95 | CNTR | Bugey reactor, 95 m |
| $0.987 \pm 0.014 \pm 0.027$ | [11] DECLAIS | 94 | CNTR | Bugey reactor, 15 m |
| $0.985 \pm 0.018 \pm 0.034$ | KUVSHINN... | 91 | CNTR | Rovno reactor |
| $1.05 \pm 0.02 \pm 0.05$ | VUILLEUMIER | 82 | | Gösgen reactor |
| $0.955 \pm 0.035 \pm 0.110$ | [12] KWON | 81 | | $\overline{\nu}_e p \to e^+ n$ |
| $0.89 \pm 0.15$ | [12] BOEHM | 80 | | $\overline{\nu}_e p \to e^+ n$ |

[1] AN 13 use six identical detectors, with three placed near the reactor cores (flux-weighted baselines of 470 and 576 m) and the remaining three at the far hall (at the flux averaged distance of 1648 m from all six reactor cores) to determine the mixing angle $\theta_{13}$ using the $\overline{\nu}_e$ observed interaction rate ratios. This rate-only analysis excludes the no-oscillation hypothesis at 7.7 standard deviations. The value of $\Delta m_{31}^2 = 2.32 \times 10^{-3}$ eV$^2$ was assumed in the analysis. This is an improved result (2.5 times increase in statistics) compared to AN 12.

[2] ABE 12 determine the $\overline{\nu}_e$ interaction rate in a single detector, located 1050 m from the cores of two reactors. The rate normalization is fixed by the results of the Bugey4 reactor experiment, thus avoiding any dependence on possible very short baseline oscillations.

[3] AHN 12 use two identical detectors, placed at flux weighted distances of 408.56 m and 1433.99m from six reactor cores, to determine the $\overline{\nu}_e$ interaction rate ratio.

[4] AN 12 use six identical detectors with three placed near the reactor cores (flux-weighted baselines of 470 m and 576 m) and the remaining three at the far hall (at the flux averaged distance of 1648 m from all six reactor cores) to determine the $\overline{\nu}_e$ interaction rate ratios. Superseded by AN 13.

[5] DENIZ 10 observe reactor $\overline{\nu}_e\,e$ scattering with recoil kinetic energies 3–8 MeV using CsI(Tl) detectors. The observed rate is consistent with the Standard Model prediction, leading to a constraint on $\sin^2\theta_W = 0.251 \pm 0.031(\text{stat}) \pm 0.024(\text{sys})$.

[6] Updated result of KamLAND, including the data used in EGUCHI 03. Note that the survival probabilities for different periods are not directly comparable because the effective baseline varies with power output of the reactor sources involved, and there were large variations in the reactor power production in Japan in 2003.

[7] EGUCHI 03 observe reactor neutrino disappearance at $\sim$ 180 km baseline to various Japanese nuclear power reactors.

[8] BOEHM 01 search for neutrino oscillations at 0.75 and 0.89 km distance from the Palo Verde reactors.

[9] APOLLONIO 99, APOLLONIO 98 search for neutrino oscillations at 1.1 km fixed distance from Chooz reactors. They use $\overline{\nu}_e\,p \rightarrow e^+\,n$ in Gd-loaded scintillator target. APOLLONIO 99 supersedes APOLLONIO 98. See also APOLLONIO 03 for detailed description.

[10] GREENWOOD 96 search for neutrino oscillations at 18 m and 24 m from the reactor at Savannah River.

[11] DECLAIS 94 result based on integral measurement of neutrons only. Result is ratio of measured cross section to that expected in standard *V-A* theory. Replaced by ACHKAR 95.

[12] KWON 81 represents an analysis of a larger set of data from the same experiment as BOEHM 80.

## —— Atmospheric neutrinos ——

Neutrinos and antineutrinos produced in the atmosphere induce $\mu$-like and $e$-like events in underground detectors. The ratio of the numbers of the two kinds of events is defined as $\mu/e$. It has the advantage 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 $\mu/e$, $R(\mu/e)$, or that of experimental to theoretical $\mu/\text{total}$, $R(\mu/\text{total})$ with total $= \mu+e$, is reported below. If the actual value is not unity, the value obtained in a given experiment may depend on the experimental conditions. In addition, the measured "up-down asymmetry" for $\mu$ ($N_{up}(\mu)/N_{down}(\mu)$) or $e$ ($N_{up}(e)/N_{down}(e)$) is reported. The expected "up-down asymmetry" is nearly unity if there is no neutrino oscillation.

## $R(\mu/e) =$ (Measured Ratio $\mu/e$) / (Expected Ratio $\mu/e$)

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $0.658 \pm 0.016 \pm 0.035$ | [1] ASHIE 05 | SKAM | sub-GeV |
| $0.702 {}^{+0.032}_{-0.030} \pm 0.101$ | [2] ASHIE 05 | SKAM | multi-GeV |
| $0.69 \pm 0.10 \pm 0.06$ | [3] SANCHEZ 03 | SOU2 | Calorimeter raw data |
| | [4] FUKUDA 96B | KAMI | Water Cherenkov |
| $1.00 \pm 0.15 \pm 0.08$ | [5] DAUM 95 | FREJ | Calorimeter |
| $0.60 {}^{+0.06}_{-0.05} \pm 0.05$ | [6] FUKUDA 94 | KAMI | sub-GeV |
| $0.57 {}^{+0.08}_{-0.07} \pm 0.07$ | [7] FUKUDA 94 | KAMI | multi-Gev |
| | [8] BECKER-SZ... 92B | IMB | Water Cherenkov |

[1] ASHIE 05 results are based on an exposure of 92 kton yr during the complete Super-Kamiokande I running period. The analyzed data sample consists of fully-contained single-ring $e$-like events with 0.1 GeV/c $< p_e$ and $\mu$-like events 0.2 GeV/c $< p_\mu$, both having a visible energy $< 1.33$ GeV. These criteria match the definition used by FUKUDA 94.

[2] ASHIE 05 results are based on an exposure of 92 kton yr during the complete Super-Kamiokande I running period. The analyzed data sample consists of fully-contained single-ring events with visible energy $> 1.33$ GeV and partially-contained events. All partially-contained events are classified as $\mu$-like.

[3] SANCHEZ 03 result is based on an exposure of 5.9 kton yr, and updates ALLISON 99 result. The analyzed data sample consists of fully-contained $e$-flavor and $\mu$-flavor events having lepton momentum $> 0.3$ GeV/c.

[4] FUKUDA 96B studied neutron background in the atmospheric neutrino sample observed in the Kamiokande detector. No evidence for the background contamination was found.

[5] 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.

[6] 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 $\mu$-like events with 0.2 $< p_\mu < 1.5$ GeV/$c$.

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

[8] BECKER-SZENDY 92B reports the fraction of nonshowering events (mostly muons from atmospheric 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 Kamiokande limits, BEIER 92 finds $R(\mu/e)$ very close to the Kamiokande value.

## $R(\nu_\mu) =$ (Measured Flux of $\nu_\mu$) / (Expected Flux of $\nu_\mu$)

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $0.84 \pm 0.12$ | [1] ADAMSON 06 | MINS | MINOS atmospheric |
| $0.72 \pm 0.026 \pm 0.13$ | [2] AMBROSIO 01 | MCRO | upward through-going |
| $0.57 \pm 0.05 \pm 0.15$ | [3] AMBROSIO 00 | MCRO | upgoing partially contained |
| $0.71 \pm 0.05 \pm 0.19$ | [4] AMBROSIO 00 | MCRO | downgoing partially contained + upgoing stopping |
| $0.74 \pm 0.036 \pm 0.046$ | [5] AMBROSIO 98 | MCRO | Streamer tubes |

|  | | | | |
|---|---|---|---|---|
|  | [6] CASPER | 91 | IMB | Water Cherenkov |
|  | [7] AGLIETTA | 89 | NUSX | |
| 0.95±0.22 | [8] BOLIEV | 81 | | Baksan |
| 0.62±0.17 | CROUCH | 78 | | Case Western/UCI |

[1] ADAMSON 06 uses a measurement of 107 total neutrinos compared to an expected rate of $127 \pm 13$ without oscillations.

[2] AMBROSIO 01 result is based on the upward through-going muon tracks with $E_\mu > 1$ GeV. The data came from three different detector configurations, but the statistics is largely dominated by the full detector run, from May 1994 to December 2000. The total live time, normalized to the full detector configuration, is 6.17 years. The first error is the statistical error, the second is the systematic error, dominated by the theoretical error in the predicted flux.

[3] AMBROSIO 00 result is based on the upgoing partially contained event sample. It came from 4.1 live years of data taking with the full detector, from April 1994 to February 1999. The average energy of atmospheric muon neutrinos corresponding to this sample is 4 GeV. The first error is statistical, the second is the systematic error, dominated by the 25% theoretical error in the rate (20% in the flux and 15% in the cross section, added in quadrature). Within statistics, the observed deficit is uniform over the zenith angle.

[4] AMBROSIO 00 result is based on the combined samples of downgoing partially contained events and upgoing stopping events. These two subsamples could not be distinguished due to the lack of timing information. The result came from 4.1 live years of data taking with the full detector, from April 1994 to February 1999. The average energy of atmospheric muon neutrinos corresponding to this sample is 4 GeV. The first error is statistical, the second is the systematic error, dominated by the 25% theoretical error in the rate (20% in the flux and 15% in the cross section, added in quadrature). Within statistics, the observed deficit is uniform over the zenith angle.

[5] AMBROSIO 98 result is for all nadir angles and updates AHLEN 95 result. The lower cutoff on the muon energy is 1 GeV. In addition to the statistical and systematic errors, there is a Monte Carlo flux error (theoretical error) of $\pm 0.13$. With a neutrino oscillation hypothesis, the fit either to the flux or zenith distribution independently yields $\sin^2 2\theta = 1.0$ and $\Delta(m^2) \sim$ a few times $10^{-3}$ eV$^2$. However, the fit to the observed zenith distribution gives a maximum probability for $\chi^2$ of only 5% for the best oscillation hypothesis.

[6] 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 $0.51 \pm 0.05$ (syst).

[7] AGLIETTA 89 finds no evidence for any anomaly in the neutrino flux. They define $\rho = $ (measured number of $\nu_e$'s)/(measured number of $\nu_\mu$'s). They report $\rho$(measured)=$\rho$(expected) $= 0.96^{+0.32}_{-0.28}$.

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

## $R(\mu/\text{total}) = (\text{Measured Ratio } \mu/\text{total}) / (\text{Expected Ratio } \mu/\text{total})$

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $1.1^{+0.07}_{-0.12} \pm 0.11$ | [1] CLARK | 97 | IMB | multi-GeV |

[1] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cherenkov detector with visible energy > 0.95 GeV.

## $N_{up}(\mu)/N_{down}(\mu)$

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $0.71 \pm 0.06$ | [1] ADAMSON | 12B MINS | contained-vertex muons |
| $0.551^{+0.035}_{-0.033} \pm 0.004$ | [2] ASHIE | 05 SKAM | multi-GeV |

[1] ADAMSON 12B reports the atmospheric neutrino results obtained with MINOS far detector in 2,553 live days (an exposure of 37.9 kton·yr). This result is obtained with a sample of high resolution contained-vertex muons. The quoted error is statistical only.

[2] ASHIE 05 results are based on an exposure of 92 kton yr during the complete Super-Kamiokande I running period. The analyzed data sample consists of fully-contained single-ring $\mu$-like events with visible energy $> 1.33$ GeV and partially-contained events. All partially-contained events are classified as $\mu$-like. Upward-going events are those with $-1 < \cos(\text{zenith angle}) < -0.2$ and downward-going events are those with $0.2 < \cos(\text{zenith angle}) < 1$. The $\mu$-like up-down ratio for the multi-GeV data deviates from 1 (the expectation for no atmospheric $\nu_\mu$ oscillations) by more than 12 standard deviations.

## $N_{up}(e)/N_{down}(e)$

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $0.961^{+0.086}_{-0.079} \pm 0.016$ | [1] ASHIE | 05 SKAM | multi-GeV |

[1] ASHIE 05 results are based on an exposure of 92 kton yr during the complete Super-Kamiokande I running period. The analyzed data sample consists of fully-contained single-ring $e$-like events with visible energy $> 1.33$ GeV. Upward-going events are those with $-1 < \cos(\text{zenith angle}) < -0.2$ and downward-going events are those with $0.2 < \cos(\text{zenith angle}) < 1$. The $e$-like up-down ratio for the multi-GeV data is consistent with 1 (the expectation for no atmospheric $\nu_e$ oscillations).

## R(up/down; $\mu$) = (Measured up/down; $\mu$) / (Expected up/down; $\mu$)

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $0.62 \pm 0.05 \pm 0.02$ | [1] ADAMSON | 12B MINS | contained-vertex muons |
| $0.62^{+0.19}_{-0.14} \pm 0.02$ | [2] ADAMSON | 06 MINS | atmospheric $\nu$ with far detector |

[1] ADAMSON 12B reports the atmospheric neutrino results obtained with MINOS far detector in 2,553 live days (an exposure of 37.9 kton·yr). This result is obtained with a sample of high resolution contained-vertex muons. The expected ratio is calculated with no neutrino oscillation.

[2] ADAMSON 06 result is obtained with the MINOS far detector with an exposure of 4.54 kton yr. The expected ratio is calculated with no neutrino oscillation.

## N($\mu^+$)/N($\mu^-$)

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $0.46^{+0.05}_{-0.04}$ | [1,2] ADAMSON | 12B MINS | contained-vertex muons |
| $0.63^{+0.09}_{-0.08}$ | [1,3] ADAMSON | 12B MINS | $\nu$-induced rock-muons |

[1] ADAMSON 12B reports the atmospheric neutrino results obtained with MINOS far detector in 2,553 live days (an exposure of 37.9 kton·yr). The muon charge ratio N($\mu^+$)/N($\mu^-$) represents the $\overline{\nu}_\mu/\nu_\mu$ ratio.

[2] This result is obtained with a charge-separated sample of high resolution contained-vertex muons. The quoted error is statistical only.

[3] This result is obtained with a charge-separated sample of high resolution neutrino-induced rock-muons. The quoted error is statistical only.

## $R(\mu^+/\mu^-) = ($Measured $N(\mu^+)/N(\mu^-)) \,/\, ($Expected $N(\mu^+)/N(\mu^-))$

| VALUE | | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $0.93 \pm 0.09 \pm 0.09$ | [1,2] | ADAMSON | 12B | MINS | contained-vertex muons |
| $1.29 ^{+0.19}_{-0.17} \pm 0.16$ | [1,3] | ADAMSON | 12B | MINS | $\nu$-induced rock-muons |
| $1.03 \pm 0.08 \pm 0.08$ | [1,4] | ADAMSON | 12B | MINS | contained |
| $1.39 ^{+0.35}_{-0.46} {}^{+0.08}_{-0.14}$ | [5] | ADAMSON | 07 | MINS | Upward and horizontal $\mu$ with far detector |
| $0.96 ^{+0.38}_{-0.27} \pm 0.15$ | [6] | ADAMSON | 06 | MINS | atmospheric $\nu$ with far detector |

[1] ADAMSON 12B reports the atmospheric neutrino results obtained with MINOS far detector in 2,553 live days (an exposure of 37.9 kton·yr). The muon charge ratio $N(\mu^+)/N(\mu^-)$ represents the $\overline{\nu}_\mu/\nu_\mu$ ratio. As far as the same oscillation parameters are used for $\nu$s and $\overline{\nu}$s, the expected $\overline{\nu}_\mu/\nu_\mu$ ratio is almost entirely independent of any input oscillations.

[2] This result is obtained with a charge-separated sample of high resolution contained-vertex muons.

[3] This result is obtained with a charge-separated sample of high resolution neutrino-induced rock-muons.

[4] The charge-separated samples of high resolution contained-vertex muons and neutrino-induced rock-muons are combined to obtain this result which is consistent with unity.

[5] ADAMSON 07 result is obtained with the MINOS far detector in 854.24 live days, based on neutrino-induced upward-going and horizontal muons. This result is consistent with *CPT* conservation.

[6] ADAMSON 06 result is obtained with the MINOS far detector with an exposure of 4.54 kton yr, based on contained events. The expected ratio is calculated by assuming the same oscillation parameters for neutrinos and antineutrinos.

--------- Solar neutrinos ---------

Solar neutrinos are produced by thermonuclear fusion reactions in the Sun. Radiochemical experiments measure particular combinations of fluxes from various neutrino-producing reactions, whereas water-Cherenkov experiments mainly measure a flux of neutrinos from decay of $^8$B. Solar neutrino fluxes are composed of all active neutrino species, $\nu_e$, $\nu_\mu$, and $\nu_\tau$. In addition, some other mechanisms may cause antineutrino components in solar neutrino fluxes. Each measurement method is sensitive to a particular component or a combination of components of solar neutrino fluxes. For details, see Section 13.4 of Reviews, Tables, and Plots.

## $\nu_e$ Capture Rates from Radiochemical Experiments

1 SNU (Solar Neutrino Unit) $= 10^{-36}$ captures per atom per second.

| VALUE (SNU) | | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $73.4 ^{+6.1}_{-6.0} {}^{+3.7}_{-4.1}$ | [1] | KAETHER | 10 | | GALX reanalysis |
| $67.6 \pm 4.0 \pm 3.2$ | [2] | KAETHER | 10 | | GNO+GALX reanalysis combined |

| | | | | |
|---|---|---|---|---|
| $65.4 \; ^{+3.1}_{-3.0} \; ^{+2.6}_{-2.8}$ | [3] ABDURASHI... | 09 | SAGE | $^{71}Ga \rightarrow \; ^{71}Ge$ |
| $62.9 \; ^{+5.5}_{-5.3} \pm 2.5$ | [4] ALTMANN | 05 | GNO | $^{71}Ga \rightarrow \; ^{71}Ge$ |
| $69.3 \pm 4.1 \pm 3.6$ | [5] ALTMANN | 05 | GNO | GNO + GALX combined |
| $77.5 \pm 6.2 \; ^{+4.3}_{-4.7}$ | [6] HAMPEL | 99 | GALX | $^{71}Ga \rightarrow \; ^{71}Ge$ |
| $2.56 \pm 0.16 \pm 0.16$ | [7] CLEVELAND | 98 | HOME | $^{37}Cl \rightarrow \; ^{37}Ar$ |

[1] KAETHER 10 reports the reanalysis results of a complete GALLEX data (GALLEX I+II+III+IV, reported in HAMPEL 99) based on the event selection with a new pulse shape analysis, which provides a better background reduction than the rise time analysis adopted in HAMPEL 99.

[2] Combined result of GALLEX I+II+III+IV reanalysis and GNO I+II+III (ALTMANN 05).

[3] ABDURASHITOV 09 reports a combined analysis of 168 extractions of the SAGE solar neutrino experiment during the period January 1990 through December 2007, and updates the ABDURASHITOV 02 result. The data are consistent with the assumption that the solar neutrino production rate is constant in time. Note that a $\sim$ 15% systematic uncertainty in the overall normalization may be added to the ABDURASHITOV 09 result, because calibration experiments for gallium solar neutrino measurements using intense $^{51}Cr$ (twice by GALLEX and once by SAGE) and $^{37}Ar$ (by SAGE) result in an average ratio of $0.87 \pm 0.05$ of the observed to calculated rates.

[4] ALTMANN 05 reports the complete result from the GNO solar neutrino experiment (GNO I+II+III), which is the successor project of GALLEX. Experimental technique of GNO is essentially the same as that of GALLEX. The run data cover the period 20 May 1998 through 9 April 2003.

[5] Combined result of GALLEX I+II+III+IV (HAMPEL 99) and GNO I+II+III.

[6] HAMPEL 99 report the combined result for GALLEX I+II+III+IV (65 runs in total), which update the HAMPEL 96 result. The GALLEX IV result (12 runs) is $118.4 \pm 17.8 \pm 6.6$ SNU. (HAMPEL 99 discuss the consistency of partial results with the mean.) The GALLEX experimental program has been completed with these runs. The total run data cover the period 14 May 1991 through 23 January 1997. A total of 300 $^{71}Ge$ events were observed. Note that a $\sim$ 15% systematic uncertainty in the overall normalization may be added to the HAMPEL 99 result, because calibration experiments for gallium solar neutrino measurements using intense $^{51}Cr$ (twice by GALLEX and once by SAGE) and $^{37}Ar$ (by SAGE) result in an average ratio of $0.87 \pm 0.05$ of the observed to calculated rates.

[7] CLEVELAND 98 is a detailed report of the $^{37}Cl$ experiment at the Homestake Mine. The average solar neutrino-induced $^{37}Ar$ production rate from 108 runs between 1970 and 1994 updates the DAVIS 89 result.

## $\phi_{ES}$ ($^8$B)

$^8$B solar-neutrino flux measured via $\nu e$ elastic scattering. This process is sensitive to all active neutrino flavors, but with reduced sensitivity to $\nu_\mu$, $\nu_\tau$ due to the cross-section difference, $\sigma(\nu_{\mu,\tau} e) \sim 0.16 \sigma(\nu_e e)$. If the $^8$B solar-neutrino flux involves nonelectron flavor active neutrinos, their contribution to the flux is $\sim$ 0.16 times of $\nu_e$.

| *VALUE* ($10^6$ cm$^{-2}$s$^{-1}$) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| $\bullet\bullet\bullet$ We do not use the following data for averages, fits, limits, etc. $\bullet\bullet\bullet$ | | | | |
| $2.32 \pm 0.04 \pm 0.05$ | [1] ABE | 11 | SKAM | SK-III average flux |
| $2.41 \pm 0.05 \; ^{+0.16}_{-0.15}$ | [2] ABE | 11 | SKAM | SK-II average flux |
| $2.38 \pm 0.02 \pm 0.08$ | [3] ABE | 11 | SKAM | SK-I average flux |
| $2.77 \pm 0.26 \pm 0.32$ | [4] ABE | 11B | KLND | average flux |
| $2.4 \pm 0.4 \pm 0.1$ | [5] BELLINI | 10A | BORX | average flux |

| | | | | |
|---|---|---|---|---|
| $1.77^{+0.24}_{-0.21}{}^{+0.09}_{-0.10}$ | [6] AHARMIM | 08 | SNO | Phase III |
| $2.38 \pm 0.05^{+0.16}_{-0.15}$ | [7] CRAVENS | 08 | SKAM | average flux |
| $2.35 \pm 0.02 \pm 0.08$ | [8] HOSAKA | 06 | SKAM | average flux |
| $2.35 \pm 0.22 \pm 0.15$ | [9] AHARMIM | 05A | SNO | Salty $D_2O$; $^8B$ shape not constrained |
| $2.34 \pm 0.23^{+0.15}_{-0.14}$ | [9] AHARMIM | 05A | SNO | Salty $D_2O$; $^8B$ shape constrained |
| $2.39^{+0.24}_{-0.23} \pm 0.12$ | [10] AHMAD | 02 | SNO | average flux |
| $2.39 \pm 0.34^{+0.16}_{-0.14}$ | [11] AHMAD | 01 | SNO | average flux |
| $2.80 \pm 0.19 \pm 0.33$ | [12] FUKUDA | 96 | KAMI | average flux |
| $2.70 \pm 0.27$ | [12] FUKUDA | 96 | KAMI | day flux |
| $2.87^{+0.27}_{-0.26}$ | [12] FUKUDA | 96 | KAMI | night flux |

[1] ABE 11 reports the Super-Kamiokande-III results for 548 live days from August 4, 2006 to August 18, 2008. The analysis threshold is 5.0 MeV, but the event sample in the 5.0–6.5 MeV total electron range has a total live time of 298 days.

[2] ABE 11 recalculated the Super-Kamiokande-II results using $^8B$ spectrum of WINTER 06A.

[3] ABE 11 recalculated the Super-Kamiokande-I results using $^8B$ spectrum of WINTER 06A.

[4] ABE 11B use a 123 kton·day exposure of the KamLAND liquid scintillation detector to measure the $^8B$ solar neutrino flux. They utilize $\nu - e$ elastic scattering above a reconstructed-energy threshold of 5.5 MeV, corresponding to 5 MeV electron recoil energy. 299 electron recoil candidate events are reported, of which $157 \pm 23.6$ are assigned to background.

[5] BELLINI 10A reports the Borexino result with 3 MeV energy threshold for scattered electrons. The data correspond to 345.3 live days with a target mass of 100 t, between July 15, 2007 and August 23, 2009.

[6] AHARMIM 08 reports the results from SNO Phase III measurement using an array of $^3He$ proportional counters to measure the rate of NC interactions in heavy water, over the period between November 27, 2004 and November 28, 2006, corresponding to 385.17 live days. A simultaneous fit was made for the number of NC events detected by the proportional counters and the numbers of NC, CC, and ES events detected by the PMTs, where the spectral distributions of the ES and CC events were not constrained to the $^8B$ shape.

[7] CRAVENS 08 reports the Super-Kamiokande-II results for 791 live days from December 2002 to October 2005. The photocathode coverage of the detector is 19% (reduced from 40% of that of Super-Kamiokande-I due to an accident in 2001). The analysis threshold for the average flux is 7 MeV.

[8] HOSAKA 06 reports the final results for 1496 live days with Super-Kamiokande-I between May 31, 1996 and July 15, 2001, and replace FUKUDA 02 results. The analysis threshold is 5 MeV except for the first 280 live days (6.5 MeV).

[9] AHARMIM 05A measurements were made with dissolved NaCl (0.195% by weight) in heavy water over the period between July 26, 2001 and August 28, 2003, corresponding to 391.4 live days, and update AHMED 04A. The *CC*, *ES*, and *NC* events were statistically separated. In one method, the $^8B$ energy spectrum was not constrained. In the other method, the constraint of an undistorted $^8B$ energy spectrum was added for comparison with AHMAD 02 results.

[10] AHMAD 02 reports the $^8B$ solar-neutrino flux measured via $\nu e$ elastic scattering above the kinetic energy threshold of 5 MeV. The data correspond to 306.4 live days with SNO between November 2, 1999 and May 28, 2001, and updates AHMAD 01 results.

[11] AHMAD 01 reports the $^8B$ solar-neutrino flux measured via $\nu e$ elastic scattering above the kinetic energy threshold of 6.75 MeV. The data correspond to 241 live days with SNO between November 2, 1999 and January 15, 2001.

[12] FUKUDA 96 results are for a total of 2079 live days with Kamiokande II and III from January 1987 through February 1995, covering the entire solar cycle 22, with threshold $E_e > 9.3$ MeV (first 449 days), $> 7.5$ MeV (middle 794 days), and $> 7.0$ MeV (last 836 days). These results update the HIRATA 90 result for the average $^8$B solar-neutrino flux and HIRATA 91 result for the day-night variation in the $^8$B solar-neutrino flux. The total data sample was also analyzed for short-term variations: within experimental errors, no strong correlation of the solar-neutrino flux with the sunspot numbers was found.

## $\phi_{CC}$ ($^8$B)

$^8$B solar-neutrino flux measured with charged-current reaction which is sensitive exclusively to $\nu_e$.

| VALUE ($10^6$ cm$^{-2}$s$^{-1}$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $1.67^{+0.05\,+0.07}_{-0.04\,-0.08}$ | [1] AHARMIM | 08 | SNO | Phase III |
| $1.68\pm0.06^{+0.08}_{-0.09}$ | [2] AHARMIM | 05A | SNO | Salty D$_2$O; $^8$B shape not const. |
| $1.72\pm0.05\pm0.11$ | [2] AHARMIM | 05A | SNO | Salty D$_2$O; $^8$B shape constrained |
| $1.76^{+0.06}_{-0.05}\pm0.09$ | [3] AHMAD | 02 | SNO | average flux |
| $1.75\pm0.07^{+0.12}_{-0.11}\pm0.05$ | [4] AHMAD | 01 | SNO | average flux |

[1] AHARMIM 08 reports the results from SNO Phase III measurement using an array of $^3$He proportional counters to measure the rate of NC interactions in heavy water, over the period between November 27, 2004 and November 28, 2006, corresponding to 385.17 live days. A simultaneous fit was made for the number of NC events detected by the proportional counters and the numbers of NC, CC, and ES events detected by the PMTs, where the spectral distributions of the ES and CC events were not constrained to the $^8$B shape.

[2] AHARMIM 05A measurements were made with dissolved NaCl (0.195% by weight) in heavy water over the period between July 26, 2001 and August 28, 2003, corresponding to 391.4 live days, and update AHMED 04A. The *CC*, *ES*, and *NC* events were statistically separated. In one method, the $^8$B energy spectrum was not constrained. In the other method, the constraint of an undistorted $^8$B energy spectrum was added for comparison with AHMAD 02 results.

[3] AHMAD 02 reports the SNO result of the $^8$B solar-neutrino flux measured with charged-current reaction on deuterium, $\nu_e d \rightarrow p p e^-$, above the kinetic energy threshold of 5 MeV. The data correspond to 306.4 live days with SNO between November 2, 1999 and May 28, 2001, and updates AHMAD 01 results. The complete description of the SNO Phase I data set is given in AHARMIM 07.

[4] AHMAD 01 reports the first SNO result of the $^8$B solar-neutrino flux measured with the charged-current reaction on deuterium, $\nu_e d \rightarrow p p e^-$, above the kinetic energy threshold of 6.75 MeV. The data correspond to 241 live days with SNO between November 2, 1999 and January 15, 2001.

## $\phi_{NC}$ ($^8$B)

$^8$B solar neutrino flux measured with neutral-current reaction, which is equally sensitive to $\nu_e$, $\nu_\mu$, and $\nu_\tau$.

| VALUE ($10^6$ cm$^{-2}$s$^{-1}$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $5.25\pm0.16^{+0.11}_{-0.13}$ | [1] AHARMIM | 13 | SNO | All three phases combined |

| | | | | | |
|---|---|---|---|---|---|
| $5.140^{+0.160}_{-0.158}{}^{+0.132}_{-0.117}$ | [2] | AHARMIM | 10 | SNO | Phase I+II, low threshold |
| $5.54^{+0.33}_{-0.31}{}^{+0.36}_{-0.34}$ | [3] | AHARMIM | 08 | SNO | Phase III, prop. counter + PMT |
| $4.94 \pm 0.21^{+0.38}_{-0.34}$ | [4] | AHARMIM | 05A | SNO | Salty $D_2O$; $^8B$ shape not const. |
| $4.81 \pm 0.19^{+0.28}_{-0.27}$ | [4] | AHARMIM | 05A | SNO | Salty $D_2O$; $^8B$ shape constrained |
| $5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$ | [5] | AHMAD | 02 | SNO | average flux; $^8B$ shape const. |
| $6.42 \pm 1.57^{+0.55}_{-0.58}$ | [5] | AHMAD | 02 | SNO | average flux; $^8B$ shape not const. |

[1] AHARMIM 13 obtained this result from a combined analysis of the data from all three phases, SNO-I, II, and III. The measurement of the $^8B$ flux mostly comes from the NC signal, however, CC contribution is included in the fit.

[2] AHARMIM 10 reports this result from a joint analysis of SNO Phase I+II data with the "effective electron kinetic energy" threshold of 3.5 MeV. This result is obtained with a "binned-histogram unconstrained fit" where binned probability distribution functions of the neutrino signal observables were used without any model constraints on the shape of the neutrino spectrum.

[3] AHARMIM 08 reports the results from SNO Phase III measurement using an array of $^3He$ proportional counters to measure the rate of NC interactions in heavy water, over the period between November 27, 2004 and November 28, 2006, corresponding to 385.17 live days. A simultaneous fit was made for the number of NC events detected by the proportional counters and the numbers of NC, CC, and ES events detected by the PMTs, where the spectral distributions of the ES and CC events were not constrained to the $^8B$ shape.

[4] AHARMIM 05A measurements were made with dissolved NaCl (0.195% by weight) in heavy water over the period between July 26, 2001 and August 28, 2003, corresponding to 391.4 live days, and update AHMED 04A. The *CC, ES*, and *NC* events were statistically separated. In one method, the $^8B$ energy spectrum was not constrained. In the other method, the constraint of an undistorted $^8B$ energy spectrum was added for comparison with AHMAD 02 results.

[5] AHMAD 02 reports the first SNO result of the $^8B$ solar-neutrino flux measured with the neutral-current reaction on deuterium, $\nu_\ell d \rightarrow n p \nu_\ell$, above the neutral-current reaction threshold of 2.2 MeV. The data correspond to 306.4 live days with SNO between November 2, 1999 and May 28, 2001. The complete description of the SNO Phase I data set is given in AHARMIM 07.

# $\phi_{\nu_\mu + \nu_\tau}$ ($^8B$)

Nonelectron-flavor active neutrino component ($\nu_\mu$ and $\nu_\tau$) in the $^8B$ solar-neutrino flux.

| VALUE ($10^6$ cm$^{-2}$s$^{-1}$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $3.26 \pm 0.25^{+0.40}_{-0.35}$ | [1] | AHARMIM | 05A SNO | From $\phi_{NC}$, $\phi_{CC}$, and $\phi_{ES}$; $^8B$ shape not const. |
| $3.09 \pm 0.22^{+0.30}_{-0.27}$ | [1] | AHARMIM | 05A SNO | From $\phi_{NC}$, $\phi_{CC}$, and $\phi_{ES}$; $^8B$ shape constrained |
| $3.41 \pm 0.45^{+0.48}_{-0.45}$ | [2] | AHMAD | 02 SNO | From $\phi_{NC}$, $\phi_{CC}$, and $\phi_{ES}$ |
| $3.69 \pm 1.13$ | [3] | AHMAD | 01 | Derived from SNO+SuperKam, water Cherenkov |

[1] AHARMIM 05A measurements were made with dissolved NaCl (0.195% by weight) in heavy water over the period between July 26, 2001 and August 28, 2003, corresponding

to 391.4 live days, and update AHMED 04A. The *CC*, *ES*, and *NC* events were statistically separated. In one method, the $^8$B energy spectrum was not constrained. In the other method, the constraint of an undistorted $^8$B energy spectrum was added for comparison with AHMAD 02 results.

[2] AHMAD 02 deduced the nonelectron-flavor active neutrino component ($\nu_\mu$ and $\nu_\tau$) in the $^8$B solar-neutrino flux, by combining the charged-current result, the $\nu e$ elastic-scattering result and the neutral-current result. The complete description of the SNO Phase I data set is given in AHARMIM 07.

[3] AHMAD 01 deduced the nonelectron-flavor active neutrino component ($\nu_\mu$ and $\nu_\tau$) in the $^8$B solar-neutrino flux, by combining the SNO charged-current result (AHMAD 01) and the Super-Kamiokande $\nu e$ elastic-scattering result (FUKUDA 01).

## Total Flux of Active $^8$B Solar Neutrinos

Total flux of active neutrinos ($\nu_e$, $\nu_\mu$, and $\nu_\tau$).

| VALUE ($10^6$ cm$^{-2}$s$^{-1}$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $5.25 \pm 0.16\,^{+0.11}_{-0.13}$ | [1] AHARMIM | 13 | SNO | All three phases combined |
| $5.046^{+0.159}_{-0.152}\,^{+0.107}_{-0.123}$ | [2] AHARMIM | 10 | SNO | From $\phi_{NC}$ in Phase I+II, low threshold |
| $5.54\,^{+0.33}_{-0.31}\,^{+0.36}_{-0.34}$ | [3] AHARMIM | 08 | SNO | $\phi_{NC}$ in Phase III |
| $4.94 \pm 0.21\,^{+0.38}_{-0.34}$ | [4] AHARMIM | 05A | SNO | From $\phi_{NC}$; $^8$B shape not const. |
| $4.81 \pm 0.19\,^{+0.28}_{-0.27}$ | [4] AHARMIM | 05A | SNO | From $\phi_{NC}$; $^8$B shape constrained |
| $5.09\,^{+0.44}_{-0.43}\,^{+0.46}_{-0.43}$ | [5] AHMAD | 02 | SNO | Direct measurement from $\phi_{NC}$ |
| $5.44 \pm 0.99$ | [6] AHMAD | 01 | | Derived from SNO+SuperKam, water Cherenkov |

[1] AHARMIM 13 obtained this result from a combined analysis of the data from all three phases, SNO-I, II, and III. The measurement of the $^8$B flux mostly comes from the NC signal, however, CC contribution is included in the fit.

[2] AHARMIM 10 reports this result from a joint analysis of SNO Phase I+II data with the "effective electron kinetic energy" threshold of 3.5 MeV. This result is obtained with the assumption of unitarity, which relates the NC, CC, and ES rates. The data were fit with the free parameters directly describing the total $^8$B neutrino flux and the energy-dependent $\nu_e$ survival probability.

[3] AHARMIM 08 reports the results from SNO Phase III measurement using an array of $^3$He proportional counters to measure the rate of NC interactions in heavy water, over the period between November 27, 2004 and November 28, 2006, corresponding to 385.17 live days. A simultaneous fit was made for the number of NC events detected by the proportional counters and the numbers of NC, CC, and ES events detected by the PMTs, where the spectral distributions of the ES and CC events were not constrained to the $^8$B shape.

[4] AHARMIM 05A measurements were made with dissolved NaCl (0.195% by weight) in heavy water over the period between July 26, 2001 and August 28, 2003, corresponding to 391.4 live days, and update AHMED 04A. The CC, ES, and NC events were statistically separated. In one method, the $^8$B energy spectrum was not constrained. In the other method, the constraint of an undistorted $^8$B energy spectrum was added for comparison with AHMAD 02 results.

[5] AHMAD 02 determined the total flux of active $^8$B solar neutrinos by directly measuring the neutral-current reaction, $\nu_\ell d \to n p \nu_\ell$, which is equally sensitive to $\nu_e$, $\nu_\mu$, and $\nu_\tau$. The complete description of the SNO Phase I data set is given in AHARMIM 07.

[6] AHMAD 01 deduced the total flux of active $^8$B solar neutrinos by combining the SNO charged-current result (AHMAD 01) and the Super-Kamiokande $\nu e$ elastic-scattering result (FUKUDA 01).

## Day-Night Asymmetry ($^8$B)

$$A = (\phi_{\text{night}} - \phi_{\text{day}}) / \phi_{\text{average}}$$

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $0.032 \pm 0.011 \pm 0.005$ | [1] RENSHAW | 14 | SKAM | Based on $\phi_{ES}$ |
| $0.063 \pm 0.042 \pm 0.037$ | [2] CRAVENS | 08 | SKAM | Based on $\phi_{ES}$ |
| $0.021 \pm 0.020 ^{+0.012}_{-0.013}$ | [3] HOSAKA | 06 | SKAM | Based on $\phi_{ES}$ |
| $0.017 \pm 0.016 ^{+0.012}_{-0.013}$ | [4] HOSAKA | 06 | SKAM | Fitted in the LMA region |
| $-0.056 \pm 0.074 \pm 0.053$ | [5] AHARMIM | 05A | SNO | From salty SNO $\phi_{CC}$ |
| $-0.037 \pm 0.063 \pm 0.032$ | [5] AHARMIM | 05A | SNO | From salty SNO $\phi_{CC}$; const. of no $\phi_{NC}$ asymmetry |
| $0.14 \pm 0.063 ^{+0.015}_{-0.014}$ | [6] AHMAD | 02B | SNO | Derived from SNO $\phi_{CC}$ |
| $0.07 \pm 0.049 ^{+0.013}_{-0.012}$ | [7] AHMAD | 02B | SNO | Const. of no $\phi_{NC}$ asymmetry |

[1] RENSHAW 14 obtains this result by using the "amplitude fit" introduced in SMY 04. The data from the Super-Kamiokande(SK)-I, -II, -III, and 1306 live days of the SK-IV measurements are used. The analysis threshold is recoil-electron kinetic energy of 4.5 MeV for SK-III, and SK-IV except for 250 live days in SK-III (6.0 MeV). The analysis threshold for SK-I and SK-II is the same as in the previous reports. (Note that in the previous SK solar-neutrino results, the analysis threshold is quoted as recoil-electron total energy.) This day-night asymmetry result is consistent with neutrino oscillations for $4 \times 10^{-5}$ eV$^2$ $< \Delta m_{21}^2 < 7 \times 10^{-5}$ eV$^2$ and large mixing values of $\theta_{12}$ at the 68% CL.

[2] CRAVENS 08 reports the Super-Kamiokande-II results for 791 live days from December 2002 to October 2005. The photocathode coverage of the detector is 19% (reduced from 40% of that of Super-Kamiokande-I due to an accident in 2001). The analysis threshold for the day and night fluxes is 7.5 MeV except for the first 159 live days (8.0 MeV).

[3] HOSAKA 06 reports the final results for 1496 live days with Super-Kamiokande-I between May 31, 1996 and July 15, 2001, and replace FUKUDA 02 results. The analysis threshold is 5 MeV except for the first 280 live days (6.5 MeV).

[4] This result with reduced statistical uncertainty is obtained by assuming two-neutrino oscillations within the LMA (large mixing angle) region and by fitting the time variation of the solar neutrino flux measured via $\nu_e$ elastic scattering to the variations expected from neutrino oscillations. For details, see SMY 04. There is an additional small systematic error of $\pm 0.0004$ coming from uncertainty of oscillation parameters.

[5] AHARMIM 05A measurements were made with dissolved NaCl (0.195% by weight) in heavy water over the period between July 26, 2001 and August 28, 2003, with 176.5 days of the live time recorded during the day and 214.9 days during the night. This result is obtained with the spectral distribution of the CC events not constrained to the $^8$B shape.

[6] AHMAD 02B results are based on the charged-current interactions recorded between November 2, 1999 and May 28, 2001, with the day and night live times of 128.5 and 177.9 days, respectively. The complete description of the SNO Phase I data set is given in AHARMIM 07.

[7] AHMAD 02B results are derived from the charged-current interactions, neutral-current interactions, and $\nu e$ elastic scattering, with the total flux of active neutrinos constrained to have no asymmetry. The data were recorded between November 2, 1999 and May 28, 2001, with the day and night live times of 128.5 and 177.9 days, respectively. The complete description of the SNO Phase I data set is given in AHARMIM 07.

## $\phi_{ES}$ ($^7$Be)

$^7$Be solar-neutrino flux measured via $\nu_e$ elastic scattering. This process is sensitive to all active neutrino flavors, but with reduced sensitivity to $\nu_\mu$, $\nu_\tau$ due to the cross-section difference, $\sigma(\nu_{\mu,\tau} e) \sim 0.2\, \sigma(\nu_e e)$. If the $^7$Be solar-neutrino flux involves nonelectron flavor active neutrinos, their contribution to the flux is $\sim 0.2$ times that of $\nu_e$.

| VALUE ($10^9$ cm$^{-2}$ s$^{-1}$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $3.26 \pm 0.52$ | [1] GANDO | 15 | KLND | average flux |
| $3.10 \pm 0.15$ | [2] BELLINI | 11A | BORX | average flux |

[1] GANDO 15 uses 165.4 kton·day exposure of the KamLAND liquid scintillator detector to measure the 862 keV $^7$Be solar neutrino flux via $\nu - e$ elastic scattering

[2] BELLINI 11A reports the $^7$Be solar neutrino flux measured via $\nu - e$ elastic scattering. The data correspond to 740.7 live days between May 16, 2007 and May 8, 2010, and also correspond to 153.6 ton·year fiducial exposure. BELLINI 11A measured the 862 keV $^7$Be solar neutrino flux, which is an 89.6% branch of the $^7$Be solar neutrino flux, to be $(2.78 \pm 0.13) \times 10^9$ cm$^{-2}$ s$^{-1}$. Supercedes ARPESELLA 08A.

## $\phi_{ES}$ (*pep*)

*pep* solar-neutrino flux measured via $\nu_e$ elastic scattering. This process is sensitive to all active neutrino flavors, but with reduced sensitivity to $\nu_\mu$, $\nu_\tau$ due to the cross section difference, $\sigma(\nu_{\mu,\tau} e) \sim 0.2\, \sigma(\nu_e e)$. If the *pep* solar-neutrino flux involves non-electron flavor active neutrinos, their contribution to the flux is $\sim 0.2$ times that of $\nu_e$.

| VALUE ($10^8$ cm$^{-2}$s$^{-1}$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $1.0 \pm 0.2$ | [1] BELLINI | 12A | BORX | average flux |

[1] BELLINI 12A reports 1.44 MeV *pep* solar-neutrino flux measured via $\nu_e$ elastic scattering. The data were collected between January 13, 2008 and May 9, 2010, corresponding to 20,4009 ton·day fiducial exposure. The listed flux value is calculated from the observed rate of *pep* solar neutrino interactions in Borexino ($3.1 \pm 0.6 \pm 0.3$ counts/(day·100 ton)) and the corresponding rate expected for no neutrino flavor oscillations ($4.47 \pm 0.05$ counts/(day·100 ton)), using the SSM prediction for the *pep* solar neutrino flux of $(1.441 \pm 0.012) \times 10^8$ cm$^{-2}$s$^{-1}$.

## $\phi_{ES}$ (CNO)

CNO solar-neutrino flux measured via $\nu_e$ elastic scattering. This process is sensitive to all active neutrino flavors, but with reduced sensitivity to $\nu_\mu$, $\nu_\tau$ due to the cross section difference, $\sigma(\nu_{\mu,\tau} e) \sim 0.2\, \sigma(\nu_e e)$. If the CNO solar-neutrino flux involves non-electron flavor active neutrinos, their contribution to the flux is $\sim 0.2$ times that of $\nu_e$.

| VALUE ($10^8$ cm$^{-2}$s$^{-1}$) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <7.7 | 90 | [1] BELLINI | 12A | BORX | MSW-LMA solution assumed |

[1] BELLINI 12A reports an upper limit of the CNO solar neutrino flux measured via $\nu_e$ elastic scattering. The data were collected between January 13, 2008 and May 9, 2010, corresponding to 20,409 ton·day fiducial exposure.

## $\phi_{ES}(pp)$

$pp$ solar-neutrino flux measured via $\nu e$ elastic scattering. This process is sensitive to all active neutrino flavors, but with reduced sensitivity to $\nu_\mu$, $\nu_\tau$ due to the cross section difference, $\sigma(\nu_{\mu,\tau} \, e) \sim 0.3 \, \sigma(\nu_e e)$. If the $pp$ solar-neutrino flux involves nonelectron flavor active neutrinos, their contribution to the flux is $\sim 0.3$ times of $\nu_e$.

| *VALUE* ($10^{10}$ cm$^{-2}$ s$^{-1}$) | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $4.4\pm0.5$ | [1] BELLINI 14A | BORX | average flux |

[1] BELLINI 14A reports $pp$ solar-neutrino flux measured via $\nu e$ elastic scattering. The data were collected between January 2012 and May 2013, corresponding to 408 days of data. The $pp$ neutrino interaction rate in Borexino is measured to be $144 \pm 13 \pm 10$ counts/(day·100 ton) by fitting the measured energy spectrum of events in the 165–590 keV recoil electron kinetic energy window with the expected signal + background spectrum. The listed flux value $\phi_{ES}(pp)$ is calculated from the observed rate and the number of $(3.307 \pm 0.003) \times 10^{31}$ electrons for 100 tons of the Borexino scintillator, and the $\nu_e e$ integrated cross section over the $pp$ neutrino spectrum, $\sigma(\nu_e e) = 11.38 \times 10^{-46}$ cm$^2$.

## $\phi_{CC}(pp)$

$pp$ solar-neutrino flux measured with charged-current reaction which is sensitive exclusively to $\nu_e$.

| *VALUE* ($10^{10}$ cm$^{-2}$ s$^{-1}$) | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $3.38\pm0.47$ | [1] ABDURASHI... 09 | FIT | Fit existing solar-$\nu$ data |

[1] ABDURASHITOV 09 reports the $pp$ solar-neutrino flux derived from the Ga solar neutrino capture rate by subtracting contributions from $^8$B, $^7$Be, $pep$ and CNO solar neutrino fluxes determined by other solar neutrino experiments as well as neutrino oscillation parameters determined from available world neutrino oscillation data.

## $\phi_{ES}$ (hep)

hep solar-neutrino flux measured via $\nu e$ elastic scattering. This process is sensitive to all active neutrino flavors, but with reduced sensitivity to $\nu_\mu$, $\nu_\tau$ due to the cross-section difference, $\sigma(\nu_{\mu,\tau} e) \sim 0.16\sigma(\nu_e e)$. If the hep solar-neutrino flux involves nonelectron flavor active neutrinos, their contribution to the flux is $\sim 0.16$ times of $\nu_e$.

| *VALUE* ($10^3$ cm$^{-2}$s$^{-1}$) | *CL%* | *DOCUMENT ID* | *TECN* |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $<73$ | 90 | [1] HOSAKA 06 | SKAM |

[1] HOSAKA 06 result is obtained from the recoil electron energy window of 18–21 MeV, and updates FUKUDA 01 result.

## $\phi_{\overline{\nu}_e}$ ($^8$B)

Searches are made for electron antineutrino flux from the Sun. Flux limits listed here are derived relative to the BS05(OP) Standard Solar Model $^8$B solar neutrino flux ($5.69 \times 10^6$ cm$^{-2}$ s$^{-1}$), with an assumption that solar $\overline{\nu}_e$s follow an unoscillated $^8$B neutrino spectrum.

| VALUE (%) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <0.013 | 90 | BELLINI | 11 | BORX | E$_{\overline{\nu}_e}$ > 1.8 MeV |
| <1.9 | 90 | [1] BALATA | 06 | CNTR | 1.8< E$_{\overline{\nu}_e}$ < 20.0 MeV |
| <0.72 | 90 | AHARMIM | 04 | SNO | 4.0< E$_{\overline{\nu}_e}$ < 14.8 MeV |
| <0.022 | 90 | EGUCHI | 04 | KLND | 8.3< E$_{\overline{\nu}_e}$ < 14.8 MeV |
| <0.7 | 90 | GANDO | 03 | SKAM | 8.0< E$_{\overline{\nu}_e}$ < 20.0 MeV |
| <1.7 | 90 | AGLIETTA | 96 | LSD | 7< E$_{\overline{\nu}_e}$ < 17 MeV |

[1] BALATA 06 obtained this result from the search for $\overline{\nu}_e$ interactions with Counting Test Facility (the prototype of the Borexino detector).

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## (B) Three-neutrino mixing parameters

# INTRODUCTION TO THREE-NEUTRINO MIXING PARAMETERS LISTINGS

Updated November 2015 by M. Goodman (ANL).

***Introduction and Notation:*** With the exception of possible short-baseline anomalies (such as LSND), current accelerator, reactor, solar and atmospheric neutrino data can be described within the framework of a $3 \times 3$ mixing matrix between the flavor eigenstates $\nu_e$, $\nu_\mu$ and $\nu_\tau$ and mass eigenstates $\nu_1$, $\nu_2$ and $\nu_3$. (See equation 14.6 of the review "Neutrino Mass, Mixing and Oscillations" by K. Nakamura and S.T. Petcov.) Whether or not this is the ultimately correct framework, it is currently widely used to parametrize neutrino mixing data and to plan new experiments.

The mass differences are called $\Delta m_{21}^2 \equiv m_2^2 - m_1^2$ and $\Delta m_{32}^2 \equiv m_3^2 - m_2^2$. In these listings, we assume

$$\Delta m_{32}^2 \sim \Delta m_{31}^2 \tag{1}$$

even though the experimental error is comparable to the difference $\Delta m_{31}^2 - \Delta m_{32}^2 = \Delta m_{21}^2$. The measurements made by $\nu_\mu$ disappearance at accelerators and by $\nu_e$ disappearance at reactors are slightly different mixtures of $\Delta m_{32}^2$ and $\Delta m_{31}^2$. The angles are labeled $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$. The CP violating phase is called $\delta$. The familiar two neutrino form for oscillations is

$$P(\nu_a \to \nu_b; a \neq b) = \sin^2(2\theta)\sin^2(\Delta m^2 L/4E). \qquad (2)$$

Despite the fact that the mixing angles have been measured to be much larger than in the quark sector, the two neutrino form is often a very good approximation and is used in many situations.

The angles appear in the equations below in many forms. They most often appear as $\sin^2(2\theta)$. The listings currently now use $\sin^2(\theta)$ because this distinguishes whether $\theta_{23}$ is larger or smaller than $45°$.

***Accelerator neutrino experiments:*** Ignoring $\Delta m_{21}^2$, *CP* violation, and matter effects, the equations for the probability of appearance in an accelerator oscillation experiment are:

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23})\cos^4(\theta_{13})\sin^2(\Delta m_{32}^2 L/4E) \qquad (3)$$
$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m_{32}^2 L/4E) \qquad (4)$$
$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m_{32}^2 L/4E) \qquad (5)$$
$$P(\nu_e \to \nu_\tau) = \sin^2(2\theta_{13})\cos^2(\theta_{23})\sin^2(\Delta m_{32}^2 L/4E) . \qquad (6)$$

Current and future long-baseline accelerator experiments are studying non-zero $\theta_{13}$ through $P(\nu_\mu \to \nu_e)$. Including the

CP terms and low mass scale, the equation for neutrino oscillation in vacuum is:

$$P(\nu_\mu \to \nu_e) = P1 + P2 + P3 + P4$$
$$P1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta m_{32}^2 L/4E)$$
$$P2 = \cos^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta m_{21}^2 L/4E)$$
$$P3 = -/+ \, J \sin(\delta) \sin(\Delta m_{32}^2 L/4E)$$
$$P4 = J \cos(\delta) \cos(\Delta m_{32}^2 L/4E) \tag{7}$$

where

$$J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times$$
$$\sin(\Delta m_{32}^2 L/4E) \sin(\Delta m_{21}^2 L/4E) \tag{8}$$

and the sign in P3 is negative for neutrinos and positive for anti-neutrinos respectively. For most new long-baseline accelerator experiments, P2 can safely be neglected but the other three terms can all be large. Also, depending on the distance and the mass hierarchy, matter effects will need to be included.

***Reactor neutrino experiments:*** Nuclear reactors are prolific sources of $\bar{\nu}_e$ with an energy near 4 MeV. The oscillation probability can be expressed

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta m_{21}^2 L/4E)$$
$$- \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta m_{31}^2 L/4E)$$
$$- \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta m_{32}^2 L/4E) \tag{9}$$

not using the approximation in Eq. (1). For short distances (L<5 km) we can ignore the second term on the right and can reimpose approximation Eq. (1). This takes the familiar two neutrino form with $\theta_{13}$ and $\Delta m_{32}^2$:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m_{32}^2 L/4E). \tag{10}$$

***Solar and Atmospheric neutrino experiments:*** Solar neutrino experiments are sensitive to $\nu_e$ disappearance and have allowed the measurement of $\theta_{12}$ and $\Delta m_{21}^2$. They are also sensitive to $\theta_{13}$. We identify $\Delta m_\odot^2 = \Delta m_{21}^2$ and $\theta_\odot = \theta_{12}$.

Atmospheric neutrino experiments are primarily sensitive to $\nu_\mu$ disappearance through $\nu_\mu \rightarrow \nu_\tau$ oscillations, and have allowed the measurement of $\theta_{23}$ and $\Delta m_{32}^2$. We identify $\Delta m_A^2 = \Delta m_{32}^2$ and $\theta_A = \theta_{23}$. Despite the large $\nu_e$ component of the atmospheric neutrino flux, it is difficult to measure $\Delta m_{21}^2$ effects. This is because of a cancellation between $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$ together with the fact that the ratio of $\nu_\mu$ and $\nu_e$ atmospheric fluxes, which arise from sequential $\pi$ and $\mu$ decay, is near 2.

***Oscillation Parameter Listings:*** In Section (B) we encode the three mixing angles $\theta_{12}$, $\theta_{23}$, $\theta_{13}$ and two mass squared differences $\Delta m_{21}^2$ and $\Delta m_{32}^2$. Our knowledge of $\theta_{12}$ and $\Delta m_{21}^2$ comes from the KamLAND reactor neutrino experiment together with solar neutrino experiments. Our knowledge of $\theta_{23}$ and $\Delta m_{32}^2$ comes from atmospheric, reactor and long-baseline accelerator neutrino experiments. For the earlier experiments, we identified the large mass splitting as $\Delta m_{32}^2$. Now that $\sigma(\Delta m_{32}^2) \approx \Delta m_{21}^2$, some experiments report separate values for the two hierarchies. Results on $\theta_{13}$ come from reactor antineutrino disappearance experiments. There are also results from long-baseline accelerator experiments looking for $\nu_e$ appearance. The interpretation of both kinds of results depends on $\Delta m_{32}^2$, and the accelerator results also depend on the mass hierarchy, $\theta_{23}$ and the CP violating phase $\delta$.

Accelerator and atmospheric experiments are beginning to have some sensitivity to the CP violation phase $\delta$ through Eq. (7). Note that P3 depends on the sign of $\Delta m_{32}^2$ so the

sensitivity depends on the mass hierarchy. For non-maximal $\theta_{23}$ mixing, it also depends on the octant of $\theta_{23}$, i.e. whether $\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$.

## $\sin^2(\theta_{12})$

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| $0.304^{+0.014}_{-0.013}$ | [1] GANDO | 13 | FIT | KamLAND + global solar + SBL + accelerator: $3\nu$ |

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

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| $0.323 \pm 0.016$ | [2] FORERO | 14 | FIT | $3\nu$ |
| $0.304^{+0.013}_{-0.012}$ | [3] GONZALEZ-G..14 | | FIT | Either mass ordering; global fit |
| $0.299^{+0.014}_{-0.014}$ | [4,5] AHARMIM | 13 | FIT | global solar: $2\nu$ |
| $0.307^{+0.016}_{-0.013}$ | [5,6] AHARMIM | 13 | FIT | global solar: $3\nu$ |
| $0.304^{+0.022}_{-0.018}$ | [5,7] AHARMIM | 13 | FIT | KamLAND + global solar: $3\nu$ |
| $0.304^{+0.014}_{-0.013}$ | [8] GANDO | 13 | FIT | KamLAND + global solar: $3\nu$ |
| $0.325^{+0.039}_{-0.039}$ | [9] GANDO | 13 | FIT | KamLAND: $3\nu$ |
| $0.30^{+0.02}_{-0.01}$ | [10] ABE | 11 | FIT | KamLAND + global solar: $2\nu$ |
| $0.30^{+0.02}_{-0.01}$ | [11] ABE | 11 | FIT | global solar: $2\nu$ |
| $0.31^{+0.03}_{-0.02}$ | [12] ABE | 11 | FIT | KamLAND + global solar: $3\nu$ |
| $0.31^{+0.03}_{-0.03}$ | [13] ABE | 11 | FIT | global solar: $3\nu$ |
| $0.314^{+0.015}_{-0.012}$ | [14] BELLINI | 11A | FIT | KamLAND + global solar: $2\nu$ |
| $0.319^{+0.017}_{-0.015}$ | [15] BELLINI | 11A | FIT | global solar: $2\nu$ |
| $0.311^{+0.016}_{-0.016}$ | [16] GANDO | 11 | FIT | KamLAND + solar: $3\nu$ |
| $0.304^{+0.046}_{-0.042}$ | [17] GANDO | 11 | FIT | KamLAND: $3\nu$ |
| $0.314^{+0.018}_{-0.014}$ | [18,19] AHARMIM | 10 | FIT | KamLAND + global solar: $2\nu$ |
| $0.314^{+0.017}_{-0.020}$ | [18,20] AHARMIM | 10 | FIT | global solar: $2\nu$ |
| $0.319^{+0.019}_{-0.016}$ | [18,21] AHARMIM | 10 | FIT | KamLAND + global solar: $3\nu$ |
| $0.319^{+0.023}_{-0.024}$ | [18,22] AHARMIM | 10 | FIT | global solar: $3\nu$ |
| $0.36^{+0.05}_{-0.04}$ | [23] ABE | 08A | FIT | KamLAND |
| $0.32 \pm 0.03$ | [24] ABE | 08A | FIT | KamLAND + global fit |
| $0.32 \pm 0.02$ | [25] AHARMIM | 08 | FIT | KamLAND + global solar |
| $0.31^{+0.04}_{-0.04}$ | [26] HOSAKA | 06 | FIT | KamLAND + global solar |
| $0.31^{+0.04}_{-0.03}$ | [27] HOSAKA | 06 | FIT | SKAM+SNO+KamLAND |

| | | | | |
|---|---|---|---|---|
| $0.31 \, {}^{+0.03}_{-0.04}$ | [28] HOSAKA | 06 | FIT | SKAM+SNO |
| $0.31 \, {}^{+0.02}_{-0.03}$ | [29] AHARMIM | 05A | FIT | KamLAND + global solar |
| $0.25$–$0.39$ | [30] AHARMIM | 05A | FIT | global solar |
| $0.29 \pm 0.03$ | [31] ARAKI | 05 | FIT | KamLAND + global solar |
| $0.29 \, {}^{+0.03}_{-0.02}$ | [32] AHMED | 04A | FIT | KamLAND + global solar |
| $0.23$–$0.37$ | [33] AHMED | 04A | FIT | global solar |
| $0.31 \, {}^{+0.04}_{-0.04}$ | [34] SMY | 04 | FIT | KamLAND + global solar |
| $0.29 \, {}^{+0.04}_{-0.04}$ | [35] SMY | 04 | FIT | global solar |
| $0.32 \, {}^{+0.06}_{-0.05}$ | [36] SMY | 04 | FIT | SKAM + SNO |
| $0.19$–$0.33$ | [37] AHMAD | 02B | FIT | global solar |
| $0.19$–$0.39$ | [38] FUKUDA | 02 | FIT | global solar |

[1] GANDO 13 obtained this result by a three-neutrino oscillation analysis using KamLAND, global solar neutrino, short-baseline (SBL) reactor, and accelerator data, assuming CPT invariance. Supersedes GANDO 11.

[2] FORERO 14 performs a global fit to neutrino oscillations using solar, reactor, long-baseline accelerator, and atmospheric neutrino data.

[3] GONZALEZ-GARCIA 14 result comes from a frequentist global fit. The corresponding Bayesian global fit to the same data results are reported in BERGSTROM 15 as $0.304 {}^{+0.013}_{-0.012}$ for normal and $0.305 {}^{+0.012}_{-0.013}$ for inverted mass ordering.

[4] AHARMIM 13 obtained this result by a two-neutrino oscillation analysis using global solar neutrino data.

[5] AHARMIM 13 global solar neutrino data include SNO's all-phases-combined analysis results on the total active $^8$B neutrino flux and energy-dependent $\nu_e$ survival probability parameters, measurements of Cl (CLEVELAND 98), Ga (ABDURASHITOV 09 which contains combined analysis with GNO (ALTMANN 05 and Ph.D. thesis of F. Kaether)), and $^7$Be (BELLINI 11A) rates, and $^8$B solar-neutrino recoil electron measurements of SK-I (HOSAKA 06) zenith, SK-II (CRAVENS 08) and SK-III (ABE 11) day/night spectra, and Borexino (BELLINI 10A) spectra.

[6] AHARMIM 13 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{32}$ fixed to $2.45 \times 10^{-3}$ eV$^2$, using global solar neutrino data.

[7] AHARMIM 13 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{32}$ fixed to $2.45 \times 10^{-3}$ eV$^2$, using global solar neutrino and KamLAND (GANDO 11) data. CPT invariance is assumed.

[8] GANDO 13 obtained this result by a three-neutrino oscillation analysis using KamLAND and global solar neutrino data, assuming CPT invariance. Supersedes GANDO 11.

[9] GANDO 13 obtained this result by a three-neutrino oscillation analysis using KamLAND data. Supersedes GANDO 11.

[10] ABE 11 obtained this result by a two-neutrino oscillation analysis using solar neutrino data including Super-Kamiokande, SNO, Borexino (ARPESELLA 08A), Homestake, GALLEX/GNO, SAGE, and KamLAND data. CPT invariance is assumed.

[11] ABE 11 obtained this result by a two-neutrino oscillation analysis using solar neutrino data including Super-Kamiokande, SNO, Borexino (ARPESELLA 08A), Homestake, GALLEX/GNO, and SAGE data.

[12] ABE 11 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{32}$ fixed to $2.4 \times 10^{-3}$ eV$^2$, using solar neutrino data including Super-Kamiokande, SNO, Borexino (ARPESELLA 08A), Homestake, GALLEX/GNO, SAGE, and KamLAND data. The normal neutrino mass ordering and CPT invariance are assumed.

[13] ABE 11 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{32}$ fixed to $2.4 \times 10^{-3}$ eV$^2$, using solar neutrino data including Super-Kamiokande, SNO, Borexino (ARPESELLA 08A), Homestake, and GALLEX/GNO data. The normal neutrino mass ordering is assumed.

[14] BELLINI 11A obtained this result by a two-neutrino oscillation analysis using KamLAND, Homestake, SAGE, Gallex, GNO, Kamiokande, Super-Kamiokande, SNO, and Borexino (BELLINI 11A) data and the SSM flux prediction in SERENELLI 11 (Astrophysical Journal **743** 24 (2011)) with the exception that the $^8$B flux was left free. CPT invariance is assumed.

[15] BELLINI 11A obtained this result by a two-neutrino oscillation analysis using Homestake, SAGE, Gallex, GNO, Kamiokande, Super-Kamiokande, SNO, and Borexino (BELLINI 11A) data and the SSM flux prediction in SERENELLI 11 (Astrophysical Journal **743** 24 (2011)) with the exception that the $^8$B flux was left free.

[16] GANDO 11 obtain this result with three-neutrino fit using the KamLAND + solar data. Superseded by GANDO 13.

[17] GANDO 11 obtain this result with three-neutrino fit using the KamLAND data only. Superseded by GANDO 13.

[18] AHARMIM 10 global solar neutrino data include SNO's low-energy-threshold analysis survival probability day/night curves, SNO Phase III integral rates (AHARMIM 08), Cl (CLEVELAND 98), SAGE (ABDURASHITOV 09), Gallex/GNO (HAMPEL 99, ALT-MANN 05), Borexino (ARPESELLA 08A), SK-I zenith (HOSAKA 06), and SK-II day/night spectra (CRAVENS 08).

[19] AHARMIM 10 obtained this result by a two-neutrino oscillation analysis using global solar neutrino data and KamLAND data (ABE 08A). *CPT* invariance is assumed.

[20] AHARMIM 10 obtained this result by a two-neutrino oscillation analysis using global solar neutrino data.

[21] AHARMIM 10 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{31}$ fixed to $2.3 \times 10^{-3}$ eV$^2$, using global solar neutrino data and KamLAND data (ABE 08A). *CPT* invariance is assumed.

[22] AHARMIM 10 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{31}$ fixed to $2.3 \times 10^{-3}$ eV$^2$, using global solar neutrino data.

[23] ABE 08A obtained this result by a rate + shape + time combined geoneutrino and reactor two-neutrino fit for $\Delta m^2_{21}$ and $\tan^2\theta_{12}$, using KamLAND data only. Superseded by GANDO 11.

[24] ABE 08A obtained this result by means of a two-neutrino fit using KamLAND, Homestake, SAGE, GALLEX, GNO, SK (zenith angle and E-spectrum), the SNO $\chi^2$-map, and solar flux data. *CPT* invariance is assumed. Superseded by GANDO 11.

[25] The result given by AHARMIM 08 is $\theta = (34.4^{+1.3}_{-1.2})^\circ$. This result is obtained by a two-neutrino oscillation analysis using solar neutrino data including those of Borexino (ARPESELLA 08A) and Super-Kamiokande-I (HOSAKA 06), and KamLAND data (ABE 08A). *CPT* invariance is assumed.

[26] HOSAKA 06 obtained this result by a two-neutrino oscillation analysis using SK $\nu_e$ data, CC data from other solar neutrino experiments, and KamLAND data (ARAKI 05). *CPT* invariance is assumed.

[27] HOSAKA 06 obtained this result by a two-neutrino oscillation analysis using the data from Super-Kamiokande, SNO (AHMAD 02 and AHMAD 02B), and KamLAND (ARAKI 05) experiments. *CPT* invariance is assumed.

[28] HOSAKA 06 obtained this result by a two-neutrino oscillation analysis using the Super-Kamiokande and SNO (AHMAD 02 and AHMAD 02B) solar neutrino data.

[29] The result given by AHARMIM 05A is $\theta = (33.9 \pm 1.6)^\circ$. This result is obtained by a two-neutrino oscillation analysis using SNO pure deuteron and salt phase data, SK $\nu_e$ data, Cl and Ga CC data, and KamLAND data (ARAKI 05). *CPT* invariance is assumed. AHARMIM 05A also quotes $\theta = (33.9^{+2.4}_{-2.2})^\circ$ as the error enveloping the 68% CL two-dimensional region. This translates into $\sin^2 2\theta = 0.86^{+0.05}_{-0.06}$.

[30] AHARMIM 05A obtained this result by a two-neutrino oscillation analysis using the data from all solar neutrino experiments. The listed range of the parameter envelops the 95% CL two-dimensional region shown in figure 35a of AHARMIM 05A. AHARMIM 05A also quotes $\tan^2\theta = 0.45^{+0.09}_{-0.08}$ as the error enveloping the 68% CL two-dimensional region. This translates into $\sin^2 2\theta = 0.86^{+0.05}_{-0.07}$.

[31] ARAKI 05 obtained this result by a two-neutrino oscillation analysis using KamLAND and solar neutrino data. *CPT* invariance is assumed. The $1\sigma$ error shown here is translated from the number provided by the KamLAND collaboration, $\tan^2\theta = 0.40^{+0.07}_{-0.05}$. The corresponding number quoted in ARAKI 05 is $\tan^2\theta = 0.40^{+0.10}_{-0.07}$ ($\sin^2 2\theta = 0.82 \pm 0.07$), which envelops the 68% CL two-dimensional region.

[32] The result given by AHMED 04A is $\theta = (32.5^{+1.7}_{-1.6})^\circ$. This result is obtained by a two-neutrino oscillation analysis using solar neutrino and KamLAND data (EGUCHI 03). *CPT* invariance is assumed. AHMED 04A also quotes $\theta = (32.5^{+2.4}_{-2.3})^\circ$ as the error enveloping the 68% CL two-dimensional region. This translates into $\sin^2 2\theta = 0.82 \pm 0.06$.

[33] AHMED 04A obtained this result by a two-neutrino oscillation analysis using the data from all solar neutrino experiments. The listed range of the parameter envelops the 95% CL two-dimensional region shown in Fig. 5(a) of AHMED 04A. The best-fit point is $\Delta(m^2) = 6.5 \times 10^{-5}$ eV$^2$, $\tan^2\theta = 0.40$ ($\sin^2 2\theta = 0.82$).

[34] The result given by SMY 04 is $\tan^2\theta = 0.44 \pm 0.08$. This result is obtained by a two-neutrino oscillation analysis using solar neutrino and KamLAND data (IANNI 03). *CPT* invariance is assumed.

[35] SMY 04 obtained this result by a two-neutrino oscillation analysis using the data from all solar neutrino experiments. The $1\sigma$ errors are read from Fig. 6(a) of SMY 04.

[36] SMY 04 obtained this result by a two-neutrino oscillation analysis using the Super-Kamiokande and SNO (AHMAD 02 and AHMAD 02B) solar neutrino data. The $1\sigma$ errors are read from Fig. 6(a) of SMY 04.

[37] AHMAD 02B obtained this result by a two-neutrino oscillation analysis using the data from all solar neutrino experiments. The listed range of the parameter envelops the 95% CL two-dimensional region shown in Fig. 4(b) of AHMAD 02B. The best fit point is $\Delta(m^2) = 5.0 \times 10^{-5}$ eV$^2$ and $\tan\theta = 0.34$ ($\sin^2 2\theta = 0.76$).

[38] FUKUDA 02 obtained this result by a two-neutrino oscillation analysis using the data from all solar neutrino experiments. The listed range of the parameter envelops the 95% CL two-dimensional region shown in Fig. 4 of FUKUDA 02. The best fit point is $\Delta(m^2) = 6.9 \times 10^{-5}$ eV$^2$ and $\tan^2\theta = 0.38$ ($\sin^2 2\theta = 0.80$).

## $\Delta m^2_{21}$

| VALUE ($10^{-5}$ eV$^2$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **7.53±0.18** | [1] GANDO | 13 | FIT | KamLAND + global solar + SBL + accelerator: $3\nu$ |

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

| | | | | |
|---|---|---|---|---|
| $7.6^{+0.19}_{-0.18}$ | [2] FORERO | 14 | FIT | $3\nu$ |
| $7.50^{+0.19}_{-0.17}$ | [3] GONZALEZ-G..14 | | FIT | Either mass ordering; global fit |
| $5.13^{+1.29}_{-0.96}$ | [4,5] AHARMIM | 13 | FIT | global solar: $2\nu$ |
| $5.13^{+1.49}_{-0.98}$ | [5,6] AHARMIM | 13 | FIT | global solar: $3\nu$ |
| $7.46^{+0.20}_{-0.19}$ | [5,7] AHARMIM | 13 | FIT | KamLAND + global solar: $3\nu$ |
| $7.53^{+0.19}_{-0.18}$ | [8] GANDO | 13 | FIT | KamLAND + global solar: $3\nu$ |

| | | | | |
|---|---|---|---|---|
| $7.54^{+0.19}_{-0.18}$ | [9] GANDO | 13 | FIT | KamLAND: $3\nu$ |
| $7.6 \pm 0.2$ | [10] ABE | 11 | FIT | KamLAND + global solar: $2\nu$ |
| $6.2^{+1.1}_{-1.9}$ | [11] ABE | 11 | FIT | global solar: $2\nu$ |
| $7.7 \pm 0.3$ | [12] ABE | 11 | FIT | KamLAND + global solar: $3\nu$ |
| $6.0^{+2.2}_{-2.5}$ | [13] ABE | 11 | FIT | global solar: $3\nu$ |
| $7.50^{+0.16}_{-0.24}$ | [14] BELLINI | 11A | FIT | KamLAND + global solar: $2\nu$ |
| $5.2^{+1.5}_{-0.9}$ | [15] BELLINI | 11A | FIT | global solar: $2\nu$ |
| $7.50^{+0.19}_{-0.20}$ | [16] GANDO | 11 | FIT | KamLAND + solar: $3\nu$ |
| $7.49 \pm 0.20$ | [17] GANDO | 11 | FIT | KamLAND: $3\nu$ |
| $7.59^{+0.20}_{-0.21}$ | [18,19] AHARMIM | 10 | FIT | KamLAND + global solar: $2\nu$ |
| $5.89^{+2.13}_{-2.16}$ | [18,20] AHARMIM | 10 | FIT | global solar: $2\nu$ |
| $7.59 \pm 0.21$ | [18,21] AHARMIM | 10 | FIT | KamLAND + global solar: $3\nu$ |
| $6.31^{+2.49}_{-2.58}$ | [18,22] AHARMIM | 10 | FIT | global solar: $3\nu$ |
| $7.58^{+0.14}_{-0.13} \pm 0.15$ | [23] ABE | 08A | FIT | KamLAND |
| $7.59 \pm 0.21$ | [24] ABE | 08A | FIT | KamLAND + global solar |
| $7.59^{+0.19}_{-0.21}$ | [25] AHARMIM | 08 | FIT | KamLAND + global solar |
| $8.0 \pm 0.3$ | [26] HOSAKA | 06 | FIT | KamLAND + global solar |
| $8.0 \pm 0.3$ | [27] HOSAKA | 06 | FIT | SKAM+SNO+KamLAND |
| $6.3^{+3.7}_{-1.5}$ | [28] HOSAKA | 06 | FIT | SKAM+SNO |
| 5–12 | [29] HOSAKA | 06 | FIT | SKAM day/night in the LMA region |
| $8.0^{+0.4}_{-0.3}$ | [30] AHARMIM | 05A | FIT | KamLAND + global solar LMA |
| 3.3–14.4 | [31] AHARMIM | 05A | FIT | global solar |
| $7.9^{+0.4}_{-0.3}$ | [32] ARAKI | 05 | FIT | KamLAND + global solar |
| $7.1^{+1.0}_{-0.3}$ | [33] AHMED | 04A | FIT | KamLAND + global solar |
| 3.2–13.7 | [34] AHMED | 04A | FIT | global solar |
| $7.1^{+0.6}_{-0.5}$ | [35] SMY | 04 | FIT | KamLAND + global solar |
| $6.0^{+1.7}_{-1.6}$ | [36] SMY | 04 | FIT | global solar |
| $6.0^{+2.5}_{-1.6}$ | [37] SMY | 04 | FIT | SKAM + SNO |
| 2.8–12.0 | [38] AHMAD | 02B | FIT | global solar |
| 3.2–19.1 | [39] FUKUDA | 02 | FIT | global solar |

[1] GANDO 13 obtained this result by a three-neutrino oscillation analysis using KamLAND, global solar neutrino, short-baseline (SBL) reactor, and accelerator data, assuming CPT invariance. Supersedes GANDO 11.

[2] FORERO 14 performs a global fit to $\Delta m^2_{21}$ using solar, reactor, long-baseline accelerator, and atmospheric neutrino data.

[3] GONZALEZ-GARCIA 14 result comes from a frequentist global fit. The corresponding Bayesian global fit to the same data results are reported in BERGSTROM 15 as $(7.50^{+0.19}_{-0.17}) \times 10^{-5}$ eV$^2$ for normal and $(7.50^{+0.18}_{-0.17}) \times 10^{-5}$ eV$^2$ for inverted mass ordering.

[4] AHARMIM 13 obtained this result by a two-neutrino oscillation analysis using global solar neutrino data.

[5] AHARMIM 13 global solar neutrino data include SNO's all-phases-combined analysis results on the total active $^8$B neutrino flux and energy-dependent $\nu_e$ survival probability parameters, measurements of Cl (CLEVELAND 98), Ga (ABDURASHITOV 09 which contains combined analysis with GNO (ALTMANN 05 and Ph.D. thesis of F. Kaether)), and $^7$Be (BELLINI 11A) rates, and $^8$B solar-neutrino recoil electron measurements of SK-I (HOSAKA 06) zenith, SK-II (CRAVENS 08), and SK-III (ABE 11) day/night spectra, and Borexino (BELLINI 10A) spectra.

[6] AHARMIM 13 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{31}$ fixed to $2.45 \times 10^{-3}$ eV$^2$, using global solar neutrino data.

[7] AHARMIM 13 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{31}$ fixed to $2.45 \times 10^{-3}$ eV$^2$, using global solar neutrino and KamLAND data (GANDO 11). CPT invariance is assumed.

[8] GANDO 13 obtained this result by a three-neutrino oscillation analysis using KamLAND and global solar neutrino data, assuming CPT invariance. Supersedes GANDO 11.

[9] GANDO 13 obtained this result by a three-neutrino oscillation analysis using KamLAND data. Supersedes GANDO 11.

[10] ABE 11 obtained this result by a two-neutrino oscillation analysis using solar neutrino data including Super-Kamiokande, SNO, Borexino (ARPESELLA 08A), Homestake, GALLEX/GNO, SAGE, and KamLAND data. CPT invariance is assumed.

[11] ABE 11 obtained this result by a two-neutrino oscillation analysis using solar neutrino data including Super-Kamiokande, SNO, Borexino (ARPESELLA 08A), Homestake, GALLEX/GNO, and SAGE data.

[12] ABE 11 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{32}$ fixed to $2.4 \times 10^{-3}$ eV$^2$, using solar neutrino data including Super-Kamiokande, SNO, Borexino (ARPESELLA 08A), Homestake, GALLEX/GNO, SAGE, and KamLAND data. The normal neutrino mass ordering and CPT invariance are assumed.

[13] ABE 11 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{32}$ fixed to $2.4 \times 10^{-3}$ eV$^2$, using solar neutrino data including Super-Kamiokande, SNO, Borexino (ARPESELLA 08A), Homestake, and GALLEX/GNO data. The normal neutrino mass ordering is assumed.

[14] BELLINI 11A obtained this result by a two-neutrino oscillation analysis using KamLAND, Homestake, SAGE, Gallex, GNO, Kamiokande, Super-Kamiokande, SNO, and Borexino (BELLINI 11A) data and the SSM flux prediction in SERENELLI 11 (Astrophysical Journal **743** 24 (2011)) with the exception that the $^8$B flux was left free. CPT invariance is assumed.

[15] BELLINI 11A obtained this result by a two-neutrino oscillation analysis using Homestake, SAGE, Gallex, GNO, Kamiokande, Super-Kamiokande, SNO, and Borexino (BELLINI 11A) data and the SSM flux prediction in SERENELLI 11 (Astrophysical Journal **743** 24 (2011)) with the exception that the $^8$B flux was left free.

[16] GANDO 11 obtain this result with three-neutrino fit using the KamLAND + solar data. Superseded by GANDO 13.

[17] GANDO 11 obtain this result with three-neutrino fit using the KamLAND data only. Supersedes ABE 08A.

[18] AHARMIM 10 global solar neutrino data include SNO's low-energy-threshold analysis survival probability day/night curves, SNO Phase III integral rates (AHARMIM 08), Cl (CLEVELAND 98), SAGE (ABDURASHITOV 09), Gallex/GNO (HAMPEL 99, ALTMANN 05), Borexino (ARPESELLA 08A), SK-I zenith (HOSAKA 06), and SK-II day/night spectra (CRAVENS 08).

[19] AHARMIM 10 obtained this result by a two-neutrino oscillation analysis using global solar neutrino data and KamLAND data (ABE 08A). *CPT* invariance is assumed.

[20] AHARMIM 10 obtained this result by a two-neutrino oscillation analysis using global solar neutrino data.

[21] AHARMIM 10 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m_{31}^2$ fixed to $2.3 \times 10^{-3}$ eV$^2$, using global solar neutrino data and KamLAND data (ABE 08A). *CPT* invariance is assumed.

[22] AHARMIM 10 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m_{31}^2$ fixed to $2.3 \times 10^{-3}$ eV$^2$, using global solar neutrino data.

[23] ABE 08A obtained this result by a rate + shape + time combined geoneutrino and reactor two-neutrino fit for $\Delta m_{21}^2$ and $\tan^2\theta_{12}$, using KamLAND data only. Superseded by GANDO 11.

[24] ABE 08A obtained this result by means of a two-neutrino fit using KamLAND, Homestake, SAGE, GALLEX, GNO, SK (zenith angle and E-spectrum), the SNO $\chi^2$-map, and solar flux data. *CPT* invariance is assumed. Superseded by GANDO 11.

[25] AHARMIM 08 obtained this result by a two-neutrino oscillation analysis using all solar neutrino data including those of Borexino (ARPESELLA 08A) and Super-Kamiokande-I (HOSAKA 06), and KamLAND data (ABE 08A). *CPT* invariance is assumed.

[26] HOSAKA 06 obtained this result by a two-neutrino oscillation analysis using solar neutrino and KamLAND data (ARAKI 05). *CPT* invariance is assumed.

[27] HOSAKA 06 obtained this result by a two-neutrino oscillation analysis using the data from Super-Kamiokande, SNO (AHMAD 02 and AHMAD 02B), and KamLAND (ARAKI 05) experiments. *CPT* invariance is assumed.

[28] HOSAKA 06 obtained this result by a two-neutrino oscillation analysis using the Super-Kamiokande and SNO (AHMAD 02 and AHMAD 02B) solar neutrino data.

[29] HOSAKA 06 obtained this result from the consistency between the observed and expected day-night flux asymmetry amplitude. The listed 68% CL range is derived from the $1\sigma$ boundary of the amplitude fit to the data. Oscillation parameters are constrained to be in the LMA region. The mixing angle is fixed at $\tan^2\theta = 0.44$ because the fit depends only very weekly on it.

[30] AHARMIM 05A obtained this result by a two-neutrino oscillation analysis using solar neutrino and KamLAND data (ARAKI 05). *CPT* invariance is assumed. AHARMIM 05A also quotes $\Delta(m^2) = (8.0^{+0.6}_{-0.4}) \times 10^{-5}$ eV$^2$ as the error enveloping the 68% CL two-dimensional region.

[31] AHARMIM 05A obtained this result by a two-neutrino oscillation analysis using the data from all solar neutrino experiments. The listed range of the parameter envelops the 95% CL two-dimensional region shown in figure 35a of AHARMIM 05A. AHARMIM 05A also quotes $\Delta(m^2) = (6.5^{+4.4}_{-2.3}) \times 10^{-5}$ eV$^2$ as the error enveloping the 68% CL two-dimensional region.

[32] ARAKI 05 obtained this result by a two-neutrino oscillation analysis using KamLAND and solar neutrino data. *CPT* invariance is assumed. The $1\sigma$ error shown here is provided by the KamLAND collaboration. The error quoted in ARAKI 05, $\Delta(m^2) = (7.9^{+0.6}_{-0.5}) \times 10^{-5}$, envelops the 68% CL two-dimensional region.

[33] AHMED 04A obtained this result by a two-neutrino oscillation analysis using solar neutrino and KamLAND data (EGUCHI 03). *CPT* invariance is assumed. AHMED 04A also quotes $\Delta(m^2) = (7.1^{+1.2}_{-0.6}) \times 10^{-5}$ eV$^2$ as the error enveloping the 68% CL two-dimensional region.

[34] AHMED 04A obtained this result by a two-neutrino oscillation analysis using the data from all solar neutrino experiments. The listed range of the parameter envelops the 95% CL two-dimensional region shown in Fig. 5(a) of AHMED 04A. The best-fit point is $\Delta(m^2) = 6.5 \times 10^{-5}$ eV$^2$, $\tan^2\theta = 0.40$ ($\sin^2 2\theta = 0.82$).

[35] SMY 04 obtained this result by a two-neutrino oscillation analysis using solar neutrino and KamLAND data (IANNI 03). *CPT* invariance is assumed.

[36] SMY 04 obtained this result by a two-neutrino oscillation analysis using the data from all solar neutrino experiments. The $1\sigma$ errors are read from Fig. 6(a) of SMY 04.

[37] SMY 04 obtained this result by a two-neutrino oscillation analysis using the Super-Kamiokande and SNO (AHMAD 02 and AHMAD 02B) solar neutrino data. The $1\sigma$ errors are read from Fig. 6(a) of SMY 04.

[38] AHMAD 02B obtained this result by a two-neutrino oscillation analysis using the data from all solar neutrino experiments. The listed range of the parameter envelops the 95% CL two-dimensional region shown in Fig. 4(b) of AHMAD 02B. The best fit point is $\Delta(m^2) = 5.0 \times 10^{-5}$ eV$^2$ and $\tan\theta = 0.34$ ($\sin^2 2\theta = 0.76$).

[39] FUKUDA 02 obtained this result by a two-neutrino oscillation analysis using the data from all solar neutrino experiments. The listed range of the parameter envelops the 95% CL two-dimensional region shown in Fig. 4 of FUKUDA 02. The best fit point is $\Delta(m^2) = 6.9 \times 10^{-5}$ eV$^2$ and $\tan^2\theta = 0.38$ ($\sin^2 2\theta = 0.80$).

## $\sin^2(\theta_{23})$

The reported limits below correspond to the projection onto the $\sin^2(\theta_{23})$ axis of the 90% CL contours in the $\sin^2(\theta_{23}) - \Delta m^2_{32}$ plane presented by the authors. Unless otherwise specified, the limits are 90% CL and the reported uncertainties are 68% CL.

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| **0.50 ±0.05** **OUR FIT** | Assuming inverted mass hierarchy | | |
| **0.51 ±0.05** **OUR FIT** | Assuming normal mass hierarchy | | |
| $0.53^{+0.09}_{-0.12}$ | [1] AARTSEN 15A | ICCB | $3\nu$ osc; normal mass ordering |
| $0.51^{+0.09}_{-0.11}$ | [1] AARTSEN 15A | ICCB | $3\nu$ osc; inverted mass ordering |
| $0.514^{+0.055}_{-0.056}$ | [2] ABE 14 | T2K | $3\nu$ osc.; normal mass ordering |
| $0.511 \pm 0.055$ | [2] ABE 14 | T2K | $3\nu$ osc.; inverted mass ordering |
| $0.41^{+0.23}_{-0.06}$ | [3] ADAMSON 14 | MINS | $3\nu$ osc., normal mass ordering |
| $0.41^{+0.26}_{-0.07}$ | [3] ADAMSON 14 | MINS | $3\nu$ osc.; inverted mass ordering |

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

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| $0.567^{+0.032}_{-0.128}$ | [4] FORERO 14 | FIT | Normal mass ordering |
| $0.573^{+0.025}_{-0.043}$ | [4] FORERO 14 | FIT | Inverted mass ordering |
| $0.452^{+0.052}_{-0.028}$ | [5] GONZALEZ-G..14 | FIT | Normal mass ordering; global fit |
| $0.579^{+0.025}_{-0.037}$ | [5] GONZALEZ-G..14 | FIT | Inverted mass ordering; global fit |
| 0.24 to 0.76 | [6] AARTSEN 13B | ICCB | DeepCore, $2\nu$ oscillation |
| $0.514 \pm 0.082$ | [7] ABE 13G | T2K | $3\nu$ osc.; normal mass ordering |
| $0.388^{+0.051}_{-0.053}$ | [8] ADAMSON 13B | MINS | Beam + Atmospheric; identical $\nu$ & $\overline{\nu}$ |
| 0.3 to 0.7 | [9] ABE 12A | T2K | off-axis beam |
| 0.28 to 0.72 | [10] ADAMSON 12 | MINS | $\overline{\nu}$ beam |
| 0.25 to 0.75 | [11,12] ADAMSON 12B | MINS | MINOS atmospheric |
| 0.27 to 0.73 | [11,13] ADAMSON 12B | MINS | MINOS pure atmospheric $\nu$ |
| 0.21 to 0.79 | [11,13] ADAMSON 12B | MINS | MINOS pure atmospheric $\overline{\nu}$ |
| 0.15 to 0.85 | [14] ADRIAN-MAR..12 | ANTR | atmospheric $\nu$ with deep see telescope |
| 0.39 to 0.61 | [15] ABE 11C | SKAM | Super-Kamiokande |
| 0.34 to 0.66 | ADAMSON 11 | MINS | $2\nu$ osc.; maximal mixing |
| $0.31^{+0.10}_{-0.07}$ | [16] ADAMSON 11B | MINS | $\overline{\nu}$ beam |

| | | | | | |
|---|---|---|---|---|---|
| 0.41 to 0.59 | [17] WENDELL | 10 | SKAM | $3\nu$ osc. with solar terms; $\theta_{13}{=}0$ | |
| 0.39 to 0.61 | [18] WENDELL | 10 | SKAM | $3\nu$ osc.; normal mass ordering | |
| 0.37 to 0.63 | [19] WENDELL | 10 | SKAM | $3\nu$ osc.; inverted mass ordering | |
| 0.31 to 0.69 | ADAMSON | 08A | MINS | MINOS | |
| 0.05 to 0.95 | [20] ADAMSON | 06 | MINS | atmospheric $\nu$ with far detector | |
| 0.18 to 0.82 | [21] AHN | 06A | K2K | KEK to Super-K | |
| 0.23 to 0.77 | [22] MICHAEL | 06 | MINS | MINOS | |
| 0.18 to 0.82 | [23] ALIU | 05 | K2K | KEK to Super-K | |
| 0.18 to 0.82 | [24] ALLISON | 05 | SOU2 | | |
| 0.36 to 0.64 | [25] ASHIE | 05 | SKAM | Super-Kamiokande | |
| 0.28 to 0.72 | [26] AMBROSIO | 04 | MCRO | MACRO | |
| 0.34 to 0.66 | [27] ASHIE | 04 | SKAM | L/E distribution | |
| 0.08 to 0.92 | [28] AHN | 03 | K2K | KEK to Super-K | |
| 0.13 to 0.87 | [29] AMBROSIO | 03 | MCRO | MACRO | |
| 0.26 to 0.74 | [30] AMBROSIO | 03 | MCRO | MACRO | |
| 0.15 to 0.85 | [31] SANCHEZ | 03 | SOU2 | Soudan-2 Atmospheric | |
| 0.28 to 0.72 | [32] AMBROSIO | 01 | MCRO | upward $\mu$ | |
| 0.29 to 0.71 | [33] AMBROSIO | 01 | MCRO | upward $\mu$ | |
| 0.13 to 0.87 | [34] FUKUDA | 99C | SKAM | upward $\mu$ | |
| 0.23 to 0.77 | [35] FUKUDA | 99D | SKAM | upward $\mu$ | |
| 0.08 to 0.92 | [36] FUKUDA | 99D | SKAM | stop $\mu$ / through | |
| 0.29 to 0.71 | [37] FUKUDA | 98C | SKAM | Super-Kamiokande | |
| 0.08 to 0.92 | [38] HATAKEYAMA | 98 | KAMI | Kamiokande | |
| 0.24 to 0.76 | [39] HATAKEYAMA | 98 | KAMI | Kamiokande | |
| 0.20 to 0.80 | [40] FUKUDA | 94 | KAMI | Kamiokande | |

[1] AARTSEN 15A obtains this result by a three-neutrino oscillation analysis using 10–100 GeV muon neutrino sample from a total of 953 days of measurement with the low-energy subdetector DeepCore of the IceCube neutrino telescope.

[2] ABE 14 results are based on $\nu_\mu$ disappearance using three-neutrino oscillation fit. The confidence intervals are derived from one dimensional profiled likelihoods.

[3] ADAMSON 14 uses a complete set of accelerator and atmospheric data. The analysis combines the $\nu_\mu$ disappearance and $\nu_e$ appearance data using three-neutrino oscillation fit. The fit results are obtained for normal and inverted mass ordering assumptions. The best fit is for lower $\theta_{23}$ quadrant and inverted mass ordering.

[4] FORERO 14 performs a global fit to neutrino oscillations using solar, reactor, long-baseline accelerator, and atmospheric neutrino data.

[5] GONZALEZ-GARCIA 14 result comes from a frequentist global fit. The corresponding Bayesian global fit to the same data results are reported in BERGSTROM 15 as 68% CL intervals of 0.433–0.496 or 0.530–0.594 for normal and 0.514–0.612 for inverted mass ordering.

[6] AARTSEN 13B obtained this result by a two-neutrino oscillation analysis using 20–100 GeV muon neutrino sample from a total of 318.9 days of live-time measurement with the low-energy subdetector DeepCore of the IceCube neutrino telescope.

[7] The best fit value is $\sin^2(\theta_{23}) = 0.514 \pm 0.082$. Superseded by ABE 14.

[8] ADAMSON 13B obtained this result from $\nu_\mu$ and $\overline{\nu}_\mu$ disappearance using $\nu_\mu$ (10.71 × $10^{20}$ POT) and $\overline{\nu}_\mu$ ($3.36 \times 10^{20}$ POT) beams, and atmospheric (37.88kton-years) data from MINOS The fit assumed two-flavor neutrino hypothesis and identical $\nu_\mu$ and $\overline{\nu}_\mu$ oscillation parameters. Superseded by ADAMSON 14.

[9] ABE 12A obtained this result by a two-neutrino oscillation analysis. The best-fit point is $\sin^2(2\theta_{23}) = 0.98$.

[10] ADAMSON 12 is a two-neutrino oscillation analysis using antineutrinos. The best fit value is $\sin^2(2\theta_{23}) = 0.95^{+0.10}_{-0.11} \pm 0.01$.

[11] ADAMSON 12B obtained this result by a two-neutrino oscillation analysis of the L/E distribution using 37.9 kton·yr atmospheric neutrino data with the MINOS far detector.

[12] The best fit point is $\Delta m^2 = 0.0019$ eV$^2$ and $\sin^2 2\theta = 0.99$. The 90% single-parameter confidence interval at the best fit point is $\sin^2 2\theta > 0.86$.

[13] The data are separated into pure samples of $\nu$s and $\overline{\nu}$s, and separate oscillation parameters for $\nu$s and $\overline{\nu}$s are fit to the data. The best fit point is $(\Delta m^2, \sin^2 2\theta) = (0.0022$ eV$^2$, 0.99) and $(\Delta \overline{m}^2, \sin^2 2\overline{\theta}) = (0.0016$ eV$^2$, 1.00). The quoted result is taken from the 90% C.L. contour in the $(\Delta m^2, \sin^2 2\theta)$ plane obtained by minimizing the four parameter log-likelihood function with respect to the other oscillation parameters.

[14] ADRIAN-MARTINEZ 12 measured the oscillation parameters of atmospheric neutrinos with the ANTARES deep sea neutrino telescope using the data taken from 2007 to 2010 (863 days of total live time).

[15] ABE 11C obtained this result by a two-neutrino oscillation analysis using the Super-Kamiokande-I+II+III atmospheric neutrino data. ABE 11C also reported results under a two-neutrino disappearance model with separate mixing parameters between $\nu$ and $\overline{\nu}$, and obtained $\sin^2 2\theta > 0.93$ for $\nu$ and $\sin^2 2\theta > 0.83$ for $\overline{\nu}$ at 90% C.L.

[16] ADAMSON 11B obtained this result by a two-neutrino oscillation analysis of antineutrinos in an antineutrino enhanced beam with $1.71 \times 10^{20}$ protons on target. This results is consistent with the neutrino measurements of ADAMSON 11 at 2% C.L.

[17] WENDELL 10 obtained this result ($\sin^2 \theta_{23} = 0.407$–$0.583$) by a three-neutrino oscillation analysis using the Super-Kamiokande-I+II+III atmospheric neutrino data, assuming $\theta_{13} = 0$ but including the solar oscillation parameters $\Delta m^2_{21}$ and $\sin^2 \theta_{12}$ in the fit.

[18] WENDELL 10 obtained this result ($\sin^2 \theta_{23} = 0.43$–$0.61$) by a three-neutrino oscillation analysis with one mass scale dominance ($\Delta m^2_{21} = 0$) using the Super-Kamiokande-I+II+III atmospheric neutrino data, and updates the HOSAKA 06A result.

[19] WENDELL 10 obtained this result ($\sin^2 \theta_{23} = 0.44$–$0.63$) by a three-neutrino oscillation analysis with one mass scale dominance ($\Delta m^2_{21} = 0$) using the Super-Kamiokande-I+II+III atmospheric neutrino data, and updates the HOSAKA 06A result.

[20] ADAMSON 06 obtained this result by a two-neutrino oscillation analysis of the L/E distribution using 4.54 kton yr atmospheric neutrino data with the MINOS far detector.

[21] Supercedes ALIU 05.

[22] MICHAEL 06 best fit is for maximal mixing. See also ADAMSON 08.

[23] The best fit is for maximal mixing.

[24] ALLISON 05 result is based upon atmospheric neutrino interactions including upward-stopping muons, with an exposure of 5.9 kton yr. From a two-flavor oscillation analysis the best-fit point is $\Delta m^2 = 0.0017$ eV$^2$ and $\sin^2(2\theta) = 0.97$.

[25] ASHIE 05 obtained this result by a two-neutrino oscillation analysis using 92 kton yr atmospheric neutrino data from the complete Super-Kamiokande I running period.

[26] AMBROSIO 04 obtained this result, without using the absolute normalization of the neutrino flux, by combining the angular distribution of upward through-going muon tracks with $E_\mu > 1$ GeV, $N_{low}$ and $N_{high}$, and the numbers of InDown + UpStop and InUp events. Here, $N_{low}$ and $N_{high}$ are the number of events with reconstructed neutrino energies $< 30$ GeV and $> 130$ GeV, respectively. InDown and InUp represent events with downward and upward-going tracks starting inside the detector due to neutrino interactions, while UpStop represents entering upward-going tracks which stop in the detector. The best fit is for maximal mixing.

[27] ASHIE 04 obtained this result from the L(flight length)/E(estimated neutrino energy) distribution of $\nu_\mu$ disappearance probability, using the Super-Kamiokande-I 1489 live-day atmospheric neutrino data.

[28] There are several islands of allowed region from this K2K analysis, extending to high values of $\Delta m^2$. We only include the one that overlaps atmospheric neutrino analyses. The best fit is for maximal mixing.

[29] AMBROSIO 03 obtained this result on the basis of the ratio R = $N_{low}/N_{high}$, where $N_{low}$ and $N_{high}$ are the number of upward through-going muon events with reconstructed neutrino energy $< 30$ GeV and $> 130$ GeV, respectively. The data came from the full detector run started in 1994. The method of FELDMAN 98 is used to obtain the limits.

[30] AMBROSIO 03 obtained this result by using the ratio R and the angular distribution of the upward through-going muons. R is given in the previous note and the angular distribution is reported in AMBROSIO 01. The method of FELDMAN 98 is used to obtain the limits. The best fit is to maximal mixing.

[31] SANCHEZ 03 is based on an exposure of 5.9 kton yr. The result is obtained using a likelihood analysis of the neutrino L/E distribution for a selection $\mu$ flavor sample while the *e*-flavor sample provides flux normalization. The method of FELDMAN 98 is used to obtain the allowed region. The best fit is $\sin^2(2\theta) = 0.97$.

[32] AMBROSIO 01 result is based on the angular distribution of upward through-going muon tracks with $E_\mu > 1$ GeV. The data came from three different detector configurations, but the statistics is largely dominated by the full detector run, from May 1994 to December 2000. The total live time, normalized to the full detector configuration is 6.17 years. The best fit is obtained outside the physical region. The method of FELDMAN 98 is used to obtain the limits. The best fit is for maximal mixing.

[33] AMBROSIO 01 result is based on the angular distribution and normalization of upward through-going muon tracks with $E_\mu > 1$ GeV. See the previous footnote.

[34] FUKUDA 99C obtained this result from a total of 537 live days of upward through-going muon data in Super-Kamiokande between April 1996 to January 1998. With a threshold of $E_\mu > 1.6$ GeV, the observed flux is $(1.74 \pm 0.07 \pm 0.02) \times 10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. The best fit is $\sin^2(2\theta) = 0.95$.

[35] FUKUDA 99D obtained this result from a simultaneous fitting to zenith angle distributions of upward-stopping and through-going muons. The flux of upward-stopping muons of minimum energy of 1.6 GeV measured between April 1996 and January 1998 is $(0.39 \pm 0.04 \pm 0.02) \times 10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. This is compared to the expected flux of $(0.73 \pm 0.16$ (theoretical error)$) \times 10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. The best fit is to maximal mixing.

[36] FUKUDA 99D obtained this result from the zenith dependence of the upward-stopping/through-going flux ratio. The best fit is to maximal mixing.

[37] FUKUDA 98C obtained this result by an analysis of 33.0 kton yr atmospheric neutrino data. The best fit is for maximal mixing.

[38] HATAKEYAMA 98 obtained this result from a total of 2456 live days of upward-going muon data in Kamiokande between December 1985 and May 1995. With a threshold of $E_\mu > 1.6$ GeV, the observed flux of upward through-going muons is $(1.94 \pm 0.10^{+0.07}_{-0.06}) \times 10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. This is compared to the expected flux of $(2.46 \pm 0.54$ (theoretical error)$) \times 10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. The best fit is for maximal mixing.

[39] HATAKEYAMA 98 obtained this result from a combined analysis of Kamiokande contained events (FUKUDA 94) and upward going muon events. The best fit is $\sin^2(2\theta) = 0.95$.

[40] FUKUDA 94 obtained the result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande. The best fit is for maximal mixing.

## $\Delta m_{32}^2$

The sign of $\Delta m_{32}^2$ is not known at this time. Only the absolute value is quoted below. Unless otherwise specified, the ranges below correspond to the projection onto the $\Delta m_{32}^2$ axis of the 90% CL contours in the $\sin^2(2\theta_{23}) - \Delta m_{32}^2$ plane presented by the authors. If uncertainties are reported with the value, they correspond to one standard deviation uncertainty.

| VALUE ($10^{-3}$ eV$^2$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **2.51 ±0.06 OUR FIT** | Assuming inverted mass hierarchy | | | |
| **2.44 ±0.06 OUR FIT** | Assuming normal mass hierarchy | | | |
| $2.72 \, {}^{+0.19}_{-0.20}$ | [1] AARTSEN | 15A | ICCB | $3\nu$ osc; normal mass ordering |
| $2.73 \, {}^{+0.18}_{-0.21}$ | [1] AARTSEN | 15A | ICCB | $3\nu$ osc; inverted mass ordering |
| $2.37 \pm 0.11$ | [2] AN | 15 | DAYA | $3\nu$ osc.; normal mass ordering |
| $2.47 \pm 0.11$ | [2] AN | 15 | DAYA | $3\nu$ osc.; inverted mass ordering |
| $2.51 \pm 0.10$ | [3] ABE | 14 | T2K | $3\nu$ osc.; normal mass ordering |
| $2.56 \pm 0.10$ | [3] ABE | 14 | T2K | $3\nu$ osc.; inverted mass ordering |
| $2.37 \pm 0.09$ | [4] ADAMSON | 14 | MINS | $3\nu$ osc., accel., atmospheric; normal mass ordering |
| $2.41 \, {}^{+0.12}_{-0.09}$ | [4] ADAMSON | 14 | MINS | $3\nu$ osc., accel., atmsopheric; inverted mass ordering |

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

| VALUE ($10^{-3}$ eV$^2$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| $2.54 \, {}^{+0.19}_{-0.20}$ | [5] AN | 14 | DAYA | $3\nu$ osc.; normal mass ordering |
| $2.64 \, {}^{+0.19}_{-0.20}$ | [5] AN | 14 | DAYA | $3\nu$ osc.; inverted mass ordering |
| $2.48 \, {}^{+0.05}_{-0.07}$ | [6] FORERO | 14 | FIT | $3\nu$; normal mass ordering |
| $2.38 \, {}^{+0.05}_{-0.06}$ | [6] FORERO | 14 | FIT | $3\nu$; inverted mass ordering |
| $2.457 \pm 0.047$ | [7,8] GONZALEZ-G.. | 14 | FIT | Normal mass ordering; global fit |
| $2.449 \, {}^{+0.048}_{-0.047}$ | [7] GONZALEZ-G.. | 14 | FIT | Inverted mass ordering; global fit |
| $2.3 \, {}^{+0.6}_{-0.5}$ | [9] AARTSEN | 13B | ICCB | DeepCore, $2\nu$ oscillation |
| $2.44 \, {}^{+0.17}_{-0.15}$ | [10] ABE | 13G | T2K | $3\nu$ osc.; normal mass ordering |
| $2.41 \, {}^{+0.09}_{-0.10}$ | [11] ADAMSON | 13B | MINS | $2\nu$ osc.; beam + atmospheric; identical $\nu$ & $\overline{\nu}$ |
| $2.2–3.1$ | [12] ABE | 12A | T2K | off-axis beam |
| $2.62 \, {}^{+0.31}_{-0.28} \pm 0.09$ | [13] ADAMSON | 12 | MINS | $\overline{\nu}$ beam |
| $1.35–2.55$ | [14,15] ADAMSON | 12B | MINS | MINOS atmospheric |
| $1.4–5.6$ | [14,16] ADAMSON | 12B | MINS | MINOS pure atmospheric $\nu$ |
| $0.9–2.5$ | [14,16] ADAMSON | 12B | MINS | MINOS pure atmospheric $\overline{\nu}$ |
| $1.8–5.0$ | [17] ADRIAN-MAR.. | 12 | ANTR | atm. $\nu$ with deep see telescope |
| $1.3–4.0$ | [18] ABE | 11C | SKAM | atmospheric $\overline{\nu}$ |
| $2.32 \, {}^{+0.12}_{-0.08}$ | ADAMSON | 11 | MINS | $2\nu$ oscillation; maximal mixing |
| $3.36 \, {}^{+0.46}_{-0.40}$ | [19] ADAMSON | 11B | MINS | $\overline{\nu}$ beam |
| $<3.37$ | [20] ADAMSON | 11C | MINS | MINOS |
| $1.9–2.6$ | [21] WENDELL | 10 | SKAM | $3\nu$ osc.; normal mass ordering |

| | | | | |
|---|---|---|---|---|
| 1.7–2.7 | [21] WENDELL | 10 | SKAM | $3\nu$ osc.; inverted mass ordering |
| 2.43 ±0.13 | ADAMSON | 08A | MINS | MINOS |
| 0.07–50 | [22] ADAMSON | 06 | MINS | atmospheric $\nu$ with far detector |
| 1.9–4.0 | [23,24] AHN | 06A | K2K | KEK to Super-K |
| 2.2–3.8 | [25] MICHAEL | 06 | MINS | MINOS |
| 1.9–3.6 | [23] ALIU | 05 | K2K | KEK to Super-K |
| 0.3–12 | [26] ALLISON | 05 | SOU2 | |
| 1.5–3.4 | [27] ASHIE | 05 | SKAM | atmospheric neutrino |
| 0.6–8.0 | [28] AMBROSIO | 04 | MCRO | MACRO |
| 1.9 to 3.0 | [29] ASHIE | 04 | SKAM | L/E distribution |
| 1.5–3.9 | [30] AHN | 03 | K2K | KEK to Super-K |
| 0.25–9.0 | [31] AMBROSIO | 03 | MCRO | MACRO |
| 0.6–7.0 | [32] AMBROSIO | 03 | MCRO | MACRO |
| 0.15–15 | [33] SANCHEZ | 03 | SOU2 | Soudan-2 Atmospheric |
| 0.6–15 | [34] AMBROSIO | 01 | MCRO | upward $\mu$ |
| 1.0–6.0 | [35] AMBROSIO | 01 | MCRO | upward $\mu$ |
| 1.0–50 | [36] FUKUDA | 99C | SKAM | upward $\mu$ |
| 1.5–15.0 | [37] FUKUDA | 99D | SKAM | upward $\mu$ |
| 0.7–18 | [38] FUKUDA | 99D | SKAM | stop $\mu$ / through |
| 0.5–6.0 | [39] FUKUDA | 98C | SKAM | Super-Kamiokande |
| 0.55–50 | [40] HATAKEYAMA | 98 | KAMI | Kamiokande |
| 4–23 | [41] HATAKEYAMA | 98 | KAMI | Kamiokande |
| 5–25 | [42] FUKUDA | 94 | KAMI | Kamiokande |

[1] AARTSEN 15A obtains this result by a three-neutrino oscillation analysis using 10–100 GeV muon neutrino sample from a total of 953 days of measurements with the low-energy subdetector DeepCore of the IceCube neutrino telescope.

[2] AN 15 uses all eight identical detectors, with four placed near the reactor cores and the remaining four at the far hall to determine prompt energy spectra. The results correspond to the exposure of $6.9 \times 10^5$ GW$_{th}$-ton-days. They derive $\Delta m^2_{ee} = (2.42 \pm 0.11) \times 10^{-3}$ eV$^2$. Assuming the normal (inverted) ordering, the fitted $\Delta m^2_{32} = (2.37 \pm 0.11) \times 10^{-3}$ $((2.47 \pm 0.11) \times 10^{-3})$ eV$^2$. Supersedes AN 14.

[3] ABE 14 results are based on $\nu_\mu$ disappearance using three-neutrino oscillation fit. The confidence intervals are derived from one dimensional profiled likelihoods. In ABE 14 the inverted mass ordering result is reported as $\Delta m^2_{13} = (2.48 \pm 0.10) \times 10^{-3}$ eV$^2$ which we converted to $\Delta m^2_{32}$ by adding PDG 14 value of $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV$^2$.

[4] ADAMSON 14 uses a complete set of accelerator and atmospheric data. The analysis combines The analysis combines the $\nu_\mu$ disappearance and $\nu_e$ appearance data using three-neutrino oscillation fit. The fit results are obtained for normal and inverted mass ordering assumptions.

[5] AN 14 uses six identical detectors, with three placed near the reactor cores (flux-weighted baselines of 512 and 561 m) and the remaining three at the far hall (at the flux averaged distance of 1579 m from all six reactor cores) to determine prompt energy spectra and derive $\Delta m^2_{ee} = (2.59^{+0.19}_{-0.20}) \times 10^{-3}$ eV$^2$. Assuming the normal (inverted) ordering, the fitted $\Delta m^2_{32} = (2.54^{+0.19}_{-0.20}) \times 10^{-3}$ $((2.64^{+0.19}_{-0.20}) \times 10^{-3})$ eV$^2$. Superseded by AN 15.

[6] FORERO 14 performs a global fit to $\Delta m^2_{31}$ using solar, reactor, long-baseline accelerator, and atmospheric neutrino data.

[7] GONZALEZ-GARCIA 14 result comes from a frequentist global fit. The corresponding Bayesian global fit to the same data results are reported in BERGSTROM 15 as $(2.460 \pm 0.046) \times 10^{-3}$ eV$^2$ for normal and $(2.445 ^{+0.047}_{-0.045}) \times 10^{-3}$ eV$^2$ for inverted mass ordering.

[8] The value for normal mass ordering is actually a measurement of $\Delta m^2_{31}$ which differs from $\Delta m^2_{32}$ by a much smaller value of $\Delta m^2_{12}$.

[9] AARTSEN 13B obtained this result by a two-neutrino oscillation analysis using 20–100 GeV muon neutrino sample from a total of 318.9 days of live-time measurement with the low-energy subdetector DeepCore of the IceCube neutrino telescope.

[10] Based on the observation of 58 $\nu_\mu$ events with $205 \pm 17$(syst) expected in the absence of neutrino oscillations. Superseded by ABE 14.

[11] ADAMSON 13B obtained this result from $\nu_\mu$ and $\overline{\nu}_\mu$ disappearance using $\nu_\mu$ ($10.71 \times 10^{20}$ POT) and $\overline{\nu}_\mu$ ($3.36 \times 10^{20}$ POT) beams, and atmospheric (37.88 kton-years) data from MINOS. The fit assumed two-flavor neutrino hypothesis and identical $\nu_\mu$ and $\overline{\nu}_\mu$ oscillation parameters.

[12] ABE 12A obtained this result by a two-neutrino oscillation analysis. The best-fit point is $\Delta m^2_{32} = 2.65 \times 10^{-3}$ eV$^2$.

[13] ADAMSON 12 is a two-neutrino oscillation analysis using antineutrinos.

[14] ADAMSON 12B obtained this result by a two-neutrino oscillation analysis of the L/E distribution using 37.9 kton·yr atmospheric neutrino data with the MINOS far detector.

[15] The 90% single-parameter confidence interval at the best fit point is $\Delta m^2 = 0.0019 \pm 0.0004$ eV$^2$.

[16] The data are separated into pure samples of $\nu$s and $\overline{\nu}$s, and separate oscillation parameters for $\nu$s and $\overline{\nu}$s are fit to the data. The best fit point is ($\Delta m^2$, $\sin^2 2\theta$) = (0.0022 eV$^2$, 0.99) and ($\Delta \overline{m}^2$, $\sin^2 2\overline{\theta}$) = (0.0016 eV$^2$, 1.00). The quoted result is taken from the 90% C.L. contour in the ($\Delta m^2$, $\sin^2 2\theta$) plane obtained by minimizing the four parameter log-likelihood function with respect to the other oscillation parameters.

[17] ADRIAN-MARTINEZ 12 measured the oscillation parameters of atmospheric neutrinos with the ANTARES deep sea neutrino telescope using the data taken from 2007 to 2010 (863 days of total live time).

[18] ABE 11C obtained this result by a two-neutrino oscillation analysis with separate mixing parameters between neutrinos and antineutrinos, using the Super-Kamiokande-I+II+III atmospheric neutrino data. The corresponding 90% CL neutrino oscillation parameter range obtained from this analysis is $\Delta m^2 = 1.7$–$3.0 \times 10^{-3}$ eV$^2$.

[19] ADAMSON 11B obtained this result by a two-neutrino oscillation analysis of antineutrinos in an antineutrino enhanced beam with $1.71 \times 10^{20}$ protons on target. This results is consistent with the neutrino measurements of ADAMSON 11 at 2% C.L.

[20] ADAMSON 11C obtains this result based on a study of antineutrinos in a neutrino beam and assumes maximal mixing in the two-flavor approximation.

[21] WENDELL 10 obtained this result by a three-neutrino oscillation analysis with one mass scale dominance ($\Delta m^2_{21} = 0$) using the Super-Kamiokande-I+II+III atmospheric neutrino data, and updates the HOSAKA 06A result.

[22] ADAMSON 06 obtained this result by a two-neutrino oscillation analysis of the L/E distribution using 4.54 kton yr atmospheric neutrino data with the MINOS far detector.

[23] The best fit in the physical region is for $\Delta m^2 = 2.8 \times 10^{-3}$ eV$^2$.

[24] Supercedes ALIU 05.

[25] MICHAEL 06 best fit is $2.74 \times 10^{-3}$ eV$^2$. See also ADAMSON 08.

[26] ALLISON 05 result is based on an atmospheric neutrino observation with an exposure of 5.9 kton yr. From a two-flavor oscillation analysis the best-fit point is $\Delta m^2 = 0.0017$ eV$^2$ and $\sin^2 2\theta = 0.97$.

[27] ASHIE 05 obtained this result by a two-neutrino oscillation analysis using 92 kton yr atmospheric neutrino data from the complete Super-Kamiokande I running period. The best fit is for $\Delta m^2 = 2.1 \times 10^{-3}$ eV$^2$.

[28] AMBROSIO 04 obtained this result, without using the absolute normalization of the neutrino flux, by combining the angular distribution of upward through-going muon tracks with $E_\mu > 1$ GeV, $N_{low}$ and $N_{high}$, and the numbers of InDown + UpStop and InUp events. Here, $N_{low}$ and $N_{high}$ are the number of events with reconstructed neutrino energies $< 30$ GeV and $> 130$ GeV, respectively. InDown and InUp represent events with downward and upward-going tracks starting inside the detector due to neutrino interactions, while UpStop represents entering upward-going tracks which stop in the detector. The best fit is for $\Delta m^2 = 2.3 \times 10^{-3}$ eV$^2$.

[29] ASHIE 04 obtained this result from the L(flight length)/E(estimated neutrino energy) distribution of $\nu_\mu$ disappearance probability, using the Super-Kamiokande-I 1489 live-day atmospheric neutrino data. The best fit is for $\Delta m^2 = 2.4 \times 10^{-3}$ eV$^2$.

[30] There are several islands of allowed region from this K2K analysis, extending to high values of $\Delta m^2$. We only include the one that overlaps atmospheric neutrino analyses. The best fit is for $\Delta m^2 = 2.8 \times 10^{-3}$ eV$^2$.

[31] AMBROSIO 03 obtained this result on the basis of the ratio R = $N_{low}/N_{high}$, where $N_{low}$ and $N_{high}$ are the number of upward through-going muon events with reconstructed neutrino energy $< 30$ GeV and $> 130$ GeV, respectively. The data came from the full detector run started in 1994. The method of FELDMAN 98 is used to obtain the limits. The best fit is for $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$.

[32] AMBROSIO 03 obtained this result by using the ratio R and the angular distribution of the upward through-going muons. R is given in the previous note and the angular distribution is reported in AMBROSIO 01. The method of FELDMAN 98 is used to obtain the limits. The best fit is for $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$.

[33] SANCHEZ 03 is based on an exposure of 5.9 kton yr. The result is obtained using a likelihood analysis of the neutrino L/E distribution for a selection $\mu$ flavor sample while the *e*-flavor sample provides flux normalization. The method of FELDMAN 98 is used to obtain the allowed region. The best fit is for $\Delta m^2 = 5.2 \times 10^{-3}$ eV$^2$.

[34] AMBROSIO 01 result is based on the angular distribution of upward through-going muon tracks with $E_\mu > 1$ GeV. The data came from three different detector configurations, but the statistics is largely dominated by the full detector run, from May 1994 to December 2000. The total live time, normalized to the full detector configuration is 6.17 years. The best fit is obtained outside the physical region. The method of FELDMAN 98 is used to obtain the limits.

[35] AMBROSIO 01 result is based on the angular distribution and normalization of upward through-going muon tracks with $E_\mu > 1$ GeV. See the previous footnote.

[36] FUKUDA 99C obtained this result from a total of 537 live days of upward through-going muon data in Super-Kamiokande between April 1996 to January 1998. With a threshold of $E_\mu > 1.6$ GeV, the observed flux is $(1.74 \pm 0.07 \pm 0.02) \times 10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. The best fit is for $\Delta m^2 = 5.9 \times 10^{-3}$ eV$^2$.

[37] FUKUDA 99D obtained this result from a simultaneous fitting to zenith angle distributions of upward-stopping and through-going muons. The flux of upward-stopping muons of minimum energy of 1.6 GeV measured between April 1996 and January 1998 is $(0.39 \pm 0.04 \pm 0.02) \times 10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. This is compared to the expected flux of $(0.73 \pm 0.16$ (theoretical error)$) \times 10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. The best fit is for $\Delta m^2 = 3.9 \times 10^{-3}$ eV$^2$.

[38] FUKUDA 99D obtained this result from the zenith dependence of the upward-stopping/through-going flux ratio. The best fit is for $\Delta m^2 = 3.1 \times 10^{-3}$ eV$^2$.

[39] FUKUDA 98C obtained this result by an analysis of 33.0 kton yr atmospheric neutrino data. The best fit is for $\Delta m^2 = 2.2 \times 10^{-3}$ eV$^2$.

[40] HATAKEYAMA 98 obtained this result from a total of 2456 live days of upward-going muon data in Kamiokande between December 1985 and May 1995. With a threshold of $E_\mu > 1.6$ GeV, the observed flux of upward through-going muons is $(1.94 \pm 0.10 {}^{+0.07}_{-0.06}) \times$

$10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. This is compared to the expected flux of $(2.46 \pm 0.54$ (theoretical error$)) \times 10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. The best fit is for $\Delta m^2 = 2.2 \times 10^{-3}$ eV$^2$.

[41] HATAKEYAMA 98 obtained this result from a combined analysis of Kamiokande contained events (FUKUDA 94) and upward going muon events. The best fit is for $\Delta m^2 = 13 \times 10^{-3}$ eV$^2$.

[42] FUKUDA 94 obtained the result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande. The best fit is for $\Delta m^2 = 16 \times 10^{-3}$ eV$^2$.

## $\sin^2(\theta_{13})$

At present time direct measurements of $\sin^2(\theta_{13})$ are derived from the reactor $\overline{\nu}_e$ disappearance at distances corresponding to the $\Delta m^2_{32}$ value, i.e. L $\sim$ 1km. Alternatively, limits can also be obtained from the analysis of the solar neutrino data and accelerator-based $\nu_\mu \rightarrow \nu_e$ experiments.

| VALUE (units $10^{-2}$) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **2.19± 0.12 OUR AVERAGE** | | | | | |
| 2.15± 0.13 | | [1] AN | 15 | DAYA | DayaBay, Ling Ao/Ao II reactors |
| 2.3 $+ 0.9 - 0.8$ | | [2] ABE | 14H | DCHZ | Chooz reactors |
| 2.12± 0.47 | | [3] AN | 14B | DAYA | DayaBay, Ling Ao/Ao II reactors |
| 2.5 ± 0.9 ±0.9 | | [4] ABE | 13C | DCHZ | Chooz reactors |
| 2.9 ± 0.3 ±0.5 | | [5] AHN | 12 | RENO | Yonggwang reactors |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 2.6 $+ 1.2 - 1.1$ | | [6] ABE | 14A | DCHZ | Chooz reactors |
| 3.0 $+ 1.3 - 1.0$ | | [7] ABE | 14C | T2K | Inverted mass ordering |
| 3.6 $+ 1.0 - 0.9$ | | [7] ABE | 14C | T2K | Normal mass ordering |
| 2.3 ± 0.2 | | [8] AN | 14 | DAYA | DayaBay, Ling Ao/Ao II reactors |
| 2.34± 0.20 | | [9] FORERO | 14 | FIT | Normal mass ordering |
| 2.40± 0.19 | | [9] FORERO | 14 | FIT | Inverted mass ordering |
| 2.18± 0.10 | | [10] GONZALEZ-G14 | | FIT | Normal mass ordering; global fit |
| 2.19 $+ 0.11 - 0.10$ | | [10] GONZALEZ-G14 | | FIT | Inverted mass ordering; global fit |
| 2.3 $+ 1.3 - 1.0$ | | [11] ABE | 13E | T2K | Normal mass ordering |
| 2.8 $+ 1.6 - 1.2$ | | [11] ABE | 13E | T2K | Inverted mass ordering |
| 1.6 $+ 1.3 - 0.9$ | | [12] ADAMSON | 13A | MINS | Normal mass ordering |
| 3.0 $+ 1.8 - 1.6$ | | [12] ADAMSON | 13A | MINS | Inverted mass ordering |
| <13 | 90 | AGAFONOVA13 | | OPER | OPERA: 3$\nu$ |
| < 3.6 | 95 | [13] AHARMIM | 13 | FIT | global solar: 3$\nu$ |
| 2.3 ± 0.3 ±0.1 | | [14] AN | 13 | DAYA | DayaBay, LIng Ao/Ao II reactors |
| 2.2 ± 1.1 ±0.8 | | [15] ABE | 12 | DCHZ | Chooz reactors |
| 2.8 ± 0.8 ±0.7 | | [16] ABE | 12B | DCHZ | Chooz reactors |
| 2.4 ± 0.4 ±0.1 | | [17] AN | 12 | DAYA | DayaBay, Ling Ao/Ao II reactors |
| 2.5 $+ 1.8 - 1.6$ | 68 | [18] ABE | 11 | FIT | KamLAND + global solar |
| < 6.1 | 95 | [19] ABE | 11 | FIT | Global solar |
| 1.3 to 5.6 | 68 | [20] ABE | 11A | T2K | Normal mass ordering |
| 1.5 to 5.6 | 68 | [21] ABE | 11A | T2K | Inverted mass ordering |

| | | | | | | |
|---|---|---|---|---|---|---|
| 0.3 to 2.3 | | 68 | [22] ADAMSON | 11D | MINS | Normal mass ordering |
| 0.8 to 3.9 | | 68 | [23] ADAMSON | 11D | MINS | Inverted mass ordering |
| 8 | $\pm$ 3 | 68 | [24] FOGLI | 11 | FIT | Global neutrino data |
| 7.8 | $\pm$ 6.2 | 68 | [25] GANDO | 11 | FIT | KamLAND + solar: $3\nu$ |
| 12.4 | $\pm$13.3 | 68 | [26] GANDO | 11 | FIT | KamLAND: $3\nu$ |
| 3 | $^{+\ 9}_{-\ 7}$ | 90 | [27] ADAMSON | 10A | MINS | Normal mass ordering |
| 6 | $^{+14}_{-\ 6}$ | 90 | [28] ADAMSON | 10A | MINS | Inverted mass ordering |
| 8 | $^{+\ 8}_{-\ 7}$ | | [29,30] AHARMIM | 10 | FIT | KamLAND + global solar: $3\nu$ |
| < 30 | | 95 | [29,31] AHARMIM | 10 | FIT | global solar: $3\nu$ |
| < 15 | | 90 | [32] WENDELL | 10 | SKAM | $3\nu$ osc.; normal $m$ ordering |
| < 33 | | 90 | [32] WENDELL | 10 | SKAM | $3\nu$ osc.; inverted $m$ ordering |
| 11 | $^{+11}_{-\ 8}$ | | [33] ADAMSON | 09 | MINS | Normal mass ordering |
| 18 | $^{+15}_{-11}$ | | [34] ADAMSON | 09 | MINS | Inverted mass ordering |
| 6 | $\pm$ 4 | | [35] FOGLI | 08 | FIT | Global neutrino data |
| 8 | $\pm$ 7 | | [36] FOGLI | 08 | FIT | Solar + KamLAND data |
| 5 | $\pm$ 5 | | [37] FOGLI | 08 | FIT | Atmospheric+LBL+CHOOZ |
| < 36 | | 90 | [38] YAMAMOTO | 06 | K2K | Accelerator experiment |
| < 48 | | 90 | [39] AHN | 04 | K2K | Accelerator experiment |
| < 36 | | 90 | [40] BOEHM | 01 | | Palo Verde react. |
| < 45 | | 90 | [41] BOEHM | 00 | | Palo Verde react. |
| < 15 | | 90 | [42] APOLLONIO | 99 | CHOZ | Reactor Experiment |

[1] AN 15 uses all eight identical detectors, with four placed near the reactor cores and the remaining four at the far hall to determine the mixing angle $\theta_{13}$ using the $\overline{\nu}_e$ observed interaction rates with neutron capture on Gd and energy spectra. The result corresponds to the exposure of $6.9 \times 10^5$ GW$_{th}$-ton-days. Supersedes AN 14.

[2] ABE 14H uses 467.9 live days of one detector, 1050 m away from two reactor cores of the Chooz nuclear power station, to determine the mixing parameter $\sin^2(2\,\theta_{13})$. The Bugey4 data (DECLAIS 94) is used to constrain the neutrino flux. The data set includes 7.24 reactor-off days. A rate and shape analysis is performed. Supercedes ABE 14A.

[3] AN 14B uses six identical anti-neutrino detectors with flux-weighted baselines of $\sim 500$ m and $\sim 1.6$ km to six power reactors. This rate analysis uses a 217-day data set and neutron capture on protons (not Gd) only. $\Delta m^2_{31} = 2.32 \times 10^{-3}$ eV$^2$ is assumed.

[4] ABE 13C uses delayed neutron capture on hydrogen instead of on Gd used previously. The physical volume is thus three times larger. The fit is based on the rate and shape analysis as in ABE 12B. The Bugey4 data (DECLAIS 94) is used to constrain the neutrino flux.

[5] AHN 12 uses two identical detectors, placed at flux weighted distances of 408.56 m and 1433.99 m from six reactor cores, to determine the mixing angle $\theta_{13}$. This rate-only analysis excludes the no-oscillation hypothesis at 4.9 standard deviations. The value of $\Delta m^2_{31} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV$^2$ was assumed in the analysis.

[6] ABE 14A uses 467.9 live days of one detector, 1050 m away from two reactor cores of the Chooz nuclear power station, to determine the mixing parameter $\sin^2(2\,\theta_{13})$. The Bugey4 data (DECLAIS 94) is used to constrain the neutrino flux. The data set includes 7.24 reactor-off days. A "rate-modulation" analysis is performed. Supercedes ABE 12B.

[7] ABE 14C result is for $\nu_e$ appearance and assumes $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$, $\sin^2(\theta_{23}) = 0.5$, and $\delta = 0$.

[8] AN 14 uses six identical detectors, with three placed near the reactor cores (flux-weighted baselines of 512 and 561 m) and the remaining three at the far hall (at the flux averaged distance of 1579 m from all six reactor cores) to determine the mixing angle $\theta_{13}$ using the $\overline{\nu}_e$ observed interaction rates with neutron capture on Gd and energy spectra. Supersedes AN 13 and superseded by AN 15.

[9] FORERO 14 performs a global fit to neutrino oscillations using solar, reactor, long-baseline accelerator, and atmospheric neutrino data.

[10] GONZALEZ-GARCIA 14 result comes from a frequentist global fit. The corresponding Bayesian global fit to the same data results are reported in BERGSTROM 15 as $(2.18^{+0.10}_{-0.11}) \times 10^{-2}$ eV$^2$ for normal and $(2.19^{+0.12}_{-0.10}) \times 10^{-2}$ eV$^2$ for inverted mass ordering.

[11] ABE 13E assumes maximal $\theta_{23}$ mixing and *CP* phase $\delta = 0$.

[12] ADAMSON 13A results obtained from $\nu_e$ appearance, assuming $\delta = 0$, and $\sin^2(2\,\theta_{23})$ = 0.957.

[13] AHARMIM 13 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{32}$ fixed to $2.45 \times 10^{-3}$ eV$^2$, using global solar neutrino data. AHARMIM 13 global solar neutrino data include SNO's all-phases-combined analysis results on the total active $^8$B neutrino flux and energy-dependent $\nu_e$ survival probability parameters, measurements of Cl (CLEVELAND 98), Ga (ABDURASHITOV 09 which contains combined analysis with GNO (ALTMANN 05 and Ph.D. thesis of F. Kaether)), and $^7$Be (BELLINI 11A) rates, and $^8$B solar-neutrino recoil electron measurements of SK-I (HOSAKA 06) zenith, SK-II (CRAVENS 08) and SK-III (ABE 11) day/night spectra, and Borexino (BELLINI 10A) spectra. AHARMIM 13 also reported a result combining global solar and KamLAND data, which is $\sin^2(2\,\theta_{13}) = (9.1^{+2.9}_{-3.1}) \times 10^{-2}$.

[14] AN 13 uses six identical detectors, with three placed near the reactor cores (flux-weighted baselines of 498 and 555 m) and the remaining three at the far hall (at the flux averaged distance of 1628 m from all six reactor cores) to determine the $\overline{\nu}_e$ interaction rate ratios. Superseded by AN 14.

[15] ABE 12 determines the $\overline{\nu}_e$ interaction rate in a single detector, located 1050 m from the cores of two reactors. A rate and shape analysis is performed. The rate normalization is fixed by the results of the Bugey4 reactor experiment, thus avoiding any dependence on possible very short baseline oscillations. The value of $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV$^2$ is used in the analysis. Superseded by ABE 12B.

[16] ABE 12B determines the neutrino mixing angle $\theta_{13}$ using a single detector, located 1050 m from the cores of two reactors. This result is based on a spectral shape and rate analysis. The Bugey4 data (DECLAIS 94) is used to constrain the neutrino flux. Superseded by ABE 14A.

[17] AN 12 uses six identical detectors with three placed near the reactor cores (flux-weighted baselines of 470 m and 576 m) and the remaining three at the far hall (at the flux averaged distance of 1648 m from all six reactor cores) to determine the mixing angle $\theta_{13}$ using the $\overline{\nu}_e$ observed interaction rate ratios. This rate-only analysis excludes the no-oscillation hypothesis at 5.2 standard deviations. The value of $\Delta m^2_{31} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV$^2$ was assumed in the analysis. Superseded by AN 13.

[18] ABE 11 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{32}$ fixed to $2.4 \times 10^{-3}$ eV$^2$, using solar neutrino data including Super-Kamiokande, SNO, Borexino (ARPESELLA 08A), Homestake, GALLEX/GNO, SAGE, and KamLAND data. This result implies an upper bound of $\sin^2\theta_{13} < 0.059$ (95% CL) or $\sin^2 2\theta_{13} < 0.22$ (95% CL). The normal neutrino mass ordering and CPT invariance are assumed.

[19] ABE 11 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{32}$ fixed to $2.4 \times 10^{-3}$ eV$^2$, using solar neutrino data including Super-Kamiokande, SNO, Borexino (ARPESELLA 08A), Homestake, and GALLEX/GNO data. The normal neutrino mass ordering is assumed.

[20] The quoted limit is for $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$, $\theta_{23} = \pi/2$, $\delta = 0$, and the normal mass ordering. For other values of $\delta$, the 68% region spans from 0.03 to 0.25, and the 90% region from 0.02 to 0.32.

[21] The quoted limit is for $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$, $\theta_{23} = \pi/2$, $\delta = 0$, and the inverted mass ordering. For other values of $\delta$, the 68% region spans from 0.04 to 0.30, and the 90% region from 0.02 to 0.39.

[22] The quoted limit is for $\Delta m^2_{32} = 2.32 \times 10^{-3}$ eV$^2$, $\theta_{23} = \pi/2$, $\delta = 0$, and the normal mass ordering. For other values of $\delta$, the 68% region spans from 0.02 to 0.12, and the 90% region from 0 to 0.16.

[23] The quoted limit is for $\Delta m^2_{32} = 2.32 \times 10^{-3}$ eV$^2$, $\theta_{23} = \pi/2$, $\delta = 0$, and the inverted mass ordering. For other values of $\delta$, the 68% region spans from 0.02 to 0.16, and the 90% region from 0 to 0.21.

[24] FOGLI 11 obtained this result from an analysis using the atmospheric, accelerator long baseline, CHOOZ, solar, and KamLAND data. Recently, MUELLER 11 suggested an average increase of about 3.5% in normalization of the reactor $\overline{\nu}_e$ fluxess, and using these fluxes, the fitted result becomes $0.10 \pm 0.03$.

[25] GANDO 11 report $\sin^2\theta_{13} = 0.020 \pm 0.016$. This result was obtained with three-neutrino fit using the KamLAND + solar data.

[26] GANDO 11 report $\sin^2\theta_{13} = 0.032 \pm 0.037$. This result was obtained with three-neutrino fit using the KamLAND data only.

[27] This result corresponds to the limit of <0.12 at 90% CL for $\Delta m^2_{32} = 2.43 \times 10^{-3}$ eV$^2$, $\theta_{23} = \pi/2$, and $\delta = 0$. For other values of $\delta$, the 90% CL region spans from 0 to 0.16.

[28] This result corresponds to the limit of <0.20 at 90% CL for $\Delta m^2_{32} = 2.43 \times 10^{-3}$ eV$^2$, $\theta_{23} = \pi/2$, and $\delta = 0$. For other values of $\delta$, the 90% CL region spans from 0 to 0.21.

[29] AHARMIM 10 global solar neutrino data include SNO's low-energy-threshold analysis survival probability day/night curves, SNO Phase III integral rates (AHARMIM 08), Cl (CLEVELAND 98), SAGE (ABDURASHITOV 09), Gallex/GNO (HAMPEL 99, ALT-MANN 05), Borexino (ARPESELLA 08A), SK-I zenith (HOSAKA 06), and SK-II day/night spectra (CRAVENS 08).

[30] AHARMIM 10 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{31}$ fixed to $2.3 \times 10^{-3}$ eV$^2$, using global solar neutrino data and KamLAND data (ABE 08A). *CPT* invariance is assumed. This result implies an upper bound of $\sin^2\theta_{13} < 0.057$ (95% CL) or $\sin^2 2\theta_{13} < 0.22$ (95% CL).

[31] AHARMIM 10 obtained this result by a three-neutrino oscillation analysis with the value of $\Delta m^2_{31}$ fixed to $2.3 \times 10^{-3}$ eV$^2$, using global solar neutrino data.

[32] WENDELL 10 obtained this result by a three-neutrino oscillation analysis with one mass scale dominance ($\Delta m^2_{21} = 0$) using the Super-Kamiokande-I+II+III atmospheric neutrino data, and updates the HOSAKA 06A result.

[33] The quoted limit is for $\Delta m^2_{32} = 2.43 \times 10^{-3}$ eV$^2$, $\theta_{23} = \pi/2$, and $\delta = 0$. For other values of $\delta$, the 68% CL region spans from 0.02 to 0.26.

[34] The quoted limit is for $\Delta m^2_{32} = 2.43 \times 10^{-3}$ eV$^2$, $\theta_{23} = \pi/2$, and $\delta = 0$. For other values of $\delta$, the 68% CL region spans from 0.04 to 0.34.

[35] FOGLI 08 obtained this result from a global analysis of all neutrino oscillation data, that is, solar + KamLAND + atmospheric + accelerator long baseline + CHOOZ.

[36] FOGLI 08 obtained this result from an analysis using the solar and KamLAND neutrino oscillation data.

[37] FOGLI 08 obtained this result from an analysis using the atmospheric, accelerator long baseline, and CHOOZ neutrino oscillation data.

[38] YAMAMOTO 06 searched for $\nu_\mu \rightarrow \nu_e$ appearance. Assumes 2 $\sin^2(2\theta_{\mu e}) = \sin^2(2\theta_{13})$. The quoted limit is for $\Delta m^2_{32} = 1.9 \times 10^{-3}$ eV$^2$. That value of $\Delta m^2_{32}$ is the one-$\sigma$ low value for AHN 06A. For the AHN 06A best fit value of $2.8 \times 10^{-3}$ eV$^2$, the $\sin^2(2\theta_{13})$ limit is < 0.26. Supersedes AHN 04.

[39] AHN 04 searched for $\nu_\mu \rightarrow \nu_e$ appearance. Assuming $2 \sin^2(2\,\theta_{\mu_e}) = \sin^2(2\,\theta_{13})$, a limit on $\sin^2(2\,\theta_{\mu_e})$ is converted to a limit on $\sin^2(2\,\theta_{13})$. The quoted limit is for $\Delta m^2_{32} = 1.9 \times 10^{-3}$ eV$^2$. That value of $\Delta m^2_{32}$ is the one-$\sigma$ low value for ALIU 05. For the ALIU 05 best fit value of $2.8 \times 10^{-3}$ eV$^2$, the $\sin^2(2\,\theta_{13})$ limit is $< 0.30$.

[40] The quoted limit is for $\Delta m^2_{32} = 1.9 \times 10^{-3}$ eV$^2$. That value of $\Delta m^2_{32}$ is the 1-$\sigma$ low value for ALIU 05. For the ALIU 05 best fit value of $2.8 \times 10^{-3}$ eV$^2$, the $\sin^2 2\,\theta_{13}$ limit is $< 0.19$. In this range, the $\theta_{13}$ limit is larger for lower values of $\Delta m^2_{32}$, and smaller for higher values of $\Delta m^2_{32}$.

[41] The quoted limit is for $\Delta m^2_{32} = 1.9 \times 10^{-3}$ eV$^2$. That value of $\Delta m^2_{32}$ is the 1-$\sigma$ low value for ALIU 05. For the ALIU 05 best fit value of $2.8 \times 10^{-3}$ eV$^2$, the $\sin^2 2\,\theta_{13}$ limit is $< 0.23$.

[42] The quoted limit is for $\Delta m^2_{32} = 2.43 \times 10^{-3}$ eV$^2$. That value of $\Delta m^2_{32}$ is the central value for ADAMSON 08. For the ADAMSON 08 1-$\sigma$ low value of $2.30 \times 10^{-3}$ eV$^2$, the $\sin^2 2\,\theta_{13}$ limit is $< 0.16$. See also APOLLONIO 03 for a detailed description of the experiment.

———— *CP* violating phase ————

## δ, *CP* violating phase

Measurements of $\delta$ come from atmospheric and accelarator experiments looking at $\nu_e$ appearance. We encode values between 0 and $2\pi$, though it is equivalent to use $-\pi$ to $\pi$.

| VALUE ($\pi$ rad) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 0 to 0.15, 0.83 to 2 | 90 | ABE | 15D | T2K | Normal mass hierarchy |
| 1.09 to 1.92 | 90 | ABE | 15D | T2K | Inverted mass hierarchy |
| 0.05 to 1.2 | 90 | [1] ADAMSON | 14 | MINS | Normal mass hierarchy |
| $1.34^{+0.64}_{-0.38}$ | | FORERO | 14 | FIT | Normal mass hierarchy |
| $1.48^{+0.34}_{-0.32}$ | | FORERO | 14 | FIT | Inverted mass hierarchy |
| $1.70^{+0.22}_{-0.39}$ | | [2] GONZALEZ-G..14 | | FIT | Normal mass hierarchy; global fit |
| $1.41^{+0.35}_{-0.34}$ | | [2] GONZALEZ-G..14 | | FIT | Inverted mass hierarchy; global fit |
| 0 to 1.5 or 1.9 to 2 | 90 | [3] ADAMSON | 13A | MINS | Normal mass hierarchy |

[1] Based on three-flavor formalism and $\theta_{23} > \pi/4$. Likelihood as a function of $\delta$ is also shown for the other three combinations of hierarchy and $\theta_{23}$ quadrant; all values of $\delta$ are allowed at 90% C.L.

[2] GONZALEZ-GARCIA 14 result comes from a frequentist global fit. The corresponding Bayesian global fit to the same data results are reported in BERGSTROM 15 as 68% CL intervals of 1.24–1.94 for normal and 1.15–1.77 for inverted mass ordering.

[3] Based on $\nu_e$ appearance in MINOS and the calculated $\sin^2(2\theta_{23}) = 0.957$, $\theta_{23} > \pi/4$, and normal mass hierarchy. Likelihood as a function of $\delta$ is also shown for the other three combinations of hierarchy and $\theta_{23}$ quadrant; all values of $\delta$ are allowed at 90% C.L.

## (C) Other neutrino mixing results

The LSND collaboration reported in AGUILAR 01 a signal which is consistent with $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations. In a three neutrino framework, this would be a measurement of $\theta_{12}$ and $\Delta m_{21}^2$. This does not appear to be consistent with most of the other neutrino data. The MiniBooNE experiment, reported in AGUILAR-AREVALO 07, does a two-neutrino analysis which, assuming *CP* conservation, rules out AGUILAR 01. However, the MiniBooNE antineutrino data reported in AGUILAR-AREVALO 13A are consistent with the signal reported in AGUILAR 01. The following listings include results which might be relevant towards understanding these observations. They include searches for $\nu_\mu \to \nu_e$, $\overline{\nu}_\mu \to \overline{\nu}_e$, sterile neutrino oscillations, and *CPT* violation.

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

| VALUE (eV$^2$) | CL% | | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 0.015 to 0.050 | 90 | [1] | AGUILAR-AR...13A | | MBOO | MiniBooNE |
| <0.34 | 90 | [2] | MAHN | 12 | MBOO | MiniBooNE/SciBooNE |
| <0.034 | 90 | | AGUILAR-AR...07 | | MBOO | MiniBooNE |
| <0.0008 | 90 | | AHN | 04 | K2K | Water Cherenkov |
| <0.4 | 90 | | ASTIER | 03 | NOMD | CERN SPS |
| <2.4 | 90 | | AVVAKUMOV | 02 | NTEV | NUTEV FNAL |
| | | [3] | AGUILAR | 01 | LSND | $\nu\mu \to \nu_e$ osc.prob. |
| 0.03 to 0.3 | 95 | [4] | ATHANASSO...98 | | LSND | $\nu_\mu \to \nu_e$ |
| <2.3 | 90 | [5] | LOVERRE | 96 | | CHARM/CDHS |
| <0.9 | 90 | | VILAIN | 94C | CHM2 | CERN SPS |
| <0.09 | 90 | | ANGELINI | 86 | HLBC | BEBC CERN PS |

[1] Based on $\nu_\mu \to \nu_e$ appearance of $162.0 \pm 47.8$ events; marginally compatible with two neutrino oscillations. The best fit value is $\Delta m^2 = 3.14$ eV$^2$.

[2] MAHN 12 is a combined spectral fit of MiniBooNE and SciBooNE neutrino data with the range of $\Delta m^2$ up to 25 eV$^2$. The best limit is 0.04 at 7 eV$^2$.

[3] AGUILAR 01 is the final analysis of the LSND full data set. Search is made for the $\nu_\mu \to \nu_e$ oscillations using $\nu_\mu$ from $\pi^+$ decay in flight by observing beam-on electron events from $\nu_e C \to e^- X$. Present analysis results in $8.1 \pm 12.2 \pm 1.7$ excess events in the $60 < E_e < 200$ MeV energy range, corresponding to oscillation probability of $0.10 \pm 0.16 \pm 0.04\%$. This is consistent, though less significant, with the previous result of ATHANASSOPOULOS 98, which it supersedes. The present analysis uses selection criteria developed for the decay at rest region, and is less effective in removing the background above 60 MeV than ATHANASSOPOULOS 98.

[4] ATHANASSOPOULOS 98 is a search for the $\nu_\mu \to \nu_e$ oscillations using $\nu_\mu$ from $\pi^+$ decay in flight. The 40 observed beam-on electron events are consistent with $\nu_e C \to e^- X$; the expected background is $21.9 \pm 2.1$. Authors interpret this excess as evidence for an oscillation signal corresponding to oscillations with probability $(0.26 \pm 0.10 \pm 0.05)\%$. Although the significance is only $2.3\,\sigma$, this measurement is an important and consistent cross check of ATHANASSOPOULOS 96 who reported evidence for $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations from $\mu^+$ decay at rest. See also ATHANASSOPOULOS 98B.

[5] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

## $\sin^2(2\theta)$ for "Large" $\Delta(m^2)$  ($\nu_\mu \to \nu_e$)

| VALUE (units $10^{-3}$) | CL% | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| < 7.2 | 90 | AGAFONOVA 13 | OPER | $\Delta(m^2) > 0.1$ eV$^2$ |
| 0.8 to 3 | 90 | [1] AGUILAR-AR...13A | MBOO | MiniBooNE |
| < 11 | 90 | [2] ANTONELLO 13 | ICAR | $\nu_\mu \to \nu_e$ |
| < 6.8 | 90 | [3] ANTONELLO 13A | ICAR | $\nu_\mu \to \nu_e$ |
| <100 | 90 | [4] MAHN 12 | MBOO | MiniBooNE/SciBooNE |
| < 1.8 | 90 | [5] AGUILAR-AR...07 | MBOO | MiniBooNE |
| <110 | 90 | [6] AHN 04 | K2K | Water Cherenkov |
| < 1.4 | 90 | ASTIER 03 | NOMD | CERN SPS |
| < 1.6 | 90 | AVVAKUMOV 02 | NTEV | NUTEV FNAL |
| | | [7] AGUILAR 01 | LSND | $\nu_\mu \to \nu_e$ osc.prob. |
| 0.5 to 30 | 95 | [8] ATHANASSO...98 | LSND | $\nu_\mu \to \nu_e$ |
| < 3.0 | 90 | [9] LOVERRE 96 | | CHARM/CDHS |
| < 9.4 | 90 | VILAIN 94C | CHM2 | CERN SPS |
| < 5.6 | 90 | [10] VILAIN 94C | CHM2 | CERN SPS |

[1] Based on $\nu_\mu \to \nu_e$ appearance of $162.0 \pm 47.8$ events; marginally compatible with two neutrino oscillations. The best fit value is $\sin^2 2\theta = 0.002$.

[2] ANTONELLO 13 use the ICARUS T600 detector at LNGS and $\sim 20$ GeV beam of $\nu_\mu$ from CERN 730 km away to search for an excess of $\nu_e$ events. Two events are found with $3.7 \pm 0.6$ expected from conventional sources. This result excludes some parts of the parameter space expected by LSND. Superseded by ANTONELLO 13A.

[3] Based on four events with a background of $6.4 \pm 0.9$ from conventional sources with an average energy of 20 GeV and 730 km from the source of $\nu_\mu$.

[4] MAHN 12 is a combined fit of MiniBooNE and SciBooNE neutrino data.

[5] The limit is $\sin^2 2\theta < 0.9 \times 10^{-3}$ at $\Delta m^2 = 2$ eV$^2$. That value of $\Delta m^2$ corresponds to the smallest mixing angle consistent with the reported signal from LSND in AGUILAR 01.

[6] The limit becomes $\sin^2 2\theta < 0.15$ at $\Delta m^2 = 2.8 \times 10^{-3}$ eV$^2$, the bets-fit value of the $\nu_\mu$ disappearance analysis in K2K.

[7] AGUILAR 01 is the final analysis of the LSND full data set of the search for the $\nu_\mu \to \nu_e$ oscillations. See footnote in preceding table for further details.

[8] ATHANASSOPOULOS 98 report $(0.26 \pm 0.10 \pm 0.05)\%$ for the oscillation probability; the value of $\sin^2 2\theta$ for large $\Delta m^2$ is deduced from this probability. See footnote in preceding table for further details, and see the paper for a plot showing allowed regions. If effect is due to oscillation, it is most likely to be intermediate $\sin^2 2\theta$ and $\Delta m^2$. See also ATHANASSOPOULOS 98B.

[9] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

[10] VILAIN 94C limit derived by combining the $\nu_\mu$ and $\overline{\nu}_\mu$ data assuming *CP* conservation.

## $\Delta(m^2)$ for $\sin^2(2\theta) = 1$  ($\overline{\nu}_\mu \to \overline{\nu}_e$)

| VALUE (eV$^2$) | CL% | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 0.023 to 0.060 | 90 | [1] AGUILAR-AR...13A | MBOO | MiniBooNE |
| <0.16 | 90 | [2] CHENG 12 | MBOO | MiniBooNE/SciBooNE |
| 0.03–0.09 | 90 | [3] AGUILAR-AR...10 | MBOO | $E_\nu > 475$ MeV |
| 0.03–0.07 | 90 | [4] AGUILAR-AR...10 | MBOO | $E_\nu > 200$ MeV |
| <0.06 | 90 | AGUILAR-AR...09B | MBOO | MiniBooNE |
| <0.055 | 90 | [5] ARMBRUSTER02 | KAR2 | Liquid Sci. calor. |

| | | | | | |
|---|---|---|---|---|---|
| <2.6 | 90 | | AVVAKUMOV 02 | NTEV | NUTEV FNAL |
| 0.03–0.05 | | [6] AGUILAR | 01 | LSND | LAMPF |
| 0.05–0.08 | 90 | [7] ATHANASSO...96 | | LSND | LAMPF |
| 0.048–0.090 | 80 | [8] ATHANASSO...95 | | | |
| <0.07 | 90 | [9] HILL | 95 | | |
| <0.9 | 90 | VILAIN | 94C | CHM2 | CERN SPS |
| <0.14 | 90 | [10] FREEDMAN | 93 | CNTR | LAMPF |

[1] Based on $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance of $78.4 \pm 28.5$ events. The best fit values are $\Delta m^2 = 0.043$ eV$^2$ and $\sin^2 2\theta = 0.88$.

[2] CHENG 12 is a combined fit of MiniBooNE and SciBooNE antineutrino data.

[3] This value is for a two neutrino oscillation analysis for excess antineutrino events with $E_\nu > 475$ MeV. The best fit is at 0.07. The allowed region is consistent with LSND reported by AGUILAR 01. Supercedes AGUILAR-AREVALO 09B.

[4] This value is for a two neutrino oscillation analysis for excess antineutrino events with $E_\nu > 200$ MeV with subtraction of the expected 12 events low energy excess seen in the neutrino component of the beam. The best fit value is 0.007 for $\Delta(m^2) = 4.4$ eV$^2$.

[5] ARMBRUSTER 02 is the final analysis of the KARMEN 2 data for 17.7 m distance from the ISIS stopped pion and muon neutrino source. It is a search for $\overline{\nu}_e$, detected by the inverse $\beta$-decay reaction on protons and $^{12}$C. 15 candidate events are observed, and $15.8 \pm 0.5$ background events are expected, hence no oscillation signal is detected. The results exclude large regions of the parameter area favored by the LSND experiment.

[6] AGUILAR 01 is the final analysis of the LSND full data set. It is a search for $\overline{\nu}_e$ 30 m from LAMPF beam stop. Neutrinos originate mainly for $\pi^+$ decay at rest. $\overline{\nu}_e$ are detected through $\overline{\nu}_e p \rightarrow e^+ n$ (20<$E_{e^+}$ < 60 MeV) in delayed coincidence with $np \rightarrow d\gamma$. Authors observe $87.9 \pm 22.4 \pm 6.0$ total excess events. The observation is attributed to $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations with the oscillation probability of $0.264 \pm 0.067 \pm 0.045\%$, consistent with the previously published result. Taking into account all constraints, the most favored allowed region of oscillation parameters is a band of $\Delta(m^2)$ from 0.2–2.0 eV$^2$. Supersedes ATHANASSOPOULOS 95, ATHANASSOPOULOS 96, and ATHANASSOPOULOS 98.

[7] ATHANASSOPOULOS 96 is a search for $\overline{\nu}_e$ 30 m from LAMPF beam stop. Neutrinos originate mainly from $\pi^+$ decay at rest. $\overline{\nu}_e$ could come from either $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ or $\nu_e \rightarrow \overline{\nu}_e$; our entry assumes the first interpretation. They are detected through $\overline{\nu}_e p \rightarrow e^+ n$ (20 MeV <$E_{e^+}$ <60 MeV) in delayed coincidence with $np \rightarrow d\gamma$. Authors observe $51 \pm 20 \pm 8$ total excess events over an estimated background $12.5 \pm 2.9$. ATHANASSOPOULOS 96B is a shorter version of this paper.

[8] ATHANASSOPOULOS 95 error corresponds to the $1.6\sigma$ band in the plot. The expected background is $2.7 \pm 0.4$ events. Corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)\%$. For a different interpretation, see HILL 95. Replaced by ATHANASSOPOULOS 96.

[9] HILL 95 is a report by one member of the LSND Collaboration, reporting a different conclusion from the analysis of the data of this experiment (see ATHANASSOPOULOS 95). Contrary to the rest of the LSND Collaboration, Hill finds no evidence for the neutrino oscillation $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ and obtains only upper limits.

[10] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types $\nu_\mu$, $\overline{\nu}_\mu$, and $\nu_e$ which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$. FREEDMAN 93 replaces DURKIN 88.

## $\sin^2(2\theta)$ for "Large" $\Delta(m^2)$ $\quad(\overline{\nu}_\mu \to \overline{\nu}_e)$

| VALUE (units $10^{-3}$) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| ••• We do not use the following data for averages, fits, limits, etc. ••• | | | | | |
| <640 | 90 | [1] ANTONELLO | 13A | ICAR | $\overline{\nu}_e$ appearance |
| <150 | 90 | [2] CHENG | 12 | MBOO | MiniBooNE/SciBooNE |
| 0.4–9.0 | 99 | [3] AGUILAR-AR...10 | | MBOO | $E_\nu > 475$ MeV |
| 0.4–9.0 | 99 | [4] AGUILAR-AR...10 | | MBOO | $E_\nu > 200$ MeV |
| < 3.3 | 90 | [5] AGUILAR-AR...09B | | MBOO | MiniBooNE |
| < 1.7 | 90 | [6] ARMBRUSTER02 | | KAR2 | Liquid Sci. calor. |
| < 1.1 | 90 | AVVAKUMOV | 02 | NTEV | NUTEV FNAL |
| $5.3\pm1.3\pm9.0$ | | [7] AGUILAR | 01 | LSND | LAMPF |
| $6.2\pm2.4\pm1.0$ | | [8] ATHANASSO...96 | | LSND | LAMPF |
| 3–12 | 80 | [9] ATHANASSO...95 | | | |
| < 6 | 90 | [10] HILL | 95 | | |

[1] ANTONELLO 13A obtained the limit by assuming $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation from the $\sim 2\%$ of $\overline{\nu}_\mu$ evnets contamination in the CNGS beam.

[2] CHENG 12 is a combined fit of MiniBooNE and SciBooNE antineutrino data.

[3] This value is for a two neutrino oscillation analysis for excess antineutrino events with $E_\nu > 475$ MeV. At 90% CL there is no solution at high $\Delta(m^2)$. The best fit is at maximal mixing. The allowed region is consistent with LSND reported by AGUILAR 01. Supercedes AGUILAR-AREVALO 09B.

[4] This value is for a two neutrino oscillation analysis for excess antineutrino events with $E_\nu > 200$ MeV with subtraction of the expected 12 events low energy excess seen in the neutrino component of the beam. At 90% CL there is no solution at high $\Delta(m^2)$. The best fit value is 0.007 for $\Delta(m^2) = 4.4$ eV$^2$.

[5] This result is inconclusive with respect to small amplitude mixing suggested by LSND.

[6] ARMBRUSTER 02 is the final analysis of the KARMEN 2 data. See footnote in the preceding table for further details, and the paper for the exclusion plot.

[7] AGUILAR 01 is the final analysis of the LSND full data set. The deduced oscillation probability is $0.264 \pm 0.067 \pm 0.045\%$; the value of $\sin^2 2\theta$ for large $\Delta(m^2)$ is twice this probability (although these values are excluded by other constraints). See footnote in preceding table for further details, and the paper for a plot showing allowed regions. Supersedes ATHANASSOPOULOS 95, ATHANASSOPOULOS 96, and ATHANASSOPOULOS 98.

[8] ATHANASSOPOULOS 96 reports $(0.31 \pm 0.12 \pm 0.05)\%$ for the oscillation probability; the value of $\sin^2 2\theta$ for large $\Delta(m^2)$ should be twice this probability. See footnote in preceding table for further details, and see the paper for a plot showing allowed regions.

[9] ATHANASSOPOULOS 95 error corresponds to the $1.6\sigma$ band in the plot. The expected background is $2.7 \pm 0.4$ events. Corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)\%$. For a different interpretation, see HILL 95. Replaced by ATHANASSOPOULOS 96.

[10] HILL 95 is a report by one member of the LSND Collaboration, reporting a different conclusion from the analysis of the data of this experiment (see ATHANASSOPOULOS 95). Contrary to the rest of the LSND Collaboration, Hill finds no evidence for the neutrino oscillation $\overline{\nu}_\mu \to \overline{\nu}_e$ and obtains only upper limits.

## $\Delta(m^2)$ for $\sin^2(2\theta) = 1$ $\quad(\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e))$

| VALUE (eV$^2$) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **<0.075** | 90 | BORODOV... | 92 | CNTR | BNL E776 |
| ••• We do not use the following data for averages, fits, limits, etc. ••• | | | | | |
| <1.6 | 90 | [1] ROMOSAN | 97 | CCFR | FNAL |

[1] ROMOSAN 97 uses wideband beam with a 0.5 km decay region.

## $\sin^2(2\theta)$ for "Large" $\Delta(m^2)$  $(\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e))$

| VALUE (units $10^{-3}$) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **<1.8** | 90 | [1] ROMOSAN | 97 | CCFR | FNAL |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <3.8 | 90 | [2] MCFARLAND | 95 | CCFR | FNAL |
| <3 | 90 | BORODOV... | 92 | CNTR | BNL E776 |

[1] ROMOSAN 97 uses wideband beam with a 0.5 km decay region.

[2] MCFARLAND 95 state that "This result is the most stringent to date for $250 < \Delta(m^2) < 450$ eV$^2$ and also excludes at 90%CL much of the high $\Delta(m^2)$ region favored by the recent LSND observation." See ATHANASSOPOULOS 95 and ATHANASSOPOULOS 96.

## $\Delta(m^2)$ for $\sin^2(2\theta) = 1$ $(\overline{\nu}_e \not\to \overline{\nu}_e)$

| VALUE (eV$^2$) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <0.01 | 90 | [1] ACHKAR | 95 | CNTR | Bugey reactor |

[1] ACHKAR 95 bound is for $L$=15, 40, and 95 m.

## $\sin^2(2\theta)$ for "Large" $\Delta(m^2)$ $(\overline{\nu}_e \not\to \overline{\nu}_e)$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <0.02 | 90 | [1] ACHKAR | 95 | CNTR | For $\Delta(m^2) = 0.6$ eV$^2$ |

[1] ACHKAR 95 bound is from data for $L$=15, 40, and 95 m distance from the Bugey reactor.

──────── **Sterile neutrino limits from atmospheric neutrino studies** ────────

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

$\nu_s$ means $\nu_\tau$ or any sterile (noninteracting) $\nu$.

| 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 | [1] OYAMA | 89 | KAMI | Water Cherenkov |
| < 4.2 or > 54. | 90 | BIONTA | 88 | IMB | Flux has $\nu_\mu$, $\overline{\nu}_\mu$, $\nu_e$, and $\overline{\nu}_e$ |

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

## Search for $\nu_\mu \to \nu_s$

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [1] AMBROSIO | 01 | MCRO | matter effects |
| | [2] FUKUDA | 00 | SKAM | neutral currents + matter effects |

[1] AMBROSIO 01 tested the pure 2-flavor $\nu_\mu \to \nu_s$ hypothesis using matter effects which change the shape of the zenith-angle distribution of upward through-going muons. With maximum mixing and $\Delta(m^2)$ around 0.0024 eV$^2$, the $\nu_\mu \to \nu_s$ oscillation is disfavored with 99% confidence level with respect to the $\nu_\mu \to \nu_\tau$ hypothesis.

[2] FUKUDA 00 tested the pure 2-flavor $\nu_\mu \to \nu_s$ hypothesis using three complementary atmospheric-neutrino data samples. With this hypothesis, zenith-angle distributions are expected to show characteristic behavior due to neutral currents and matter effects. In the $\Delta(m^2)$ and $\sin^2 2\theta$ region preferred by the Super-Kamiokande data, the $\nu_\mu \to \nu_s$ hypothesis is rejected at the 99% confidence level, while the $\nu_\mu \to \nu_\tau$ hypothesis consistently fits all of the data sample.

——— *CPT* tests ———

## $\langle \Delta m^2_{21} - \Delta \overline{m}^2_{21} \rangle$

| VALUE ($10^{-4}$ eV$^2$) | CL% | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| <1.1 | 99.7 | [1] DEGOUVEA 05 | FIT | solar vs. reactor |

[1] DEGOUVEA 05 obtained this bound at the $3\sigma$ CL from the KamLAND (ARAKI 05) and solar neutrino data.

## $\langle \Delta m^2_{32} - \Delta \overline{m}^2_{32} \rangle$

| VALUE ($10^{-3}$ eV$^2$) | CL% | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $0.6^{+2.4}_{-0.8}$ | 90 | [1] ADAMSON 12B | MINS | MINOS atmospheric |

[1] The quoted result is the single-parameter 90% C.L. interval determined from the 90% C.L. contour in the $(\Delta m^2, \Delta \overline{m}^2)$ plane, which is obtained by minimizing the four parameter log-likelihood function with respect to the other oscillation parameters.

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| KUVSHINN... | 91 | JETPL 54 253 | A.A. Kuvshinnikov *et al.* | (KIAE) |
| BERGER | 90B | PL B245 305 | C. Berger *et al.* | (FREJUS Collab.) |
| HIRATA | 90 | PRL 65 1297 | K.S. Hirata *et al.* | (Kamiokande II Collab.) |
| AGLIETTA | 89 | EPL 8 611 | M. Aglietta *et al.* | (FREJUS Collab.) |
| DAVIS | 89 | ARNPS 39 467 | R. Davis, A.K. Mann, L. Wolfenstein | (BNL, PENN+) |
| OYAMA | 89 | PR D39 1481 | Y. Oyama *et al.* | (Kamiokande II Collab.) |
| BIONTA | 88 | PR D38 768 | R.M. Bionta *et al.* | (IMB Collab.) |
| DURKIN | 88 | PRL 61 1811 | L.S. Durkin *et al.* | (OSU, ANL, CIT+) |
| ABRAMOWICZ | 86 | PRL 57 298 | H. Abramowicz *et al.* | (CDHS Collab.) |
| ALLABY | 86 | PL B177 446 | J.V. Allaby *et al.* | (CHARM Collab.) |
| ANGELINI | 86 | PL B179 307 | C. Angelini *et al.* | (PISA, ATHU, PADO+) |
| VUILLEUMIER | 82 | PL 114B 298 | J.L. Vuilleumier *et al.* | (CIT, SIN, MUNI) |
| BOLIEV | 81 | SJNP 34 787 | M.M. Boliev *et al.* | (INRM) |
| | | Translated from YAF 34 1418. | | |
| KWON | 81 | PR D24 1097 | H. Kwon *et al.* | (CIT, ISNG, MUNI) |
| BOEHM | 80 | PL 97B 310 | F. Boehm *et al.* | (ILLG, CIT, ISNG, MUNI) |
| CROUCH | 78 | PR D18 2239 | M.F. Crouch *et al.* | (CASE, UCI, WITW) |