Neutrino Oscillation Workshop 2000: Conference Summary

Paul Langacker[a]

[a]Department of Physics and Astronomy
University of Pennsylvania, Philadelphia PA 19104-6396, USA

The NOW2000 Workshop summarized the present status and future possibilities for all aspects of neutrino physics and astrophysics. Neutrino oscillation physics has truly come of age in the last few years. It is now data driven (analogous to cosmology and much of high energy physics in general). Experimental techniques and the theoretical interpretation have developed dramatically. An example of the latter includes the more realistic analysis of neutrino oscillations in the framework of 3 or more mass eigenstates. The phenomenological emphasis has shifted from degenerate to hierarchical neutrino spectra.

1. OUTLINE

- Neutrinos as a Probe
- Theoretical Framework
- Cosmology (BBN, CMB, ΔB, ΔL, relic)
- Violent Astrophysical Events (GRBs, AGNs, supernovae)
- Low Energy Neutrinos (Astrophysical and Laboratory)
- Outlook

2. NEUTRINOS AS A PROBE

Neutrinos are a unique probe of many aspects of physics and astrophysics, on scales ranging from 10^{-33} to 10^{+28} cm. Particle physics applications include:

- $\nu N, \mu N, eN$ scattering: existence/ properties of quarks, QCD
- Weak decays ($n \to pe^-\bar{\nu}_e, \mu^- \to e^-\nu_\mu\bar{\nu}_e$): Fermi theory, parity violation, mixing
- Neutral current, Z-pole, atomic parity: electroweak unification, field theory, m_t; severe constraint on physics to TeV scale
- Neutrino mass: constraint on TeV physics, grand unification, superstrings, extra dimensions

Similarly, their relevance to astrophysics and cosmology includes

- Core of Sun
- Supernova dynamics
- Atmospheric neutrinos (cosmic rays)
- Violent events: GRBs, AGNs, cosmic rays
- Large scale structure (dark matter)
- Nucleosynthesis (big bang: small A; stellar: to iron; supernova: large A)
- Baryogenesis

Astrophysical applications are especially challenging, because one must often simultaneously disentangle the properties of the neutrinos and of the astrophysical sources.

3. THEORETICAL FRAMEWORK

There are a confusing variety of models of neutrino mass. Here, I give a brief survey of the principle classes and of some of the terminology. For more detail, see [1,2].

3.1. Weyl, Dirac, and Majorana neutrinos

A Weyl two-component spinor is a left (L)-handed[1] particle state, ψ_L, which is necessarily

[1]The subscripts L and R really refer to the left and right chiral projections. In the limit of zero mass these correspond to left and right helicity states.

associated by CPT with a right (R)-handed antiparticle state[2] ψ_R^c. One refers to active (or ordinary) neutrinos as left-handed neutrinos which transform as $SU(2)$ doublets with a charged lepton partner. They therefore have normal weak interactions, as do their right-handed anti-lepton partners,

$$\left(\begin{array}{c}\nu_e\\ e^-\end{array}\right)_L \overset{\text{CPT}}{\longleftrightarrow} \left(\begin{array}{c}e^+\\ \nu_e^c\end{array}\right)_R. \qquad (1)$$

Sterile[3] neutrinos are $SU(2)$-singlet neutrinos, which can be added to the standard model and are predicted in most extensions. They have no ordinary weak interactions except those induced by mixing with active neutrinos. It is usually convenient to define the R state as the particle and the related L anti-state as the antiparticle.

$$N_R \overset{\text{CPT}}{\longleftrightarrow} N_L^c. \qquad (2)$$

(Sterile neutrinos will sometimes also be denoted ν_s.)

Mass terms describe transitions between right (R) and left (L)-handed states. A Dirac mass term, which conserves lepton number, involves transitions between two distinct Weyl neutrinos ν_L and N_R:

$$-L_{\text{Dirac}} = m_D(\bar{\nu}_L N_R + \bar{N}_R \nu_L) = m_D \bar{\nu}\nu, \qquad (3)$$

where the Dirac field is defined as $\nu \equiv \nu_L + N_R$. Thus a Dirac neutrino has four components ν_L, ν_R^c, N_R, N_L^c, and the mass term allows a conserved lepton number $L = L_\nu + L_N$. This and other types of mass terms can easily be generalized to three or more families, in which case the masses become matrices. The charged current transitions then involve a leptonic mixing matrix (analogous to the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix), which can lead to neutrino oscillations between the light neutrinos.

For an ordinary Dirac neutrino the ν_L is active and the N_R is sterile. The transition is $\Delta I = \frac{1}{2}$, where I is the weak isospin. The mass requires $SU(2)$ breaking and is generated by a Yukawa coupling

$$-L_{\text{Yukawa}} = h_\nu (\bar{\nu}_e \bar{e})_L \left(\begin{array}{c}\varphi^0\\ \varphi^-\end{array}\right) N_R + H.C. \qquad (4)$$

One has $m_D = h_\nu v/\sqrt{2}$, where the vacuum expectation value (VEV) of the Higgs doublet is $v = \sqrt{2}\langle\varphi^o\rangle = (\sqrt{2}G_F)^{-1/2} = 246$ GeV, and h_ν is the Yukawa coupling. A Dirac mass is just like the quark and charged lepton masses, but that leads to the question of why it is so small: one requires $h_{\nu_e} < 10^{-11}$ to have $m_{\nu_e} < 1$ eV.

A Majorana mass, which violates lepton number by two units ($\Delta L = \pm 2$), makes use of the right-handed antineutrino, ν_R^c, rather than a separate Weyl neutrino. It is a transition from an antineutrino into a neutrino. Equivalently, it can be viewed as the creation or annihilation of two neutrinos, and if present it can therefore lead to neutrinoless double beta decay. The form of a Majorana mass term is

$$\begin{aligned} -L_{\text{Majorana}} &= \frac{1}{2} m_T(\bar{\nu}_L \nu_R^c + \bar{\nu}_R^c \nu_L) = \frac{1}{2} m_T \bar{\nu}\nu \\ &= \frac{1}{2} m_T(\bar{\nu}_L C \bar{\nu}_L^T + H.C.), \qquad (5) \end{aligned}$$

where $\nu = \nu_L + \nu_R^c$ is a self-conjugate two-component state satisfying $\nu = \nu^c = C\bar{\nu}^T$, where C is the charge conjugation matrix. If ν_L is active then $\Delta I = 1$ and m_T must be generated by either an elementary Higgs triplet or by an effective operator involving two Higgs doublets arranged to transform as a triplet.

One can also have a Majorana mass term

$$-L_{\text{Majorana}} = \frac{1}{2} m_N (\bar{N}_L^c N_R + \bar{N}_R N_L^c) \qquad (6)$$

for a sterile neutrino. This has $\Delta I = 0$ and thus can be generated by the VEV of a Higgs singlet[4].

3.2. Models of neutrino mass

Almost all extensions of the standard model lead to nonzero neutrino masses at some level, often in the observable ($10^{-5} - 10$ eV) range. One should therefore view neutrino mass as *top-down*

[2] Which is referred to as the particle or the antiparticle is a matter of convenience.

[3] Sterile neutrinos are often referred to as "right-handed" neutrinos, but that terminology is confusing and inappropriate when Majorana masses are present.

[4] In principle this could also be generated by a bare mass, but this is usually forbidden by higher symmetries in extensions of the standard model.

physics. e.g., one can hope to compare the predictions of a specific superstring, GUT, or other model with the observed spectra, but it is hard to work backwards and infer the underlying theory from the observations. There are large numbers of models of neutrino mass. Some of the principle classes and general issues are:

- A triplet majorana mass m_T can be generated by the VEV v_T of a Higgs triplet field. Then, $m_T = h_T v_T$, where h_T is the relevant Yukawa coupling. Small values of m_T could be due to a small scale v_T, although that introduces a new hierarchy problem. The simplest implementation is the Gelmini-Roncadelli (GR) model [3], in which lepton number is spontaneously broken by v_T. The original GR model is now excluded by the LEP data on the Z width.

- A very different class of models are those in which the neutrino masses are zero at the tree level (typically because no sterile neutrino or elementary Higgs triplets are introduced), but only generated by loops [4], *i.e.,* radiative generation. Such models generally require the *ad hoc* introduction of new scalar particles at the TeV scale with nonstandard electroweak quantum numbers and lepton number-violating couplings. They have also been introduced in an attempt to generate large electric or magnetic dipole moments.

- In the seesaw models [5], a small Majorana mass is induced by mixing between an active neutrino and a very heavy Majorana sterile neutrino M_N. The light (essentially active) state has a naturally small mass

$$m_\nu \sim \frac{m_D^2}{M_N} \ll m_D. \tag{7}$$

  There are literally hundreds of seesaw models, which differ in the scale M_N for the heavy neutrino (ranging from the TeV scale to grand unification scale), the Dirac mass m_D which connects the ordinary and sterile states and induces the mixing (e.g., $m_D \sim m_u$ in most grand unified theory (GUT) models, or $\sim m_e$ in left-right symmetric models), the patterns of m_D and M_N in three family generalizations, etc.

- There are many mechanisms for neutrino mass generation in supersymmetric models with R parity breaking [6]. Breaking induced by bilinear terms connecting Higgs and lepton doublets in the superpotential or by the expectation values of scalar neutrinos leads to seesaw-type mixings of neutrinos with heavy neutralinos. Cubic R parity violating terms lead to loop-induced neutrino masses.

- Grand unified theories are excellent candidates for seesaw models, with M_N at or a few orders of magnitude below the unification scale. In addition to the gauge and Yukawa unification, realistic models for the quark and charged-lepton masses generally involve complicated Higgs structures and additional family symmetries to constrain the Yukawa couplings (fermion textures), often leading to interesting predictions for the neutrino spectrum. Detailed $SO(10)$ models were described by Raby [7]. The most predictive versions are excluded, while generalizations have less predictive power. It is difficult to embed such structures into superstring models.

- Heterotic superstring models often predict the existence of higher-dimensional (nonrenormalizable) operators (NRO) such as

$$-L_{\rm eff} = \bar{\psi}_L H \left(\frac{S}{M_{\rm str}}\right)^P \psi_R + H.C., \tag{8}$$

  where H is the ordinary Higgs doublet, S is a new scalar field which is a singlet under the standard model gauge group, and $M_{\rm str} \sim 10^{18}$ GeV is the string scale. In many cases S will acquire an intermediate scale VEV (e.g., 10^{12} GeV), leading to an effective Yukawa coupling

$$h_{\rm eff} \sim v \left(\frac{\langle S\rangle}{M_{\rm str}}\right)^P \ll v. \tag{9}$$

  Depending on the dimensions P of the various operators and on the scale $\langle S\rangle$, it may be possible to generate an interesting hierarchy for the quark and charged lepton masses and to obtain naturally small Dirac neutrino masses [8]. Similarly, one may obtain triplet and singlet Majorana neutrino masses, m_T and m_N by analogous higher-dimensional operators. The former are generally too small to be relevant. Depending on the operators the latter (m_N) may be absent, implying small Dirac masses; small, leading to the possibility of significant mixing between ordinary and sterile neutrinos [9]; or large, allowing a conventional seesaw.

- There are many models in which large extra dimensions affect the neutrino masses, generally involving singlet neutrinos propagating in the bulk and/or coupling with Kaluza-Klein excitations. These couplings could even lead to oscillations without neutrino masses [10,11].

- Realistic models for three or more neutrinos often involve fermion textures [2,12,13], i.e., particular forms for the fermion mass matrices involving zeroes or hierarchies of non-zero entries. Such textures are usually assumed to be due to broken family symmetries. However, they could also be associated with unknown dynamics, such as string selection rules in an underlying theory.

- It is often assumed that small neutrino masses are most likely Majorana. This is expected in the simplest seesaw models. However, the possibility of small Dirac masses should not be excluded. These can easily come about in (string-motivated) intermediate scale models, and possibly in loop-induced scenarios.

- Mixed models, in which comparable Majorana and Dirac mass terms are both present, will be further discussed in the next section.

3.3. Light sterile neutrinos

Most extensions of the standard model predict the existence of sterile neutrinos. For example, simple $SO(10)$ and E_6 grand unified theories predict one or two sterile neutrinos per family, respectively. The only real questions are whether the ordinary and sterile neutrinos of the same chirality mix significantly with each other, whether some or all of the mass eigenstate neutrinos are sufficiently light, and how many (e.g., whether there are 1, 3, 6 or some other number of light sterile neturinos).

When there are only Dirac masses, the ordinary and sterile states do not mix because of the conserved lepton number. Pure Majorana masses do not mix the ordinary and sterile sectors either. In the seesaw model the mixing is negligibly small, and the (mainly) sterile eigenstates are too heavy to be relevant to oscillations. The only way to have significant mixing and small mass eigenstates is for the Dirac and Majorana neutrino mass terms to be extremely small and to also be comparable to each other. This appears to require two miracles in conventional models of neutrino mass.

One promising possibility involves the generation of neutrino masses from higher-dimensional operators in theories involving an intermediate scale [8], as described in Section 3.2. Another [14] involves sterile neutrinos associated with a parallel hidden sector of nature, as suggested in some superstring and supergravity theories. Yet another associates the sterile neutrino with the light (10^{-3} eV) Kaluza-Klein modes associated with a large (mm) extra dimension [15].

3.4. Mass and mixing patterns

Various scenarios for the neutrino spectrum are possible, depending on which of the experimental indications one accepts [17].

3.4.1. 3 neutrino schemes [18–23]

The simplest scheme, which accounts for the Solar (S) and Atmospheric (A) neutrino results, is that there are just three light neutrinos, all active, and that the mass eigenstates ν_i have masses in a hierarchy, analogous to the quarks and charged leptons. In that case, the atmospheric and solar neutrino mass-squared differences are measures of the mass-squares of the two heavier states, so that $m_3 \sim (\Delta m^2_{\rm atm})^{1/2} \sim 0.03 - 0.1$ eV; $m_2 \sim (\Delta m^2_{\rm solar})^{1/2} \sim 0.003$ eV (for MSW) or $\sim 10^{-5}$ eV (vacuum oscillations), and $m_1 \ll m_2$. The weak eigenstate neutrinos $\nu_a = (\nu_e, \nu_\mu, \nu_\tau)$ are related to the mass eigenstates ν_i by a unitary transformation $\nu_a = U_{ai}\nu_i$. If one makes the simplest assumption (from the Superkamiokande, CHOOZ, and Palo Verde data), that the ν_e de-

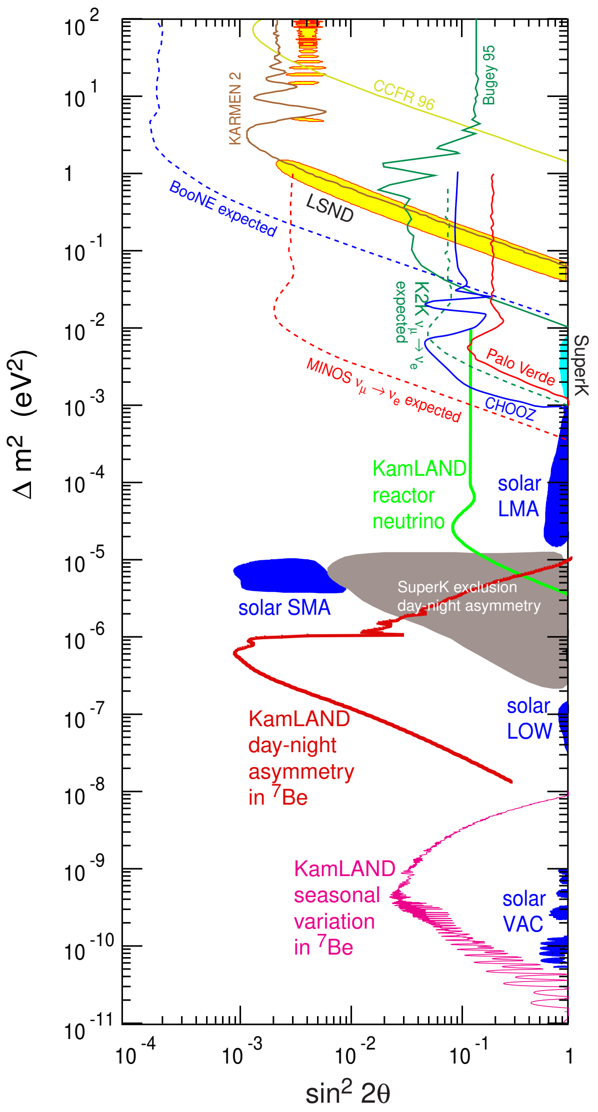

Figure 1. Neutrino oscillation plot, indicating the solar neutrino small mixing angle (SMA), large mixing angle (LMA), low mass (LOW), and vacuum (VAC) solutions, as well as the Superkamiokande atmospheric neutrino range, the LSND region, and various exclusion regions. From [16].

couples entirely from the atmospheric neutrino oscillations, $U_{e3} = 0$, (of course, one can relax this assumption somewhat) and ignores possible CP-violating phases, then

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\alpha & -s_\alpha \\ 0 & s_\alpha & c_\alpha \end{pmatrix} \times \begin{pmatrix} c_\theta & -s_\theta & 0 \\ s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \quad (10)$$

where α and θ are mixing angles associated with the atmospheric and solar neutrino oscillations, respectively, and where $c_\alpha \equiv \cos\alpha$, $s_\alpha \equiv \sin\alpha$, and similarly for c_θ, s_θ.

For maximal atmospheric neutrino mixing, $\sin^2 2\alpha \sim 1$, this implies $c_\alpha = s_\alpha = 1/\sqrt{2}$, so that

$$U = \begin{pmatrix} c_\theta & -s_\theta & 0 \\ \frac{s_\theta}{\sqrt{2}} & \frac{c_\theta}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{s_\theta}{\sqrt{2}} & \frac{c_\theta}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}. \quad (11)$$

For small θ, this implies that $\nu_{3,2} \sim \nu_{+,-} \equiv (\nu_\tau \pm \nu_\mu)/\sqrt{2}$ participate in atmospheric oscillations, while the solar neutrinos are associated with a small additional mixing between ν_e and ν_-. Another limit, suggested by the possibility of vacuum oscillations for the solar neutrinos, is $\sin^2 2\theta \sim 1$, or $c_\theta = s_\theta = 1/\sqrt{2}$, yielding

$$U = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}, \quad (12)$$

which is referred to as bi-maximal mixing [24–26]. A number of authors have discussed this pattern and how it might be obtained from models, as well as how much freedom there is to relax the assumptions of maximal atmospheric and solar mixing (the data actually allow $\sin^2 2\alpha \gtrsim 0.8$ and $\sin^2 2\theta \gtrsim 0.6$) or the complete decoupling of ν_e from the atmospheric neutrinos. Another popular pattern,

$$U = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix}, \quad (13)$$

known as democratic mixing [26], yields maximal solar oscillations and near-maximal (8/9) atmospheric oscillations.

The atmospheric neutrino data only determine the magnitude of $|\Delta m^2_{32}| \equiv |m_3^2 - m_2^2| = \Delta m^2_{\rm atm}$, so there is a variant inverted hierarchy in which $m_3 < m_1 < m_2$, with $m_2^2 - m_1^2 = \Delta m^2_{\rm solar} \ll m_2^2$, i.e., there is a quasi-degeneracy[5], and $m_2^2 - m_3^2 = \Delta m^2_{\rm atm}$.

In the hierarchical and inverted patterns, the masses are all too small to be relevant to mixed dark matter, in which one of the components of the dark matter is hot, i.e., massive neutrinos. However, the solar and atmospheric oscillations only determine the differences in mass squares, so there are variants on these scenarios in which the three mass eigenstates are nearly degenerate rather than hierarchical, with small splittings associated with $\Delta m^2_{\rm atm}$ and $\Delta m^2_{\rm solar}$. For the common mass $m_{\rm av}$ in the 1 – several eV range, the hot dark matter could be relevant on large scales. Such mixed dark matter (with another, larger, component of cold dark matter accounting for smaller structures) models [27] were once quite popular. However, recent evidence for dark energy (cosmological constant or quintessence) eliminates most of the motivation for considering degenerate models, although they are still not excluded. Another problem with both the degenerate and inverted schemes is that the near degeneracies are usually unstable with respect to radiative corrections [28].

If the neutrinos are Majorana they could also lead to neutrinoless double beta decay, $\beta\beta_{0\nu}$ [29]. Current limits imply an upper limit of

$$\langle m_{\nu_e} \rangle = \sum_i \eta_i U_{ei}^2 |m_i| \lesssim 0.35 \text{ eV}, \tag{14}$$

on the effective mass for a mixture of light Majorana mass eigenstates, where η_i is the CP-parity (or phase) of ν_i. There is an additional uncertainty on the right due to the nuclear matrix elements. (There is no constraint on Dirac neutrinos.) This constraint is very important for the degenerate scheme for $m_{\rm av}$ in the eV range. The combination of small $\langle m_{\nu_e} \rangle \ll m_{\rm av}$, maximal atmospheric mixing, and $U_{e3} = 0$ would imply cancellations, so that $\eta_1\eta_2 = -1$ and $c_\theta = s_\theta = 1/\sqrt{2}$, i.e., maximal solar mixing. However, there is room to relax all of these assumptions considerably. For the hierarchical and inverted schemes $\langle m_{\nu_e} \rangle$ is small compared to the current experimental limit. However, proposed future experiments could be sensitive to the inverted case.

[5]For MSW oscillations, the data implies that most likely $m_2^2 > m_1^2$ under the convention that $\theta < \pi/4$. For vacuum oscillations, the sign of $\Delta m^2_{\rm solar}$ is undetermined.

3.4.2. 4 neutrino schemes [18,30–32]

The LSND results [33], if confirmed, would almost certainly imply a fourth, sterile, neutrino ν_s (the Z lineshape does not allow a fourth light active neutrino), in which one or two of the neutrinos are separated from the others by $\sqrt{\Delta m^2_{\rm LSND}} \sim 0.4 - 1$ eV. There could be even more sterile neutrinos.

In the 3+1 schemes, ν_4 is heavier or lighter than $\nu_{1,2,3}$ by $\sqrt{\Delta m^2_{\rm LSND}}$, with the splittings between the latter controlled by $\Delta m^2_{\rm atm}$ and $\Delta m^2_{\rm solar}$. This case has generally been considered excluded by limits from ν_e and ν_μ disappearance. However, small recent changes in the LSND favored range (to lower Δm^2) imply that these schemes are barely allowed for $\nu_4 \sim \nu_s$, and possibly for $\nu_4 \sim \nu_\tau$. The $\nu_4 \sim \nu_s$ case may offer a theoretical advantage over $2+2$ schemes in that the ν_s is more distinct from the active neutrinos.

In the $2+2$ schemes, one has two pairs of mass eigenstates $\nu_{1,2}$ and $\nu_{3,4}$, with $\pm\Delta m^2_{34} \sim \Delta m^2_{\rm atm} \sim 10^{-3} - 10^{-2}$ eV^2, $\Delta m^2_{12} \sim \Delta m^2_{\rm solar} \sim 10^{-5}$ eV^2 (MSW) or 10^{-10} eV^2 (vacuum), and $\pm\Delta m^2_{24} \sim \Delta m^2_{\rm LSND} \sim 0.2 - 1$ eV^2, where $\Delta m^2_{ij} \equiv m_j^2 - m_i^2$. The reactor data imply that ν_e must be largely restricted to one of the pairs. The cases $\Delta m^2_{24} > 0$ and < 0 are referred to as hierarchical and inverted, respectively. The inverted case, and to a somewhat lesser extent the hierarchical case, are quasi-degenerate, and may be unstable under radiative corrections [28].

The $2+2$ and some versions of the $3+1$ models involve a significant hot or warm neutrino component to the dark matter. The extra sterile neutrino may be of importance for big bang nucleosynthesis. The versions with ν_1 in the heavier group may give significant contributions to $\beta\beta_{0\nu}$, although there may be major cancellations for large mixing.

The recent SuperKamiokande [19] and MACRO [34] atmospheric neutrino data exclude the pure $\nu_{\mu,s} \sim \nu_{3,4}$ case, in which the atmospheric neutrino results are associated with $\nu_\mu \to \nu_s$, while Super-K solar neutrino data [35] probably eliminates the pure $\nu_e \to \nu_s$ (i.e., $\nu_{e,s} \sim \nu_{1,2}$) explanation for the solar neutrinos. These were the simplest and perhaps most plausible cases. However, more general mixing schemes with significant ν_s admixtures in the solar and atmospheric neutrinos are possible [18,30,36].

3.5. Alternatives to neutrino oscillations

Alternative explanations of the atmospheric and solar neutrino anomalies were reviewed by Lusignoli [11].

For the atmospheric neutrinos, flavor changing neutral currents (FCNC) [37], Lorentz invariance violation (LIV), and Equivalence Principle Violation (EPV) [38,39] models for neutrino mixing have been suggested as alternatives to conventional flavor mixing. However, they are not consistent with zenith or upward throughgoing distributions. For example, LIV and EPV predict an LE^n dependence with $n \neq -1$, contrary to the SuperK data. L and E refer to the distance travelled and energy of the ν_μ, respectively. Pure ν_μ decay models are not viable, but a hybrid oscillation and decay model with two nearly degenerate states, the lightest decaying to sterile states, cannot be excluded. Also, decoherence models, in which the coherence between two states is lost by some unknown mechanism (e.g., interaction with quantum foam), are consistent with the data.

There are viable descriptions of the solar neutrino data involving involving FCNC, LIV, and EPV. Another alternative is resonant spin flavor precession (RSPF) [11,17,40], in which ν_{eL} is transformed into a sterile or active right-handed state. This requires a much larger neutrino magnetic moment μ_ν (which can be Dirac for a sterile N_R final state, or a Majorana transition moment for an active $\nu^c_{\mu R}$ or $\nu^c_{\tau R}$) than is predicted by most models and a rather large solar magnetic field. The original motivation for RSPF for magnetic transitions was an apparent time dependence in the Homestake data. This is no longer wanted experimentally, but time independent magnetic effects could still be relevant for transitions occurring below the convective zone. $\nu_{eL} \to \nu^c_{eR}$ can be generated by combined magnetic and flavor-oscillation effects.

3.6. What is needed?

For the future, one wants to establish neutrino oscillations (or constrain small admixtures of other effects in hybrid scenarios), establish which mixing scenarios are occurring, and determine the neutrino properties. In particular:

- It is very imporant to actually observe a neutrino oscillation (or at least a dip) consistent with the characteristic L/E dependence. The dedicated MONOLITH experiment [41], or a future ν factory should be able to do this cleanly. Long baseline experiments (K2K [42], MINOS [43], ICARUS [44,45]) may also observe oscillation patterns, as may the full (two detector) BOONE [33].

- One wants to determine the number of neutrinos and their nature, e.g., are there sterile neutrinos, and are the active neutrinos Dirac or Majorana? Mini-BOONE [33] should be able to confirm or eliminate the LSND results, clarifying the need for sterile neutrinos. $\beta\beta_{0\nu}$ may help resolve the Dirac/Majorana issue, although only for some mass/mixing patterns.

- The neutrino mass and mixing spectrum is important for its theoretical implications, for choosing the solar neutrino solution, and for possible astrophysical implications. It will be difficult to observe the absolute scale of the spectrum, but some improvement may still be possible from $\beta\beta_{0\nu}$ and from kinematic (laboratory [46] and, especially, supernova [47]) observations.

- It may be possible to confirm that the atmospheric neutrino effects are mainly due to $\nu_\mu \to \nu_\tau$ by τ appearance in future long baseline experiments (or possibly in atmospheric observations), but it will be harder to constrain small admixtures of ν_s.

- Leptonic CP violation is of theoretical interest. This may be observable (depending on the parameters) at a neutrino factory or possibly a superbeam.

4. COSMOLOGY [27]

4.1. Baryon asymmetry

An important cosmological issue is the origin of the baryon asymmetry

$$\Delta B \sim \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}. \tag{15}$$

In the standard model sphaleron solutions describe tunneling between vacua with different B at temperatures T above the electroweak phase transition $T_{\rm EW} = {\rm O}(100 \text{ GeV})$, which erase any preexisting baryon asymmetry with $B - L = 0$. This includes asymmetries generated by the standard out-of-equilibrium decay scenario for heavy colored scalars in grand unified theories. It is possible that an asymmetry is regenerated by the standard model sphaleron effects at the time of the electroweak transition (e.g., in processes involving expanding bubble walls), but the necessary CP violation and out of equilibrium constraints are not satisfied in the standard model or the MSSM.

One attractive scenario involves the initial generation of a nonzero lepton asymmetry (or an assymetry in $B - L$) in the early universe, which is then converted into comparable baryon and lepton asymmetries by sphalerons during the electroweak transition. For example, the heavy Majorana neutrino N expected in seesaw models may have asymmetric decays into a Higgs scalar h and neutrino [48]

$$\Gamma(N \rightarrow h\nu) \neq \Gamma(N \rightarrow h\bar{\nu}) \tag{16}$$

if there is sufficient leptonic CP violation, leading to a nonzero ΔL, which is later converted to $\Delta B \neq 0$ and $\Delta L \neq 0$. Such scenarios place constraints which are in principle stringent on the (L-violating) neutrino masses, to avoid wiping out both ΔB and ΔL [48], typically $m_\nu < {\rm O}(1 - 10)$ eV, but with large theoretical uncertainties. This applies to ν_τ and ν_μ as well as ν_e.

4.2. Relic neutrinos and mixed dark matter

The active neutrinos decoupled just prior to big bang nucleosynthesis, when the age of the universe was around 1s and the temperature around 1 MeV. Their momentum distribution subsequently redshifted to an effective temperature $T_\nu \sim 1.9$ K, and they have an average density of around $300/{\rm cm}^3$. The direct detection of such low-energy neutrinos remains an ultimate challenge.

Massive neutrinos in the eV range will contribute a significant hot dark matter (HDM) component to the total matter of the universe. Constraints on the total energy density imply

$$\sum m_{\nu_i} \lesssim 35 \text{ eV}, \tag{17}$$

where the sum extends over the light, stable, active neutrinos, and also includes light sterile neutrinos for some ranges of masses and mixings. However, pure HDM models have long been excluded by observations of structure, since neutrinos free-stream and produce large structures first, and there has not been enough time for the observed smaller structures to form. Until recently, mixed dark matter (MDM) models were very popular. In these, neutrinos with

$$\sum m_{\nu_i} \lesssim \text{few} \quad \text{eV} \tag{18}$$

contribute a hot component and account for large scales such as superclusters, while a larger component of cold dark matter (CDM) explains structure on smaller scales. These MDM models were a primary motivation for the degenerate 3 neutrino models and an attractive aspect of 4 ν models. Most assumed $\Omega_{\rm matter} = \Omega_\nu + \Omega_{\rm CDM} = 1$, as expected in inflation models.

Recently things have changed dramatically, because:

- Most determinations now yield $\Omega_{\rm matter} \sim 0.3$.
- Studies using Type IA supernovae as standard candles suggest an accelerating universe, with a cosmological constant (or other form of dark energy, such as quintessence), with $\Omega_\Lambda \sim 0.7$.
- Consistent and independent information comes from recent observations of the location of the

first Doppler peak in the cosmic microwave background radiation (CMB) asymmetry spectrum, which implies $\Omega_{\rm matter} + \Omega_\Lambda \sim 1$.

There is therefore emerging a fairly compelling picture involving a low $\Omega_{\rm matter}$ and larger Ω_Λ. This is consistent with the expectations of inflation ($\Omega_{\rm matter}+\Omega_\Lambda = 1$), but the evidence is purely observational. In this scenario, there is no need for a significant component of HDM, although it is not excluded.

Nevertheless, the observation of neutrino mass implies a small contribution to $\Omega_{\rm matter}$. In particular, $m_3 \sim (\Delta m^2_{\rm atm})^{1/2}$ (hierarchical neutrinos) implies $\Omega_\nu \sim 0.001 - 0.003$, while in the degenerate schemes Ω_ν could be as large as ~ 0.1. Masses less than $m_\nu \sim 1$ eV are not important for the observed structure, but may be noticeable in the CMB spectrum for $m_\nu > 0.1$ eV.

4.3. Big bang nucleosynthesis

The abundances of primordial ^4He and D can be used to determine the equivalent number $N_\nu^{\rm eff}$ of light neutrinos in equilibrium at the time of neutrino decoupling ($t \sim 1$ s, $T \sim 1$ MeV) and the baryon density $h^2\Omega_B$, where $h \sim 0.65 \pm 0.05$:

$$1.7 < N_\nu^{\rm eff} < 3.3; \qquad h^2\Omega_B \sim 0.017(3). \tag{19}$$

$N_\nu^{\rm eff}$ is actually an effective parameter, incorporating any contribution to the n/p ratio at the time of decoupling, i.e.,

$$N_\nu^{\rm eff} = n^{\rm eff}_{\rm active} + n^{\rm eff}_{\rm sterile} + n^{\rm eff}_{\rm asym}, \tag{20}$$

where $n^{\rm eff}_{\rm active} \sim 3$ is from the active neutrinos, and $n^{\rm eff}_{\rm sterile}$ represents the number of light sterile neutrino species present at decoupling. It has long been known that sterile neutrinos could be generated in equilibrium numbers by mixing with active neutrinos prior to nucleosynthesis for a wide range of Δm^2 and $\sin^2 2\theta$. In particular, it was believed that $n^{\rm eff}_{\rm sterile} \sim 1$ for mixing parameters corresponding to atmospheric $\nu_\mu \to \nu_s$ oscillations, in conflict with (19). (The recent Super K data also directly exclude pure $\nu_\mu \to \nu_s$). For the solar neutrinos, the rates have always allowed a small mixing angle (SMA) $\nu_e \to \nu_s$ solution analogous to the SMA $\nu_e \to \nu_\mu$, but in this case the mixing would *not* have been sufficient to generate ν_s cosmologically[6].

There has been considerable interest in ways to modify (or lower) the prediction for $N_\nu^{\rm eff}$, motivated by: (a) the observed value, which depends on the somewhat controversial determinations of the relic ^4He abundance, may eventually settle at a value lower than 3. (b) If there really is a light sterile neutrino, as suggested by the LANL data, then the possible contributions of $n^{\rm eff}_{\rm sterile}$ become crucial. There are several canonical ways to change the prediction:

- If ν_τ is unstable, then the active contribution to $N_\nu^{\rm eff}$ may fall below 3, depending on the ν_τ lifetime and the energy density in its decay products.

- Large lepton asymmetries $\Delta L_a \simeq (n_{\nu_a} - n_{\bar\nu_a})/n_\gamma$ lead to increased energy densities $n^{\rm eff}_{\rm asym} > 0$, increasing $N_\nu^{\rm eff}$. For $a = \mu, \tau$ this is the only effect. However, a positive ΔL_e can actually decrease $N_\nu^{\rm eff}$ because it preferentially drives the rate for $\nu_e n \to e^- p$ compared to its inverse, and thus decreases the n and therefore the ^4He abundance. Neither of these effects are important unless the asymmetry is very much larger than the baryon asymmetry $\sim 10^{-9}$.

- A massive τ neutrino in the range between $\sim$ 0.5 MeV and the laboratory limit $\sim$ 18 MeV would *increase* $n^{\rm eff}_{\rm active}$ above 3, because the large rest energy would be more important than the reduced number density. This range is therefore most likely excluded.

Foot and Volkas and others [49] have recently reexamined the effects of sterile neutrinos on nucleosynthesis, and argued that they could actually *decrease* $N_\nu^{\rm eff}$. The current status was discussed by Kirilova [50] and Wong [51]. There may be a strong interplay between active-sterile mixing and a nonzero asymmetry ΔL_a (e.g., a small preexisting $\Delta L_a \sim 10^{-9}$ or one generated by the oscillations). In particular, such effects can suppress the production of ν_s, deplete the

[6]There is no viable large mixing angle (LMA) or low mass (LOW) solar neutrino solution for $\nu_e \to \nu_s$. These are most likely excluded independently by the BBN data.

number of ν_e, distort the active neutrino spectrum and therefore the reaction rates (a very important effect), and amplify (or generate) a small initial ΔL_e asymmetry. The net result is that the bounds on active-sterile mixing may be weakened, especially for small mixing. However, there is still considerable debate as to the details and the size of these effects.

4.4. Cosmic microwave background radiation

Neutrino masses as small as 0.1 eV may lead to observable effects in the CMB anisotropies. Pastor reviewed [52] the cosmological implications of large lepton asymmetries, e.g., generated by an Affleck-Dine [53] scenario or active-sterile mixing. In addition to the BBN effects, the asymmetry increases the radiation density and postpones the onset of matter domination. This would suppress the CMB power spectrum on small scales even for $m_\nu = 0$, with larger effects for $m_\nu \neq 0$. Masses as small as 10^{-2} eV might be observable in the presence of an asymmetry.

Mangano [54] reviewed precision cosmology, emphasizing the interplay between BBN, CMB, and large scale structure data. He described the implications of the recent MAXIMA and BOOMERANG CMB data, which indicate a suppressed second Doppler peak. Several models of the cosmological parameters fit the new data, but should be separable in future (MAP, PLANCK) data on the third peak. One possibility is to increase the baryon density $h^2\Omega_B$ to a higher value ($0.030^{+0.012}_{-0.006}$) than is allowed by the BBN data in (19). One rather creative resolution would be to somehow increase to $4 < n^{\rm eff}_{\rm active} + n^{\rm eff}_{\rm sterile} < 13$, with 8 favored, and to simultaneously assume a large $\Delta L_e \sim 0.24\mu_{\nu_e}/T$, corresponding to $0.07 < \mu_{\nu_e}/T < 0.43$, where μ_{ν_e} is the ν_e chemical potential.

5. VIOLENT ASTROPHYSICAL EVENTS

5.0.1. High energy neutrinos

There are many possible sources of ultra high energy astrophysical neutrinos, including gamma ray bursts (GRB), active galactic nuclei (AGN), and particle physics exotica. They are a particularly useful probe because high energy γ rays tend to be absorbed in the astrophysical source, while protons are magnetically deflected. Also, protons above 10^{20} eV can be observed only from local sources because of the Greisen-Zatsepin-Kuzmin (GZK) cutoff (scattering from the CMB).

Waxman [55], Halzen [56], and Perrone [57] described the theoretical expectations for GRBs, and the need for km^3 scale detectors. GRBs are now understood to be mainly at cosmological distances, and arise from the expansion of a relativistic fireball. The expanding shock accelerates protons and high energy e^-, which emit the γ's by synchrotron emission. Outstanding issues are the fireball progenitor (e.g., coalescence of neutron stars or of a neutron star and black hole) and the $e-p$ coupling mechanism.

Reactions such as $\gamma p \rightarrow \pi^+ n$ from the GRB photons are expected to produce a burst of 100 TeV ν's, followed by the production of 10^{18} eV ν's for about 10 s associated with the expansion of the shock into the interstellar medium (the afterglow). $pn \rightarrow \pi^+$ processes also lead to lower energy (10 GeV) neutrinos. Estimates of the fluxes suggest the need for a km^3 detector for a reasonable event rate of order 10's/yr. One also expects a few/yr from the diffuse scattering of protons from the CMB photons. The γ's from π^0 decay are absorbed and cascade to lower energies $\lesssim$ TeV. These may be ultimately observable.

The observed ultra high energy cosmic ray protons may also be due to this mechanism (those above 10^{20} would have to be due to nearby GRBs to evade the GZK cutoff). One can turn this argument around: any mechanism that produces high energy ν's from γp (or pN) interactions in an optically thin source should produce high energy p's as well as ν's. The observed p flux therefore limits the possible ν flux (the Bahcall-Waxman bound), invalidating some early optimistic estimates. The bound can be evaded in optically thick sources, but most plausible models are thin.

There are other possible sources of high energy ν's. These include the annihilation of WIMPs in the earth, the sun, or the galactic center; monopole annihilation; the decay of topological defects (lattice calculations are being carried out by the TRENTO group [58]); or local astrophysical sources. High energy neutrinos may also produce Z's by annihilation with the relic neutrinos.

One spectacular prediction [55] for oscillations is that an initial ν_μ source should yield equal numbers of ν_μ and ν_τ for $\Delta m^2 > 10^{-17}$ eV^2 for maximal mixing ($\sin^2 2\theta \sim 1$).

The present experimental status and future prospects were reviewed by Halzen [56], Vignaud [59], van Dantzig [60], and de Marzo [61]. The MACRO and Lake Baikal detectors had areas $A < 10^3$ m^2. (Baikal observed some events). In the $A \sim 10^4$ m^4 range, AMANDA (S. Pole) has been running for some time, and observed 193 atmospheric ν's (it has mainly vertical sensitivity), and NESTOR (near Greece) is under development. The larger AMANDA II with $A \sim 10^5$ m^2 is taking data. It may eventually be succeeded by the km^3 ICE-CUBE. Also in the $A \sim 10^5$ m^2 range is ANTARES [60] in the Mediterranean, which should run in 2002-2003. This should be succeeded by ANTARES II. Another project, NEMO [61] is under study. It could be deployed near Sicily, or merge with ANTARES II.

5.0.2. Supernova implications

A Type II supernova is due to the collapse of the iron core of a star with mass exceeding $\sim 8M_\odot$. The core collapses into a neutron star or black hole. The initial collapse leads to a ms neutronization pulse of ν_e from $e^- p \to \nu_e n$. The collapsing core eventually bounces, with an expanding shock, leaving behind a dense hot core and neutrinosphere. The latter radiates neutrinos of all types over a period of $\sim$ 10 s. The characteristic temperature of the $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ is ~ 8 MeV. The ν_e and $\bar{\nu}_e$ stay in equilibrium longer due to charged current interactions with matter, implying smaller temperatures, e.g., $T_{\nu_e} \sim 3.5$ MeV, $T_{\bar{\nu}_e} \sim 4.5$ MeV [62]. Neutrinos are relevant because:

- Almost all (99%) of the energy ($\gtrsim 3\times 10^{53}$ ergs) is radiated in neutrinos. The spectacular optical effects are a perturbation.
- Observation of a neutrino burst may give an early warning of a supernova, with the Solar ν Early Warning System (SNEWS) network under organization [47].
- Neutrinos are important for the dynamics. Scattering of neutrinos radiated from the neutrinospere may revive a stalled shock, leading to the observed explosion.
- The ν-heated supernova ejecta is a favored candidate for the site of the r-process, which refers to the synthesis of nuclei heavier than iron by the rapid capture of neutrons on a heavy core in a neutron-rich environment. However, some estimates [63] suggest that $\nu_e n \to e^- p$, with the p immediately incorporated into an α, will be too efficient at destroying neutrons, preventing the r-process. The situation can be worsened or improved in the presence of neutrino mixing.
- The kinematic effects of neutrino mass can distort the time and energy spectrum of the neutrinos. The observed Kamiokande and IMB events from SN 1987A, which were sensitive to $\bar{\nu}_e$ from the neutrinosphere, allowed a limit of around $m_{\nu_e} \lesssim 20$ eV. This limit, as well as many other constraints, depended on the theoretical modelling of the supernova.
- A future supernova within our galaxy should yield large numbers of events in large detectors if they are running. This should allow much more stringent direct limits on m_{ν_μ,ν_τ} than by any laboratory method [47]. For example, SNO should be sensitive to 30 eV, and Super K to 50 eV neutrinos [64]. A collapse into a black hole would provide a sharp cutoff in time for the neutrino signal, allowing even more precise constraints (in the few eV range) for all neutrino types [65]. With large numbers of events it will be possible to study the supernova dynamics in detail and to constrain other neutrino properties. SNO should be especially useful because it can separately observe ν_e , $\bar{\nu}_e$, and the neutral current scattering of all neutrinos.
- Neutrino mixing can lead to a variety of oscillation and MSW resonance effects. Because the densities are higher than in the Sun, there may be resonant conversions for higher Δm^2 than the solar neutrinos. In particular,
  - $\nu_e \leftrightarrow \nu_{\mu,\tau}$ conversions can increase the final ν_e energy because of the harder initial $\nu_{\mu,\tau}$

spectrum. This makes ν_e scattering more efficient in reviving the stalled shock. On the other hand, it aggravates the problem of destroying neutrons before they can participate in the r-process, excluding $\Delta m^2 >$ few eV^2 escept for very small mixing [63].

  - For the LMA solar neutrino solution, there may have been a partial conversion of $\bar{\nu}_e$ and $\bar{\nu}_\mu$, in contrast with the observed SN 1987A spectrum [66,67]. However, it has recently been argued that matter effects may reduce this difficulty, or even help reconcile the observed Kamiokande and IMB spectra [68].
  - Minakata [21] argued that the observed spectra would be very different for an inverted spectrum, e.g., with the the dominant ν_e mass eigenstate heavier than ν_τ. This could lead to a determination of the sign of Δm^2_{23}.
  - It has been argued that active-sterile conversions could solve the r-process problem [69] by the sequence of $\nu_\mu \to \nu_s$ followed by $\nu_e \to \nu_\mu$.

- One expects a supernova in our galaxy on average every 30-100 years. This is an unfortunate mismatch with the practical human time scale for carrying out experiments, but we should make an attempt. Large neutrino detectors should be designed to run for a minimum of 10-20 yr, and preferably longer.

6. LOW ENERGY NEUTRINOS

6.0.3. Solar neutrinos [70]

The Solar neutrinos gave the first convincing evidence for neutrino mass and mixing. Bahcall reviewed [71] the status of the standard solar model (SSM), emphasizing that "Solar model predictions have been robust for 30 years."

- The new Bahcall-Pinnsoneault (BP00) code for the standard solar model incorporates improved opacities (at the edge of the table); minor nuclear refinements; a detailed electron density profile $n_e(r)$; a denser model grid, improved treatment of helioseismology constraints; and detailed studies of the time dependences in the solar radius, luminosity, and radius of the convective zone. These latter will be measured for solar-type stars (e.g., by interferometry), testing a new aspect of the solar models.

- Helioseismology now confirms most aspects of the standard solar model (except some nuclear cross sections and the neutrino properties) in more than sufficient detail for the interpretation of solar neutrino data [71,72].

- The data indicate in a model independent way that the suppression of ^7Be neutrinos is much greater than the ^8B suppression. This implies, independent of any specific solar model, that the explanation of the solar neutrino anomaly cannot be due to astrophysics. (It is still very useful to use the standard solar model results as the starting point for the parameters and uncertainties in MSW and vacuum oscillation analyses.)

- Changes in the predictions from BP98 include a +4% increase in the ^8B flux, and a 2% increase for ^7Be. This leads to an increase of 1 SNU (to 130^{+9}_{-7}) for ^{71}Ga, and of 0.3 SNU (to $8.0^{+1.2}_{-1.0}$) for ^{37}Cl.

- The largest residual theory uncertainties are from nuclear cross sections.

  - The largest uncertainly is still from the $^7Be(p,\gamma)^8B$ reaction. Four new experiments are expected to reduce the uncertainty to the 5-10% range. One would prefer 5%.
  - The next most important uncertainty is from $^3He(\alpha,\gamma)^7Be$, for which there are experimental discrepancies.
  - There is still no firm uncertainty in the predicted hep ($^3He{+}p{\to}^4He{+}e^+\nu_e$) flux. With improved energy resolution in the SuperK experiment this can be determined independently from events beyond the ^8B endpoint of $\gtrsim$ 14 MeV, so it is no longer so crucial in the interpretation of the energy spectrum.
  - Kubodera [73] reviewed the theoretical status of the $\nu_e d \to e^- pp$ and $\nu_X d \to \nu_X pn$ ($X = e, \mu, \tau$) cross sections, which will be needed

for the interpretation of the SNO results. He described a new potential model calculation in which the potential and exchange currents were calculated consistently, and also a one-parameter effective field theory treatment which is in good agreement. The conclusion is that the theory errors are under control, especially for the (neutral current)/(charged current) ratio.

Ferrari [74] described the results of Run I of the Gallium Neutrino Observatory (GNO). They obtain a rate of $65.8^{+10.2+3.4}_{-\ 9.6-3.6}$ SNU, consistent with the earlier GALLEX and SAGE results, and about half of the SSM prediction.

Suzuki [35] presented new solar neutrino results for Superkamiokande:

- The current results are based on 1117 d of running, compared to the 824 d reported last year. There is a unified new analysis of all of the data.
- The rate (compared to the BP98 prediction) is $0.465 \pm 0.005^{+0.015}_{-0.013}$.
- The energy threshold has been lowered to 5 MeV. However, the 5-5.5 MeV bin is not yet used in the oscillation analysis.
- The recoil spectrum (compared to the SSM) is flatter than before, and is now consistent with flat ($\chi^2/df = 13.7/17$). The first moment of the recoil energy is 8.14 ± 0.02 MeV. Distortions are mainly expected for the SMA and vacuum solutions.
- The small excess of events at night (N) compared to day (D) has been reduced from 1.8σ to 1.3σ, i.e.,

$$\frac{N-D}{(N+D)/2} = 0.034 \pm 0.022^{+0.013}_{-0.012}. \tag{21}$$

  Day-night differences may be important for the LMA and LOW solutions.
- No seasonal variation (as expected for vacuum oscillations) has been observed beyond the $1/r^2$ effect. The seasonal data has not yet been fit quantitatively.
- A fit in which the hep flux is left free yields a flux 5.4 ± 4.5 compared with BP98. Leaving the flux free has no significant effect on the oscillation analysis.
- There is no evidence for long term time variation (as expected in RSPF models with transitions in the convective zone).

Suzuki presented the SuperK oscillation analysis (including the rates from other experiments). He argued that there is no smoking gun for one solution over another. However, the data favors the LMA solution; the SMA solution is disfavored but not excluded; vacuum solutions are disfavored; and the pure $\nu_e \to \nu_s$ is disfavored at 95%, by a combination of day-night, spectrum, and rate information. (A significant admixture of ν_s is still allowed in 3ν fits [36], especially for small mixing angles.)

Smirnov [24] discussed the various solar neutrino solutions, commenting that "Nature selects the most ambiguous solution", i.e., no solution is strongly excluded or preferred, and hints are at the level of systematics. He argued that the LMA is favored, but SMA may be back. Smirnov described that the SuperK zenith spectrum has a small excess in the first night-time bin, contrary to any of the solutions (LMA is flat at night, LOW may yield an excess in the second bin, and SMA may imply an excess in the last (core) bin), adding to the confusion. He argued the importance of studying the correlations between various observables (e.g., charged current rate vs. day-night) for distinguishing solutions in the future.

A number of global analyses of the solar data were presented at the conference or in the recent literature [18,24,35,36], allowing mixing between 2, 3, or 4 neutrinos, including sterile. The 2ν solutions are shown schematically in Figure 1. The small mixing angle (SMA) solution, with $\Delta m^2 \lesssim 10^{-5}$ eV^2 and $10^{-3} < \sin^2 2\theta < 10^{-2}$, is most analogous to the (small) quark mixings. The large mixing angle (LMA) and low mass (LOW) solutions, with $\Delta m^2 \sim (10^{-5} - 10^{-4})$ and 10^{-7} eV^2, respectively, are close to the vacuum solutions ($\sin^2 2\theta = 1$). Regeneration in the earth is important in these solutions. The original vacuum (VAC) solutions with $\Delta m^2 \sim 10^{-10}$

eV^2 involved an accidental coincidence between the Earth-Sun distance and the vacuum oscillation length, and therefore predicted large energy and seasonal variations that are now mainly excluded. Matter effects are starting to be relevant in the transition or quasi-vacuum region [75], ($10^{-10} - 10^{-7}$ eV^2). There is a SMA solution for transitions to sterile neutrinos, but no viable analogs of the other regions. The major difference compared with active neutrinos is the absence of a neutral current component to $\nu_e e \rightarrow \nu_e e$ in Kamiokande and Superkamiokande. There is a smaller effect from the small neutron density in the Sun.

All of the analyses, which had slightly different inputs, favor the LMA solution, with the SMA, LOW, vacuum, and pure sterile (with parameters in the SMA range) solutions disfavored to various extents, depending on the analysis. One of the differences was in the simultaneous application of the SuperK spectrum and zenith angle distributions. The full two-dimensional distribution with correlations has never been presented, so each analysis has either used separate distributions (which double counts the same data), or ignored some of the data. Another problem or source of ambiguity is the statistical treatment of non-Gaussian effects, such as the allowed regions of parameters when there are multiple minima.

Many of the recent studies have used $\tan^2\theta$ rather than $\sin^2 2\theta$ as the mixing parameter. Allowing $\tan^2\theta > 1$ includes the second octant $\pi/4 < \theta \leq \pi/2$. This "dark side" [76] was usually ignored in past studies, which assumed implicitly that $0 \leq \theta \leq \pi/4$ and $\Delta m^2 > 0$. (The second octant solutions correspond to exchanging ν_e and the second neutrino, i.e., they are equivalent to restricting $\theta \leq \pi/4$ but allowing $\Delta m^2 < 0$.) The effect is mainly important for the LOW solutions, which extend well into the dark side [36]. However, LMA does also at high confidence level. Vacuum solutions do not depend on the sign of Δm^2, so they are mirror-symmetric.

There are many future experiments underway or proposed:

- Noble [77] described the status of SNO. The Phase I, charged current (CC), running is near complete, and the collaboration may publish the CC flux soon. When combined with the SuperK electron scattering (ES) results, this would allow an indirect determination of the (neutral current (NC))/CC ratio, and therefore of the ν_s flux. It remains to be determined whether the systematics would allow a meaningful indirect determination. In any case, SNO will then proceed to Phase II, in which salt is added to allow a clean direct measure of the NC/CC ratio. SNO will also measure the CC recoil spectrum. Although the statistics will be lower than SuperK, SNO has the advantage that the e^- energy is a direct measure of the ν_e energy, i.e., there is no convolution. They will also be sensitive to day/night and seasonal effects, and be an excellent supernova detector.

- The Borexino experiment [78] will determine the ^7Be flux (actually, a combination of the ν_e and converted $\nu_{\mu,\tau}$ flux), as well as day/night and seasonal effects.

- Proposed future experiments [79,80], including HELLAZ, HERON, LENS, MOON, and GENIUS, would be sensitive to the pp and ^7Be neutrinos. Their day/night and seasonal sensitivities would be especially useful for the LOW solution.

- KAMLAND [81] is a long baseline reactor $\bar{\nu}_e$ disappearance experiment in the Kamiokande mine. It would be sensitive to most of the power reactors in Japan, and should probe into the LMA range. It may also be used to observe solar ^7Be neutrinos.

- The proposed GENIUS [29] $\beta\beta_{0\nu}$ experiment could possibly be sensitive to masses in the (hierarchical) LMA range, but only with a sensitivity to $\langle m_{\nu_e}\rangle \sim 10^{-3}$ eV (the anticipated sensitivity is 2×10^{-3} for a 10 ton detector run for 10 yr).

The theoretical and experimental situation for the solar neutrinos has become very mature. Refined and multiple experiments are needed to simultaneously determine the neutrino solutions (especially if nature chooses a complicated scenario, e.g., with 3 relevant neutrinos) and constrain the astrophysics. As we enter into a "precision" phase with several high statistics experiments with multiple observables, it is important that the data be presented and analyzed in a manner that allows us to extract the maximum and most reliable conclusions. In particular, it is important for each group to publish all of their data with fully correlated errors (e.g., the spectral and zenith data should be presented as a two-dimensional distribution). Similarly, to ensure an optimal treatment of common sytematics and theory uncertainties, it would be useful for the experiments to perform combined analyses, analogous to the highly successful LEP Electroweak Working Group.

6.0.4. Atmospheric neutrinos [82,83]

The theoretical flux calculations were reviewed by Stanev [84], Battistoni [85], and Lipari [82]. The largest uncertainties are in the primary flux and in the pion yield in p-nucleon scattering. The agreement between the Bartol and Honda flux calculations was somewhat accidental, since the Bartol group used a lower flux and higher π yield, while Honda assumed the reverse. Recent new measurements of the primary flux by AMS [86] and BESS [87] have clarified the situation up to a few hundred GeV (the range relevant for fully contained and for partially contained or stopping events), indicating that the old (high) "Weber data" should be discarded. There is still a need for new measurements at middle energy (up to a few TeV), relevant to throughgoing muons. There has been some theoretical work on the pion yields, but major progress is expected from the HARP cross section measurements at CERN [88] (which are also critical to a possible ν factory).

In addition to the Bartol and Honda calculations, the newer FLUKA group [85] has explored theoretically-motivated (as opposed to semi-empirical) cross sections. Moreover, they have done a new 3-dimensional calculation. This yields somewhat higher fluxes in the horizontal ($\cos\theta \sim 0$) direction than the older one-dimensional codes, leading to slightly higher Δm^2. Many smaller effects, including geometry, geomagnetic effects, seasonal variations, etc., have been carefully considered.

The conclusion is that the flux is well understood. There are no large problems, and the predicted ν_μ/ν_e ratio and zenith distributions are under control. All of the groups are working on refined calculations.

Ronga [34] reviewed the data from Soudan 2 and MACRO. Soudan 2 obtains a ν_μ/ν_e ratio of 0.68(11)(6) compared to expectations, and their up/down asymmetry is becoming significant. MACRO excludes pure $\nu_\mu \to \nu_s$ at 98%, mainly from the ratio of vertical to horizontal upward throughgoing events. (There are matter effects for $\nu_\mu \to \nu_s$, or for $\nu_\mu \to \nu_e$, but not for $\nu_\mu \to \nu_\tau$.)

Kajita [19] summarized the current status of Superkamiokande data:

- The zenith angle distributions are now very precise and beautiful. They are consistent with oscillations. However, they do not have the sensitivity to resolve oscillation wiggles, so neutrino decay scenarios cannot be excluded.

- Analysis of the data using the new 3d flux calculations will increase Δm^2 slightly from the value ($\sim 3.2\times 10^{-3}$ eV^2) obtained using a 1d flux. The precise number is under investigation. The higher Δm^2 is good news for long baseline experiments.

- Pure $\nu_\mu \to \nu_s$ is excluded at 99% by a combination of upward throughgoing, high energy PC, and NC-enhanced multi-ring events. However, significant admixtures of ν_s, such as $\nu_\tau + \nu_s$, in the final state cannot be excluded.

- SuperK has fit to a transition probability $\propto \sin^2(\alpha L E^n)$, with α and n free. They obtain $n = -1.0 \pm 0.14$, consistent with oscillations ($n = -1$), but excluding CPT violation ($n = 0$), or violations of Lorentz invariance or the equivalence principle ($n = +1$).

In the future there will be refined flux calculations. It is possible that SuperK will be able to observe τ appearance at the 2-3σ level, further constraining the sterile neutrino scenarios. Atmospheric neutrinos may be studied in new generation experiments, including MONOLITH [41] and ICARUS [44] at Gran Sasso and the ANTARES underwater experiment [89]. MONOLITH should have excellent capabilities for observing an oscillation dip, as well as matter effects [90]. Finally, terrestrial long baseline experiments K2K (KEK to Kamiokande) [42], MINOS (Fermilab-Soudan) [43], and CNGS (Cern-Gran Sasso) [44, 45,91] will be able to study the atmospheric neutrino parameter range in much more detail.

6.0.5. Laboratory oscillation experiments [92]

- The CERN short baseline (SBL) experiments NOMAD [93] and CHORUS [94] are appearance experiments searching for $\nu_\mu \to \nu_\tau$ and, with less sensitivity, to $\nu_e \to \nu_\tau$, in the region of large Δm^2 and small $\sin^2 2\theta$ that was especially motivated by mixed dark matter scenarios. The NOMAD limits are almost final, and CHORUS has completed Phase I. They imply $\sin^2 2\theta < (4-6)\times 10^{-4}$ for large Δm^2.

- LSND [33] is the only oscillation experiment with a positive appearance signal. Their final transition probability, based on both $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$, is $P(\nu_\mu \to \nu_e) = (0.25 \pm 0.06 \pm 0.04)\%$. This is slightly lower than their earlier results, reopening the possibility of $3+1$ scenarios (Section 3.4.2). KARMEN 2 [95] sees no evidence for oscillations. However, there is a small region of parameters ($\Delta m^2 \sim (0.2-1)$ eV^2, $\sin^2 2\theta \sim (10^{-3} - 10^{-2})$ for which they are consistent when analyzed the same way. The LSND, atmospheric, and solar neutrino results imply three distinct values of Δm^2, most likely requiring four neutrinos. Since the Z lineshape only allows three light active neutrinos, this would imply the need for a light sterile neutrino mixing with the active ones. It is therefore crucial to confirm (or not) the LSND results. The miniBoone (or later two-detector version, Boone) at Fermilab will be sensitive to the LSND range [33]. An additional experiment would be useful.

- The reactor long baseline experiments [81] CHOOZ and Palo Verde exclude $\bar{\nu}_e$ disappearance for $\sin^2 2\theta \gtrsim 0.1$ down to $\Delta m^2 \sim 10^{-3}$ eV^2. They therefore excluded $\nu_\mu \to \nu_e$ as the dominant effect in atmospheric neutrinos. (The ν_e zenith distributions from SuperK excluded this possibility independently.) However, ν_e could still play a subleading role. The future Kamland experiment in Kamiokande [81] will have a sensitivity to reactors within several hundred km. It should be sensitive to $\sin^2 2\theta$ down to $(1.3-3)\times 10^{-1}$ for $\Delta m^2 \geq 10^{-5}$ eV^2, i.e., all of the solar LMA range. There is also a Krasnoyarsk proposal to go down to $\sin^2 2\theta \sim$ few $\times 10^{-2}$.

- Accelerator long baseline experiments are designed to search for ν_μ disappearance and/or ν_τ or ν_e appearance in the atmospheric neutrino range in a cleaner laboratory environment. The K2K (KEK to Kamiokande) experiment [42], which is already running, looks for ν_μ disappearance. It is sensitive to the upper part of the atmospheric Δm^2 range. MINOS-NUMI (Fermilab-Soudan) [43] will search for disappearance in the first phase, while the CNGS (Cern-Gran Sasso) program (OPERA and ICARUS) [44,45,91] will concentrate on ν_τ appearance. They should cover most of the atmospheric range.

6.0.6. More distant possibilities

Blondel [96] and Gavela [20] described the possibilities for a future neutrino factory, which has been discussed for CERN or Fermilab [97,33]. A neutrino factory refers to intense and precisely understood ν_e, ν_μ, $\bar{\nu}_e$, and $\bar{\nu}_\mu$ beams produced at a dedicated muon storage ring. Compared to more convention alternatives, a ν factory would produce the best physics, but would be very expensive and require a long time scale. However, it could be the first step towards a muon collider.

Dydak [98] compared and contrasted the possibilities of a ν factory with those of a superbeam, which refers to a much more intense (e.g., by 100) version of the conventional beams from π and K decay. A superbeam could be built, for example, at the Japan Hadron Facility (JHF), or at CERN or Fermilab. A superbeam might be much less expensive and faster to build than a ν factory, and might be built first or instead. However, given the nature of conventional beams (less well understood energies, ν_e contamination) the detector needs might increase the costs unacceptably.

In particular, the 1% ν_e contained in a conventional wide band beam might be fatal for oscillation studies. It has been suggested that this could be reduced by using a low energy narrow band beam generated by low energy (1-2 GeV) protons [99], but the rate is reduced by 100, and there is still a 0.1% ν_e contamination from μ decay. There are also uncertainties in the flux estimates. Another alternative is to use low energy (few hundred MeV) ν_e produced by the PRISM muon source [100], which might allow the observation of CP violation without needing matter effects.

The motivations for a neutrino factory (or conventional alternative) are especially strong if the LMA solution for the solar neutrinos turns out to be correct. The goals include:

- A precise determination of the atmospheric parameters $U_{\mu 3}$ and $|\Delta m^2_{23}|$.

- A measure of the admixture U_{e3} of ν_e into ν_3, with a sensitivity down to $|U_{e3}|^2 \sim 10^{-3}$–10^{-4}.

- The sign of Δm^2_{23}, which distinguishes the hierarchical and inverted models, can be determined provided $|U_{e3}|^2 \neq 0$ can be observed.

- The CP-violating phase δ in the leptonic mixing might be observable, provided that the parameters correspond to the LMA with $\Delta m^2_{12} > 2\times10^{-5}$ eV^2 and $|U_{e3}|^2 \neq 0$.

- It will be necessary to determine δ, $|U_{e3}|^2$, and matter effects simultaneously. They can in principle be separated by exploiting their different L/E dependences. In principle one could use the E dependence at a single detector, but in practice one needs 2 or preferably 3 detectors to handle systematics. Typical distances considered include $\sim$ 700 km (Cern-Gran Sasso), 3000 km (Fermilab to California or Cuba, Cern to Canary Islands or northern Norway), or 7300 km (Fermilab-Gran Sasso). The latter would require an extremely challenging nearly vertical beam.

- The physics possibilities would be much easier and richer in most 4 ν schemes.

- One could carry out a fine program of other physics, such as deep inelastic scattering.

Learned [83] emphasized that future large-scale oscillation experiments (e.g., the far detector at a neutrino factory) should also be designed to search for proton decay, with the goal of sensitivity to a 10^{35} yr lifetime.

6.0.7. Non-oscillation experiments

Direct kinematic limits on neutrino mass were reviewed by Vissani [46]. At present $m_{\nu_e} < 2.2$ eV from Mainz and Troisk, possibly improvable to around 0.4 eV. There is little room for laboratory improvement on m_{ν_μ} or m_{ν_τ}. We must wait for a supernova.

Klapdor [29] reviewed neutrinoless double beta decay ($\beta\beta_{0\nu}$), which can be driven by Majorana neutrino masses, as well as by other mechanisms involving supersymmetry with R-parity violation, heavy Majorana neutrinos, leptoquarks, extended gauge interactions, compositeness, or the violation of Lorentz invariance or the equivalence principle.

For light Majorana neutrinos, the amplitude is proportional to $\langle m_{\nu_e}\rangle$, defined in (14). The current upper limit of 0.35 eV at 90% is from the Heidelberg-Moscow experiment. Some authors would allow larger values because of theoretical uncertainties in the nuclear matrix elements. There can be cancellations between the contributions of the individual terms in (14), so that $\langle m_{\nu_e}\rangle$ can be smaller than the mass eigenvalues. In fact, a Dirac neutrino, for which $\langle m_{\nu_e}\rangle = 0$, can be usefully be thought of as two degenerate Majorana neutrinos with equal U_{ei} and opposite CP-parities.

The existing limit eliminates the degenerate 3ν scenarios motivated by mixed dark matter, unless they are Dirac or there are finely tuned cancellations, and it excludes some of the 4ν schemes. There are proposals to extend the $\langle m_{\nu_e}\rangle$ sensitivity considerably. These include MOON (0.03 eV), EXO (0.01-0.03 eV) [81], CUORE (0.05 eV), and GENIUS [29]. The latter is a proposed enriched Ge detector shielded by liquid nitrogen. A one ton version could reach 0.02 (0.006) eV in 1 (10) years, with 0.02 a typical expectation for the inverted model. A later 10 ton version could reach

2×10^{-3}, slightly above the 0.001 needed to probe the LMA hierarchical solution. GENIUS could also search for WIMPs and could detect solar *pp* and ^7Be ν's in real time.

7. OUTLOOK

With the direct observation of the ν_τ by the DONUT experiment [101] the standard model is complete except for the Higgs boson. Neutrinos played a significant role in establishing the standard model, while the observation of neutrino mass has also provided the first evidence for new physics. The evidence for neutrino mass and mixing is now convincing. New generations of experiments should establish the neutrino mass and mixings, hopefully determine their nature (Dirac or Majorana) and number, and perhaps establish leptonic CP violation. Not only will this be a superb constraint on what underlies the standard model, but neutrinos are also a critical probe of astrophysical processes, from stars to gamma ray bursts and the universe as a whole.

8. ACKNOWLEDGMENTS

It is a pleasure to thank the conference organizers, particularly Gianluigi Fogli and Eligio Lisi, for organizing such a successful meeting, as well as the speakers who did such an excellent job summarizing this exciting field. This work was supported by the U.S. Department of Energy grant DOE-EY-76-02-3071 and by the workshop organizers.

REFERENCES

1. See the articles in *Neutrinos in Physics and Astrophysics, from* 10^{-33} *to* 10^{+28} *cm* (Proceedings of TASI 98), ed. P. Langacker (World, Singapore, 2000).
2. F. Feruglio, these proceedings.
3. G. B. Gelmini and M. Roncadelli, Phys. Lett. **99B**, 411 (1981); H. Georgi *et al.*, Nucl. Phys. **B193**, 297 (1983).
4. A. Zee, Phys. Lett. **93B**, 389 (1980).
5. M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, ed. F. van Nieuwenhuizen and D. Freedman, (North Holland, Amsterdam, 1979) p. 315; T. Yanagida, *Proc. of the Workshop on Unified Theory and the Baryon Number of the Universe*, KEK, Japan, 1979; S. Weinberg, Phys. Rev. Lett. **43**, 1566 (1979).
6. N. Polonsky, in [1].
7. S. Raby, these proceedings.
8. G. Cleaver, M. Cvetic, J. R. Espinosa, L. Everett, P. Langacker, Phys. Rev. **D57**, 2701 (1998).
9. P. Langacker, Phys. Rev. **D58** (1998).
10. For a recent review, see K. Dienes, hep-ph/0004129.
11. M. Lusignoli, these proceedings.
12. F. Joaquim, these proceedings.
13. M. Tanimoto, these proceedings.
14. B. Brahmachari and R. N. Mohapatra, Phys. Lett. **B437**, 100 (1998).
15. D. O. Caldwell, R. N. Mohapatra and S. J. Yellin, hep-ph/0101043.
16. C. Albright et al., hep-ex/0008064.
17. E. Akhmedov, these proceedings.
18. E. Lisi, these proceedings.
19. T. Kajita, these proceedings.
20. M. B. Gavela, these proceedings.
21. H. Minakata, these proceedings.
22. M. Lindner, these proceedings.
23. A. Donini, these proceedings.
24. A. Yu Smirnov, these proceedings.
25. A. Palazzo, these proceedings.
26. M. Jezabek, these proceedings.
27. A. Masiero, these proceedings.
28. S. Lola, these proceedings.
29. H. V. Klapdor-Kleingrothaus, these proceedings.
30. C. Giunti, these proceedings.
31. O. Peres, these proceedings.
32. A. Marrone, these proceedings.
33. P. Spentzouris, these proceedings.
34. F. Ronga, these proceedings.
35. Y. Suzuki, these proceedings.
36. M. C. Gonzalez-Garcia and C. Pena-Garay, hep-ph/0011245.
37. F. Guzzo, these proceedings.
38. T. K. Kuo, these proceedings.
39. H. Nunokawa, these proceedings.
40. C. Broggini, these proceedings.
41. P. Antonioli, these proceedings.
42. J. Hill, these proceedings.

43. V. Paolone, these proceedings.
44. A. Rubbia, these proceedings.
45. A. Ereditato, these proceedings.
46. F. Vissani, these proceedings.
47. C. Virtue, these proceedings.
48. For a recent review, see, W. Buchmuller, hep-ph/0101102.
49. P. Di Bari, R. Foot, R. R. Volkas and Y. Y. Wong, hep-ph/0008245, and references theirin.
50. D. Kirilova, these proceedings.
51. Y. Wong, these proceedings.
52. S. Pastor, these proceedings.
53. I. Affleck and M. Dine, Nucl. Phys. **B249**, 361 (1985).
54. G. Mangano, these proceedings.
55. E. Waxman, these proceedings.
56. F. Halzen, these proceedings.
57. L. Perrone, these proceedings.
58. M. Gibilisco, these proceedings.
59. D. Vignaud, these proceedings.
60. R. van Dantzig, these proceedings.
61. C. de Marzo, these proceedings.
62. W. Haxton, in [1].
63. Y. Qian et al., Phys. Rev. Lett. **71**, 1965 (1993).
64. J. F. Beacom, hep-ph/9909231.
65. J. F. Beacom, R. N. Boyd and A. Mezzacappa, Phys. Rev. Lett. **85**, 3568 (2000).
66. A. Y. Smirnov, D. N. Spergel and J. N. Bahcall, Phys. Rev. D **49**, 1389 (1994).
67. D. Cline, these proceedings.
68. C. Lunardini and A. Y. Smirnov, hep-ph/0009356.
69. D. O. Caldwell, G. M. Fuller and Y. Qian, Phys. Rev. D **61**, 123005 (2000).
70. P. Krastev, these proceedings.
71. J. Bahcall, these proceedings.
72. F. Villante, these proceedings.
73. K. Kubodera, these proceedings.
74. N. Ferrari, these proceedings.
75. D. Montanino, these proceedings.
76. A. de Gouvea, A. Friedland and H. Murayama, hep-ph/9910286 and Phys. Lett. **B490**, 125 (2000); G. L. Fogli et al., Phys. Rev. **D62**, 013002 (2000); A. Friedland, Phys. Rev. Lett. **85**, 936 (2000).
77. T. Noble, these proceedings.
78. E. Meroni, these proceedings.
79. H. de Kerret, these proceedings.
80. M. Laubenstein, these proceedings.
81. G. Gratta, these proceedings.
82. P. Lipari, these proceedings.
83. J. Learned, these proceedings.
84. T. Stanev, these proceedings.
85. G. Battistoni, these proceedings.
86. B. Bertucci, these proceedings.
87. T. Sanuki, these proceedings.
88. G. Catanesi, these proceedings.
89. C. Carloganu, these proceedings.
90. M. Chizov, these proceedings.
91. A. Bettini, these proceedings.
92. B. Saitta, these proceedings.
93. G. Sitjes, these proceedings.
94. P. Zucchelli, these proceedings.
95. M. Steidl, these proceedings.
96. A. Blondel, these proceedings.
97. B. Autin, these proceedings.
98. F. Dydak, these proceedings.
99. B. Richter, hep-ph/0008222.
100. J. Sato, hep-ph/0008056.
101. K. Okada, these proceedings.