SUMMARY OF NEUTRINO 2000

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Aspects of neutrino physics beyond the Standard Model are emphasized, including the emerging default options for atmospheric and solar neutrino oscillations, namely $\nu_\mu \rightarrow \nu_\tau$ and $\nu_e \rightarrow \nu_\mu, \tau$, respectively, and the need to check them, the prospects opened up by the successful starts of SNO and K2K, the opportunities for future long-baseline neutrino experiments and high-energy astrophysical neutrinos. Finally, comments are made on the road map for realizing the exciting physics potential of neutrino factories.

1. Models for Neutrino Masses and Oscillations

It was in 1989 that LEP measured the number of light neutrino species to be three, and a milestone of this meeting has been the first detection of $\nu_\tau$ interactions by the DONUT experiment [1]. In this talk, I concentrate on aspects of physics beyond the Standard Model being revealed by neutrinos, principally associated with neutrino masses and oscillations [2]. There is no good reason why the neutrinos should be massless [3], since there is no corresponding exact gauge symmetry coupling to lepton number $L$ that could forbid their masses, analogously to the way the $U(1)$ of electromagnetism forbids a photon mass. A neutrino mass term $m_\nu \nu \cdot \nu$ involves a $\Delta L = 2$ transition and is generic in Grand Unified Theories (GUTs) [4]. However, it is already possible in the Standard Model, even without invoking ‘right-handed’ singlet neutrinos $\nu_R$, if one admits non-renormalizable interactions:

$$\frac{1}{M} \nu H \cdot \nu H \Rightarrow m_\nu = \frac{\langle |H|^2 \rangle}{M}, \quad (1)$$

where $M$ is some heavy mass scale $m_W \ll M \ll m_P$, and $H$ is a Standard-Model Higgs field.

An interaction of the form (1) arises naturally from renormalizable interactions within a GUT,

$$m_\nu = \frac{1}{M} m_D T_D, \quad (2)$$

where one expects a seesaw structure

$$(\nu_L, \nu_R) \left( \begin{array}{cc} 0 & M_D \\ m_T & M \end{array} \right) \left( \begin{array}{c} \nu_L \\ \nu_R \end{array} \right) \quad (2)$$

for neutrino masses, where $m = O(m_q)$ or $O(m_\ell)$, leading to

$$m_\nu = m_D T_D, \quad (3)$$

which is naturally small if $M \sim M_{GUT}$. For example, with $m = O(10)$ GeV and $M = O(10^{13})$ GeV one finds $M_\nu = O(10^{-2})$ eV. It is important to note, though, that the gauge group of the GUT does not play an essential rôle.

Any such mechanism may be expected to lead to mixing in generation space:

$$V_{MNS} = V_\ell V_\nu^T, \quad (4)$$

where $V_\ell$ diagonalizes the charged-lepton mass matrix, and $V_\nu$ the neutrino mass matrix [5]. A priori, $V_\nu$ would originate either in the Dirac mass $m$ or in the heavy singlet mass matrix $M$. Since the mechanism generating neutrino masses and mixing is different from that for quarks, and more complicated, perhaps one should not be surprised if the patterns of masses and mixing are different, too.

An extreme variation on the seesaw mechanism is the way neutrino masses may arise in models...
with extra dimensions. For each flavour, one could have an infinite set of Kaluza-Klein excitations contributing via mixing to a generalized seesaw:

\[
\begin{pmatrix}
0 & \cdots & m_1 & m_2 & \cdots \\
m_1 & M_1 & 0 & 0 & \cdots \\
m_2 & 0 & M_2 & 0 & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{pmatrix}
\]

(5)

In this model, the diagonal entries \(M_i\) need not be very large, because the off-diagonal entries \(m_i\) may be suppressed by the large size(s) of (one of) the extra dimension(s). A curiosity of this picture is that the neutrino oscillation pattern is no longer simply sinusoidal, emphasizing how essential it will be to measure the oscillation pattern experimentally.

A possibility intermediate between (3) and the simple GUT model (2) is when there are \(3 < N < \infty\) singlet states mixing in the seesaw mass matrix:

\[
\begin{pmatrix}
0_{3\times3} & m_{N\times3} \\
m_{3\times N} & M_{N\times N}
\end{pmatrix}
\]

(6)

This offers more possibilities for large mixing, e.g., in the case that \(M_{N\times N}\) is ‘dense’ with many similar entries, just three entries in \(m_{3\times3}\) of comparable magnitudes would suffice to give three similar light neutrino masses with large mixing.

### 2. Upper Limits on Neutrino Masses

As we heard at this meeting, the end-point of Tritium \(\beta\) decay now provides the upper limit:

\[m_{\nu_e} < 2.2 \text{ eV},\]  

(7)

there is no longer a problem with \(m^2 < 0\), and there are prospects to reach a sensitivity to \(m_{\nu_e} < 0.5 \text{ eV}\). The puzzle of the Troitsk seasonal anomaly remains, but we learnt here that it is not supported by the Mainz experiment. From \(\pi \to \mu\nu\) decay we have:

\[m_{\nu_\mu} < 190 \text{ keV},\]  

(8)

and there are ideas how this might be improved by a factor \(\sim 20\) using the BNL \((g-2)_\mu\) experiment. From \(\tau \to (n\pi)_\nu\) decay we now have:

\[m_{\nu_\tau} < 15.5 \text{ MeV},\]  

(9)

and there are prospects at \(B\) factories to improve this by a factor \(\sim 5\), closing definitively the cosmological window for a decaying massive \(\nu_\tau\). Neutrinoless double-\(\beta\) decay experiments currently establishes the upper limit:

\[\langle m_\nu\rangle_e \equiv \sum_i m_\nu_i V_{ei}^2 \lesssim 0.2 \text{ eV},\]  

(10)

and there are prospects to improve the sensitivity to \(\langle m_\nu\rangle_e \sim 0.01 \text{ eV}\). As discussed later, the limit (10) is already causing problems for models with degenerate massive neutrinos, and this improved sensitivity could impact many more.

### 3. Quo Vadis LSND?

As we heard here, a re-analysis of the full LSND data set confirms their previous results for both decays at rest (\(32.7 \pm 9.2\) events with \(R - \gamma > 10\)) and in flight. Their data are neither confirmed nor excluded by KARMEN, whose timing anomaly has not reappeared in their latest data set. It is desirable to repeat the previous global analysis of LSND and KARMEN data using their likelihood functions in the \((\sin^2 \theta, \Delta m^2)\) plane, so that future experiments know what target region in this plane to aim at.

A definitive test of LSND will be made by MiniBooNE, working at similar \(L/E\) but with \(E \sim 1 \text{ GeV}\) and starting at the end of 2001. If needed, this may be followed up by the full BooNE experiment. There is also an opportunity to pursue the LSND effect still further with the ORLaND project at the SNS, so I conclude that there is adequate follow-up of the LSND experiment.

If confirmed, the LSND data would require the presence of a fourth, sterile light neutrino species \(\nu_s\) which should mix with either atmospheric and/or solar neutrinos.
4. Atmospheric Neutrinos

Recent experiments are providing improved understanding of the cosmic-ray neutrino ‘beams’. AMS [20] and BESS [21] provide improved measurements of the primary flux, balloon experiments constrain shower models [22], and the HARP experiment [23] will provide improved data on $\pi$ and $K$ production. Three-dimensional shower simulations are now available [22]: first studies indicate that the conclusions drawn from one-dimensional simulations are robust, and that any bias in the previous inferred value of $\Delta m^2$ is within the quoted error range [24].

The impressive statistics on atmospheric neutrinos from Super-Kamiokande [24] and other experiments [25–27] provide plenty of smoking guns, in the forms of zenith-angle distributions, up-down asymmetries, etc. It is clear that something happens to atmospheric $\nu_\mu$ as a function of $L E^0 \approx n \approx -1$. Interpreted in terms of neutrino oscillations, Chooz [28] and Palo Verde [29,30] tell us that $\sin^2 2\theta_{\mu e} \lesssim 0.1$, and Super-Kamiokande favours $\nu_\mu \to \nu_\tau$ over $\nu_\mu \to \nu_s$ at the 99% confidence level, based on separate analyses of the zenith-angle distributions for neutral-current-enriched multi-ring events, partially-contained events with $E \lesssim 5$ GeV and upward-going muons, as seen in Fig. 1. The rate of $\pi^0$ production may also favour $\nu_\mu \to \nu_\tau$ over $\nu_\mu \to \nu_s$, but this needs to be confirmed by data from the K2K near detector, to reduce systematic uncertainties.

However, these conclusions should still be taken with a pinch of salt. The new atmospheric-neutrino data should be analyzed for a mixture of $\nu_\mu \to \nu_s$ and $\nu_\mu \to \nu_\tau$ oscillations [31], and in particular to determine to what extent four-neutrino scenarios motivated by the LSND experiment can be accommodated. The silver bullet would be direct evidence for $\tau$ production: Super-Kamiokande is trying, but may find it difficult. At a more fundamental level, there is as yet no direct evidence of an oscillation pattern [32].

These lacunae provide elbow-room for theorists to speculate about more neutrino species and/or novel neutrino dynamics. Neutrino decay and decoherence scenarios have both been considered, and appear indistinguishable with present data.

Figure 1. Domains of the $\sin^2 \theta, \Delta m^2$ plane allowed by the Super-Kamiokande analysis of fully-contained (FC) single-ring events and excluded by the zenith-angle distributions. They are compatible for the $\nu_\mu \to \nu_\tau$ hypothesis (top panel), but not for the $\nu_\mu \to \nu_s$ hypothesis (bottom two panels) [24].
On the other hand, any significant violation of the principle of equivalence seems excluded by the energy dependence ($\text{LE}^n : n = -1.06 \pm 0.14$) of the $\nu_\mu$ deficit \[^{[2]}\].

These lacunae also provide motivations for future experiments, e.g., to improve the sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations, to look directly for $\tau$ appearance, and to measure an oscillation pattern. They also motivate the long-baseline accelerator experiments to be discussed later. In some cases, it may be possible to use the same detector for both accelerator and atmospheric ‘beams’: one example is Super-Kamiokande, MONOLITH \[^{[3]}\] and OPERA could be others.

5. Solar Neutrinos

We have all been very happy to welcome SNO \[^{[34]}\], the new kid on this particular block \[^{[35]}\]. SNO has shown us some beautiful events, and they see a clear signal for the charged-current (CC) reactions $\nu_e + d \rightarrow p + p + e^-$, with a clean energy spectrum that seems to be proportional to that of the Standard Solar Model (SSM), as seen in Fig. 2. They also see a clear signal for elastic scattering (ES) $\sum_i \nu_i + e \rightarrow \sum_i \nu_i + e$, as seen in Fig. 3.

In the present year-long Phase I, they plan to measure the ratio of CC and ES rates sufficiently accurately to tell us at the 3-$\sigma$ level that $i \neq e$ high-energy neutrinos are coming from the Sun at the rate expected in the SSM. Subsequently, for a year in Phase II, they will run with salt to measure also the neutral-current (NC) cross-section $\sum_i \nu_i + d \rightarrow p + p + \sum_i \nu_i$. Finally, in Phase III they will add $^3$He detectors to make an independent NC measurement. In Phases II and III, SNO should be able to discriminate decisively between different solar-neutrino scenarios \[^{[10]}\].

Another newcomer to the solar neutrino field is GNO, which reported here a new Gallium measurement \[^{[37]}\]. Combined with the previous GALLEX measurements, their result is $77.5 \pm 6.2^{+4.3}_{-4.7}$ SNU, far below the SSM. For comparison, SAGE now report $75.4^{+7.8}_{-7.4}$ SNU \[^{[38]}\].

Meanwhile, the solar pace continues to be set by Super-Kamiokande \[^{[39]}\], who announced here data from running for 1117 days, with a lower
5 MeV and background reduced by 60%. A re-analysis of all their data yields $0.465 \pm 0.005^{+0.016}_{-0.013}$. Their energy spectrum is now very consistent with a constant suppression: $\chi^2 = 13.7$ for 17 d.o.f.\(^1\)

They have established an upper limit on the hep neutrino flux: $\text{hep}/\text{SSM} < 13.2$ for $E > 18$ MeV, which means they are essentially irrelevant for global fits. Super-Kamiokande also report a reduced day-night asymmetry: $2(D_N)/(D+N) = -0.034^{+0.022}_{-0.012}$, only 1.3σ away from zero.

Moreover, the observed seasonal variation is compatible with the Earth’s orbital eccentricity, and there is no significant correlation with the sunspot number\(^4\). On the other hand, as we heard here, the SSM describes very well the available helioseismological data, indicating that the true sound speed differs from the SSM by at most 0.002 in the central regions $R/R_\odot \lesssim 0.1$. Thus it appears difficult to blame the solar neutrino deficits on a failure of the SSM\(^2\).

The day-night and spectral data from Super-Kamiokande create problems for the vacuum oscillation (VO) scenario, which they now find to be disfavoured at the 95% confidence level. They reach the same conclusion for the small-mixing-angle (SMA) scenario: the day-night data want a larger value of $\sin^2 \theta$ than is favoured by the spectral data. What remain are $\nu_e \rightarrow \nu_{\mu,\tau}$ oscillation scenarios with a large mixing angle (LMA) and $\Delta m^2 \gtrsim 2 \times 10^{-5}$ eV\(^2\), and perhaps the LOW scenario with $\Delta m^2 \sim 10^{-7}$ eV\(^2\)\(^3\).

However, all these conclusions need to be confirmed by updated global analyses\(^{13,32}\). These should include unified treatments of the ‘dark side’ with $\theta > \pi/4$, as well as of matter and vacuum effects. It is also important to analyze the data in three- and four-neutrino scenarios. Even if $\nu_e \rightarrow \nu_s$ is disfavoured, at what upper limit can such a component be tolerated\(^2\)?

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\(^1\)This impressive agreement is further improved if new measurements of the Boron $\beta$-decay spectrum\(^1\) are used.

\(^2\)These are three- and four-neutrino scenarios.

\(^3\)This includes both atmospheric and solar neutrinos.

\(^4\)The helioseismological data are from the Solar and Heliospheric Observatory (SOHO) project, which includes the Michelson Doppler Imager (MDI) and the Helioseismic and Magnetic Imager (HMI) instruments.

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\(\Delta m^2\) is the squared mass difference of the neutrinos.

\(\nu_e\) and $\nu_s$ are the electron and solar neutrinos respectively.

\(\nu_{\mu,\tau}\) are the muon and tau neutrinos.
6 The Emerging Default Option

The scenario most favoured by the current neutrino data comprises just three light neutrinos, probably with hierarchical masses (more on this later), and approximately bimaximal mixing:

\[
U_{\text{MNS}} \simeq \begin{pmatrix}
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\
\frac{1}{2} & \frac{1}{2} & \frac{-1}{\sqrt{2}} \\
0 & \frac{1}{2} & \frac{1}{2}
\end{pmatrix}
\] (11)

The masses of the light neutrinos should be mainly Majorana, they should have small dipole moments, and have lifetimes much longer than the age of the Universe.

This list of defaults raises many questions. How may one rule out light \( \nu_s \)? Can one exclude degenerate neutrinos or an inverse hierarchy of masses? How large is \( \theta_{13} \)? Are the SMA and VO solutions really excluded? How can one discriminate between the LMA and LOW solutions? Is CP violation measurable in the neutrino sector? Can the neutrino mass scale be fixed by \( \beta\beta \) measurements? Can the neutrino oscillation pattern be seen and decay interpretations of the atmospheric experiments be excluded? Finally, how do we actually PROVE that \( m_\nu \neq 0 \)?

7 Future Solar Neutrino Experiments

We have seen that the present data disfavour many oscillation scenarios (SMA, VO, \( \nu_e \to \nu_s \)) but there is no 'smoking gun' yet: no spectral distortion, no day-night effect, and no abnormal seasonal effect. This provides an opportunity for SNO (comparing NC, CL and ES rates), BOREXINO [47] and KamLAND [48] (pinning down the \( ^7\text{Be} \) flux). It also motivates a new generation of low-energy solar neutrino experiments, to measure the \( \nu_e \) energy spectrum and the NC/CC ratio [49], as discussed here at a pre-conference workshop [50].
Figure 7. The time structure of events observed by K2K in coincidence with the KEK beam spill [51].

8. Long-Baseline Experiments

These are needed (a) to convince the remaining sceptics, e.g., by using a controllable beam and measuring an oscillation pattern, (b) to enable precision measurements, e.g., of $\Delta m_{23}^2$ and $\sin^2 2\theta_{23}$, and (c) to make new measurements possible, e.g., of $\tau$ production and $\theta_{13}$.

One of the highlights of this meeting was the triumphant start reported by K2K [51]. They now have data from $\sim 3 \times 10^{19}$ protons on target: see Fig. 7. The beam monitors agree with Monte Carlo predictions. Events are seen without significant background in Super-Kamiokande. Moreover, K2K is sensitive to the ‘interesting’ range of $\Delta m^2$ suggested by the atmospheric neutrino data.

Excitingly, K2K reports a promising deficit of events (27 fully-contained events in the fiducial volume, compared with $40.3^{+4.7}_{-4.6}$ expected in the absence of oscillations), although this is still only a 2-$\sigma$ effect, and one must beware of the tricks of low statistics. The rate of accumulation of events has not been particularly uniform, as seen in Fig. 8, though it is consistent with statistical fluctuations. More data are eagerly awaited, as well as the analyses of the energy spectrum and of $\pi^0$ production in the nearby detector.

Next in line will be KamLAND [48], starting in 2001, which should be able to test definitively...
the LMA solution to the solar neutrino deficit, using neutrinos from nuclear power reactors. This experiment will also make other contributions to studies of solar neutrinos, e.g., by measuring the day-night and seasonal effects for \(^7\)Be neutrinos.

MINOS construction is underway [52]. In addition to confirming \(\nu_\mu\) disappearance, it should be able to see an oscillation pattern, which will convince sceptics and enable precision measurements of \(\Delta m^2_{23}\) and \(\sin^2 2\theta_{13}\). MINOS also has good sensitivity to \(\sin^2 2\theta_{13}\). It even has some potential to discriminate between \(\nu_\mu \rightarrow \nu_\tau\) and \(\nu_\mu \rightarrow \nu_s\). We all hope there will be no unnecessary delays due to financial problems, etc..

The CERN–Gran Sasso neutrino beam was approved at the end of 1999 [53]. Its primary objective is \(\tau\) detection, as the ‘smoking gun’ for \(\nu_\mu \rightarrow \nu_\tau\) oscillations. Two experiments are being proposed for this beam: OPERA, which will use an emulsion technique profiting from the experiences of CHORUS [54] and DONUT [1], and ICANOE, which proposes to use a kinematic reminiscent of NOMAD [55]. In addition, to \(\tau\) observation, experiments in this beam could have sensitivity to \(\sin^2 2\theta_{13}\), and the proposed MONOLITH atmospheric neutrino experiment could also use the beam for oscillation studies [56].

9. Cosmological Relic Neutrinos

The numerical abundance of any light neutrino weighing \(\ll 1\) MeV is independent of its mass. Hence its relic mass density \(\rho_\nu \propto m_\nu\), and the simple requirement that neutrinos not exceed the critical density: \(\Omega_\nu = \rho_\nu / \rho_{\text{crit}} \lesssim 1\) implies that \(m_\nu \lesssim 30\) eV. Neutrinos in this range would constitute hot dark matter. A ‘neutrino’ weighing a few GeV might also have \(\Omega_\nu \lesssim 1\), and there is another window for dark matter particles weighing \(> m_{Z^2}\). Either of these two latter cases would correspond to cold dark matter, and we return later to searches for supersymmetric relics that would inhabit the third window [54].

In point of fact, studies of cosmological structure formation imply that \(\Omega_{\nu_{\text{hot}}} \lesssim 0.1\), corresponding to \(m_\nu \lesssim 3\) eV [55]. The relic neutrino density can be at most comparable to the baryon density: \(\Omega_\nu \simeq 0.05\). The concordance (better than a factor of two) between the values of \(\Omega_\nu\) extracted from Big Bang nucleosynthesis and measurements of the cosmic microwave background (CMB) radiation is truly impressive [53]. Data on structure formation and the CMB also suggest that \(\Omega_{\text{cold}} \sim 0.3\) [56] and \(\Omega_{\text{total}} \simeq 1\). The missing ‘dark energy’ may be a true cosmological constant or slowly-varying vacuum energy [60]: \(\Omega_\Lambda \sim 0.65\), as indicated concordantly by data on large-scale structure, the CMB and high-redshift supernovae [7].

The question arises how likely it may be that the three light neutrinos are almost degenerate with \(m \sim 2\) eV \(\gg \sqrt{\Delta m^2_{\text{atmo}}} \gg \sqrt{\Delta m^2_{\text{sol}}}\), close to the upper limits imposed independently by tritium end-point measurements [7] and cosmology. Any such scenario must respect the strong constraint [10] from \(\beta\beta\nu\) decay [62]:

\[
\langle m_\nu \rangle_e \simeq m \times (c_2^2 c_3^2 e^{i\phi} + s_2^2 s_3^2 e^{i\phi'} + s_3^2 e^{2i\varphi'}) \lesssim 0.2 \text{ eV},
\]

where \(m\) is the degenerate neutrino mass, \(\theta_2\) and \(\theta_3\) are mixing angles and \(\phi, \phi', \varphi\) are phases. The Chooz experiment [28] suggests that the third term in (14) may be neglected, in which case the first two must cancel: \(\phi' = \phi + \pi\) and

\[
c_2^2 - s_2^2 = \cos 2\theta_2 \lesssim 0.1 \Rightarrow \sin^2 2\theta_2 \gtrsim 0.99 .
\]

Thus maximal mixing is necessary, ruling out the SMA and probably even the LMA solutions. If VO is the answer, \(\Delta m \sim 10^{10}\) m, whereas SMA and LMA would both require \(\Delta m \sim 10^{-5}\) m. There is a question whether such extreme degeneracy can be reconciled with renormalization effects [63]. In models with strictly degenerate neutrinos before renormalization, there may also be problems with maintaining the required maximal mixing [1, 14, 53, 1].

Thus there are theoretical question marks against degenerate neutrino masses and hence substantial hot dark matter. However, there are no such concerns with supersymmetric relics \(\chi\) and cold dark matter. Constraints from LEP impose \(m_\chi \gtrsim 50\) GeV [57], and the required cos-
mological density $\Omega_\chi \sim 0.3$ is found in generic domains of parameter space.

10. Searches for Cold Dark Matter Particles

There are three major strategies to search for supersymmetric dark matter, namely via annihilation in the galactic halo yielding $\bar{p}, e^+$ or $\gamma$'s, annihilation in the Sun or Earth yielding neutrinos that may be detected directly or via muons produced by their interactions in rock surrounding an underground detector, and direct detection of the elastic scattering of relic particles within the detector.

Indirect searches for annihilation neutrinos via the muons they produce already appear to rule out some supersymmetric models, and more could be tested with a 1km$^2$ or 1 km$^3$ detector, although some models would still lie beyond the reach of such an experiment. Moreover, one should not forget neutrino mixing and oscillations, which might alter the flux of muon neutrinos between their production in relic annihilation and their detectable interactions.

There is a recent claim to have observed an annual modulation effect in a direct search experiment, which could be due to the elastic scattering of supersymmetric relics with $50 \text{ GeV} < m_\chi < 100 \text{ GeV}$. However, this has not yet been confirmed, and is difficult to reconcile with other experiments' upper limits on the elastic cross section. Theoretically, the elastic cross section required to reproduce the DAMA data appears difficult to accommodate in supersymmetric models.

11. High-Energy Astrophysical Neutrinos

Astrophysical neutrinos offer many prospects for probing fundamental physics as well as possible sources. The first experiments have been taking data for some time, and are beginning to challenge a few models of neutrino emission from AGNs and GRBs. New detectors are being constructed, and concepts for the next generation of larger detectors (1 km$^2$ or 1 km$^3$) are being discussed actively, and there are ideas for increasing further the detector sensitivity. Based on a couple of approaches to quantum gravity, it has been suggested that energetic particles might travel at less than the nominal (low-energy) velocity of light:

$$c(E) \approx c_0 (1 - \frac{E}{m} + \ldots)$$

and $\gamma$-ray data from GRBs have been used to set the lower limit $M \gtrsim 10^{15} \text{ GeV}$ on the possible quantum-gravity scale $M$. Even if $M \sim 10^{19} \text{ GeV}$, it could wash out completely the high-energy $\nu$ pulses that might be emitted by GRBs. The modification of relativistic kinematics implicit in (15) provides one exotic mechanism for evading the GZK cutoff on ultra-high-energy cosmic rays, by forbidding particle production. There should be analogous cutoff for $\gamma$ rays due to the reaction $\gamma + \gamma_{\text{IR}} \rightarrow e^+ e^-$.
TeV γ rays from the AGN Mk 501 have been reported \cite{94}, and the corrected initial γ flux would need to be extremely high \cite{95}. Moreover, it was shown here \cite{79} that energetic ν’s from Mk 501 are not present at a level similar to this corrected spectrum. Does this mean that the cutoff has been evaded by a violation \cite{15} of Lorentz invariance? We should wait and see, before jumping to such a speculative conclusion!

12. Neutrino Factories

For the long-term future of neutrino physics, an attractive concept is a neutrino factory \cite{96–98}. Starting with an intense proton source – in the range of 1 to 20 MW – with beam energy in the range of a few to 30 GeV, one hopes to capture and cool \(\sim 0.1 \mu/p\), and store them in a ‘ring’. The muons are then allowed to decay, producing \(\sim 10^{20}\) to \(10^{21}\) ν\(_\mu\) and \(\bar{\nu}_e/\gamma\) in two or three given directions. Such a ‘ring’ may resemble more a bent paper-clip, serving detectors between a few hundred and a few thousand kilometres away, for different oscillation studies, as well perhaps as a nearby detector for other aspects of neutrino physics.

Such a facility promises more precise measurements of \(\Delta m_{23}^2\) and \(\sin^2 2\theta_{23}\), optimal sensitivity to \(\theta_{13}\), and the production and observation of many τ leptons.

The jewel in the crown of neutrino factory physics \cite{96,99}, however, could be the discovery of CP violation in the neutrino sector \cite{100}, via the asymmetry

\[
A_{\text{CP}} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}
\approx 4 \frac{\sin^2 \theta_{12} \sin \delta}{\sin \theta_{13}} \sin \left(\frac{2 \Delta m_{12}^2 L}{4E}\right).
\]

For this to be observable, large \(\Delta m_{12}^2\) and \(\theta_{12}\) are both needed, and both seems to be favoured by the latest Super-Kamiokande data on solar neutrinos. There is, however, no good theoretical idea how large the crucial CP-violating phase δ might be. Care must be taken to disentangle matter effects that could mimic \(A_{\text{CP}}\), and the optimal distance for measuring \(A_{\text{CP}}\) seems to be in the range \(\sim 2000\) to \(3000\) km. Moreover, it has...
recently been suggested \cite{101} that neutrino CP violation might also be detectable using a conventional low-energy beam, a possibility that should be reviewed carefully \cite{102}.

Moreover, much of the physics interest of a neutrino factory hinges on the validity of the LMA solution for solar neutrinos, which remains to be established. In addition to neutrino oscillations, the potential physics cases for ‘standard’ $\nu$ and $\mu$ scattering physics should be explored, likewise stopped-muon physics \cite{103}, and perhaps physics with intense kaon beams \cite{104}, if the beam energy of the proton source is high enough.

As we were reminded here \cite{105}, interest in neutrino physics is rising monotonically, at least as measured by the relative numbers of papers with the words ‘neutrino’ and ‘quark’ in their titles. The neutrino factory is a very exciting project, with the potential to maintain this rise. It could be a true world machine, involving experiments in a different region of the world from the accelerator. However, it remains a strong intellectual and technical challenge. Building a neutrino factory will not be a cheap and small project. The targeting, muon capture, cooling and acceleration, and the engineering of the storage ring itself are all non-trivial. The proton driver, by itself, is not a large fraction of the total effort. To realize a neutrino factory, the neutrino community needs to reach out other communities, so as to develop the broadest possible coalition of interested physicists.

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30. Future reactor prospects were presented by L. Mikaelyan, talk at this meeting and hep-ex/0008046, hep-ex/0008063.

31. V. Barger, B. Kayser, J. Learned, T. Weiler and K. Whisnant, hep-ph/0008019.

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33. A. Geiser, for the MONOLITH Collaboration, talk at this meeting and hep-ex/0008067.

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35. The oldest kid on the block was represented here by K. Lande, for the Homestake Collaboration, talk at this meeting. See also K. Lande et al., Nucl. Phys. Proc. Suppl. 77 (1999) 13.

36. J. N. Bahcall, P. I. Krastev and A. Y. Smirnov, hep-ph/0002293 and hep-ph/0006078.

37. E. Bellotti, for the GNO Collaboration, talk at this meeting. See also M. Altmann et al., GNO Collaboration, hep-ex/0006054.

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45. C. Broggini, for the MUNU Collaboration,
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47. G. Ranucci, for the BOREXINO Collaboration, talk at this meeting. See also F. P. Calaprice, for the Borexino Collaboration, Nucl. Phys. Proc. Suppl. 87 (2000) 180.

48. A. Piepke, for the KamLAND Collaboration, talk at this meeting. See also L. De Breaeleer, for the KamLAND Collaboration, Nucl. Phys. Proc. Suppl. 87 (2000) 312.

49. F. von Feilitzsch, talk at this meeting.

50. For further information, see J.N. Bahcall, http://www.sns.ias.edu/~jnb/Meetings/Lownu/index.html.

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