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 ν_τ 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 ν_R , if one admits non-renormalizable interactions:

$$\frac{1}{M} \nu H \cdot \nu H \Rightarrow m_\nu = \frac{\langle 0|H|0\rangle^2}{M}, \quad (1)$$

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

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

where one expects a seesaw structure

$$(\nu_L, \nu_R) \begin{pmatrix} 0 & M_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \quad (2)$$

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

$$m_\nu = m_D \frac{1}{M} m_D^T, \quad (3)$$

which is naturally small if $M \sim M_{\text{GUT}}$. For example, with $m = \mathcal{O}(10)$ GeV and $M = \mathcal{O}(10^{13})$ GeV one finds $M_\nu = \mathcal{O}(10^{-2})$ 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:

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

where V_ℓ diagonalizes the charged-lepton mass matrix, and V_ν the neutrino mass matrix (3). *A priori*, V_μ 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 [5]. For each flavour, one could have an infinite set of Kaluza-Klein excitations contributing via mixing to a generalized seesaw:

$$\begin{pmatrix} 0 & \vdots & m_1 & m_2 & \cdots \\ \cdots & \vdots & \cdots & \cdots & \cdots \\ m_1 & \vdots & M_1 & 0 & \\ m_2 & \vdots & 0 & M_2 & \\ \vdots & \vdots & & & \ddots \end{pmatrix} \quad (5)$$

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 (5) and the simple GUT model (2) is when there are $3 < N < \infty$ singlet states [6] mixing in the seesaw mass matrix:

$$\begin{pmatrix} 0_{3 \times 3} & m_{N \times 3} \\ m_{3 \times N}^T & M_{N \times N} \end{pmatrix} \quad (6)$$

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 $m_{N \times 3}$ 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 β decay now provides the upper limit [7, 8]

$$m_{\nu_e} < 2.2 \text{ eV} , \quad (7)$$

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 [7], but we learnt here [8] that it is not supported by the Mainz experiment [9]. From $\pi \rightarrow \mu\nu$ decay we have [10]

$$m_{\nu_\mu} < 190 \text{ keV} , \quad (8)$$

and there are ideas how this might be improved by a factor ~ 20 using the BNL $(g-2)_\mu$ experiment. From $\tau \rightarrow (n\pi)_\nu$ decay we now have [11]

$$m_{\mu_e} < 15.5 \text{ MeV} , \quad (9)$$

and there are prospects at B factories to improve this by a factor ~ 5 , closing definitively the cosmological window for a decaying massive ν_τ . Neutrinoless double- β decay experiments [12] currently establishes the upper limit

$$\langle m_\nu \rangle_e \equiv \sum_i m_{\nu_i} V_{e_i}^2 \lesssim 0.2 \text{ eV} , \quad (10)$$

and there are prospects to improve the sensitivity to $\langle m_\nu \rangle_e \sim 0.01 \text{ eV}$ [13]. As discussed later, the limit (10) is already causing problems for models with degenerate massive neutrinos, and this improved sensitivity could impact many more [14].

3. Quo Vadis LSND ?

As we heard here [15], a re-analysis of the full LSND data set confirms their previous results for both decays at rest (32.7 ± 9.2 events with $R - \gamma > 10$) and in flight. Their data are neither confirmed nor excluded by KARMEN [16], whose timing anomaly has not reappeared in their latest data set. It is desirable to repeat the previous global analysis [17] 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 Mini-BooNE [18], 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 [19], 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 ν_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 π 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 Δm^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 ν_μ as a function of $LE^n : n \approx -1$. Interpreted in terms of neutrino oscillations, Chooz [28] and Palo Verde [29,30] tell us that $\sin^2 \theta_{\mu e} \lesssim 0.1$, and Super-Kamiokande favours $\nu_\mu \rightarrow \nu_\tau$ over $\nu_\mu \rightarrow \nu_s$ 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 π^0 production may also favour $\nu_\mu \rightarrow \nu_\tau$ over $\nu_\mu \rightarrow \nu_s$, 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 $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ 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 τ 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 $\nu_\mu \rightarrow \nu_\tau$ hypothesis (top panel), but not for the $\nu_\mu \rightarrow \nu_s$ hypothesis (bottom two panels) [24].

On the other hand, any significant violation of the principle of equivalence seems excluded by the energy dependence ($LE^n : n = -1.06 \pm 0.14$) of the ν_μ deficit [32].

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 τ 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 [33] 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 $3\text{-}\sigma$ 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 ^3He detectors to make an independent NC measurement. In Phases II and III, SNO should be able to discriminate decisively between different solar-neutrino scenarios [36].

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

Figure 2. The energy spectrum of CC events observed by SNO [34], compared with the SSM. The relative normalization is not yet specified.

Figure 3. The angular distribution of ES events observed by SNO [34].

Figure 4. The energy spectrum for solar neutrinos observed by Super-Kamiokande [39].

threshold of 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: $hep/SSM < 13.2$ for $E > 18$ MeV, which means they are essentially irrelevant for global fits. Super-Kamiokande also report a reduced day-night asymmetry: $2(D_N)/(D+N) = -0.034 \pm 0.022^{+0.013}_{-0.012}$, 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 [41]. 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

¹This impressive agreement is further improved if new measurements of the Boron β -decay spectrum [40] are used.

Figure 5. The Super-Kamiokande data on solar neutrinos observed during different periods of the day and night [39].

it appears difficult to blame the solar neutrino deficits on a failure of the SSM [42].

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 $\Delta m^2 \gtrsim 2 \times 10^{-5} \text{ eV}^2$, and perhaps the LOW scenario with $\Delta m^2 \sim 10^{-7} \text{ eV}^2$ [39].

However, all these conclusions need to be confirmed by updated global analyses [43,32]. 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 [31]? Conventional interpretations of the LSND experiment require either atmospheric $\nu_\mu \rightarrow \nu_s$ oscillations, or solar $\nu_e \rightarrow \nu_s$ oscillations. If both these are

Figure 6. The regions of $\sin^2 \theta, \Delta m^2$ for $\nu_e \rightarrow \nu_{\mu, \tau}$ oscillations that are allowed by analyses of the solar neutrino rates (shaded) and the day-night and spectrum information. The SMA and VO solutions are excluded at the 95 % confidence level, as are $\nu_e \rightarrow \nu_s$ oscillations [39].

disfavoured, how can one interpret LSND?

6. The Emerging Default Option

The scenario most favoured [44] by the current neutrino data comprises just three light neutrinos, probably with hierarchical masses (more on this later), and approximately bimaximal mixing:

$$U_{MNS} \simeq \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & \frac{-1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} \quad (11)$$

The masses of the light neutrinos should be mainly Majorana, they should have small dipole moments [45], and have lifetimes much longer than the age of the Universe.

This list of defaults raises many questions [46]. How may one rule out light ν_s ? Can one exclude degenerate neutrinos or an inverse hierarchy of masses? How large is θ_{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 $\beta\beta_{0\nu}$ 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, $\nu_e \rightarrow \nu_s$) 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 ν_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 Δm_{23}^2 and $\sin^2 2\theta_{23}$, and (c) to make new measurements possible, e.g., of τ production and θ_{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 Δm^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 $2\text{-}\sigma$ 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 π^0 production in the nearby detector.

Next in line will be KamLAND [48], starting in 2001, which should be able to test definitively

Figure 8. The accumulation of FC events in Super-Kamiokande, as a function of the number of protons on target [51].

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 ${}^7\text{Be}$ neutrinos.

MINOS construction is underway [52]. In addition to confirming ν_μ disappearance, it should be able to see an oscillation pattern, which will convince sceptics and enable precision measurements of Δm_{23}^2 and $\sin^2 2\theta_{23}$. 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 τ 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 τ 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 [33].

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: $\Omega_\nu \equiv \rho_\nu / \rho_{\text{crit}} \leq 1$ 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 [56].

In point of fact, studies of cosmological structure formation imply that $\Omega_{\text{hot}} \lesssim 0.1$, corresponding to $m_\nu \lesssim 3$ eV [57]. The relic neutrino density can be at most comparable to the baryon density: $\Omega_b \simeq 0.05$. The concordance (better

than a factor of two) between the values of Ω_b extracted from Big Bang nucleosynthesis and measurements of the cosmic microwave background (CMB) radiation is truly impressive [58]. Data on structure formation and the CMB also suggest that $\Omega_{\text{cold}} \sim 0.3$ [59] 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 [61].

The question arises how likely it may be that the three light neutrinos are almost degenerate with

$$m \sim 2 \text{ eV} \gg \sqrt{\Delta m_{\text{atmo}}^2} \gg \sqrt{\Delta m_{\text{solar}}^2}, \quad (12)$$

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 $\beta\beta_{0\nu}$ decay [62]:

$$\langle m_\nu \rangle_e \simeq m \times |c_2^2 c_3^2 e^{i\phi} + s_2^2 c_3^2 e^{i\phi'} + s_3^2 e^{2\phi''}| \lesssim 0.2 \text{ eV}, \quad (13)$$

where m is the degenerate neutrino mass, θ_2 and θ_3 are mixing angles and ϕ, ϕ', ϕ'' are phases. The Chooz experiment [28] suggests that the third term in (14) may be neglected, in which case the first two must cancel: $\phi' \simeq \phi + \pi$ and

$$c_2^2 - s_2^2 = \cos 2\theta_2 \lesssim 0.1 \Rightarrow \sin^2 2\theta_2 \gtrsim 0.99. \quad (14)$$

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 (11,14) [63]².

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 χ and cold dark matter. Constraints from LEP impose $m_\chi \gtrsim 50$ GeV [65], and the required cos-

²For a way to evade this question, see [64].

mological density $\Omega_\chi \sim 0.3$ is found in generic domains of parameter space [66,65].

10. Searches for Cold Dark Matter Particles

There are three major strategies to search for supersymmetric dark matter [67], namely via annihilation in the galactic halo yielding $\bar{p}, e^+$ or γ 's [68], 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 [69], and direct detection of the elastic scattering of relic particles within the detector [70,71].

Indirect searches for annihilation neutrinos via the muons they produce already appear to rule out some supersymmetric models [72], 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 [73].

There is a recent claim to have observed an annual modulation effect in a direct search experiment [74], which could be due to the elastic scattering of supersymmetric relics with $50\text{ GeV} \lesssim m_\chi \lesssim 100\text{ GeV}$. However, this has not yet been confirmed [75], and is difficult to reconcile with other experiments' upper limits on the elastic cross section [71]. Theoretically, the elastic cross section required to reproduce the DAMA data appears difficult to accommodate in supersymmetric models, unless the sparticle spectrum is rather unconventional [76]. Future experiments with greater sensitivity may be needed to see supersymmetric dark matter directly [77].

11. High-Energy Astrophysical Neutrinos

Astrophysical neutrinos offer many prospects for probing fundamental physics as well as possible sources [78]. The first experiments have been taking data for some time [79,80], and are beginning to challenge a few models of neutrino emission from AGNs and GRBs [81–83]. New detec-

Figure 9. *The possible rates of elastic scattering for supersymmetric relics calculated [76] in the MSSM (light shading) and with universal scalar masses (dark shading), compared with the region favoured by DAMA [74], the regions excluded by other experiments [71] (solid lines), and the possible sensitivities of future experiments [77] (dashed lines).*

tors are being constructed [84,85], concepts for the next generation of larger detectors (1 km^2 or 1 km^3) are being discussed actively, and there are ideas (acoustic detection, radio detection, observation from space) for increasing further the detector sensitivity [86]. Here I should just like to mention the possibility of using high-energy astrophysical neutrinos [87,88] to probe fundamental physics [89].

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 [90]:

$$c(E) \simeq c_0 \left(1 - \frac{E}{m} + \dots\right) \quad (15)$$

and γ -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 [91]. Even if $M \sim 10^{19}\text{ GeV}$, it could wash out completely the high-energy ν 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 [93], by forbidding particle production. There should be analogous cutoff for γ rays due to the reaction $\gamma + \gamma_{\text{IR}} \rightarrow e^+e^-$ [93]. However,

TeV γ rays from the AGN Mk 501 have been reported [94], and the corrected initial γ flux would need to be extremely high [95]. Moreover, it was shown here [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 (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 [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 $10^{21}\nu_\mu$ 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 Δm_{23}^2 and $\sin^2 2\theta_{23}$, optimal sensitivity to θ_{13} , and the production and observation of many τ leptons.

The jewel in the crown of neutrino factory physics [96,99], however, could be the discovery of CP violation in the neutrino sector [100], via the asymmetry

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \quad (16)$$

$$\simeq \frac{4 \sin^2 \theta_{12} \sin \delta}{\sin \theta_{13}} \sin \left(\frac{2 \Delta m_{12}^2 L}{4E} \right).$$

For this to be observable, large Δm_{12}^2 and θ_{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_{CP} , and the optimal distance for measuring A_{CP} seems to be in the range ~ 2000 to 3000 km. Moreover, it has

Figure 10. Possible outline design of a neutrino factory [97].

Figure 11. Sensitivity of possible neutrino factory experiments to θ_{13} [96,98,99].

Figure 12. Sensitivity of possible neutrino factory experiments in the δ, θ_{13} plane [96,98,99].

recently been suggested [101] that neutrino CP violation might also be detectable using a conventional low-energy beam, a possibility that should be reviewed carefully [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’ ν and μ scattering physics should be explored, likewise stopped-muon physics [103], and perhaps physics with intense kaon beams [104], if the beam energy of the proton source is high enough.

As we were reminded here [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 tar-

geting, 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.

REFERENCES

1. B. Lundberg, for the DONUT Collaboration, talk at this meeting. See also <http://vmsstreamer1.fnal.gov/Lectures/colloquium/lundberg/index.htm>, http://www.fnal.gov/directorate/public_affairs/press_releases/donut.html.
2. For more conventional physics with a neutrino beam, see K. McFarland, for the NUTeV Collaboration, talk at this meeting.
3. E. Witten, talk at this meeting and hep-ph/0006332.
4. R. Mohapatra, talk at this meeting and hep-ph/0008232.
5. K. Dienes, talk at this meeting; K. Dienes and I. Sarcevic, hep-ph/0008144.
6. J. Ellis, G. K. Leontaris, S. Lola and D. V. Nanopoulos, Eur. Phys. J. C9 (1999) 389.
7. V. Lobashev, talk at this meeting. See also V. M. Lobashev *et al.*, Phys. Lett. B460 (1999) 227.
8. C. Weinheimer, talk at this meeting. See also C. Weinheimer *et al.*, Phys. Lett. B460 (1999) 219.
9. For the progress and prospects of microcalorimetric measurements, see F. Gatti, talk at this meeting.
10. D. E. Groom *et al.*, Particle Data Group, Eur. Phys. J. C15 (2000) 1.
11. M. Roney, talk at this meeting.
12. H. Ejiri, talk at this meeting.
13. E. Fiorini, talk at this meeting. See also A. Nucciotti *et al.*, Nucl. Instrum. Meth. A444 (2000) 77.
14. H. V. Klapdor-Kleingrothaus, H. Päs and A. Y. Smirnov, hep-ph/0003219.
15. G. Mills, for the LSND Collaboration, talk

- at this meeting. See also C. Athanassopoulos *et al.*, LSND Collaboration, Phys. Rev. Lett. 75 (1995) 2650; Phys. Rev. C54 (1996) 2685; Phys. Rev. Lett. 77 (1996) 3082; Phys. Rev. C58 (1998) 2489; Phys. Rev. Lett. 81 (1998) 1774.
16. K. Eitel, for the KARMEN Collaboration, talk at this meeting and hep-ex/0008002.
 17. K. Eitel, New Jour. Phys. 2 (2000) 1.
 18. A. Bazarko, for the BooNE Collaboration, talk at this meeting.
 19. F. Avignone, for the ORLaND Collaboration, talk at this meeting.
 20. J. Alcaraz *et al.*, AMS Collaboration, Phys. Lett. B472 (2000) 215.
 21. Y. Ajima *et al.*, BESS Collaboration, Nucl. Instrum. Meth. A443 (2000) 71.
 22. P. Lipari, talk at this meeting and Astropart. Phys. 14 (2000) 153.
 23. M. G. Catanesi *et al.*, HARP Collaboration, CERN-SPSC-99-35 (1999).
 24. H. Sobel, for the Super-Kamiokande Collaboration, talk at this meeting. See also E. Kearns, plenary talk at ICHEP2000, <http://www.ichep2000.rl.ac.uk/scan/0801/pl/kearns/index.html>.
 25. W.A. Mann, for the Soudan-2 Collaboration, talk at this meeting and hep-ex/0007031. See also W. W. Allison *et al.*, Soudan-2 Collaboration, Phys. Lett. B449 (1999) 137.
 26. B. Barish, for the MACRO Collaboration, talk at this meeting.
 27. See, however, S. Mikheyev, for the Baksan Collaboration, talk at this meeting.
 28. M. Apollonio *et al.*, Chooz Collaboration, Phys. Lett. B420 (1998) 397 and Phys. Lett. B466 (1999) 415.
 29. G. Gratta, for the Palo Verde Collaboration, talk at this meeting. See also F. Boehm *et al.*, hep-ex/0003022.
 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.
 32. E. Lisi, talk at this meeting. See also G. L. Fogli, E. Lisi, D. Montanino and A. Palazzo, Phys. Rev. D62 (2000) 013002 for a three-neutrino treatment, E. Lisi, A. Marone and D. Montanino, hep-ph/0002053 for a treatment of decoherence effects; G. L. Fogli, E. Lisi, D. Montanino and A. Palazzo, hep-ph/0005261 for a treatment of quasi-vacuum effects.
 33. A. Geiser, for the MONOLITH Collaboration, talk at this meeting and hep-ex/0008067.
 34. A. McDonald, for the SNO Collaboration, talk at this meeting. See also J. Boger *et al.*, SNO Collaboration, Nucl. Instrum. Meth. A449 (2000) 172.
 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/0006034.
 38. V. Gavrin, for the SAGE Collaboration, talk at this meeting. See also J. N. Abdurashitov *et al.*, SAGE Collaboration, Phys. Rev. Lett. 83 (1999) 4686.
 39. Y. Suzuki, for the Super-Kamiokande Collaboration, talk at this meeting. See also Y. Fukuda *et al.*, Super-Kamiokande Collaboration, Phys. Rev. Lett. 81 (1998) 1562.
 40. C. Ortiz *et al.*, nucl-ex/0003006.
 41. A large ν_e magnetic moment could induce such a correlation: see L. B. Okun, M. B. Voloshin and M. I. Vysotsky, Sov. J. Nucl. Phys. 44 (1986) 440; Sov. Phys. JETP 64 (1986) 446.
 42. S. Turck-Chieze, talk at this meeting. See also A. S. Brun, S. Turck-Chieze and P. Morel, astro-ph/9806272; A. S. Brun, S. Turck-Chieze and J. P. Zahn, astro-ph/9906382;
 43. M. Gonzalez-Garcia, talk at this meeting. See also C. Giunti, M. C. Gonzalez-Garcia and C. Pena-Garay, hep-ph/0007154; M. C. Gonzalez-Garcia, C. Pena-Garay, Y. Nir and A. Y. Smirnov, hep-ph/0007227.
 44. B. Kayser, talk at this meeting.
 45. C. Broggini, for the MUNU Collaboration,

- talk at this meeting, presented a new experiment to probe the ν_e magnetic moment.
46. A. Smirnov, talk at this meeting.
 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 Braeckeleer, 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>.
 51. K. Nakamura, for the K2K Collaboration, talk at this meeting. See also K. Nishikawa, <http://www.ichep2000.rl.ac.uk/scan/0801/pl1/nishikawa/index.html>. For previous preliminary results, see T. Ishida, for the K2K Collaboration, hep-ex/0008047.
 52. S. Wojcicki, for the MINOS Collaboration, talk at this meeting. See also E. Ables *et al.*, MINOS Collaboration, FERMILAB-PROPOSAL-P-875.
 53. A. Rubbia, for the OPERA and ICANOE Collaborations, talk at this meeting and hep-ex/0008071. See also M. Guler *et al.*, OPERA Collaboration, CERN-SPSC-2000-028, CERN-SPSC-P-318, LNGS-P25-00 (2000); F. Cavanna *et al.*, ICANOE Collaboration, LNGS-P21-99-ADD-2, CERN-SPSC-99-40, CERN-SPSC-P-314-ADD-2 (1999).
 54. L. Ludovici, for the CHORUS Collaboration, talk at this meeting. For previous results, see E. Radicioni, for the CHORUS Collaboration, Nucl. Phys. Proc. Suppl. 85 (2000) 95.
 55. M. Mezzetto, for the NOMAD Collaboration, talk at this meeting. See also P. Astier *et al.*, NOMAD Collaboration, Phys. Lett. B483 (2000) 387.
 56. Coherent axions are another possibility for the cold dark matter: the prospects for their detection were reviewed here by K. van Bibber, talk at this meeting. See also L. J. Rosenberg and K. A. van Bibber, Phys. Rept. 325 (2000) 1.
 57. M. Tegmark, talk at this meeting. See also M. Tegmark and M. Zaldarriaga, astro-ph/0004393; M. Tegmark, M. Zaldarriaga and A. J. Hamilton, hep-ph/0008145 and astro-ph/0008167.
 58. J.R. Bond, talk at this meeting. See also P. de Bernardis *et al.*, Nature 404 (2000) 955; A. E. Lange *et al.*, astro-ph/0005004.
 59. J. Navarro, talk at this meeting and astro-ph/9908114. See also L.L.R. Williams, J. Navarro and M. Steinmetz, astro-ph/9905134; J. Navarro and M. Steinmetz, astro-ph/9908114.
 60. M.S. Turner, talk at this meeting and astro-ph/9912211.
 61. A. G. Riess *et al.*, Astron. J. 116 (1998) 1009; S. Perlmutter *et al.*, Astrophys. J. 517 (1999) 565.
 62. L. Baudis *et al.*, Phys. Rev. Lett. 83 (1999) 41.
 63. J. Ellis and S. Lola, Phys. Lett. B458 (1999) 310.
 64. R. Barbieri, L. J. Hall, G. L. Kane and G. G. Ross, hep-ph/9901228.
 65. J. Ellis, T. Falk, G. Ganis and K. A. Olive, hep-ph/0004169.
 66. J. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. Olive and M. Srednicki, Nucl. Phys. B238 (1984) 453.
 67. It now seems unlikely that most of our galactic halo is composed of MACHOs: K. Griest and A. Milsztajn, talks at this meeting. See also C. Renault *et al.*, EROS Collaboration, astro-ph/9612102; C. Alcock *et al.*, MACHO Collaboration, astro-ph/0001272
 68. J. Silk and M. Srednicki, Phys. Rev. Lett. 53 (1984) 624.
 69. J. Silk, K. Olive and M. Srednicki, Phys. Rev. Lett. 55 (1985) 257.
 70. M. W. Goodman and E. Witten, Phys. Rev. D31 (1985) 3059.
 71. D. Akerib, talk at this meeting.
 72. P. Gondolo, talk at this meeting. See also L. Bergstrom, hep-ph/0002126.
 73. J. Ellis, R. A. Flores and S. S. Masood, Phys. Lett. B294 (1992) 229; A. de Gouvea, hep-ph/0006157.
 74. R. Bernabei, talk at this meeting. See also R. Bernabei *et al.*, DAMA Collaboration,

- Phys. Lett. B450 (1999) 448, and Phys. Lett. B480 (2000) 23.
75. R. Abusaidi *et al.*, CDMS Collaboration, Phys. Rev. Lett. 84 (2000) 5699.
 76. J. Ellis, A. Ferstl and K. A. Olive, Phys. Lett. B481 (2000) 304, and hep-ph/0007113.
 77. V. Zacek, talk at this meeting.
 78. J.N. Bahcall, IUPAP Centennial speech at this meeting.
 79. S. Barwick, for the AMANDA Collaboration, talk at this meeting and Nucl. Phys. Proc. Suppl. 87 (2000) 402.
 80. C. Domogatsky, for the Baikal Collaboration, talk at this meeting. See also V. A. Balkanov *et al.*, Baikal Collaboration, astro-ph/0001151.
 81. R. Mukherjee, talk at this meeting.
 82. For a review of γ -ray bursters, see P. Meszaros, Nucl. Phys. Proc. Suppl. 80 (2000) 63.
 83. E. Waxman, talk at this meeting and hep-ph/0004102.
 84. L. Resvanis, for the NESTOR Collaboration, talk prepared for this meeting. See also S. Bottai, for the NESTOR Collaboration, Nucl. Phys. Proc. Suppl. 85 (2000) 153.
 85. L. Thompson, for the ANTARES Collaboration, talk at this meeting. See also J. J. Hernandez, for the ANTARES Collaboration, Nucl. Phys. Proc. Suppl. 81 (2000) 174.
 86. C. Spiering, talk at this meeting.
 87. R. Ghandi, talk at this meeting.
 88. T. Weiler, talk at this meeting and hep-ph/9910316.
 89. The prospects for detecting (lower-energy) supernova neutrinos were discussed here by K. Scholberg, hep-ex/0008044. See also A. Mezzacappa, Y. Qian and M. Prakash, talks at this meeting.
 90. G. Amelino-Camelia, J. Ellis, N. E. Mavromatos and D. V. Nanopoulos, Int. J. Mod. Phys. A12 (1997) 607; G. Amelino-Camelia, J. Ellis, N. E. Mavromatos, D. V. Nanopoulos and S. Sarkar, Nature 393 (1998) 763.
 91. J. Ellis, K. Farakos, N. E. Mavromatos, V. A. Mitsou and D. V. Nanopoulos, Astrophys. J. 535 (2000) 139. This paper contains a statistical analysis and references to previous indicative limits.
 92. J. Ellis, N. E. Mavromatos, D. V. Nanopoulos and G. Volkov, gr-qc/9911055.
 93. A. Letessier-Selvon, talk at this meeting and astro-ph/0006111.
 94. F.A. Aharonian *et al.*, HEGRA Collaboration, Astron. Astrophys. 349 (1999) 11.
 95. R. J. Protheroe and H. Meyer, astro-ph/0005349.
 96. A. De Rujula, talk at this meeting. See also A. De Rujula, M. B. Gavela and P. Hernandez, Nucl. Phys. B547 (1999) 21. S. Dutta, R. Gandhi and B. Mukhopadhyaya, hep-ph/9905475; M. Tanimoto, Phys. Lett. B462 (1999) 115; A. Romanino, Nucl. Phys. B574 (2000) 675; V. Barger, S. Geer, R. Raja and K. Whisnant, Phys. Rev. D62 (2000) 013004; M. Freund, M. Lindner, S. T. Petcov and A. Romanino, Nucl. Phys. B578 (2000) 27; A. Cervera, A. Donini, M. B. Gavela, J. J. Gomez Cadenas, P. Hernandez, O. Mena and S. Rigolin, hep-ph/0002108; I. Mocioiu and R. Shrock, hep-ph/0002149; V. Barger, S. Geer, R. Raja and K. Whisnant, hep-ph/0003184; A. Blondel *et al.*, CERN-EP-2000-053; M. Freund, P. Huber and M. Lindner, hep-ph/0004085; V. Barger, S. Geer, R. Raja and K. Whisnant, hep-ph/0004208; O. Yasuda, hep-ph/0005134; K. Dick, M. Freund, P. Huber and M. Lindner, hep-ph/0006090, hep-ph/0008016.
 97. E. Keil, talk at this meeting and CERN preprint CERN-SL-2000-043-AP (2000). See also B. Autin, A. Blondel and J. Ellis, (eds.) *Prospective study of muon storage rings at CERN*, CERN-99-02 (1999); D. Ayres *et al.*, Neutrino Factory and Muon Collider Collaboration, *Expression of interest for R & D towards a neutrino factory based on a storage ring and a muon collider*, physics/9911009; N. . Holtkamp *et al.*, *A feasibility study of a neutrino source based on a muon storage ring*, FERMILAB-PUB-00-108-E (2000).
 98. H. Schellman, talk at this meeting. See also S. Geer, Phys. Rev. D57 (1998) 6989; C. Albright *et al.*, *Physics at a Neutrino Factory*, hep-ex/0008064.
 99. A. Bueno, M. Campanelli and A. Rubbia,

- hep-ph/0005007.
100. Measuring this might cast some light on leptogenesis scenarios: see R. Volkas, talk at this meeting.
101. See, for example: J. Sato, hep-ph/0006127, hep-ph/0008056.
102. B. Richter, hep-ph/0008222.
103. J. Ellis, M. E. Gomez, G. K. Leontaris, S. Lola and D. V. Nanopoulos, Eur. Phys. J. C14 (2000) 319, and references therein.
104. A. Belyaev, M. Chizhov, A. Dorokhov, J. Ellis, M. E. Gomez and S. Lola, hep-ph/0008276.
105. Plot by John Learned, presented here by Tom Weiler [88].