Summary of the Neutrino Oscillation Physics Working Group at NuFact04

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A variety of experimental techniques are required to determine the properties of the neutrino; end-point measurements are required to determine the mass, neutrinoless-double-beta-decay-search experiments are required to find out if the neutrino is its own antiparticle and oscillation experiments, with various sources and baselines, are required to determine the mixing parameters. The contributions to Working Group 1 at NuFact04 reviewed the status of the present generation of experiments in each of these classes as well as addressing the prospects for the near and the not so near future. The status of neutrino phenomenology was also discussed and a number of non-standard theoretical descriptions of the neutrino were presented. This paper summarizes the experimental, phenomenological and theoretical contributions to the working group as well as the conclusions of a session dedicated to the discussion of the long-term future of neutrino-oscillation experiments.

1. Introduction

Since NuFact03, substantial progress has been made in both the experimental determination of the properties of the neutrino and in the phenomenology required to describe the presently available data and to assess the performance of future experiments. The investigation of non-standard approaches to generating neutrino masses and mixing angles has also progressed. These issues were addressed in the various contributions to Working Group 1 at NuFact04. The standard framework in which neutrino mass and neutrino oscillations are discussed as well as the status of the present generation of experiments is summarized in section 2 while section 3 contains a survey of the next generation of experiments. Energetic R&D programs are underway to develop the facilities required to make precision measurements of the properties of the neutrino and to search for leptonic-CP violation with great sensitivity. These, long-term developments, are reviewed in section 4. Developments in neutrino phenomenology and the non-standard description of the neutrino are discussed at appropriate points in the text. Of course the material presented here is intended only as a summary, and reflects the personal view of the working group conveners. Many of the important details of the individual contributions have of necessity been omitted. The reader is referred to the contributions from the individual presentations that are to be found elsewhere in these proceedings.

2. Theoretical framework and current experiments

The last few decades of neutrino oscillation experiments have produced a picture where the three known neutrino flavors are mixtures of three mass eigenstates with the PMNS matrix describing this relationship [1]. As shown in Figure 1 the matrix can be usefully broken down into 3 components: the 12 sector, the 23 sector and the 13 sector each handling a mass eigenstate pairing and it's associated Δm^2.

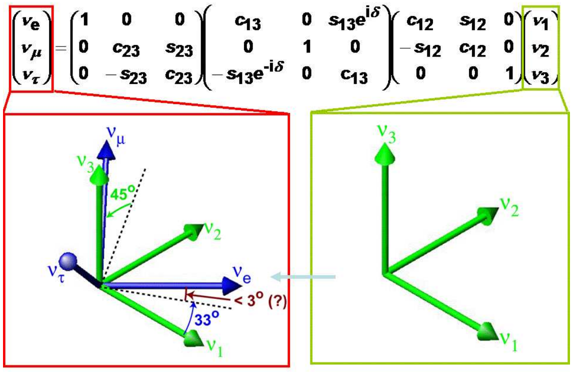

Figure 1. The PMNS matrix rotating the neutrino mass eigenstates that propagate in vacuum into the eigenstates of the Weak Interaction. The matrix is decomposed into 3 components: The 23 sector, historically probed by atmospheric oscillation experiments and by the K2K long baseline measurement, the 12 sector describing solar neutrino oscillations and the KamLand result, and the 13 sector that will be the main focus of the next generation(s) of neutrino experiments.

2.1. The 12 Sector

With its relatively small Δm^2, the 12 sector has historically only been probed by solar neutrino experiments, most notably SNO [2] and SuperK [3], and, more recently by the reactor experiment Kamland [4]. With its neutral current channel SNO has demonstrated that solar neutrinos of electron flavor oscillate into neutrinos of either muon or tau flavor (i.e. active rather than sterile neutrinos). There exists a very nice complementarity between the solar experiments and Kamland. The reactor experiment can see the oscillation effect on the energy spectrum and so can make better measurements of Δm^2_{12}, but the MSW effect ensures that the solar experiments have good sensitivity to the mixing angle θ_{12}. As reported in this meeting [5] the 99% confidence range for Δm^2_{12} is now $(7.3 - 9.4) \times 10^{-5}$ eV^2 and for $\sin^2\theta_{12}$ it is $0.22 - 0.36$. It should be noted that maximal mixing for θ_{12} is now ruled out at greater than 5σ. Continuing measurements by SNO, SuperK, and Kamland and possible enhancements in future experiments will continue to sqeeze down the uncertainties on the 12 sector to the level where they are not expected to add much uncertainty to future measurements in other sectors.

2.2. The 23 Sector

Nature has chosen Δm^2_{23} in such a way that the 23 sector can be probed by the energies and baselines of experiments looking at atmospheric neutrino oscillations and, historically, SuperK has been the standard bearer in this domain. In recent years, however, the long baseline experiment K2K [6] has been using accelerator produced neutrinos to study oscillations in the 23 sector over the 250km long baseline to the SuperK detector. As reported in this meeting [6] K2K has confirmed the atmospheric neutrino oscillation results at the 3.9σ level and has seen the effect in both the reduction of flux and in the energy shape distortion. Δm^2_{23} is pretty well measured by both SuperK and K2K, but the maximal or near maximal value of θ_{23} makes it hard to pin down precisely. If it's value is maximal it is likely that some new symmetry is being revealed. A more precise value of θ_{23} and, to a lesser extent, Δm^2_{23}

will be extremely important to the next generation of accelerator neutrino experiments probing the 13 sector for a non-zero value for θ_{13}, for the CP violation in neutrinos, and to choose between the 2 choices for the neutrino mass hierarchy.

2.3. Some Less Standard Physics

To date the only indication that the 3x3 PMNS matrix may not be the whole story in neutrino oscillations has come from the LSND experiment in the mid 90's, which measured an excess of electron anti-neutrinos in a muon anti-neutrino beam. This oscillation indication is being comprehensively checked by the MiniBooNE experiment [7]. If the LSND result does prove to come from oscillations then the situation becomes far more complex and interesting. As well as the currently planned experiments an array of short baseline measurements will be needed, as described by [8], to fully understand the field.

Cosmology also has the potential to teach us about neutrino mass. It is likely that future precision CMB measurements combined with galaxy surveys will yield limits perhaps as low as 0.04 eV on the sum of neutrino masses [9]. There are interesting measurements possible with astrophysical neutrinos with a future detector capable of distinguishing flavor. Our current understanding of neutrino oscillations predicts that the amounts of electron, muon, and tau neutrinos reaching us from astrophysical sources should be equal, any deviation from this provides important information on the neutrino source and neutrino properties [10]. Finally the next generation or two of neutrinoless double β decay measurements should get the limit on the effective mass down to 20 meV, a level where effects should be seen if the mass hierarchy is inverse [11].

3. Next-generation experiments

3.1. Goals of neutrino oscillation physics in the near future

The physics goals of the next generation of neutrino oscillation experiments are

- The precision measurement of the oscillation parameters: Δm^2_{12}, Δm^2_{23}, θ_{12}, and θ_{23}.
- A confirmation of oscillation behavior by the measurement of the oscillation curve and by an appearance signal of $\nu_\mu \to \nu_\tau$.
- A discovery of unmeasured parameter, θ_{13}[1].

In order to reach these goals within five years or so, many experiments are proposed. In this section the neutrino oscillation experiments in the near future are reviewed.

3.2. High energy neutrino beam experiments

In order to confirm the $\nu_\mu \to \nu_\tau$ oscillation, the ICARUS [12] and OPERA [13] experiments are currently in preparation. Both experiments use the CERN CNGS neutrino beam with the mean energy of 17.4 GeV. Both experiments are planned to start in 2006. The ICARUS experiment uses the liquid Argon TPC technology to identify tau interactions, and the OPERA experiment uses the emulsion technique. With the current best knowledge of neutrino oscillation parameters, $(\sin^2 2\theta_{23}, \Delta m^2_{23}) \sim (1.0, 2.5 \times 10^{-3} eV^2)$, each experiment is expected to observe $10 \sim 12$ tau neutrino interactions in five years. So, the tau appearance signal by neutrino oscillation is expected to be firmly confirmed soon.

3.3. Super-neutrino beam experiments

For the precision measurements of neutrino oscillation parameters and the discovery of non-zero θ_{13} through $\nu_\mu \to \nu_e$ appearance, the MINOS [14] and T2K [15] experiments are approved and under construction, and the NOνA [14] experiment is proposed. A feature of these experiments are the use of very intense neutrino beam, so called a super-neutrino beam. The MINOS and NOνA experiments use the Fermilab Main Injector and NuMI beam line. The accelerator for T2K is J-PARC [16] which is expected to start operation in 2007. The experiments are expected to improve the accuracy of oscillation parameters by a factor of $3--5$ in MINOS, and by a factor of $10--20$ in T2K and NOνA. The MINOS experiment will start data taking in 2005 while the T2K

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[1] Although the CP violation phase δ has not been measured yet, it is the scope of far-future experiments.

and NOνA projects are expected to start operation in 2009. There is a great chance that θ_{13} will be discovered within 10 years. The discovery will open a new window on the study of CP violation in neutrino oscillations, which will be carried out by a next-next generation experiment.

3.4. Reactor θ_{13} experiments

There is an impressive improvement in the proposals of reactor θ_{13} experiments all over the world recently. In the NuFact04 workshop, three experimental proposals were presented: one experiment in Japan [17], the second in the USA [18], and the third one in the Europe [19]. The experimental sensitivities in the Japanese and European experiments are similar, and are sensitive θ_{13} as low as $0.02 \sim 0.03$. The experiments are planned to start in 2008. The US experiment is designed to have the better sensitivity of θ_{13} down to 0.01, but it is uncertain when it would start.

Since the measurement of θ_{13} with a reactor provides complementary information to the long baseline oscillation experiments with a superneutrino beam, it is highly desirable that these experiments are approved and run together with the long baseline program.

3.5. Summary

All of experiments introduced in this section are approved and under preparation apart from NOνA and the reactor θ_{13} experiments. So, within five to ten years, the knowledge of neutrino sector will enter a new era with precision measurement and sensitive searches for rare processes conducted in several new experiments.

In addition to the proposals of experiments, many theoretical models and studies were presented in NuFact04, which could guide a future experiment after the discovery of θ_{13}.

4. Toward high-precision neutrino experiments

4.1. Precision and sensitivity

Comparisons of the performance of proposed facilities are often made on the basis of the precision of a measurement of θ_{13} and sensitivity to the CP phase δ. It is also important to take into account the degree to which a proposed experiment can distinguish non-standard models of neutrinos and their interactions from the standard scenario. Non-standard scenarios that have been discussed [20–22] include the possibility:

- That there are four generations of neutrino;
- That there may be a relationship between the spin and flavor of the neutrino and the observed neutrino oscillations may be the consequence of spin-flavor precession;
- That the neutrino may have a magnetic moment; and
- That the neutrino might have non-standard interactions.

The distinguishing features of each of these scenarios must be identified and taken into account when the facility is specified. For example, non-standard interactions can lead to oscillation effects similar to those associated with a non-zero value of θ_{13}. To disentangle the standard θ_{13} from such non-standard effects using beams from the Neutrino Factory would require a near detector sensitive to the non-standard contributions.

The facilities described in this section are assumed to begin when the first phase of the T2K and NOνA experiments have taken data. Therefore, using sensitivity to θ_{13} and δ as the touchstones, future facilities must have a sensitivity to $\sin^2 2\theta_{13}$ significantly better than 10^{-3} and a sensitivity to δ significantly better that 90°. To do this requires a new generation of high-intensity neutrino sources, significant improvements in the technologies employed in massive detectors and very careful attention to sources of systematic error. To determine the mass hierarchy, long-baseline experiments using appropriate high-energy neutrino beams are required. For such experiments to reach the required sensitivity, it will be important to develop a much more complete understanding of the matter density profile along the path from source to detector than has been available to date [23].

4.2. Second generation super-beam experiments

The reach of the present generation of off-axis conventional neutrino-beam experiments, T2K and NOνA, can be extended by upgrading the power of the source and increasing the fiducial mass of the detector. The off-axis technique leads to a neutrino beam with an energy spectrum peaked at around 0.5 GeV. The ideal detector is therefore a very large water Cerenkov.

To give a significant improvement over the performance of the first-generation experiments requires a proton beam power of $\sim$ 4 MW and a fiducial mass of between 0.5 and 1 MTon. The first-phase beam power at the J-PARC facility will be 0.75 MW and it is planned to upgrade this, in stages, to 4 MW. The HyperKamiokande collaboration have made a proposal to construct a MTon-scale water Cerenkov close to the site of SuperKamiokande [24]. To simplify the cavern excavation, it is proposed to build the experiment in two 0.5 MTon modules. Each module will be composed of 10 compartments each with a length of 50 m. A neutrino beam from the 4 MW J-PARC upgrade, viewed by HyperKamiokande (T2K II) has been estimated to have a sensitivity to δ at 3σ of $|\delta| > 20^\circ$ for $\sin^2 2\theta_{13} > 0.01$ assuming that the systematic uncertainties can be reduced to the 2% level.

At CERN, a proposal to build a superconducting proton linac (SPL) cable of producing 4 MW of proton beam power at 2.2 GeV has been developed [25]. A MTon-scale water Cerenkov is again well matched the neutrino beam energy that will be produced. It is proposed to construct an experimental hall close to Frejus in the French Alps. The sensitivity of this facility (SPL – Frejus) would be similar to that of T2K II. The proponents argue that incorporating the results of the hadron-production experiments HARP and MIPP in the simulation of the beam line will significantly reduce the systematic uncertainty associated with the composition of the neutrino beam.

Both the Japanese and CERN proposals match the low neutrino energy to a short baseline. At Brookhaven, a proposal to produce an intense wide-band neutrino beam using the AGS has been prepared. The beam is viewed by UNO, a 0.5 MTon water Cerenkov, at a baseline of 2500 km. The advantages of this approach (BNL – VLBL) are that the first and second oscillation maxima can, in principle, be observed and the long baseline gives some sensitivity to matter effects. Simulations indicate that there will be a substantial contribution of background events in the samples accumulated which will require a careful statistical analysis to remove.

It is important to note that the measurement of neutrino-oscillation parameters is only one part of the broad and exciting physics program that can be carried out with a MTon scale water Cerenkov detector [26]. The highlights of this physics program include the search for nucleon decay, the study of atmospheric and solar neutrinos, the search for super-nova relic neutrinos and neutrino astrophysics.

4.3. Beta beams

A recent, and highly novel, idea is to generate pure, low energy electron neutrino (or electron anti-neutrino) beams from the decay of stored beams of radioactive ions. The concept originated as an upgrade to the CERN accelerator complex [27] in which the SPL was used to drive an upgraded Isotope Separation On Line (ISOL) ion source. Following a dedicated series of low energy accelerators it was proposed to accelerate the ions to their final energy by using CERN's PS and SPS accelerators and to build a new storage ring with straight sections $\sim$ 2.5 km long that would fit within the present confines of the CERN North Area. Studies indicate that it will be possible to store simultaneously beams of ^{6}He and ^{18}Ne, so generating $\bar{\nu}_e$ beams with a mean energy of 250 MeV and ν_e beams with a mean energy of 400 MeV [25]. The neutrino beams would be directed to the 0.5 MTon water Cerenkov proposed for the Frejus laboratory and outlined above. The 3σ sensitivity to δ at such a facility would be $|\delta| > 35^\circ$ for $\sin^2 2\theta_{13} \approx 0.01$ assuming that the systematic uncertainties can be reduced to the 2% level. The combination of the SPL super beam and the SPS-based beta beam serving the same detector in parallel might allow tests of CP, T and CPT conservation to be carried out.

Accelerating the ions to higher energies would offer a number of advantages. There would be an 'automatic' increase in the size of the data samples since the charged-current cross section grows linearly with energy. In addition, the larger neutrino energy would require a longer baseline, giving access to matter effects and so allowing the mass hierarchy to be determined. In addition, it would be possible to determine the energy spectrum of the neutrinos and so obtain an increase in sensitivity by using this information in fits to extract θ_{13} and δ. If it were possible to use a 1 TeV proton accelerator to accelerate the ions, the sensitivity to δ at 99% confidence level in the absence of systematic errors might be as low as 10°. An interesting, long term, option might be to use the LHC to accelerate the ions. In this case the event rates are large enough that a small detector, with a fiducial mass of only 40 kTon would give excellent sensitivity [28].

The beta beam offers great potential for the study of neutrino oscillations. However, when fits are performed to determine the oscillation parameters, it is not possible to distinguish between sets of solutions for which the fit probability is similar. It will not be possible to disentangle all such degeneracies using data from super-beam and beta-beam experiments alone [29]. This emphasizes the need for a broad program of measurements.

4.4. The Neutrino Factory

The Neutrino Factory, an intense high-energy neutrino source derived from the decay of a stored muon beam, has been the subject of several dedicated conceptual design studies [30]. The composition of the neutrino beam produced at the Neutrino Factory is determined by the muon charge circulating in the storage ring and the neutrino-beam energy spectrum is precisely known. As a result, at the Neutrino Factory, the systematic errors associated with the neutrino beam will be reduced to a minimum. The high neutrino-beam energy offers two additional advantages: since neutrino cross sections increase linearly with energy, a large event rate will be produced in a detector of moderate size ($\sim$ 100 kTon); and baselines long enough to allow matter effects to be observed must be employed. Phenomenological studies presented at this workshop upheld the conclusions of previous workshops in this series: that the Neutrino Factory is the most sensitive of the proposed neutrino facilities. Figure 2 shows the one-standard-deviation error on δ that could be achieved at a Neutrino Factory as a function of the true value of $\sin^2 2\theta_{13}$. For $\sin^2 2\theta_{13} \sim 10^{-3}$, the uncertainty on δ will be $\sim 20^\circ$. The figure also demonstrates that the Neutrino Factory extends the CP coverage of the super-beam experiments to much smaller values of $\sin^2 2\theta_{13}$. Together, the super-beam and Neutrino Factory experiments will cover a significant part of the parameter space.

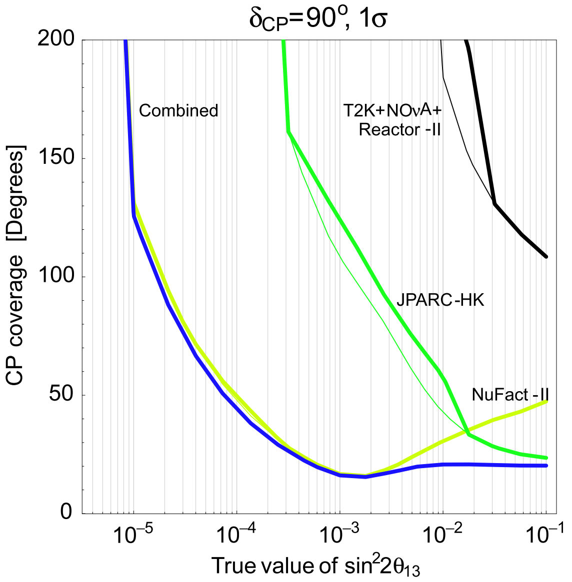

Figure 2. The one-standard-deviation precision on δ at a Neutrino Factory compared with that of T2K II and the next generation off-axis super-beam experiments, together with the combined Neutrino Factory and super-beam sensitivity. The sensitivities are shown as a function of the assumed true value of $\sin^2 2\theta_{13}$. The thin curves correspond to cases where the sign degeneracy is not taken into account. The figure is taken from the US APS sponsored Study IIa [31], the calculation is from [32].

The principle challenges presented by the Neutrino Factory accelerator complex (the proton driver front end, the high-power pion-production target, the ionization-cooling channel and the rapid, large aperture acceleration system) are being addressed by hardware R&D programs carried out by international collaborations. In addition, conceptual design work is being carried out in Europe, Japan, the US and the UK. The most recent, US Study IIa [31], achieved a performance as good as that of the Study II accelerator complex but at approximately 67% of the cost [33]. The goal of the Neutrino Factory community – to produce a single conceptual design for the facility by the end of the decade [34] – requires an increasing emphasis to be placed on the development of the next generation of long-baseline detectors. Large magnetic detectors are an option for muon detection and measurement [35]. However, the principle detector challenge at the Neutrino Factory is to distinguish electrons from positrons in a 100 kTon scale detector. A large liquid-argon time-projection chamber such as that described in [36] is a promising option. To optimize the facility for performance and cost will require a substantially better understanding of the various detector technologies that have been proposed.

4.5. Comparison of future facilities

As part of the Working Group 1 program, a discussion of future facilities for the study of neutrino oscillations was held. The discussion focused on the era of precision neutrino-oscillation measurements after the present generation of off-axis super-beam experiments are complete. The possible future facilities are listed in table 1 together with the date at which the proponents argued that the facility could be ready to start taking data. Also shown are sensitivities to $\sin^2 2\theta_{13}$ and δ that could be obtained after a specified number of years running. The striking feature of the table is that, if a start-date uncertainty of ±5 years is assumed, each of the facilities could be available at more-or-less the same time. The conclusion drawn by those present at the discussion was that it is both essential and urgent for a detailed comparison to be made in which the performance, cost and timescale of each facility is placed on as equal a footing as possible. Such a comparison will allow the Neutrino Factory community to identify the option that is most likely to deliver precision measurements of the neutrino-oscillation parameters as well as giving the best sensitivity to leptonic-CP violation.

5. Conclusion

The contributions to, and the discussions that took place at, the Working Group 1 sessions at NuFact04 leave us in no doubt that significant advances will come in the near future from the present generation of experiments and that, in the near to medium term, the next generation of experiments that will push down the limit on (or provide a first measurement of) $\sin^2 2\theta_{13}$. There are many exciting proposals for facilities capable of delivering precision studies of neutrino oscillations. The need for a like-for-like comparison of these future facilities was identified as a high-priority issue. We look forward to the progress on each of these issues that will be reported at NuFact05.

Acknowledgments

We very much enjoyed this well organized workshop in the vibrant city of Osaka and we thank the organizers for the support and hospitality given to us. We would also like to thank all those who contributed to the Neutrino Oscillations Working Group session either by preparing talks or by taking part in the lively debates. We greatly appreciate the help that we have been given by the speakers in preparing the summary talks and in the preparation of these proceedings.

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Table 1
Comparison of options for future facilities for neutrino-oscillation studies. Each of the facilities was described in a presentation to the Working Group and an outline description is given in the text. The start date is the date by which the advocates believe that the facility could be taking data. The three-standard-deviation sensitivities for $\sin^2 2\theta_{13}$ and δ would be achieved after 'Duration' years of running.

	Start	Duration	Sensitivity		
Facility	(year)	(years)	$\sin^2 2\theta_{13}$	δ (°)	Comments
T2K II	2014	8	0.001	20	Assumes 2% systematic errors.
SPL to Frejus	2013	10	0.0005 – 0.009	35	
Beta beam (low γ)	2015	10	0.0003 – 0.009	35	Assumes 2% systematic errors.
BNL – VLBL	2011	5	0.005	$20^{\dagger}$	Assuming background estimation.
Neutrino Factory	2015	5	0.00001	10	

† One-standard-deviation resolution.

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