Roadmap for the international, accelerator-based neutrino programme

Discussion document

The ICFA Neutrino Panel

Overview

The neutrino, with its tiny mass and large mixings, offers a window on physics beyond the Standard Model. Precise measurements are required to understand the nature of the neutrino and to elucidate the phenomena that give rise to its unique properties. Accelerator-driven sources of neutrinos will play a critical role in determining these properties since such sources provide the only means by which neutrino and anti-neutrino transitions between all three neutrino flavours can be studied precisely.

The ICFA Neutrino Panel [1] is developing a roadmap for the international, accelerator-based neutrino programme. The roadmap presented in this discussion document was drawn up after the peer-group-consultation process presented in the Panel's initial report [2]. The roadmap is consistent with the conclusions drawn in [2].

With its roadmap the Panel will document the approved objectives and milestones of the experiments that are presently in operation or under construction. Approval, construction and exploitation milestones are presented for experiments that are being considered for approval. The timetable proposed by the proponents is presented for experiments that are not yet being considered formally for approval. Based on this information, the evolution of the precision with which the critical parameters governing the neutrino are known has been evaluated. Branch or decision points have been identified based on the anticipated evolution in precision. The branch or decision points have in turn been used to identify desirable timelines for the neutrino-nucleus cross section and hadro-production measurements that are required to maximise the integrated scientific output of the programme. The branch points have also been used to identify the timeline for the R&D required to take the programme beyond the horizon of the next generation of experiments. The theory and phenomenology programme, including nuclear theory, required to ensure that maximum benefit is derived from the experimental programme is also discussed.

The roadmap, interim conclusions and draft recommendations presented in this document will be used as the basis for discussion amongst the neutrino community—and more broadly, the particle- and astroparticle-physics communities—and with the various stakeholders in the programme. These discussions will take place over the summer and autumn of 2016. An important element of these discussions will be those following the presentation of the roadmap at Neutrino 2016 [3]. After a period of revision and further consultation the document will be revised in time for it to be presented to ICFA at its meeting in February 2017.

Contents

1 Introduction

The Standard Model (SM) gives a precise, quantitative description of the fundamental constituents of matter and the forces through which they interact. The study of the properties and interactions of the neutrino has been seminal in the development of the electroweak theory and decisive in the development of the quark-parton model and quantum chromodynamics. Recently, the discovery of neutrino oscillations, which implies that neutrinos have mass and that the flavour eigenstates mix, has led to the realisation that the SM is incomplete.

Measurements of the parameters that govern neutrino oscillations will have a profound impact on our understanding of particle physics, astrophysics and cosmology. Such a breadth of impact justifies a far-reaching experimental programme. Accelerator-based measurements of neutrino oscillations are an essential component of this programme since they are the only means by which each of the possible oscillation channels can be studied with sufficient precision.

ICFA established a Neutrino Panel [1] with the mandate to "*promote international cooperation in the development of the accelerator-based neutrino-oscillation program and to promote international collaboration in the development a neutrino factory as a future intense source of neutrinos for particle physics experiments* [4, 5]. In its Initial Report the Panel outlined an ambitious programme by which the discovery potential of the accelerator-based neutrino programme could be optimised [2]. Greater international cooperation was identified as being key to the successful delivery of this programme. The establishment of the Deep Underground Neutrino Experiment (DUNE) [6, 7], the Short Baseline Programme (SBN) [8] and the Long Baseline Neutrino Facility (LBNF) at the Fermi National Accelerator Laboratory (FNAL) [9] and the CERN Neutrino Platform [10] as international facilities for the advancement of the field represents substantial progress in the necessary internationalisation of the programme. The Panel notes the recent developments in the consideration of the international Hyper-K programme [11, 12]. Together, the complementary long-baseline experiments DUNE and Hyper-K [13], the SBN programme and the CERN Neutrino Platform will provide the basis for a robust discovery programme.

To complete our understanding of neutrino oscillations it will be necessary to determine [2]:

- Whether mixing among the three neutrino flavours violates the matter-antimatter (CP) symmetry. Such leptonic CP-invariance violation (CPiV) would be something new and might have cosmological consequences;
- What the ordering of the three neutrino mass eigenstates is. While there are constraints on the absolute neutrino-mass scale our knowledge of the mass spectrum is incomplete;
- Whether empirical relationships between neutrino-mixing parameters, or between neutrino- and quark-mixing parameters, can be established; and
- Whether the few measurements of neutrino oscillations that are not readily accommodated within the elegant framework of three-neutrino mixing are statistical fluctuations, systematic effects or indications that there is even more to discover.

By addressing these issues it may be possible to develop a theory that can explain why neutrino masses are so tiny, at least a million times smaller than any other known matter particle, and why the strength of mixing among the neutrino flavours is so much stronger than the mixing among the quarks.

The purpose of this discussion document is to present concisely the elements of the global neutrino programme in such a way that branch or decision points can be identified. Consideration of the programme as a whole will allow choices to be made that exploit regional strengths and ambitions to optimise the discovery potential. In this way the impact of each contribution on the global programme will be maximised.

1.1 The roadmap

A vibrant programme that is able to attract the interest of researchers and the support of funding agencies and laboratories must:

- Have both discovery potential and deliver critical measurements in the short term (< 5 years) and in the medium term (between 5 and 15 years); and
- Develop the capabilities required to build on and go beyond the performance of the near- and medium-term experiments through appropriately-resourced detector and accelerator R&D programmes.

By preparing this roadmap, the Panel seeks to identify an accelerator-based programme that satisfies these imperatives. In the short term (less than five years), experiments such as T2K [14], NOνA [15], MicroBooNE [16] and MINERνA [17] will provide a steady stream of results. Over the five- to fifteen-year timescale, the medium-term programme will seek evidence for CPiV by exploiting the Deep Underground Neutrino Experiment (DUNE) in the USA and the Hyper-K experiment in Japan. The branch or decision points identified in the analysis of the roadmap are intended to facilitate the discussions necessary to maximise the scientific output of, and technological benefit from, the global investment in the accelerator-based neutrino programme.

The categories into which the neutrino programme has been broken down are:

1. The study of neutrino oscillations;
2. Searches for sterile neutrinos;
3. The supporting programme that includes:
   (a) The study of hadro-production and neutrino-nucleus scattering necessary to allow the neutrino flux and interaction rates to be estimated with the requisite precision; and
   (b) The detector, accelerator and software R&D that supports the current programme and builds capability for the discovery programme in the medium to long term;
4. Experiments that use neutrinos produced by nuclear reactors;
5. Experiments that exploit non-terrestrial sources and radio-active sources; and
6. The non-oscillation programme.

Categories 1, 2 and 3 constitute the accelerator-based neutrino discovery and measurement programmes. Categories 4 and 5 are included as the results from these programmes may impact the accelerator-based programme. The needs of the discovery and measurement programmes were considered when analysing the timetable for the programme of supporting measurements and R&D (category 3). The objectives and approved or proposed timetable is reported for each of the projects considered together with an indication of the number of scientists engaged in the execution or development of the activity.

1.2 The international accelerator-based neutrino-physics community

It is of interest to consider the strength of the neutrino-physics community that exploits accelerator-generated neutrino beams. Surveys of the particle-physics community have been carried out on a national or regional basis [18, 19]. No consistent survey of the international accelerator-based neutrino community exists, making it necessary to draw information from a number of sources to give an indication of the size of the community.

The European Committee on Future Accelerators (ECFA) [20] carries out a regular survey of the particle-physics community in Europe. The most recent [18], published in 2010, was based on data collected in 2009. The ECFA survey counted personnel, rather than "full-time equivalents"; only persons spending 20% or more of their time on particle-physics activities were counted, each such person was counted with a weight of one. The fraction of research time allocated by a particular individual to a particular project was then recorded. Personnel were classified as permanent staff, time-limited researchers, PhD students and engineers with a

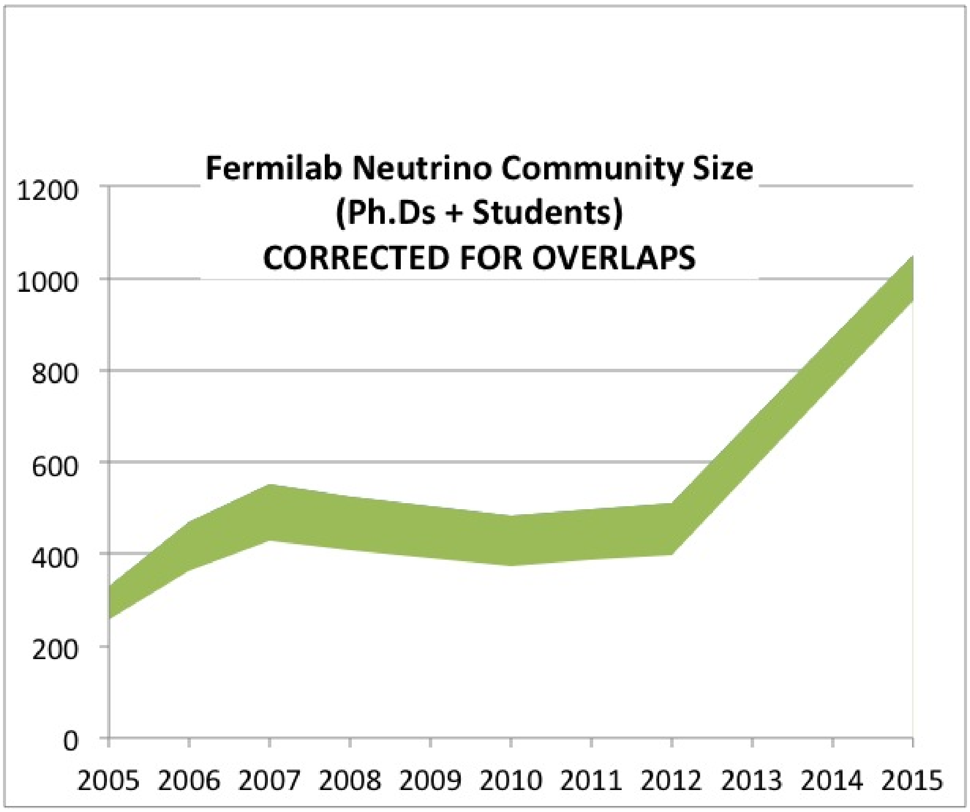

Figure 1: The number of PhD-holding researchers and graduate students engaged in neutrino experiments based at Fermi National Accelerator Laboratory. The data has been corrected for “overlaps”; cases in which an individual is listed on more than one experiment. The uncertainty on the overlap-correction is indicated by the shaded band. The data were taken from the archives of the Fermi National Accelerator Laboratory.

University degree. With these definitions, ~ 1000 members (approximately 10%) of the European particle-physics community were engaged in neutrino physics. Of these, $\sim 40\%$ were involved in the accelerator-based programme. The 2009 survey is now somewhat outdated and ECFA is considering repeating the survey in preparation for the European Strategy update that is pencilled in for 2017/18.

The number of researchers involved in neutrino experiments based at FNAL is shown in figure 1. Researchers holding a PhD and graduate students are included in the count; all such researchers who are engaged in the programme are included in the count, regardless of their affiliation. The data has been drawn from the archives held at FNAL. The raw number of researchers and graduate students has been corrected for the effect of “overlaps”; cases in which an individual is recorded against more than one experiment. The size of this correction is 20%. An estimate of the uncertainty arising from the overlap correction is also shown. The data indicate that the FNAL-based neutrino community grew by $\sim 55\%$ from 2005 to 2007. The community was stable during the period when the Tevatron $p\bar{p}$ collider was in operation (2007–2012). The change of emphasis of the Laboratory in recent years is clearly seen in the steady growth in the accelerator-based neutrino community supported by FNAL.

In Canada, a survey of particle physics activities was conducted in the context of a long-range planning exercise [21] held in 2015. According to this survey, approximately 35 scientists and graduate students participate in accelerator-based long-baseline neutrino physics through the T2K and Hyper-K collaborations. An additional 70 scientists and graduate students are members of other neutrino efforts, such as EXO [22], IceCube [23] and SNO+ [24].

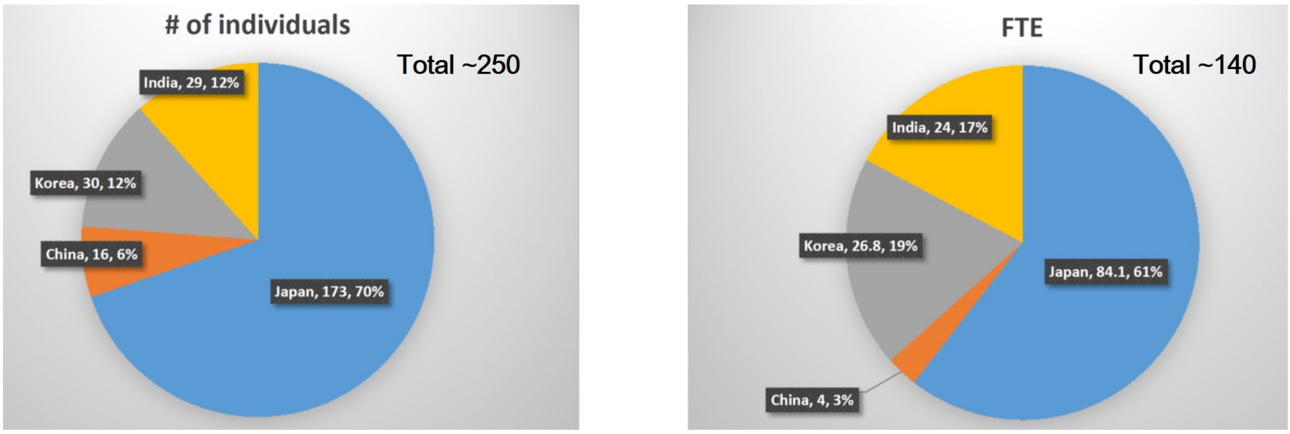

Figure 2: The number of Asian researchers (staff, post-doc and students) engaged in accelerator-based neutrino experiments around the world. (a) number of individuals counted with a weight of one if the individual is working on an accelerator-based experiment with any fraction of their time. (b) full time equivalent (FTE) number of persons working on accelerator-based neutrino experiments.

For Asia, there had been no survey of the size of community for accelerator-based neutrino experiments. As a first trial, Asian members of the Panel compiled the number of researchers (staff members, post-docs, and students) employed by Asian institutes who are working on accelerator-based neutrino experiments around the world; experiments such as T2K, Hyper-K, MINOS [25], DUNE, etc. were included in the survey. Two statistics were prepared: (a) individuals were counted with weight one if they were working on an accelerator-based experiment; the count did not take into account the fraction of time spent by an individual on an accelerator-based neutrino experiment; and (b) the full-time equivalent effort invested in accelerator-based neutrino experiments. The results of the survey are ~ 250 and ~ 140 for (a) and (b) respectively. The distribution of the number of individuals engaged in the accelerator-based programme and the effort invested is shown for the Asian countries taking part in the survey in figure 2.

1.3 Interim conclusions and recommendations

1.1: The neutrino has a tiny mass, much smaller than any other fundamental fermion, and its type, or “flavour”, changes as it propagates through space and time. These properties imply the existance of new phenomena not described by the Standard Model of particle physics and may have profound consequences for our understanding of the Universe. The tiny neutrino mass seems likely to be related to phenomena that occur at very high energy scales, well beyond the reach of the present or proposed colliding-beam facilities. The study of the neutrino is therefore the study of physics beyond the Standard Model and a fundamentally important component of the particle-physics programme.

1.2: The accelerator-based neutrino programme is global in scope, engagement and intellectual contribution. Continued and enhanced cooperation in a coherent global programme will maximise the impact of each individual contribution and of the programme as a whole.

Recommendation 1.1: The present roadmap discussion document should be completed through discussion with the stakeholders. The roadmap should then be revised and updated at appropriate intervals.

1.3: By collating data from a number of sources the Panel has gained a partial understanding of the strength of the global accelerator-based neutrino community. Accurate, up-to-date, consistent and complete census data for the global accelerator-based neutrino community will be valuable in planning the development of the programme.

Recommendation 1.2: ICFA should support the Panel in its efforts to work with the stakeholders to gather the necessary census data as part of the consultation process that will follow the completion of this roadmap discussion document.

2 Accelerator-based long-baseline neutrino-oscillation programme

Neutrino oscillation, in which a neutrino created in an eigenstate of flavour α is detected in flavour state β, may readily be described in terms of the mixing of three mass eigenstates, ν_i, $i = 1, 2, 3$ [26, 27]. The probability for the transition $\nu_\alpha \to \nu_\beta$ in vacuum is given by [28]:

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left[-i \frac{\Delta m^2_{ji}}{2} \frac{L}{E} \right] \; ; \qquad (1)$$

where E is the neutrino energy, L is the distance between source and detector and $\Delta m^2_{ji} = m^2_j - m^2_i$. The unitary matrix, U, may be parameterised in terms of three mixing angles, θ_{ij} and one phase parameter $\delta_{\rm CP}$:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (2)$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. The values of the various parameters that define the "Standard Neutrino Model" (SνM) obtained in fits to the present data are given in table 1 [28]. Possible Majorana phases can not be measured in neutrino-oscillation experiments and are omitted from equation 2. Values for all of the mixing angles and Δm^2_{21} have been determined. The magnitude of Δm^2_{32} is also known. The value of the CP-invariance violating phase, $\delta_{\rm CP}$, and the sign of Δm^2_{32} are unknown.

The goals of the future neutrino-oscillation programme are to:

- Complete the SνM:
  - Determine the mass hierarchy; and
  - Search for (and discover?) leptonic CP-invariance violation;
- Establish the SνM as correct description of nature:
  - Determine precisely the degree to which θ_{23} differs from $\pi/4$;
  - Determine θ_{13} precisely; and
  - Determine θ_{12} precisely;
- Search for deviations from the SνM:
  - Provide redundant measurements of sufficient precision to:
    - Test the unitarity of the neutrino-mixing matrix;
    - Seek relationships between the parameters of the SνM or between neutrinos and quarks;
  - Search for sterile neutrinos and non-standard neutrino interactions.

The accelerator-based neutrino-oscillation experiments presently in operation are presented in section 2.1 and the planned next-generation of experiments is presented in section 2.2. Projects that seek to go beyond the performance of the present or planned experiments are presented in section 2.3.

2.1 Present accelerator-based neutrino-oscillation programme

2.1.1 T2K

Physics goals

The collaboration will use the off-axis J-PARC neutrino beam, for which the neutrino-energy distribution peaks at 0.6 GeV, to collect large samples in the near (ND280) and far (Super-K) detectors to [29]:

- Search for CP-invariance violation using $\overset{(-)}{\nu}_e$ appearance;
- Measure θ_{23} with high precision using $\overset{(-)}{\nu}_\mu$ disappearance;

Table 1: Summary of neutrino oscillation parameters [28]. The best-fit values and 3σ allowed ranges of the 3-neutrino oscillation parameters, derived from a global fit of the current neutrino oscillation data. The definition of Δm^2 used is: $\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. Thus, $\Delta m^2 > 0$, if $m_1 < m_2 < m_3$, and $\Delta m^2 < 0$ for $m_3 < m_1 < m_2$.

Parameter	Value ($\pm 1\sigma$)	(3σ range)
$\sin^2\theta_{12}$	0.308 ± 0.017	0.259 - 0.359
$\sin^2\theta_{23}, \Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	0.374 - 0.628
$\sin^2\theta_{23}, \Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$	0.380 - 0.641
$\sin^2\theta_{13}, \Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	0.0176 - 0.0295
$\sin^2\theta_{13}, \Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	0.0178 - 0.0298
Δm^2_{21}	$(7.54^{+0.26}_{-0.22}) \times 10^{-5}$ eV^2	$(6.99 - 8.18) \times 10^{-5}$ eV^2
$\lvert\Delta m^2\rvert, \Delta m^2 > 0$	$(2.43 \pm 0.06) \times 10^{-3}$ eV^2	$(2.23 - 2.61) \times 10^{-3}$ eV^2
$\lvert\Delta m^2\rvert, \Delta m^2 < 0$	$(2.38 \pm 0.06) \times 10^{-3}$ eV^2	$(2.19 - 2.56) \times 10^{-3}$ eV^2
sign of Δm^2_{32}	unknown	
$\delta_{\rm CP}$	unknown	

- Make a variety of measurements of neutrino-nucleus interactions, to improve neutrino oscillation measurements;
- Contribute to the neutrino mass-hierarchy determination; and
- Search for non-standard interactions and exotic phenomena.

The T2K programme is approved for an exposure of 7.8×10^{21} protons on target (POT). A data set corresponding to 1.4×10^{21} POT has been accumulated. T2K has published results corresponding to 6.6×10^{20} POT which, in conjunction with the reactor constraint on θ_{13}, disfavour values of $\delta_{\rm CP}$ around $\frac{\pi}{2}$ (see figure 3). A total exposure of 2×10^{21} POT is projected by the end of 2016. The projected sensitivity to CPiV is shown in figure 3 [30].

Institutes 59; collaborators 500

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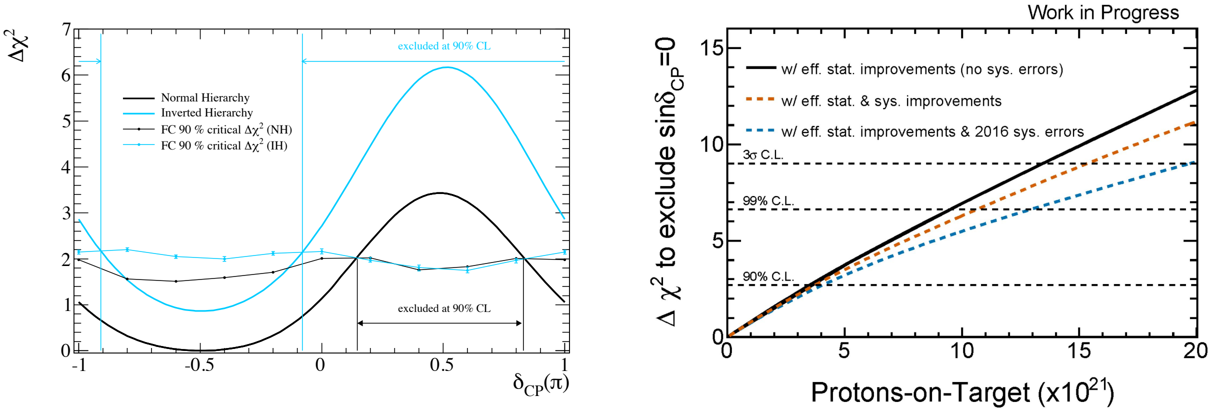

Figure 3: Left panel: Profiled $\Delta\chi^2$ as a function of the CP phase ($\delta_{\rm CP}$) for a fit to T2K ν_e appearance data corresponding to 6.6×10^{20} POT combined with the reactor measurement of θ_{13} (taken from [30]). Right panel: Sensitivity to CP violation as a function of POT with a 50% improvement in the effective statistics, assuming the true the normal mass hierarchy and the true value of $\delta_{\rm CP} = -\pi/2$ and $\sin^2\theta_{23} = 0.50$ for different assumptions of the systematic uncertainties [31].

Brook University, University of California, Irvine, University of Colorado, University of Pittsburgh, University of Rochester, University of Washington (United States).

Future programme

Following the J-PARC Main Ring upgrade, the beam power will be 700 kW in 2018, 800 kW in 2019 and 900 kW in 2020. Assuming these beam-power projections and "five-cycle" operation (one "cycle" is 22–23 days of operation in a month), T2K will achieve the approved number of POT goal by around 2021. The far detector (Super-Kamiokande) will be loaded with gadolinium to enhance the neutrino-tagging capability at a time to be determined. Data-taking must be suspended during the gadolinium-loading procedure. An upgraded near detector is being studied. A second phase of the experiment, aiming at $> 3\sigma$ discovery of CP violation when CP is maximally violated by accumulating $\sim 2 \times 10^{22}$ POT by around 2026 with the beam power reaching 1.3 MW, is under discussion.

2.1.2 NOνA

Physics goals

The NOνA detector is located 810 km from the source of the Main Injector neutrino beam [32]. The off-axis angle of 14 mrad results in a neutrino-energy spectrum peaked at ~ 2 GeV. The collaboration will use the near and far detectors to:

- Maximise sensitivity to the neutrino mass hierarchy;
- Constrain the value of $\delta_{\rm CP}$;
- Resolve the octant of θ_{23} at better than 1.5σ for 80% of all values of $\delta_{\rm CP}$ for either mass hierarchy;
- Achieve world-leading precision on Δm^2_{32} and $\sin^2(\theta_{23})$; and
- Search for oscillations associated with sterile neutrinos.

Using an exposure of 2.74×10^{20} POT the NOνA collaboration has isolated a ν_e appearance signal in the far detector [33]. These events have been used to determine allowed regions in the $\sin^2 2\theta_{13}, \delta_{\rm CP}$ plane (see figure 4). A first measurement of muon-neutrino disappearance has also been made [34]. The sensitivity to the mass hierarchy with the proposed exposure of 36×10^{20} POT is shown in figure 4.

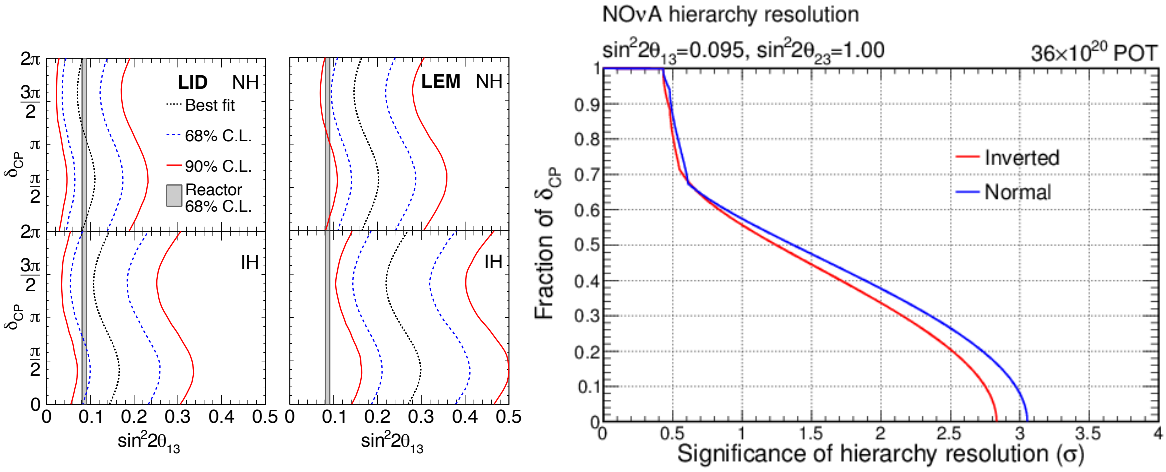

Figure 4: Left panel: Allowed regions in the $\sin^2 2\theta_{13}, \delta_{\mathrm{CP}}$ plane determined using the NOνA detector and an exposure corresponding to 2.74×10^{20} POT; 14 kt-equivalent with $\sin^2(\theta_{23})$ fixed at 0.5 [33]. Right panel: NOνA sensitivity to the mass hierarchy. The fraction of all values of δ_{CP} for which the mass hierarchy can be resolved as a function of sensitivity with with an exposure of $\sim 36 \times 10^{20}$ POT [35].

Institutes 41; collaborators 190

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Future programme

It is anticipated that results from a data set twice the size of that presented in [33, 34] will be available by the summer of 2016. The power delivered by the Main Injector proton beam to the neutrino target will increase to 700 kW during operations in 2016. The exact timetable for increasing the proton-beam power will be determined by the level of losses in the Recycler. It is likely that NOνA will switch to anti-neutrino running in 2017; the precise timetable for the change in polarity will be determined by the evolution of the proton-beam power. An exposure of 36×10^{20} POT is expected to be delivered by US fiscal year 2023.

2.2 Next generation accelerator-based neutrino-oscillation programme

Efforts to deliver the large, high-precision data sets required to observe CP-invariance violation, measure $\delta_{\rm CP}$, determine the mass hierarchy and measure the neutrino-mixing parameters with a precision that significantly exceeds that which will be achieved by T2K and NOνA have coalesced around the Deep Underground Neutrino Experiment (DUNE) served by the FNAL Long Baseline Neutrino Facility (LBNF) and the Hyper-K experiment served by the J-PARC neutrino beam. The physics program at DUNE and Hyper-K also includes neutrino astrophysics and the search for proton decay.

The primary physics goals and projected timescales for the two experiments are similar. The complementarity of the two experiments [13] rests on key differences in the their specification:

Baseline: Hyper-K will be sited 295 km from J-PARC, while DUNE will be located 1300 km from FNAL. With these baselines, the energy at which the first oscillation maximum occurs is different; $\sim$ 600 MeV for Hyper-K and $\sim$ 3 GeV for DUNE; and

Neutrino energy spectrum: Hyper-K will be located at an off-axis angle of 2.5°, yielding a narrow neutrino-energy spectrum peaked at $\sim$ 600 MeV with a high signal-to-background ratio in the critical $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ channel. DUNE will be located on axis so that the beam with which it will be illuminated will have a broad energy spectrum, peaked at $\sim$ 3 GeV, which will allow the second oscillation maximum to be studied.

Matter effects in the long-baseline programme at Hyper-K will be small and neutrino-oscillation effects such as asymmetries in the neutrino and anti-neutrino oscillations will be dominated by "vacuum" effects such as CP-invariance violation. Matter effects will be significant for DUNE, allowing a detailed study of related phenomena and the resolution of the mass hierarchy. The deep underground location of both experiments permits detailed studies of atmospheric neutrinos to be made over a large range of energies and baselines. The study of the atmospheric-neutrino sample is a complementary probe of the oscillation physics.

The Hyper-K and DUNE detectors are each designed to give optimal performance given the beam with which they will be illuminated. Hyper-K will use a water Cherenkov detector since the technique is proven, scaleable and cost effective for the detection of neutrino interactions at $\sim$ 1 GeV where low multiplicity channels such as quasi-elastic and resonant single-pion production dominate. The high granularity and fine tracking capabilities of the liquid-argon time-projection chamber (LAr-TPC) technology used at DUNE will allow the reconstruction of the more complex events resulting from neutrino interactions $\gtrsim 2$ GeV. The two detectors are also complementary in their sensitivity to proton decay and supernova-burst neutrinos. For example, in proton decay, the best sensitivity for many modes is achieved by a large water Cherenkov detector, however, for some key modes such as $p \rightarrow K^+ + \bar{\nu}_\mu$, a LAr-TPC has the potential to deliver nearly background-free samples due to its ability to detect the complete final state. Likewise, in the study of supernova-burst neutrinos, a LAr-TPC will single out ν_e through the process $\nu_e + {}^{40}{\rm Ar} \rightarrow e^- + {}^{40}{\rm K}^*$, while a water Cherenkov detector will primarily observe $\bar{\nu}_e$ through the inverse β decay process on the free protons in the water. A megaton-scale water Cherenkov detector such as Hyper-K also has the potential to extend the reach for observing supernovæ to the Mpc scale, thereby including supernovae in nearby galaxies such as M31 (Andromeda).

2.2.1 Deep Underground Neutrino Experiment

Physics goals/measurement programme

The Deep Underground Neutrino Experiment (DUNE) has successfully completed the "CD1 refresh" required by the DOE "Critical Decision" process. Following a CD3a review in 2015, LBNF has received the authorization to start construction in the US President Budget for FY2017. The headlines of the collaboration's physics programme are [7]:

- CP-invariance violation in neutrino oscillations:
  - Observe CPiV with a significance of $\geq 3\sigma$ for 75% of all values of $\delta_{\rm CP}$ using an exposure of 850 kt $\cdot$ MW $\cdot$ year;
  - Observe CPiV with a significance of $\geq 5\sigma$ for 50% of all values of $\delta_{\rm CP}$ using an exposure of 550 kt $\cdot$ MW $\cdot$ year;
  - Measure $\delta_{\rm CP}$ with a precision better than 10°.
- Determination of the neutrino mass hierarchy:
  - Determine the neutrino mass hierarchy with $\geq 5\sigma$ significance for all values of $\delta_{\rm CP}$ with an exposure of 230 kt $\cdot$ MW $\cdot$ year.
- Precision measurements and tests of the SνM:
  - Measure $\sin^2\theta_{23}$ with a precision of ~ 0.005, assuming $\sin^2\theta_{23} = 0.45$;
  - Determine the θ_{23} octant with a significance of 3σ if $\theta_{23} > 48^\circ$ or $\theta_{23} < 43^\circ$;
  - Measure $\sin^2 2\theta_{13}$ with a precision of ~ 0.003 assuming $\sin^2 2\theta_{13} = 0.085$; and $\sin^2\theta_{23} = 0.45$
  - Measure Δm^2_{31} with a precision of $\sim 0.5 \times 10^{-5}$ eV^2.
- Search for proton decay with zero backgrounds:
  - Provide 90% CL sensitivity to $p \rightarrow K^+ + \bar{\nu}$ and $n \rightarrow K^+ + e^-$ for a nucleon lifetime of $\sim 6 \times 10^{34}$ years in 10 years.
  - Provide 90% CL sensitivities to $p \rightarrow K^0 + e^+$, $p \rightarrow K^0 + \mu^+$ and $n \rightarrow \pi^- + e^+$ for a nucleon lifetime of $\sim 3 \times 10^{34}$ years in 10 years.
- Detection of neutrinos from core-collapse supernovæ:
  - Observe 3–4 thousand neutrino interactions from an intragalactic core-collapse supernova; and
  - Deliver unique sensitivity to ν_es from the core-collapse process, particularly from the neutronisation process.

Figure 5 shows the projected sensitivity for the DUNE experiment as a function of exposure [7]. An exposure of 288 kt·MW·years will be achieved after seven years running, a 40 kt detector and a proton beam-power of 1.2 MW.

Institutes 149; collaborators 848

ABC Federal University, Brazil, APC-Paris, University of Alabama (Tuscaloosa), Federal University of Alfenas, Brasil, Aligarh Muslim University, India, Antananarivo University, Madagascar Argonne National Laboratory, University of Athens, Universidad del Atlantico, Kolumbia, Banaras Hindu University, Bhabha Atomic Research Center, University of Bern, Boston University, Brookhaven National Laboratory Institute of Physics CAS, CERN, Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas (CIEMAT), Center for Nanotechnology Innovation (Pisa), University of California (Berkeley), University of California (Davis), University of California (Irvine), University of California (Los Angeles), California Institute of Technology, University of Cambridge, University de Campinas, University di Catania, Charles University, University of Chicago, University of Cincinnati, CINVESTAV, Mexico, Universidad de Colima, University of Colorado (Boulder) Colorado State University, Columbia University, Cornell University, Czech Technical University (Prague), Dakota State University, University of Delhi, Drexel University, Duke University, University of Durham, University Estadual de Feira de Santana, Brasil, Fermi National Accelerator Laboratory, University Federal de Goias, Gran Sasso Science Institute, Universidad de Guanajuato, Harish-Chandra Research Institute, University of Hawaii, University of Houston, Horia Hulubei National Institute of Physiscs and Nuclear Engineering, University of Hyderabad, IFAE, Barcelona, Illinois Institute of Technology, IIT Bombay, IIT Gowahani, IIT Hyderabad, Institute for Nuclear Research, Institute for Research in Fundamental Sciences (IPM), Idaho State University, Imperial College of Science Tech. & Medicine, Indiana University, Iowa State University, Institute of Nuclear Physics of Lyon (IPNL), University of Jammu, India, University of Jyvaskyla,

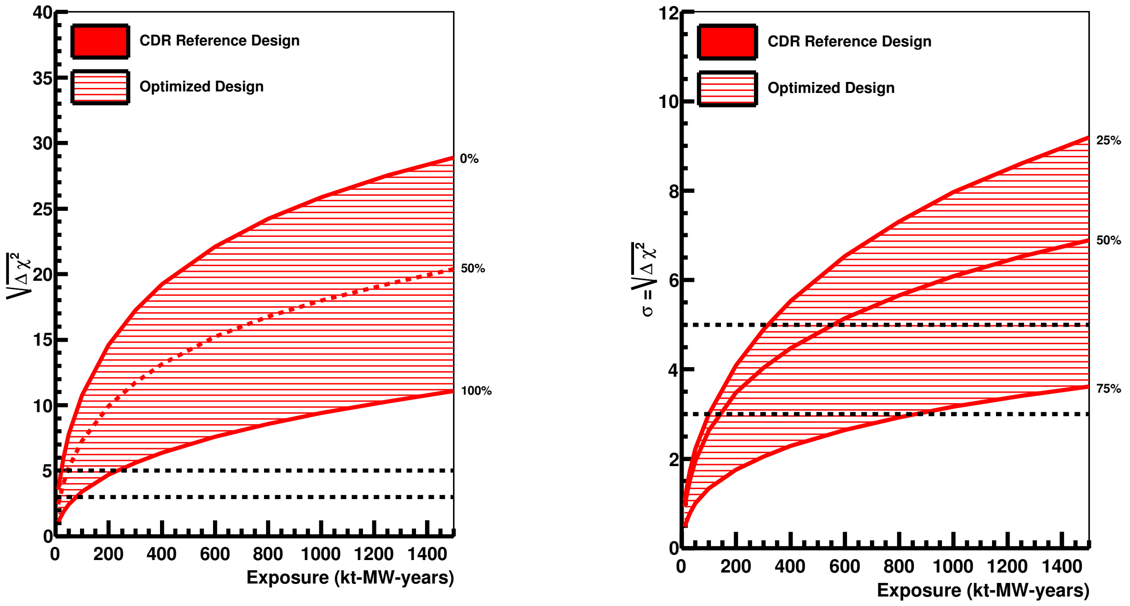

Figure 5: Left panel: DUNE sensitivity to the mass hierarchy: the minimum significance with which the mass hierarchy can be determined is plotted as a function of exposure for all values of the CP phase (δ_{CP} (100%), 50% and in the most optimistic scenario of maximum CPiV (0%). Right panel: DUNE sensitivity to CPiV: assuming the normal mass hierarchy, the minimum significance with which CP violation can be determined for 25%, 50% and 75% of all values of δ_{CP} is plotted as a function of exposure. In each plot, the results projected for the optimised design of the LBNF neutrino beam are presented. Taken from [7].

KTH Royal Institute of Technology, Kansas State University, Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, High Energy Accelerator Research Organization (KEK) Kyiv National University, Koneru Lakshmaiah Education Foundation, India, Jagiellonian University (Cracow), Annecy-le-Vieux Particle Physics Laboratory, Laboratori Nazionali del Gran Sasso, Lancaster University, Lawrence Berkeley National Laboratory, University of Liege, University of Liverpool, University College London, Los Alamos National Laboratory, Louisiana State University, University of Lucknow, India, Madrid Autonoma University, University of Manchester, University of Maryland, Massachusetts Institute of Technology, University of Puerto Rico, Michigan State University, University di Milano, INFN Milano, INFN Milano Bicocca, University of Minnesota (Twin Cities), University of Minnesota (Duluth), NIKHEF, INFN Napoli, National Centre for Nuclear Research, Jawaharlal Nehru University, University of New Mexico, Northern Illinois University, Northwestern University, University of Notre Dame, Observatorio Nacional, Ohio State University, Oregon State Univ, University of Oxford, Pacific Northwest National Laboratory, Pennsylvania State Univ, PUCP, INFN Padova, Panjab University, University of Pavia, INFN Pavia, University of Pennsylvania, University di Pisa, University of Pittsburgh, Princeton University, Punjab Agricultural University, University of Rochester, SLAC National Accelerator Laboratory, STFC Rutherford Appleton Laboratory, CEA/Saclay, IPhT, Institute de Physique Theorique, University of Sheffield, University of Sofia, University of South Carolina, University of South Dakota, South Dakota School of Mines and Technology, South Dakota Science and Technology Authority, South Dakota State University, Southern Methodist University (Dallas), Stony Brook University, University of Sussex, Syracuse University, University of Tennessee, University of Texas (Arlington), University of Texas (Austin), TUBITAK Space Technologies Research Institute, Tufts University, Variable Energy Cyclotron Center, Instituto de Fisica Corpuscular (IFIC, Valencia), Virginia Tech, University of Warsaw, University of Warwick, Wichita State University, College of William & Mary, University of Wisconsin, Wrocław University, Yale University, Yerevan Institute for Theoretical Physics and Modeling, York University, ETH Zürich

Future programme

Following the successful "CD1 refresh", the principal milestones of the project are:

- Construction and operation of ProtoDUNE detectors at CERN (2016-2018);
- Excavation of detector caverns at SURF (2017-2021);
- Construction of first two 10 kt far detector modules (2022-2025);
- Fill and commission first two far detector modules (2024-2026);
- Install two more 10 kt far detector modules (2024-2027);
- Fill and commission additional far detector modules (2026-2027);
- Beam line complete (2026);
- Near detector complete (2026); and
- Project early completion in 2027; DOE CD4 (with 40 months contigency) in 2030.

2.2.2 Hyper-Kamiokande

Physics goals/measurement programme

An international proto-collaboration has been formed to carry out the Hyper-K experiment. The Institute for Cosmic Ray Research of the University of Tokyo (UTokyo-ICRR) and the Institute of Particle and Nuclear Studies of the High Energy Accelerator Research Organization (KEK-IPNS) have signed an MoU affirming cooperation in the Hyper-K project to review and develop the program in its comprehensive aspects. The Japanese High-Energy-Physics community sets Hyper-K and ILC as its top two projects. The Japanese Cosmic Ray Community (CRC) also sets Hyper-K as one of top priority projects and recognises Hyper-K as the next CRC very large project after the current KAGRA construction completes. It has also been selected as one of 27 high priority projects among 207 large-scale projects by Science Council of Japan in "Master plan 2014."

Hyper-K is a large underground water Cherenkov detector. The group has succeeded in developing new 50-cm PMTs with double single-photon-sensitivity and has re-optimised the detector configuration. The Hyper-K is built in 2 cylindrical tanks with the dimension of 60 m depth and 74 m diameter corresponding to 187 kt $\times 2 = 374$ kt fiducial volume with about 80,000 50-cm PMTs giving 40% photo cathode coverage. The proto-collaboration is aiming to realise the 2 tanks in staging with the possible schedule of starting the 2nd tank operation 6 years after the start of the 1st tank.

The headlines of the Hyper-K physics programme are updated from [11, 12]:

- CP violation in neutrino oscillations:
  - Observe CPiV with a significance of $\geq 3\sigma$ for 78% of all values of $\delta_{\rm CP}$ by 10 years or an exposure of $1.3\,{\rm MW} \times (0.187\,{\rm Mt} \times 6 \cdot 10^7\,{\rm sec} + 0.374\,{\rm Mt} \times 4 \cdot 10^7\,{\rm sec})$;
  - Observe CPiV with a significance of $\geq 5\sigma$ for 62% of all values of $\delta_{\rm CP}$ by 10 years; and
  - Measure $\delta_{\rm CP}$ with a precision of 7° (21°) precision for $\delta_{\rm CP} = 0°$ (90°).
- Determination of the neutrino mass hierarchy:
  - Determine the neutrino mass hierarchy with $> 3\sigma$ significance after 4 years by combination of atmospheric neutrinos and beam data.
- Precision measurements and tests of the SνM:
  - Determine the θ_{23} octant with a significance of >3σ if $\theta_{23} > 49°$ or $\theta_{23} < 41°$;
  - Measure $\sin^2\theta_{23}$ with a precision of ± 0.015 assuming that $\sin^2\theta_{23} = 0.5$; and
  - Measure Δm^2_{32} with a precision of up to $\sim 1.4 \times 10^{-5}\,{\rm eV}^2$.
- Search for proton decay in various decay modes:

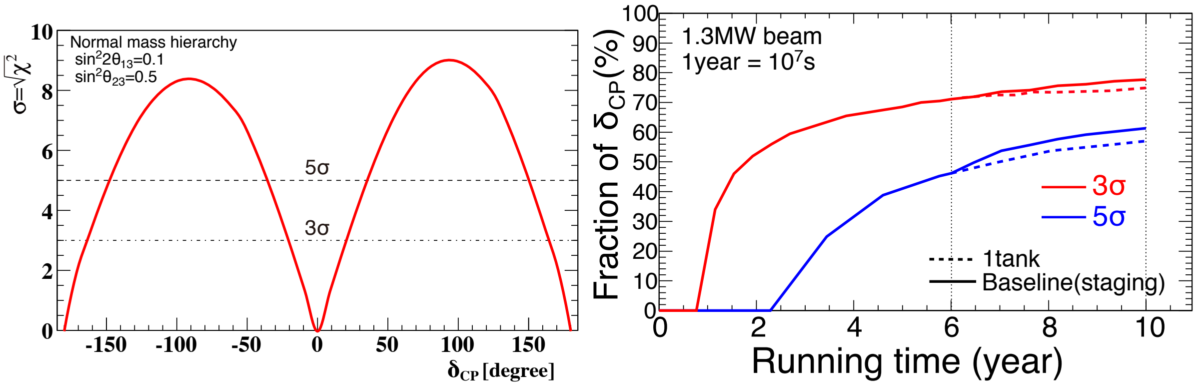

Figure 6: Left panel: Expected significance to exclude $\sin\delta_{\text{CP}} = 0$ for the case of the normal mass hierarchy and assuming 10 years running. Right panel: fraction of all values of the CPiV phase, δ_{CP}, for which $\delta_{\text{CP}} = 0, \pi$ can be excluded at 3σ (red) or 5σ (blue). An exposure of 13 MW $\times\, 10^7$ s is expected to be achieved after 10 years of operation.

  - Provide 90% CL sensitivity to $p \to e^+ + \pi^0$, a dominant channel in a number of modern grand unified theories, for a proton lifetime of 1×10^{35} years; and
  - Provide 90% CL sensitivity to $p \to K^+ + \bar{\nu}$, a key channel in grand unifies theories that include supersymmetry, for a proton lifetime of up to 3×10^{34} years.
- Detection of Solar neutrinos:
  - Record a data set corresponding to $>$250 ^{8}B ν's per day with 2 tanks;
  - Measurement of the day/night flux difference with a precision of 1% with 1 year data;
  - Make a first measurement of hep neutrinos; and
  - Provide unique, high-precision measurements of Δm^2_{21} and $\sin^2\theta_{12}$ using neutrinos (rather than anti-neutrinos).
- Detection of neutrinos from core-collapse supernovae:
  - Observe $\sim 130,000$ ($\sim$ 26) neutrinos with 2 tanks from an intragalactic (Andromeda) core-collapse supernova;
  - Observe 100 supernova relic neutrinos in 10 years with non-zero significance of 4.8σ.

Figure 6 shows the projected sensitivity for the Hyper-K experiment which is updated from [12]. An exposure of 13 MW $\times\, 10^7$ s will be achieved after ten years assuming 1:3 ratio between neutrino and anti-neutrino running time, one or two 187 kt detector(s) and a proton beam-power of 1.3 MW at 30 GeV.

Institutes 70; collaborators 277 (including interested members)

Boston University, University of British Columbia, University of California (Davis), University of California (Irvine), California State University, Institute of Research into the Fundamental Laws of the Universe, CEA Saclay, Chonnam National University, Dongshin University, Duke University, Ecole Polytechnique, IN2P3-CNRS, University of Edinburgh, University of Geneva, University of Hawaii, Imperial College London, INFN Bari, Bari University, Politecnico di Bari, INFN Napoli, Napoli University, INFN Padova, Padova University, INFN Roma, Institute for Nuclear Research of the Russian Academy of Sciences, Iowa State University, High Energy Accelerator Research Organization (KEK), Kobe University, Kyoto University, Laboratori Nazionali di Frascati, Lancaster University, University of Liverpool, Los Alamos National Laboratory, Louisiana State University, University Autonoma Madrid, Michigan State University, Miyagi University of Education, Nagoya University, Nagoya University, Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya

University, Institute for Space-Earth Environmental Research, National Centre for Nuclear Research, Okayama University, Osaka City University, Oxford University, University of Pittsburgh, University of Regina, Pontificia Universidade Catolica do Rio de Janeiro, University of Rochester, Queen Mary University of London, Royal Holloway University of London, Universidade de Sao Paulo, University of Sheffield, Seoul National University, Seoyeong University, Stony Brook University, STFC Rutherford Appleton Laboratory, Sungkyunkwan University, South Korea, Research Center for Neutrino Science, Tohoku University, University of Tokyo, Earthquake Research Institute, University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory, University of Tokyo, Institute for Cosmic Ray Research, Pennsylvania State University, Research Center for Cosmic Neutrinos, University of Tokyo, Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, Tokyo Institute of Technology, TRIUMF, University of Toronto, University of Warsaw, University of Warwick, University of Washington, University of Winnipeg, Virginia Tech, Wrocław University, Wrocław University of Technology, Yerevan Physics Institute, York University

Next steps
The next steps in the Hyper-K approval process is a review by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2017. Assuming this review to be successful, the principal project milestones include:

- Construction of far detector Hyper-Kamiokande (2018-2025); and
- Start data taking (2026).

2.3 Future opportunities

2.3.1 Neutrino Factory

Physics goals
The Neutrino Factory, in which a broad-band neutrino beam is produced from the decay of muons confined within a storage ring, has been shown to offer unparalleled performance in terms of its sensitivity to CPiV and the precision with which it can be used to measure parameters of the SνM [36–39]. This exquisite performance results from the large flux of $\overset{(-)}{\nu}_e$ combined with the precise knowledge of the neutrino-beam flux and energy spectrum. Once sufficient muons have been transported to the muon-acceleration system, the stored-muon energy can be tuned to optimise the physics reach and in response to constraints imposed by detector technology and source-detector distance.

The scientific potential of the facility may be summarised as follows [36–39]:

- CP violation in neutrino oscillations:
  - Observe CPiV with $\gtrsim 5\sigma$ ($\gtrsim 3\sigma$) significance for 80% (90%) of all $\delta_{\rm CP}$ values with a ten-year exposure of a 100 kt magnetised iron detector and a flux corresponding to 10^{21} muon decays per year; and
  - Measure $\delta_{\rm CP}$ with $\lesssim 5^\circ$ precision.
- Precision measurements and tests of the three-flavour neutrino oscillation paradigm:
  - Resolve the θ_{23} octant with a sensitivity of 2σ if $\theta_{23} > 48^\circ$ or $\theta_{23} < 43^\circ$;
  - Measure θ_{13} with precision of 1.5% assuming $\theta_{13} = 9^\circ$; and
  - Measure Δm^2_{31} with a precision of 0.5%.

In addition, the large electron- and muon-neutrino flux at the near detector, the flux of which may be determined precisely by the instrumentation of the storage ring, may be used to carry out a definitive neutrino-nucleus scattering programme and search for physics beyond the SνM.

Institutes 46

Harish-Chandra Research Institute, Brookhaven National Laboratory, Brunel University (London), CERN, Institute of Mathematical Sciences (Tamil Nadu), India, Institute for Particle Physics Phenomenology (Durham), Fermi National Accelerator Laboratory, University of Geneva, University of Glasgow, Max Planck Institute for Nuclear Physics (Heidelberg), Imperial College London, Thomas Jefferson National Laboratory, Saha Institute of Nuclear Physics (Kolkata), Kyoto University, Research Reactor Institute (Osaka), Lawrence Berkeley National Laboratory, University of California (Los Angeles), Universidad Autonoma de Madrid, Michigan State University, INFN Milano Bicocca, University of Mississippi, Institute for Nuclear Research of Russian Academy of Sciences, Tata Institute of Fundamental Research, Max Planck Institute for Physics (Munich), Muons Inc., Napoli University, Northwestern University, Illinois Institute of Technology, Oak Ridge National Laboratory, Osaka University, Oxford University, Padova University, INFN Padova, Princeton University, University of California (Riverside), INFN Roma Tre, STFC Rutherford Appleton Laboratory, University of Sheffield, University of Sofia, Stony Brook University, University of South Carolina, IPHC, University of Strasbourg, Toyko Metropolitan University, Instituto de Fisica Corpuscular (IFIC, Valencia), Centro Mixto CSIC-UVEG, Virginia Tech, University of Warwick, University of Würzburg

Next steps

A number of feasibility studies of the Neutrino Factory have been completed [37–44]. The staged implementation of the Neutrino Factory has been studied by the International Design Study (IDS-NF) for the Neutrino and in the Muon Accelerator Staging Study (MASS) that was carried out within the US Muon Accelerator Program (MAP) [45]. Work on the necessary high-power, pulsed proton beams is underway at CERN, FNAL, J-PARC and RAL; FNAL and J-PARC. The MERIT experiment [46] at CERN demonstrated the principle of the mercury-jet target, while the EMMA accelerator [47, 48] at the Daresbury Laboratory demonstrated the principle of the non-scaling Fixed Field Alternating Gradient (FFAG) technique. The remaining system demonstration is the proof-of-the principle of the ionization cooling technique. This is being carried out by the international Muon Ionization Cooling Experiment (MICE) collaboration [49] at the STFC Rutherford Appleton Laboratory for which further details are provided in section 4.4.

The Neutrino Factory offers the potential to deliver sensitivity and precision beyond those offered by the next generation of experiments (DUNE and Hyper-K). The successful demonstration of ionization cooling with MICE will complete the proof-of-principal, system-level R&D for the accelerator facility. The construction of a muon storage ring to serve a neutrino-cross-section-measurement and, perhaps, a sterile-neutrino-search, programme is would demonstrate that muon beams can serve a front-rank neutrino programme, to gain experience with the operation of such facilities and to build the user community necessary to mount the Neutrino Factory programme.

2.3.2 DAEδALUS

Physics goals/measurement programme

DAEδALUS [50–55] will use three high-power proton cyclotrons to generate neutrino beams from pion decay-at-rest. It is proposed to place the cyclotrons at baselines of 1.5 km, 8 km and 20 km from a large liquid-scintillator or gadolinium-doped water Cherenkov. The staged implementation of the programme has been considered. The goals of the programme are to:

- Measure δ_{CP} with a precision of $5 - 10^{\circ}$ using the spectrum of $\bar{\nu}_e$ events generated by the transition $\bar{\nu}_\mu \to \bar{\nu}_e$; and
- At an intermediate (IsoDAR [56]) stage, search for sterile neutrino oscillations using ν_e from ^{8}Li decays at rest and a large scintillator detector ~ 16 meters away.

Institutes 36
Amherst College, Argonne National Laboratory, Bartoszek Engineering, Black Hills State University, University of California, Sicilian Center of Nuclear Physics and Physics of Matter, The Cockcroft Institute for Accelerator Science & the University of Manchester, Columbia University, Duke University, Harvard University, IBA Research, Imperial College London, Instituto De Fisica Nucleare, Iowa State University, Kavli Institute for the Physics and Mathematics of the Universe, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Massachusetts Institute of Technology, Michigan State University, New Mexico State University, North Carolina State University, Northwestern University, Paul Scherrer Institut, RIKEN, Japan, University of South Carolina, Tahoku University, Texas Agricultural and Mechanical University, University of California (Los Angeles), University of Chicago, University of Huddersfield, University of Maryland, University of Wisconsin (Madison) University of Tennessee, University of Texas, University of Tokyo, Wellesley College.

Next steps
The next steps in the development of the DAEδALUS programme are the:

- Development of an ion source using H_2^+ ions to reduce space charge effects;
- Development of a ^{8}Li source using H_2^+ on a ^{8}Be target surrounded by a ^{7}Li sleeve. This will be used to produce a low energy, β decay-at-rest beam to study sterile neutrinos with a large liquid scintillator-detector; and
- Construction of a superconducting 800 MeV cyclotron and target and beam dump systems at a near site, followed by two more cyclotrons at medium and long baseline.

2.3.3 ESSnuSB

Physics goals
It is proposed to upgrade the ESS linac to deliver an average power of 10 MW to be shared between neutrino and neutron production [57]. The neutrino beam would illuminate a megaton-scale underground water-Cherenkov detector located at the second oscillation maximum where the effect of CPiV is approximately three times larger than at the first oscillation maximum. Assuming a ten-year exposure with two-years running time in neutrino mode and eight-years in anti-neutrino mode, the goals of the programme are to:

- Search for CPiV with a significance of 5σ over more than 50% of all values of δ_{CP} values; and
- Perform a non-accelerator programme including, for example, the study of neutrinos from supernovæ, the search for proton decay etc.

Institutes 13
IHEP (Beijing), Virginia Tech, STFC Rutherford Appleton Laboratory, CERN, University of Science and Technology (Cracow), Lund University, European Spallation Source, Universidad Autonoma de Madrid, INFN Padova, Ohridski University of Sofia, Bulgaria, KTH Royal Instittue of Technology (Stockholm), Université de Strasbourg, Uppsala University.

Next steps
The next steps in the development of the ESSnuSB concept are the:

- Design of an accumulator ring to reduce bunch lengths from 2.86 ms to 1.5 μsec to support horn focusing and the design of modifications of the LINAC to upgrade its average power form 5 MW to 10 MW by increasing the repetition frequency from 14 Hz to 28 Hz and to support H^--ion acceleration, interleaved with the ESS proton beam, in order to facilitate injection of protons in the presence of protons already circulating in the ring;
- Development of a four target/horn system to spread the full beam power such that 1.25 MW of power impinges on each;
- Design of a system for the extraction of muons produced alonside the neutrinos in pion decay to serve a Neutrino Factory or Muon Collider; and
- Identification and evaluation of a suitable underground site for a large water Cherenkov detector. Surveys at the Garpenberg mine 540 km are under way.

2.4 Interim conclusions and recommendations

2.1: The present accelerator-based long-baseline neutrino-oscillation programme is vibrant and has substantial discovery potential.

Recommendation 2.1: Full exploitation of the present generation of experiments should continue thereby maximising their discovery potential and the scientific return on historical investment.

2.2: The measurements that will be made by the DUNE and the Hyper-K collaborations are complementary and the combination of the data from the two experiments offers the potential for insights beyond those that either experiment can provide on its own.

Recommendation 2.2: Both the DUNE and the Hyper-K programmes should be pursued through the established approval and funding processes.

2.3: The sensitivity of long-baseline neutrino-oscillation experiments may be enhanced by including events at the second oscillation maximum. DUNE may exploit the second oscillation maximum since the LBNF broad-band beam will provide an interesting flux at the relevant energy. The baseline of Hyper-K places the relevant energy significantly below the peak of the J-PARC narrow-band beam making it harder for Hyper-K to profit from the second oscillation maximum. ESSnuSB has been optimised for the study of the second oscillation maximum thereby maximising its sensitivity to CP-invariance violation.

Recommendation 2.3: The timeliness of the ESSnuSB proposal should be considered in the light of the likely timescales and performance of the DUNE programme and, if approved, the Hyper-K programme.

2.4: The focus of the long-baseline neutrino community has recently been on establishing DUNE and proposing Hyper-K. If the science demands a further program with a performance that substantially exceeds that of the ambitious DUNE and Hyper-K experiments, new accelerator and/or detector technologies will be required. An R&D program will be needed to deliver feasible options at the appropriate time. This R&D is likely to take many years and needs to be well justified and carefully planned.

Recommendation 2.4: ICFA should encourage a process, informed by the neutrino community, to assess the scientific case for a long-term accelerator and/or detector R&D programme aimed at the post-DUNE/Hyper-K era as a first step in defining the R&D programme that is required. Assessment of the scientific case will require sustained activity in neutrino theory and phenomenology including significant developments in the understanding of neutrino-nucleus scattering.

Recommendation 2.5: The forum provided by the series of International Meetings for Large Neutrino Infrastructures is invaluable to ensure the coherent development of the global programme and should be continued with a strong accelerator-based component.

3 Sterile neutrino searches at accelerators

Three-flavour mixing provides a simple and elegant framework for understanding the phenomenology of neutrino oscillations. Most of the current oscillation measurements can be described within this framework, enabling a self-consistent set of oscillation parameters to be extracted from global fits to the data. However, the measurements are not yet sufficient to provide a stringent and comprehensive test of the framework. Indeed, there are a number of measurements that, if interpreted as resulting from neutrino oscillations, cannot be accommodated within the three-flavour framework. The resolution of these "neutrino anomalies" is an important part of the future neutrino programme, one that will test the three-flavour-mixing framework with reasonable precision. Possible extensions to the framework involve the addition of non-standard interactions and/or the addition of neutrino states beyond the three known flavours. The intermediate vector bosons do not decay into these states, therefore, if the additional states are light, they must also be "sterile", in the sense that they have no electroweak couplings. The search for sterile neutrinos is, perhaps, the primary way of testing the three-flavour-mixing framework and of attempting to resolve neutrino anomalies.

Deviations from three-flavour mixing (neutrino anomalies) have been reported from accelerator-based, reactor-based, and radioactive-source-based measurements [58–64]. Individually, these tensions with three-flavour mixing, which are at the level of two- to four-standard-deviations, do not provide definitive evidence of new physics. Some, or all, of the anomalies may be due to statistical fluctuations and/or systematic effects that have not been taken into account. Taken together, the anomalies suggest new neutrino-flavour transitions with a frequency characterised by $L/E \sim 1$ m/MeV, but the evidence is inconclusive. This L/E corresponds to a $\Delta m^2 \sim 1\,\text{eV}^2$ which is much larger than the two Δm^2s determined from the three-flavour-mixing measurements. The anomalies are intriguing and persistent enough to warrant definitive investigation.

The accelerator-based neutrino anomalies come from the LSND [59] and MiniBooNE [60, 64] experiments, which provide evidence for the appearance of $\nu_e(\overline{\nu}_e)$ in a $\nu_\mu(\overline{\nu}_\mu)$ beam with $L/E \sim 1$ m/MeV. These experiments, however, could not distinguish between electrons and photons and therefore could not establish definitively the phenomenon as due to neutrino-flavour transitions.

The next steps in the accelerator-based sterile-neutrino-search program are well under way. MINOS+ is expected to complete its data taking at FNAL this year, measuring the time-dependent oscillation probabilities over a long-baseline at energies that correspond to oscillation times away from the three-flavour-mixing oscillation maxima [65]. This enables the MINOS+ collaboration to search for small deviations from expectations that could be attributed to additional oscillations characterised by as yet unobserved values of Δm^2. In addition, a new liquid-argon TPC, MicroBooNE, has just begun taking data at FNAL [66]. Within a few years, MicroBooNE will be capable of confirming (or otherwise) the MiniBooNE anomaly and distinguishing between a ν_e-appearance or photon-appearance interpretation of the phenomenon. In 2018, MicroBooNE will be complemented with new near (SBND) and far (ICARUS) liquid-argon TPCs to make the three-detector SBN program setup [67] that, after a few years of data taking, is expected to provide definitive resolutions of the LSND and MiniBooNE observations. These timeliness suggest that around 2020 a decision could be made about the need for further accelerator-based short-baseline experiments beyond those in the presently foreseen program.

3.1 Present accelerator-based sterile-neutrino searches

3.1.1 MINOS+

Physics goals
The "NuMI" neutrino beam from the FNAL Main Injector has been tuned to deliver a wide-band beam on axis to the MINOS near and far detectors. The neutrino energy spectrum (see figure 7) spans the range 2 GeV to

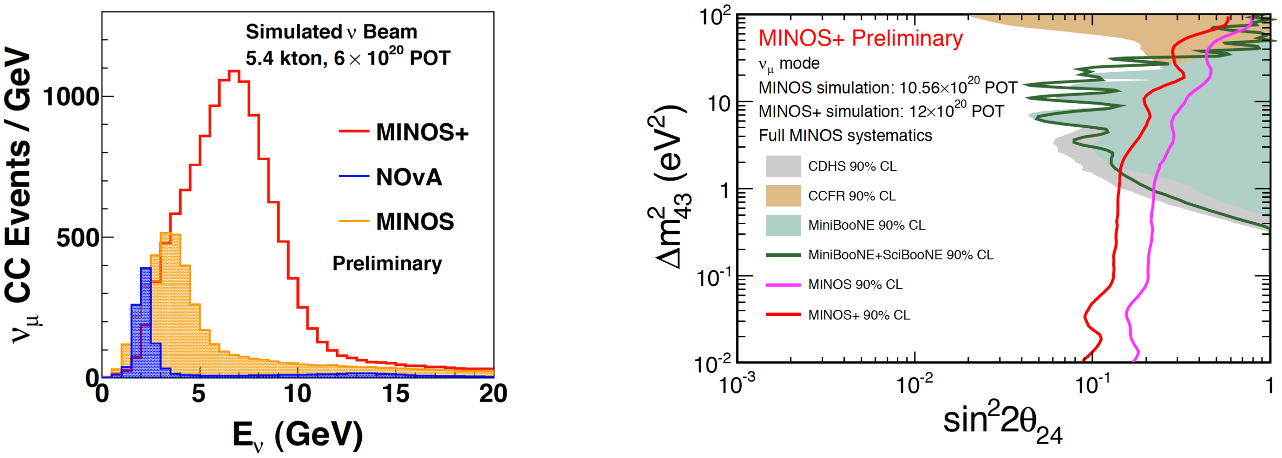

Figure 7: Left panel: The NuMI neutrino energy spectrum for the MINOS+ medium-energy tune, shown as the red solid line. For comparison, the NOνA spectrum is shown as the blue shaded histogram and the low-energy tune used by MINOS is shown as the gold histogram. Right panel: MINOS+ reach in probing ν_μ disappearance into sterile neutrinos for NuMI neutrino running (red solid line). The MINOS+ sensitivity is compared to that of CDHS (grey shaded region), CCFR (orange shaded region) and MiniBooNE (green shaded region). A recent, preliminary limit provided by MINOS is shown as the solid purple line.

15 GeV and an exposure corresponding to $\sim 10^{21}$ POT will be delivered by the end of US fiscal year 2016 (September 2016). The goals of the MINOS+ programme are to [65]:

- Enhance understanding of the SνM scheme and constrain or discover new phenomena that go beyond it.
- Search for sterile neutrinos using muon-neutrino disappearance and electron-neutrino appearance; and
- Search for non-standard interactions and exotic phenomena such as large extra dimensions.

Figure 7 (right panel) shows the projected sensitivity of the experiment to a single sterile neutrino with an effective mixing angle θ_{24} and mass-squared splitting Δm^2_{42}.

Institutes 30; collaborators 50

BNL, Caltech, University of Cambridge, University of Cincinnati, Federal University of Goias, Fermi National Accelerator Laboratory, Harvard University, University of Houston, Iowa State, Lancaster University, Los Alamos National Laboratory, University College London, University of Manchester, University of Minnesota (Twin-Cities), University of Minnesota (Duluth), Otterbein University, University of Oxford, University of Pittsburgh, University of South Carolina, Stanford University, University of Sussex, University of Texas at Austin, Tufts University, University of Campinas, University of Sao Paulo, University of Warsaw, College of William & Mary

Future programme

MINOS+ will run through to the end of US fiscal year 2016 and it is anticipated that all data analyses will be completed within a year after the last run. In the meantime, MINOS+ will be releasing results based on a partial data set.

3.1.2 MicroBooNE

Physics goals

MicroBooNE is a 170 t liquid-argon TPC located 470 m from the source of the FNAL Booster Neutrino Beam [66]. The detector will be operated for three years on its own and then continue as the intermediate detector in the Short Baseline Neutrino programme (see below) [67]. In standalone operation, MicroBooNE will integrate an exposure corresponding to $\approx 6.6 \times 10^{20}$ POT. The principal goals of the collaboration are to:

- Investigate the currently-unexplained excess of low-energy electromagnetic events observed by MiniBooNE;
- Measure neutrino cross sections on argon for multiple reaction channels; and
- Advance the development of the liquid-argon TPC technology towards the realisation of the future short- and long-baseline neutrino programs.

Institutes 25; collaborators 161

University of Bern, Brookhaven National Laboratory, University of Cambridge, University of Chicago, University of Cincinnati, Columbia University, Fermi National Accelerator Laboratory, Illinois Institute of Technology, Kansas State University, Lancaster University, Los Alamos National Laboratory, University of Manchester, Massachusetts Institute of Technology, University of Michigan (Ann Arbor), New Mexico State University, Oregon State University, Otterbein University, University of Oxford, Pacific Northwest National Laboratory, University of Pittsburgh, Princeton University, Saint Mary's University of Minnesota, SLAC, Syracuse University, Virginia Tech, Yale University

Future programme

The cross-section measurements that MicroBooNE will make are reported in section 4.2. The principal goal of the sterile-neutrino search programme is to:

- Determine the source of the MiniBooNE low-energy excess with a statistical significance $> 5\sigma$ if it arises due to a source of electrons and with a statistical significance $> 4\sigma$ if it arises due to a source of photons. These sensitivities assume 6.6×10^{20} protons on target.

The achievement of the exploitation milestones depends on the rate of beam delivery to the Booster Neutrino Beam. To complete the low-energy analysis will require the full POT request, 6.6×10^{20} protons on target. It is anticipated that the full data set needed for this analysis will be delivered by mid-to-late 2018, allowing the low-energy-analysis results to be presented in 2019.

First neutrino cross-section results will be prepared using the first year's data set (it is expected that 2×10^{20} POT will have been delivered by summer 2016). In particular, the collaboration is actively working on charged current (CC) inclusive, CC 0π, and neutral current π^0 analyses. By summer 2016, the statistics of the MicroBooNE data set will have exceeded that of ArgoNeuT.

3.2 Next-generation accelerator-based sterile-neutrino searches

3.2.1 Short Baseline Neutrino (SBN) programme

Physics goals

The Short Baseline Neutrino (SBN) Program [67] will exploit the Booster Neutrino Beam (BNB) at FNAL by continuing MicroBooNE running beyond its initial 3 years, and complement the 170 t MicroBooNE detector at a baseline of 470 m by adding a new 220 t LAr-TPC detector (Short Baseline Near Detector - SBND) at a baseline of 110 m and installing a refurbished 760 t ICARUS-T600 detector at a baseline of 600 m. Thus the

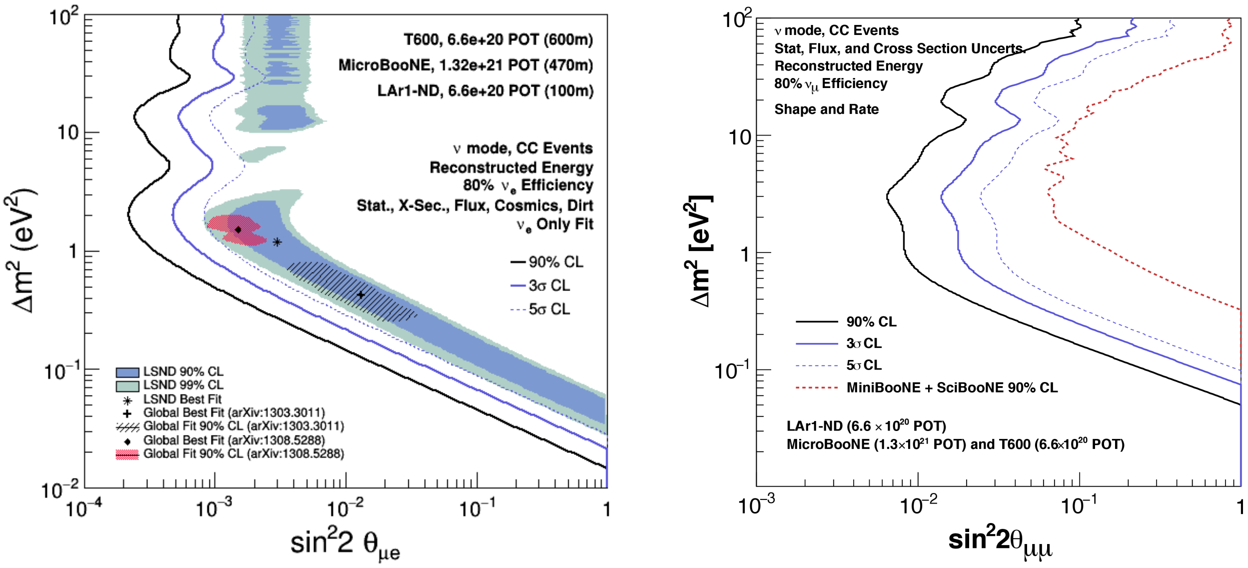

Figure 8: Left panel: SBN Program to sensitivity to $\nu_\mu \to \nu_e$ oscillations. The regions of parameter space allowed by LSND and two global fits are also shown as the shaded bands. Right panel: SBN Program sensitivity to ν_μ disappearance. The exclusion limit derived from the MiniBooNE and SciBooNE data are also shown. Figures taken from [67].

SBN setup will have near, intermediate, and far detectors, all of them based on liquid-argon TPCs. The SBN Program is designed to deliver a programme that includes the resolution of the experimental anomalies in short-baseline neutrino physics and the most sensitive search to date for sterile neutrinos at the eV mass-scale through both appearance and disappearance oscillation channels (see figure 8). In addition the SBN Program includes the study of neutrino-argon cross sections with millions of interactions using the well-characterised neutrino fluxes of the BNB. The SBN detectors will also record events from the off-axis flux of the NuMI neutrino beam with its higher electron neutrino content and different energy spectrum.

SBND institutes 30; collaborators 138

Argonne National Laboratory, University of Bern, Brookhaven National Laboratory, University of Cambridge, University of Campinas, CERN, University of Chicago, Columbia University, Federal University of ABC, Federal University of Alfenas, Fermi National Accelerator Laboratory, Illinois Institute of Technology, Indiana University (Bloomington), Kansas State University, Lancaster University, University of Liverpool, Los Alamos National Laboratory, University of Manchester, University of Michigan, Massachusetts Institute of Technology, University of Oxford, Pacific Northwest National Laboratory, University of Pennsylvania, University of Puerto Rico, University of Sheffield, Syracuse University, University of Texas Arlington, University College London, Virginia Tech, Yale University

MicroBooNE institutes

As listed above.

ICARUS institutes 20; collaborators 56

CERN, Catania University, INFN Catania, Pavia University, INFN Pavia, Padova University, INFN Padova, Gran Sasso Science Institute, Italy, Laboratori Nazionali di Gran Sasso, Italy, Institute of Nuclear Physics (Cracow), Laboratori Nazionali di Frascati (Roma), Laboratori Nazionali del Gran Sasso, Italy, INFN Milano

Bicocca, INFN Milano, INFN Napoli, Institute for Nuclear Research of the Russian Academy of Sciences (Moscow), University of Silesia (Katowice) Poland, Wrocław University, Poland, Argonne National Laboratory, Colorado State University, Los Alamos National Laboratory, Fermi National Accelerator Laboratory, University of Pittsburgh, SLAC

Future programme

Preparations for the SBN program are under way with civil construction ongoing and the refurbishment of the ICARUS-T600 detector proceeding along with the design and construction of the new SBND detector. The projected start of data taking in the SBN era is 2018. The Program is approved for an exposure of 6×10^{20} POT on top of the 6×10^{20} POT to be accumulated by MicroBooNE in the pre-SBN-era. These data sets will enable a search for $\nu_\mu \to \nu_e$ appearance with a 5σ sensitivity covering the full LSND-allowed region and the search for anomalies in the disappearance modes both for $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$.

3.2.2 JSNS^2

Physics goals/measurement programme

The JSNS^2 experiment aims to search for the existence of neutrino oscillations with Δm^2 near 1 eV^2 at the J-PARC Materials and Life Science Experimental Facility (MLF). An intense neutrino beam from muon decay at rest is available from the 1 MW, 3 GeV proton beam from the J-PARC Rapid Cycling Synchrotron striking the spallation-neutron target. The neutrinos come predominantly from μ^+ decay, $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$, which allows the search for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions through the detection of the inverse β-decay reaction, $\bar{\nu}_e + p \to e^+ + n$ and the photons subsequently produced through neutron capture on gadolinium in the 50 t fiducial mass of two liquid-scintillator detectors located 24 m away from the mercury target. A cross-section measurement programme will also be carried out using neutrinos with energies of a few times 10 MeV.

Institutes 12; collaborators 31

University of Alabama, Brookhaven National Laboratory, Colorado State University, University of Florida, JAEA, High Energy Accelerator Research Organization (KEK), University of Kyoto, Los Alamos National Laboratory, University of Michigan, University of Osaka, Research Center for Nuclear Physics, University of Tohoku (RCNS)

Future programme

The background rate and energy response have been measured using a 500 kg prototype plastic-scintillator detector. Stage 1 approval was granted by the J-PARC PAC in 2015 based on these measurements. The next steps in the development of the programme are:

- The completion of a Technical Design Report (TDR) that will be used to seek approval to start construction of the experiment from the J-PARC PAC. The TDR will be completed within the next 1.5 years.
- Following approval, construct the detector within a further 1.5 years and start the experiment.

3.3 Future opportunities for accelerator-based sterile-neutrino searches

3.3.1 IsoDAR

Physics goals

IsoDAR is an isotope decay-at-rest experiment that had been proposed as the first stage of a phased Decay-At-rest Experiment for δ_{CP} studies (DAEδALUS) that would ultimately search for evidence of CP-invariance

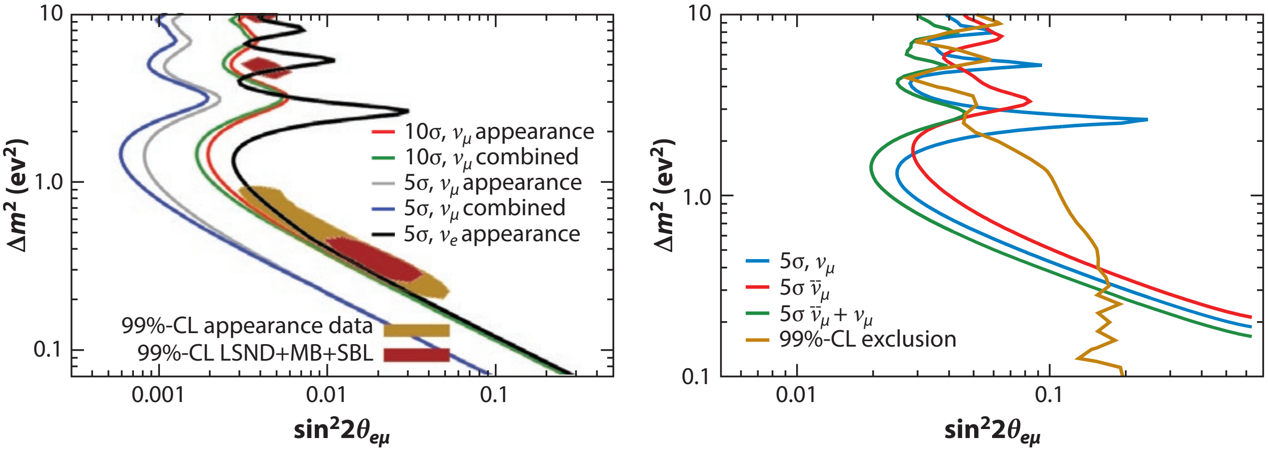

Figure 9: nuSTORM sensitivity to sterile neutrinos in a 3+1 model. Left panel: The combination of ν_μ appearance and disappearance experiments expressed in terms of the effective mixing angle $\theta_{e\mu}$. Right panel: Sensitivity of the ν_μ disappearance experiment from the pion-decay source and the $\bar{\nu}_\mu$ disappearance experiment from the muon-decay source. The green line represents the sensitivity of the combination of the experiments. Taken from [78].

violation in the neutrino sector [54, 68, 69]. Using the injector cyclotron setup being devised for DAEδALUS, IsoDAR would be a short-baseline experiment using a $\sim$ 1 kt scintillator-based detector. With an electron-anti-neutrino flux of sufficient intensity from ^{8}Li decay at rest, the experiment would facilitate a conclusive test of sterile neutrino oscillation models using the L/E dependence of inverse beta-decay. In the report from the US High Energy Physics Advisory Panel (HEPAP) Particle Physics Projects Prioritization Panel (P5) [70], IsoDAR is one of the experiments the development of which "…is not yet advanced to a point at which it would be possible to consider recommendations to move forward." However "…the R&D for these projects would fit as candidates in the small projects portfolio, with a path to eventual implementation presumably being among the evaluation criteria." IsoDAR would provide a definitive way to explore electron-antineutrino disappearance and could therefore be a candidate to add to the programme if the R&D confirms its feasibility in intensity and cost.

3.3.2 nuSTORM

Physics goals

The Neutrinos from Stored Muons (nuSTORM) facility provides neutrino beams from the decay of 3.8 GeV muons confined within a storage ring [71–77]. It is proposed that the muon beam be instrumented with a magnetised-iron-scintillator sampling calorimeter at a distance of $\sim$ 1.5 km from the end of the production straight and a magnetised near detector at a distance of 50 m from the end of the straight. Pions are injected into the neutrino-production straight. The pion-muon transition in the first pass of the beam through the production straight creates a flash of ν_μ from pion decay.

With an appropriately optimised detector and an exposure of $\sim 10^{18}$ muon decays, corresponding to 10 years of operation, nuSTORM can provide a 10σ exclusion limit in the region of sterile-neutrino parameter space indicated by the results of the LSND and MiniBooNE experiments (see figure 9) [78]. nuSTORM is also capable of supporting a definitive neutrino-nucleus cross-section measurement programme (see section 4.2.2) and the R&D programme required for the development of muon accelerators for particle physics.

Institutes (36), collaborators (112)

Fermi National Accelerator Laboratory, Institute of Physics, Orissa, India, Muons Inc., University of Geneva, University of Warwick, University of Strasbourg, University of Glasgow, York University, University of Oxford, Thomas Jefferson National Accelerator Facility, University of Sheffield, Instituto de Fisica Corpuscular (IFIC, Valencia), Imperial College London, Virginia Tech, University of California, Riverside, STFC Rutherford Appleton Laboratory, Northwestern University, University of Santiago de Compostela, Max Planck Institute for Nuclear Physics (Heidelberg), Lancaster University, Osaka University, Brunel University, Kyoto University, TRIUMF, University of Toronto, University of Liverpool, Princeton University, University of South Carolina, University College London, Institute for Particle Physics Phenomenology, Durham, Wrocław University, Poland, CERN, Illinois Institute of Technology, INFN Padova, The University of British Columbia, University of Würzburg

Next steps

nuSTORM allows the study of two-thirds of all possible appearance and disappearance channels in which signals for sterile neutrinos may appear. In addition, the detailed knowledge of the neutrino flux allows the neutral-current rate to be measured precisely. These features make nuSTORM a candidate to succeed the present generation of sterile-neutrino-search experiments. Further, as described in section 4.2.2, nuSTORM is capable of delivering a νN-scattering programme that includes the precise determination of $\overset{(-)}{\nu}_e N$-scattering cross sections. The nuSTORM facility can also support the accelerator R&D programme necessary to deliver the capability necessary to mount a future neutrino factory of muon collider [78].

A proposal to the FNAL PAC [75] was well received, but nuSTORM was not recommended by P5 [70]. An expression of interest to mount nuSTORM at CERN was well received by the CERN SPSC [71, 72]. nuSTORM is being discussed in Europe as part of a potential international muon-accelerator programme [79, 80].

The SBN Programme at FNAL will reach its full sensitivity by ~ 2020. On this timescale the results from the SBN and other sterile-neutrino-search experiments will be available; these results may indicate that nuSTORM should be considered as part of the sterile-neutrino programme. Since, in addition, nuSTORM allows precise studies of $\overset{(-)}{\nu}_e N$ scattering to be carried out, the Panel believes 2020 to be a natural point at which to consider nuSTORM as part of the sterile-neutrino programme.

3.4 Interim conclusions and recommendations

3.1: Unambiguous evidence for sterile neutrinos would constitute a breakthrough of fundamental significance and would revolutionise the field while unambiguous confirmation of the short-baseline anomalies would warrant energetic investigation.

Recommendation 3.1: The present generation of accelerator-based sterile-neutrino-search experiments, including those that constitute the SBN Program at FNAL, should be exploited so as to maximise their sensitivity.

3.2: Results from the SBN Program and other sterile-neutrino-search experiments will be available by $\approx$2020. It will then be timely to decide on the future direction of the accelerator-based sterile-neutrino-search programme.

Decision point 3.1: $\approx$2020: Decide on the future direction of the accelerator-based sterile-neutrino-search programme.

3.3: Beyond the SBN Program, the way forward will depend on the strength of the evidence for sterile neutrinos.

Recommendation 3.2: The sensitivity, cost, schedule and relative strengths of the proposed next-generation accelerator-based sterile-neutrino-search experiments (IsoDAR, nuSTORM) should be evaluated in preparation for a decision to be made on the future direction of the sterile-neutrino-search programme in $\approx$2020. In the mean time, the R&D programme necessary to establish the requisite capabilities should be carried out.

4 Supporting programme

For the long- and short-baseline neutrino programmes to reach their full sensitivity requires a programme of measurement the results of which are to be used in the estimation of the neutrino flux and to estimate the rate and the characteristics of neutrino interactions in the near and far detectors. Accelerator and detector R&D programmes are required to deliver the present generation of experiments and to create the capability to mount the next generation. Innovation and development of software tools is also required to meet the needs of the programme. The development of the programme required to support the neutrino-oscillation and sterile-neutrino-search experiments is discussed in the paragraphs that follow.

4.1 Hadroproduction

Conventional neutrino beams produced from the decay in flight of pions and kaons will serve the present and next generation accelerator-based neutrino experiments. The absolute flux normalisation, the neutrino energy spectrum and the flavour-composition of the neutrino beam are determined by the absolute yield and momentum distributions of the hadrons produced in the proton-nucleus interactions in the target. All present and planned long-baseline experiments exploit a near detector to constrain the un-oscillated neutrino flux. Extrapolation of the neutrino flux from the near to the far detector is necessary; the secondary-particle distributions are a critical input to this extrapolation. Therefore, the precise knowledge of hadron-production cross sections from the particle-production target is required for neutrino-oscillation experiments to deliver to their specified precision.

However, in general, the hadro-production data that is “tailor-made” for a particular neutrino-oscillation experiment, i.e. particle-production cross sections measured using protons of same energy interacting with the same target material as used in the oscillation experiment, is unavailable. Phenomenological parametrisations of the available data are therefore used to estimate the production rates for a particular experiment. This procedure introduces a source of systematic uncertainty. Therefore, dedicated hadro-production experiments that use the same target material at the same proton energy as in the oscillation experiment are an essential part of the accelerator-based neutrino programme.

Several experiments have been mounted to make the necessary measurements. The HARP experiment took place at CERN and made essential contributions to the K2K and MiniBooNE experiments. The MIPP experiment used a 120 GeV proton beam to measure particle production spectra for the experiments served by the Main Injector neutrino beam. At present, the only running hadro-production experiment is NA61 at CERN.

4.1.1 Facilities and experiments

NA61/SHINE

Physics goals

The principal goals of the NA61 experiment are to [81]:

1. Measure inclusive spectra and fluctuations in nucleus-nucleus collisions;
2. Measure hadron production spectra of relevance to the prediction of the cosmic-ray flux; and
3. Provide hadron production spectra of relevance to the prediction of neutrino fluxes generated in conventional neutrino sources.

To serve the T2K experiment, NA61 took data between 2007 and 2009 with thin targets ($\sim$ 6M triggers) and with a replica of the T2K graphite target ($\sim$ 13M triggers) [82–89]. Final results for the thin-target data are already incorporated into the T2K physics analysis. Currently, the uncertainty of the neutrino-flux (Φ)

prediction at the T2K near or far detector is $\delta\Phi \sim 10\%$. This uncertainty is dominated by the hadron-production uncertainty of $\delta\Phi_{\mathrm{H}} \sim 9\%$. The uncertainty on the near-to-far extrapolation (far-to-near flux ratio) now reaches the $\sim 3\%$ level. To reduce the systematic uncertainties will require the measurement of the hadrons produced in secondary and tertiary interactions inside/outside the particle-production target. This will require measurements with a variety of beams (proton and pion), at various momenta and with various target materials. Such a programme is possible if requested.

There is a new initiative in NA61 to provide hadron production data for US-based neutrino experiments [81]. The goal of this programme is to measure identified-hadron spectra with an uncertainty of 4–5% (10%). Measurements of hadron production from thin carbon and aluminium targets as well as replicas of the particle-production targets in use at FNAL will be made. Running with proton and pion beams with momenta in the range 30 GeV/c to 120 GeV/c has been approved. These measurements are expected to bring the total uncertainty of the Main Injector neutrino-beam flux down to 5–6%.

Institutes 37; collaborators 145

National Nuclear Research Center, Baku, Azerbaijan, University of Sofia, Ruđer Bošković Institute, Zagreb, Croatia, LPNHE, University of Paris VI and VII, Paris, France, Karlsruhe Institute of Technology, Karlsruhe, Germany, Fachhochschule Frankfurt, Frankfurt, Germany, University of Frankfurt, Frankfurt, Germany, University of Athens, Athens, Greece, Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Budapest, Hungary, Institute for Particle and Nuclear Studies, Tsukuba, Japan, University of Bergen, Bergen, Norway, Jan Kochanowski University in Kielce, Poland, National Centre for Nuclear Research, Warsaw, Poland, Jagiellonian University, Cracow, Poland, University of Silesia, Katowice, Poland, University of Warsaw, Warsaw, Poland, University of Wrocław, Wrocław, Poland, Warsaw University of Technology, Warsaw, Poland, Institute for Nuclear Research, Moscow, Russia, Joint Institute for Nuclear Research, Dubna, Russia, National Research Nuclear University (Moscow Engineering Physics Institute), Moscow, Russia, St. Petersburg State University, St. Petersburg, Russia, University of Belgrade, Belgrade, Serbia, ETH Zürich, Zürich, Switzerland, University of Bern, Bern, Switzerland, University of Geneva, Geneva, Switzerland, Fermilab, Batavia, USA, Los Alamos National Laboratory, Los Alamos, USA, University of Colorado, Boulder, USA, University of Pittsburgh, Pittsburgh, USA.

Future programme

NA61 started taking data in 2007. NA61 is approved to run from until 2018 to accumulate the data required to support the FNAL neutrino programme and complete measurments of nucleus-nucleus scattering with xenon and lead beams. The NA61 collaboration is preparing a proposal to extend the programme of measurement beyond 2020.

4.2 Neutrino interactions

The increased precision of the measurements made by present and future long- and short-baseline neutrino experiments places greater demands on the precision with which neutrino-nucleus interactions must be understood. Neutrino-scattering uncertainties are a dominant source of systematic uncertainty in current experiments such as T2K. Studies of the sensitivity of future experiments show that it is very important to reduce systematic uncertainties to the 1% level. At present, individual neutrino-nucleon/nucleus cross sections are known with a precision of $\sim 20\%$; the level of uncertainty depending on the reaction mechanism. Recent neutrino-nucleus-scattering measurements reveal significant deficiencies in our understanding of the physics of neutrino scattering and point to the importance of previously neglected interactions, such as multi-nucleon correlations. At the same time, a coherent and unified theoretical view of neutrino-nucleus interactions that encompasses all recent developments does not exist and, in some cases, models with similar underlying assumptions produce inconsistent results. To advance our understanding to the level required to support the future neutrino-oscillation program requires a coordinated campaign of measurements and theoretical calculation. In the near term this program seeks to address the following questions:

- What is causing the apparent tensions between different data sets (e.g. single charged-pion production)? Are the comparisons valid? If they are, do the discrepancies point to processes that are being neglected or to mis-modelling? What additional measurements and/or theoretical calculations are needed to resolve remaining tensions?
- What is causing the large differences between theoretical calculations and/or event generator predictions? What additional measurements and/or theoretical calculations are needed to address these differences?
- What additional nuclear-theory calculations are needed and what is the optimal path for getting these improved models consistently and completely incorporated into neutrino-event generators so that they can be used to interpret neutrino oscillation measurements? Can these advanced calculations cover the necessary kinematic phase space? Can they be extended reliably to nuclei as heavy as argon?
- Are there nuclear effects that impact the axial current and if so, how large are these effects and how uncertain are they?
- Nuclear physics aside, is there physics associated with the basic neutrino-nucleon interaction that requires further attention, e.g. the elastic axial-vector form factor, the nucleon-Δ axial form factors, and/or radiative corrections?
- Can the relation between different approaches (e.g. local/global Fermi gas, spectral function, random phase approximation, relativistic mean field, super-scaling, ab initio and Green's Function Monte Carlo to name a few) be understood?
- Are there specific ways in which the neutrino experimental and theoretical (nuclear and particle) communities can communicate more effectively in order to make more rapid progress?

To address these points efficiently and to make rapid progress requires an effective and structured means of communication between both the nuclear and particle experimental and theoretical communities. NuSTEC (Neutrino Scattering Theory Experiment Collaboration) [90], consisting of experimentalists from every neutrino interaction experiment, theorists from major nuclear theoretical initiatives and representatives of all major Monte Carlo simulation tools has been formed explicitly to address this need.

On the experimental side, we can expect new data in the coming few years from MicroBooNE, MINERνA/CAPTAIN-MINERνA [17, 91], NOνA, SBND [8], and T2K. This data will span neutrino energies ranging from a few hundred MeV up to a few GeV and will probe a variety of nuclear targets including helium, carbon, oxygen, argon, iron and lead. It is generally recognised that for this next-generation data to be used to address the questions listed above it must:

- Include measurements of both $\overset{(-)}{\nu}_{\mu}N$ and $\overset{(-)}{\nu}_{e}N$ scattering to support the future neutrino CP-invariance violation program;
- Report cross sections in the form of physical observables so as to decrease the model dependence of the measurements;
- Cover a large range of energies, targets, and final-state topologies to constrain uncertainties in theoretical models and simulation tools;
- Maintain as large a muon (electron) angular acceptance as possible and examine hadron emission to probe the physics of multi-nucleon correlations in charged-current neutrino interactions;
- Include tests of how well we know electron- versus muon-neutrino scattering to support future $\overset{(-)}{\nu}_{e}$ appearance searches; and
- Rely on accurate neutrino-flux simulations to produce precise neutrino cross-section measurements.

The experiments listed above will carry the programme forward for the next four to five years.

The measurement of neutral-current coherent elastic neutrino-nucleus scattering is important for experiments searching for astrophysical phenomena such as supernovæ and in searches for dark matter. The reaction is predicted by the Standard Model but is very difficult to measure because the signal comes from low-energy nuclear recoil only. Coherence requires that the neutrino energy should not exceed a few tens of MeV. The most promising experimental projects are COHERENCE [92] and νGeN [93] experiments. COHERENCE proposes to set up three detectors with different target materials (xenon, germanium, CsI[Na]) close to the target at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. νGeN will be located at the Kalininskaya nuclear plant in Russia and use low-threshold germanium detectors developed at JINR in Dubna.

While it is challenging to predict the exact requirements of the programme in the next decade, it is likely that increased precision will be required. NuPRISM [94] and nuSTORM [71–77] are examples of experiments that have been proposed to provide the necessary increase in precision. NuPRISM exploits the off-axis technique to detect neutrinos at a variety of narrow energy bands. nuSTORM produces beams with equal quantities of muon and electron neutrinos with a well known energy spectrum from the decay of muons confined within a storage ring.

Over the coming years, significant theoretical advances are also to be anticipated. For example, reliable ab-initio computations of nuclear response functions are expected to be performed in the region of the quasi-elastic peak for light nuclear targets (nuclei up to carbon). A collaboration of theorists within NuSTEC has been formed with the goal of expanding these computations to nuclei up to argon and into the relativistic regions necessary for pion production. Together with the experimentalists and representatives of teh Monte Carlo developers of NuSTEC these improvements will be incorporated in the major Monte Carlo simulation tools. These considerations indicate that a decision on the future direction of the neutrino-scattering programme could be made around 2020.

4.2.1 Facilities and experiments

MINERνA

Physics goals

MINERνA is a fine-grained detector that uses the Main Injector neutrino (NuMI) beam [17]. The experiment is approved to collect an exposure corresponding to 10×10^{20} POT in neutrino mode and 12×10^{20} POT in anti-neutrino mode in the medium-energy beam in addition to the samples that have been collected using the low-energy beam. The principal goals of the approved programme are to:

- Study both signal and background reactions relevant to oscillation experiments;
- Study nuclear effects in inclusive reactions and exclusive final states;

- Study neutrino-scattering processes as a function of neutrino energy;
- Study differences between neutrinos and anti-neutrinos; and
- Measure the "EMC Effect" using neutrino deep inelastic scattering on lead, iron, carbon and hydrocarbon targets.

Institutes 20; collaborators 70
Brazilian Center for Research in Physics (CBPF), Fermi National Accelerator Laboratory, University of Florida, University of Geneva, University of Guanajuato, Mexico, Hampton University, Massachussetts College of Liberal Arts, Northwestern University, Oregon State University, Otterbein University, Oxford University. Pontifical Catholic University of Peru, University of Pittsburgh, University of Rochester, Rutgers University, Tufts University, University of Minnesota (Duluth), Universidad Nacional de Ingeniería, Peru, Universidad Técnica Federico Santa María, Chile, College of William & Mary.

Measurement programme
MINERνA completed the data taking using the low-energy beam, which has a mean energy of 3.5 GeV, with an exposure corresponding to 4×10^{20} POT. Running using the medium-energy beam, with mean energy 6 GeV, has started and an exposure corresponding to 9×10^{20} POT in neutrino mode has been accumulated. Running continues with the objective of integrating the approved exposure.

CAPTAIN-MINERνA

Physics goals
CAPTAIN-MINERνA [17, 91] proposes to use a detector system consisting of the CAPTAIN LArTPC and MINERνA fine-grained detector in the on-axis NuMI beam. The principal goals of the experiment are to:

- Measure neutrino-argon cross sections in the energy region of the first oscillation maximum for DUNE;
- Measure cross-section ratios on argon to scintillator to test models of nuclear effects; and
- Take 6×10^{20} POT in both neutrino mode and antineutrino mode in the NuMi medium-energy beam.

Institutes 31
University of Alabama, Argonne National Laboratory, Brookhaven National Laboratory, University of California (Davis), University of California (Irvine), University of California, (Los Angeles), University of California, (Davis), Brazilian Center for Research in Physics (CBPF), University of Florida, Fermi National Accelerator Laboratory, University of Guanajuato, Mexico, Hampton University, University of Hawaii, University of Houston, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, Louisiana State University, Massachusetts College Liberal Arts, Massachusetts Institute of Technology, University of Minnesota (Twin Cities), University of Minnesota (Duluth), University of New Mexico, Oregon State University, University of Pennsylvania University of Pittsburgh, Pontifical Catholic University of Peru, University of Rochester, Stony Brook University, Tufts University, Universidad Nacional de Ingenieria, Peru, Universidad Tecnica Federico Santa Maria, Chile, College of William and Mary.

Next steps
Captain-MINERνA received Phase 1 approval from the Fermilab PAC in June 2015.

MicroBooNE

Physics goals

An outline of the MicroBooNE experiment was given in section 3.1.2. In addition to the sterile-neutrino search programme, MicroBooNE will study the properties of neutrino interactions in argon and will measure the cross sections for a wide variety of inclusive and exclusive channels.

Institutes

The institutes that form the MicroBooNE collaboration are listed in section 3.1.2.

Measurement programme

The MicroBooNE collaboration plans to measure charged-current (CC) and neutral-current (NC) neutrino-interaction cross sections on argon for neutrino energies in the range $\sim 0.2 < E_\nu < 2\,\mathrm{GeV}$ with a precision of $\sim 10\%$. This uncertainty is dominated by neutrino-flux uncertainties and is at the level with which the Booster Neutrino beam flux was determined for MiniBooNE. It may be possible to reduce this uncertainty after incorporating recent results from the HARP experiment which measured hadrons produced by a replica of the Booster Neutrino Beam (BNB) target.

Specific cross section measurements will include:

- ν_μ CC inclusive (muon kinematics, hadronic energy, neutrino energy);
- ν_μ CC 0π (muon and proton kinematics, proton multiplicities);
- ν_μ CC π^+ (muon and pion kinematics, nucleon emission);
- ν_μ CC π^0 (muon and pion kinematics, nucleon emission);
- ν_μ NC π^0 (pion kinematics, nucleon emission);
- ν_μ NC $\pi^\pm$ (pion kinematics, nucleon emission);
- ν_μ-induced single photon production; and
- ν_μ-induced kaon, η, ρ, multi-pion production.

ν_e and ν_μ cross section measurements can also be made from the far off-axis NuMI beam, although this beam is not expected to be as well-known as the on-axis BNB.

Short Baseline Near Detector (SBND)

Physics goals

The SBND will record ~ 2 million interactions per year (~ 1.5 million ν_μ charged current (CC) and ~ 12k ν_e CC) in the TPC active volume. Measurements of ν_μAr and ν_eAr cross sections will be made. The well-characterised neutrino flux will be used to measure:

- Rare processes such as ν-e scattering, strange-particle production, and coherent scattering with an argon nucleus; and
- Differential cross sections exclusive channels and studies of nuclear effects in νAr interactions.

Institutes

The institutes that form the SBND collaboration are listed in section 3.2.1.

Measurement programme

Sufficient statistics to produce cross section measurements on partial data set will be acquired quickly. It is anticipated that all cross-section analysis will be completed within a few years of the end of the approved exposure (6.6×10^{20} POT).

NOνA

Physics goals

The NOνA near detector is placed off-axis in the NuMI beam to measure neutrino interaction cross sections with a liquid-scintillator detector as part of the NOνA neutrino-oscillation programme. The principal goals for the near detector are to:

- Advance the understanding of neutrino-nucleus interactions in an intermediate energy range;
- Constrain the off-axis NuMI flux with measurements of better-known interactions; and
- Search for non-standard interactions and exotic phenomena.

To achieve these goals data will be taken under the following conditions:

- Neutrino energy range between 1 GeV and 20 GeV, with the bulk of ν_μ flux between 1 GeV and 3 GeV; and
- Baseline exposure: 36×10^{20} POT over 6 years. The fraction of the total exposure to dedicated to anti-neutrino running remains to be determined.

Institutes

The institutes that form the NOνA collaboration are listed in section 2.1.2.

Measurement programme

The NOνA neutrino-interaction programme will run through the duration of the NOνA experiment. Approximately 850,000 muon-neutrino charged-current interactions, before cuts, are expected annually in neutrino-mode running in a 10 t fiducial mass. This sample will contain contributions from quasi-elastic (nominally 26%), resonant (39%), pion-continuum/DIS (34%) and coherent (1%) channels. A neutral-current sample of one-third the size will also be collected. The electron-neutrino content is about 0.6% of the total flux. First results from the NOνA neutrino-interaction program are anticipated in US fiscal year 2016 and regular updates from the multiple ongoing analyses will be released as they become available.

T2K (ND280)

Physics goals

The T2K ND280 detector is sited 280 m from the source of the J-PARC off-axis neutrino beam to allow large neutrino- and anti-neutrino-scattering data sets, which can be distinguished event-by-event using ND280's 0.2 T magnetic field, to be collected. The principal goal of the ND280 experiment is to:

- Make a variety of measurements of neutrino-nucleus interactions to improve the precision of the T2K neutrino-oscillation measurements.

Institutes

The institutes that form the T2K collaboration are listed in section 2.1.1.

Measurement programme

The present exposure of 1.1×10^{21} POT is expected to rise to 2×10^{21} POT by the end of 2016. The experiment is approved to take data until 2021 by which time it is expected that an exposure corresponding to 7.8×10^{21} POT will have been delivered. The plan is to collect an equal exposure (POT) in neutrino and antineutrino modes.

To achieve this exposure it is planned that the power to the J-PARC neutrino target will rise to 750 kW in 2018. An upgrade to the near detector suite is being studied. A second phase of the experiment, exceeding 750 kW beam power, is under discussion.

WAGASCI test experiment

Physics goals

The principal goals of the WAGASCI experiment are to measure the charged-current neutrino cross section on water and the ratio of the neutrino-water cross section to the neutrino-plastic and neutrino-iron cross sections with high precision and large angular acceptance. The detector exploits a 3D grid-like structure of scintillator bars to detect charged particles with 4π acceptance and high efficiency. The experiment will be exposed to the T2K off-axis neutrino beam at J-PARC. By focusing positive particles, the beam will be used to measure the neutrino-water cross section with a total uncertainty of 10% and the cross section ratio with a total uncertainty of 3% using an exposure corresponding to 1×10^{20} POT. By focusing negative particles, the anti-neutrino-water cross section and the cross-section ratio will be measured with a statistical uncertainty of 5% using 2×10^{20} POT.

Institutes 8

University of Tokyo, Institute for Nuclear Research of the Russian Academy of Sciences, Laboratoire Leprince-Ringuet, Ecole Polytechnique, Kyoto University, Osaka City University, Institute for Cosmic Ray Research, University of Tokyo, University of Geneva, Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo.

Milestones

The WAGASCI test experiment was approved by the IPNS/KEK Director and endorsed by the J-PARC PAC in 2014. Construction began in the summer of 2015. The principal milestones for the project are:

- Autumn 2016: start of data taking with the WAGASCI prototype at on-axis in the J-PARC neutrino beam;
- Within calendar year 2017: start data taking with the full WAGASCI detector off-axis in the J-PARC neutrino beam.

ANNIE

Physics goals

The ANNIE experiment has been proposed to measure the rate of neutron production in neutrino-water interactions using the Booster Neutrino Beam at Fermilab. The goal is to contribute to the fundamental understanding of neutrino interactions in nuclei. The measurements will benefit neutrino and nucleon-decay studies that exploit large water-Cherenkov and liquid-scintillator detectors.

Institutes 16

Argonne National Laboratory, Fermi National Accelerator Laboratory, Iowa State University, Ohio State University, Queen Mary University of London, University of California at Berkeley, University of California at Davis, University of California at Irvine, University of Chicago, University of Sheffield.

Programme

In 2015 ANNIE was approved for a Phase I run. The principal milestones of the project are:

- Phase I; technical development and background characterization: installation of the necessary equipment began in the summer of 2015 with data taking before the shutdown of the Booster Neutrino Beam in 2016. Additional data taking with protype LAPPDs and MCPs is possible in the last quarter of calendar 2016 and the first two quarters of 2017;
- Phase IIa; ANNIE physics run I with a moderate photo-cathode coverage: installation will start in the summer of 2017 with data taking from the autumn of 2017 through to spring 2018; and

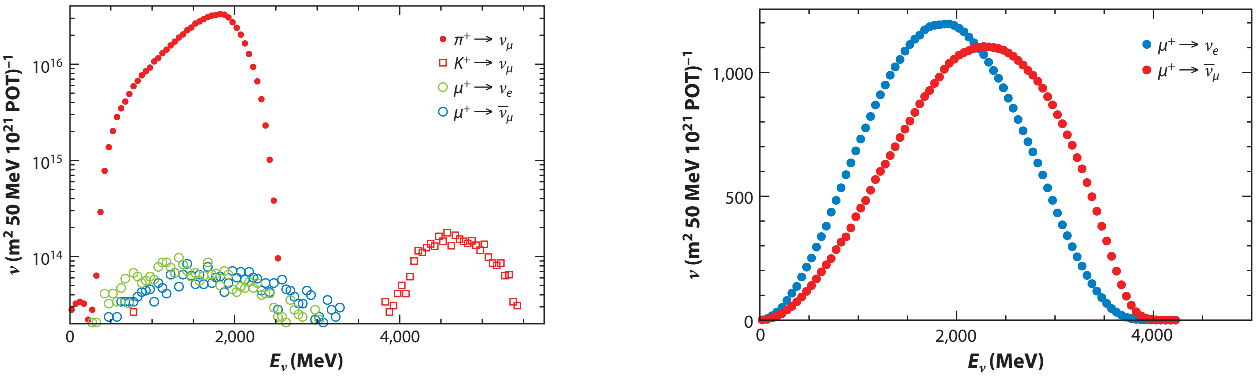

Figure 10: Left panel: simulated neutrino flux at the near detector location arising from pion decay during injection into the production straight. Right panel: simulated neutrino flux at the near detector location arising from muon decay.

- Phase IIb; ANNIE physics run II with full photo-cathode coverage: installation in the summer of 2018 with running from the autumn of 2018 to the autumn of 2020.

4.2.2 Future opportunities

nuSTORM

Physics goals/measurement programme

The nuSTORM concept was outlined in section 3.3.2. For the future neutrino-scattering programme nuSTORM offers the following advantages:

- The neutrino flux is precisely known; the normalisation may be determined to better than 1% from the storage-ring instrumentation;
- The energy spectrum may be calculated precisely, exploiting constraints imposed by the storage ring and its instrumentation. The falling edge of the spectrum at high energy can be used to calibrate the detector response; and
- The muon-decay beam contains equal numbers of ν_μ and $\bar{\nu}_e$ (or $\bar{\nu}_\mu$ and ν_e). Since the $\pi \rightarrow \mu$ transition takes place in the neutrino-production straight, a bright "flash" of $\overset{(-)}{\nu}_\mu$ is produced in the first pass of the beam through the production straight (see figure 10).

The simulated flux at the near detector 50 m from the end of the production straight is shown in figure 10. The event rate in a 100 T detector is large, making it possible to measure single-differential cross sections at the few percent level. The flux is sufficient for double-differential cross-section measurements to be made.

Institutes

The list of institutions was given in the nuSTORM entry in section 3.3.2.

Outlook

The unique features of the nuSTORM beam (large $\overset{(-)}{\nu}_e$ flux, precisely known energy spectrum) may be of substantial value in determining cross sections for use in the analysis of the next generation long-baseline oscillation experiments (DUNE and Hyper-K) when the data samples are large. Accounting for correlated and uncorrelated sources of systematic uncertainty with a precision commensurate with the statistical precision of the data samples will be critical in the combination of results from a number of experiments. The constraints that nuSTORM can provide are likely to be particularly valuable in this combination.

Over the next four years or so, results from the present neutrino-scattering programme will inform detailed studies of the systematic uncertainties that will impact the search for CPiV. Consideration of these studies may indicate that the precision which nuSTORM can provide will be of benefit when the statistical weight of the DUNE and Hyper-K data samples are large. Since the DUNE and Hyper-K experiments seek to accumulate large data sets towards the end of the next decade the Panel believes 2020 to be a natural point at which to consider nuSTORM as part of the future neutrino-nucleus cross-section measurement programme.

4.3 Detector development

A substantial detector R&D effort is underway to deliver the capabilities necessary to deliver the present and next generation of accelerator-based neutrino-oscillation experiments. The principal elements of this programme are reviewed in the paragraphs which follow.

4.3.1 ProtoDUNE at the CERN Neutrino Platform

Physics goals
ProtoDUNE [95] is a full scale prototype single-phase liquid-argon TPC (LAr-TPC) that will be operated at the CERN Neutrino Platform [96]. The principal goal is to demonstrate the construction techniques that will be used in the DUNE first 10 kt single-phase detector module. ProtoDUNE will also allow experience to be gained with the reconstruction and analysis of data from a large LAr-TPC. Its contribution to the DUNE programme will be:

- The measurement of the response of the detector to charged particles; and
- The validation of the performance of all the components, and the commissioning of the detector.

Institutes
Since protoDUNE is part of the DUNE programme, the institute and collaborator lists are those presented in section 2.2.1.

Future programme
Schedule is driven by the DUNE timescale: detector commissioning and data run before end of 2018.

4.3.2 WA104 at the CERN Neutrino Platform; ICARUS refurbishment

Physics goals
The ICARUS-WA104 collaboration is refurbishing the ICARUS T600 liquid argon TPC with new cryostats, new fast, and high-performance electronics and with an upgraded light-detection system. The two TPCs were moved from the Gran Sasso Laboratory in Italy to CERN in December 2014. After the modules have been refurbished at CERN they will be shipped to FNAL to be used as the far detector in the Short Baseline Neutrino Programme described in section 3.2.1.

Institutes 10; collaborators 60
CERN, Catania University, INFN Catania, Pavia University, INFN Pavia, Padova University, INFN Padova, Gran Sasso Science Institute, Italy Laboratori Nazionali di Frascati (Roma), Laboratori Nazionali del Gran Sasso, Italy, INFN Milano Bicocca, INFN Milano, INFN Napoli

Future programme
The refurbished detectors will be moved from CERN to Fermilab in 2017. The modules will be installed at the 600 m location on the Booster Neutrino Beam for start of operation in 2018.

4.3.3 WA105 at the CERN Neutrino Platform; LBNO Dual-phase prototype

Physics goals

The WA105 collaboration is building a large liquid-argon TPC working in double-phase (liquid and gas) mode [97, 98]. The TPC will be operated at the CERN Neutrino Platform [96]. The TPC will contain a $6 \times 6 \times 6\,\mathrm{m}^3$ volume of liquid argon in a cryostat that is based on an industrial liquid-natural-gas vessel. Charge amplification and readout occurs in the gas phase allowing long drift distances, a lower energy threshold and an improved signal-to-noise ratio to be achieved. The main goals are the development and test of the double-phase technique, the validation of the technologies proposed to deliver larger scale detectors and the measurement of the response of the detector to beams of charged particles with energies ranging from 1 GeV to 10 GeV. Since December 2015, the project is embedded in the DUNE experiment as ProtoDUNE-DP, one of the two prototype efforts towards the deployment of four 10 kt FD detectors at SURF.

The WA105 technical programme includes:

- The delivery of very high LAr purity in a non-evacuated tank (an oxygen contamination of $< 100\,\mathrm{ppt}$ is needed for an electron lifetime of 10 ms);
- The construction and operation at very high voltage of a large field cage;
- Commissioning and operation of a large area micro-pattern charge readout system;
- Implementation of the cold front-end charge readout electronics;
- Test of the long term stability of the WLS coating; and
- Integrated light readout and electronic technical solutions.

The WA105 physics programme includes:

- The reconstruction of e, $\pi^{\pm}$, π^0 and muons;
- Electron/π^0 separation;
- Calorimetry to reconstruct the full neutrino energy;
- Hadronic secondary interactions; and
- Measurements of pion/proton interaction cross sections on argon.

Institutes 20; collaborators 152

Barcelona/IFAE (ESP), Bucharest(RO), CERN, Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas (CIEMAT), ETH Zürich (CH), IFIN-HH (RO), IN2P3/APC, IN2P3/IPNL, IN2P3/LAPP, IN2P3/LPNHE, IN2P3/OMEGA, Iwate University (Japan), CEA Saclay, Jyvaskyla (FI), Kyiv National University, National Centre for Nuclear Research (POL), National Institute of Technology, Kure College (Japan), High Energy Accelerator Research Organization (KEK), University College London (UK), University Texas Arlington (USA)

Future programme

The principal steps in the development of the WA105 programme are:

- Build the cryostat by April 2017;
- Assemble the detector in the cryostat in December 2017; and
- Be ready to take beam data in March 2018.

4.3.4 Liquid Argon In A Testbeam (LArIAT)

Physics goals

LArIAT, the Liquid Argon In A Testbeam experiment, is located at the Fermilab Test Beam Facility in a tertiary beam of pions, muons, electrons, protons, and kaons, with momentum in the range of $\sim$ 200 MeV/c–1400 MeV/c. Operating a LArTPC in a well-understood beam of charged particles enables detailed characterisation of the response of the detector to each type of particle (corresponding to a range of deposited ionization energy, dE/dx) over the full range of incoming particle energies. The experimentally measured response characteristics will be used to tune simulations for neutrino experiments in order to reproduce more accurately the characteristics of particles traveling through the argon. The data collected in LArIAT will also allow the collaboration to evaluate how well the existing LArTPC particle identification algorithms are functioning and to improve these algorithms based on data rather than simulation.

During its two running periods, LArIAT will record more than 1 million interactions of charged particles in liquid argon in the range of energies that is relevant to current and future short- and long-baseline neutrino experiments. The products of neutrino interactions seen in MicroBooNE, SBND, and DUNE exactly match the type and energy range of particles collected in LArIAT. The collaboration will use the data collected in this LArTPC to:

- Measure total and exclusive interaction cross sections of charged pions, kaons, and protons;
- Experimentally evaluate the capability of LArTPCs to distinguish electrons from photons, which is key to understanding the primary background of neutrino oscillation experiments;
- Develop criteria for charge-sign determination in the absence of a magnetic field, based on topologies;
- Study kaon identification, and its implications for LAr proton decay experiments;
- Study stopping muons and decay electrons; and
- Extend the use of scintillation light readout beyond its traditional function in neutrino detectors (for triggering purposes) to a better system that can aid in full calorimetric energy reconstruction.

Institutes (21), collaborators (85)

Universidade Federal do ABC, Universidade Federal de Alfenas, Boston University, Universidade Estadual de Campinas, University of Chicago, University of Cincinnati, Fermi National Accelerator Laboratory, Universidade Federal de Goias, Istituto Nazionale di Fisica Nucleare, KEK, Lousiana State University, University of Manchester, Michigan State University, University of Minnesota, Duluth, University of Pittsburgh, Syracuse University, University of Texas, Arlington, University of Texas, Austin, University College London, The College of William and Mary, Yale University.

Future programme

Sufficient statistics to produce differential cross section measurements for charged pions have been acquired, and the additional data being collected in Run-II will enable high-statistics cross section measurements of particles that are less abundant in the beam. It is anticipated that all analyses listed above will be completed within a few years of the end of the approved Run-II period (ending July 2016).

Future plans under consideration for additional short runs include:

- Direct comparison of 3-mm vs. 5-mm wire pitch, under the reproducible experimental conditions afforded by the test beam environment;
- Addition of LAPPDs (new, very fast large area photon detectors) to the beamline;
- Novel scintillation light collection studies in the TPC using: LAPPDs, ARAPUCA (a new type of light wavelength converter and concentrator), acrylic bars with SiPM readout, capacitively-coupled SiPM readout via TPC wire planes, and detection of the infrared component of LAr scintillation light;
- Methane doping of the LAr for charge response linearization; and
- New cold electronics, including a fast ADC stage.

4.3.5 CHIPS

Physics goals

The Cherenkov detectors In mine PitS (CHIPS) collaboration seeks to develop a water containment and purification system for deployment in lakes created by mining (“pits”) [99]. The water-containment system will be instrumented with a relatively sparse (7%–10%) covering of 3-inch photo-multipliers which use time and charge information to reconstruct electron- and muon-neutrino events, thus forming a water Cherenkov detector that is potentially game-changing in terms of cost per kilo-ton. The deepest pit illuminated by the Main Injector neutrino beam from Fermilab has been identified and a 35 ton prototype detector was deployed underwater for two seasons. The full detector is envisaged to be capable of measuring the CP phase, $\delta_{\rm CP}$, with a precision of $\sim 30^\circ$ standalone and with a precision of $\sim 20^\circ$ when CHIPS is combined with T2K and NOνA. Water purification has been demonstrated and light-attenuation lengths greater than 50 m at a wavelength of 405 nm has been demonstrated. In the present phase of the experiment the collaboration seeks to demonstrate a water containment structure that would be applicable to any water-Cherenkov detector.

Institutes (13), collaborators (36)
University of Cincinnati, Fermi National Accelerator Laboratory, Iowa State University (Ames), University College London, University of Minnesota (Twin Cities), University of Minnesota (Duluth), University of Pittsburgh, Stanford University, University of Texas (Austin), College of William & Mary, University of Wisconsin (Madison), Large Lakes Observatory, University of Minnesota (Duluth), Brookhaven National Laboratory

Future programme
The principal steps in the proposed CHIPS development programme are:

- Construction of 30 m diameter endcaps on the surface at the Wentworth pit;
- Technical review followed by construction of 10 kt structure; and
- Instrumentation of the 10 kt detector.

4.3.6 NuPRISM and TITUS

Currently, two “intermediate” baseline detectors, NuPRISM and TITUS, to be situated between 1 km and 2 km from the target of the J-PARC neutrino beam are under consideration.

Physics goals
NuPRISM exploits the trend for the peak of the energy spectrum of conventional neutrino beams to move towards lower and narrower energy distributions as one moves “off” the beam axis. By observing neutrinos produced at a large range of off-axis angles in a large water Cherenkov detector, NuPRISM can measure neutrino-interaction properties as a function of the incident neutrino energy due to this variation. The method allows the direct measurement of critical quantities and distributions, such as the outgoing lepton differential cross section as a function of neutrino energy, that are inaccessible to conventional techniques where only the flux-averaged distributions can be measured in a model-independent way. Extensions of this technique also allow NuPRISM data to be used to predict the lepton kinematics of the oscillated neutrinos at a far detector site (e.g. Super-Kamiokande in the case of T2K or Hyper-Kamiokande) and to constrain cross section differences between $\nu_{e,\mu}/\bar{\nu}_{e,\mu}$ that are important sources of systematic uncertainty in a CP-invariance violation study. As described below, gadolinium sulfate ($\mathrm{Gd_2(SO_4)_3}$) can be dissolved in the water to enhance the detection of neutrons emitted in neutrino interactions. The same energy variation also allows highly sensitive searches for large Δm^2 neutrino oscillations that may result from the presence of sterile neutrinos. With an exposure of 7.5×10^{21} protons-on-target in neutrino mode during the T2K second phase, NuPRISM has sensitivity to exclude LSND allowed values of the sterile oscillation parameters with 5σ significance for most values of Δm^2, and with 3σ significance for all values of Δm^2.

TITUS is a proposed water Cherenkov detector in the J-PARC neutrino beam consisting of a cylindrical vessel oriented horizontally to increase containment of high energy muons. Situated at the same off-axis angle as Hyper-Kamiokande, the intermediate distance reduces near/far flux differences in the unoscillated flux to $\lesssim 1\%$. A magnetised muon range detector (MRD) allows sign selection for muons which exit the water volume. A key element of the detector design is $Gd_2(SO_4)_3$ loading; the very high cross section and energetic photon emission from neutron capture on gadolinium nuclei provide a clean signature by which to identify neutrons emitted from neutrino interactions. The $Gd_2(SO_4)_3$-loading allows TITUS to perform detailed studies of neutron emission in neutrino interactions with a powerful capability to separate ν_μ and $\bar{\nu}_\mu$ interactions using the MRD. This may have important applications for the long-baseline neutrino oscillation program at Hyper-K, where neutron counting can allow statistical separation of neutrino and anti-neutrino interactions, leading to improvements in sensitivity. Moreover, the physics programme of the TITUS detector goes beyond the oscillation analysis extending to neutrino interaction measurements, supernova detection, Standard Model measurements and dark matter searches.

Institutes

Currently, TITUS is formally part of the Hyper-Kamiokande collaboration, but its unique benefits are also applicable to T2K and its second phase. NuPRISM is proposed as a separate experiment that can serve as an intermediate detector for T2K or Hyper-Kamiokande while independently pursuing other measurements such as neutrino interaction studies and sterile neutrino searches.

NuPRISM: institutes 27; collaborators 50

University of British Columbia, University of California (Irvine), University of Geneva, High Energy Accelerator Research Organization (KEK), IFAE, Barcelona, Imperial College London, Institute for Nuclear Research of the Russian Academy of Sciences, Kavli Institute for the Physics and Mathematics of the Universe, Todai Institute for Advanced Study, University of Tokyo, Kyoto University, Michigan State University, Stony Brook University, Osaka University, Research Center for Nuclear Physics (RCNP), University of Regina, Canada, University of Rochester, University of Sheffield, STFC Rutherford Appleton Laboratory, University of Tokyo, Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos, Tokyo Institute of Technology, University of Toronto, TRIUMF, Warsaw University of Technology, York University, Canada, Tokyo Metropolitan University

Next steps:

NuPRISM:

- Seek Stage 1 approval at J-PARC
- Construction of intermediate detector facility outside of J-PARC to house detector; and
- Detector construction, with the goal of starting operations as soon as possible after the J-PARC Main Ring power supply upgrades that will increase the repetition cycle needed for >750 kW neutrino beams at J-PARC.

TITUS:

- Submit proposal for running during T2K-II.
- Phased implementation.

4.4 Accelerator development

Advances in accelerator technique are required to deliver the next-generation of experiments. In addition, R&D is required to provide beams for which the associated systematic uncertainties can be reduced substantially below those of the conventional, pion-decay, beams. Such beams will be necessary to take the programme beyond the next generation of accelerator-based neutrino experiments.

4.4.1 MICE

Physics goals

Muon beams of low emittance provide the basis for the intense, well-characterised neutrino beams necessary to elucidate the physics of flavour at the neutrino factory and to provide lepton-antilepton collisions of up to several TeV at the muon collider. To deliver beams with the properties necessary to meet the specifications of these facilities requires that the volume of phase space occupied by the tertiary muon beam be reduced (cooled). Conventional beam-cooling techniques can not be used as the short muon lifetime ($2.2\,\mu$s at rest) would lead to unacceptably large loss of beam intensity. Ionization cooling is the novel technique by which it is proposed to cool the muon beam. The international Muon Ionization Cooling Experiment (MICE) has been approved to [100, 101]:

- Design, build, commission and operate a realistic section of cooling channel; and
- Measure its performance in a variety of modes of operation and beam conditions.

The results will allow the optimisation of cooling-channel design for use at the neutrino factory and muon collider.

Institutes 28; collaborators 155

Department of Atomic Physics, St. Kliment Ohridski University of Sofia, Institute of High Energy Physics, Chinese Academy of Sciences, Sichuan University, Sezione INFN Milano Bicocca, Sezione INFN Napoli and Dipartimento di Fisica, Sezione INFN Pavia and Dipartimento di Fisica, Sezione INFN Roma Tre e Dipartimento di Fisica, Osaka University, Graduate School of Science, High Energy Accelerator Research Organization (KEK), Nikhef, Amsterdam, CERN, DPNC, Section de Physique, Université de Genève, School Of Engineering and Design, Brunel University, STFC Daresbury Laboratory, School of Physics and Astronomy, Kelvin Building, The University of Glasgow, Department of Physics, Blackett Laboratory, Imperial College London, Department of Physics, University of Liverpool, Department of Physics, University of Oxford, STFC Rutherford Appleton Laboratory, Department of Physics and Astronomy, University of Sheffield, Department of Physics, University of Strathclyde, Department of Physics, University of Warwick, Brookhaven National Laboratory, Fermilab, Illinois Institute of Technology, Chicago, Department of Physics and Astronomy, University of Iowa, Lawrence Berkeley National Laboratory, University of Mississippi, University of California, Riverside.

Future programme

The cooling-demonstration experiment will be carried out in 2018 [102, 103]. In order to study the manner in which the properties of beam-energy absorber materials and lattice parameters determine the ionization-cooling effect, the collaboration is carrying out “Step IV”. In Step IV, a single absorber is sandwiched between two spectrometer modules allowing control of optical functions at the absorber and precision measurement of muon parameters upstream and downstream of the absorber. The goals of the Step IV programme are to [102]:

- Measure the material properties of liquid hydrogen and lithium hydride that determine the ionization-cooling performance; and

- Observe reduction in the normalised transverse emittance.

The Step IV programme will be executed in 2016/17 after which the experiment will be reconfigured for the demonstration of ionization cooling. The goals of the cooling-demonstration experiment are to [102]:

- Observe of transverse-emittance reduction with re-acceleration; and
- Observe of transverse-emittance reduction and the evolution of longitudinal emittance and canonical angular momentum.

4.4.2 RaDIATE

Scientific goals

As proton accelerator particle sources become increasingly powerful, there is a pressing need to better understand and predict the radiation response of structural window, target and related component materials. The RaDIATE Collaboration (Radiation Damage In Accelerator Target Environments) draws on existing expertise in related fields in fission and fusion materials research to formulate and implement a research program that will apply the unique combination of facilities and expertise at participating institutions to a broad range of high power accelerator projects of interest to the collaboration (in general, these projects include neutrino and muon sources, neutron spallation sources, rare isotope ion beam sources, and collimation for high intensity accelerator facilities). The broad aims of the RaDIATE collaboration are:

- Generate new and useful materials data for application within the accelerator and fission/fusion materials communities;
- Recruit and develop new scientific and engineering experts who can cross the boundaries between these communities; and
- Initiate and coordinate a continuing synergy between research in these currently disparate communities, benefiting both proton accelerator applications in science and industry and nuclear fission and fusion energy technologies.

The ultimate ambition is to be able to not only predict operating lifetimes for as many materials of interest as possible in terms of integrated proton fluence for the high energy proton accelerator parameter space (e.g. temperature, dose rate, duty factor, dynamic stress), but also enable the development of radiation damage and thermal shock tolerant materials. Results of these studies will enable the robust and safe design, fabrication, and operation of high power/intensity accelerator target facilities such as the Long Baseline Neutrino Facility (DUNE), the neutrino factory and muon collider.

Institutes 11; collaborators 32

FNAL, Science and Technology Facilities Council, GSI, Darmstadt, Oxford University, Brookhaven National Laboratory, Pacific Northwest National Laboratory, Oak Ridge National Laboratory, Michigan State University, European Spallation Source, Los Alamos National Laboratory, Argonne National Laboratory, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Center of Energy, Environmental and Technological Research)

In addition, an MOU revision is being prepared to add CERN and J-PARC.

Current and future programme

RaDIATE related activities are focused on the determination of critical properties of irradiated materials for application in the accelerator-target environment, determining optimal irradiation-environment parameters (e.g. irradiation temperature) for maximum target-component lifetime, developing application-specific material-testing methods and verifying models in prototypic loading environments and educating and developing new experts in the accelerator-target community. Major current and near future activities include:

- Post-irradiation examination (PIE) of the recovered NuMI beryllium primary beam window at Oxford University (2015-16);
- High intensity beam test of beryllium, “BeGrid”, at CERNâĂŹs HiRadMat facility and subsequent PIE at Oxford University (2015-16);
- Development of a hot-cell compatible fatigue testing machine at Fermilab (2015-16);
- PIE of the recovered NuMI target, NT-02, graphite fins at Pacific Northwest National Laboratory (PNNL) (2016);
- Determination of strength model parameters describing high-strain-rate mechanical behaviour of beryllium at Southwest Research Institute (SwRI) (2016);
- Irradiation and subsequent PIE of multiple materials at the Brookhaven Linac Isotope Producer (BLIP) at Brookhaven National Laboratory (BNL) (2016–2018). PIE will occur at multiple institutions. Materials include beryllium, graphite, SiC-coated graphite, silicon, aluminium alloys, titanium alloys, molybdenum alloy (TZM) and iridium;
- Follow-on high intensity beam experiment(s) at CERNâĂŹs HiRadMat facility on beryllium and other target/window candidate materials, including materials irradiated in BLIP irradiation (2017–2018); and
- Triple-beam ion irradiation and subsequent PIE of beryllium at the Michigan Ion Beam Laboratory (MIBL) and University of Michigan, PNNL, and Oxford University (2017–2019).

It is expected that, starting in 2019 and extending to about 2023, there will be at least one more high-energy proton irradiation run on multiple materials and several low-energy ion irradiations with subsequent PIE from both irradiations. In addition, it is expected that PIE activities will continue on irradiated materials recovered from operating beam-lines as they become available. The culmination of all studies is expected in 2024–2025 when material-irradiation data and validated modelling methods will be available to inform the design, construction and operation of next generation accelerator-target facilities.

4.5 Development of software tools

Cross-sections: In recent years, a large number of experimental results on neutrino-nucleus cross-sections have become available. At the same time, considerable theoretical activity has been devoted to gaining a better understanding of nuclear- and particle-physics effects. On the other hand, computational tools commonly used in Monte Carlo event generators often show a time-lag in the implementation of such new results. This delay is partly due to the lack of a unified framework for communicating theoretical or experimental advances, which requires an ad-hoc implementation of each of them by the Monte Carlo developers. Progress requires the development of a common interface between nuclear- and neutrino-physics experiments, particle- and nuclear-theory models and computations with Monte Carlos. To achieve such a goal, in turn, requires coherent, cooperative interaction between nuclear theorists, particle theorists, and neutrino experimentalists. There is a growing, currently ongoing activity (e.g. NuSTEC [90]) to establish collaborative efforts and to identify the most pressing questions. Nonetheless, there is still the need to develop coherent mid-term and long-term strategies. A possible strategy is to start working on a universal Monte Carlo event generator. The following issues must be addressed in order to ensure the success of the program:

- The Monte Carlo must get every-day support to answer questions, fix bugs, etc.;
- Regular training should be organised for users from neutrino oscillation experimental groups;
- Detailed documentation must be maintained and made available to the community; and
- Results of new neutrino cross-section measurements should be made available in a useful format and promptly included in data-analysis tools and global fits.

Combining different experimental results and global fits: The importance of combined fits to the data from the various neutrino experiments, which allows advantage to be taken of the complementary information on the parameters that the different experiments provide, has been widely demonstrated in recent years. Going forward, the combination of information contained in different data sets is bound to become more important and more challenging, especially when it comes to looking for CP-invariance violation and testing the three-flavour paradigm. In order to facilitate this process, it is important to develop data formats and data analyses such that communication between the experimental and theory communities, and among different experimental efforts, is optimal. Future releases of data should not be limited to the final results or to the experimental data themselves, but also include all the information (such as effective areas or resolution functions) required to reproduce the fit outside of the collaboration. The main goal is to allow apples-to-apples comparisons of different experimental results and the combination of different data sets in order to test the validity of different theoretical and phenomenological models, and to measure parameters, including mass-squared differences, mixing angles, and CP-odd phases.

4.6 Interim conclusions and recommendations

4.1: An appropriate programme of hadro-production and neutrino cross-section measurement is required to allow the present and next generation of long- and short-baseline experiments to achieve their full potential.

4.2: Measurements of hadro-production cross sections are critical to reducing the systematic error budget of future accelerator-based neutrino-oscillation measurements. At present, the only experiment that is in operation is NA61/SHINE, which is scheduled to complete operation in 2018. It is timely to consider the requirements for measurements of hadron spectra beyond those that NA61/SHINE will provide.

Recommendation 4.1: ICFA should encourage careful and timely consideration of the requirements for a hadro-production measurement programme to follow NA61/SHINE including possible extensions to the NA61/SHINE programme.

4.3: The present neutrino-nucleus cross-section measurement program is vibrant and appropriate to serve the present generation of experiments over the next five years. The detectors that serve the Short Baseline Neutrino (SBN) Program and MINERνA will support an excellent neutrino scattering programme.

4.4: In the medium term, the near detectors that are part of the DUNE and Hyper-K experiments will take the neutrino-interaction programme forward. Novel techniques such as the high-resolution tracking detector proposed for DUNE and NuPRISM proposed for T2K/Hyper-K have the potential to enhance the precision with which muon-neutrino interactions are known. Robust, timely execution of the near-detector programme at DUNE and Hyper-K is essential for the experiments to meet their sensitivity goals.

Recommendation 4.2: The near detector programme at DUNE and at Hyper-K should be pursued energetically so that neutrino-scattering measurements of the requisite precision are available to allow the experiments to perform to their specified sensitivity.

4.5: Over the coming four to five years, progress in the measurement of neutrino-nucleus scattering will be made using, for example, the SBN detectors and MINERνA. Substantial theoretical and phenomenological progress in the particle and nuclear physics of neutrino-nucleus scattering, beyond the current effort, which is sub-critical, will be required over this period.

Recommendation 4.3: ICFA should encourage and promote a vibrant, sustained effort towards reliable, precision calculation of neutrino-nucleon and neutrino-nucleus scattering. An approach that promotes and exploits the synergy between the particle theory, nuclear theory and experimental neutrino communities should be adopted.

4.6: Captain-MINERνA, which has Stage I approval from the Fermilab PAC, and the near detectors that form part of the DUNE and Hyper-K programmes will take the neutrino-scattering programme forward. If approved, Captain-MINERνA will provide valuable, detailed information on neutrino-argon scattering by the end of the present decade. The detailed specification of the DUNE and Hyper-K near detectors will be resolved over a similar timescale. It will therefore be timely to decide on the long-term development of the $\overset{(-)}{\nu}N$-scattering programme around ≈2020.

Decision point 4.3: ≈2020: Decide on the future direction of the neutrino-nucleus-scattering programme based on experimental and theoretical progress and the needs of the future neutrino programme.

4.7: The requirements of DUNE and Hyper-K will drive the specification of the neutrino-cross-section-measurement programme. The path forward, beyond the present generation of $\overset{(-)}{\nu}N$ scattering experiments, will be determined by the degree to which existing techniques (on and off-axis near detectors illuminated with pion-decay beams) can deliver measurements of the requisite precision.

Recommendation 4.4: The proposed next-generation neutrino-scattering experiments, for example nuSTORM, should be evaluated in preparation for a decision on the future direction of the neutrino-scattering programme to be made in ≈2020.

4.8: An exciting programme of detector R&D is being carried out across the world targeted at delivering the technologies required by DUNE, Hyper-K and the Short Baseline Neutrino Program.

Recommendation 4.5: The present detector R&D portfolio should be completed. Provision should be made for an appropriately resourced detector-development programme over the lifetime of the next generation of experiments.

4.9: The development of MW-class sources at FNAL and J-PARC are critical to the delivery of the experimental programme. To go beyond the sensitivity and precision of the next generation of accelerator-based experiments is likely to require the development of novel accelerator capabilities. It is likely that increased international cooperation and collaboration will be required to deliver these programmes. The MICE experiment and the RaDIATE programme are recognised as important contributions to the field, each offering the possibility of generating a legacy of enhanced capability.

Recommendation 4.6: Opportunities for international cooperation and/or collaboration in the development of MW-class neutrino sources should be actively pursued.

Recommendation 4.7: The MICE experiment should be completed to deliver the critical demonstration of ionization cooling. ICFA should encourage the timely consideration of the accelerator R&D programme that is required beyond MICE to develop the capability to deliver high-brightness muon beams.

5 Measurements using neutrinos from nuclear reactors and radioactive sources

Nuclear reactors have played a key role in understanding the properties of the neutrino. They provide an intense source of electron anti-neutrinos with energies between a few keV and several MeV and therefore allow precise measurements of oscillation parameters to be made. The discovery of unknown phenomena through measurements of the properties of the neutrino may only be possible if the of oscillation parameters are precisely measured. In addition, precision measurements will be a sensitive test of the SνM framework and will allow searches for physics beyond the Standard Model to be carried out. Table 2 provides a list of the experimental collaborations contributing to the reactor-neutrino oscillation programme.

Precision measurements of the mixing parameters are expected from reactor experiments that are in operation or that are being proposed. To date, reactor experiments have determined the values of θ_{13} and Δm^2_{ee} through the observation of electron-anti-neutrino disappearance at baselines of 1–2 km. The precision with which the running reactor experiments are expected to determine parameters of the neutrino-mixing matrix are:

- $\sin^2 2\theta_{13}$: $3-4\%$ at Daya Bay [104, 105], 10% at Double Chooz [106–108], and 5% at RENO [109, 110]; and
- Δm^2_{ee}: $\sim 7 \times 10^{-5}$ eV^2 at Daya Bay; and $\sim 1 \times 10^{-4}$ eV^2 at RENO.

It is anticipated that these measurements will be made by $\sim$2017.

For the solar Δm^2_{21}, the current uncertainties are determined by KamLAND [111]. A reactor experiment with a large liquid-scintillator detector and a medium-baseline around 50 km, such as JUNO [112, 113] and RENO-50 [114], can provide measurements of θ_{12}, Δm^2_{21} and Δm^2_{ee} with a precision better than 1% by $\sim$ 2025. Combined with results from other experiments for θ_{23} and θ_{13}, the unitarity of the neutrino-mixing matrix can be tested at the 1% level. This effort will be valuable to explore physics beyond the Standard Model.

The large value of θ_{13} has opened up the possibility of the determination of the ordering of the neutrino masses. A medium-baseline reactor experiment, such as JUNO and RENO-50, would be able to determine the mass hierarchy using the sub-dominant oscillation pattern if an energy resolution of $\sim$ 3% at 1 MeV is achieved. JUNO is approved to start civil construction in January 2016 and expects to start of data-taking in 2020. RENO-50 has obtained R&D funding and will seek to secure construction funding with the aim of taking data in 2020. The neutrino-mass hierarchy is expected to be determined with 3σ–4σ significance by JUNO after 6 years of data taking and by RENO-50 after 10 years of data taking.

While most neutrino-oscillation data fits the three-flavour-mixing hypothesis quite well, some experiments have reported intriguing exceptions, including the anomalous disappearance of $\bar{\nu}_e$ and ν_e produced in reactors and by radioactive sources. Although these hints currently have only modest statistical significance, if confirmed, they would be evidence for particles and interactions beyond the Standard Model.

Various projects will perform searches for sterile neutrinos using reactor neutrinos over short baselines of between 5 m and 20 m. Compact anti-neutrino sources are available at research reactors while powerful anti-neutrino fluxes are provided at commercial reactors. Challenging background mitigation is necessary because of the shallow depth at which the experiments operate. Two identical detectors at different baselines are desirable to look for spectral distortions and to be insensitive to uncertainties in the spectrum of neutrinos produced in the reactor. The short-baseline reactor experiments that are under consideration or are being prepared are: DANSS; Hanaro; Neutrino-4; Nucifer; NuLat; Poseidon; PROSPECT; SoLid; and Stereo. Sterile-neutrino mixing will be explored to a sensitivity of $\sin^2 2\theta_{14} \sim 0.01$ and the reactor anti-neutrino anomaly will be proven or rejected with a significance of 5σ before 2020 by multiple experiments.

It is also possible to carry out a sterile-neutrino search using neutrinos or anti-neutrinos produced by strong (0.1–10 MCi) nuclear-decay sources. Neutrino radioactive-source experiments can be sensitive to Δm^2 around 1 eV^2 due to the low energies ($1-10$ MeV) of the neutrinos that are produced. Such experiments could observe sterile-neutrino oscillations at baselines of between 1 m and 10 m, i.e., in a single detector or in several closely separated detectors. Possible sources include ^{51}Cr, ^{37}Ar, ^{144}Ce, ^{144}Pr, ^{37}Sr and ^{8}Li. The advantages of using radioactive sources are that the spectra and flux are precisely known and the neutrino-nucleus scattering cross sections in the MeV region are also known precisely. SOX [115], the source experiment at Borexino, plans to take data in 2016 with a ^{144}Ce source followed by a ^{51}Cr source; in both cases the source will be placed beneath the detector. The SOX sensitivity to $\sin^2 2\theta_{14}$ is 0.03−0.04 at 95% confidence level with two to three years of data taking. An experiment in which the source is placed at the centre of the detector may be proposed.

Table 2: Experiments contributing to, or in preparation as part of, the reactor-based neutrino-oscillation programme.

Experiment	**Collaboration**				**Status**
	European				
	Americas	**Asia**	**European**	**Total**	
Double Chooz	18	7	14	39	Running
RENO	0	12	12	24	Running
Daya Bay	17	23	2	42	Running
KamLAND-ZEN	6	4	1	11	Running
JUNO	3	27	25	55	In preparation
RENO-50	0	12	12	24	In preparation
DANSS					
Hanaro					
Neutrino-4	0	0	3	3	
Nucifer					
NuLat	6	0	0	6	
PROSPECT	16	0	0	16	
SoLid	1	0	10	11	In preparation
Stereo	0	0	7	7	
SOX	14	0	3	17	

6 Non-terrestrial source

In this section the expected oscillation physics results that can be obtained from present and future experiments studying atmospheric neutrinos are reviewed. There are three main categories of detector that are used to study of atmospheric neutrinos:

- Water Cherenkov detectors such as Super-Kamiokande;
- Large magnetised iron calorimeter detectors such as INO; and
- Large Cherenkov detectors that exploit deep ice or deep sea water as the radiating medium.

Water Cherenkov detectors continue to be successful in the study of atmospheric neutrinos over a wide energy range; from a few hundred MeV to a few GeV. The sensitivity of this class of detector results from the photo-detector density with which the sensitive volume is viewed. The deep ice, or deep sea, detectors have a neutrino-energy threshold of a few tens of GeV, which is higher than conventional atmospheric-neutrino detectors, due to the lower density of light sensors. However, the physics goals of both categories of detector are to improve the precision on oscillation parameters and to perform mass-hierarchy studies.

Atmospheric neutrinos remain an important probe of neutrino oscillations and provide a sensitive technique for the determination of the neutrino-mass hierarchy. A difference of up to 20% in the oscillation probability between the normal and inverted hierarchy is expected for specific energies and zenith angles (baselines). The Earth's density transitions can cause an additional enhancement of the oscillation signal. Table 3 provides a list of the experimental collaborations contributing to the detection of neutrinos from non-terrestrial sources.

6.1 Atmospheric-neutrino experiments

6.1.1 Super-Kamiokande

Super-Kamiokande is a water Cherenkov detector with a fiducial mass of 22 kt. It is instrumented with $\sim$ 12000 20-inch PMTs. Super-Kamiokande has been taking data since 1996 and, in 1998, was the first experiment to demonstrate the existence of oscillations in the atmospheric sector. Since then the Super-Kamiokande collaboration has provided ground-breaking results on oscillation parameters in the three-flavour framework from atmospheric-neutrino studies especially on Δm^2_{32} and $\sin^2\theta_{23}$.

Table 3: Experiments contributing to, or in preparation as part of, the detection of neutrinos from non-terrestrial sources.

Experiment	**Collaboration**				**Status**
	European				
	Americas	**Asia**	**European**	**Total**	
Super-Kamiokande	11	20	2	33	Running
INO	0	24	0	24	In preparation
PINGU	21	5	20	46	In preparation
ORCA (KM3NET)	0	0	42	42	In preparation
Hyper-K	23	23	24	70	Under review
Borexino	5		19	24	Running
SNO+	18	0	8	26	Running

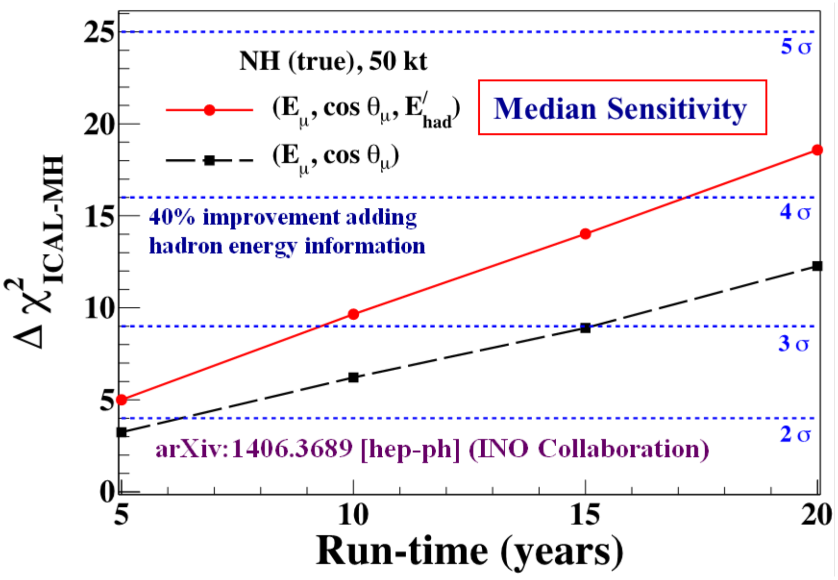

Figure 11: Sensitivity of the ICAL detector to the mass hierarchy as a function of the running time for both hierarchies.

Physics goals

It is planned that the Super-Kamiokande experiment (see, for example, [116]) will run for a further ten years. This will allow the sensitivity to the mass hierarchy to reach 0.7–1.5σ to 1–2σ depending on the octant. The sensitivity to the octant should be slightly more than 2σ.

6.1.2 India Neutrino Observatory Iron Calorimeter (INO-ICAL)

The main detector to be built at the India Neutrino Observatory (INO) is the Magnetized Iron Calorimeter (ICAL) composed of 3 modular 17 kt modules of resistive plate chambers and iron plates for a total of 52 kt detector [117–119]. The detector offers an excellent $\nu/\bar{\nu}$ separation thanks to the magnetic field of about 1.5 T that allows the measurement of the charge and momentum of the muons produced in neutrino interactions.

The latest study concerning the hierarchy sensitivity of the ICAL detector, including both muon and associated hadron energy, shows that a 3σ sensitivity can be achieved in 10 years of running if the true values of $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$ are 0.5 and 0.1 respectively (see figure 11). Combining the ICAL results with information from T2K and NOνA can give rise to an enhanced sensitivity of 3σ in 6 years. Improved precision on the mixing parameters Δm^2_{32} and $\sin^2\theta_{23}$ can be obtained after 10 years of running. The planning foresees the site infrastructure being developed and the excavation of the tunnel and cavern taking place over the next three to four years.

An engineering prototype of one module will be constructed over the next 2.5 years. The construction of the ICAL detector should progress at a rate of one module per year, which brings the full detector into operation in about 10 years.

6.1.3 Pingu

Physics goals

The Precision IceCube Next Generation Upgrade (PINGU) [120] is a proposed extension to the IceCube Obser-

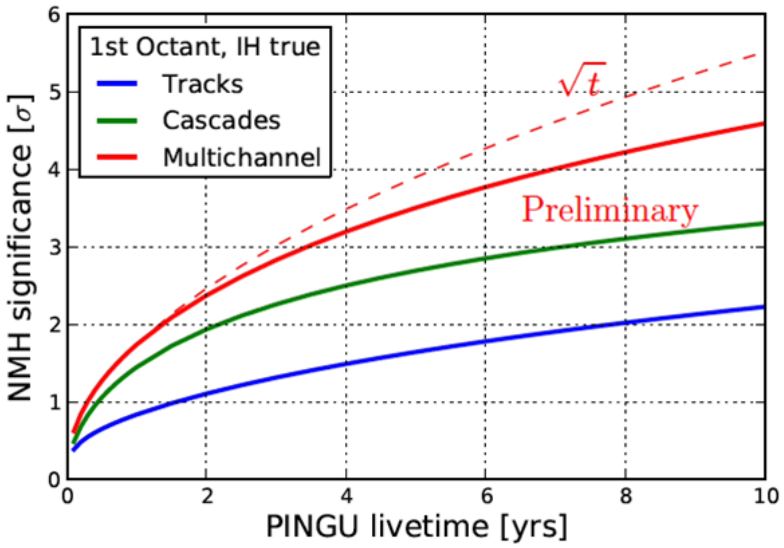

Figure 12: Sensitivity of PINGU detector to the mass hierarchy assuming the inverted hierarchy as a function of the running time.

vatory that will lower the energy threshold by increasing the photo-detector density for a portion of the fiducial volume. An initial detector geometry has been defined comprising of 40 new strings of 60 optical modules (OM) each, deployed in the DeepCore region of the IceCube array. This extension should be deployed over the next 2–3 years and the instrumented volume should be $\sim$ 4 Mt, 2400 OM (see figure 12).

This configuration would allow the mass hierarchy to be determined with a sensitivity of 3σ reach after four years of data taking with an analysis that combines tracks and showers. After 5 years the θ_{23} octant can be probed with a sensitivity competitive with other atmospheric-neutrino experiments. The PINGU detector will allow the observation of $\overset{(-)}{\nu}_\tau$ appearance with a sensitivity of more than 5σ using the energy and zenith angle distributions. PINGU will then be able to study three-flavour oscillations with high statistics.

Future programme

Following approval, construction and deployment of the strings of optical modules can be completed in five years. PINGU could be in operation as early as 2020.

6.1.4 ORCA

Physics goals

The ORCA (Oscillation Research with Cosmics in the Abyss) project aims to study low energy atmospheric neutrinos [121]. It is a deep-sea neutrino telescope in the Mediterranean Sea, using the technology developed for the KM3NeT project. The geometrical configuration considered is the deployment of 115 vertical lines with 18 optical modules per string at the KM3NeT-French site in Mediterranean. The corresponding instrumented volume amounts to $\sim$ 3.8 Mt with 2070 optical modules. The physics performance expected would allow a 3σ reach of MH after 4 years with an analysis combining tracks and showers (see figure 13).

ORCA and Pingu end up with very similar results even with their differences which are that water has longer scattering length while ice has longer attenuation length. They both plan to have a trigger level with O(100k)/neutrinos year.

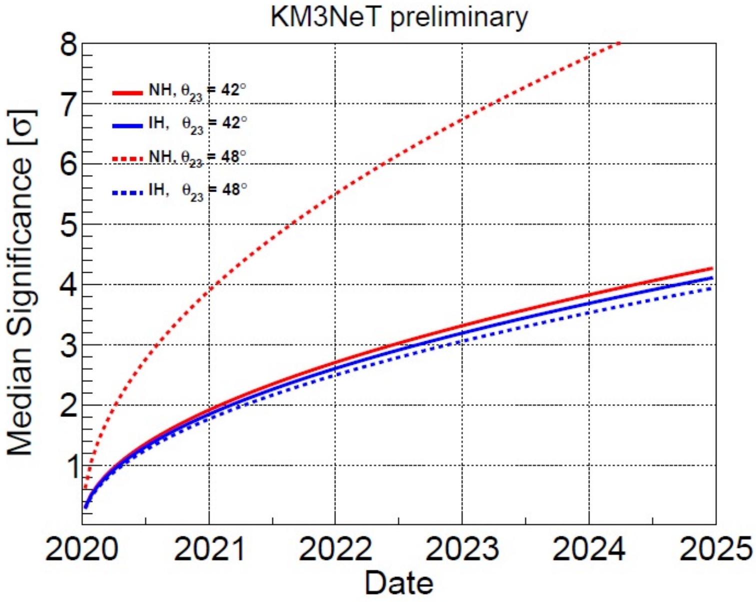

Figure 13: Sensitivity of ORCA detector to the mass hierarchy assuming IH as a function of the running time [122].

Next steps
Two steps have been identified for the construction of the detector. The first step corresponds to the deployment of 6–7 strings in ORCA configuration. It is funded as Phase 1 of the project and should demonstrate that this detection method works in the GeV range. Following the completion of Phase 1, the project should go on by pursuing phase 1.5 with 115 lines at French KM3NeT site which would be deployed by 2019.

6.1.5 Hyper-K

Physics goals
Hyper-K is a large underground WC detector with a total mass of 1 Mt [12]. It is comprised of two, 250 m long, egg-shaped tanks which together have a fiducial volume corresponding to 560 kt. The detector is instrumented with approximately 100,000 20-inch PMTs giving a 20% photo cathode coverage. The sensitivity of Hyper-Kamiokande to the mass hierarchy and the determination of the octant of θ_{23} is shown in figure 14. After 10 years of data taking, using the atmospheric-neutrino data set only, the sensitivity to the mass hierarchy will reach $\approx 3\sigma$. The octant can be determined with a significance greater than 3σ for $\sin^2 2\theta_{23} < 0.99$.

Institutes
The institutes comprising the Hyper-K collaboration were listed in section 2.2.2.

Next steps
The planning is to start excavation in 2018 to start operating the detector after 2025.

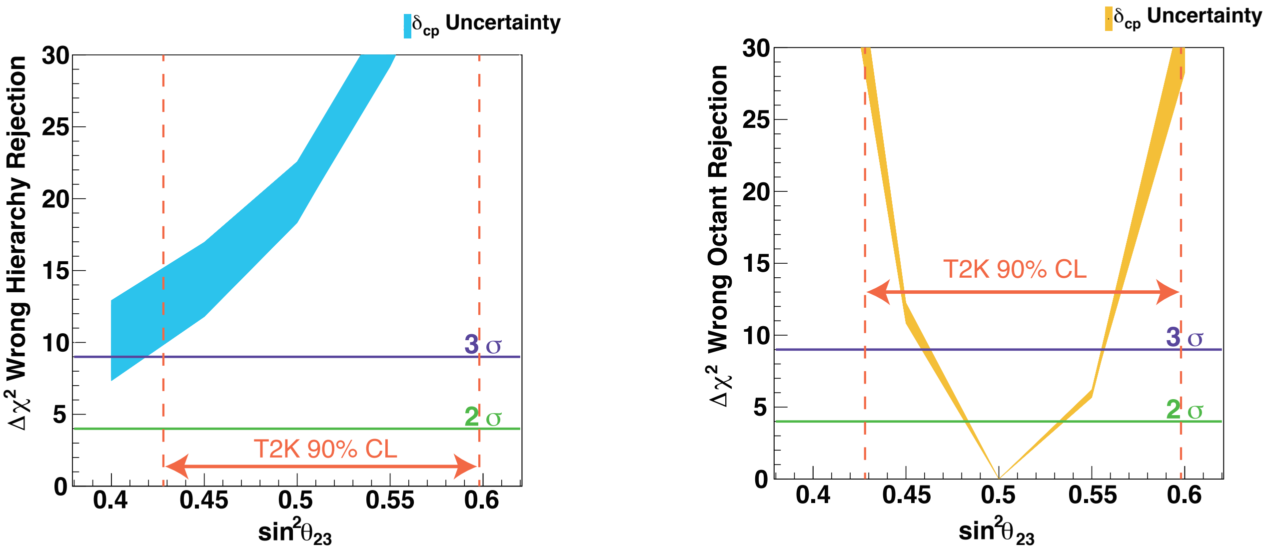

Figure 14: Sensitivity of Hyper-K to the mass hierarchy (left) and to octant (right) as a function of the $\sin^2 2\theta_{23}$ value after 10 years of running.

6.1.6 Baikal experiment

It has been proposed to set up a large, cubic-km detector in the Baikal Lake to study atmospheric and astrophysical neutrino fluxes and, in particular, to map the high-energy neutrino sky in the Southern Hemisphere, including the region of the galactic center [93]. The detector will use the water in Lake Baikal, instrumented at depth with optical sensors that detect the Cherenkov radiation from secondary particles produced in the interactions of high-energy neutrinos inside or near the instrumented volume. The detector is to be completed by 2020 [93].

6.2 Solar-neutrino experiments

Important questions concerning the nature of solar neutrinos will be addressed in the coming years by existing and upcoming projects. The items are: low energy neutrino, pep neutrino measurements, studies of the metallicity model from CNO neutrino measurement.

6.2.1 Borexino

Physics goals
Data for a possible measurement of pp neutrinos are being analysed. Recent improvements in scintillator repurification can reduce backgrounds to lower levels for a possible measurement of CNO neutrinos. The CNO flux is a direct probe of the heavy element composition in the core of the Sun.

Plans for 2015–2018: The plans for the Borexino programme over the period 2015–2018 are:

- Improved precision of present results of solar pp, pep, ^{7}Be and ^{8}B neutrinos, as well as geo- and reactor-anti-neutrinos;
- CNO neutrinos: improve limit or try to quote a rate ("solar metallicity puzzle");

- Sterile neutrino search with ^{144}Ce anti-neutrino and ^{51}Cr neutrino sources (SOX); and
- Supernova neutrinos and anti-neutrinos: BX member of SNEWS, keep high duty cycle of 95

6.2.2 SNO+

Physics goals

SNO+ is a large liquid scintillator-based experiment located 2 km underground at SNOLAB, Sudbury, Canada. It reuses the Sudbury Neutrino Observatory detector, consisting of a 12 m diameter acrylic vessel which will be filled with about 780 t of ultra-pure liquid scintillator. The primary goal of SNO+ is to search for the neutrinoless double-beta decay of ^{130}Te. However, it will have the potential to explore other physics including low energy pep and CNO solar neutrinos.

With scintillator purity at Borexino level, there will be sensitivity to CNO, pep and low-energy ^{8}B with unloaded scintillator:

- If source scintillator is with reduced (one order magnitude) ^{14}C level can also measure pp;
- ^{8}B with energy above the ^{130}Te end-point can be measured in the scintillator loaded phases.

Programme:

The next steps in the SNO+ programme are':

- 2015-2016: water commissioning phase;
- 2016: scintillator phase; and
- 2017: Te loading phase.

7 Non-oscillation programme

To date, all the effects of non-zero neutrino have been observed in neutrino-oscillation experiments. Neutrino masses can also manifest themselves in several other physics observables. Here we briefly review the three most promising classes of observable in terms of the sensitivity to physics beyond the Standard Model and the expected improvements in the near and medium term.

The direct observation of kinematical effects arising from non-zero neutrino mass is exceptionally challenging because neutrino mass is tiny compared to the energy scales that pertain in the relevant particle- and nuclear-physics experiments. Precise measurements of the shape of the β-decay spectrum close to its end point is the most sensitive direct probe of neutrino mass. End-point measurements are sensitive to the effective electron-neutrino mass-squared, $m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$, where U_{ei} are elements of the electron-row of the neutrino mixing matrix, $i = 1, 2, \ldots$ summed over the neutrino mass eigenvalues m_i. Current measurements of the β-spectrum of tritium decay constrain $m_\beta^2 < 4.0$ eV^2 at the 95% confidence level. The Katrin experiment [123, 124], currently under construction, aims at being sensitive to $m_\beta^2 > 0.04$ eV^2 (90% confidence level upper limit), hence two orders of magnitude more sensitive to m_β^2 than the current bound, after three years of data-taking. Katrin is expected to start collecting data late in 2016 so results are expected by the end of the decade. In order to improve significantly on these bounds using tritium, qualitatively better experiments are required. Project 8 [125, 126], which just passed its proof-of-concept milestone, and is currently in the design phase, appears to offer a path towards $m_\beta^2 < 0.01$ eV^2. The time-scale for Project 8 is currently uncertain. Isotopes other than lithium are being considered, including ^{187}Re or ^{163}Ho, embedded in microcalorimeters. These experiments ultimately aim at achieving sensitivities similar to those of Katrin but they still need to overcome several challenges. Competitive results are not expected in the foreseeable future.

Precision measurements of β-decay translate into very robust bounds on neutrino properties. While they are also sensitive to certain types of new phenomena (e.g. new neutrino mass-eigenstates), the relation between the current bound on m_β and the known neutrino masses and mixing angles is well-defined. The current neutrino-oscillation data, for example, guarantee that $m_\beta^2 > 8 \times 10^{-5}$ eV^2. If the neutrino mass-hierarchy were known to be inverted, $m_\beta^2 > 2.5 \times 10^{-3}$ eV^2 would be guaranteed. On the other hand, if Katrin were to observe a signal by the end of the decade, we would be able to conclude that the three known neutrino masses were almost exactly degenerate in magnitude, $m_1 \simeq m_2 \simeq m_3$.

If the neutrinos are Majorana fermions, lepton-number is not an exactly conserved quantum number. On the flip-side, the observation of lepton-number violation would reveal that neutrinos are Majorana fermions. Neutrino oscillation experiments are, for all practical purposes, unable to see lepton-number-violating effects. The most sensitive probes of lepton-number violation are searches for neutrinoless double-beta decay. If neutrinos are Majorana fermions, neutrino exchange contributes to the decay width for neutrinoless double-beta decay in a calculable way. This contribution is proportional to the effective neutrino mass $m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$, which also depends on the Majorana phases (note $U_{ei}^2 \neq |U_{ei}|^2$). Hence, if active neutrino exchange is the dominant contribution to neutrinoless double-beta decay, one can translate lower bounds on the decay lifetime to upper bounds on $m_{\beta\beta}$. There are several on-going and planned searches for neutrinoless double-beta decay, using a variety of isotopes (^{76}Ge, ^{130}Te, ^{136}Xe, ^{4}8Ca, ^{8}2Se etc.). The current generation of experiments aims at being sensitive to $m_{\beta\beta} \gtrsim 0.1$ eV by the end of the decade. Next-generation experiments, currently under serious consideration and expected by the middle of the next decade, aim at an order-of-magnitude-improved sensitivity, $m_{\beta\beta} \gtrsim 0.01$ eV.

Unlike the case of β-decay, the connection between neutrinoless double-beta decay and neutrino properties is more indirect. Failure to observe neutrinoless double-beta decay at the level indicated by $m_{\beta\beta}$ does not necessarily imply that neutrinos are Dirac fermions, neither is it guaranteed that the observation of neutrinoless double-beta decay can be directly translated into a measurement of $m_{\beta\beta}$. It is possible, for example, that the lepton-number violating physics impacts neutrinoless double-beta decay in a way that is not captured by active neutrino exchange. There are also technical computational challenges—the associated nuclear matrix elements are only known rather poorly—when it comes to translating the rate for neutrinoless double-beta decay and the effective neutrino mass.

Current neutrino oscillation data do not allow one to compute a lower bound for $m_{\beta\beta}$, even if one assumes the neutrinos are Majorana fermions. If the neutrino mass hierarchy were known to be inverted, on the other hand, $m^2_{\beta\beta} > 0.02$ eV would be guaranteed—and within reach of next-generation experiments—as long as neutrinos are Majorana fermions. More information on $m_{\beta\beta}$ would become available if more information on the neutrino masses from, e.g., Katrin were available.

Finally, neutrino masses leave a non-trivial imprint in the large scale structure of the Universe. Neutrinos are one of the relics from the Big Bang and play a role in the evolution of the Universe. Hence, cosmic surveys sensitive to the expansion rate of the Universe at different epochs, or to the formation of structure at different scales, can be used to measure neutrino properties assuming the different ingredients that contribute to the thermal history of the Universe are known and constrained well enough. In particular, cosmic surveys are sensitive to the sum of neutrino masses $\Sigma = \sum_i m_i$. Current data translate into $\Sigma < 0.26$ eV at the 95% confidence level. In the next ten years, improvements to cosmic microwave background (CMB) lensing data, including polarisation, from CMB observations (e.g. POLARBEAR, SPTPol, BICEP3, etc.), along with next-generation large scale structure surveys (DESI, Euclid, LSST) should translate into sensitivity to $\Sigma \gtrsim 0.015$ eV. Given what we currently know about neutrino masses $\Sigma > 0.05$ eV, next-generation cosmic surveys are “guaranteed” to see the effects of non-zero neutrino masses at, at least, the three-sigma level.

The relation between cosmic surveys and neutrino properties is quite indirect. If the ingredients that determine the thermal history of the Universe are different from what we currently anticipate, or if the properties of these ingredients are not as prescribed by our current understanding of particle physics, the interpretation of cosmic-survey data can change significantly. Information from all different probes of neutrino masses and neutrino properties—including oscillations, tritium β-decay, neutrinoless double-beta decay—will be required in order to interpret unambiguously future data and extract the most amount of information concerning not only neutrino physics but a also a potentially large wealth of new phenomena.

8 Interim conclusions and recommendations

The Panel's interim conclusions are collected below together with the interim decision points identified by the Panel and the Panel's interim recommendations. The numbering, "$n.m$", is such that n refers to the chapter of this document in which the background to the conclusion, decision point or recommendation may be found.

1 Introduction

1.1: The neutrino has a tiny mass, much smaller than any other fundamental fermion, and its type, or "flavour", changes as it propagates through space and time. These properties imply the existance of new phenomena not described by the Standard Model of particle physics and may have profound consequences for our understanding of the Universe. The tiny neutrino mass seems likely to be related to phenomena that occur at very high energy scales, well beyond the reach of the present or proposed colliding-beam facilities. The study of the neutrino is therefore the study of physics beyond the Standard Model and a fundamentally important component of the particle-physics programme.

1.2: The accelerator-based neutrino programme is global in scope, engagement and intellectual contribution. Continued and enhanced cooperation in a coherent global programme will maximise the impact of each individual contribution and of the programme as a whole.

Recommendation 1.1: The present roadmap discussion document should be completed through discussion with the stakeholders. The roadmap should then be revised and updated at appropriate intervals.

1.3: By collating data from a number of sources the Panel has gained a partial understanding of the strength of the global accelerator-based neutrino community. Accurate, up-to-date, consistent and complete census data for the global accelerator-based neutrino community will be valuable in planning the development of the programme.

Recommendation 1.2: ICFA should support the Panel in its efforts to work with the stakeholders to gather the necessary census data as part of the consultation process that will follow the completion of this roadmap discussion document.

2 Accelerator-based long-baseline neutrino-oscillation programme

2.1: The present accelerator-based long-baseline neutrino-oscillation programme is vibrant and has substantial discovery potential.

Recommendation 2.1: Full exploitation of the present generation of experiments should continue thereby maximising their discovery potential and the scientific return on historical investment.

2.2: The measurements that will be made by the DUNE and the Hyper-K collaborations are complementary and the combination of the data from the two experiments offers the potential for insights beyond those that either experiment can provide on its own.

Recommendation 2.2: Both the DUNE and the Hyper-K programmes should be pursued through the established approval and funding processes.

2.3: The sensitivity of long-baseline neutrino-oscillation experiments may be enhanced by including events at the second oscillation maximum. DUNE may exploit the second oscillation maximum since the LBNF broad-band beam will provide an interesting flux at the relevant energy. The baseline of Hyper-K places the relevant energy significantly below the peak of the J-PARC narrow-band beam making it harder for Hyper-K to profit from the second oscillation maximum. ESSnuSB has been optimised for the study of the second oscillation maximum thereby maximising its sensitivity to CP-invariance violation.

Recommendation 2.3: The timeliness of the ESSnuSB proposal should be considered in the light of the likely timescales and performance of the DUNE programme and, if approved, the Hyper-K programme.

2.4: The focus of the long-baseline neutrino community has recently been on establishing DUNE and proposing Hyper-K. If the science demands a further program with a performance that substantially exceeds that of the ambitious DUNE and Hyper-K experiments, new accelerator and/or detector technologies will be required. An R&D program will be needed to deliver feasible options at the appropriate time. This R&D is likely to take many years and needs to be well justified and carefully planned.

Recommendation 2.4: ICFA should encourage a process, informed by the neutrino community, to assess the scientific case for a long-term accelerator and/or detector R&D programme aimed at the post-DUNE/Hyper-K era as a first step in defining the R&D programme that is required. Assessment of the scientific case will require sustained activity in neutrino theory and phenomenology including significant developments in the understanding of neutrino-nucleus scattering.

Recommendation 2.5: The forum provided by the series of International Meetings for Large Neutrino Infrastructures is invaluable to ensure the coherent development of the global programme and should be continued with a strong accelerator-based component.

3 Sterile neutrino searches at accelerators

3.1: Unambiguous evidence for sterile neutrinos would constitute a breakthrough of fundamental significance and would revolutionise the field while unambiguous confirmation of the short-baseline anomalies would warrant energetic investigation.

Recommendation 3.1: The present generation of accelerator-based sterile-neutrino-search experiments, including those that constitute the SBN Program at FNAL, should be exploited so as to maximise their sensitivity.

3.2: Results from the SBN Program and other sterile-neutrino-search experiments will be available by $\approx$2020. It will then be timely to decide on the future direction of the accelerator-based sterile-neutrino-search programme.

Decision point 3.1: $\approx$2020: Decide on the future direction of the accelerator-based sterile-neutrino-search programme.

3.3: Beyond the SBN Program, the way forward will depend on the strength of the evidence for sterile neutrinos.

Recommendation 3.2: The sensitivity, cost, schedule and relative strengths of the proposed next-generation accelerator-based sterile-neutrino-search experiments (IsoDAR, nuSTORM) should be evaluated in preparation for a decision to be made on the future direction of the sterile-neutrino-search programme in $\approx$2020. In the mean time, the R&D programme necessary to establish the requisite capabilities should be carried out.

4 Supporting programme

4.1: An appropriate programme of hadro-production and neutrino cross-section measurement is required to allow the present and next generation of long- and short-baseline experiments to achieve their full potential.

4.2: Measurements of hadro-production cross sections are critical to reducing the systematic error budget of future accelerator-based neutrino-oscillation measurements. At present, the only experiment that is in operation is NA61/SHINE, which is scheduled to complete operation in 2018. It is timely to consider the requirements for measurements of hadron spectra beyond those that NA61/SHINE will provide.

Recommendation 4.1: ICFA should encourage careful and timely consideration of the requirements for a hadro-production measurement programme to follow NA61/SHINE including possible extensions to the NA61/SHINE programme.

4.3: The present neutrino-nucleus cross-section measurement program is vibrant and appropriate to serve the present generation of experiments over the next five years. The detectors that serve the Short Baseline Neutrino (SBN) Program and MINERνA will support an excellent neutrino scattering programme.

4.4: In the medium term, the near detectors that are part of the DUNE and Hyper-K experiments will take the neutrino-interaction programme forward. Novel techniques such as the high-resolution tracking detector proposed for DUNE and NuPRISM proposed for T2K/Hyper-K have the potential to enhance the precision with which muon-neutrino interactions are known. Robust, timely execution of the near-detector programme at DUNE and Hyper-K is essential for the experiments to meet their sensitivity goals.

Recommendation 4.2: The near detector programme at DUNE and at Hyper-K should be pursued energetically so that neutrino-scattering measurements of the requisite precision are available to allow the experiments to perform to their specified sensitivity.

4.5: Over the coming four to five years, progress in the measurement of neutrino-nucleus scattering will be made using, for example, the SBN detectors and MINERνA. Substantial theoretical and phenomenological progress in the particle and nuclear physics of neutrino-nucleus scattering, beyond the current effort, which is sub-critical, will be required over this period.

Recommendation 4.3: ICFA should encourage and promote a vibrant, sustained effort towards reliable, precision calculation of neutrino-nucleon and neutrino-nucleus scattering. An approach that promotes and exploits the synergy between the particle theory, nuclear theory and experimental neutrino communities should be adopted.

4.6: Captain-MINERνA, which has Stage I approval from the Fermilab PAC, and the near detectors that form part of the DUNE and Hyper-K programmes will take the neutrino-scattering programme forward. If approved, Captain-MINERνA will provide valuable, detailed information on neutrino-argon scattering by the end of the present decade. The detailed specification of the DUNE and Hyper-K near detectors will be resolved over a similar timescale. It will therefore be timely to decide on the long-term development of the $\overset{(-)}{\nu}N$-scattering programme around ≈2020.

Decision point 4.3: ≈2020: Decide on the future direction of the neutrino-nucleus-scattering programme based on experimental and theoretical progress and the needs of the future neutrino programme.

4.7: The requirements of DUNE and Hyper-K will drive the specification of the neutrino-cross-section-measurement programme. The path forward, beyond the present generation of $\overset{(-)}{\nu} N$ scattering experiments, will be determined by the degree to which existing techniques (on and off-axis near detectors illuminated with pion-decay beams) can deliver measurements of the requisite precision.

Recommendation 4.4: The proposed next-generation neutrino-scattering experiments, for example nuSTORM, should be evaluated in preparation for a decision on the future direction of the neutrino-scattering programme to be made in ≈2020.

4.8: An exciting programme of detector R&D is being carried out across the world targeted at delivering the technologies required by DUNE, Hyper-K and the Short Baseline Neutrino Program.

Recommendation 4.5: The present detector R&D portfolio should be completed. Provision should be made for an appropriately resourced detector-development programme over the lifetime of the next generation of experiments.

4.9: The development of MW-class sources at FNAL and J-PARC are critical to the delivery of the experimental programme. To go beyond the sensitivity and precision of the next generation of accelerator-based experiments is likely to require the development of novel accelerator capabilities. It is likely that increased international cooperation and collaboration will be required to deliver these programmes. The MICE experiment and the RaDIATE programme are recognised as important contributions to the field, each offering the possibility of generating a legacy of enhanced capability.

Recommendation 4.6: Opportunities for international cooperation and/or collaboration in the development of MW-class neutrino sources should be actively pursued.

Recommendation 4.7: The MICE experiment should be completed to deliver the critical demonstration of ionization cooling. ICFA should encourage the timely consideration of the accelerator R&D programme that is required beyond MICE to develop the capability to deliver high-brightness muon beams.

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A The ICFA Neutrino Panel

ICFA established the Neutrino Panel with the mandate [4]:

> *To promote international cooperation in the development of the accelerator-based neutrino-oscillation program and to promote international collaboration in the development a neutrino factory as a future intense source of neutrinos for particle physics experiments.*

The membership of the Panel agreed by ICFA at its meeting in February 2013 is shown in table 4. The terms of reference for the panel [5] may be found on the Panel's WWW site [1].

Table 4: Membership of the ICFA Neutrino Panel.

Name	**Institution**
J. Cao	IHEP/Beijing
A. de Gouvêa	Northwestern University
D. Duchesneau	CNRS/IN2P3
S. Geer	Fermi National Laboratory
R. Gomes	Federal University of Goias
S.B. Kim	Seoul National University
T. Kobayashi	KEK
K. Long (chair)	Imperial College London and STFC
M. Maltoni	Universidad Automata Madrid
M. Mezzetto	University of Padova
N. Mondal	Tata Institute for Fundamental Resarch
M. Shiozawa	Tokyo University
J. Sobczyk	Wroclaw University
H. A. Tanaka	University of Toronto, IPP, TRIUMF
M. Wascko	Imperial College London
G. Zeller	Fermi National Accelerator Laboratory