NUFACT11 Round Table Discussion – Questions & Answers

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Abstract. This presents the response to questions formulated by a round table discussion panel to the NUFACT11 participants. The main points made were as follows.
Neutrino mass is physics beyond the Standard Model; it presents a very deep puzzle to solve, with the answers to several fundamental questions as potential reward. Precision measurement of oscillation parameters is one essential way to access information needed to solve this puzzle and there is a relatively clear (but not easy) way forward. Large $\theta_{13}$ makes the appearance signals larger, but does not allow to relax the requirements on high beam intensity and large detector masses; it creates a difficult challenge on systematic errors, which will require dedicated ancillary experiments. Of particular interest is a low intensity muon storage ring for required cross-section measurements.

There exist already extended bottom-up international collaboration in both physics and R&D experiments. All three main regions have plans for upgraded super-beams and associated detectors, with a variety of (mostly) complementary baselines, proceeding in an incremental way. The ultimate precision and verification of the neutrino mixing picture requires new types of neutrino beams based on storage rings. For low energy neutrinos, the beta-beam is a possible (but substantial) intermediate step. The Neutrino Factory offers the best precision and best sensitivity to deviations from the standard picture. Coordinated international R&D is pursued. International collaboration at the top level would be beneficial in acknowledging the process, so as make sure that intermediate steps are effectively building up in complementary fashion towards the ultimate goals.

1. The round table and the questions.

The round table discussion took place on 1st August in the CERN main auditorium. The invited members were: S. Bertolucci (CERN), K. Nishikawa (KEK), J. Strait (Fermilab), J. Womersley (STFC), T. Nakada (ECFA), S. Myers (CERN), S. Komamya (ICFA). The discussion was chaired by John Ellis (CERN). A number of questions had been prepared by the NUFACT11 scientific program committee and were used as a starting point for the discussion (see appendix). Somewhat unconventionally this round table discussion took place on the first day of the meeting. As an outcome the panel members addressed the participants with a number of questions.

Sergio Bertolucci
I hear that international collaboration on coordinated R&D is lacking. Could the community propose a realistic plan for common and staged neutrino R&D?
Sachio Komamiya
Physics question: $\theta_{13}$ & $\delta$ are similar to $V_{ub}$ and CP phase in the quark sector. In heavy flavors, angles are not really the interesting thing – and CP violation there is found to be insufficient to generate Baryogenesis. How about neutrinos? We know about Lepto-genesis, is there further fundamental physics in neutrinos beyond the numerical values of the angle and phase?

Steve Myers
As an accelerator physicist, there are too many options – we need to kill some to make progress. Need to make a choice, define the next steps, define critical R&D and move on. What is it that the community really wants to build?

Tatsuya Nakada
In the incremental approach, where does a Beta Beam fit? This question is in regard both to the physics case and the R&D needs.

Koichiro Nishikawa
In the near term, the international framework should be bottom up and not top down? At what point should an international framework be forced from the top?

Jim Strait
A. If you didn’t have a Neutrino Factory, how precise a measurement of parameters can be done with Superbeams before reaching their limitations?
B. What “external” measurements, e.g. particle production, neutrino cross sections, etc., can be done to improve the current systematic error limits on Superbeam experiments, and what are the ultimately limiting systematic errors?

John Womersley
A. Do I need to worry whether neutrino and antineutrino oscillation parameters are the same, or worry about the LSND anomaly?
B. Do neutrinos play a role in dark matter, especially if there is no light neutralino?
C. Since STFC and funding agencies from other countries in Europe, the US, and Japan are investing substantially in MICE, please consider, given the new indications that $\theta_{13}$ may be large, the importance of continuing to support R&D for the Neutrino Factory (and ionization cooling in particular).

2. The Answers
These questions were written up by the organizers and distributed to the participants, then debated during dedicated Working Group sessions at the workshop (which thus really did some work!) – or as usual during informal discussions at coffee breaks or workshop dinner. The answers were collected through the NUFACT working group conveners or directly by messages to the editors. These questions can be grouped in three sets, which are not completely disconnected:
2.1 Fundamental physics questions (Komamiya, Womersley A and B)
2.2 Technical physics questions regarding neutrino oscillation experiments (Strait A and B, Nakada)
2.3 Strategic questions regarding staging, international collaborations and R&D programs

2.1. Fundamental Physics questions
The information we can obtain from neutrinos is complementary to the one from the quark sector. We stress that the study of quark flavor physics led to many more results than just the determination of the CP phase and of the mixing angles, it led to a precise experimental verification of the CKM
mechanism and is very sensitive to new physics at scales around and above the electro-weak scale and couplings commensurate to those of the Standard Model particles, which would contribute to observables via direct or loop processes. In that way quark flavor physics leads to stringent constraints on this type of physics beyond the Standard Model.

In contrast, neutrino mass is direct manifestation of Physics Beyond the Standard Model. The relevant energy scale can be anywhere from very low scale (sub-eV) up to the GUT scale ($10^{16}$ GeV).

We do not know the mechanism for the generation of neutrino masses; many models have been proposed, invoking such concepts as Grand Unification, String Theories or compositeness. It is fair to say that so far none of these has proven very predictive, the neutrino masses and mixing themselves having been subject to a large number of incorrect predictions.

In this context, the precise measurement of mixing angles and CP phase (the neutrino “PMNS” matrix) is one essential element (a “first step”?) in deciphering this fascinating puzzle. The values of the parameters of the PMNS mixing matrix and of the neutrino mass matrix (or matrices?) are either fundamental constants of nature or are derivable from some currently-unknown higher theory. In either case we must determine these numbers experimentally, and there is no other way to do it than by dedicated oscillation experiments of the type that were discussed at NuFact11. We must explore neutrino mixing experimentally to the full before we will be in any position to create or test any higher scale model. A guideline recommendation (in absence of a more quantitative argument) is to test the neutrino mixing paradigm with the same level of accuracy as that of the quarks.

The puzzle receives complexity with respect to charged quarks and leptons because Majorana mass terms are allowed in addition to the more standard Dirac mass terms. In many models it arises naturally that there should exist in addition to the three known (left-handed) neutrino species, an additional set of, at least two and generally three, right-handed neutrinos. These ‘sterile’ neutrinos may have the same masses as the known left-handed ones in the situation where neutrinos receive their mass only from Dirac mass terms, e.g. from the Higgs Yukawa couplings. If there exist, in addition, Majorana mass terms, right-handed neutrinos acquire different masses from the left-handed ones by the “see-saw mechanism”. Although most Grand Unified Theory scenarios send these right-handed neutrinos to very high masses, this needs not be the case and one or more of the ‘sterile’ neutrinos could exist at low masses, providing a possible candidate for dark matter, or providing visible signals at the LHC. Some could be massive enough to provide a natural mechanism for the Baryon-Antibaryon asymmetry of the Universe via Leptogenesis. The presentations by Shaposhnikov, Mavromatos, Mohapatra and Senjanovic among others have highlighted the depth of the neutrino questions and the variety of solutions neutrinos have to propose to well known cosmological and particle physics questions.

More specifically for Dark Matter (DM): we know that the left-handed neutrinos are a small part of the DM (hot DM); it is known that keV right-handed (sterile) neutrinos can provide all of the dark matter (warm DM). This possibility is maybe even slightly favored over cold DM by structure formation arguments. Furthermore, if DM is made of WIMPs, neutrinos do play a role in the search for it: DM annihilates into neutrinos, solar neutrinos are a background in DM direct detection experiments, NC neutrino scattering experiments are needed to get information on DM-nucleus interactions, and finally there are experimental similarities between neutrino and DM detector requirements.

Measuring the masses of neutrinos and establishing the existence or otherwise of Majorana mass terms are further aspects of this detective work which may become accessible in the upcoming decades. Yet these important steps will not answer all questions. We still do not know for instance how the
Majorana phases could be measured should neutrinos be Majorana particles. We certainly do not have the slightest idea yet how to perform measurements on sterile neutrinos and if or how they can ever be discovered. For these reasons, any hints, however experimentally disputed they may be, like the LSND anomaly -- or the recent OPERA neutrino time-of-flight anomaly -- must be followed up carefully because sterile neutrinos may quite naturally exist -- or because some other anomaly may exist that we have not actually thought about theoretically.

To conclude: we know enough about neutrinos to predict that they offer an extremely rich and deep field of investigation, and we know of a reasonably well defined experimental track to follow. However it is fair to expect surprises along the way. Experiments should be ready for that.

2.2. Technical questions regarding neutrino oscillation experiments.

The physics reach of future neutrino oscillation experiments in CP violation and Mass Hierarchy is intimately associated with issues of systematic errors and backgrounds in a way that is connected to the exact value of the mixing angle \( \theta_{13} \). This is a rapidly evolving field and the following will provide a snapshot of the present situation. More definite answers will certainly be available by NUFACT12!

A summary of present sensitivity estimates can be found in the report by W. Winter at the workshop.

Several studies have shown that unless \( \theta_{13} \) is very large (above \( \sin^2 2 \theta_{13} \gtrsim 0.11 \)) it will be very difficult for the combination of presently approved experiments (T2K, NOvA, and the reactor experiments Double Chooz, Reno, Daya Bay) to make a definitive determination of the neutrino mass hierarchy, \( \text{sign}(\Delta m^2_{13}) \). (see e.g. S. Prakash et al in these proceedings and the article of Patrick Huber, Manfred Lindner, Thomas Schwetz, Walter Winter, JHEP 0911:044,2009, arXiv:0907.1896v1 [hep-ph]). Superbeam experiments with a longer baseline than NOvA will be needed to answer that question.

Concerning the CP violation, the evidence from T2K, MINOS (and in November 2011, Double Chooz) indicates a value of \( \sin^2 \theta_{13} \) in the vicinity of 0.08\( \pm \)0.03; the error is asymmetric so the value is non-zero with a significance in excess of more than 3\( \sigma \). The situation will evolve rapidly in 2012. This large value has the advantage that the signal reaction \( \nu_\mu \to \nu_e \) is larger and easier to separate from backgrounds. The counter-intuitive effect that it reduces to less than 20% the CP asymmetry:

\[
A_{CP} = \frac{(P( \nu_\mu \to \nu_e) - P( \bar{\nu}_\mu \to \bar{\nu}_e))}{(P( \nu_\mu \to \nu_e) + P( \bar{\nu}_\mu \to \bar{\nu}_e))}
\]

The reason is that, while the numerator is proportional to \( \sin \theta_{13} \), the denominator is driven by the appearance probability itself which scales with \( \sin^2 2 \theta_{13} \). As a consequence the relative statistical accuracy on the asymmetry itself does not improve. The large value of \( \theta_{13} \) does not allow to relax the need for high intensity and high detector mass.

Furthermore, the measurement becomes very sensitive to systematic uncertainties on the signal itself, i.e. on cross-sections within experimental cuts, and to the knowledge of the matter effect. One should bear in mind that \( \nu_e \) and \( \bar{\nu}_e \) cross sections can be different from those of \( \nu_\mu \) and \( \bar{\nu}_\mu \) of the same energy because of the interplay of muon mass effects with i) nuclear effects and ii) pion production thresholds; they should be measured.

The estimates of sensitivity to \( \delta \) that can be found in the literature are often relatively vague about the assumptions made on systematic uncertainties; their dedicated understanding will be a major subject of study towards NUFACT12. In this context several aspects of neutrino experiments will be emphasized:

1. The near detector design
2. The ancillary experiments to improve predictions of neutrino flux (hadroproduction experiments) for the Superbeam experiments

3. Ancillary measurements of appearance signal cross-sections

The best (2-3% precision) measurements of neutrino cross-sections were made with muon (anti)neutrino beams in the early 80’s above 40 GeV neutrino energy, on heavy isoscalar targets with dedicated exposures to a narrow band beam (at CERN) or dichromatic quad-triplet beam (at Fermilab). In the energy range of interest (200 MeV to 5 GeV) for the determination of the neutrino mixing angles in beam experiments, the best measurements are rather in the 7-15% range. To measure a CP asymmetry, the maximum value of which is at most about 20%, when one or two of the four relevant neutrino cross-sections is measured to ±7%, and the others not at all, is a difficult starting point for a 5σ discovery. In addition to the high intensity neutrino beams and large detector masses required, a demonstration that the experiment can be designed to control systematic errors at the few % level will be mandatory before a clear conclusion on the chance of a future project to “discover Leptonic CP” can be assessed.

The Neutrino Factory design studies have developed at this point the most complete discussion of systematic uncertainties – with a stored beam of muons, the flux can be predicted from muon decay to better than a percent, so a well designed near detector can measure all relevant cross-sections ($\nu_\mu$, $\nu_e$, $\bar{\nu}_\mu$, $\bar{\nu}_e$) to this accuracy.

Does this imply that a definitive measurement of CP violation must await construction of a Neutrino Factory? The answer is: perhaps not. A mini-Neutrino Factory may provide the Superbeam experiments with the cross-section measurements they need. One of the highlights of the NUFACT10 and NUFACT11 workshops was the presentation, (A. Bross et al), of the ‘mini-neutrino-factory’ or Low-energy Low-intensity Low-cost Neutrino Factory (L3NF), in which a storage ring of medium energy is used to store muons directly in a way similar to the antiproton production systems of CERN and FNAL. The quality of cross-section measurements which are trademarks of the Neutrino Factory should be preserved, but the required muon intensity is considerably reduced. This experiment can also pursue search for sterile neutrinos in its own right and constitutes an interesting R&D step towards the full size Neutrino Factory. The experiment is under evaluation but seems to be promising.

It remains very likely that the Neutrino Factory will offer the best precision and there exist a significant fraction of phase space where only the Neutrino Factory can make a definitive measurement. In addition, measurements specific to high energy electron neutrinos such as $\nu_e \rightarrow \nu_\tau$ cannot be made anywhere else. However, as was emphasized in the round table discussion, the Neutrino Factory is a large step to climb, and there is considerable interest from the community to proceed in an incremental fashion, building up expertise and community, ascertaining the limitations of the Superbeam experiments along the way.

What is the role of the beta-beam in an incremental approach? The Working Group WG1 (neutrino oscillations) could not reach a consensus on this issue; we summarize here the pros and cons.

By construction the Beta Beam provides a low energy (up to 1 GeV for the CERN-SPS baseline scenario) beam of pure $\nu_e$ or $\bar{\nu}_e$ depending on the stored ion. There has been considerable progress on understanding how to produce sufficient amounts of the baseline ions, $^{6}\text{He}$ and more critically $^{18}\text{Ne}$. The perceived virtue of beta-beam lies in the fact that it can be deployed on the CERN site using the PS and SPS as ion accelerators; it remains true that the ion source and pre-acceleration, as well as the storage ring, equivalent in magnetic rigidity to a 300 GeV/c proton storage ring, are non-trivial. Moreover, the issue of irradiation by ion losses and decay products of the CERN accelerators and of the storage ring is considerable. The baseline scenario Beta Beam matches well the Water Cherenkov
technology and a distance of the order of 300-500 km. Here the physics aim would be essentially the search and measurement of the CP violation. The baseline to the Frejus site at 130 km is acknowledged to be on the short side of optimal. At large values of $\theta_{13}$ the backgrounds are not critical, so the duty cycle requirements can be somewhat relaxed.

From the point of view of flux control, the Beta Beam should offer many of the advantages offered by the Neutrino Factory: the number of ions can be directly measured and the neutrino flux prediction should be accurate to better than 1%. Beta Beams will be able to measure the relevant $\nu_e$ ($\bar{\nu}_e$) cross-sections with an accuracy of this order. However since the signal is the appearance of a $\nu_\mu$, ($\bar{\nu}_\mu$), these cross-sections need to be known, especially in the ~250 MeV region of the first oscillation maximum for the Frejus experiment, where nuclear effects and the muon mass effect are important. The Beta Beam will rely on measurements that have to be performed in a low energy pion decay beam (or mini-Neutrino Factory of low energy), in a rather unfavorable region – it remains to be demonstrated that the desired accuracy can be reached. There is at the moment no proposal worked out for a near detector station in the beta-beam and it is difficult to judge what precision can be achieved on a CP asymmetry. The sensitivity curves shown so far indicate that a Beta Beam to Frejus would be of similar accuracy (and nicely complementary) to a Superbeam in measuring the CP phase. Both the Superbeam in question, which involves a 4MW Superconducting Proton Linac to be built, and the Beta Beam, are seen as rather high steps for an ‘incremental’ path. A more complete assessment of these issues will be available when EUROnu and LAGUNA-LBNO design studies will be completed, in 2012 and 2014 respectively.

2.3 Strategic questions regarding staging, international collaborations and R&D programs

There are presently four neutrino beams in operation performing neutrino oscillation experiments. The CNGS beam at CERN serves the experiments OPERA and ICARUS. The NUMI beam at Fermilab serves MINOS, MINERvA, ArgoNeuT and will serve NOvA; the Booster neutrino beam at Fermilab serves MiniBooNE, SciBooNE, and will serve the MicroBooNE experiment. The T2K beam serves the T2K experiment.

There exist already a number of bottom-up international collaborations to study future projects. Several regular international meetings occur yearly: the NBI workshops for neutrino beams and instrumentation, the NUFACT workshops, dedicated to Superbeam, Beta Beam and neutrino factories; the NNN workshops dedicated to the large underground detectors for nucleon decay and neutrino experiments; the NUINT workshops for studies of neutrino interaction cross-sections. The ongoing oscillation experiments T2K, MINOS, OPERA, Double Chooz are international collaborations involving physicists originating from two or all of the three world regions. The ongoing design studies for DUSEL (USA), T2HK (Japan), EUROnu and LAGUNA-LBNO are more regional and address a more concrete localized scenario – a necessary step to identify and solve concrete issues. The International Design Study for the Neutrino Factory is inter-regional, but it is not addressing a localized scenario. The R&D experiments such as MERIT (at CERN), MICE (at RAL) and EMMA (at Darsbury lab) for the Neutrino Factory, or 60GHz ion source (LPSC, Grenoble, and IAP, Nizhny Novgorod), isotope production (ANL, INFN Legnaro) for Beta Beams, are run by international collaborations.

The question of top-down coordination was already raised after the first NUFACT99 workshop and while it did not materialize by a program of coordinated oscillation experiments, it led to the international collaboration for the Neutrino Factory R&D experiments mentioned above.

Has time come for a top-down coordination?
The number of questions to be answered in neutrino physics is large: CP violation, mass hierarchy, precise measurements of parameters, tests of unitarity, searches for sterile neutrinos and search for other more exotic scenarios. While a Neutrino Factory is claimed to be able to solve a large fraction of these questions in a definitive way, no large laboratory has proposed to host it, and it is hoped that one can have a first look at these questions by a number of incremental and complementary steps with advantages in terms of funding profile and continuity of activity, while the most critical R&Ds for the long term are being pursued.

There appears to be three next-generation Superbeam experiments being discussed or proposed – one in Japan with T2HK (295 km) or Tokai to Okinoshima (658km), on in the the USA with DUSEL (1300 km), and, one in Europe with either the CERN to Frejus (130km) project which is also suitable to a Beta Beam, or from CERN to Pyhasalmi (2285km), with an improved replica of the CNGS beam, which is a good baseline for a Neutrino Factory. (The DUSEL baseline itself would be suitable for a lower energy Neutrino Factory). One can see from the variety of baselines (and detectors) that there are complementarities in these approaches, both for physics and for the detector technologies. As mentioned above it is almost certain that once choices have been made international collaborations will be put in place for each of the successful projects. Note that care is sometimes taken to make sure that the project is suitable for a long term vision with more ambitious beams.

The question is the following. Is there space and need for collaboration and focusing of efforts to realize sooner a more ambitious project? Or is the variety and wealth of physics such that regional projects can be carried out in such a way that different experiments situated in different places provide each their piece of the puzzle or the necessary verifications while maintaining a deliberate level of competition? In the longer term we will no doubt pursue even more ambitious facilities, however it would appear premature to decide on the exact makeup and location of such projects now. Enhanced high-level support for performing the R&D necessary to position ourselves to be able to build such facilities constitutes a much valued investment for the future to ensure that progress in this important field continues in a healthy way. The working group were unanimous that e.g. the Muon Cooling R&D should be pursued actively and efficiently, as it will certainly be needed for the Neutrino Factory or a Muon Collider.

Acknowledgements
We would like to thank wholeheartedly the round table participants for their enthusiastic response to our invitation and of their careful preparation of the questions asked by the program committee. That the committee replied by formulating questions of their own was a tremendous stimulus to the whole workshop. The program committee prepared the initial questions and contributed substantially to phrasing and correcting the answers. The answers themselves originated from discussions in the working groups. The working group conveners animated these discussions, worked hard and late in concatenating and formulating the answers in their conclusions; the success of NUFACT is greatly due to their dedication and skill.
APPENDIX: Questions asked to the panel by the NUFACT11 Program Committee

21 May 2011

**Future Neutrino Facilities in the Global Physics Environment**

**Proposed Questions for NuFact11 Round Table**
by the NUFACT11 Scientific Program Committee

(NB emphasis is placed on neutrino oscillation experiments)

1. Is the “incremental” approach to experimental neutrino oscillation physics the best way for the international community to proceed, or should a big step to a Neutrino Factory be advocated? If a big step is deemed appropriate, when should it be envisioned?

2. Up to what levels do you think the regional neutrino programs should work, and when and how do you envision that a fully international framework of neutrino projects is needed and should be formed? What do you think is “missing” that prevents a decision being made on a large international neutrino project: a determination of $\theta_{13}$, a community consensus, a political decision at ICFA level, technological issues…?

3. What room do you see for accelerator-based neutrino projects besides the other particle physics projects (e.g. in Europe besides the LHC)?

4. What might be the scientific impact of LHC results on the neutrino program?

5. What do you think are the most important goals in neutrino oscillation physics and what do you think are the best ways to get there? What relative importance/organization should be given to the mainline program (unraveling 3x3 mixing including CP violation) with respect to search for exotics such as sterile neutrinos, Non-standard interactions, etc

6. How important is it that proposed giant neutrino detectors serve additional physics needs – how bad is it if they don’t?

7. What importance do you attach to the Neutrino Factory being on the upgrade path toward a Muon Collider?