The UK neutrino-physics programme:

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1. Neutrino oscillations: the window on Physics beyond the Standard Model

The international scientific community has recognised the fundamental importance of the observation of neutrino oscillations. Mixing among the three flavours of neutrino leads to the possibility that CP violation occurs in neutrino oscillations; the search for leptonic CP violation is therefore of first importance. Of the challenges that face the particle-physics community, understanding the physics of flavour and the observed hierarchy of particle masses are two of the most important. The properties of the neutrino are unique: its mass is tiny compared to that of the other fundamental fermions; the neutrino mixing-matrix elements are huge compared to those of the quark-mixing matrix; and the neutrino appears to have no conserved ‘internal’ quantum numbers, implying that the neutrino may be its own antiparticle. The consensus is, therefore, that a detailed understanding of the properties of the neutrino is essential for the theory describing the physics of flavour to be discovered.

Neutrino masses and mixings have fundamentally important implications for cosmology. As an example, consider the removal of all the antimatter created in the Big Bang. It is believed that CP violation in the quark sector is too weak to cause the removal of antimatter at the level observed. CP violation in the lepton sector may give the required additional contribution. Leptogenesis, the process by which a lepton-number asymmetry is turned into a baryon asymmetry, is driven by additional sources of CP violation present in the mixing matrix of heavy Majorana neutrinos. Though the observation of CP violation in neutrino oscillations is not a sufficient condition for leptogenesis, there are indications that, if leptogenesis occurs at the required level, CP violation is likely to occur in neutrino oscillations.

Neutrino oscillations are the only established indication of physics beyond the Standard Model. The ultimate theory must surely unify the quark and lepton sectors, making measurements of the properties of the neutrino with an accuracy comparable to that which is available in the quark sector essential. These observations justify an energetic experimental programme encompassing the measurement of the neutrino mixing parameters, the search for leptonic CP violation, and the search for neutrinoless double-beta decay. The following paragraphs will address the UK neutrino-oscillation programme.

2. The UK neutrino-oscillation programme

To accommodate neutrino oscillations, the Standard Model has been extended to include three mixing angles, $\theta_{12}$, $\theta_{23}$, and $\theta_{13}$, a phase, $\delta$, which if non-zero (and not equal to $\pi$) implies CP violation, and two mass-squared differences, $\Delta m_{31}^2$ and $\Delta m_{21}^2$. The parameters $\theta_{12}$ and $\Delta m_{21}^2$ (magnitude and sign) have been determined using solar and reactor neutrinos. Atmospheric and long-baseline muon-neutrino beams have been used to determine $\theta_{23}$ and $\Delta m_{31}^2$ (magnitude only). Fits to oscillation data have allowed an upper limit on $\theta_{13}$ to be extracted. There is no information on the sign of $\Delta m_{31}^2$ or the CP-violating phase, $\delta$.

The experimental neutrino-oscillation programme in the UK is designed to:

- Make a precise measurement of $|\Delta m_{31}^2|$ and potentially improve the lower limit on $\sin^2 2\theta_{23}$, verify the neutrino-oscillation paradigm, and make an initial search for a non-zero value of $\theta_{13}$ (MINOS);
Seek to determine $\theta_{13}$, refine the measurement of $\theta_{23}$, and $|\Delta m^2_{31}|$, and make an initial search for leptonic-CP violation (T2K); and

Carry out an R&D programme by which the conceptual and technical feasibility of the Neutrino Factory, the facility that offers the best discovery reach in $\delta$, the mass hierarchy, and the best precision on the oscillation parameters will be established (UK Neutrino Factory collaboration and MICE).

2.1 MINOS

MINOS is a long-baseline neutrino oscillation experiment designed to study neutrino physics at the $|\Delta m^2_{31}|$ scale responsible for atmospheric neutrino oscillations. The experiment uses two, functionally identical, detectors to measure the neutrino spectra from the intense NuMI beam at two different distances. The MINOS Near Detector at Fermilab samples the unoscillated beam at a distance of 1 km from its source. The measurements in the Near Detector provide a strong constraint on the neutrino beam spectrum. The MINOS Far Detector, deep underground in Northern Minnesota, samples the beam after it has travelled 735 km allowing a precise study of neutrino oscillations. The NuMI beam has been operational since 2005 and the MINOS experiment will be at the forefront of neutrino physics until the end of its planned running in 2010.

The MINOS far detector is able to identify efficiently charged current (CC) muon-neutrino interactions and neutral current interactions. It is also able to tag charged current electron-neutrino interactions. The main physics goals of the experiment are:

- To make a measurement of $|\Delta m^2_{31}|$ with a precision of better than 5%, a factor of five better than the best measurement from atmospheric neutrino data;
- To search for sub-dominant $\nu_\mu \rightarrow \nu_\tau$ oscillations, in order to obtain either the first measurement of $\theta_{13}$ or to set the most restrictive limits. Recent studies using a data-driven background determination show that MINOS is sensitive to values of $\sin^2 2\theta_{23}$ down to 0.06, considerably below the current Chooz limit, $\sin^2 2\theta_{23} < 0.15$;
- Using the high statistics samples of charged and neutral current events, MINOS can make a precise test of the neutrino oscillation hypothesis. For example, resolving the oscillation minimum in the energy spectrum of CC interactions can be used to exclude alternative models such as neutrino decay and quantum decoherence. The neutral current event rate measures the flux of all active neutrino flavours and the rate and energy distribution can be used to search for possible mixing with sterile neutrinos. It should not be forgotten that it is only relatively recently that neutrino oscillations were discovered. If our picture of neutrino oscillations is incomplete, MINOS is well placed to observe deviations from the current expectations; and
- The 1.2 T magnetic field of the MINOS far detector allows atmospheric-neutrino oscillations to be studied separately for neutrinos and anti-neutrinos, providing a test of possible CPT violating effects in the neutrino sector. It is also possible to make a more precise measurement of the oscillation parameters for anti-neutrinos by changing the direction of the current in the neutrino horns used to focus the beam.

The MINOS collaboration consists of about 180 scientists, with the UK making up approximately 20% of the collaboration. The UK is responsible for a number of essential aspects of the MINOS detectors, including: the DAQ and timing systems; the light-injection calibration system; PMTs and electronics; and major contributions to the reconstruction and analysis software. The UK was responsible for the MINOS calibration detector which was exposed to a test beam at CERN. Throughout the design, construction and
initial analysis of the data, the UK has played a major role in the scientific leadership of MINOS. The UK has provided the analysis coordinator, the chair of the publications committee, the chair of the institutional board, and four out of 14 members of the executive board. The UK also provides seven working group convenors covering all the main analysis working groups. The contribution from the UK far outweighs that which might be expected based on the 20% fraction of MINOS authors from UK institutes.

The next two or three years will see the most significant results and publications from the MINOS collaboration with UK physicists central to the analysis of the data. In addition, experience gained from working on a high intensity long-baseline neutrino oscillation experiment will strengthen the UK’s position in future neutrino experiments.

2.2 T2K
The T2K experiment has been fully described in recent submissions to STFC and in an accompanying submission to the consultation exercise. Here it is worthwhile pointing out that T2K fits into a general UK programme in neutrino oscillation physics that started with SNO and MINOS and will lead through T2K, MICE, and accelerator activities (and perhaps Double Chooz as well) to proposals to play a significant role in ultimate neutrino oscillation facilities such as the Neutrino Factory. The MNSP neutrino mixing matrix is at least as complicated as the CKM mixing matrix for quarks (the MSNP matrix actually came first, and the CKM matrix was modelled upon it), and it is therefore not surprising that a sequence of experiments will be necessary to explore it (we have, after all, been exploring the CKM matrix for more than 40 years with dozens of experiments, an exploration which continues today). T2K plays a central role in this programme. First, the more precise measurements of $\theta_{23}$ and more sensitive search for evidence for a non-zero $\theta_{13}$ will provide valuable understanding of the underlying models of neutrino mixing. Second, better understanding of the value of $\theta_{13}$ is essential to guide and motivate the future oscillation programme. Third, working on T2K is providing the UK with an ideal opportunity to build its expertise in key technologies for future neutrino facilities, in particular, high-power proton targetry (the UK is providing the engineering for the design of the target itself, and is designing and building a number of key components such as the target remote handling equipment and beam window) and detailed control of systematics in the near/far comparisons which are critical to any new precision long baseline experiment. Fourth, and by no means the least important, T2K is building a larger active experimental neutrino physics community in the UK, and therefore providing the bridge for the community between MINOS and future neutrino oscillation experiments.

2.3 UKNF and MICE
The UK Neutrino Factory (UKNF) collaboration has established an R&D programme that is internationally recognised. The programme encompasses: the development of capability in the key technologies required to generate high-power proton beams; the detailed investigation of the effect that beam-induced thermal shock will have on the high-power, pion-production target; and the demonstration of ionisation cooling through the MICE experiment. This work has been carried out in the context of the development of a complete conceptual design for the facility. In addition to creating teams of experts capable of taking the UKNF programme forward, the UKNF collaboration has played key leadership roles within the international Neutrino Factory community:

- The international MICE collaboration chose to site the experiment at the Rutherford Appleton Laboratory (RAL);
- The International Scoping Study of a future Neutrino Factory and super-beam Facility (the ISS) was initiated from the UK. The principal objective of the ISS was to “…lay the foundations for a full conceptual-design study of the facility.” The study achieved this objective; the reports from the
three working groups document the physics case and define an internationally agreed baseline for the Neutrino Factory accelerator complex and neutrino detectors;

- The International Design Study for the Neutrino Factory (IDS-NF) was established with a mandate to produce a Reference Design Report for the Neutrino Factory by 2012 with UK personnel again playing seminal roles; and
- The successful Design Study proposal to EU FP6 (EuroNu) is led from the UK and the UK provides the conveners of the Neutrino Factory and Detector work packages as well as the Neutrino Factory representative on the Management Board. EuroNu is of great significance: European labs have negotiated a common programme that will lead to the definition of a European strategy for the provision of high-intensity neutrino beams for the detailed study of neutrino oscillations.

UK personnel hold key positions of responsibility in each of these activities: in MICE the UK provides the Project Manager and Technical Coordinator, the Analysis Forum Convener, the MICE Muon Beam hardware and optics coordinators, the Tracker Module coordinator, and the Collaboration Board chair; the ISS was lead from the UK and the UK provided Council members in each of the ISS working groups; the IDS-NF is lead from the UK and, in each of the IDS-NF working groups, the UK provides one of the four working-group conveners.

UKNF and MICE-UK personnel are making world-leading contributions in each of the areas of UK responsibility. The UK is responsible for the MICE Muon Beam, the liquid-hydrogen system, the refurbishment of high-power RF amplifiers, the charged-particle tracking devices, and the focus-coil modules. The UK has provided designs for the proton driver, the muon front end, the ionisation cooling system, muon acceleration, and the storage rings. The proton driver Front End Test Stand, which is now going into the build phase in R8 at RAL has attracted collaborators from Spain and is coupled to the CERN-based HIPPI project. In addition, contacts are being established with HINS, a similar test-stand project at FNAL. The target-studies programme has demonstrated that solid targets could be used at the Neutrino Factory. EMMA, the proof-of-principal of the rapid acceleration of muons using non-scaling FFAGs, is being built at the Daresbury Laboratory. Finally, the UK is collaborating with the MuCool collaboration (part of the US Neutrino Factory and Muon Collider Collaboration) in the development of manufacturing techniques for high-gradient cavities. This work, which leverages significant resources from the US, and the work on non-scaling FFAGs (EMMA and PAMELA) has considerable potential for industrial involvement and knowledge transfer.

By carrying out and developing this programme, the UKNF collaboration will establish UK competence in the key technologies and design techniques that are required to make the Neutrino Factory an option for the field. In so doing, the collaboration seeks to position the UK to mount a bid to host the facility or to provide significant parts of the facility wherever it is sited.

3. Conclusions

The UK has established a neutrino-oscillation programme focussed on providing experimental confirmation of the neutrino mixing paradigm, measuring the main parameters, and developing the techniques required to perform sensitive searches for CP violation in the lepton sector. In implementing the conclusions of the Programmatic Review, we believe it is vital to ensure that the UK neutrino-oscillation programme can:

- Continue to deliver world-leading measurements of the key properties of the neutrino in both the short and medium term;
- Maintain the strong neutrino community in the UK and enhance the positions of leadership that UK personnel have established; and
- Maintain and enhance the world-leading Neutrino Factory accelerator R&D programme with a view to making the Neutrino Factory an option for the field and possibly for the UK.

This exciting and relatively new field has already delivered major scientific breakthroughs and neutrino physics will be one of the most significant areas of research in particle physics in the next decade and beyond. Through hard work and strategic investment, the UK has established a coherent programme of research into neutrino oscillations that is internationally recognised and in which UK personnel hold key positions of leadership. It is important that the implementation of the Programmatic Review protect and enhance this position across the field of neutrino physics.