Update of proposed French roadmap for Neutrino Physics

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Forewords:

Following the IN2P3-IRFU prospective days in April 2012, where a clear view on the possible research program from the French neutrino community was presented, the Scientific Council of the GDR2819 (neutrino) has prepared this short letter to recall and update the roadmap.

This roadmap was also submitted as an input to the European Strategy Preparatory Group for the symposium held in Krakow on September 2012. The document is available at: https://indico.cern.ch/contributionDisplay.py?contribId=31&confId=175067

Introduction:

For the last two decades, neutrino physics has been producing major discoveries including neutrino oscillations. These results gave clear confirmation that active neutrinos oscillate and therefore have mass with three different mass states. This is a very important result showing that the Minimal Standard Model is incomplete and requires an extension which is not yet known. The neutrino research field is very broad and active, at the frontier of today's particle physics. Several experiments have recently brought us another important step forward in our understanding of the flavour oscillation mechanism by measuring the third mixing angle of the PMNS matrix. Nevertheless, despite these great advances, many fundamental questions remain open in this area, which will require pursuing and developing a challenging experimental program. Among those important questions we find:

- What is the absolute scale of neutrino mass?
- What is the mass hierarchy?
- Are neutrinos their own antiparticles?
- Are there "sterile" neutrinos?
- Is there CP violation phenomena associated with the lepton mixing matrix?

These probable future discoveries will have important consequences for our understanding of matter and of the Universe, such as baryon asymmetry in the Universe, the nature of particle masses and questions of flavours. They may open a window on the physics beyond the Standard Model and on Grand Unification that is otherwise unattainable by searches at the high energy frontier. They would have an important impact in astrophysics, e.g. on core-collapse supernova physics and might be relevant as well in the context of the search for high energy neutrinos in the Universe. Throughout the recent prospective work on physics in France we showed how the next decade will see

the efforts of the French community in neutrino physics concentrated on four priority areas of investigation.

1. Pursue the PMNS mixing matrix investigation with the Borexino, OPERA, T2K and Double Chooz experiments.

These four experiments, among which three of them (OPERA, T2K and Double Chooz) have a strong involvement of French groups, are currently taking data or completing data analysis and that for the next three to five years. OPERA is expected to conclude its analysis by providing a clear proof of the ν_τ appearance in the CNGS ν_μ beam in less than 2 years. The T2K and Double Chooz experiments have provided in 2011 early indications and evidence of the large value of θ_{13}. These indications and observations have been confirmed in 2012 by the Daya Bay and RENO reactor experiments which have made measurements of this third mixing angle with unprecedented precision. The measurement of this angle is of great importance for the definition of the future experimental program to study CP violation in the PMNS matrix and determine the mass hierarchy.
The experiments will continue their data taking in order to provide improved measurements with careful systematics studies. Double Chooz is continuing with the construction and commissioning of the near detector for 2013. T2K has recently updated its ν_μ disappearance measurement leading to the best constraint of the θ_{23} mixing angle and this measurement will be continuously improved with the increased data sample. The physics program of T2K could be complemented by data taken in anti-neutrino mode, followed by an upgrade phase of the accelerator complex to increase the JPARC beam intensity. The combination of a precise measurement of θ_{13} by reactor experiments and the measurement of ν_e appearance may bring important information on the CP violation phase delta of the PMNS matrix.
It is interesting to mention that the measurement of a third large neutrino mixing angle has initiated new studies to investigate the possible complementarity of the mass hierarchy measurement using deep-sea/ice atmospheric neutrino detectors (like ORCA or PINGU).

2. Prepare future long baseline neutrino oscillation experiments and the quest for leptonic CP violation and mass hierarchy.

The recent measurements of large θ_{13} angle clarify the possible next steps in the exploration of the PMNS matrix. A large θ_{13} should allow a clear determination of the neutrino mass hierarchy and open the exciting possibility to measure the CP violation phase. These studies will require accelerator-based intense neutrino beams. Several approaches with various beam and detector technologies are considered in the world.
Considerable efforts are deployed on this program worldwide, with proposals in the USA (LBNE) and Japan (Hyper-Kamiokande, with a JPARC upgrade). In these studies Europe has considerable assets, especially with the possibility of a short baseline, CERN to Frejus 130

km, and that of a very long baseline, CERN to Pyhäsalmi of 2300 km. It is on these two options that LAGUNA-LBNO (European project that brings together the community interested in these studies) is working until 2014. The work relies on the significant role of CERN in these projects and is primarily focused on the option with a Liquid argon detector in Finland with an incremental approach, in which the mass of the detectors increases in successive stages, by modulating the construction effort. For each stage the physics goals are well defined for the neutrino PMNS matrix study. In addition to neutrino beam programs, major subjects such as astrophysical studies and the search for proton decay are covered by this experimental program. After a preliminary phase of studies (LAGUNA, EURONu, LAGUNA-LBNO) and a comparison of the various options the French community is in the position to make more explicit recommendations.

Those recommendations include also outputs from the European Strategy Group which states *the strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector* and that *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments.*

Having in mind these recent ESG recommendations, the CERN priorities and ongoing discussions on the Finnish position we also recognize the validity of the CERN to Pyhäsalmi option, outcome from the LAGUNA-LBNO studies. We are as well considering alternative options for beam and detector sites but keeping similar detector technologies and baselines as the ones foreseen in the context of the CERN to Pyhäsalmi program. In this situation:

- We strongly support such option for the first phase of the exploration of the Matter Hierarchy and CP phase with a powerful beam and a 20 to 100 kton Liquid Argon TPC plus a magnetised iron scintillator calorimeter.
- We stress the high potential of this underground observatory for a range of astrophysical measurements, including atmospheric, solar and SN neutrinos, and for GUT-related studies of nucleon decay.
- We recognize that this challenging program over more than a decade needs a matching program of R&D, both in the areas of high power proton accelerators and neutrinos beams and for the ambitious large mass neutrino detectors of the new generation.
- The French community has developed a coherent participation to the necessary detector R&D at CERN and proposes to contribute to the construction, operation and data analysis of a LBNO LAr prototype (6x6x6 m^3 -300 tons) proposed to the SPSC (June 2013).

A second phase in a long term strategy should be based on a better defined neutrino beam with well controlled flux intensity and flavours aiming at studying precisely the CP violation phase and performing a full investigation of the neutrino properties with a full coverage of all

neutrino transitions. In this respect, the Neutrino Factory seems to be the optimal solution for an ultimate neutrino beam.
A recent proposal of long baseline project based on the European Spallation Source (ESS) under construction at Lund emerged. ESS should have by 2023 the most powerful (5 MW, 2.5 GeV) proton driver in the world for neutron applications also providing an opportunity to produce in Europe a very intense, low energy neutrino beam. This machine, when coupled to the performance of a 500 kton Water Cerenkov detector, like MEMPHYS studied in the context of Laguna and Euronu projects, can perform CP violation search over a large fraction of the CP phase range, and mass hierarchy determination. We recognize that the investigation of using ESS proton driver to produce a very intense neutrino beam and work on the project design study is interesting and should be pursued. Thanks to MEMPHYS, this project can also address with very good performances a large range of astrophysical measurements, including atmospheric, solar and super novae neutrinos, and nucleon decay studies.
At the French level, R&D effort for Megaton class detectors should be supported.

3. Study the reactor and Gallium anomalies search for sterile neutrinos

The various anomalies related to the LSND experiment, to the calibration measurements of GALLEX and SAGE with an intense source, and more recently to the anomaly with neutrino flux reactor measurements cannot be easily described within a global interpretation with neutrino flavour oscillations in a minimal three-state model. Actually, some of them could indicate the existence of sterile neutrinos with mass of the order of eV. The clarification of the possible source of these anomalies or the absence of such physics anomalies should be addressed by the community and studied. Several experimental methods are proposed based on nuclear sources, reactors or short baseline accelerator experiments. The French groups are mainly involved in projects based on nuclear sources and reactors. The Nucifer experiment originally designed for nuclear non-proliferation could provide early indications in the direction of sterile neutrinos. Other experiments are under study, especially with very intense radioactive sources deployed in existing detectors (like KamLAND or Borexino) and with new measurements close to compact nuclear reactor cores, like at ILL and the STEREO project. The physics case and the short to medium term experiments foreseen may provide important neutrino physics results which are worth to get. The 2 types of experiments (source and reactor) should be strongly supported.

4. Neutrinoless Double beta decay search

The search for neutrinoless double beta decay is the only experiment which can tell us about the nature of the neutrino: Dirac or Majorana fermion. In addition, while difficult, it could

probe the type of mass hierarchy independently from the oscillation experiments. From a more general point of view, the observation of this rare process would imply total lepton number violation.

Given the fundamental and unique contribution that the search for a neutrinoless double beta decay can bring to neutrino physics and in general to physics beyond the Standard Model, a very rich experimental program is in progress worldwide on this subject, with several projects able in principle to approach the exploration of the inverted hierarchy region of the neutrino mass pattern. Two very promising detection approaches have been adopted by French laboratories.

- The approach of tracking and calorimetry, continues a long tradition that has seen France at the forefront of the search for this rare decay in the last years. These are the only technologies that provide access to all parameters of the two-electron final state. After Nemo-3, the SuperNEMO project aims to achieve sensitivity on the Majorana neutrino of about 0.05 eV with a scenario based on a sequential SuperNEMO module construction and commissioning after 2016. The construction of a demonstrator module of SuperNEMO has been accepted. It will host 7 kg of Selenium-82 and from the beginning of 2015 demonstrate the ability to reach the SuperNEMO background specifications, as well as have the sensitivity to the controversial signal observed by part of the Heidelberg-Moscow collaboration.
- An extremely promising development, based on the technique of scintillating bolometers, began recently. In this context, a pilot experiment (project LUMINEU) is now funded and will be performed within 2015. This search will be based on ZnMoO4 crystals enriched in 100Mo, a favourable double beta decay isotope. Further developments foresee the use of 10 kg of enriched material. Recently, the underground operation of large mass crystals of ZnMoO4 (about 300 g) showed that their internal contamination is compatible with the demanded background level of the final experiment.

Recommendations

The research program in neutrino physics proposed by the French community for the next ten years concerns:

- Oscillation studies and PMNS precision measurements.
- Anomaly investigation and search for sterile neutrinos.
- Future long baseline neutrino experiment for mass hierarchy determination and search for CP violation in the leptonic sector, proton decay.

- Study of the nature of the neutrino with the search for neutrinoless double beta decay process.

These research projects cover most of the fundamental questions of the field and short, medium and long term plans. The French neutrino community, both experimentalists and theorists, amounts to about 80-100 people. Their expertise is recognised internationally in various domains. It is important that the effort is maintained to keep the competence and the expertise in France. It is essential to guarantee a constant rate of new fresh positions along the time and the proper financing.
This research program requires developing several R&D for detectors and accelerators in the coming years. We also consider that it is essential for the next decades to have new world-class neutrino projects **in Europe** as complementary frontier research to the one performed at LHC.

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