Panel 1: 3-flavor Neutrino Oscillation

Marcos Dracos,[1] Mark Hartz,[2, 3] Patrick Huber,[4] Ryan Patterson,[5] Serguey Petcov,[6] and Ewa Rondio[7]
[1]*IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France*
[2]*TRIUMF, Canada*
[3]*Kavli IPMU (WPI), University of Tokyo*
[4]*Center for Neutrino Physics, Virginia Tech, Blacksburg, USA*
[5]*California Institute of Technology, Pasadena, USA*
[6]*SISSA/INFN, Trieste, Italy, and Kavli IPMU (WPI), University of Tokyo, Kashiwa, Japan*
[7]*National Centre for Nuclear Research (NCBJ), Warsaw, Poland*
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PREAMBLE

In this brief document we will focus on experimental programs and ideas which have at some level been recognized by funding agencies, either by outright funding them or by at least providing significant support for the R&D for the neutrino oscillation related aspects of the program.

INTRODUCTION

The discovery of neutrino oscillation dates back two decades and to this day is the most direct laboratory evidence for the existence of physics beyond the Standard Model (SM). Our theoretical understanding is lagging behind the experimental results in this field: neutrino physics remains data driven. In the absence of a generally accepted theory of flavor, the only path forward is to study neutrinos, and specifically for this write-up, neutrino oscillations, at ever increasing precision. The goal is to either find discrepancies relative to 3-flavor oscillations or to discover patterns and correlations among neutrino properties, which would guide us towards a theory of flavor.

Discrepancies with respect to 3-flavor oscillations can arise for a number of reasons, Wolfenstein proposed new interactions of neutrinos with quarks, but more exotic proposals exist, like neutrinos travelling through extra-dimensions. The enormous success of the SM in direct tests is tempered by the fact that the SM only describes about 5% of the energy content of the Universe. Leaving us with so-called portals: these are SM operators which are neutral under the SM gauge groups and thus can mix with dark-sector counterparts. There is a limited number of these portals, and for fermions this portal is realized by neutrinos. Neutrino oscillation is an interference phenomenon over long distances and therefore exquisitely sensitive to even the smallest new contributions to the phase evolution of mass eigenstates.

Most flavor theories invoke some type of symmetry, the observed pattern of neutrino mixing and the specific form of the neutrino mixing can have its origin in the existence of new fundamental symmetry in the lepton sector. The most distinctive feature of the symmetry approach to neutrino mixing are the predictions of the values of some of the neutrino mixing angles and leptonic CP phases, and/or of existence of correlations between the values of at least some the neutrino mixing angles and/or between the values of the neutrino mixing angles and the Dirac CP phase in the PMNS matrix, etc. This implies that a sufficiently precise measurement of the Dirac phase δ of the PMNS neutrino mixing matrix in current and future neutrino oscillation experiments, combined with planned improvements of the precision on the neutrino mixing angles, might provide unique information about the possible discrete symmetry origin of the observed pattern of neutrino mixing and, correspondingly, about the existence of new fundamental symmetry in the lepton sector. Thus, these experiments will not simply provide high precision data on neutrino mixing and Dirac CP parameters, but will probe at fundamental level the origin of the observed form of neutrino mixing. In order for this probe to be really effective one should aim at measuring the solar, atmospheric and reactor neutrino mixing angle parameters $\sin^2\theta_{12}$, $\sin^2\theta_{23}$ and $\sin^2\theta_{13}$ with 1σ relative uncertainties not exceeding approximately 0.7%, 3% and 3%, respectively, and the Dirac CP violation phase δ with 1σ uncertainty of approximately 10° at $\delta \sim 270^\circ$.

There is a global effort in neutrino oscillation physics, notably NOvA and T2K are currently running and are providing a first glimpse of CP violation in the lepton sector. JUNO in China will study oscillations of reactor antineutrinos related to the solar mass splitting starting in the early 2020s. Later in the same decade, DUNE in the U.S. and Hyper-K in Japan will study leptonic CP violation with great precision. Neutrino physics has become big science with collaborations of a size comparable to the LHC experiments. In the U.S. and Asia neutrino physics has taken center stage, at least for now, and the question is what role will Europe play?

STATUS QUO

Experiments with solar, atmospheric, reactor and accelerator neutrinos have provided compelling evidence for oscillations of neutrinos, which in turn implies a non-zero neutrino mass. Presently oscillation parameters within the 3-flavor framework are measured with few per cent level accuracy. This knowledge is based on contributions made by many experiments. Disappearance of solar ν_e, reactor $\bar{\nu}_e$ and of atmospheric ν_μ and $\bar{\nu}_\mu$ due to oscillations have been observed respectively, in solar neutrino [1]-[9], KamLAND [10, 11] and Super-Kamiokande [12, 13] experiments. Precision in this measurements has reached a level where 3-flavor treatment of oscillations is necessary for all experiments.

The absolute values of the mass squared differences have been measured. The sign of the Δm^2_{21} is known thanks to the matter effects in the Sun (called MSW effect [24]), but the sign of Δm^2_{31} is still to be determined and constitutes one of the important open questions (mass hierarchy – MH) for upcoming measurements. An answer possibly could come from global fits, current experiments, in particular NOvA and future experiments using atmospheric neutrinos (INO, PINGU, ORCA) and from JUNO, which is specifically designed for this purpose.

All three mixing angles are presently known, although with different precision [19]. There is an open question if the value of θ_{23} corresponds to maximal mixing, $\pi/4$, which is equivalent to equal ν_μ and ν_τ components of the ν_3 mass eigenstate. If it is not maximal, one would like to know in which octant it lies. The most current global fits, see for instance [20] to all available data have a best fit of θ_{23} which is not maximal and that allows for two degenerate solutions, one in the lower octant ($\theta_{23} < \pi/4$) and the other one in the upper octant ($\theta_{23} > \pi/4$); however maximal mixing is still consistent with the data.

T2K and the atmospheric experiments (Super-Kamiokande, IceCube, Antares) tend to see the θ_{23} angle closer to maximal, with best fit points for $\sin^2\theta_{23}$ reported at NEUTRINO 2018 conference than NOvA and an older long-baseline experiment, MINOS (which has already finished to take data).

The measurement of θ_{13} reached very high precision in the second generation reactor experiments, Daya Bay [21], Reno [22] and Double Chooz [23] opening possibility of search for CP violation in neutrino oscillations.

The CP violation parameter is not well constrained at this point. The observation of CP violation in lepton sector would be interesting, as it may help to understand the matter-antimatter asymmetry observed in the Universe. CP violation for neutrinos would manifest itself as a difference in the oscillation probability of $\nu_\alpha \to \nu_\beta$ between neutrinos and antineutrinos in vacuum. In matter, the resulting matter potential induces a difference which has to taken into account in interpreting the experimental measurements. Realistically, with current neutrino sources, the only channel available for experiments is electron (anti)neutrino appearance in a muon (anti)neutrino beam: $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$.

The first hint of possible CP violation for neutrinos came from T2K, which showed a preference for δ_{CP} close to $-\pi/2$ (maximal CP violation) [25]. Since that time, with significantly more data collected, T2K sees an excess of electron neutrino events and no statistically significant rate of electron antineutrino events [26]-[28], leading to a 95% C.L. exclusion of the CP conserving values $\delta_{CP} = 0, \pi$ [30]. NOvA recently achieved first evidence ($>4\sigma$ C.L.) of electron antineutrino appearance. The combined fit of all NOvA oscillation channels prefers δ_{CP} values between 0 and π, but the results are compatible with those of T2K [29].

The trends and preferred values of the oscillation parameters can be well observed in global fits, where all available data sets are used as inputs. An example of such fit using data available at the beginning of 2018 published in [31], where the detailed status of our knowledge about oscillation parameters is discussed. Presently these fits show that for the CP violation parameter δ_{CP} values around $\pi/2$ are strongly disfavoured while $-\pi/2$ is preferred. For $\sin^2\theta_{23}$ the maximal mixing is still allowed and but the preferred region is $\theta_{23} > \pi/4$, for mass ordering the normal mass hierarchy is favored, but the preference is weak.

During the next few years additional data will be obtained from the T2K and NOvA experiments, where more data is being collected with neutrino and antineutrino beams with increasing intensities. These two experiments could provide better constraints for the above mentioned parameters, and reduce the allowed parameter space, but measurements with exclusions at the level of $4-5\sigma$ for δ_{CP} can be obtained only from the next generation of experiments.

The T2K (phase II) and NOvA experiments are going to continue to take data until the next generation of neutrino oscillation experiments comes on-line, which are expected to start around 2026. If the true δ_{CP} is close to current global best fits, the expected results from combined analysis of both experiments could allow for: the exclusion of CP conservation at 3σ significance; determination of the neutrino mass hierarchy at 4σ significance; a precise determination of θ_{23} with an uncertainty of 1.7° or better; a precise measurement of Δm^2_{31} with about 1% precision.

JUNO, DUNE AND HYPER-K

Three large-scale next-generation neutrino oscillation experiments using man-made neutrino sources are under construction or at an advanced stage of design with approved construction start dates. The DUNE [33–35] and Hyper-Kamoikande [36] experiments use accelerator neutrinos to study $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, searching for CP (non)conservation. Additionally, DUNE uses these oscillation modes to determine the neutrino mass hierarchy, while Hyper-Kamiokande will determines the hierarchy from the oscillations of atmospheric neutrinos. The JUNO [37] experiment detects the survival of reactor electron antineutrinos over a baseline of 53 km, determining the mass hierarchy by detecting the oscillation difference arising from the different mass splitting identities $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$ and $|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$ in the normal and inverted hierarchies respectively. All three experiments also will make precision oscillation parameter measurements.

The JUNO detector is a 20 kton liquid scintillator detector located 53 km from the Yangjiang and Taishan Nuclear Power Plants in Guang-dong, China. The experiment utilizes newly developed 50 cm diameter microchannel plate (MCP) PMTs, dynode type 50 cm diameter PMTs and 8 cm diameter PMTs to achieve the 78% photo-coverage required for 3% energy resolution at 1 MeV. JUNO determines the mass hierarchy by measuring the phase in the sub-leading fast oscillation pattern arising from the mass splittings Δm^2_{31} and Δm^2_{32}, which differs by 9×10^{-3} MeV^{-1} between the mass hierarchy hypotheses. JUNO determines the mass hierarchy with 3σ significance after 6 years of operation if there is no external constraint on the $\Delta m^2_{\mu\mu}$, and with 4σ significance if $\Delta m^2_{\mu\mu}$ constrained to 1% by accelerator-based experiments [39]. JUNO also make measurements of Δm^2_{21}, $\sin^2(\theta_{12})$ and Δm^2_{ee} with 0.6%, 0.7% and 0.4% precision respectively. Civil construction for the JUNO experiment began in 2015, and construction of the detector will begin in 2019. Detector construction will be completed in 2020, with the detector operating from 2021 on.

The DUNE experiment incorporates four 10 kton fiducial mass Liquid Argon (LAr) Time Projection Chamber (TPC) detectors located in the Sanford Underground Research Facility (SURF) in Lead, South Dakota. An on-axis neutrino beam peaked at 3 GeV neutrino energy will be generated at Fermilab and travel 1300 km before reaching the DUNE detectors. This broadband beam will provide neutrino interactions primarily at the first oscillation maximum, but with a smaller fraction of interactions near the second oscillation maximum. The 1300 km baseline of DUNE enhances the matter effect, leading to a sensitivity to determine the mass order with more than 5σ significance for all allowed true values of the oscillation parameters in 7 years of operation. In DUNE the neutrino-antineutrino asymmetry at the peak energy due to the matter effect is ±40%, larger than the maximum CP violation effect, removing any approximate degeneracies in the determination of the mass ordering and CP phase. In 10 years of operation DUNE has a 5σ (3σ) CP violation discovery sensitivity for 54% (74%) of δ_{CP} values. Over the same period, the phase can be measured with 7.5°(15°) precision for $\delta_{cp} = 0$ ($\delta_{cp} = -\pi/2$). DUNE can determine the octant of θ_{23} with greater than 3σ significance for values less than 43.5° or greater than 47.9°, has 0.3° precision on the measurement of θ_{23} for $\theta_{23} = 42°$, and can achieve 0.3% precision on the measurement of Δm^2_{32}. DUNE will also detect atmospheric neutrino interactions that will add to the constraint on neutrino oscillation parameters, although the constraints will be dominated by the accelerator neutrino measurements. For both DUNE and Hyper-K (below), the stated precision with which θ_{23} and Δm^2_{32} can ultimately be measured depends somewhat on the systematic uncertainty assumptions taken.

Both single phase and dual phase detector technologies are being developed for the DUNE detectors, with ProtoDUNE prototype modules in operation at the CERN Neutrino Platform. Far detector site construction for DUNE is expected to begin in 2019, with detector installation starting in 2022 and the first detector operation starting in 2024. A staged approach for detector construction will be followed with the four detector modules completing construction over several years. The beam will start operation in 2026 with 1.2 MW beam power, followed by a future upgrade to 2.4 MW.

The Hyper-Kamiokande experiment will comprise a 186 kton water Cherenkov detector at a new detector site in Tochibora, Gifu Prefecture, located 2.5° off-axis from the J-PARC neutrino beam at a baseline of 295 km. The J-PARC accelerator and neutrino beam line will be upgraded to provide 1.3 MW beam power for Hyper-K, giving an increase by a factor of 20 for the accelerator neutrino rate in Hyper-K compared to current operation of the T2K experiment. The off-axis beam produces a narrow spectrum at the first oscillation maximum, while the 295 km baseline minimizes the matter effect. For accelerator neutrinos, the CP violation effect is dominant, with a maximum asymmetry of ±40% compared to an asymmetry of ±10% from the matter effect. The Hyper-K experiment has sensitivity to determine the mass ordering with atmospheric neutrino measurements, achieve a 4σ sensitivity for mass ordering determination after 10 years when combining atmospheric and accelerator neutrinos. Assuming determination of the mass ordering, Hyper-K has 5σ (3σ) CP violation sensitivity for 57% (76%) of δ_{cp} values after 10 years of operation. Over the same period, the phase can be measured with 7.2°(23°) precision for $\delta_{cp} = 0$ ($\delta_{cp} = \pi/2$). Hyper-K can determine the octant of θ_{23} with greater than 3σ significance for values less than 42.7° or greater than 47.3°, and after 10 years of operation can achieve 1°(0.5°) degree precision for the θ_{23} measurements at $\theta_{23} = 45°(45° \pm 3°)$. After 10 years of operation, Hyper-K can achieve 0.6% precision on the measurement of Δm^2_{32}. Hyper-K would also make measurements of solar neutrino oscillation parameters and the matter effect for solar neutrinos in the

	now	JUNO	DUNE	Hyper-K
$\theta_{12}[^\circ]$	$33.62^{+0.78}_{-0.76}$	± 0.13		
$\theta_{23}[^\circ]$	$47.2^{+1.9}_{-3.9}$		± 0.3	± 0.5
$\theta_{13}[^\circ]$	8.54 ± 0.15			
$\delta[^\circ]$	234^{+43}_{-31}		7.5-15	7.2-23
$\Delta m^2_{32}[10^{-3}\text{eV}^2]$	$2.494^{+0.033}_{0.031}$		± 0.007	± 0.014
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.4^{+0.21}_{0.20}$	± 0.03		
binary questions				
mass ordering $[\sigma]$	2-3	3-4	> 5	4
octant of θ_{23} $[\sigma]$	0		> 3	> 3

TABLE I. . Shown are the currently allowed $1\,\sigma$ ranges for the oscillation parameters taken from Ref. [40] (column labeled now) as well as the expected precision of future experiments.

Sun and Earth.

The Hyper-K detector utilizes established water Cherenkov detection technology, while pursuing improvements to the photo detection from new high quantum efficiency photo-multiplier tubes and high resolution multi-PMT photodetectors. The Hyper-K detector construction will begin in 2020 and the detector will be ready for operation starting in 2027. The J-PARC beam power upgrade work has started, and the initial upgrade to allow for greater than 750 kW operation will take place in 2021. Additional upgrades will achieve 1.3 MW operation by the start of Hyper-K in 2027. The Hyper-K experiment considers a staged approach for the realization of a second detector, with the potential for a second detector located in Korea at a baseline of ∼1100 km [38].

The expected measurement accuracies from JUNO, DUNE and Hyper-K as discussed above are summarized in Tab. I. We would like to point out that these error bars are all based on *asssumptions* about the atainable level of control of systematic errors. Also, note that some of the current results are exceeding the sensivity of the respective experiment. From this comparison it is apparent that DUNE and Hyper-K will provide similar accuracies, which is not surprising, since they will accummulate compararable statistics.

ALTERNATIVE EXPERIMENTAL CONCEPTS

Mass Hierarchy

KM3NET-ORCA and PINGU (IceCube Upgrade/Gen2) can provide valuable information on neutrino mass hierarchy using 2–12 GeV atmospheric neutrinos and the oscillation channel $\nu_\mu \to \nu_e$. This is possible thanks to the matter effect produced when neutrinos cross the earth. For this, a relatively high angular resolution of the order of 5° (at 10 GeV) and energy resolution better than 30% are needed.

The expected sensitivity depends on the mass hierarchy (normal or inverted). It varies from 2 σ significance to 6 σ for normal hierarchy and from 2 σ to 4 σ for inverted hierarchy, with θ_{23} varying from 46° to 54°. This is obtained after 3 years data taking with a full detector configuration and provided that all systematic errors are well understood. PINGU has very similar capabilities. ORCA is now partially funded and started deploying at sea the first few experimental PMT lines. A full line deployment is foreseen to be finished by 2021. PINGU is not yet financed while the deployment is expected to take place between 2025 and 2031 [41].

These results combined with those expected from JUNO, probably will allow to determine the mass hierarchy with a significance exceeding 5 σ by 2027.

Second oscillation maximum

To observe a possible CP violation in the lepton sector the neutrino oscillation channel $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ have to be studied and compared. The oscillation probability has mainly three terms, commonly called "atmospheric", "solar" and "interference": The interference term carries the CP violating parameter δ_{CP} and ideally is made to be as large as possible compared to the other two terms, in order to avoid to reduce the impact of systematic errors.

For $\theta_{13} \sim 8^\circ$, the interference term dominates the two other terms at a position corresponding to the second oscillation maximum instead of the first one [42], leading to a greatly reduced sensitivity to systematic errors. Moreover, at the second oscillation maximum the CP-induced asymmetry is of the order of $\mathcal{A} = 0.75 \sin \delta_{CP}$ while at the first oscillation maximum this is only $\mathcal{A} = 0.3 \sin \delta_{CP}$ [43], resulting in significantly more sensitivity to observe a possible CP violation. The drawback is that, for the same neutrino energy, the baseline has to be about three times larger than for the first oscillation maximum, decreasing statistics by nearly one order of magnitude. To overcome this loss of luminosity, a very intense neutrino beam is needed, necessitating a multi–MW proton beam.

ESSνSB[44] is a proposal to use the European Spallation Source (ESS) 5 MW proton linac as neutrino source and would cover completely and exclusively the second oscillation maximum by placing the far detector, based on water Cherenkov technology, at a distance of about 500km from the neutrino source. Due to the very high power of the proton linac, ESSνSB could cover up to 60% of the CP violation parameter δ_{CP} with a significance of more than 5 σ. The expected resolution on δ_{CP} near 0° and 180° is about 6°.

Together with the neutrino production the ESSνSB facility would also produce a huge number of muons from pion decays These muons could be collected at the level of the beam dump and used for other applications. The mean momentum of the muons is of the order of

0.46 MeV. A magnet and a collecting device could be placed at near the beam dump to deflect and collect a significant fraction of these muons. Preliminary calculations show that more than 4×10^{20} muons per year can be extracted. These muons can be used for a nuSTORM-like neutrino experiments [45], for a Neutrino Factory and for R&D toward 6D muon cooling and studies for a possible future muon collider.

Since 2016, the COST Action CA15139/EuroNuNet [46] supports the ESSνSB project and all activities in Europe on CP violation discovery in the neutrino sector. This COST Action which will last up to 2020 and gathers up to now 13 European countries. Since the beginning of 2018, a European H2020 INFRADEV project also called ESSνSB[47] has started for a duration of four years in order to perform a design study and produce a Conceptual Design Report.

ADDITIONAL CONSIDERATIONS

Through the next decade, the accelerator-based long baseline neutrino program outlined above aims to constrain PMNS parameters – or find deviations from the standard paradigm – through highly precise measurements of flavor oscillations. This measurement program will require unprecedented percent-level systematic uncertainties, and a significant piece of that uncertainty budget will stem from our understanding of neutrino-nucleus interactions.

Mitigating interaction uncertainties begins with careful experimental design to eliminate, to as large a degree as possible, the impact that neutrino interaction modeling can have on the physics analyses. Approaches used in the past and/or under consideration for the future include deploying highly capable near detector suites, matching target isotopes where possible between near and far detectors, and obtaining near detector samples with different neutrino energy spectra (*e.g.*, by varying elements of the beamline or the detector's transverse location relative to the beam). These experimental mitigations are most critical, but ultimately they only minimize – not fully eliminate – interaction model dependence. Improving our understanding and modeling of neutrino-nucleus interactions through dedicated fixed-target experiments and investments in theoretical efforts is an invaluable part of the program. Additional discussion can be found in Ref. [32]. It appears prudent to provide support for a design study for a neutrino scattering experiment, in particular based on the ENUBET [48] and nuSTORM [45] beam concepts; the detector design effort could be shared between the two, as should the theory effort.

Finally, each experiment described herein brings unique strengths and challenges to measurements of 3-flavor oscillations. The current and next generation accelerator-based experiments differ substantially in key aspects: neutrino baseline, narrow-band versus broad-band flux, mean neutrino energy, detector technology and corresponding reconstruction and event selection techniques. Accelerator, atmospheric, and reactor neutrino experiments are attempting to determine the mass hierarchy using different physical observables. JUNO offers precision measurements of Δm^2_{21}-driven oscillations. The systematic uncertainties faced and the regions of 3-flavor parameter space probed by these experiments are highly complementary, allowing for additional sensitivity through combined measurements as well as robustness in a systematics-limited era.

Additionally, this breadth in experiment design translates into a broader physics program overall, including nucleon decay searches, neutrinos from supernovae, high-energy astrophysics, and a plethora of beyond-the-Standard-Model searches.

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