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Standard three-neutrino oscillations : Session Summary

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We provide a brief summary of the parallel session I, “Standard three-neutrino oscillations". The topics discussed in this session are the current status of neutrino mass-mixing parameters in the three neutrino framework, as well as other standard model applications of neutrino physics.

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1. Introduction

In the standard three neutrino oscillation framework there are three mass states (ν_1, ν_2, ν_3) that mix to form three weak neutrino states $(\nu_e, \nu_\mu, \nu_\tau)$ via three mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$ and a CP phase δ_{CP}. The neutrino oscillation probability depends also on the two mass-squared differences $(\Delta m^2_{21}, |\Delta m^2_{31}|)$. Most of these parameters are now known to better than 5% precision. However, questions still remain, motivating further precision measurements of all oscillation phenomena. For example, the sign of $\Delta m^2_{31} = m^2_3 - m^2_1$ remains unknown thus allowing for two possible orderings of the three mass states (Normal Ordering (NO): $m_1 < m_2 < m_3$ or Inverted Ordering (IO): $m_3 < m_1 < m_2$). The value of δ_{CP} remains unmeasured, too. Indeed, there is some disagreement in the measurements from current long-baseline experiments T2K and NOvA. We know that the value of θ_{23} is close to 45° but at current precision we cannot be sure if this mixing is truly maximal, and if not, which octant it lies in.

In this session of NOW we have discussed advancements in some of these measurements and the related theory. Other fields of neutrino physics, such as neutrino scattering and Supernova physics were also covered. We refer the reader to the proceedings for individual talks for more information and references.

2. Experimental Results

We started the experimental talks with the largest experiments: IceCUBE and KM3NeT, instrumented Cherenkov detectors made up of Antarctic ice and Mediterranean sea-water respectively. (Andrii Terliuk: "IceCuber-DeepCore oscillation results" and Luc Cerisy: "Undersea measurements of neutrino oscillations (KM3NeT)") Although these km-scale experiments are motivated to measure very high energy neutrinos, upwards of $\sim$ 100 GeV, of astronomical origin, they both factor in capability to measure atmospheric neutrinos down to energies of a few GeV, with more densely instrumented detector regions. The atmospheric neutrinos provide baselines of 20–12740 km suitable for probing the mixing between the 2 and 3 mass states. The higher energy atmospheric neutrinos that these experiments focus on sit above the τ lepton production threshold, thus allowing both disappearance and appearance oscillation measurements. The τ row of the PMNS matrix is the least constrained and therefore, such measurements, though difficult, are strongly motivated to test for non-unitarity.

The central bottom part of IceCUBE, named DeepCore, with closer packed digital optical units (DOMs), is utilised for the atmospheric neutrino analysis, with the rest of the IceCUBE detector providing essential veto information to separate contained events, from atmospheric muon background events. IceCUBE DeepCore has accumulated $\sim 150k$ events in 9.3 years showing a clear signature of neutrino disappearance. To exploit these high statistics data sets for precision measurements, systematic uncertainties must be carefully handled, with the most impactful such as detector related systematics included as parameters in the oscillation fit. Best fit results from IceCUBE are $\Delta m^2_{32} = 2.40^{+0.05}_{-0.04} \times 10^{-3}\mathrm{eV}^2$ and $\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}$. Further studies have been conducted by IceCUBE to test compatibility with a 3+1 neutrino model, search for sterile neutrinos and non-standard interactions with these data. A further upgrade of IceCUBE is planned to be deployed in the 2025/26 season, ready for data taking in 2027, with over 800 new D-Egg modules plus dedicated calibration devices. With this upgrade, as well as improved sensitivity to θ_{23} and Δm^2_{32}, IceCUBE anticipates up to 3σ sensitivity to the neutrino mass ordering and 5% sensitivity to τ appearance.

The KM3NeT experiment is divided into two detector sites, with a different physics focus for each. ORCA, which we focus on in this session, is the more densely instrumented array designed for probing GeV-energy neutrinos, whilst the ARCA array probes TeV–EeV energy neutrinos. ORCA, which pursues the atmospheric oscillation measurement, currently has 20% (23 detection strings) of its total fiducial volume installed and has so far collected 1.6 Mt.years of data. As with, IceCUBE, deployment of sensors is a time-consuming process run in seasonal campaigns. With the data so far, KM3NeT see a clear L/E oscillation dip in the atmospheric ν_μ data and the analysis shows a preference for maximal θ_{23} mixing and a slight preference for inverted neutrino mass ordering.

We next heard about reactor neutrino oscillation experiments from Liang Zhan ("Neutrino oscillation measurement with reactor antinus"). Nuclear reactors provide a flux of $\bar{\nu}_e$ with energies up to $\sim$ 8 MeV, which can be measured through the inverse beta decay (IBD) interaction. Scintillator detectors are adept at measuring both the prompt e^+, whose energy spectrum is a proxy for the neutrino spectrum, and the delayed neutron capture on either H or Gd giving a clear coincidence tag. The disappearance channel is sensitive to θ_{13} and Δm^2_{31} with no dependence on CP violation or θ_{23}. Indeed, both the original discovery of non-zero θ_{13} in 2012 and now the most precise values of this parameter come from short-baseline (1–2 km) reactor experiments. Final results from the original three scintillator experiments: Daya Bay, RENO and Double Chooz were summarised, including measurements with neutron capture on both H and Gd (although we heard that the nH analysis of the full Double Chooz data set is still ongoing). The shape distorted spectrum from these experiments is consistent with the three-flavour oscillation model and the combined reactor experiments constrain $\theta_{13} = 0.0839 \pm 0.0021$, now the most precisely measured of all the mixing angles.

Anthony Zummo discussed mixing between the 1 and 2 mass states, which is accessible by both solar experiments and reactor experiments at a baseline of order 100 km ("Reactor and solar tension with measurements (SNO+)"). Reactor experiments can measure a dip in the anti-neutrino L/E spectrum, which is mostly sensitive to the mass difference. KamLAND, a reactor experiment with an average baseline of 180 km provided the best limits on this of $\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5}\mathrm{eV}^2$. Whilst solar experiments are more sensitive to the mixing angle θ_{12} than the mass difference, they can still place constraints on this parameter due to the combined impact of three effects: matter enhanced MSW mixing in the Sun, vacuum oscillations, and a day-night asymmetry due to matter effects in the Earth. The Super-Kamiokande experiment has measured a turn up in the solar ν_e survival probability at low energy with low significance and a day-night asymmetry at 3.2σ significance, which together push global solar analyses to prefer a lower value of Δm^2_{21} than reactor experiments.

This tension between the reactor and solar measurements of Δm^2_{21} is of order 1.5σ. If real, such an effect could be indicative of new physics such as CPT violation, non-standard interactions (NSI), mass varying neutrinos, or new forces. The SNO+ liquid scintillator experiment can measure both reactor neutrinos and solar neutrinos in the same detector. First low statistics reactor fits from SNO+ were shown to be in good agreement with KamLAND data, and SNO+ expects to improve on this with around 100 $\bar{\nu}_e$ reactor events per year.

In the future, JUNO will also measure reactor neutrinos at a longer baseline, and Hyper-K and DUNE will measure solar neutrinos. Together, these experiments could confirm or resolve the tension in Δm^2_{21} at 5σ. Whilst Hyper-K will measure solar neutrinos through elastic scattering, DUNE can measure them through the $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}$ charged current channel, which has a high cross-section and is more sensitive to higher energy solar neutrinos where the day-night effect is greater.

Vanessa Cerrone presented how JUNO will be the first experiment to simultaneously probe two different oscillation frequencies (both slow (Δm^2_{21}) and fast (Δm^2_{31}) oscillations) with the same flux of reactor neutrinos ("JUNO sensitivity to mass ordering and oscillation parameters"). The 20kt liquid scintillator far detector located 52.5 km from two major nuclear power plants, sits at the first disappearance maximum for 1–2 oscillations, but will also measure the impact of 1–3 oscillations as a 'wiggle' in the energy spectrum. Interference of the two oscillation effects results in an energy-dependent phase shift in the antineutrino spectrum, so the position of the 'wiggle' will differentiate between normal and inverted mass ordering.

The main challenges for this measurement are achieving the unprecedented energy resolution of 3% at 1 MeV and controlling backgrounds. A model independent reference spectrum will be measured by the TAO detector located 44 m from one of the reactor cores. The collaboration will start filling the JUNO detector with liquid scintillator soon and project sub percent level precision measurements of Δm^2_{12}, $\sin^2\theta_{12}$ and Δm^2_{13} in the first year of data taking, and 3σ sensitivity to the mass ordering with 7.1 years of reactor data. This sensitivity could be boosted by incorporating atmospheric neutrino data into the analysis.

The current long-baseline experiments, T2K and NOvA, both study muon (anti) neutrino disappearance and electron (anti) neutrino appearance to probe 2–3 and 1–3 mixing, and test for CP violation. Having heard about their current status in the plenary talks, Lorenzo Magaletti focused on recent improvements of the T2K experiment in this session ("T2K upgrades: near detector and beam"). T2K uses a suite of near detectors to help reduce systematic uncertainties on the predicted energy spectra at the Super-K far detector. We heard about an upgrade to the off-axis near detector, ND280, which was installed in spring 2024. Part of the tracking detector was replaced with a fine grained scintillator target (SFGD) capable of measuring low energy protons and neutrons produced in CC interactions, and two high angle TPCs to increase angular acceptance, along with 6 super-fast Time of Flight (ToF) panels to identify the direction of charged particles. Details about beam upgrades to deliver increased statistics and a new cross-section model with more freedom to accommodate uncertainties were also presented.

Looking further to the future, we heard about design studies for a future neutrino oscillation measurement linked to the European Spallation Source (ESS) in LUND: "ESSnuSB future beam experiment" from Joakim Cederkall. The ESS will produce cold and ultra-cold neutrons via spallation using a high power proton LINAC (designed for 2GeV p and 5MW on target) with first beam scheduled in 2026. This infrastructure could be exploited to provide a neutrino beam powerful enough to measure δ_{CP} at the second oscillation maximum, which would be at a baseline of around 360 km from LUND in an old mining area of Sweden with good potential to locate two 270 kton water cherenkov far detectors. The design studies shows that such an experiment would provide 70% coverage of all δ_{CP} values at 5σ with 5% normalisation error after 10 years of data collection.

Our last two experimental talks stepped outside the realm of standard three-neutrino oscillations.

We heard from Clementina Agodi about the NUclear Matrix Element for Neutrinoless double beta decay (NUMEN) experiment that aims to accumulate data driven information on neutrino matrix elements for double beta decay from measured heavy ion double charge exchange (DCE) cross-sections (“NUMEN project: status and perspective”). Although DCE processes are mediated by the strong interaction and include a sequential transfer mechanism, they can have the same initial and final states as $0\nu\beta\beta$ decay and proceed via a similar operator. We heard about initial measurements on the ^{76}Se-^{76}Ge and ^{48}Ti-^{48}Ca systems, and plans for a systematic experimental campaign of all the interesting isotopes for $0\nu\beta\beta$ after upgrades to the experimental setup. The challenge to measure these very small cross-sections with energy and angular dependence requires high heavy ion beam intensities from a superconducting cyclotron, and high precision measurement with a large acceptance magnetic spectrometer.

We also heard about geo-neutrino analysis plans at JUNO from Fernanda Rodrigues (“Geoneutrino physics at JUNO”). Current geo-$\bar{\nu}_e$ measurements come from Borexino and KamLAND with many years of data each achieving 15% and 17% precision from $\sim$ 170 and $\sim$ 50 geo-nu events respectively. JUNO expects to measure around 400 geo-$\bar{\nu}_e$ events per year via IBD (roughly 1.2/day). However, their reactor neutrino signal is at a much higher rate and constitutes an irreducible background, but can be accurately constrained by fitting the higher energy reactor spectrum. The unoscillated spectral shape will be well constrained by TAO measurements so oscillation effects will contribute the largest systematic uncertainty. The JUNO collaboration expect 22% precision on their geo-$\bar{\nu}_e$ flux measurement after 1 year and 8% after 10 years. They also plan to measure individual Uranium and Thorium contributions, with a predicted precision of 70% on the ^{232}Th/^{238}U ratio with 6 years of data.

3. Theoretical Results

The first talks (Fedor Simkovic: "Neutrino oscillations and entanglement" and Massimo Blasone: "Neutrino oscillations in the interaction picture") in the theoretical session were oriented toward more formal aspects of neutrino oscillations. An approach to neutrino oscillations in vacuum, based on quantum field theory (QFT) was proposed, in which the neutrino emission and detection were identified with the charged-current vertices of a single second-order Feynman diagram. One of the main points of the approach is the definition of the space-time setup typical for neutrino oscillation experiments, implying macroscopically large but finite volumes of the source and detector separated by a sufficiently large distance. A master formula for the charged lepton production rate was derived, which provides the QFT basis for the analysis of neutrino oscillations. This formula depends on the underlying process and is not reducible to the conventional approach resorting to the concept of neutrino oscillation probability, which originates from non-relativistic quantum mechanics. It was shown that for some particular choices of the underlying process the derived master formula approximately coincides with the conventional one under some assumptions. In this context not only entanglement in neutrino oscillation but also neutrino-antineutrino oscillations were discussed.

The second talk was dedicated to the formulation of neutrino oscillations in the interaction picture. It was argued that neutrino oscillations can actually be described as a standard perturbative QFT, with the mixing handled by the interaction picture. A 0+1D toy model, “scalar” neutrinos and their “realistic” Dirac fermion counterparts can all be described by this approach, the various transition amplitudes can be related via Feynman diagrams and the differences reduced to spin-statistics differences. In the fermionic case, the same oscillation formula as in non-perturbative flavor-Fock space approach is obtained. The methods developed could be applied to a calculation of observables beyond tree level which systematically includes neutrino oscillation effects. A possible example of such a calculation could be the magnetic dipole moment of the neutrino.

The third talk of the session, "Analytic and efficient ways to compute oscillation probabilities" by Peter Denton, was dedicated to a fast way to calculate neutrino oscillation probabilities in constant matter. Neutrino oscillation experiments will be entering the precision era in the next decade with the advent of high statistics experiments like DUNE, Hyper-K, and JUNO. Correctly estimating the confidence intervals from data for the oscillation parameters requires very large Monte Carlo data sets involving calculating the oscillation probabilities in matter many, many times. A new, fast, and precise technique for calculating neutrino oscillation probabilities in matter optimized for long-baseline neutrino oscillations in the Earth’s crust including both accelerator and reactor experiments is presented in a way which makes it straight-forward to implement for new users. The new method is more precise and faster to execute than any other method proposed in the past.

The last talk of the first theory session, "Global analysis of neutrino oscillations with GAMBIT" by Wilf Shorrock, was dedicated to global fits to neutrino oscillation data, which have been a staple of the research in neutrino physics for the last few decades, and the inferred values of the oscillation parameters from experimental data have achieved high accuracy. In this talk, the first global study of neutrino oscillations using GAMBIT (Global and Modular Beyond-the-Standard-Model Inference Tool), a fully open-source software framework for performing statistical inference studies of models of new physics was presented. Its modular design allows for an extensible implementation of likelihood functions and models. The built-in scanners provide robust and efficient statistical sampling techniques. So far, the experimental likelihoods for eight neutrino oscillation experiments have been included, including solar, atmospheric, reactor and long-baseline accelerator experiments, all subject to the available data made publicly accessible by the experiments. Realistic and physics-motivated systematic models, along with sets of nuisance parameters, are introduced to account for systematic uncertainties for the detector effects and the neutrino fluxes, to name a few. Using a self-adapting differential evolution sampling algorithm to explore the vast parameter space, and applying rigorous and modern statistical methods in the interpretation of the sampling results, an accurate fit to the oscillation data is presented.

In the first talk of the second session, "Recent theory results on CEνNS" by Matteo Cadeddu, recent results from analyses of COHERENT data were discussed. The first part is dedicated to the determination of the weak mixing angle and the neutron radius of ^{133}Cs. Different probes are sensitive to its values, among which atomic parity violation, coherent elastic neutrino-nucleus scattering and parity-violating electron scattering on different nuclei. It is attempted to combine all these various determinations by performing a global fit that also takes into account the unavoidable dependence on the experimentally poorly known neutron distribution radius of the nuclei employed. In the second part focus is set on BSM searches with neutrino scattering data. It is shown that COHERENT data can be used to search for new neutrino-philic light mediators, while data from dark matter direct detection experiments was used to bound neutrino electromagnetic properties, in particular magnetic moments and millicharges.

The last two presentations ("Neutrino quantum kinetics in SN and binary mergers" by Hiroki Nagakura and "Thermodynamics of oscillating neutrinos" by Luke Johns) were dedicated to Supernova physics, focusing on advancements in modelling neutrino transport during core-collapse supernovae and binary neutron star mergers, particularly leveraging the Boltzmann equation. Accurate neutrino transport is critical for understanding the dynamics and outcomes of supernova explosions, as neutrinos carry away most of the energy and influence key phenomena such as matter heating and nucleosynthesis. The study emphasizes challenges in balancing accuracy with computational efficiency and explores novel approaches to capture the multi-dimensional and non-equilibrium nature of neutrino interactions in dense environments. These improvements are crucial for refining theoretical predictions and interpreting observations, contributing to a deeper understanding of stellar evolution and the role of neutrinos in the cosmos.