

Neutrino properties from experiments

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The neutrino field has recently received much attention and several new experiments are ready to take or analyze data which have a potentially large impact on the standard model of particle physics. An overview of current neutrino physics is here followed by a summary of the latest results, and finally a list of important results anticipated in the near future is given.

1 Open issues

It is by now well established that neutrinos oscillate between the three weak states ν_e, ν_μ, ν_τ . That flavor changes are possible over time shows that neutrinos have non-equal masses, and that the interaction states are not equal to the mass states ν_1, ν_2, ν_3 . The relation between interaction state i and mass state j is written with a mixing matrix U as $\nu_i = \sum_j (U_{ij} \nu_j)$. The matrix U is characterized by three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ relating the mass states, a CP-violation phase δ_{CP} , and two Majorana phases α, β .

The probability of passing from a weak state to another is a function of the squared mass difference and the mixing angle (and the distance to energy ratio L/E), and these are therefore the quantities that experiments have measured. Current best values are $\Delta m_{21}^2 \sim +8 \cdot 10^{-5} eV^2$, $\Delta m_{32}^2 \sim 2 \cdot 10^{-3} eV^2$, $\theta_{12} \sim 32^\circ$, $\theta_{23} \sim 45^\circ$, $\theta_{13} < 7^\circ$.

These five values represent what we currently know about neutrinos, and thus the pieces missing and sought after are the following: the sign on Δm_{32} (*Mass hierarchy*), the value of δ_{CP} (*CP-violation*), values of α, β (*Dirac/Majorana*), absolute values of m_1, m_2, m_3 (*Absolute mass scale*), the value of θ_{13} (*Non-zero θ_{13}*). To this list of open issues we can add the existence of sterile neutrinos, and the asymptotic form of the mixing matrix. Apart from these unknowns, the parameters $\Delta m_{32}^2, \theta_{23}$ and the νN cross-sections also need to be better understood.

2 Methods of measurement

The study of oscillation parameters needs powerful neutrino sources, which apart from extraterrestrial natural sources can be either nuclear reactors ($\bar{\nu}_e$) or neutrino beams (ν_μ or $\bar{\nu}_\mu$). Reactor neutrinos are produced at MeV scale and are emitted isotropically, whereas neutrino beams (from protons on target $p + N \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$) are directed and can be produced at GeV energies.

Studying a neutrino beam over long distances, the probability that a ν_μ disappears from the beam depends mainly on $\Delta m_{32}^2, \theta_{23}$ (*disappearance search*) and the probability that a ν_e appears mainly depends on $\Delta m_{32}^2, \theta_{23}, \theta_{13}$ (*appearance search*), meaning that both oscillations can be

studied. The presence of CP-violations would imply that the probabilities for the transitions $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ are different. Measuring appearances with ν_μ and $\bar{\nu}_\mu$ beams thus gives a handle on δ_{CP} .

Looking instead at reactor neutrinos over much shorter distances, the probability that a $\bar{\nu}_e$ disappears depends mainly on $\Delta m_{32}^2, \theta_{13}$. The lower neutrino energy makes L/E comparable to beam neutrinos, near oscillation maximum, while still exploiting the high flux near the reactors.

The search for the absolute scale of neutrino masses can be addressed by the study of β -decay spectra, where the endpoint of the observed electron spectrum, studied in a sensitive spectrometer, depends on the value of m_{ν_e} .

Whether neutrinos are Majorana particles can be tested by searching for ν -less double β -decay events. In this process, a β -decay in a nucleus is followed by an inverse β -decay in the same nucleus. For this to be possible the $\bar{\nu}_e$ from the first reaction must act as a ν_e in the second, requiring $\bar{\nu}_R = \nu_R$ and the Lorentz transition $\nu_R \rightarrow \nu_L$, of which the former is only possible for Majorana particles. The process is commonly studied in Ge-detectors, where the detector acts at once as source and target.

3 Recent results

Several interesting oscillation results have recently been presented.

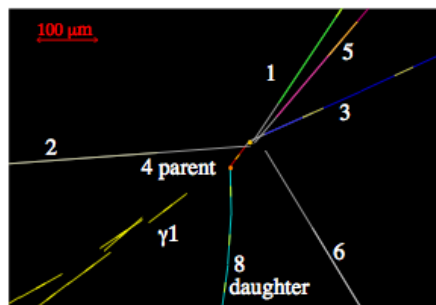


Figure 1: Tau event from a ν_μ beam observed in OPERA [1] viewed in the transverse plane of the neutrino direction. Track 4 is identified as a τ decaying to a μ (track 8).

OPERA [1], using a ν_μ beam from CERN to Gran Sasso (730 km), has presented one observed τ event (see Fig refopera) appearing in the detector, consisting of lead plates interlayered with emulsion plates. While disappearance has long been studied, this result is the very first evidence of neutrino flavour appearance. The result is reported as a 2.1σ effect, and is thus not enough to firmly exclude neutrino decay or decoherence models, but certainly strengthens the oscillation case.

MINOS [2] has new disappearance results using ν_μ and $\bar{\nu}_\mu$ beams from Fermilab to the Soudan mine (735 km). A near detector, made of steel and scintillator plates) close to the start of the beam measures the neutrino flux, which then is compared to the flux observed in the far detector, a larger version of the near detector. The derived parameters for ν_μ (see Fig 2) nicely match earlier measurements using atmospheric neutrinos by Super-K, but a comparison with the parameters derived from the $\bar{\nu}_\mu$ beam (see Fig 2) shows only a small overlap of confidence regions. The uncertainty is dominated by statistics and precision is therefore expected to

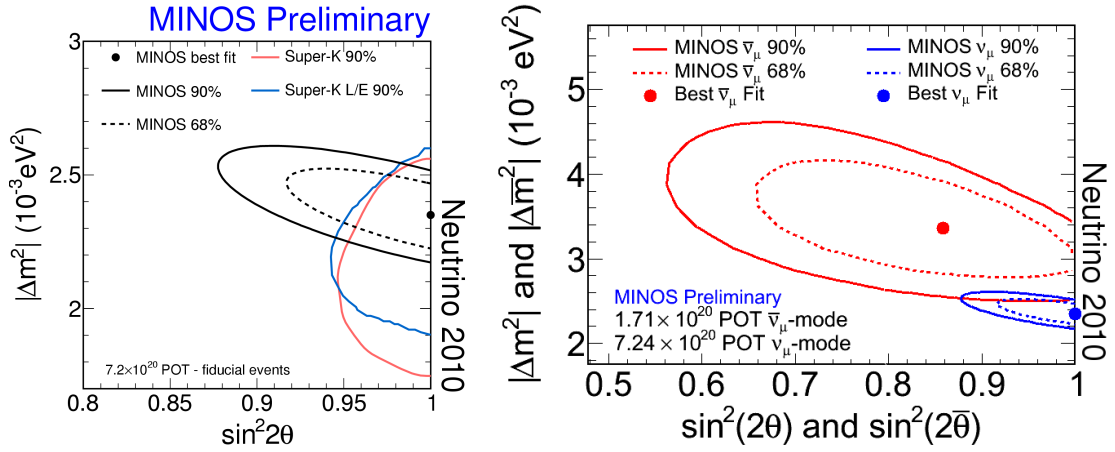


Figure 2: MINOS 90% confidence regions for ν_μ (left) and $\bar{\nu}_\mu$ (right) disappearance [2].

improve in the near future. It is worth to note here that a non-agreement of ν_μ and $\bar{\nu}_\mu$ parameters implies CPT-violation, a much unexpected scenario.

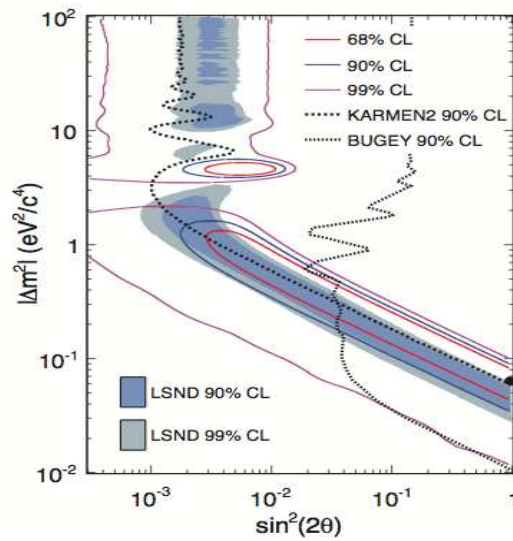


Figure 3: MiniBooNE confidence regions for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance [3]. The black dot shows the best fit and shaded areas show the LSND allowed regions [4].

MiniBooNE [3] has studied a $\bar{\nu}_\mu$ beam at 0.5 km and has found an excess in the search for appearing $\bar{\nu}_e$, see Fig 3 with low significance. The fit of appearance parameters agrees with the previous LSND excess [4]. An excess is not observed using a ν_μ beam. The derived oscillation parameters are not consistent with the other three oscillations and would therefore require new transitions to one or more sterile neutrinos. MiniBooNE has no near detector and has therefore

a lesser control of systematic effects compared to *e.g.* MINOS.

4 Anticipated results

Several important experimental quests, aimed at answering the fundamental questions listed above, are in a start-up phase.

The T2K experiment, using a ν_μ beam from J-PARC to Kamioka (295 km), [5] has started taking data early 2010. Its near and far detectors, ND280 and Super-K, respectively, are placed 2.5° off-axis to allow an optimal neutrino energy distribution. ND280 is a composite tracking detector expected to give a precise flux prediction and also measure background rates and νN cross-sections for Super-K. T2K is designed to measure $\Delta m_{32}^2, \theta_{23}$ with high precision, and θ_{13} for which the expected 5y sensitivity from ν_e appearance is $\sin 2\theta_{13} < 0.02$.

Double Chooz [6], using $\bar{\nu}_e$ from the two Chooz reactors, will consist of two identical water-Cherenkov detectors at 400 m and 1.05 km. Measurements in the far detector has started in 2010, and the near detector is planned to start in 2012. The expected 90% sensitivity after three years of full detector running is $\sin 2\theta_{13} < 0.03$.

Precise νN cross-sections is being studied at GeV-scale by Minerva, which is placed on the MINOS ν_μ beamline. Muon information from MINOS will be used in Minerva to reconstruct events. The results from Minerva will be an important input for oscillation experiments, *e.g.* T2K.

EXO has started a search for ν -less double β -decay, using a liquid Xe TPC, in 2010. The detector is equipped with Ba^{2+} -tagging, making it able to count the resulting nuclei. In two years time the sensitivity to Majorana masses is expected to reach down to the level of 0.1 eV.

The large electron spectrometer KATRIN studies tritium β -decay in the search for the absolute neutrino mass. After five years running, starting in 2012, the expected 90% sensitivity is $m_\nu < 0.2eV$.

5 Summary

Over the last few years neutrino physics has evolved into a test bench for various exciting physics scenarios (CP-violation, CPT-violation, lepton number violation, sterile particles) that now come in reach of experimenters. The oscillation model is now firmly established and the neutrino community enter a region of precision measurements. In parallel to this detailed knowledge, several essential parameters are waiting to be measured for the first time.

References

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