

Neutrino Physics

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Abstract. The observation of neutrino oscillations is firm evidence of non-zero neutrino mass. Neutrino mass and mixing have been studied by neutrino oscillation experiments so far. One of the remaining questions is whether neutrinos violate CP symmetry. Exploring new CP violation is also a subject of kaon physics. There are other common physics topics between neutrino and kaon experiments. In this talk, recent progress and future prospects of neutrino experiments for topics related to kaon physics will be discussed.

1. Introduction

Neutrinos are unique tools to study particle physics. In particular, the extremely small neutrino mass may be related to new physics at a high energy scale. The neutrino mass and mixing have been studied through neutrino oscillation measurements. In three flavor neutrino mixing, a flavor eigenstate can be expressed by $\nu_l = \sum_{j=1}^3 U_{lj} \nu_j$ ($l = e, \mu, \tau$), where the U_{lj} is an element of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. It is parameterized by three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and a complex phase (δ_{CP}). Neutrino oscillation is also sensitive to the difference of the mass squared, $\Delta m_{ij}^2 = m_i^2 - m_j^2$. These oscillation parameters have been measured experimentally. The precision of all of the mixing angles are now around the 3 % level[1]. On the other hand, the CP violation (CPV) of neutrinos, as well as the mass ordering, whether $m_1 < m_3$ (normal ordering) or $m_1 > m_3$ (inverted ordering), are not determined yet. Moreover, it was found that the structure of the PMNS matrix and the CKM matrix look different, i.e., the neutrino mixing is large while the quark mixing is small.

One of the remaining questions in the neutrino sector is whether neutrinos violate CP symmetry. It is still unknown but the size of lepton CPV could be $O(10^3)$ larger than for quarks. The Jarlskog invariant ($J_{CP} = \sin \theta_{13} \cos^2 \theta_{13} \sin \theta_{12} \cos \theta_{12} \sin \theta_{23} \cos \theta_{23} \sin \delta_{CP}$) for PMNS can be expressed as $J_{CP}^{PMNS} \approx 0.033 \times \sin \delta_{CP}$, while the one for CKM is $J_{CP}^{CKM} \approx 3 \times 10^{-5}$. The neutrino is a possible source of CPV, which can explain the matter-antimatter asymmetry in the universe. There are models in which the CPV in neutrino oscillations is large enough to generate the matter-antimatter asymmetry[2, 3, 4].

Exploring the source of the matter-antimatter asymmetry in the universe is a common subject in particle physics. New sources of CP violation is also a main subject in kaon physics. There are also other neutrino physics topics which are relevant to kaon physics. One of them is flavor symmetry. In neutrino, one of the mixing angles, θ_{23} , could be maximal, and then $|U_{\mu 3}| \sim |U_{\tau 3}|$. This may indicate that there is a flavor symmetry generated by physics at the high energy scale. The nature of neutrinos, Majorana or Dirac, is also a related subject. The see-saw mechanism introduces a heavy neutral lepton and lepton number violation ($\Delta L = 2$). If there is such a process, it also affects the branching fraction of kaon decays. As was also discussed in other



talk in this conference, the existence of sterile neutrinos may be relevant to the Cabibbo angle anomaly, which can be tested by kaon experiments[5].

In this talk, the recent progress and further prospects on neutrino physics topics which are relevant to kaons were discussed.

2. Review of neutrino experiments

2.1. Long baseline neutrino oscillation experiments

Neutrino CPV and mass ordering can be studied by comparing the oscillation probabilities between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. The mixing angle θ_{23} can be studied by the measurement of the ν_μ disappearance probability. Recent long baseline neutrino oscillation experiments are conducting these measurements by producing a high intensity muon neutrino beam.

The current ongoing long baseline neutrino oscillation experiments are T2K[6] and NOvA[7]. T2K produces a muon neutrino beam at the J-PARC Main-Ring accelerator. The muon neutrino (anti-neutrino) beam is then directed to the Super-Kamiokande detector, located 295 km away from J-PARC. T2K operated with 515kW of J-PARC Main-Ring beam power, while the beam power will be increased to 1.3MW. NOvA produces a muon neutrino beam at the FNAL Main Injector and directs the beam to the NOvA far detector located 810 km away from FNAL. The beam power of the FNAL Main Injector is recently around 900 kW. The difference of the baseline length between the two experiments can provide complementary information. In T2K, the matter effect is negligible because of the short baseline length. Therefore, an almost pure CPV measurement is possible. On the other hand, in the case of NOvA, the matter effect during the neutrino flight over the 810 km will give a large difference between the oscillation probabilities for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. Therefore, NOvA has a sensitivity to the mass ordering in addition to CPV.

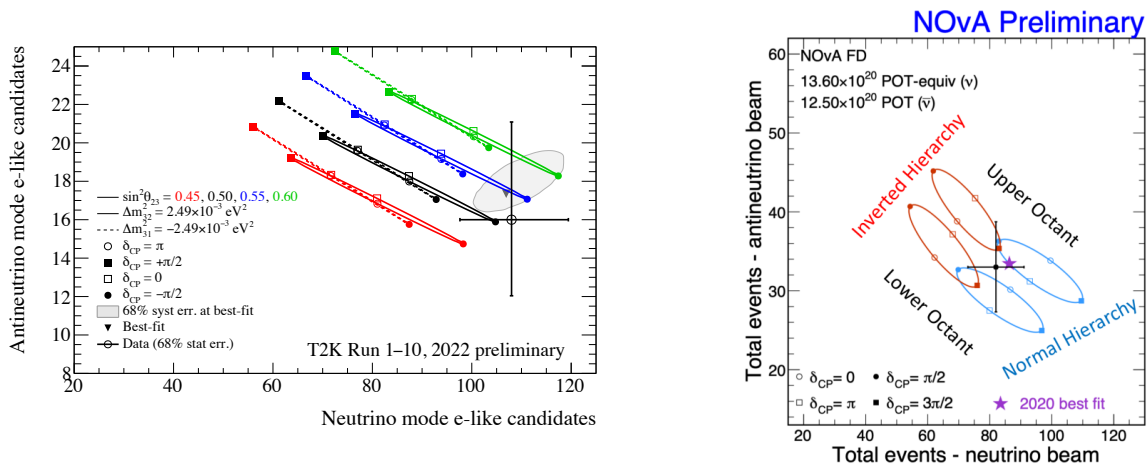


Figure 1. A comparison of the number of events for the neutrino and antineutrino mode electron-like candidates for T2K (left) and NOvA (right). The point with error bars shows the data and the ellipses show different theoretical predictions.

Figure 1 shows recent results from T2K and NOvA. These plots show a comparison between candidate events of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. Based on the data analysis of T2K, CP conservation is excluded at the 90% confidence level (C.L.). T2K also performed a measurement of CP violation using the Jarlskog invariant. T2K data prefers a maximal and negative value of J_{CP}^{PNMS} [6]. On the other hand, there is no strong asymmetry observed between the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ in the case of NOvA. There are therefore no strong preferences for the mass ordering and δ_{CP} based on the NOvA data analysis[7]. Figure 2 shows a comparison of the 90% C.L. contours in the δ_{CP}

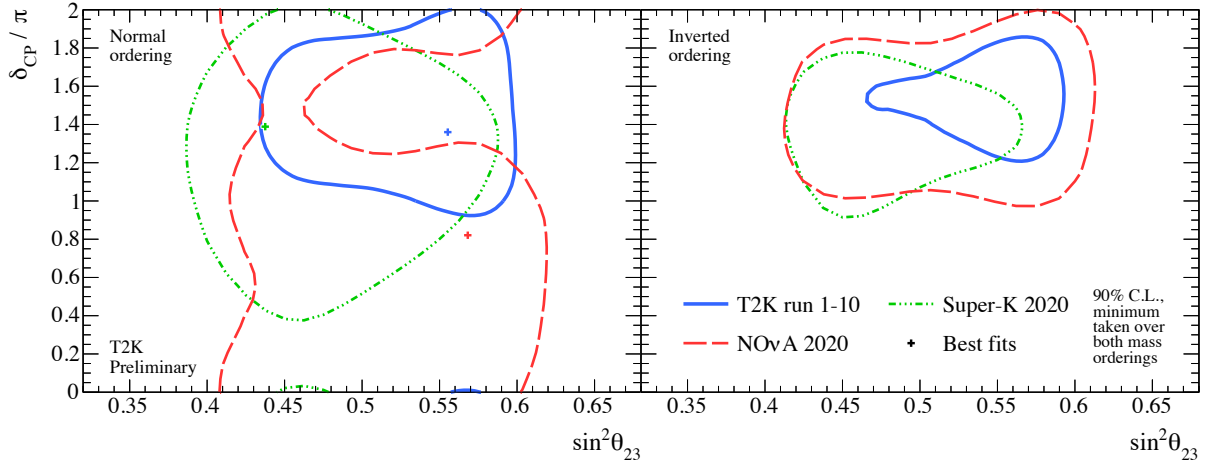


Figure 2. A comparison of the 90% C.L. contours in the $\delta_{CP} - \sin^2 \theta_{23}$ space among T2K, NOvA and SK[9].

- $\sin^2 \theta_{23}$ space among T2K, NOvA and SK[8]. It is expected that combining the experimental data will give a narrow allowed region for δ_{CP} . Among these experiments, there are differences in the neutrino energy and the baseline length. These differences can resolve the parameter degeneracies between the mass ordering and δ_{CP} , and the θ_{23} octant and δ_{CP} . Currently, two joint analyses, T2K and NOvA and T2K and SK are on-going.

Future prospects of the CPV, mass ordering and θ_{23} measurements were also discussed in this talk. T2K has a potential to search for CPV with $\sim 3\sigma$ sensitivity if the value of δ_{CP} is -90° [11]. T2K will continue taking data with an upgraded beamline and near detectors. The next generation experiments, such as Hyper-K and DUNE, can give a definite answer after 2027. These experiments have a potential to discover CPV with more than 5σ for a large fraction of the possible values of δ_{CP} , as shown in Fig. 3. It is expected that an era of searching for CPV will change to one of measurement of the size of the CPV in the next decade. For the mass ordering, NOvA has a sensitivity to determine the mass ordering with more than 3σ significance in the next 5 years, although it depends on the true value of δ_{CP} [10]. Future experiments such as HK, DUNE, JUNO[14, 15], KM3NeT/ORCA[16] and IceCube have a more significant sensitivity of the mass ordering. These future experiments also can improve the θ_{23} precisions down to the 1% level. These measurements can test if θ_{23} is maximal or not. JUNO can also measure $\sin^2 \theta_{12}$ with 0.5% precision. The precision measurements of the mixing parameters are important to validate neutrino flavor models[17].

2.2. Neutrino-less double beta decay search experiments

The search for neutrino-less double beta decay ($0\nu\beta\beta$) can address a fundamental property of the neutrino masses. If $0\nu\beta\beta$ is observed, neutrinos are Majorana particles. The half-life of $0\nu\beta\beta$ is inversely proportional to the square of the effective mass of the neutrino, $(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$, where $\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_i|^2$. Therefore, $0\nu\beta\beta$ measurements can constrain the neutrino mass. Based on the current knowledge of the mixing parameters, the lower bound of the predicted $m_{\beta\beta}$ is 15 meV (0 meV) in case of the inverted (normal) mass ordering.

There are several $0\nu\beta\beta$ search experiments active around the world. The current best upper limit on the effective mass of 36 – 156 meV was set by the KamLAND-Zen experiment[18]. This is the first search in the region of the effective mass which is allowed in the case of the inverted

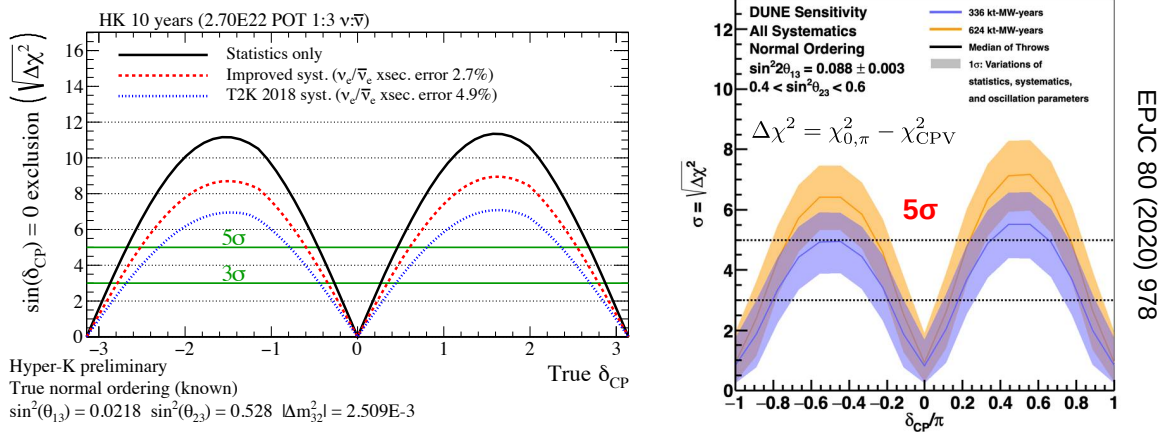


Figure 3. Sensitivity to exclude CP violation as a function of the true value of δ_{CP} for HK (left)[12] and DUNE (right)[13].

mass ordering.

For future experiments, reduction of background events is one of the critical points. There are several experiments proposed with various isotopes with the target mass of around 1 ton scale. Some experiments consider measuring the event topology in order to reduce the background. The next generation experiments will cover the full region of the inverted mass ordering[19, 20].

2.3. Sterile neutrino search experiments

Anomalies at $\Delta m^2 \sim 1 \text{ eV}^2$ were observed by the LSND, MiniBooNE (accelerator based experiments), reactor experiments and Gallium experiment. They cannot be explained by the model of three active neutrinos. On the other hand, a simple 3+1 neutrino model is also unable to explain all the experimental data. In particular, there is a tension between appearance and disappearance mode results. Several new experiments are going to check if this anomaly is really due to the existence of any sterile neutrinos. For example, two accelerator based experiments, SBN at FNAL[21] and JSNS²(-II) at J-PARC[22] will test the LSND anomaly. There are also several reactor and source ν experiments planned/running.

3. Summary

In this talk, neutrino experiments on topics related to kaon physics are reviewed. The T2K and NOvA experiments are exploring neutrino CPV and mass ordering. Based on the results so far, neutrino CPV might be large, but measurements are still statistics limited. Stay tuned for exciting results in the near future. Moreover, many new results are expected for $0\nu\beta\beta$ and sterile neutrino experiments in the next decade.

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