Snowmass2021 - Letter of Interest

T2K Experiment: future plans and capabilities

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
□ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
□ (NF7) Applications
■ (NF8) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
□ (Other) *[Please specify frontier/topical group(s)]*

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Abstract: The Tokai-to-Kamioka (T2K) experiment uses an intense (anti)neutrino source produced at J-PARC, which is sampled by detectors close to production (280 m) and far from it (295 km). The unique capabilities of T2K have been used to make precision measurements of oscillation physics, neutrino interactions, and searches for exotic phenomena. T2K has made important contributions to the evolving landscape of oscillation physics, including the discovery of charged current ν_e appearance and significant constraints on CP violation (CPV) in the lepton sector. T2K also has the strongest constraints on other important physics parameters of interest (e.g. $\sin^2\theta_{23}$). Major improvements to key components of the experiment (neutrino beam, near and far detectors) are planned, which will enhance sensitivity to oscillation physics parameters, including CPV, and will enable improved or new neutrino cross section measurements. In addition, efforts to perform a combined analysis of T2K data with other experiments (Super-Kamiokande, NOvA) are underway. T2K expects to take data with an upgraded near detector until the start of Hyper-Kamiokande, aiming to collect data corresponding to 10×10^{21} protons-on-target (POT), for a continued, vibrant physics program which will pursue 3σ observation of CPV in neutrinos and support the next generation of neutrino experiments.

The Tokai-to-Kamioka (T2K) experiment [1] is an accelerator-driven neutrino oscillation experiment, which hosts a broad physics program of precision neutrino oscillation, neutrino cross section measurements, as well as searches for exotic physics. It has operated since 2009 and has taken $1.97(1.63) \times 10^{21}$ POT to date in neutrino(antineutrino)-enhanced beam modes. In 2013, T2K discovered $\nu_\mu \rightarrow \nu_e$ appearance [2] and in 2019, T2K presented the most stringent constraints on CPV in the lepton sector [3].

Upgraded Beam and Detector Capabilities: The J-PARC neutrino beam source for T2K can produce neutrino-enhanced and antineutrino-enhanced beams. The beam has been stably operated above 500 kW. A magnet power supply upgrade in 2021 will decrease the time between beam pulses from 2.48 s to 1.32 s, increasing the beam power. Additional RF upgrades and machine development should allow the beam power to reach 1 MW by Japanese Fiscal Year (JFY) 2025. Starting in 2020, oscillation analyses incorporate the charged pion yields measured by NA61/SHINE from a T2K-replica target [4] to constrain the beam flux prediction and will expand to include more species in the future [5]. This has reduced the flux uncertainty from about 10% to around 5% near the flux peak. Future hadron production data at lower energies and high-statistics replica-target data will reduce these uncertainties further, and improvements in proton beam monitoring and analysis are also being developed; this effort is relevant to the future global program.

Multiple detectors sample the neutrino beam at different locations close (280m) and far (295km) from the source. T2K's near detector suite includes a detector colinear with the neutrino source axis ("on-axis") detector (INGRID [6]), and two tracking detectors at different positions transverse to the beam ("off-axis", ND280, WAGASCI+BabyMIND [7]). The far detector, Super-Kamiokande (SK) is an enormous (50kt) water-Cherenkov detector, also off-axis. The different positions in the beam result in three distinct energy spectra for use in physics analyses. A new, upgraded ND280 detector, with a fully active target [8] (SuperFGD), surrounded by new horizontal TPCs with a resistive Micromegas for gas amplification [9], will have significantly increased acceptance to particles emitted at high and backward angles, and to low energy protons. It will be operational in 2022 [10]. The improved capabilities of this detector will help reduce the systematic uncertainties due to the neutrino-interactions model to an unprecedented level.

Oscillation Physics Program: T2K uses two primary oscillation channels in both neutrino and antineutrino beams: in the $\nu_\mu(\overline{\nu}_\mu)$ disappearance channel, the initially produced ν_μ oscillate into other flavors, which is studied by observing the interaction of the remaining ν_μ in the far detector. In the $\nu_e(\overline{\nu}_e)$ appearance channel, ν_e interactions from the $\nu_\mu \rightarrow \nu_e$ oscillation and the intrinsic ν_e in the beam are studied. Since 2016, T2K has utilized a joint fit of all four modes of oscillation in extracting three-flavor mixing parameters, including the magnitude and sign of $\Delta m^2_{32/31}$, $\sin^2\theta_{23}$, and δ_{CP}, and compare the channels separately. As T2K measures fundamental parameters of neutrino mixing, the T2K program is fully aligned with the P5 Science Driver to "Pursue the physics associated with neutrino mass" and for the next several years will be at the forefront of addressing "some of the most significant questions" such as whether neutrinos and antineutrinos oscillate differently and how the neutrino masses are ordered. As a general strategy, the experiment expects to alternate between antineutrino and neutrino-enhanced beam configurations to integrate roughly equal exposure in each. T2K expects to take data with an upgraded ND280 detector until the start of the Hyper-Kamiokande [11] experiment, aiming to collect data corresponding to 10×10^{21} POT. The new data, combined with development of the selection of ν_μ and ν_e candidates in SK and upgrades to the beamline and near detector, will improve statistical precision and sensitivity to CPV and mass ordering; precision measurements of $\Delta m^2_{32/31}$, $\sin^2\theta_{23}$ are also planned [12].

Joint analyses of T2K data with other experiments enhance the scientific reach of the T2K program. As such, MoUs and joint working groups have been established with the Super-Kamiokande (atmospheric neutrino) and NOvA [13] (accelerator neutrino) experiments. The oscillation probability has degeneracies which make interpretation of the observed oscillated rates as unique parameter values difficult. This includes the (unknown) mass ordering, θ_{23} octant, and intrinsic degeneracy of θ_{13} , δ_{CP}, and θ_{23} in the appearance channel. Combinations of experimental data from different baselines and neutrino energies also resolves degeneracies in a complementary way, which provides improved sensitivity to the physics and/or physics reach outside parameter space accessible by each experiment. As significant correlations between experiments are expected from the neutrino interaction model, direct collaboration between the experiments is essential.

Neutrino Interaction Progress and Measurements: Continuing development of the neutrino interaction models is a scientific goal of T2K. T2K utilizes an important feedback loop between model development, implementation and application to analyses, which has resulted in reduced model systematic uncertainties and more robust oscillation and cross section analyses. First, T2K has close contact with model builders; T2K collaborates actively with theory groups within and outside the collaboration. Second, T2K performs comprehensive tests of models against external data sets, where the NUISANCE [14] framework and strong connections to other experiments are critical. T2K has developed new methods to parameterize model uncertainties and deficiencies, and propagate these uniformly to external data sets, and the oscillation analysis. Finally, T2K revisits modelling limitations yearly, where new or updated models and uncertainties are incorporated into the analysis. As a consumer and a producer of neutrino cross section measurements, T2K is an integral component of cross-collaboration workshops (e.g. TENSIONS [15], NuSTEC [16]) which critically reflected on the use of and needs of cross section measurements. Theory groups, and experiments, such as MicroBooNE [17], Super-Kamiokande, have made extensive use of T2K data.

A key output of the T2K program is measurements of neutrino interactions on a variety of targets; these are provided to the community to further improve interaction models of interest to those studying neutrino oscillation, atmospheric neutrinos and supernova neutrinos[18–35]. In addition, T2K has made important measurements of rare processes [36–38]. An improved set of measurements will be possible due to the increased data collected, the presence of new, highly capable detectors in the beamline and improved neutrino flux model. These new measurements will be specifically tailored to confront the sources of the primary systematic uncertainties in neutrino oscillation analyses. They will include measurements of correlations between outgoing hadrons and leptons to probe nuclear-medium effects, joint analyses between the different T2K near detectors to directly study the energy dependence of cross sections, and the improved use of calorimetry. Moreover, the new SuperFGD's neutron tagging capabilities and WAGASCI's high purity water target will allow such measurements to be made separately for neutrinos and antineutrinos on carbon and oxygen targets.

Exotics Reach: T2K's unique experimental set up has provided for novel searches for exotic phenomena, including Lorentz violation [39], sterile neutrinos [40, 41], and neutral heavy leptons [42]. T2K plans to perform new and improved measurements of those channels and will continue performing tests of the three flavor framework, such as tests of CPT, larger-than-predicted CP violation, and comparisons of oscillation parameters to those estimated by other experiments, especially reactor experiments. The intense beam may also produce neutral heavy leptons and light dark matter candidates, which can be searched for with T2K's extensive suite of near and far detectors.

Impact and Future: T2K's program provides a roadmap to the precision needed by the next generation of long-baseline experiments. Over the last decade, T2K has trained a new generation of students and postdoctoral researchers in advanced analysis methods. These people will perform the next set of measurements in neutrino oscillation, cross sections, and exotic searches planned by the DUNE and Hyper-Kamiokande experiments. The planned extensions to the experiment are important to the future as well. In particular, T2K data and operation offer important constraints on the flux and interaction model, and T2K analysis methodology has been used extensively by the future program. T2K will continue to develop novel beamline measurements and improved estimates of systematic uncertainties associated to the neutrino flux. T2K will use new detector information (SK-Gd [43, 44] and ND280 upgrade) to assess and improve a comprehensive interaction model. In particular, both the near and far detectors will have sensitivity to the composition of neutrons in the final state relevant for (anti)neutrino energy reconstruction. Finally, the technology used in the SuperFGD component of the ND280 detector is planned to be used in a DUNE detector (SAND).

[1] K. Abe et al. The T2K Experiment. *Nucl. Instrum. Meth. A*, 659:106–135, 2011. doi:10.1016/j.nima.2011.06.067.

[2] K. Abe et al. Observation of Electron Neutrino Appearance in a Muon Neutrino Beam. *Phys. Rev. Lett.*, 112: 061802, 2014. doi:10.1103/PhysRevLett.112.061802.

[3] K. Abe et al. Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations. *Nature*, 580 (7803):339–344, 2020. doi:10.1038/s41586-020-2177-0. [Erratum: Nature 583, E16 (2020)].

[4] N. Abgrall et al. Measurements of $\pi^{\pm}$ differential yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS. *Eur. Phys. J. C*, 76(11):617, 2016. doi:10.1140/epjc/s10052-016-4440-y.

[5] N. Abgrall et al. Measurements of $\pi^{\pm}$, $K^{\pm}$ and proton double differential yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS. *Eur. Phys. J. C*, 79(2):100, 2019. doi:10.1140/epjc/s10052-019-6583-0.

[6] K. Abe et al. Measurements of the T2K neutrino beam properties using the INGRID on-axis near detector. *Nucl. Instrum. Meth. A*, 694:211–223, 2012. doi:10.1016/j.nima.2012.03.023.

[7] K. Abe et al. Measurements of $\bar{\nu}_\mu$ and $\bar{\nu}_\mu + \nu_\mu$ charged-current cross-sections without detected pions nor protons on water and hydrocarbon at mean antineutrino energy of 0.86 GeV. 4 2020.

[8] A. Blondel et al. The SuperFGD Prototype Charged Particle Beam Tests. 8 2020.

[9] D. Attié et al. Performances of a resistive Micromegas module for the Time Projection Chambers of the T2K Near Detector upgrade. *Nucl. Instrum. Meth. A*, 957:163286, 2020. doi:10.1016/j.nima.2019.163286.

[10] K. Abe et al. T2K ND280 Upgrade - Technical Design Report. 1 2019.

[11] K. Abe et al. Hyper-Kamiokande Design Report. 5 2018.

[12] K. Abe et al. Neutrino oscillation physics potential of the T2K experiment. *PTEP*, 2015(4):043C01, 2015. doi: 10.1093/ptep/ptv031.

[13] M.A. Acero et al. First Measurement of Neutrino Oscillation Parameters using Neutrinos and Antineutrinos by NOvA. *Phys. Rev. Lett.*, 123(15):151803, 2019. doi:10.1103/PhysRevLett.123.151803.

[14] P. Stowell et al. NUISANCE: a neutrino cross-section generator tuning and comparison framework. *JINST*, 12 (01):P01016, 2017. doi:10.1088/1748-0221/12/01/P01016.

[15] M. Betancourt et al. Comparisons and Challenges of Modern Neutrino Scattering Experiments (TENSIONS2016 Report). *Phys. Rept.*, 773-774:1–28, 2018. doi:10.1016/j.physrep.2018.08.003.

[16] L. Alvarez-Ruso et al. NuSTEC White Paper: Status and challenges of neutrino–nucleus scattering. *Prog. Part. Nucl. Phys.*, 100:1–68, 2018. doi:10.1016/j.ppnp.2018.01.006.

[17] R. Acciarri et al. Design and Construction of the MicroBooNE Detector. *JINST*, 12(02):P02017, 2017. doi: 10.1088/1748-0221/12/02/P02017.

[18] K. Abe et al. Measurement of the inclusive ν_μ charged current cross section on carbon in the near detector of the T2K experiment. *Phys. Rev. D*, 87(9):092003, 2013. doi:10.1103/PhysRevD.87.092003.

[19] K. Abe et al. Measurement of the neutrino-oxygen neutral-current interaction cross section by observing nuclear deexcitation γ rays. *Phys. Rev. D*, 90(7):072012, 2014. doi:10.1103/PhysRevD.90.072012.

[20] K. Abe et al. Measurement of the inclusive ν_μ charged current cross section on iron and hydrocarbon in the T2K on-axis neutrino beam. *Phys. Rev. D*, 90(5):052010, 2014. doi:10.1103/PhysRevD.90.052010.

[21] K. Abe et al. Measurement of the ν_μ charged-current quasielastic cross section on carbon with the ND280 detector at T2K. *Phys. Rev. D*, 92(11):112003, 2015. doi:10.1103/PhysRevD.92.112003.

[22] K. Abe et al. Measurement of the ν_μ charged current quasielastic cross section on carbon with the T2K on-axis neutrino beam. *Phys. Rev. D*, 91(11):112002, 2015. doi:10.1103/PhysRevD.91.112002.

[23] K. Abe et al. Measurement of the electron neutrino charged-current interaction rate on water with the T2K ND280 π^0 detector. *Phys. Rev. D*, 91:112010, 2015. doi:10.1103/PhysRevD.91.112010.

[24] K. Abe et al. Measurement of the muon neutrino inclusive charged-current cross section in the energy range of 1–3 GeV with the T2K INGRID detector. *Phys. Rev. D*, 93(7):072002, 2016. doi:10.1103/PhysRevD.93.072002.

[25] Ko Abe et al. Measurement of double-differential muon neutrino charged-current interactions on C_8H_8 without pions in the final state using the T2K off-axis beam. *Phys. Rev. D*, 93(11):112012, 2016. doi: 10.1103/PhysRevD.93.112012.

[26] K. Abe et al. First measurement of the muon neutrino charged current single pion production cross section on water with the T2K near detector. *Phys. Rev. D*, 95(1):012010, 2017. doi:10.1103/PhysRevD.95.012010.

[27] K. Abe et al. Measurement of the single π^0 production rate in neutral current neutrino interactions on water. *Phys. Rev. D*, 97(3):032002, 2018. doi:10.1103/PhysRevD.97.032002.

[28] K. Abe et al. Measurement of $\bar{\nu}_\mu$ and ν_μ charged current inclusive cross sections and their ratio with the T2K off-axis near detector. *Phys. Rev. D*, 96(5):052001, 2017. doi:10.1103/PhysRevD.96.052001.

[29] K. Abe et al. First measurement of the ν_μ charged-current cross section on a water target without pions in the final state. *Phys. Rev. D*, 97(1):012001, 2018. doi:10.1103/PhysRevD.97.012001.

[30] K. Abe et al. Measurement of inclusive double-differential ν_μ charged-current cross section with improved acceptance in the T2K off-axis near detector. *Phys. Rev. D*, 98:012004, 2018. doi:10.1103/PhysRevD.98.012004.

[31] K. Abe et al. Characterization of nuclear effects in muon-neutrino scattering on hydrocarbon with a measurement of final-state kinematics and correlations in charged-current pionless interactions at T2K. *Phys. Rev. D*, 98(3): 032003, 2018. doi:10.1103/PhysRevD.98.032003.

[32] K. Abe et al. Measurement of the ν_μ charged-current cross sections on water, hydrocarbon, iron, and their ratios with the T2K on-axis detectors. 4 2019. doi:10.1093/ptep/ptz070.

[33] K. Abe et al. Measurement of the muon neutrino charged-current single π^+ production on hydrocarbon using the T2K off-axis near detector ND280. *Phys. Rev. D*, 101(1):012007, 2020. doi:10.1103/PhysRevD.101.012007.

[34] K. Abe et al. Measurement of neutrino and antineutrino neutral-current quasielasticlike interactions on oxygen by detecting nuclear deexcitation γ rays. *Phys. Rev. D*, 100(11):112009, 2019. doi:10.1103/PhysRevD.100.112009.

[35] K. Abe et al. Simultaneous measurement of the muon neutrino charged-current cross section on oxygen and carbon without pions in the final state at T2K. *Phys. Rev. D*, 101(11):112004, 2020. doi:10.1103/PhysRevD.101.112004.

[36] K. Abe et al. Measurement of the Inclusive Electron Neutrino Charged Current Cross Section on Carbon with the T2K Near Detector. *Phys. Rev. Lett.*, 113(24):241803, 2014. doi:10.1103/PhysRevLett.113.241803.

[37] K. Abe et al. Measurement of Coherent π^+ Production in Low Energy Neutrino-Carbon Scattering. *Phys. Rev. Lett.*, 117(19):192501, 2016. doi:10.1103/PhysRevLett.117.192501.

[38] K. Abe et al. Search for neutral-current induced single photon production at the ND280 near detector in T2K. *J. Phys. G*, 46(8):08LT01, 2019. doi:10.1088/1361-6471/ab227d.

[39] Ko Abe et al. Search for Lorentz and CPT violation using sidereal time dependence of neutrino flavor transitions over a short baseline. *Phys. Rev. D*, 95(11):111101, 2017. doi:10.1103/PhysRevD.95.111101.

[40] K. Abe et al. Search for short baseline ν_e disappearance with the T2K near detector. *Phys. Rev. D*, 91:051102, 2015. doi:10.1103/PhysRevD.91.051102.

[41] K. Abe et al. Search for light sterile neutrinos with the T2K far detector Super-Kamiokande at a baseline of 295 km. *Phys. Rev. D*, 99(7):071103, 2019. doi:10.1103/PhysRevD.99.071103.

[42] K. Abe et al. Search for heavy neutrinos with the T2K near detector ND280. *Phys. Rev. D*, 100(5):052006, 2019. doi:10.1103/PhysRevD.100.052006.

[43] Hiroyuki Sekiya. The Super Kamionade Gadolinium Project. *J. Phys. Conf. Ser.*, 1342(1):012044, 2020. doi: 10.1088/1742-6596/1342/1/012044.

[44] C. Simpson et al. Sensitivity of Super-Kamiokande with Gadolinium to Low Energy Anti-neutrinos from Pre-supernova Emission. *Astrophys. J.*, 885:133, 2019. doi:10.3847/1538-4357/ab4883.

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