Snowmass2021 - Letter of Interest

Ongoing Science Program of Super-Kamiokande

Thematic Areas:

- ■ (NF1) Neutrino Oscillations
- ■ (NF3) Beyond the Standard Model
- ■ (NF4) Neutrinos from Natural Sources
- ■ (NF5) Neutrino Properties
- ■ (NF10) Neutrino Detectors
- ■ (RF4) Baryon and Lepton Number Violating Processes
- ■ (CF1) Dark Matter: Particle-like
- ■ (CF7) Cosmic Probes of Fundamental Physics

Contact Information:
Ed Kearns, Boston University [`kearns@bu.edu`]

Additional Authors:
The Super-Kamiokande Collaboration is an international collaboration of about 190 people and about 50 institutes from Japan, the United States, Korea, China, Poland, Spain, Canada, United Kingdom, Italy, and France. A recent author list is available at: `https://arxiv.org/abs/2005.05109`

Abstract: The Super-Kamiokande experiment will have completed three decades of operation by 2027, the estimated commencement of operation for Hyper-Kamiokande. In the meantime, continued operation of the detector and continued scientific research by the collaboration is relevant and valuable on a number of important topics in particle physics and astrophysics. These include supernova neutrino bursts, diffuse supernova neutrino background, atmospheric neutrino oscillation, nucleon decay, solar neutrinos, and neutrino astrophysics. In this document we outline how Super-K will continue to address questions under consideration by the Snowmass 2021 study.

The Super-Kamiokande Experiment

The Super-Kamiokande experiment (Super-K, SK) has been operating with continual improvements since 1996. It was conceived as a massive, highly instrumented, water Cherenkov detector to resolve the atmospheric neutrino anomaly, resolve the solar neutrino puzzle, and search for nucleon decay. Today and for several years to come, SK is the leading operating experiment sensitive to a burst of neutrinos from a supernova in the Milky Way galaxy, a signal whose detection is just a matter of patience.

A significant aspect of continued operation is the recent upgrade to a new phase of the experiment, dubbed SK-Gd. In 2018, the detector and water purification system was upgraded to allow operation with dissolved gadolinium sulfate, $\mathrm{Gd_2(SO_4)_3}$, 0.2% by mass. Neutron capture on gadolinium will improve differentiation between neutrinos and antineutrinos, enhancing nearly every physics topic in the SK portfolio. First operation commenced in 2020 with 0.02% loading.

Supernova Neutrino Bursts

The chance of a Type II supernova in the Milky Way galaxy is a few percent per year. What we might learn from such an event is relatively unknown. What is certain is that the statistical signal will dwarf the 19 events observed by Kamiokande and IMB from SN1987A. Until DUNE or Hyper-Kamiokande commence operation, Super-K will provide the largest sample of the most detailed events, including elastic scatter events that reveal the direction of the supernova and enable the astronomical community to engage in multi-messenger discoveries. For a supernova at 10 kpc, somewhere between 3K to 10K neutrino events would be detected by Super-K in a few seconds, depending on the supernova model and the neutrino mass ordering. Supernova neutrinos are expected to precede the optical brightening by hours, and Super-K is prepared to alert the astronomical community directly and through SNEWS.

Studying the time, energy, and flavor structure of the neutrino burst may reveal astrophysical secrets of the core collapse as well as fundamental neutrino physics. The observed burst may reveal the effects of neutrino-neutrino interactions in a regime inaccessible by any other means, as well as effects due to beyond-the-Standard-Model physics. Since the matter effect resonance is directly connected to the neutrino mass ordering, it is possible that structure in the time-energy spectrum may reveal whether the neutrino mass ordering is inverted or normal.

Efficient neutron tagging provided by SK-Gd will enable event-by-event flavor identification, as inverse beta decay will be accompanied by a neutron, whereas elastic scatters, which comprise 3-5% of the events, will not. Background subtraction of IBD events is estimated to improve the pointing accuracy to the progenitor star by a factor of two. Event-by-event subtraction could allow identification of the “neutronization burst” due to collapsing stellar matter, a key prediction in supernova dynamics. Recording even a handful of ν_e during the first few milliseconds would be evidence of the formation of the proto-neutron star. The IBD signature enabled by neutron tagging should also extend measurement of neutrino emission to later times than otherwise possible. Black hole formation may be revealed by a cutoff in neutrino emission in the later cooling stages of the supernova.

Diffuse Supernova Neutrino Background

Neutrinos emitted by distant supernovae suffuse the universe. These comprise the so-called “diffuse supernova neutrino background” (DSNB). The DSNB is one of the few remaining neutrino signals that has not yet been detected by any experiment. When observed, the measured rate of the DSNB provides information about stellar collapse, nucleosynthesis, and the rate of star formation. The SK-Gd upgrade to Super-Kamiokande directly addresses the backgrounds that limited our prior searches. SK-Gd should detect roughly six DSNB neutrinos per year.

Atmospheric Neutrino Oscillation

The atmospheric neutrino flux has both electron and muon neutrinos, both neutrinos and antineutrinos, a wide energy range, and a wide range of baselines including significant distance through matter, and tau neutrino appearance due to neutrino oscillation. Atmospheric neutrinos oscillation offers an independent comparison to measurements by long-baseline and reactor experiments, as well as the opportunity for joint fits with T2K as well as global neutrino data. Atmospheric neutrinos have sensitivity to the unknown parameters of the 3-flavor PMNS model: the octant of θ_{23}, the neutrino mass ordering, and the value of δ_{CP}.

While operating the experiment, there is continual activity to improve the atmospheric neutrino analysis. The analysis benefits from the ongoing refinement of neutrino interaction models derived from near detector measurements at T2K and dedicated experiments such as MINERvA. Some of the analysis improvements will leverage the improved neutron tagging made possible by new exposure during the SK-Gd phase. Other improvement can be applied retroactively to the earlier SK-I through SK-IV data sets.

Nucleon Decay

Baryon number violation may be key to a number of questions in fundamental physics and cosmology, making the continued search for proton decay and related processes a high priority, as recognized in the prior P5 report. In the future, we expect the Hyper-Kamiokande experiment to pick up where the SK program leaves off. In the meantime, proton lifetimes characteristic of a variety of grand unified theories continue to be probed by further SK running.

Ten more years of SK running would increase the exposure by roughly 70% (our latest publications are based on 316 kton-years). For a generic analysis, a 90% CL limit would improve by about 50%, reaching 2.5×10^{34} years. The key to even this modest improvement is maintaining a low background rate. Our expectation is that a neutron will be ejected by the nucleus only about 7% of the time when a proton decays in ^{16}O, and never for the free proton. On the other hand, neutrino interactions are frequently accompanied by neutrons, even when the interaction is on a free proton due to subsequent elastic scattering. We have already used neutron capture on hydrogen in a recent SK-IV analysis, where the background rate was reduced by a factor of two. With SK-Gd, we will be able to further suppress backgrounds as well as characterize the neutron production in atmospheric neutrinos, which will benefit future experiments.

Solar Neutrinos

With the addition of Gd, SK will more cleanly separate solar ^{8}B neutrino interactions from radioactive background due to cosmic ray induced spallation. This will enable stronger constraints on the neutrino energy spectrum, testing adiabatic conversion (MSW effect), which only solar and supernova neutrinos are subject to. In addition, matter effects in the Earth induce the “day/night” difference. SK’s measurements of rate, spectrum and day/night asymmetry improves constraints on the solar neutrino oscillation parameters.

Neutrino Astrophysics

The Super-K detector is searching for astrophysical sources over a wide range of energies, with few-degree pointing for muon neutrinos in the 10 GeV to 1 TeV range. Super-K is actively checking coincident signatures in both time and direction. For cases where the originating object is non-transient, SK also has the capability of looking backwards in its 20-year data set for overlooked coincidence. An example of this is our recent (negative) search for neutrinos from blazar TXS 0506+056, identified by a 100 TeV neutrino by IceCube in coincidence with gamma ray observations by several experiments.

Operation of the T2K Far Detector

The SK detector serves as the far detector for the T2K experiment. Super-K delivers supplementary data sets that are useful for understanding reconstruction algorithms, their efficiencies, and systematic uncertainties. Atmospheric neutrino interactions are used to validate the neutrino interaction Monte Carlo on water nuclei. Cosmic ray data is critical for tuning the detector simulation. The atmospheric neutrino single-π^0 sample is the most important in situ energy scale calibration in the T2K energy range, and is also a valuable sample for studying and improving software algorithms.

References:

Refereed publications by the Super-Kamiokande Collaboration as well as Masters and Ph.D. theses may be found at: http://www-sk.icrr.u-tokyo.ac.jp/sk/publications/index-e.html

Host Institute

Kamioka Observatory, Institute of Cosmic Ray Research (ICRR), University of Tokyo, Research Center for Cosmic Neutrinos (RCCN), ICRR, University of Tokyo

Collaborating Institutes

Boston University; British Columbia Institute of Technology; California State University; Chonnam National University; Department of Physics, Faculty of Science & Graduate School of Science, The University of Tokyo; Duke University; Gifu University; Gwangju Institute of Science and Technology; High Energy Accelerator Research Organization (KEK); IN2P3- Laboratoire Leprince-Ringuet, Ecole Polytechnique; INFN, Sezione di Napoli and Universita‘ di Napoli; INFN, Sezione di Padova and Universita‘ di Padova; INFN, Sezione di Roma; INFN, sezione di Bari; Imperial College London; Junior College, Fukuoka Institute of Technology; Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), The University of Tokyo; Keio University; King’s College London; Kobe University; Kyoto University; Miyagi University of Education; Nagoya University; National Centre for Nuclear Research (NCBJ); Okayama University; Osaka University; Rutherford Appleton Laboratory; Seoul National University; Shizuoka University of Welfare; Stony Brook University; Sungkyunkwan University; TRIUMF; Tokai University; Tokyo Institute of Technology; Tokyo University of Science; Tsinghua University; University Autonoma Madrid; University of British Columbia; University of California, Irvine; University of Hawaii; University of Liverpool; University of Oxford; University of Sheffield; University of Toronto; University of Warsaw; University of Winnipeg; Warwick University; Yokohama National University