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Neutrinos: DRAFT

Conveners: A. de Gouvêa[38], K. Pitts[25], K. Scholberg[22], G.P. Zeller[23]

Subgroup Conveners: J. Alonso[34], A. Bernstein[30], M., S. Elliott[31], K. Heeger[64], K. Hoffman[32], P. Huber[60], L.J. Kaufman[27], B. Kayser[23], J. Link[60], C. Lunardini[3], B. Monreal[11], J. Morfin[23], H. Robertson[61], R. Tayloe[27], N. Tolich[61]

K. Abazajian[8], C. Albright[23], J. Asaadi[54], K.S Babu[40], B. Balantekin[63], P. Barbeau[22], A. Blake[14], E. Blucher[16], N. Bowden[30], S. Brice[23], A. Bross[23], B. Carls[23], P. Coloma[60], A. Connolly[39], J. Conrad[34], M. Convery[48], D. Cowen[43], H. da Motta[15], F. Di Lodovico[45], Z. Djurcic[2], M. Dracos[53], Y. Efremenko[55], T. Ekelof[59], J. Feng[8], J. Formaggio[34], A. Friedland[31], G. Fuller[11], H. Gallagher[58], M. Gilchriese[29], M. Goodman[2], G. Gratta[51], C. Hall[32], F. Halzen[63], D. Harris[23], M. Heffner[30], R. Henning[36], J.L. Hewett[48], R. Hill[23], G. Horton-Smith[28], E. Kearns[4], S. Kettell[5], J. Klein[42], Y. Kim[47], Y.K. Kim[16], Y. Kolomensky[6], M. Kordosky[62], K. Luk[6], K. Lande[42], K. Lang[56], R. Lanza[34], H. Lee[2], C.J. Lin[29], K. Long[26], W. Louis[31], W. Marciano[5], C. Mariani[60], C. Mauger[31], K. McFarland[46], R. McKeown[62], M. Messier[27], S. Mishra[50], U. Mosel[24], P. Mumm[35], D. Nygren[6], G. Orebi-Gann[6], J. Osta[23], S. Parke[23], R. Patterson[13], A. Piepke[1], R. Plunkett[23], A. Poon[29], X. Qian[5], J. Raaf[23], R. Rameika[23], M. Ramsey-Musolf[33], B. Rebel[23], R. Roser[23], J. Rosner[16], G. Rybka[61], S. Sangiorgio[30], D. Schmitz[16], R. Shrock[52], M. Shaevitz[21], N. Smith[49], M. Smy[8], P. Sorensen[30], A. Sousa[17], J. Spitz[34], R. Svoboda[7], R. Tschirhart[23], J. Thomas[18], C. Tully[44], K. Van Bibber[6], P. Vahle[62], P. Vogel[13], C.W. Walter[22], D. Wark[26], D. Webber[63], H. Weerts[2], L. Winslow[9], H. White[23], R.J. Wilson[20], M. Yokoyama[57], J. Yoo[23], E. Zimmerman[19]

[1]University of Alabama, Tuscaloosa, AL 35487, USA
[2]Argonne National Laboratory, Argonne, IL 60439, USA
[3]Arizona State University, Tempe, AZ, 85287-1504, USA
[4]Boston University, Boston, MA 02215, USA
[5]Brookhaven National Laboratory, Upton, NY, 11973-5000, USA
[6]University of California, Berkeley, Berkeley, CA 94720, USA
[7]University of California, Davis, Davis, CA 95616, USA
[8]University of California, Irvine, Irvine, CA 92698, USA
[9]University of California, Los Angeles, Los Angeles, CA 90095, USA
[10]University of California, Riverside, Riverside, CA 92521, USA
[11]University of California, San Diego, La Jolla, CA 92093, USA
[12]University of California, Santa Barbara, Santa Barbara , CA 93106, USA
[13]California Institute of Technology, Pasadena, CA 91125, USA
[14]University of Cambridge, Cambridge, CB3 0HE, United Kingdom
[15]Centro Brasileiro de Pesquisas F'isicas, Rio de Janeiro, Brazil
[16]University of Chicago, Enrico Fermi Institute, Chicago, IL 60637, USA
[17]University of Cincinnati, Cincinnati, OH 45221, USA
[18]University College London, London WC1E 6BT, United Kingdom
[19]University of Colorado, Boulder, CO 80309, USA
[20]Colorado State University, Fort Collins, CO 80523, USA
[21]Columbia University, New York, NY 10027, USA
[22]Duke University, Durham, NC 27708-0754, USA

[23]Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[24]Giessen University, Giessen, D-35392, Germany
[25]University of Illinois, Urbana, IL 61801, USA
[26]Imperial College London, London, SW7 2AZ, United Kingdom
[27]University of Indiana, Bloomington, IN 47405-7105, USA
[28]Kansas State University, Manhattan, KS 66506-2601, USA
[29]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[30]Lawrence Livermore National Laboratory, Livermore, CA, 94550, USA
[31]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[32]University of Maryland, College Park, MD 20742, USA
[33]University of Massachusetts, Amherst, MA 01003, USA
[34]Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[35]National Institute of Standards and Technology, Gaithersburg, MD 20899-1070, USA
[36]University of North Carolina, Chapel Hill, NC 27599, USA
[37]Northern Illinois University, Dekalb, IL 60115, USA
[38]Northwestern University, Evanston, IL 60208 USA
[39]Ohio State University, Columbos, OH 43210, USA
[40]Oklahoma State University, Stillwater, OK 74078, USA
[41]University of Oxford, Oxford, OX1 3RH, United Kingdom
[42]University of Pennsylvania, Philadelphia, PA 19104, USA
[43]Pennsylvania State University, University Park, PA 16802, USA
[44]Princeton University, Princeton, NJ 08544, USA
[45]Queen Mary University of London, London, E1 4NS, United Kingdom
[46]University of Rochester, Rochester, NY, 14627, USA
[47]Sejong University, Seoul, 143-747, Republic of Korea
[48]SLAC National Accelerator Laboratory, Menlo Park CA 94025, USA
[49]SNOLAB, Lively, ON P3Y 1N2, Canada
[50]University of South Carolina, Columbia, SC 29208, USA
[51]Stanford University, Stanford, CA 94305, USA
[52]Stony Brook University, Stony Brook, NY, 11790
[53]University of Strasbourg, Strasbourg, F-67037, France
[54]Syracuse University, Syracuse, NY, 13244-5040, USA
[55]University of Tennessee, Knoxville, TN 37996-1200, USA
[56]University of Texas, Austin, TX 78712-0587, USA
[57]University of Tokyo, Tokyo Japan
[58]Tufts University, Medford, MA 02155, USA
[59]Uppsala University, Uppsala, 753 12, Sweden
[60]Virginia Tech, Blacksburg, VA 24061, USA
[61]University of Washington, Seattle, WA, 98195 USA
[62]College of William and Mary, Williamsburg, VA 23187-8795, USA
[63]University of Wisconsin, Madison, WI 53706, USA
[64]Yale University, New Haven, CT 06511-8962, USA

1.1 Executive Summary

Decades of experimental and observational scrutiny have revealed less than a handful of phenomena outside the standard model, among them evidence for dark energy and dark matter, and the existence of nonzero neutrino masses. While many experiments continue to look for other new phenomena and deviations from standard model predictions, it is clear that continued detailed study of the neutrino sector is of the utmost importance.

Compared to the other fermions, the elusive nature of the neutrinos has made them extremely difficult to study in detail. In spite of the challenges, **neutrino physics has advanced quickly and dramatically since the end of the last century**. Thanks to a remarkable suite of experiments and associated theoretical work, two previously unknown and closely related features of neutrinos now stand out clearly: neutrinos have mass and leptons mix. Starting from almost no knowledge of the neutrino masses or lepton mixing parameters twenty years ago, we have built a robust, simple, three-flavor paradigm which successfully describes most of the data.

Experiments with solar, atmospheric, reactor and accelerator neutrinos have established, beyond reasonable doubt, that a neutrino produced in a well-defined flavor state (say, a muon-type neutrino ν_μ) has a nonzero probability of being detected in a different flavor state (say, an electron-type neutrino ν_e). This flavor-changing probability depends on the neutrino energy and the distance traversed between the source and the detector. The only consistent explanation of nearly all neutrino data collected over the last two decades is a phenomenon referred to as "neutrino-mass-induced flavor oscillation."

In two different oscillation sectors, similar parallel stories unfolded: hints of neutrino flavor change in experiments studying natural neutrinos were confirmed, and later refined, by experiments with artificial neutrinos. The disappearance of atmospheric ν_μ was unambiguously confirmed by several beam ν_μ disappearance experiments, which have now achieved high precision on the driving "atmospheric" mixing parameters, i.e., the mass-squared difference $|\Delta m^2_{32}|$ and the mixing parameter θ_{23}. The observation of the disappearance of ν_e from the Sun, a decades-long mystery, was definitively confirmed as evidence for flavor change using flavor-blind neutral-current interactions. This "solar" oscillation was further confirmed, and the driving "solar" mixing parameters (θ_{12} and the mass-squared difference Δm^2_{21}) were very well measured, using reactor antineutrinos and further solar data. This complementarity illustrates the importance of exploring the diverse neutrino sources available (see Fig. 1-1).

The current generation of detectors is now exploring oscillations in a three-flavor context, with both accelerator and reactor tour-de-force experiments having now measured, with good precision, the value of the third mixing angle, θ_{13}, via positive searches for $\nu_\mu \to \nu_e$ appearance and $\bar{\nu}_e$ disappearance respectively.

Furthermore, while most of the data fit the three-flavor paradigm very well, some experiments have uncovered intriguing anomalies that do not fit this simple picture. These exceptions include apparent short-baseline $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions, and the anomalous disappearance of reactor and radioactive source electron-type antineutrinos and neutrinos. Although these hints currently have only modest statistical significance, if confirmed they would be evidence for beyond-the-standard-model states or interactions.

The observation of neutrino oscillations implies that neutrinos have nonzero masses, a discovery of fundamental significance. We do not know the mechanism responsible for the generation of neutrino masses, but we can state with some certainty that new degrees of freedom are required. The number of options is enormous. The current data do not reveal, for example, whether the new physics scale is very low (say, 1 eV) or very high (say, 10^{15} GeV). The origin of neutrino masses is one of the biggest puzzles in particle physics today, and will only be revealed, perhaps only indirectly, with more experimental information from different probes in the different frontiers of particle physics research. Furthermore, the pattern of lepton mixing is very different from that of quarks. We do not yet know what that means, but precision studies of lepton mixing via neutrino oscillations may reveal crucial information regarding the long-standing flavor puzzle.

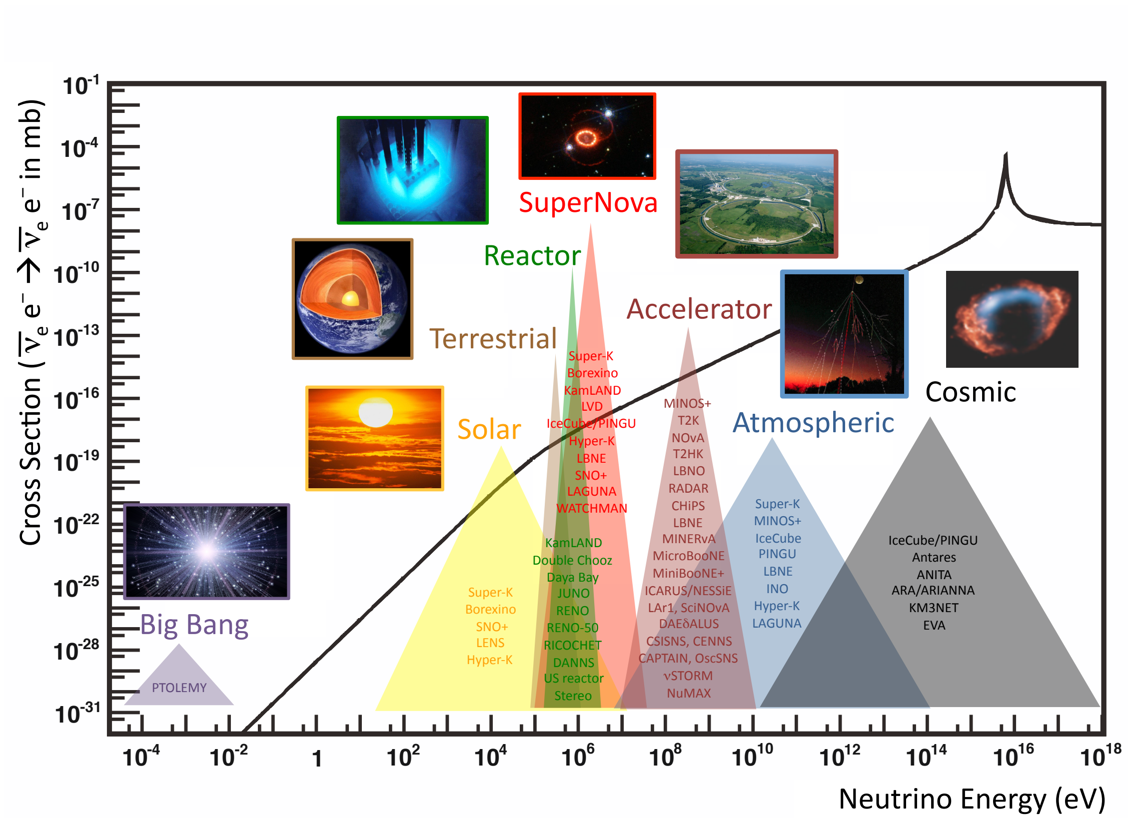

Figure 1-1. *Neutrino interaction cross section as a function of energy, showing typical energy regimes accessible by different neutrino sources and experiments. The curve shows the scattering cross section for $\bar{\nu}_e\, e^- \to e^-\, \bar{\nu}_e$ on free electroens, for illustration. Plot modified from [1].*

1.1.1 The Big Questions and Physics Opportunites

We are now poised to answer some of the most fundamental and important questions of our time. **There is a clear experimental path forward**, which builds heavily on the recent successful history of this rapidly-evolving field of particle physics.

What is the pattern of neutrino masses? Is there CP violation in the lepton sector? To what extent does the three-flavor paradigm describe Nature?

The current neutrino data allow for very large deviations from the three-flavor paradigm. New neutrino–matter interactions as strong as the standard-model weak interactions are not ruled out, and the existence of new "neutrino" states with virtually any mass is allowed, and sometimes expected from different mechanisms for generating neutrino masses.

Even in the absence of more surprises, we still do not know how the neutrino masses are ordered: do we have two "light" and one "heavy" neutrino (the so-called normal mass hierarchy) or two "heavy" and one "light" neutrino (the inverted hierarchy)? The resolution of this issue is of the utmost importance, for both practical and fundamental reasons. As will become more clear below, resolving the neutrino mass hierarchy will allow one to optimize the information one can obtain from other neutrino experimental probes, including searches for leptonic CP invariance violation, searches for the absolute value of the neutrino masses, and searches for the violation of lepton number via neutrinoless double-beta decay. In addition, the mass hierarchy will also reveal invaluable information concerning the origin of neutrino masses. If the mass hierarchy were inverted, for example, we would learn that at least two of the three neutrino masses are quasi-degenerate, a condition that is not observed in the spectrum of charged leptons or quarks.

Experimental neutrino oscillation data revealed that CP invariance can be violated in the lepton sector. The lepton sector accommodates up to three new sources of CP violation – two Majorana phases and one Dirac phase. Neutrino oscillation studies have the opportunity to explore a brand new source of CP violation, the so-called Dirac phase. The Majorana phases are physical only if neutrinos are Majorana fermions. Some of these may be constrained (depending on the physics of lepton-number violation) from the rate of neutrinoless double-beta decay, a determination of the mass hierarchy, and a direct measurement of the neutrino mass. Currently, two sources of CP violation are known: the CP-odd phase in the CKM matrix, and the QCD θ parameter. The former is known to be large, while the latter is known to be at most vanishingly small. Exploring CP violation in the lepton sector is guaranteed to significantly increase our understanding of this phenomenon. It is also likely that information regarding CP violation in the lepton sector will play a key role when it comes to understanding the mechanism for baryogenesis.

These questions can only be addressed by neutrino oscillation experiments. The current generation of oscillation experiments, including Double Chooz, RENO, Daya Bay, T2K, and NOvA, will start to resolve the neutrino mass hierarchy and, especially combined, may provide a first glimpse at CP violation in the lepton sector. These will also provide improved measurements of almost all neutrino oscillation parameters. Next-generation experiments, along with very intense proton beams, will definitively resolve the neutrino mass hierarchy and substantially improve our ability to test CP invariance in the lepton sector. Next-generation reactor neutrinos with intermediate (around 50 km) baselines and atmospheric neutrino experiments may also independently shine light on the neutrino mass hierarchy. The former will also provide precision measurements of the "solar" parameters, Δm^2_{21} and θ_{12}. Different experiments with different energies, baselines and detector technologies will allow good constraints on physics beyond the three-flavor paradigm. For the farther future, a more definitive probe of the three-flavor paradigm and precision measurements of CP violation in the lepton sector (or lack thereof) will require long-baseline experiments with different neutrino beams. Leading candidates include neutrinos from pion decay at rest produced by high-intensity cyclotron proton sources, and neutrinos from muon storage rings. A muon-storage-ring facility should be able to measure the Dirac CP-odd phase with a precision on par with the quark sector, and provide the most stringent constraints on the three-flavor paradigm, thanks to its capability to measure several different oscillation channels with similar precision.

Comprehensive detailed studies of neutrino-matter scattering not only serve as tests of the standard model and probes of nuclear structure but are also a definite requirement for precision neutrino oscillation experiments. The convolution of an uncertain neutrino flux with imprecise scattering cross sections and roughly estimated nuclear effects can result in large, even dominant, systematic errors in the measurement of neutrino oscillation parameters. More generally, we need to fully characterize, requiring dedicated experimental and theoretical efforts, neutrino–matter interactions to enable deeper understanding of neutrino oscillations, supernova dynamics, and dark matter searches.

Are neutrinos Majorana or Dirac particles?

Massive neutrinos are special. Among all known fermions, neutrinos are the only ones not charged under the two unbroken gauge symmetries: electromagnetism and color. This implies that, unlike all known particles, neutrinos may be Majorana fermions. Majorana neutrinos would imply, for example, that neutrino masses are a consequence of a new fundamental energy scale in physics, potentially completely unrelated to the electroweak scale. Dirac neutrinos, on the other hand, would imply that $U(1)_{B-L}$, or some subgroup, is a fundamental symmetry of nature, with deep consequences for our understanding of the laws of physics.

If neutrinos are Majorana fermions, lepton number cannot be a conserved quantum number. Conversely, lepton number-violation indicates that massive neutrinos are Majorana fermions. Hence, the best (perhaps only) probes for the hypothesis that neutrinos are Majorana fermions are searches for lepton-number violation. By far, the most sensitive probe of lepton-number conservation is the pursuit of neutrinoless double-beta decay ($0\nu\beta\beta$), $(Z) \to (Z+2)e^-e^-$, where (Z) stands for a nucleus with atomic number Z. Independent from the strict connection to the nature of the neutrino, the observation of $0\nu\beta\beta$ would dramatically impact our understanding of nature (similar to the potential observation of baryon number violation) and would provide clues concerning the origin of the baryon asymmetry.

In many models for the origin of lepton-number violation, $0\nu\beta\beta$ is dominated by the exchange of virtual massive Majorana neutrinos, in such a way that its amplitude is, assuming all neutrinos are light, proportional to $m_{ee} \equiv \sum_i U_{ei}^2 m_i$, $i = 1, 2, 3, \ldots$. Under these circumstances, the observation of $0\nu\beta\beta$ would not only reveal that neutrinos are Majorana fermions, it would also provide information concerning the absolute values of the neutrino masses. Conversely, given that we know the neutrino mass-squared differences and the magnitude of the relevant elements of the mixing matrix, one can predict the rate for $0\nu\beta\beta$ as a function of the unknown value of the lightest neutrino mass. In particular, if the neutrino mass hierarchy is inverted, there is a lower bound to $|m_{ee}| \gtrsim 20$ meV.

The current generation of 100-kg-class $0\nu\beta\beta$ search experiments should reach effective masses in the 100 meV range; beyond that, there are opportunities for multi-ton-class experiments that will reach sub-10 meV effective mass sensitivity, pushing below the inverted hierarchy region. In order to fully exploit the relation between $0\nu\beta\beta$ and nonzero Majorana neutrino masses, it is imperative to understand in detail the associated nuclear matrix elements. These require detailed theoretical computations beyond those carried out to date.

What is the absolute neutrino mass scale?

While the values of the neutrino mass-squared differences are known, their absolute values remain elusive. In order to properly understand particle physics in general, and neutrinos in particular, it is clear that knowledge of particle masses – not just mass-squared differences – is mandatory. The current neutrino data still allow for the possibility that the lightest neutrino mass is vanishingly small, or that all three known neutrino masses are quasi-degenerate. These two possibilities are qualitatively different and point to potentially different origins for the nonzero neutrino masses.

Neutrino masses can only be directly determined via non-oscillation neutrino experiments. The most model-independent observable sensitive to sub-eV neutrino masses is the shape of the endpoint of beta decay spectra. Precision studies of tritium beta decay provide the most stringent bounds, and are expected to play a leading role in next-generation experiments. KATRIN, the most ambitious current-generation tritium-beta-decay experiment, will directly probe neutrino masses a factor of 10 smaller than the best current bounds. Innovative new ideas may help to go beyond this level of sensitivity.

Other probes of the absolute value of the neutrino masses include $0\nu\beta\beta$, discussed above, and different maps of the large-scale structure of the Universe. Both are, in their own way, much more model-dependent than precision studies of beta decay. Today, cosmological observables provide the most stringent bounds on the absolute values of the neutrino masses, constraining their sums to be below several tenths of an eV, and the prospects for the next several years are very exciting.

Are there already hints of new physics in existing data?

There are intriguing anomalies that cannot be accommodated within the three-flavor paradigm, and suggest new physics beyond it. In particular, there is marginal (two to four sigma) yet persistent evidence for oscillation phenomena at baselines not consistent with the well-established oscillation lengths associated to the "solar" and "atmospheric" mass-squared differences. These anomalies, which are not directly ruled out by other experiments, include the excess of $\bar{\nu}_e$ events observed by the LSND experiment, the ν_e and $\bar{\nu}_e$ excesses observed by MiniBooNE (particularly at low-energies), the deficit of $\bar{\nu}_e$ events observed by reactor neutrino experiments and the deficit of ν_e events observed in the SAGE and GALLEX radioactive source experiment. Although there may be several possible ways to explain these anomalies by introducing new physics, the most credible ones, while not ruled out, do not provide a very good fit to *all* available neutrino data. Combined, the anomalies are often interpreted as evidence for one or more additional neutrino states, known as sterile neutrinos. The $3 + N$ sterile neutrino model, in which there are three light mostly-active neutrinos and N mostly-sterile neutrinos which mix with the active flavors, is often used to fit the existing data and gauge the reach of proposed next-generation experiments. For $N > 1$, these models allow for CP-violating effects in short-baseline appearance experiments.

Beyond particle physics, there are hints of additional neutrinos coming from cosmology. Fits to astrophysical data sets (including the cosmic microwave background, large scale structure, baryon acoustic oscillations and Big Bang nucleosynthesis) are sensitive to the effective number of light degrees of freedom ($N_{\rm eff}$). In the standard model, $N_{\rm eff}$ is equivalent to saying the effective number of neutrino species, although in principle this could include other types of light, weakly-coupled states. The recent Planck data are consistent with $N_{\rm eff} = 3$ but still allow $N_{\rm eff} = 4$. Potential connections between this hint and the short-baseline anomalies above are tantalizing but neither established nor excluded.

These anomalies may go away with more data; but if they are confirmed, the consequences would open up a whole new sector to explore experimentally and theoretically. The discovery of new neutrino states, for example, would revolutionize our understanding of particle physics. Definitive tests are clearly needed and concrete efforts are already underway. The MicroBooNE experiment, for example, aims at addressing the low-energy excesses observed at MiniBooNE. A variety of neutrino sources and flavor-changing observables are being pursued as potential means to address the different anomalies.

What new knowledge will neutrinos from astrophysical sources bring?

Neutrinos come from natural sources as close as the Earth and Sun, to as far away as distant galaxies, and even as remnants from the Big Bang. They range in kinetic energy from less than one meV to greater than one PeV. As weakly-interacting particles, they probe otherwise inaccessible properties of the astrophysical sources they come from; astrophysical neutrino sources furthermore shed light on the nature of neutrinos themselves, and on cosmology.

At the very lowest energies, we can access information about the $T_\nu = 1.95$ K Big Bang relic neutrinos via cosmological observables; direct detection of these is extremely challenging but nevertheless can be pursued.

In the few to few-tens-of-MeV energy range, large underground liquid-scintillator, water-Cherenkov and liquid-argon detectors are the instruments of choice. Solar neutrinos may have more to tell us about neutrino oscillations and other neutrino properties, and about solar physics. Neutrinos from stellar core collapse have the potential not only to shed light on the astrophysics of gravitational collapse, but provide a unique probe of neutrino properties. It is now even possible to study the Earth via MeV geoneutrinos from terrestrial radioactivity.

One of the most tantalizing questions in astronomy and astrophysics is the origin and the evolution of the cosmic accelerators that produce the observed spectrum of cosmic rays, which extends to astonishingly high energies. This question may be best addressed through the observation of neutrinos. Because neutrinos only interact via the weak force, neutrinos travel from their source undeflected by magnetic fields and unimpeded by interactions with the cosmic microwave background, unlike photons and charged particles. Due to the ultra-low expected fluxes, the construction of high energy neutrino telescopes requires the instrumentation of large natural reservoirs of water. The recent detection of the first ultra-high-energy astrophysical neutrinos by IceCube has opened a crucial new window of investigation into the study of nature's highest-energy particle accelerators.

1.1.2 The Path Forward

Table 1.1.2 gives a summary of the many current and proposed experiments, in the U.S. and abroad, designed to address various physics questions. The number of possibilities is endless. We now describe a specific path forward, both in the U.S. and in an international context. Neutrino physics is a broad subfield of fundamental particle physics, and requires a multi-pronged approach in order to address all the outstanding questions and fully explore the new physics revealed by neutrino oscillation experiments. Investment in a range of large, medium and small-scale neutrino experiments (as well as in detector R&D and theory) will ensure a healthy program.

- *Comprehensive test of the three-flavor paradigm, via long-baseline, precision neutrino oscillation experiments:* The next-generation experiments will take full advantage of conventional neutrino beams from pion decay in flight. These will begin to over-constrain the parameter space, and will start to seriously explore CP-violating phenomena in the lepton sector. The U.S., with the Long-Baseline Neutrino Experiment (LBNE) and a future multi-megawatt beam from Project X, is uniquely positioned to lead an international campaign to measure CP violation and aggressively test the three-flavor paradigm. Complementary experiments with different energies, baselines and detector technologies (e.g., Hyper-K in Japan) are required in order to fully exploit conventional neutrino beams. The accompanying very-large detectors, if placed underground, also allow for the study of atmospheric neutrinos, nucleon decay, and precision measurements of neutrinos from a galactic supernova explosion. PINGU, an upgrade of IceCube, provides a promising opportunity to measure the mass hierarchy using atmospheric neutrinos.

  Next-next generation experiments will require better (both more intense, and better understood) neutrino beams. Promising possibilities include neutrinos from muon storage rings (e.g., NuMAX), and neutrinos from very intense cyclotron-based sources of pion decay at rest (e.g., DAEδALUS). Muon-based neutrino beams in particular have strong synergies with Project X and provide a necessary step in the R&D for a high-energy muon collider. While these large, ambitious projects are vigorously developed, the following medium and small-scale neutrino activities need to be pursued.

  - *Precision measurements of neutrino cross sections and a detailed understanding of the neutrino flux from pion-decay-in-flight neutrino beams.* These activities can be pursued in the "near-detectors" associated with the large long-baseline projects or alongside R&D projects related to next-next generation neutrino beams, as well as by small-scale dedicated experiments. The community needs a well-considered program of precision scattering experiments in both low- and high-energy regimes, combined with a renewed dedicated theoretical effort to develop a model of neutrino interactions deep within a heavy nucleus.
  - *Definite resolution of the current short-baseline anomalies.* These will (probably) require neutrino sources other than pion-decay-in-flight and the pursuit of different flavor-changing channels, including $\nu_{e,\mu}$ disappearance and $\nu_\mu \to \nu_e$ appearance, using a combination of reactor, radioactive source and accelerator experiments. In addition to small-scale dedicated experiments, such

experiments can be carried out as part of R&D projects related to next-next generation neutrino beams (e.g., nuSTORM, IsoDAR).

– *Vigorous pursuit of R&D projects related to the development of next-next generation neutrino experiments.* As discussed above, these medium and small experiments will also address several key issues in neutrino physics.

- *Searches for neutrinoless double-beta decay:* The current generation of experiments is pursuing different detector technologies with different double-beta decaying isotopes. The goals of these experiments are to (a) discover neutrinoless double-beta decay, which is guaranteed if the neutrinos are Majorana fermions and their masses are quasi-degenerate, (b) provide information regarding the most promising techniques for the next generation. Next-generation experiments aim at discovering neutrinoless double-beta decay if neutrinos are Majorana fermions and if the neutrino mass hierarchy is inverted. In the case of a negative result, assuming oscillation experiments have revealed that the neutrino mass-hierarchy is inverted, these experiments will provide strong evidence that the neutrinos are Dirac fermions. As with precision measurements of beta decay (see below), the information one can extract from the current and the next generation of neutrinoless double-beta decay experiments increases significantly if indirect evidence for neutrino masses is uncovered, e.g., with cosmological probes.

- *Determination of the absolute values of the neutrino masses:* Precision measurements of beta decay remain the most promising model-independent probes. While the KATRIN experiment is taking data, vigorous R&D efforts for next-generation probes (e.g., ECHo, Project 8, PTOLEMY) are required in order to identify whether it is possible to reach sensitivities to the effective "electron-neutrino mass" below 0.05 eV. Nontrivial information is expected from different cosmological probes of the large-scale structure of the Universe.

The relevance of neutrino science and technology extends well beyond the fundamental research community. The neutrino signal itself may be useful for monitoring reactors in the context of international nuclear nonproliferation. The essential building blocks of neutrino science – detectors and accelerators – have important spin-off applications for medicine and in industry. Finally, the unusual, ghostlike properties of neutrinos are fascinating to the general public. The success of our field depends on our ability to convey both the mystery and utility of neutrino science to the public, policy-makers and funding agencies.

The diversity of physics topics within the neutrino sector is enormous and the interplay between neutrino physics and other fields is rich. Neutrinos have and will continue to provide important information on structure formation in the early universe, Earth, solar and supernova physics, nuclear properties, and rare decays of charged leptons and hadrons. Conversely, information regarding neutrino properties and the origin of neutrino masses is expected from the Energy and Cosmic frontiers, and from other areas of Intensity Frontier research (as well as nuclear physics).

In the remainder of this document, we describe in more detail the many exciting possibilities for the future. Section 1.2 is a pedagogical introduction to the basics of neutrino physics and experiments, and is intended primarily to be a guide for the non-expert to the neutrino physics that can be addressed using different kinds of neutrino sources and various experimental approaches. The remaining sections provide more details of future opportunities, following our Neutrino Working Group substructure. Section 1.5 describes measurements addressing remaining unknowns and precision tests of the standard three-flavor paradigm. Section 1.6 describes the $0\nu\beta\beta$ decay subfield, and Sec. 1.7 describes approaches for addressing the question of absolute neutrino mass. Section 1.8 describes neutrino scattering experiments. Section 1.9 describes existing anomalies and other beyond-the-standard-model tests, and the wide range of possible experiments to address them. Section 1.10 describes physics and astrophysics that can be done using neutrinos from astrophysical sources. Finally, Sec. 1.11 describes direct and spin-off applications of neutrino physics, as well as relevant education and outreach.

Table 1-1. *Summary of the many current and proposed experiments, in the U.S. and abroad, designed to address various physics questions. Rows refer to neutrino sources and columns refer to categories of physics topics these sources can address (roughly corresponding to the neutrino working groups). The intent is not to give a "laundry list", but to give a sense of the activity and breadth of the field. Some multipurpose experiments appear under more than one physics category. Experiments based in the U.S. (or initiated and primarily led by U.S. collaborators) are shown in blue and underlined (note that many others have substantial U.S. participation or leadership). Proposed and future experiments are in bold; current experiments (running or with construction well underway) are in regular font. More details and references can be found in the subsections of the Neutrino Working Group report.*

Source	3-flavor osc.	Maj./Dirac	Abs. Mass	Interactions	Anomalies/Exotic[2]	Astro/Cosmo
Reactor	KamLAND, Double Chooz, Daya Bay, **JUNO**, RENO, **RENO-50**			**RICOCHET**	**DANSS**, **Stereo**, **US Reactor**, **RICOCHET**	
Solar	Super-K, Borexino, SNO+, **Hyper-K**, **LENS**					Super-K, Borexino, SNO+, **Hyper-K**, **LENS**
Supernova[1]	Super-K, Borexino, KamLAND, LVD, IceCube/**PINGU**, **Hyper-K**, **LBNE**, SNO+, **LAGUNA**, **ESSνSB**, **WATCHMAN**					Super-K, Borexino, KamLAND, LVD IceCube/**PINGU**, **Hyper-K**, **LBNE**, SNO+, **LAGUNA**, **ESSνSB**, **WATCHMAN**
Atmospheric	Super-K, MINOS+ , IceCube/**PINGU**, **LBNE**, **ICAL**, **Hyper-K**, **ESSνSB**, **LAGUNA**					
Pion DAR	**DAEδALUS**			**OscSNS**, **CSI**, **CENNS**, **CAPTAIN**	**OscSNS**	
Pion DIF	MINOS+, T2K, NOvA, **Hyper-K**, **LAGUNA-LBNO**, **RADAR**, **CHIPS**, **LBNE**, **ESSνSB**			MicroBooNE, MINERνA, **NOvA**, **SciNOvA**	MicroBooNE, **MiniBooNE+/II**, **Icarus/NESSiE**, **LAr1**, **LAr1-ND**, MINOS+	
μDIF	**NuMAX**			**nuSTORM**	**nuSTORM**	
Radioactive Isotopes		Many: see Nu2 report for table	KATRIN, **Project 8**, **ECHo**, **PTOLEMY**		**SOX**, **CeLAND**, **Daya Bay Source**, **IsoDAR**	
Cosmic neutrinos						IceCube/**PINGU**, ANTARES/**ORCA**, **ARA**,**ARIANNA**, ANITA, **EVA**, **KM3NET**

[1]Included are only kt-class underground detectors; many others would also record events. [2]We note that nearly all experiments can address anomalies or exotic physics at some level; we include in this column only those with this as a primary physics goal.

1.2 Introduction: Physics of Neutrinos

Neutrinos are the most elusive of the known fundamental particles. They are color-neutral and charge-neutral spin-one-half fermions. To the best of our knowledge, they only interact with charged fermions and massive gauge bosons through the weak interactions. For this reason, neutrinos can only be observed and studied because there are very intense neutrino sources (natural and artificial) and only if one is willing to work with large detectors.

The existence of neutrinos was postulated in the early 1930s, but they were only first observed in the 1950s [2]. The third neutrino flavor eigenstate, the tau-type neutrino ν_τ, was the last of the fundamental matter particles to be observed [3], eluding direct observation six years longer than the top quark [4, 5]. More relevant to this report, in the late 1990s the discovery of nonzero neutrino masses moved the study of neutrino properties to the forefront of experimental and theoretical particle physics.

Experiments with solar [6, 7, 8, 9, 10, 11], atmospheric [12, 13], reactor [14, 15] and accelerator [16, 17] neutrinos have established, beyond reasonable doubt, that a neutrino produced in a well-defined flavor state (say, a muon-type neutrino ν_μ) has a nonzero probability of being detected in a different flavor state (say, an electron-type neutrino ν_e). This flavor-changing probability depends on the neutrino energy and the distance traversed between the source and the detector. The simplest and only consistent explanation of all neutrino data collected over the last two decades is a phenomenon referred to as "neutrino mass-induced flavor oscillation." These neutrino oscillations, which will be discussed in more detail in Sec. 1.3, in turn imply that neutrinos have nonzero masses and neutrino mass eigenstates are different from neutrino weak eigenstates, i.e., leptons mix.

In a nutshell, if the neutrino masses are distinct and leptons mix, a neutrino can be produced, via weak interactions, as a coherent superposition of mass-eigenstates, e.g., a neutrino ν_α with a well-defined flavor, and has a nonzero probability to be measured as a neutrino ν_β of a different flavor ($\alpha, \beta = e, \mu, \tau$). The oscillation probability $P_{\alpha\beta}$ depends on the neutrino energy E, the propagation distance L, and on the neutrino mass-squared differences, $\Delta m^2_{ij} \equiv m^2_i - m^2_j$, $i, j = 1, 2, 3, \ldots$, and the elements of the leptonic mixing matrix,[1] U, which relates neutrinos with a well-defined flavor (ν_e, ν_μ, ν_τ) and neutrinos with a well-defined mass ($\nu_1, \nu_2, \nu_3, \ldots$). For three neutrino flavors, the elements of U are defined by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{e\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. \tag{1.1}$$

Almost all neutrino data to date can be explained assuming that neutrinos interact as prescribed by the standard model, there are only three neutrino mass eigenstates, and U is unitary. Under these circumstances, it is customary to parameterize U in Eq. (1.1) with three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ and three complex phases, δ, ξ, ζ, defined by

$$\frac{|U_{e2}|^2}{|U_{e1}|^2} \equiv \tan^2\theta_{12}; \qquad \frac{|U_{\mu3}|^2}{|U_{\tau3}|^2} \equiv \tan^2\theta_{23}; \qquad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}, \tag{1.2}$$

with the exception of ξ and ζ, the so-called Majorana CP-odd phases. These are only physical if the neutrinos are Majorana fermions, and have no effect in flavor-changing phenomena.

In order to relate the mixing elements to experimental observables, it is necessary to properly define the neutrino mass eigenstates, i.e., to "order" the neutrino masses. This is done in the following way: $m^2_2 > m^2_1$ and $\Delta m^2_{21} < |\Delta m^2_{31}|$. In this case, there are three mass-related oscillation observables: Δm^2_{21} (positive-definite), $|\Delta m^2_{31}|$, and the sign of Δm^2_{31}. A positive (negative) sign for Δm^2_{31} implies $m^2_3 > m^2_2$ ($m^2_3 < m^2_1$)

[1] Often referred to as the Maki-Nakagawa-Sakata (MNS) Matrix, or the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix.

and characterizes a so-called normal (inverted) neutrino mass hierarchy. The two mass hierarchies are depicted in Fig. 1-2.

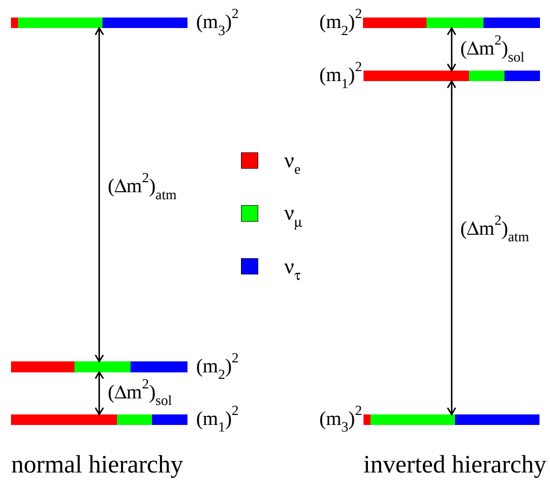

Figure 1-2. *Cartoon of the two distinct neutrino mass hierarchies that fit nearly all of the current neutrino data, for fixed values of all mixing angles and mass-squared differences. The color coding (shading) indicates the fraction $|U_{\alpha i}|^2$ of each distinct flavor ν_α, $\alpha = e, \mu, \tau$ contained in each mass eigenstate ν_i, $i = 1, 2, 3$. For example, $|U_{e2}|^2$ is equal to the fraction of the $(m_2)^2$ "bar" that is painted red (shading labeled as "ν_e").*

Our knowledge of neutrino oscillation parameters has evolved dramatically over the past two decades. As summarized in Sec. 1.5, all three mixing angles have been measured relatively well, along with (the magnitudes of) the mass-squared differences. On the other hand, we have virtually no information concerning δ (nor, for that matter, ξ and ζ) or the sign of Δm^2_{32}. We also don't know the value of the neutrino masses themselves – only differences of the masses-squared. We can't rule out the possibility that the lightest neutrino is virtually massless ($m_{\rm lightest} \ll 10^{-3}$ eV) or that all neutrino masses are virtually the same (e.g., $m_1 \sim m_2 \sim m_3 \sim 0.1$ eV). Probes outside the realm of neutrino oscillations are required to investigate the values of the neutrino masses. These are described in Sec. 1.7.

One of the main goals of next-generation experiments is to test whether the scenario outlined above, the standard three-massive-neutrinos paradigm, is correct and complete. This can be achieved by next-generation experiments sensitive to neutrino oscillations via not simply determining all of the parameters above, but by "over-constraining" the parameter space in order to identify potential inconsistencies. This is far from a simple task, and the data collected thus far, albeit invaluable, allow for only the simplest consistency checks. Precision measurements, as will be discussed in Sec. 1.5, will be required.

In more detail, given all we know about the different neutrino oscillation lengths, it is useful to step back and appreciate what oscillation experiments have been able to measure. Solar data, and data from KamLAND, are, broadly speaking, sensitive to $|U_{e2}|$, $|U_{\mu 2}|^2 + |U_{\tau 2}|^2$, and $|U_{e2}U_{e1}|$. Data from atmospheric neutrinos and long-baseline, accelerator-based experiments are sensitive to $|U_{\mu 3}|$ and, to a much lesser extent, $|U_{\mu 3}U_{\tau 3}|$ and $|U_{\mu 3}U_{e3}|$. Finally, km-scale reactor experiments are sensitive to $|U_{e3}|$. Out of the nine (known) complex entries of U, we have information, usually very limited, regarding the magnitude of around six of them. Clearly, we have a long way to go before concluding that the three-flavor paradigm is the whole story.

Life may, indeed, already be much more interesting. There are several, none too significant, hints in the world neutrino data that point to a neutrino sector that is more complex than the one outlined above. These will be discussed in Sec. 1.9. Possible surprises include new, gauge singlet fermion states that manifest themselves only by mixing with the known neutrinos, and new weaker-than-weak interactions.

Another issue of fundamental importance is the investigation of the status of CP invariance in leptonic processes. Currently, all observed CP-violating phenomena are governed by the single physical CP-odd phase parameter in the quark mixing matrix. Searches for other sources of CP violation, including the so-called strong CP-phase θ_{QCD}, have, so far, failed. The picture currently emerging from neutrino-oscillation data allows for a completely new, independent source of CP violation. The CP-odd parameter δ, if different from zero or π, implies that neutrino oscillation probabilities violate CP-invariance, i.e., the values of the probabilities for neutrinos to oscillate are different from those of antineutrinos! We describe this phenomenon in more detail in Secs. 1.3, 1.5.

It should be noted that, if neutrinos are Majorana fermions, the CP-odd phases ξ and ζ also mediate CP-violating phenomena [18] (alas, we don't yet really know how to study these in practice). In summary, if neutrinos are Majorana fermions, the majority of CP-odd parameters in particle physics — even in the absence of other new physics — belong to the lepton sector. These are completely unknown and can "only" be studied in neutrino experiments. Neutrino oscillations provide a unique opportunity to revolutionize our understanding of CP violation, with potentially deep ramifications for both particle physics and cosmology. An important point is that all modifications to the standard model that lead to massive neutrinos change it qualitatively. For a more detailed discussion of this point see, e.g., [19].

Neutrino masses, while nonzero, are tiny when compared to all other known fundamental fermion masses in the standard model, as depicted in Fig. 1-3. Two features readily stand out: (i) neutrino masses are at least six orders of magnitude smaller than the electron mass, and (ii) there is a "gap" between the largest allowed neutrino mass and the electron mass. We don't know why neutrino masses are so small or why there is such a large gap between the neutrino and the charged fermion masses. We suspect, however, that this may be Nature's way of telling us that neutrino masses are "different."

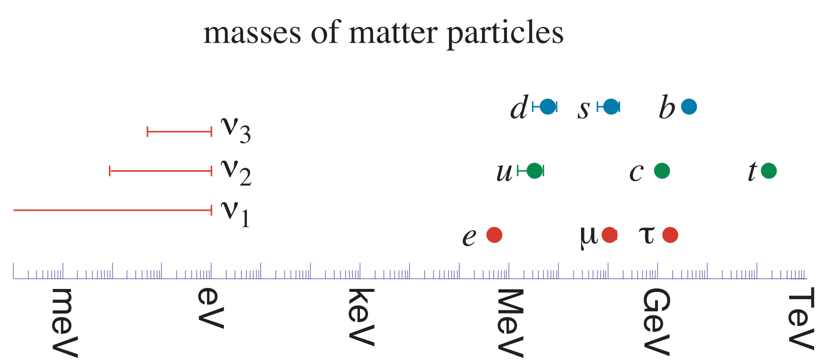

Figure 1-3. *standard model fermion masses. For the neutrino masses, the normal mass hierarchy was assumed, and a loose upper bound $m_i < 1$ eV, for all $i = 1, 2, 3$ was imposed.*

This suspicion is only magnified by the possibility that massive neutrinos, unlike all other fermions in the standard model, may be Majorana fermions. The reason is simple: neutrinos are the only electrically-neutral fundamental fermions and hence need not be distinct from their antiparticles. Determining the nature of the neutrino – Majorana or Dirac – would not only help to guide theoretical work related to uncovering the origin of neutrino masses, but could also reveal that the conservation of lepton number is not a fundamental law of Nature. The most promising avenue for learning the fate of lepton number, as will be discussed in Sec. 1.6, is to look for neutrinoless double-beta decay, a lepton-number violating nuclear process. The observation of a nonzero rate for this hypothetical process would easily rival, as far as its implications for our understanding of nature are concerned, the first observations of parity violation and CP-invariance violation in the mid-twentieth century.

It is natural to ask what augmented, "new" standard model (νSM) leads to nonzero neutrino masses. The answer is that we are not sure. There are many different ways to modify the standard model in order to accommodate neutrino masses. While these can differ greatly from one another, all succeed – by design – in explaining small neutrino masses and all are allowed by the current particle physics experimental data. The most appropriate question, therefore, is not what are the candidate νSM's, but how can one identify the "correct" νSM? The answers potentially lie in next-generation neutrino experiments, which are described throughout this report.

Before discussing concrete examples, it is important to highlight the potential theoretical significance of nonzero neutrino masses. In the standard model, the masses of all fundamental particles are tied to the phenomenon of electroweak symmetry breaking and a single mass scale – the vacuum expectation value of the Higgs field. Nonzero neutrino masses may prove to be the first direct evidence of a new mass scale, completely unrelated to electroweak symmetry breaking, or evidence that electroweak symmetry breaking is more complex than dictated by the standard model.

Here we discuss one generic mechanism in more detail. The effect of heavy new degrees of freedom in low-energy phenomena can often be captured by adding higher-dimensional operators to the standard model. As first pointed out in [20], given the standard model particle content and gauge symmetries, one is allowed to write only one type of dimension-five operator – all others are dimension-six or higher:

$$\frac{1}{\Lambda}\,(LH)(LH) + h.c. \quad\Rightarrow\quad \frac{v^2}{\Lambda}\nu\nu + h.c., \tag{1.3}$$

where L and H are the lepton and Higgs boson $SU(2)_L$ doublets, and the arrow indicates one of the components of the operator after electroweak symmetry is broken. v is the vacuum expectation value of the neutral component of H, and Λ is the effective new physics scale. If this operator is indeed generated by some new physics, neutrinos obtain Majorana masses $m_\nu \sim v^2/\Lambda$. For $\Lambda \sim 10^{15}$ GeV, $m_\nu \sim 10^{-1}$ eV, in agreement with the current neutrino data. This formalism explains the small neutrino masses via a seesaw mechanism: $m_\nu \ll v$ because $\Lambda \gg v$.

Λ is an upper bound for the masses of the new particles that lead to Eq. (1.3). If the new physics is strongly coupled and Eq. (1.3) is generated at the tree-level, the new degrees of freedom are super-heavy: $M_{\rm new} \sim 10^{15}$ GeV. If that turns out to be the case, we will only be able to access the new physics indirectly through neutrino experiments and the study of relics in the Cosmic Frontier. If, however, the new physics is weakly coupled or Eq. (1.3) is generated at the loop level, virtually any value for $M_{\rm new} \gtrsim 1$ eV is allowed. There are many scenarios where the new physics responsible for nonzero neutrino masses can be probed at the Energy Frontier or elsewhere in the Intensity Frontier [21]. In summary, if Eq. (1.3) is correct, we expect new physics to show up at a new mass scale $M_{\rm new}$ which lies somewhere between 10^{-9} GeV and 10^{15} GeV. Clearly, more experimental information is required!

Neutrino data also provide a new piece to the flavor puzzle: the pattern of neutrino mixing. The absolute value of the entries of the CKM quark mixing matrix are given by

$$|V_{\rm CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}, \tag{1.4}$$

while those of the entries of the PMNS matrix are given by

$$|U_{\rm PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}. \tag{1.5}$$

It is clear that the two matrices look very different. While the CKM matrix is almost proportional to the identity matrix plus hierarchically ordered off-diagonal elements, the PMNS matrix is far from diagonal and, with the possible exception of the U_{e3} element, all elements are $\mathcal{O}(1)$. Significant research efforts are concentrated on understanding what, if any, is the relationship between the quark and lepton mixing matrices and what, if any, is the "organizing principle" responsible for the observed pattern of neutrino masses and lepton mixing. There are several different theoretical ideas in the market (for summaries, overviews and more references see, e.g., [22, 23]). Typical results include predictions for the currently-unknown neutrino mass and mixing parameters (θ_{23} octant, the mass hierarchy, CP-violating δ) and the establishment of sum rules involving different parameters. Some of the challenges are discussed in Sec. 1.5.

Precision neutrino oscillation measurements are required to address the flavor questions above. That can only be achieved as the result of significant investments in intense, well-characterized neutrino sources and massive high-precision detectors. Some of these are summarized later in this section and spelled out in more detail throughout this report. Excellent understanding of neutrino interactions – beyond the current state of the art – is also mandatory. This will require a comprehensive experimental program on neutrino scattering, as summarized in Sec. 1.8. These, of course, are not only ancillary to neutrino oscillation experiments, but are also interesting in their own right. Neutrinos, since they interact only weakly, serve as a unique probes of nucleon and nuclear properties, and may reveal new physics phenomena at the electroweak scale, including some that are virtually invisible to the Tevatron and the LHC.

(Massive) neutrinos also serve as unique messengers in astrophysics and cosmology, as discused in Sec. 1.10. Astrophysical neutrino searches may uncover indirect evidence for dark matter annihilation in the Earth, the Sun, or the center of the Galaxy. Neutrinos produced in supernova explosions contain information from deep within the innards of the exploding stars and their studies may also help reveal unique information regarding neutrino properties. Big Bang neutrinos play a definitive role in the thermal history of the universe. Precision cosmology measurements also may reveal neutrino properties, including the absolute values of the neutrino masses. Finally, the unique character of the neutrinos and the experiments used to study them provide unique opportunities outside the realm of particle physics research. More details along these lines are discussed in Sec. 1.11.

1.3 Overview of Neutrino Oscillations

Physical effects of nonzero neutrino masses, to date, have been observed only in neutrino oscillation experiments. Those are expected to remain, for the foreseeable future, the most powerful tools available for exploring the new physics revealed by solar and atmospheric neutrino experiments at the end of the twentieth century.

The standard setup of a neutrino oscillation experiment is as follows. A detector is located a distance L away from a source, which emits ultra-relativistic neutrinos or antineutrinos with, most often, a continuous spectrum of energies E, and flavor $\alpha = e, \mu$, or τ. According to the standard model, the neutrinos interact with matter either via W-boson exchange charged-current (CC) interactions where a neutrino with a well-defined flavor ν_α gets converted into a charged lepton of the same flavor ($\nu_e X \to e X'$, *etc.*) or via Z-boson exchange neutral-current (NC) interactions, which preserve the neutrino flavor ($\nu_\mu X \to \nu_\mu X'$). The occurrence of a neutral-current process is tagged by observing the system against which the neutrinos are recoiling. The detector hence is capable of measuring the flux of neutrinos or antineutrinos with flavor $\beta = e, \mu$, or τ, or combinations thereof, often as a function of the neutrino energy. By comparing measurements in the detector with expectations from the source, one can infer $P_{\alpha\beta}(L,E)$ or $\bar{P}_{\alpha\beta}(L,E)$, the probability that a(n) (anti)neutrino with energy E produced in a flavor eigenstate ν_α is measured in a flavor ν_β after it propagates a distance L. In practice, it is often preferable to make multiple measurements of neutrinos at different distances from the source, which can be helpful for both the cancellation of systematic uncertainties and for teasing out effects beyond the standard three-flavor paradigm.

In the standard three-flavor paradigm, $P_{\alpha\beta}$ is a function of the mixing angles $\theta_{12,13,23}$, the Dirac CP-odd phase δ, and the two independent neutrino mass-squared differences $\Delta m^2_{21,31}$. Assuming the neutrinos propagate in vacuum, and making explicit use of the unitarity of U, one can express $P_{\alpha\beta}(L,E) = |A_{\alpha\beta}|^2$, where

$$A_{\alpha\beta} = \delta_{\alpha\beta} + U_{\alpha 2}U^*_{\beta 2}\left(\exp\left(-i\frac{\Delta m^2_{21}L}{2E}\right) - 1\right) + U_{\alpha 3}U^*_{\beta 3}\left(\exp\left(-i\frac{\Delta m^2_{31}L}{2E}\right) - 1\right), \tag{1.6}$$

$$\bar{A}_{\alpha\beta} = \delta_{\alpha\beta} + U^*_{\alpha 2}U_{\beta 2}\left(\exp\left(-i\frac{\Delta m^2_{21}L}{2E}\right) - 1\right) + U^*_{\alpha 3}U_{\beta 3}\left(\exp\left(-i\frac{\Delta m^2_{31}L}{2E}\right) - 1\right), \tag{1.7}$$

up to an unphysical overall phase. A ($\bar{A}$) is the amplitude for (anti)neutrino oscillations. It is easy to see that $P_{\alpha\beta}$ are oscillatory functions of L/E with, in general, three distinct, two independent oscillation lengths proportional to Δm^2_{21}, Δm^2_{31} and $\Delta m^2_{32} \equiv \Delta m^2_{31} - \Delta m^2_{21}$, as depicted in Fig. 1-4. Ideally, measurements of some $P_{\alpha\beta}$ as a function of L/E would suffice to determine all neutrino oscillation parameters. These would also allow one to determine whether the standard paradigm is correct, i.e., whether Eqs. (1.6,1.7) properly describe neutrino flavor-changing phenomena.

For example, if one could measure both P_{ee} and $P_{\mu\mu}$ as a function of L/E, one should be able to determine not only Δm^2_{21} and $|\Delta m^2_{31}|$, but also $|U_{e2}|^2$, $|U_{e3}|^2$, $|U_{\mu 2}|^2$ and $|U_{\mu 3}|^2$, and the sign of Δm^2_{31}. This in turn would translate into measurements of all mixing parameters, including the CP-odd phase δ. One would also be able to determine, for example, whether there are other oscillation lengths, which would indicate there are new, yet-to-be-observed, neutrino states, or whether $P_{ee,\mu\mu} \neq 1$ in the limit $L \to 0$, which would indicate, for example, the existence of new, weaker-than-weak, charged-current type interactions.

In the real world, such measurements are, to say the least, very hard to perform, for several reasons. Δm^2_{21} is much smaller than the magnitude of $\Delta m^2_{31,32}$, which in turn makes it challenging to observe two independent oscillation frequencies in the same experimental setup. For this reason, for all measurements of $P_{\mu\mu}$ performed to date the L/E factors probed are too small to "see" the Δm^2_{21}-driven oscillations or distinguish Δm^2_{31} from Δm^2_{32}. On the other hand, the magnitude of $|U_{e3}|$ is much smaller than that of the other entries of U. For this reason, measurements of P_{ee} for solar neutrinos have only been precise enough to definitively observe Δm^2_{21}-driven oscillations and hence determine its magnitude, along with that of U_{e2}.

Another real-world issue is that, for any setup, it is not possible to measure any $P_{\alpha\beta}$ with perfect L/E resolution. Furthermore, the available L/E ranges are, in many cases, narrow. More realistically, one expects to measure, with decent statistics and small systematic errors, $P_{\alpha\beta}$ integrated over a few finite-sized L/E bins. This discreteness of the data leads to ambiguities when it comes to measuring the different mixing parameters. For example, different pairs of θ_{13}, δ values lead to identical values for $P_{\alpha\beta}$ integrated over a fixed L/E. The same is true for pairs of θ_{13}, θ_{23}, and so on. A so-called eight-fold degeneracy has been identified and studied in great detail in the neutrino literature (see, for example, [24, 25, 26]). The solution to this challenge is to perform several measurements of different $P_{\alpha\beta}$ at different values of L and E (and L/E). This is especially true if one is interested in not only measuring the three-flavor neutrino mixing parameters but also, much more importantly, over-constraining the standard paradigm and hence testing its

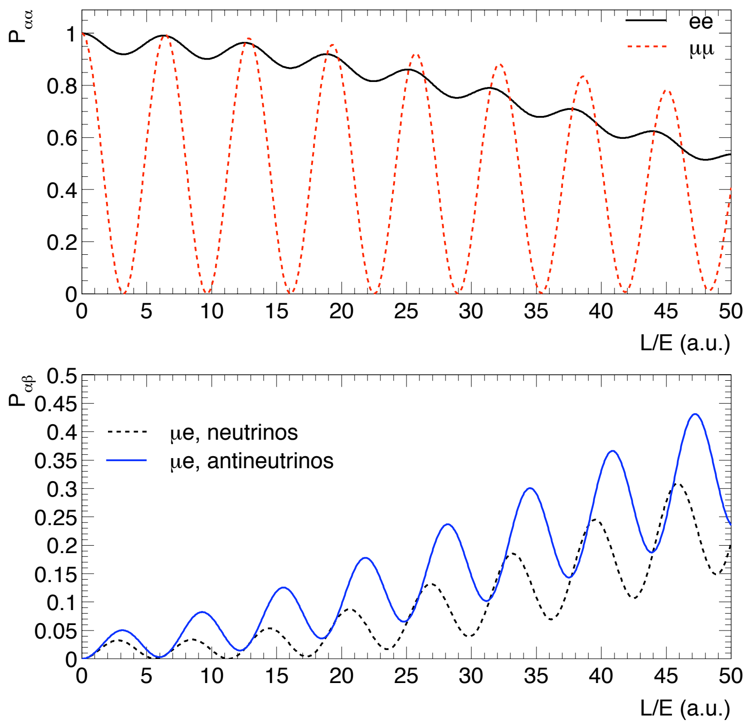

Figure 1-4. *Top: P_{ee} and $P_{\mu\mu}$ in vacuum as a function of L/E (in arbitrary units), for representative values of the neutrino oscillation parameters, including a nonzero value of δ. Bottom: $P_{\mu e}$ and $\bar{P}_{\mu e}$ in vacuum as a function of L/E, for representative values of the neutrino oscillation parameters.*

validity. For example, one would like to precisely measure θ_{13} in different channels, for different values of L and E, to find out if all of them agree.

Measurements of vacuum survival probabilities, $P_{\alpha\alpha}$ or $\bar{P}_{\alpha\alpha}$ do not violate CP invariance: $P_{\alpha\alpha} = \bar{P}_{\alpha\alpha}$ is guaranteed by CPT-invariance. In order to directly observe CP-invariance violation, one needs to measure an appearance probability, say $P_{\mu e}$. $P_{\mu e}$ is different from $\bar{P}_{\mu e}$,[2] as depicted in Fig. 1-4 (bottom), if the following conditions are met, as one can readily confirm by studying Eqs. (1.6,1.7): (i) all $U_{\alpha i}$ have nonzero magnitude, (ii) $U_{\alpha 2}U^*_{\beta 2}$ and $U_{\alpha 3}U^*_{\beta 3}$ are relatively complex, (iii) L/E is large enough that both $\Delta m^2_{21,31} \times L/E$ are significantly different from zero. Given what is known about the oscillation parameters, condition (iii) can be met for any given neutrino source by choosing a large enough value for L. This, in turn, translates into the need for a very intense source and a very large, yet high-precision, detector, given that for all known neutrino sources the neutrino flux falls off like $1/L^2$ for any meaningful value of L. Whether conditions (i) and (ii) are met lies outside the control of the experimental setups. Given our current understanding, including the newly acquired knowledge that $|U_{e3}| \neq 0$, condition (i) holds. That being the case, condition (ii) is equivalent to $\delta \neq 0, \pi$. In the standard paradigm, the existence of CP-invariance violation is entirely at the mercy of the value of CP-odd phase δ, currently unconstrained.

High-energy (accelerator and atmospheric) neutrino data accumulated so far provide evidence for nonzero $P_{\mu\tau}$ [27, 28] and $P_{\mu e}$ [29, 30].[3] Both results are only sensitive to one scale of mass-squared difference

[2]Note that T-invariance violation, $P_{e\mu} \neq P_{\mu e}$, is also present under the same conditions.

[3]Solar data translate into overwhelming evidence for $P_{e\mu} + P_{e\tau} \neq 0$. In the standard paradigm, this is indistinguishable from $1 - P_{ee} \neq 1$ and hence cannot, even in principle, provide more information than a disappearance result.

($|\Delta m^2_{31}| \sim |\Delta m^2_{32}|$) and to $|U_{\mu 3}U_{\tau 3}|$ and $|U_{\mu 3}U_{e3}|$, respectively. The goal of the current neutrino oscillation experiments NOvA and T2K is to observe and study $P_{\mu e}$ and $\bar{P}_{\mu e}$ governed by Δm^2_{31}, aiming at measuring U_{e3} and, perhaps, determining the sign of Δm^2_{31} through matter effects, as will be discussed promptly.

Eqs. (1.6, 1.7) are valid only when the neutrinos propagate in a vacuum. When neutrinos propagate through a medium, the oscillation physics is modified by so-called matter effects [31]. These are due to the coherent forward scattering of neutrinos with the electrons present in the medium, and they create an additional contribution to the phase differences. Notably, this additional contribution distinguishes between neutrinos and antineutrinos, since there are no positrons present in the Earth.[4] Matter effects also depend on whether the electron neutrino is predominantly made out of the heaviest or lightest mass eigenstates, thus allowing one to address the ordering of the neutrino mass eigenstates. For one mass hierarchy, the oscillation of neutrinos for a certain range of L/E values can be enhanced with respect to that of antineutrinos, while for the other mass hierarchy the effect is reversed. On the flip side, if the mass hierarchy is not known, matter effects lead to ambiguities in determining the oscillation parameters, as discussed briefly earlier. Matter effects have already allowed the determination of one "mass hierarchy," that of ν_1 and ν_2. Thanks to matter effects in the Sun, we know that ν_1, which is lighter than ν_2, has the larger electron component: $|U_{e1}|^2 > |U_{e2}|^2$. A similar phenomenon should be observable in the Δm^2_{31} sector, given the recent discovery that $|U_{e3}|$ is not zero. Quantitatively, the importance of matter effects will depend on the density of the medium being traversed, which determines the so-called matter potential $A \equiv \sqrt{2}G_F N_e$, where G_F is the Fermi constant and N_e is the electron number-density of the medium, and on the value of $\Delta m^2_{21,31}/E$. Matter effects are irrelevant when $A \ll \Delta m^2_{21,32}/E$. For $\Delta m^2_{31(21)}$, matter effects in the Earth's crust are significant for $E \gtrsim 1$ GeV (20 MeV).

1.4 Neutrino Experiments: Sources and Detectors

Next-generation experiments have at their disposal a handful of neutrino sources, which we describe qualitatively here, concentrating on their prospects for neutrino oscillation searches. The sources span many orders of magnitude in energy: see Fig. 1-1. Associated with each experiment is an appropriate detector. The requirements for the detectors depend on the neutrino source.

The Sun is a very intense source of ν_e with energies between 100 keV and 10 MeV. Precision measurements of the low-energy component of the solar neutrino flux (the so-called *pp* neutrinos) may provide an unique opportunity to improve on the precision with which $\sin^2\theta_{12}$ is known [32]. The detection of very low-energy solar neutrinos is very challenging, but R&D related to building such detectors profits from significant synergy with efforts to look for dark matter and observe neutrinoless double-beta decay. Solar neutrinos in the few-MeV range are very sensitive to solar matter effects, and provide a unique opportunity to test the standard model through the Mikheev-Smirnov-Wolfenstein (MSW) matter effect [31, 33]. Indeed, data from the SNO experiment seem to hint at potential deviations from standard model expectations [34]. During this decade, more (neutrino) light is expected to shine on this potentially very important matter, from the Borexino [35] and the SNO+ [36] experiments.

Nuclear reactors are an intense, very pure source of $\bar{\nu}_e$ with energies between a few and several MeV. Due to the low neutrino energies, only $\bar{\nu}_e$ can be detected in the final state, which is done via inverse β-decay, $\bar{\nu}_e + p \to e^+ + n$. The current generation of reactor experiments aims at percent-level measurements of the $\bar{\nu}_e$ spectrum, one or two kilometers away from the source. At these distances and energies one is sensitive only to $\Delta m^2_{31,2}$-driven oscillations. The necessary precision is expected has been achieved through the comparison

[4] In fact, the electron background effectively violates CPT symmetry. For neutrinos oscillating in matter, it is no longer true, for example, that $P_{\alpha\alpha} = \bar{P}_{\alpha\alpha}$.

of data obtained at near and far detectors. In a nutshell, the near detector measures the neutrino flux before oscillations have had time to act, while the far detector measures the effects of the oscillations [37, 38, 39, 40]. Reactor neutrino experiments with much longer baselines (say, 50 km) have been considered: see, for example, [41, 42]. These would be sensitive to both $\Delta m^2_{31,2}$ and Δm^2_{21}-driven oscillations, and, in principle, would allow much more precise measurements of Δm^2_{21} and $|U_{e2}|$. A large reactor experiment with exquisite energy resolution may also be sensitive to the neutrino mass hierarchy (see, for example, [43]). A concrete proposal for 60-km reactor neutrino experiment, JUNO, is currently under serious consideration in China [44], as is a proposal, RENO-50, for South Korea [45].

Meson decays are a very good source of ν_μ and ν_τ and their antiparticles. The heavy τ-lepton mass, however, prevents any realistic means of producing anything that would qualify as a ν_τ-beam, so we will only discuss ν_μ beams. Pions and, to a lesser extent, kaons are produced in large numbers through proton–nucleus interactions. These, in turn, can be sign-selected in a variety of ways to yield a mostly pure ν_μ or $\bar{\nu}_\mu$ beam. The neutrino energy is directly related to the pion energy.

The lowest energy ν_μ "beams" (really, isotropic sources) are achieved from pion decay at rest. A large sample of mostly π^+ at rest yields a very well-characterized flux of mono-energetic ν_μ (from the π^+ decay), along with $\bar{\nu}_\mu$ and ν_e from the subsequent daughter muon decay. All neutrino energies are below the muon production threshold, so only ν_e and $\bar{\nu}_e$ can be detected via charged-current interactions. An interesting experimental strategy is to search for $\bar{\nu}_e$ via inverse β-decay, a very well understood physics process, and hence measure with good precision $\bar{P}_{\mu e}$ [46]. Matter effects play an insignificant role for the decay-at-rest beams, rendering oscillation results less ambiguous. On the other hand, even very precise measurements of $\bar{P}_{\mu e}$ from pion decay at rest are insensitive to the neutrino mass hierarchy.

Boosted pion-decay beams are the gold standard of readily accessible neutrino oscillation experiments. A pion beam is readily produced by shooting protons on a target. These can be charge- and energy-selected, yielding a beam of either mostly ν_μ or $\bar{\nu}_\mu$. Larger neutrino energies allow one to look for ν_e, ν_μ and, for energies above a few GeV, ν_τ in the far detector. Large neutrino energies, in turn, require very long baselines[5] and hence very intense neutrino sources and very large detectors. Intense neutrino sources, in turn, require very intense proton sources. For this reason, these pion-decay-in-flight beams are often referred to as superbeams. Larger neutrino energies and longer baselines also imply nontrivial matter effects even for Δm^2_{31}-driven oscillations. A neutrino beam with energies around 1 GeV and baselines around 1000 km will allow the study of $P_{\mu\mu}$ and $P_{\mu e}$ (and, in principle, the equivalent oscillation probabilities for antineutrinos) as long as the far detector is sensitive to both ν_μ and ν_e charged-current interactions. One may choose to observe the neutrino flux a few degrees off the central beam axis, where the pion decay kinematics result in a narrowly-peaked neutrino spectrum. This is beneficial for optimizing sensitivity at the oscillation maximum and for reducing backgrounds outside the energy regime of interest.

The constant collision of cosmic rays with the atmosphere produces mesons (mostly pions and kaons) and, upon their decays, ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$. These atmospheric neutrinos cover a very wide energy range (100 MeV to 100 GeV and beyond) and many different distances (15 km to 13000 km), some going through the core of the Earth and hence probing matter densities not available for Earth-skimming neutrino beams. This is, by far, the broadest (in terms of L/E range) neutrino "beam." However, uncertainties in the atmospheric neutrino flux are not small, and the incoming neutrino energy and direction must be reconstructed only with information from the neutrino detector.

In the past, atmospheric neutrinos have provided the first concrete evidence for neutrino oscillations, and at present they are still a major contributor to the global fits to neutrino oscillation parameters. They will continue to be important in the future. They are also ubiquitous and unavoidable. IceCube DeepCore is already taking data and will accumulate close to a million events with energies above about 10 GeV over

[5] The oscillation phase scales as L/E. For a 1 GeV beam, one aims at L values close to 1000 km.

the next decade [47]. Any other very large detector associated with the Intensity Frontier program will also collect a large number of atmospheric neutrino events in various energy ranges, through different types of signatures. While atmospheric neutrino data suffer from larger systematic uncertainties, some of these can be greatly reduced by studying angular and energy distributions of the very high statistics data. Their study can complement that of the high precision measurements from fixed baseline experiments. For example, non-standard interactions of neutrinos, additional neutrino flavors and other new physics phenomena affecting neutrinos could be present, and their effects are likely to be more important at higher energies or in the presence of matter, thus making atmospheric neutrinos an ideal testing ground (see, for example, [48]). Furthermore, a precise, very high statistics measurement of the atmospheric neutrino flux itself over a very large range of energies will also contribute to a better understanding of cosmic ray propagation through the atmosphere [49, 50, 51].

Muon decays are also excellent sources of neutrinos. The physics and the kinematics of muon decay are very well known and yield two well-characterized neutrino beams for the price of one: $\nu_\mu + \bar{\nu}_e$ in case of μ^- decays, $\bar{\nu}_\mu + \nu_e$ in the case of μ^+. A neutrino factory is a storage ring for muons with a well-defined energy. Depending on the muon energy, one can measure, with great precision, $P_{\mu\mu}$ and $P_{e\mu}$, assuming the far detector can tell positive from negative muons, potentially along with $P_{\mu e}$ and P_{ee}, if the far detector is sensitive to electron charged-current events and can deal with the π^0 backgrounds, or $P_{\mu\tau}$ and $P_{e\tau}$, if the muon energy is large enough and if the far detector has the ability to identify τ-leptons with enough efficiency. Neutrino factories are widely considered the ultimate sources for neutrino oscillation experiments [52], and probably allow for the most comprehensive tests of the standard three-neutrino paradigm.

Finally, nuclei that undergo β-decay serve as a very well-characterized source of ν_e or $\bar{\nu}_e$. An intense, highly boosted beam of β-decaying nuclei would allow for the study of $P_{e\mu}$. Such sources are known as "β-beams" [53]. Radioactive sources at rest can also be used for low-energy neutrino experiments (see Sec. 1.9).

To do neutrino experiments, one must of course detect neutrinos. Neutrino detectors span a huge range of technologies, some standard for particle physics and others highly specialized. Detectors are typically quite large, up to multi-kt scale and higher, due to the smallness of neutrino-interaction cross sections. Specific detector needs depend on neutrino energy and physics goals. In general, good reconstruction capabilities, i.e., ability to reconstruct momenta and particle types of interaction products, are needed. For long-baseline beams and atmospheric neutrinos, for which energies are high ($\sim$GeV), a variety of tracking detector technologies can be used, each with advantages and disadvantages. Commonly-employed detector technologies include segmented trackers (e.g., Soudan, MINOS, NOvA, ICAL), some of which have magnetic fields to enable interaction-product sign selection, water-Cherenkov detectors (Super-K, Hyper-K), and liquid argon time projection chambers (Icarus, LBNE). At the very highest energies, astrophysical neutrino detectors employ enormous volumes of water or ice (IceCube, ANTARES). For low-energy neutrinos (few to tens of MeV neutrinos from the Sun, reactors, supernovae, stopped-pion sources), homogeneous volumes of liquid scintillator are frequently employed (Borexino, KamLAND, SNO+, Daya BAY, RENO, Double Chooz, JUNO, LENA). For the lowest-energy interaction products, dark-matter WIMP detector technology sensitive to nuclear recoils can be used (see Secs. 1.8.2, 1.11.1.2).

Many R&D activities related to neutrino detection are currently underway [54]. For neutrino-beam experiments, for which neutrinos can be easily separated from cosmogenic backgrounds because they tend to arrive in sharp bursts associated with beam pulses, surface detectors are possible. However for physics involving natural neutrinos or steady-state sources, cosmogenic backgrounds become critical. Siting underground, away from cosmic rays, then becomes essential [55].

Tables 1-2 and 1-3 summarize the capabilities of current and future neutrino-oscillation experiments.

Table 1-2. *Types of current or proposed neutrino oscillation experiments, with some current and future examples (not exhaustive), along with their accessibility to different oscillation channels. $\surd\surd$ indicates the most important oscillation channel(s) while $\surd$ indicates other accessible channels. '$\nu_{e,\mu}$ disapp' refers to the disappearance of ν_e or ν_μ (neutrinos or antineutrinos) which are related to P_{ee} and $P_{\mu\mu}$, respectively. '$\nu_\mu \leftrightarrow \nu_e$' refers to the appearance of ν_e in a ν_μ beam or vice versa, related to $P_{e\mu}$ or $P_{\mu e}$. 'ν_τ app' refers to the appearance of ν_τ from an initial state ν_e or ν_μ, related to $P_{(e,\mu)\tau}$. 'Pion DAR/DIF' refers to neutrinos from pion decay at rest or in flight. 'μ DAR/DIF' and 'β Beam' refer to neutrinos from muon decay and nuclear decay in flight, respectively. In particular Pion DIF stands for a so-called conventional neutrino beam. For examples of experiments, see Table 1.1.2.*

Expt. Type	ν_e disappearance	ν_μ disappearance	$\nu_\mu \leftrightarrow \nu_e$	ν_τ appearance[1]
Reactor	$\surd\surd$	–	–	–
Solar[2]	$\surd\surd$	–	$\surd$	–
Supernova[3]	$\surd\surd$	$\surd$	$\surd\surd$	–
Atmospheric	$\surd$	$\surd\surd$	$\surd$	$\surd$
Pion DAR	$\surd$	–	$\surd\surd$	–
Pion DIF	–	$\surd\surd$	$\surd\surd$	$\surd$
μ DIF[4]	$\surd$	$\surd\surd$	$\surd\surd$	$\surd$
Isotope DAR	$\surd$	–		–
β beam	$\surd$	–	$\surd\surd$	–

[1]In order to observe ν_τ appearance, a dedicated detector or analysis is required, along with a high-enough neutrino energy. [2]Solar neutrino experiments are sensitive, at most, to the ν_e and the $\nu_e + \nu_\mu + \nu_\tau$ components of the solar neutrino flux. [3]Signatures of neutrino oscillation occurring both in the collapsed star matter and in the Earth will be present in the spectra of observed fluxes of different flavors, and do not strictly fall in these categories; detectors are sensitive to ν_e and $\bar{\nu}_e$ fluxes, and to all other flavors by NC interactions. [4]The "standard" high-energy neutrino factory setups are not sensitive to electron appearance or disappearance.

Table 1-3. *Types of current or proposed neutrino oscillation experiments and their ability to address some of the outstanding issues in neutrino physics. 'NSI' stands for non-standard neutrino interactions, while ν_s (s for sterile neutrino) stands for the sensitivity to new neutrino mass eigenstates (see Sec. 1.9). '$\star\star\star$' indicates a very significant contribution from the current or proposed version of these experimental efforts, '$\star\star$' indicates an interesting contribution from current or proposed experiments, or a significant contribution from a next-next generation type experiment, '$\star$' indicates a marginal contribution from the current or proposed experiments, or an interesting contribution from a next-next generation type experiment. See Table 1.1.2 and text for more details.*

Expt. Type	$\sin^2\theta_{13}$	$\text{sign}(\Delta m^2_{31})$	δ	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	Δm^2_{21}	NSI	ν_s
Reactor	$\star\star\star$	$\star\star$	–	–	$\star$	$\star\star$	$\star\star$	–	$\star\star$
Solar	$\star$	–	–	–	–	$\star\star\star$	$\star$	$\star\star$	$\star\star$
Supernova	$\star$	$\star\star\star$	–	–	–	$\star$	$\star$	$\star\star$	$\star\star$
Atmospheric	$\star\star$	$\star\star$	$\star\star$	$\star\star$	$\star\star$	–	–	$\star\star\star$	$\star\star$
Pion DAR	$\star\star\star$	–	$\star\star\star$	$\star$	$\star\star$	$\star$	$\star$	–	$\star\star$
Pion DIF	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star$	$\star$	$\star$	$\star\star$	$\star\star$
μ DIF	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star$	$\star$	$\star\star$	$\star\star$
Isotope DAR	–	–						$\star\star$	$\star\star$
β Beam	$\star\star\star$	–	$\star\star\star$	$\star\star$	$\star\star$	$\star$	$\star$	–	$\star\star$

1.5 The Standard Oscillation Paradigm

The three-flavor oscillation framework is quite successful in accounting for a large number of results obtained in very different contexts: the transformation of ν_e into $\nu_{\mu,\tau}$ from the Sun [34]; the disappearance of ν_μ and $\bar{\nu}_\mu$ from neutrinos produced by cosmic ray interactions in the atmosphere [56, 57]; the disappearance of ν_μ and $\bar{\nu}_\mu$from neutrino beams over distances from 200-740 km [58, 59, 60]; the disappearance of $\bar{\nu}_e$ from nuclear reactors over a distance of about 160 km [61]; the disappearance of $\bar{\nu}_e$ from nuclear reactors over a distance of about 2 km [40, 38, 62]. Now also the appearance of ν_e [63, 29] and, at relatively low significance, the appearance of ν_τ [27, 28] have been observed. All these experimental results can be succinctly and accurately described by the oscillation of three active neutrinos governed by the following parameters, including their $1\,\sigma$ ranges from a global fit [64][6]

$$\Delta m^2_{21} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\,\mathrm{eV}^2\,,(3.2\%) \qquad \Delta m^2_{32} = 2.43^{-0.06}_{+0.1} \times 10^{-3}\,\mathrm{eV}^2\,,(3.3\%) \tag{1.8}$$

$$\sin^2\theta_{12} = 3.07^{+0.18}_{-0.16} \times 10^{-1}\,,(16\%) \qquad \sin^2\theta_{23} = 3.86^{+0.24}_{-0.21} \times 10^{-1}\,,(21\%) \tag{1.9}$$

$$\sin^2\theta_{13} = 2.41 \pm 0.25 \times 10^{-1}\,,(10\%) \qquad \delta/\pi = 1.08^{+0.28}_{-0.31}\,\mathrm{rad}\,,(27\%)\,, \tag{1.10}$$

where for all parameters whose value depends on the mass hierarchy, we have chosen the values for the normal mass ordering. The choice of parametrization is guided by the observation that for those parameters the χ^2 in the global fit is approximately Gaussian, except for δ. The percentages given in parentheses indicate the relative error on each parameter. For the mass splitting we reach errors of a few percent; however, for all of the mixing angles the errors are in the 10-30% range, while the CP-odd phase is unconstrained at the two-sigma level. The mass hierarchy and octant of θ_{23} (i.e., whether θ_{23} is smaller or larger than $\pi/4$) are not constrained at all. Therefore, while three-flavor oscillation is able to describe a wide variety of experiments, it would seem premature to claim that we have entered the era of precision neutrino physics or that we have established the three-flavor paradigm at a high level of accuracy. This is also borne out by the fact that there are interesting hints at short baselines for a fourth neutrino [65]. Also, more generally, so-called non-standard interactions (NSI) are not well constrained by neutrino data; for a recent review on the topic see Ref. [66]. The issue of what may exist beyond three-flavor oscillations will be discussed in detail in Sec. 1.9 of this report.

The next question is: how well do we want to determine the various mixing parameters? The answer can be given on two distinct levels. One is a purely technical one – if I want know X to a precision of x, I need to know Y with a precision of y; an example is, where Y is given by θ_{13} and X could be the mass hierarchy. At another level, the answer is driven by theory expectations of how large possible phenomenological deviations from the three-flavor framework could be. In order to address the technical part of the question, one first has to define the target precision from a physics point of view. Guidance from other subareas of particle physics reveals that the target precision evolves over time. For example, history shows that before the top quark discovery, theoretical estimates of the top quark mass from electroweak precision data and other indirect observables seem to have been, for the most part (and with very large uncertainties), only several GeV ahead of the experimental reach – at the time, there always was a valid physics argument for why the top quark was "just around the corner." A similar evolution of theoretical expectations can be observed in, for example, searches for new phenomena in quark flavor physics. Thus, any argument based on model-building-inspired target precisions is always of a preliminary nature, as our understanding of models evolves over time. With this caveat in mind, one argument for a target precision can be based on a comparison to the quark sector. Based on theoretical guidance from Grand Unification, one would expect that the answer

[6] See [64] for more details. When it comes to the "large" mass-squared difference, different experiments, in principle, are most sensitive to different linear combinations of Δm^2_{31} and Δm^2_{32}. Throughout this document, however, we will refer to these different quantitates as Δm^2_{32}, unless otherwise noted, as the current data, and most of the data expected from near-future efforts, are not precise enough to be sensitive to the slight differences.

to the flavor question should find a concurrent answer for leptons and quarks. Therefore, tests of such models are most sensitive if the precision in the lepton and quark sector is comparable. For instance, the CKM angle γ, which is a very close analog of δ in the neutrino sector, is determined to $(70.4^{+4.3}_{-4.4})^\circ$ [67] and thus, a precision target for δ of roughly 5° would follow.

Beyond those very general arguments, one has to look at specific models, and each model presumably will yield a different answer. In the context of neutrino physics this problem is exacerbated by the fact that we currently have no experimental evidence for the scale of physics responsible for neutrino masses and this, in turn, limits the number of models which have clear, fully worked-out predictions. In the following, we will show *one* specific example, but the example was chosen to also highlight certain general features. In general, symmetries imply structure and structure implies well defined relationships between the physical parameters of a theory. A significant test of these relationships requires considerable precision, especially if the goal is to distinguish between models or to determine the underlying symmetries. Neutrino sum rules [68] arise, for example, in models where the neutrino mixing matrix has a certain simple form or texture at a high energy scale and the actual low-energy mixing parameters are modified by a non-diagonal charged lepton mass matrix. The simplicity of the neutrino mixing matrix is typically a result of a flavor symmetry, where the overall Lagrangian possesses an overall flavor symmetry G, which can be separated into two sub-groups G_ν and G_l for the neutrinos and charged leptons; it is the mismatch between G_ν and G_l which will yield the observed mixing pattern; see e.g., [69]. Typical candidates for G are given by discrete subgroups of SU(3) which have a three-dimensional representation, e.g., A_4. In a model-building sense, these symmetries can be implemented using so-called flavon fields which undergo spontaneous symmetry breaking, and it is this symmetry breaking which picks the specific realization of G; for a recent review see [70]. The idea of flavor symmetries is in stark contrast to the idea that neutrino mixing parameters are anarchic, i.e., random numbers with no underlying dynamics. For the most recent version of this argument, see Ref. [71]. To find out whether the patterns observed in lepton mixing correspond to an underlying symmetry is one of the prime tasks of neutrino physics. Of course, distinguishing among the many candidate underlying symmetries is also a very high priority.

In practice, flavor symmetries will lead to relations between measurable parameters, whereas anarchy will not. For example, if the neutrino mixing matrix is of tri-bi-maximal form, $|U_{e3}| = 0$ is naively expected to vanish, which is clearly in contradiction to observations. In this case, a non-diagonal charged lepton mass matrix can be used to generate the right value of $|U_{e3}|$. For one concrete model, the following sum rule arises:

$$\theta_{12} - \theta_{13}\cos\delta = \arcsin\frac{1}{\sqrt{3}}\,, \tag{1.11}$$

which can be tested if sufficiently precise measured values for the three parameters $\theta_{12}, \theta_{13}, \delta$ are available. Depending on the underlying symmetry of the neutrino mixing matrix, different sum rules are found. In Fig. 1-5 several examples are shown and for each case the values of θ_{13} and θ_{12} or θ_{23} are drawn many times from a Gaussian distribution where the mean values and ranges are taken from Eq. 1.8. The resulting predictions of the value of the CP phase δ are histogrammed and shown as colored lines. The width of the distribution for each sum rule arises from the finite experimental errors on θ_{12} or θ_{23} and θ_{13}. Two observations arise from this simple comparison: first, the distance between the means of the distributions is as small as 15°, and second, the width of the distributions is significant compared to their separation and a reduction of input errors is mandated. The thin lines show the results if the errors are reduced to the value given in the plot, which would be achieved by Daya Bay for $\sin^2 2\theta_{13}$, by JUNO for $\sin^2\theta_{12}$, and by NOvA for $\sin^2\theta_{23}$. Assuming that the errors on θ_{12}, θ_{23} and θ_{13} are reduced to this level, the limiting factor is the natural spread between models, which is about 15°. A $3\,\sigma$ distinction between models translates into a target precision for δ of 5°. A measurement at this precision would allow to obtain valuable information on whether indeed there is an underlying symmetry behind neutrino mixing. Moreover, it is likely to also provide hints

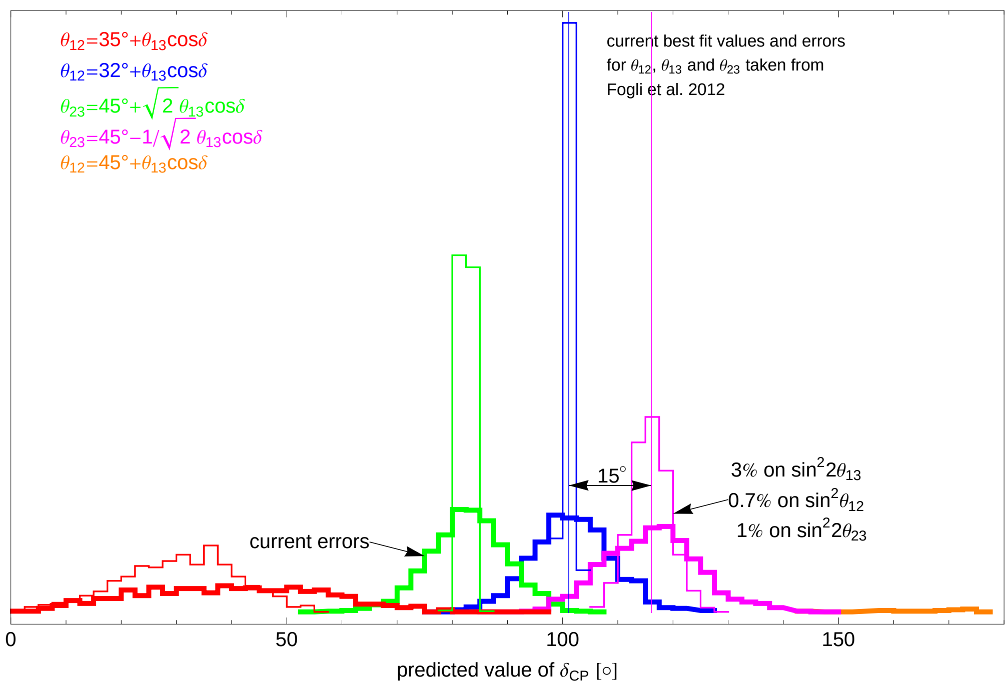

Figure 1-5. *Shown are the distributions of predicted values for δ from various sum rules as denoted in the legend and explained in the text.*

regarding which specific class of symmetries is realized. This would constitute a major breakthrough in our understanding of flavor.

For the parameter $\sin^2 2\theta_{13}$ the *status quo* is determined by the results from the reactor experiments Double Chooz [40], Daya Bay [72] and RENO [38] and their results agree well. It is expected that Double Chooz will improve its systematic error by a significant amount with the planned addition of a near detector by the end of 2013. Daya Bay started running in its full eight-detector configuration only in the summer of 2012 and it is expected that a three-year run with all detectors will eventually reach a 3% error on $\sin^2 2\theta_{13}$, compared to currently about 12.5% on this parameter. Of all beam experiments, only a neutrino factory will be able to match this precision [73]. A comparison of the values of θ_{13} obtained in $\bar{\nu}_e$ disappearance at reactors with the result of ν_e and $\bar{\nu}_e$ appearance in beams will be a sensitive test of the three-flavor framework, which is particularly sensitive to non-standard matter effects.

For the atmospheric Δm^2_{32}, currently the most precise measurement comes from MINOS [59] with an error of 3.2% and MINOS+ [74] will slightly improve on this result. It is expected that both NOvA and T2K will contribute measurements with errors of $\sim 3\%$ and $\sim 4\%$, respectively. Daya Bay will provide a measurement of this parameter in $\bar{\nu}_e$ disappearance of about 4%. By increasing the size of the event sample and going to an off-axis location, CHIPS [75] (see next section) has the potential to reduce the current error by perhaps as much as a factor 2-3, which is of course subject to sufficient control of systematic errors and needs further study. JUNO [44] ultimately may have the potential to bring the error down to below one percent. For θ_{23}, two related but distinct questions arise. First, what is the precise value of $\sin^2 2\theta_{23}$ or how close it is to unity? Secondly, if $\sin^2 2\theta_{23} \neq 1$, is θ_{23} smaller or larger than $\pi/4$, i.e., what is the so-called octant of θ_{23}? An experiment can be very good at determining the value of $\sin^2 2\theta_{23}$ without obtaining any information on the octant question. The resolution of the octant question can be either achieved by comparing long-baseline data obtained at different baselines, like NOνA and T2K, or by comparing a precise $\nu_\mu \to \nu_e$ long-baseline measurement with a precise determination of $\bar{\nu}_e \to \bar{\nu}_e$ oscillations from a reactor experiment like Daya Bay. Within the U.S. program, the long-baseline pieces of data can come from the NuMI beam, and NOvA is well positioned to provide information, as would be potential extensions of the NuMI program in the form of extended NOvA running [74], RADAR [76] and CHIPS [75]. Eventually, LBNE, with its very long baseline and wide beam spectrum, will provide good sensitivity to the octant on its own. NOvA and T2K have the potential to reduce the error on $\sin^2 2\theta_{23}$ to 1-2% and most likely further improvements in beam experiments will require an improved understanding of systematics.

For the solar Δm^2_{21}, the current uncertainties are determined by KamLAND and a future improvement is necessary to measure the mass hierarchy without using matter effects as proposed by JUNO. JUNO may able to reduce the error to below 1%. The solar mixing parameter $\sin^2\theta_{12}$ has been most accurately measured by SNO. There are basically two independent ways to further improve this measurement. One is to do a precision measurement of the solar pp-neutrino flux. Since this flux can be predicted quite precisely from the solar luminosity and the $\nu - e$ scattering cross section is determined by the standard model, an error of 1% may be achievable. The experimental challenge is the required very low threshold and associated low backgrounds in a large detector. The other method relies on the observation of $\bar{\nu}_e$ disappearance at a distance of about 60 km as proposed in JUNO, with the potential to bring this error to below 1%. The value of θ_{12} and its associated error play an important role for sum rules, as explained previously, but also for neutrinoless double β-decay.

1.5.1 Towards the Determination of the Neutrino Mass Hierarchy

The recently observed "large" value of θ_{13} has opened the possibility of determining, mostly using matter effects, the mass hierarchy through a variety of different experiments and observations. This includes accelerator-based neutrino oscillation experiments, atmospheric neutrino detectors, as well as reactor antineutrino experiments, and observations of astrophysical neutrinos from supernovae, as well as cosmology. A broad suite of experiments has been proposed to study the mass hierarchy using these possibilities and R&D is underway to address the viability of these options. It is possible that one or more of these experiments will be able to make an unambiguous determination of the mass hierarchy in the next decade. More likely, we will obtain a suite of results with indications that may point to the ordering of the neutrino mass eigenstates in a joint analysis. Now that we know the size of θ_{13}, a measurement of the neutrino mass hierarchy is within reach and may well be one of the next big milestones in neutrino physics [77].

1.5.1.1 Mass Hierarchy from Oscillations and Other Observables

The neutrino mass hierarchy manifests itself in different types of phenomena, most of which are potentially observable in neutrino oscillation experiments. We review them here, before discussing the reach of different types of experiments and opportunities for the near and intermediate future.

If all mixing angles are nonzero, the neutrino mass hierarchy manifests itself in all oscillation probabilities, including those associated with neutrinos propagating in vacuum. This can be quickly understood via a concrete example. The survival probability of, say, electron neutrinos in vacuum is given by

$$P_{ee} = 1 - \left[A^e_{21}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) + A^e_{31}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + A^e_{32}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right], \tag{1.12}$$

where $A^e_{ij} \equiv 4|U_{ei}|^2|U_{ej}|^2$. A measurement of P_{ee} capable of establishing that there are three (related) oscillation frequencies can determine the mass hierarchy as along as the three A^e_{ij} are nonzero and distinct (and known). This comes from the fact that under these circumstances one can tell whether $|\Delta m^2_{31}| > |\Delta m^2_{32}|$ or vice-versa. For the normal mass hierarchy $|\Delta m^2_{31}| > |\Delta m^2_{32}|$ as one can readily see from Fig. 1-2, with the situation reversed for the inverted mass hierarchy. For a more detailed discussion see, e.g., [78]. The fact that $|\Delta m^2_{31}| \gg \Delta m^2_{21}$ and $\sin^2\theta_{13} \ll 1$ renders such a measurement, in practice, very hard as, for almost all experimental set-ups, observations are very well-described by an effective two-flavor oscillation scheme, completely blind to the mass hierarchy. A large reactor neutrino experiment with exquisite energy resolution and an intermediate baseline (around 50 km) should be able to see the interplay of all oscillation terms with Δm_{31} and Δm_{32} and would be sensitive to the mass hierarchy.

Matter effects allow one to probe the mass hierarchy in a different way, as already discussed in Sec. 1.3. Electron-type neutrinos interact with electrons differently from muon-type and tau-type neutrinos. As neutrinos propagate inside a medium filled with electrons the neutrino dispersion relation, and hence the oscillation probabilities, are modified in a way that can distinguish electron-type neutrinos from muon-type or tau-type neutrinos. This translates into a sensitivity to whether the mass eigenstates containing "more" electron-type neutrinos – ν_1 and ν_2 – are lighter (normal hierarchy) or heavier (inverted hierarchy) than the eigenstates containing "less" electron-type neutrinos – ν_3. Such a measurement is have possible even for very small Δm^2_{12}, as long as θ_{13} was not vanishingly small and one is probing oscillations of or into electron-type neutrinos. In practice, sensitivity to matter effects requires small values of $|\Delta m^2_{32}|/E$ and, since one requires L such that $|\Delta m^2_{32}|L/E$ is large enough, long distances. For neutrino energies around 1 GeV, L values of order at least several hundred kilometers are required.

Core-collapse supernovae (SN) from massive stars are an abundant source of neutrinos of all flavors: see Sec. 1.10.2.1, and matter effects are abundant and qualitatively different from the ones encountered anywhere else (except, perhaps, for the very early universe). There are multiple possible signatures are sensitive to mass hierarchy in the supernova neutrino flux. During neutrino emission from the SN core the MSW effects are encountered twice at high and low density, and the resulting flavor conversion depends on the neutrino mass hierarchy in addition to the star's density, neutrino energy, and the oscillation parameters. In addition, shock waves in the SN envelope and Earth matter effects can impact the observed neutrino spectra. Shock waves change the adiabatic to non-adiabatic conversion and multiple MSW effects take place. They occur either in the ν_e or $\bar{\nu}_e$ channel and depend on the mass hierarchy. Turbulence can have similar effects as shock waves. In addition, neutrino conversion can take place near the neutrinosphere due to ν-ν interactions. The conversion probability is energy dependent and may introduce a spectral split. Model-dependent effects in the emitted SN spectrum will have to considered in the use of SN data for a mass hierarchy determination.

Finally, observables outside of neutrino oscillations sensitive to the neutrino masses themselves, as opposed to only mass-squared differences, are also in principle sensitive to the neutrino mass hierarchy. Some of these are discussed in Secs. 1.6, 1.7, 1.10. For example, if the sum of all neutrino masses were constrained to be less than around 0.1 eV, the inverted mass hierarchy hypothesis would be ruled out. Such a sensitivity (or better) is expected from several next-generation probes of the the large-scale structure of the universe, as will be discussed in more detail in Sec. 1.10.

1.5.1.2 Experimental Approaches

Accelerator Experiments: Ongoing and future accelerator experiments are a key element in a program to determine the neutrino mass hierarchy. Very intense beams of muon neutrinos from pion sources can be used to search for electron neutrino appearance. For intermediate and long baselines the appearance probability will depend on the ordering of the neutrino mass states. The upcoming NOvA experiment together with T2K will have a chance of determining the neutrino mass hierarchy with accelerator neutrinos for a range of oscillation parameters. In the long term, the long-baseline neutrino oscillation experiment (LBNE) or experiments at neutrino factories will allow the definitive measurement of the neutrino mass hierarchy. See Fig. 1-6. The CHIPS and RADAR proposals seek to exploit the NuMI beam from FNAL with new detectors at baselines similar to MINOS and NOvA. The experimental advantages of LBNE over current experiments such as NOvA and T2K include an optimum baseline from the neutrino source to the detector, a large and sophisticated far detector, a high-power, broadband, sign-selected muon neutrino beam, and a highly-capable near neutrino detector. If placed underground, the LBNE far detector may even allow the possibility of atmospheric neutrino studies and oscillation measurements through a channel with different systematics than the accelerator-based experiments. Optimization of the LBNE baseline to determine the mass hierarchy with no ambiguities depends only on the known oscillation parameters. To achieve mass hierarchy sensitivity over all phase space requires a baseline >1000 km.

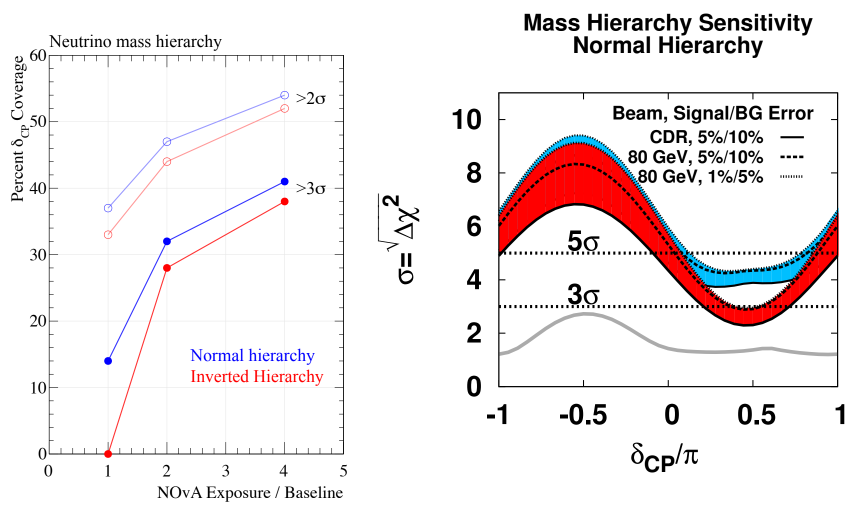

Figure 1-6. *Left: Percent of δ_{CP} values for which NOvA can resolve the neutrino mass hierarchy at 2 and 3 σ C.L. NOvA is in construction and has started data taking with a partial detector configuration. Right: Significance with which mass hierarchy can be determined as a function of δ_{CP} (assuming normal hierarchy), for different combinations of experiments. The beam exposure assumed is 5+5 years ($\nu + \bar{\nu}$) in a 708-kW beam for LBNE10; for NOvA the assumption is 3+3 ($\nu + \bar{\nu}$) and for T2K the assumption is 5×10^{21} protons on target. T2K is operational and taking data. NOvA is in the commissioning phase and will finish construction in 2014. LBNE10 is in preliminary design and R&D and preparing for Critical Decision 2. Figures from [79, 80].*

Reactor Experiments: The success of recent reactor experiments in the measurement of θ_{13} at baselines of ∼1 km has resulted in proposals for the precision study of neutrino oscillation at medium baselines of 50-60 km. A high-precision, high-statistics reactor experiment at 60 km may be able to determine the mass hierarchy from the difference in the oscillation effects from Δm^2_{31} and Δm^2_{32}. See Fig. 1-7. Such a measurement is challenging due to the finite detector resolution, the absolute energy scale calibration, as well as degeneracies caused by current experimental uncertainty of Δm^2_{32}. Two experiments are currently proposed to make this measurement: JUNO in China and RENO-50 in South Korea, although other locations may be suitable. The current design of RENO-50 includes a 18-kt liquid scintillator detector ∼47 km from a ∼17-GWth power plant. JUNO proposes a 20 kt liquid scintillator detector ∼700 m underground and ∼60 km from two nuclear power plants with ∼40 GWth power.

Atmospheric Neutrino Experiments: Atmospheric neutrinos remain an important probe of neutrino oscillations and the large statistics that can be collected by large Cherenkov detectors at the Mton-scale

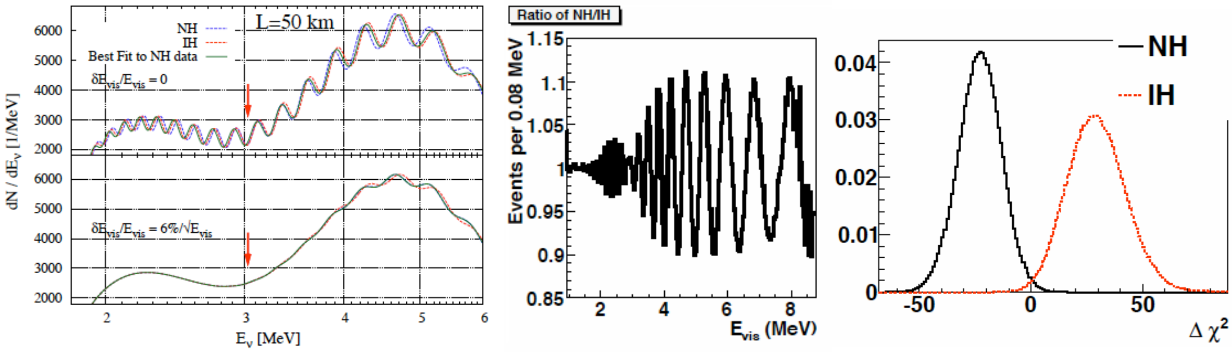

Figure 1-7. *Left: Energy distribution of reactor antineutrinos with baseline length of 50 km. The solid line shows the best fit of IH assumption to the NH data. The red arrow points out the energy at which the difference due to the mass hierarchy vanishes. The lower panel shows the effect of 6% energy resolution. Figure from [81]. Middle: Ratio of reactor antineutrino spectra for NH and IH case for the ideal energy spectrum without fluctuation and fixed Δm^2_{32} . Statistical fluctuations, the unknown true value of Δm^2_{32}, as well as experimental effects such as energy scale uncertainty, will degrade the observable effect. Right: The $\Delta\chi^2$ spectrum from Monte Carlo simulation. The probability of the mass hierarchy being NH is calculated as $P_{NH}/(P_{NH} + P_{IH})$ and found to be 98.9% for 100-kt-year exposure. Figures from [82].*

such as Hyper-K, PINGU, and ORCA will offer an an unprecedented opportunity to study them in detail. Atmospheric neutrinos exist in both neutrino and antineutrino varieties in both muon and electron flavors. Up to 10^6 events are expected to be collected in a 10-year period in half megaton detectors such as Hyper-K. There are two experimental approaches to the study of the mass hierarchy with atmospheric neutrinos. One approach is based on charge discrimination and distinguishes between neutrinos and antineutrinos. Large magnetized calorimeters such as ICAL with good energy and angular resolution and thresholds of 1-2 GeV are an example of this type of detector. The second approach uses water Cherenkov detectors and makes use of the different cross-sections and different ν and $\overline{\nu}$ fluxes. Examples of future water Cherenkov detectors include Hyper-K [83], a larger version of the successful water-based Super-K detector, ORCA [84], an extension of ANTARES in the Mediterranean Sea, and PINGU, an upgrade of the IceCube Deep Core detector at the South Pole [85, 86]. Atmospheric neutrino measurements are also possible in large liquid argon TPCs such as that being planned for LBNE [80]. Key to the measurement of the mass hierarchy with these experiments will be a large statistical sample collected in a large fiducial volume, good energy and angular resolution for the study of the L/E oscillation effects and discrimination of backgrounds. See Figs. 1-8.

Supernova Neutrinos: – A suite of neutrino observatories is currently operational worldwide with a variety of target materials including water or ice (Super-K, IceCube), liquid scintillator (KamLAND, Borexino, Daya Bay, LVD), and lead (HALO) [87]. They offer several detection channels through the scattering of $\bar{\nu}_e$ with protons, the ν_e scattering with nuclei and ν_x interactions with electrons and nucleons. Together they have the ability to measure the SN flux at different thresholds and different flavor sensitivities, although most current detectors are primarily sensitive to $\bar{\nu}_e$. Future detectors will have broader flavor sensitivity; in particular liquid argon will be valuable for observation of the ν_e component of the flux. There will multiple signatures of the MH in the flux; see, e.g. [88, 89, 90, 91, 92, 93].

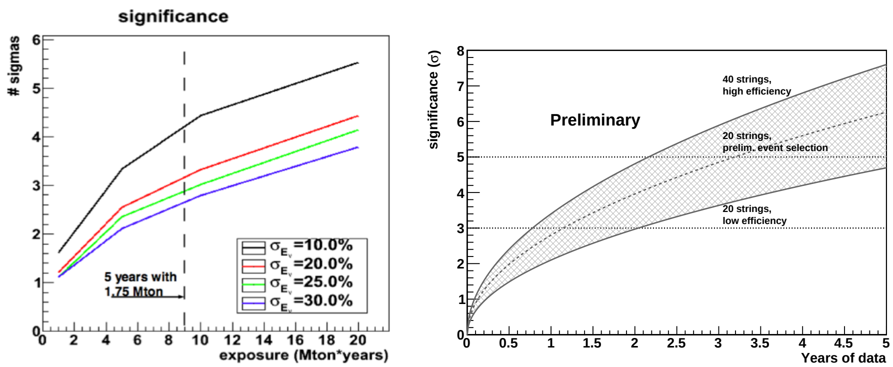

Figure 1-8. *Preliminary sensitivities of the ORCA [84] (left) and PINGU [86] (right) proposals to mass hierarchy as a function of exposure.*

1.5.1.3 Experimental Status and Opportunities

The measurement of large θ_{13} has opened a broad range of possibilities for the determination of the neutrino mass hierarchy. Several experiments with complementary approaches have been proposed that will allow us to determine the neutrino mass hierarchy in oscillation experiments using neutrinos from accelerators, reactors, or the atmosphere. NOvA is the only funded oscillation experiment under way to start an experimental investigation of the neutrino mass hierarchy in a range of the allowed parameter space. T2K is taking data but has relatively low sensitivity due to its short baseline. For some of the recent proposals under consideration sometimes significant R&D and design work is still required. A dedicated experiment to measure the neutrino mass hierarchy with atmospheric or reactor neutrinos may be feasible by 2018. After 2022, the planned LBNE experiment will be able to determine the neutrino mass hierarchy for the entire range of CP values. In the meantime, $0\nu\beta\beta$ and direct neutrino mass experiments combined with data from cosmology may also tell us about the hierarchy if $\sum m_\nu$ is measured to be less than 0.1 eV. A supernova event detected in one or several of the existing large neutrino observatories would enable a rich physics program and may allow the determination of the ordering of the neutrino mass states, although astrophysics and uncertainties in the supernova models may make this challenging. Table 1-4 summarizes the status of the ongoing and proposed experiments.

1.5.2 Towards the Determination of CP Violation in Neutrinos

The standard approach to measuring CP violation in neutrinos is to use long-baseline beams of both neutrinos and antineutrinos. As for the mass hierarchy determination, nature provides beams of atmospheric neutrinos and antineutrinos free of charge, over a wide range of energies and baselines– the catch is that one has no control over their distribution and so one must measure their properties precisely, and/or gather immense statistics in order to extract information on CP violation from these sources. Alternate approaches include using well-controlled, well-understood accelerator-based beams of ~GeV neutrinos or else lower-energy neutrinos from pion decay-at-rest sources. Here, we will discuss the CP reach of all three possibilities: accelerator-based long-baseline neutrinos, atmospheric neutrinos, and pion decay-at-rest sources.

Category	Experiment	Status	Osc params
accelerator	MINOS+	data-taking	MH/CP/octant
accelerator	T2K	data-taking	MH/CP/octant
accelerator	NOvA	commissioning	MH/CP/octant
accelerator	RADAR	design/ R&D	MH/CP/octant
accelerator	CHIPS	design/ R&D	MH/CP/octant
accelerator	LBNE	design/ R&D	MH/CP/octant
accelerator	Hyper-K	design/ R&D	MH/CP/octant
accelerator	LBNO	design/ R&D	MH/CP/octant
accelerator	ESSνSB	design/ R&D	MH/CP/octant
accelerator	DAEδALUS	design/ R&D	CP
reactor	JUNO	design/R&D	MH
reactor	RENO-50	design/R&D	MH
atmospheric	Super-K	data-taking	MH/CP/octant
atmospheric	Hyper-K	design/R&D	MH/CP/octant
atmospheric	LBNE	design/R&D	MH/CP/octant
atmospheric	INO	design/R&D	MH/octant
atmospheric	PINGU	design/R&D	MH
atmospheric	ORCA	design/R&D	MH
atmospheric	LAGUNA-LBNO	design/R&D	MH/CP/octant
atmospheric	ESSνSB	design/R&D	MH/CP/octant
supernova	existing and future	N/A	MH

Table 1-4. *Ongoing and proposed oscillation experiments for the measurement of neutrino oscillation parameters. The last column indicates sensitivity to unknown oscillation parameters. (Note that many of these experiments can improve precision on known parameters as well.)*

1.5.2.1 CP Violation with Accelerator-Based Long-Baseline Neutrinos

The study of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions using accelerator-based beams is sensitive to CP-violating phenomena arising from the CP-odd phase δ in the neutrino mixing matrix. The evidence for CP violation (assuming $\delta \neq 0, \pi$) manifests itself both as an asymmetry in the oscillation of neutrinos and antineutrinos and as a distortion in the electron-type (anti)neutrino energy spectrum. For experiments that need to tag the muon-type neutrino flavor at production or detection, baselines longer than 100 km are required. For long enough baseline (see Sec. 1.5.1), the matter effects also induce an asymmetry in the oscillation of neutrinos and antineutrinos. The matter asymmetry, however, is largest for higher neutrino energies and hence maximal at the first oscillation maximum, whereas the CP asymmetry induced by δ is more significant at the secondary oscillation nodes and is constant as a function of baseline. An experiment with a wide-band beam of neutrinos and antineutrinos that can cover at least two oscillation nodes over a long enough baseline ($>$ 1000 km) can unambiguously determine both the mass hierarchy and the CP phase simultaneously. This is the philosophy behind the Long-Baseline Neutrino Experiment (LBNE) [80]. Additionally, the study of $\nu_\mu \to \nu_e$ oscillations can help determine the θ_{23} quadrant since the oscillation probability is also proportional to $\sin^2 2\theta_{23}$.

Figure 1-9 shows examples of observed spectra for a 1300-km baseline and a beam of a few GeV (the LBNE/Project X configuration with a LAr TPC far detector) for ν_e and $\bar{\nu}_e$ appearance. Different values of δ_{CP} correspond to different spectral shapes for neutrinos versus antineutrinos; also, the ν_e signal is larger in neutrinos for the normal mass hierarchy and in antineutrinos for the inverted hierarchy. Good event reconstruction and rejection of background are critical for this measurement. In the case of LBNE, a LAr TPC was chosen as the far detector technology, given its excellent 3D position resolution and superior particle identification in large volumes. In addition to detailed event topologies and measurements of particle kinematics, such detectors can also unambiguously distinguish electrons from photons over a wide range of energies, an important asset in the precision measurement of CP-violating effects in $\nu_\mu \to \nu_e$ oscillations.

Figure 1-10 illustrates the significance with which measurements of CP violation and the unknown CP phase can be made with a staged long-baseline neutrino program in LBNE [80]. Ultimately, a 5σ determination of CP violation and a $\leq 10°$ measurement of the CP violating phase are possible with such an experimental program.

LBNE plays a central role in the future U.S. program, and while being the most advanced of all the proposals to measure CP violation in the neutrino sector, there is a large number of alternative proposals in the U.S. and abroad. In this document, we will not be able to provide an in-depth comparison of the scientific merit of each of these proposals, which vary in maturity. Nonetheless, we can give an impression of how their performance for specific measurements might look. The most challenging measurement within the framework of oscillation of three active neutrinos for long-baseline experiment is the search for leptonic CP violation and a precise measurement of the associated CP phase, δ_{CP}. Therefore, apart from the value of a determination of δ_{CP}, as outlined in Sec. 1.5, the ability to measure the CP phase with precision is a reasonable proxy for the overall potential to have a major scientific impact.

The results of this comparison are shown in Fig. 1-11 using the methods and common systematics implementation including near detectors as in Ref. [95]. The lines labeled 2020 and 2025 show what can be achieved by those dates using a combination of the existing experiments T2K and NOvA and Daya Bay, where the implementation of all three follows Ref. [96] and the NOvA description has been updated for this report [97]. This is the precision that can be reached without any new experiments. Furthermore, we will compare two phases of LBNE: LBNE-10 with a 10-kt detector and a 700-kW beam and LBNE-PX with a 34-kt detector and the 2.3-MW beam from Project-X; both phases do include a near detector and the other details can be found in [80]. After sufficient exposure, LBNE operating in the intense beams from Project X could

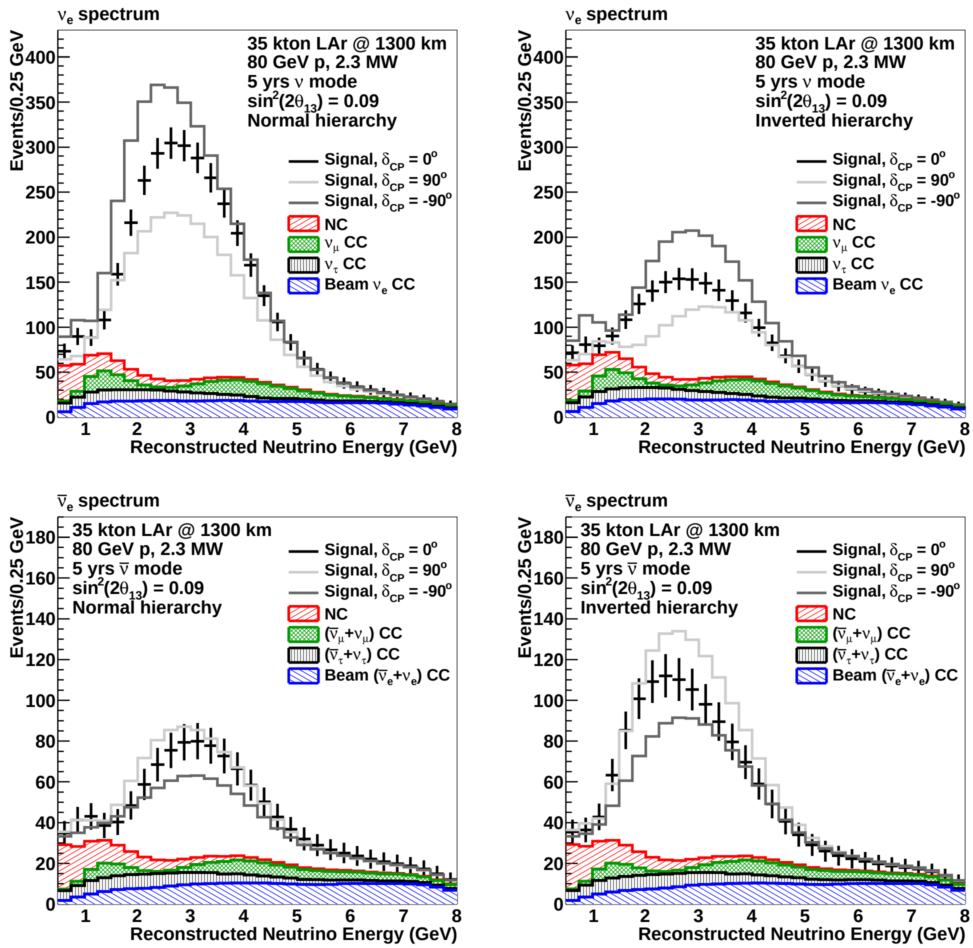

Figure 1-9. *The expected appearance of ν_e (top) and $\bar{\nu}_e$ (bottom) signals for the possible mass orderings (left: normal hierarchy, right: inverted hierarchy) and varying values of CP δ for the example of LBNE/Project X. Figures from [80].*

approach a precision for the CP-odd phase in the lepton sector comparable to that achieved for the CP-odd phase in the quark sector. In order to accomplish this, however, systematic uncertainties on the signal and the background need to be controlled at the percent level – almost an order of magnitude improvement. No studies of the feasibility of this increase in systematics control have been performed to date.

Beyond LBNE, we compare three different superbeam experiments, the European LBNO proposal for two different exposures and the Japanese proposal to send a beam to Hyper-Kamiokande. LBNO plans to use liquid argon TPC, based on dual-phase readout in contrast to LBNE, and a baseline of 2 300 km. The initial detector size will be 20-kt (labeled $\mathrm{LBNO_{EOI}}$) as descibed in detail in Ref. [98] and a later phase using a 100-kt detector (labeled $\mathrm{LBNO_{100}}$); the beam power assumied is around 700 kW derived from the CERN SPS. The Hyper-K setup [83] in Japan will use a 560-kt (fiducial) water-Cherenkov detector and a ~ 1 MW beam. A more recent European proposal (ESSνSB) is to upgrade the superconducting 5-MW and 14-Hz-pulse-rate proton linac of the European Spallation Source linac, which is under construction in Lund in Sweden, and use it in conjunction with a 600-kt water Cherenkov at a 500-km-baseline site in Sweden [99]. Finally, we

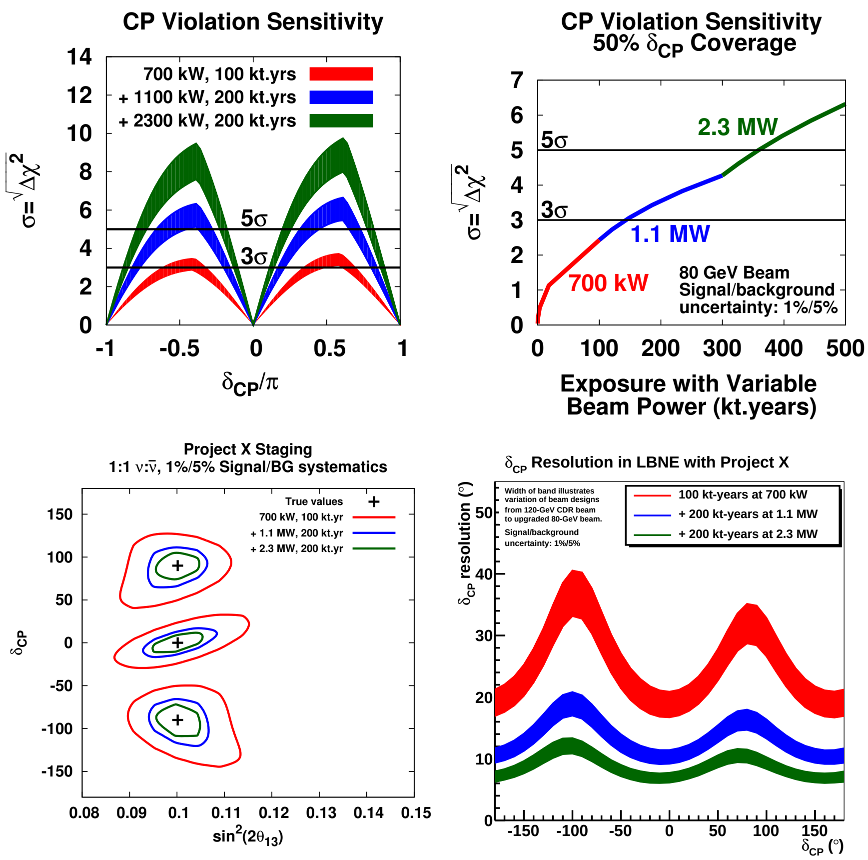

Figure 1-10. *CP-violation sensitivity as a function of δ_{CP} (top left) and exposure for 50% coverage of the full δ_{CP} range (top right). Also shown are the projected precision on the measurement of δ_{CP} for various true points in the δ_{CP}-$\sin^2 2\theta_{13}$ plane (bottom left) and as a function of δ_{CP} (bottom right). All plots show the increasing precision possible in a staged long-baseline neutrino program in LBNE starting from nominal 700-kW running (red), through 1.1 MW using Project X Stage 1 (blue), to 2.3 MW with Project X Stage 2 (green). Figures from [80, 94].*

also show the results obtained from a neutrino factory (NF) – in a neutrino factory an intense beam of muons is put in a storage ring with long straight sections and a neutrino beam consisting of equal numbers of ν_μ and $\bar{\nu}_e$ results. The current standard design of a neutrino factory will produce 10^{21} useful muon decays (summed over both stored μ^- and μ^+) per 10^7 s at a muon energy of 10 GeV aimed a 100-kt magnetized iron detector (MINOS-like) at a distance of ~2,000 km [100]. This facility requires a 4 MW proton beam at around 8 GeV, muon phase-space cooling and subsequent muon acceleration. This considerable technical challenge should be contrasted with the resulting advantages: a neutrino beam with known flux, better than 1%, beam spectrum and flavor composition with an easy to identify final state in the far detector. The NF offers a unique level of systematics control paired with very high-intensity beams; therefore they are considered the ultimate tool for precision neutrino physics, see, e.g., [101]. The NF facility would provide the most stringent tests of the standard three-flavor paradigm.

Several new proposals have been submitted in the form of white papers, notably a series of ideas how to use the existing Main Injector neutrino beam line (NuMI) by adding new detectors. RADAR [76] proposes to add a 6-kt liquid-argon TPC following the proposed LBNE TPC design in the NOvA far detector hall at a baseline of 810 km, to act as an R&D stepping-stone that also advances the physics reach of the overall U.S. program. CHIPS [75] proposes to build water Cherenkov detectors in shallow, flooded mine pits, which could provide potentially large fiducial masses in the range of 100 kt. According to the CHIPS proponents, in terms of physics reach, this would be equivalent to about 20 kt of liquid argon TPC.

A staged approach to a neutrino factory is proposed [108], where an initial stage called the low-luminosity low-energy neutrino factory is built on the basis of existing accelarator technology and Project X Phase 2. In this facility, which does not require muon cooling and which starts with a target power of 1 MW, 10^{20} useful muon decays per polarity and year can be obtained. The muon energy is chosen to be 5 GeV as to match the baseline of 1,300 km. In combination, this allows to target the LBNE detector, maybe with the addition of a magnetic field. This approach would allow for a step-wise development from nuSTORM (see Sec. 1.9), via the low-luminosity low-energy neutrino factory to a full neutrino factory, and if desired, to a multi-TeV muon collider. This phased muon-based program is well aligned with the development of Project X [110, 94].

In summary, a measurement of the leptonic CP phase at levels of precision comparable to those of the CP phase in the quark sector will ultimately be possible in long-baseline oscillation experiments, given that θ_{13} has been measured to be nonzero. To do so will require a product of very high proton beam intensity and very large detector mass– nominally beams in excess of 1 MW, paired with detectors in the 100-kt range or larger, and running times of order one decade – regardless of the specifics of the chosen technology or proposal. Experiments with baselines in excess of 1000 km and wide-band neutrino beams that cover the first two oscillation maxima have the best sensitivity to leptonic CP violation for the minimal required exposure. Wide-band very long-baseline experiments such as LBNE and LBNO can reach better than 10° precision on δ with exposures under 1000 kt·MW·years – provided that systematic uncertainties can be controlled to the level of a few percent or better. A neutrino factory with similar exposure – a next-next generation project – should be able to measure δ at the 5° level, and provide the most stringent constraints on the three-flavor paradigm, thanks to its capability to measure several different oscillation channels with similar precision.

1.5.2.2 CP Violation with Atmospheric Neutrinos

As noted above, neutrinos and antineutrinos from the atmosphere come with a range of baselines and energies, and in principle similar CP-violating observables are accessible as for beams, so long as the detectors have sufficient statistics and resolution. Water Cherenkov detectors have relatively low resolution in energy and direction, and have difficulty distinguishing neutrinos from antineutrinos, although some information is to be had via selection of special samples [57] and using statistical differences in kinematic distributions from ν and $\bar{\nu}$. In spite of worse resolution, water Cherenkov detectors have potentially vast statistics and reasonable sensitivity [83]. Large long-string ice and water-based detectors, while sensitive to hierarchy if systematics can be reduced, lack resolution for CP studies. LArTPC detectors, in contrast, should have significantly improved resolution on both neutrino energy and direction, and even in the absence of a magnetic field can achieve better ν vs $\bar{\nu}$ tagging than water Cherenkov detectors [80]. Atmospheric neutrino information can be combined with beam information in the same or different detectors to improve overall sensitivity.

1.5.2.3 CP Violation with Pion Decay-at-Rest Sources

A different approach for measuring CP violation is DAEδALUS [46, 111, 112, 113]. The idea is to use muon antineutrinos produced by cyclotron-produced stopped-pion decay ($\pi^+ \rightarrow \mu^+ \nu_\mu$) at rest (DAR) neutrino sources, and to vary the baseline by having sources at different distances from a detector site. For DAR

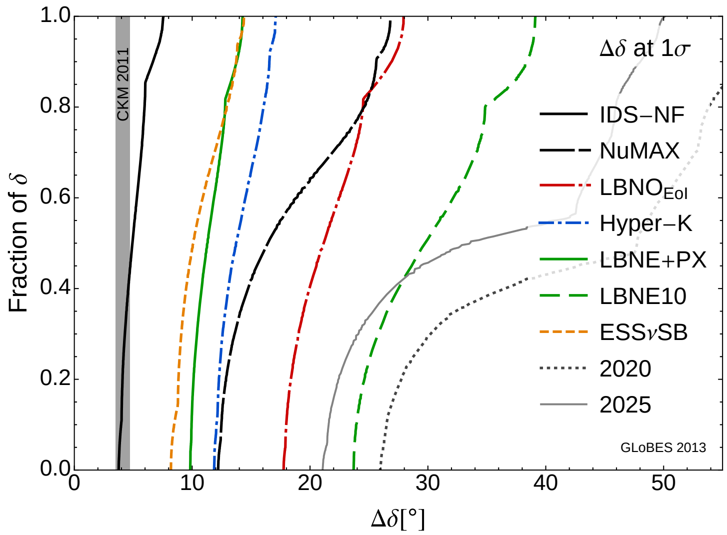

Figure 1-11. *Expected precision for a measurement of δ at present and future long-baseline oscillation experiments. Results are shown as a function of the fraction of possible values of δ for which a given precision (defined as half of the confidence interval at 1σ, for 1 d.o.f.) is expected. All oscillation parameters are set to their present best fit values, and marginalization is performed within their allowed intervals at 1σ, with the exception of θ_{13} for which marginalization is done within the allowed interval expected at the end of the Daya Bay run. Matter density is set to the value given by the PREM profile, and a 2% uncertainty is considered. The hierarchy is assumed to be normal, and no sign degeneracies are accounted for. Systematic uncertainties are implemented as in Ref. [95]. All facilities include an ideal near detector, and systematics are set to their "default" values from Tab. 2 in Ref. [95]. The different lines correspond to the following configurations.* ***2020*** *shows the expected combination of NOvA and T2K by the year 2020, simulated following Refs. [102]and [96], respectively. NOvA is assumed to run for three years per polarity while T2K is run for five years only with neutrinos. The line labeled as* ***2025*** *is an extrapolation of* ***2020****, where NOvA is run for a longer period and five years of $\bar{\nu}$ running at T2K are added following [96].* ***ESSνSB*** *corresponds to the performance of a 500-kt water Cherenkov detector placed at 360 km from the source; see [99]. The beam would be obtained from 2-GeV protons accelerated at the ESS proton linac. Migration matrices from Refs. [103, 104] have been used for the detector response.* ***LBNE10*** *corresponds to the first phase of the LBNE project. The CDR [105] beam flux has been used. The detector performance has been simulated as in Ref. [105] as well, using migration matrices for NC backgrounds from Ref. [106]. The exposure corresponds to 70 MW×kt×years.* ***LBNE+PX*** *corresponds to an upgrade of the previous setup, but exposure is set in this case to 750 MW×kt×years.* ***Hyper-K*** *stands for a 750-kW beam aiming from Tokai to the Hyper-Kamiokande detector (560-kt fiducial mass) in Japan. The baseline and off-axis angle are the same as for T2K. The detector performance has been simulated as in Ref. [95].* ***$\mathbf{LBNO_{EoI}}$*** *stands for the LBNO Expression of Interest [98] to place a 20-kt LAr detector at a baseline of 2,300 km from CERN. The results shown here correspond to the same statistics used in Fig. 75 therein. Neutrino fluxes corresponding to 50 GeV protons (from Ref. [107]) have been used, rescaling the number of protons on target to match the beam power in [98]. A similar detector performance as for LBNE10 is assumed, and five years of data taking per polarity are assumed in this case.* ***NuMAX*** *corresponds to a low-luminosity neutrino factory obtained from the decay of 5 GeV muons, simulated as in Ref. [108]. The beam luminosity is set to 2×10^{20} useful muon decays per year, and the flux is aimed to a 10-kt magnetized LAr detector placed at 1300 km from the source.* ***LENF*** *corresponds to the IDS-NF setup. It considers a 100-kt MIND detector placed at 2000 km from the source, and 2×10^{21} useful muon decays per year. Migration matrices, kindly provided by R. Bayes (see also Ref. [109]), are used to simulate the detector response.*

sources, the neutrino energy is a few tens of MeV. For baselines ranging from 1 to 20 km, both L and E are smaller than for the conventional long-baseline beam approach, and the ratio of L/E is similar. Matter effects are negligible at short baseline. This means that the CP-violating signal is clean; however there is a degeneracy in oscillation probability for the two mass hierarchies. This degeneracy can be broken by an independent measurement of the hierarchy.

The electron-type antineutrino appearance signal from the oscillation of muon-type antineutrinos from pion DAR is detected via inverse beta-decay ($\bar{\nu}_e p \to e^+ n$). Consequently very large detectors with free protons are required. The original case was developed for a 300-kt Gd-doped water detector at Homestake, in coordination with LBNE [114]. Possibilities currently being explored for the detector include LENA [115] or Super-K/Hyper-K [83]. Figure 1-12 shows the projected CP sensitivity of DAEδALUS.

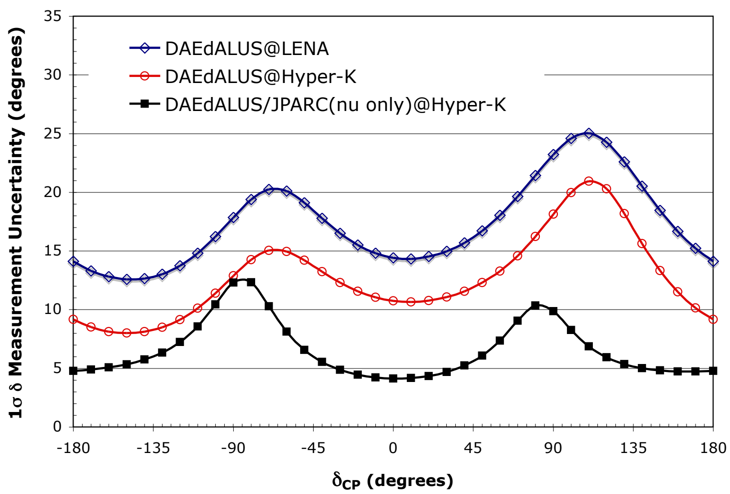

Figure 1-12. *Sensitivity of a CP search for DAEδALUS combined with LENA or Hyper-K [113].*

The DAEδALUS collaboration proposes a phased approach [113], with early phases involving IsoDAR (see Sec. 1.9.1.3) with sterile neutrino sensitivity. The phased program offers also connections to applied cyclotron research (see Section 1.11.1.4).

1.6 The Nature of the Neutrino – Majorana versus Dirac

Understanding the neutrino mass generation mechanism, the absolute neutrino mass scale, and the neutrino mass spectrum are essential topics to be addressed by future neutrino experiments. Whether neutrinos are Dirac fermions (i.e., exist as separate massive neutrino and antineutrino states) or Majorana fermions (neutrino and antineutrino states are equivalent) is a key experimental question, the answer to which will guide the theoretical description of neutrinos.

All observations involving leptons are consistent with their appearance and disappearance in flavor-matched particle anti-particle pairs. This property is expressed in the form of lepton number, L, being conserved by all fundamental forces. We know of no fundamental symmetry relating to this empirical conservation law. Neutrinoless double-beta decay, a weak nuclear decay process in which a nucleus decays to a different nucleus emitting two beta-rays and no neutrinos, violates lepton number conservation by two units and thus, if observed, requires a revision of our current understanding of particle physics. In terms of field theories, such as the Standard Model, neutrinos are assumed to be massless and there is no chirally right-handed neutrino field. The guiding principles for extending the Standard Model are the conservation of electroweak isospin and renormalizability, which do not preclude each neutrino mass eigenstate ν_i to be identical to its antiparticle $\overline{\nu}_i$, or a Majorana particle. However, L is no longer conserved if $\nu = \overline{\nu}$. Theoretical models, such as the seesaw mechanism that can explain the smallness of neutrino mass, favor this scenario. Therefore, the discovery of Majorana neutrinos would have profound theoretical implications in the formulation of a new Standard Model while yielding insights into the origin of mass itself. If neutrinos are Majorana particles, they may fit into the leptogenesis scenario for creating the baryon asymmetry, and hence ordinary matter, of the Universe.

As of yet, there is no firm experimental evidence to confirm or refute this theoretical prejudice. Experimental evidence of neutrinoless double-beta ($0\nu\beta\beta$) decay would establish the Majorana nature of neutrinos. It is clear that $0\nu\beta\beta$ experiments sensitive at least to the mass scale indicated by the atmospheric neutrino oscillation results are needed.

For $0\nu\beta\beta$ decay the summed energy of the emitted electrons takes a single value. Observation of a sharp peak at the $\beta\beta$ endpoint would thus quantify the $0\nu\beta\beta$ decay rate, demonstrate that neutrinos are Majorana particles, indicate that lepton number is not conserved, and, paired with nuclear structure calculations, provide a measure of an effective Majorana mass, $\langle m_{\beta\beta}\rangle$. There is consensus within the neutrino physics community that such a decay peak would have to be observed for at least two different decaying isotopes at two different energies to make a credible claim for $0\nu\beta\beta$ decay.

In more detail, the observed half-life can be related to an effective Majorana mass according to $(T_{1/2,0\nu\beta\beta})^{-1} = G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$, where $\langle m_{\beta\beta}\rangle^2 \equiv |\sum_i U_{ei}^2 m_i|^2$. $G_{0\nu}$ is a phase space factor, m_i is the mass of neutrino mass eigenstate ν_i, and $M_{0\nu}$ is the transition nuclear matrix element. The matrix element has significant nuclear theoretical uncertainties, dependent on the nuclide under consideration.

In the standard three-massive-neutrinos paradigm,

$$\langle m_{\beta\beta}\rangle = |\cos^2\theta_{12}\cos^2\theta_{13}e^{-2i\xi}m_1 + \sin^2\theta_{12}\cos^2\theta_{13}e^{-2i\zeta}m_2 + \sin^2\theta_{13}e^{-2i\delta}m_3|. \tag{1.13}$$

If none of the neutrino masses vanish, $\langle m_{\beta\beta}\rangle$ is a function of not only the oscillation parameters $\theta_{12,13}$ and the neutrino masses $m_{1,2,3}$ but also the two Majorana phases ξ, ζ [117]. Neutrino oscillation experiments indicate that at least one neutrino has a mass of ~ 45 meV or more. As a result and as shown in Fig. 1-13, in the inverted hierarchy mass spectrum with $m_3 = 0$ meV, $\langle m_{\beta\beta}\rangle$ is between 10 and 55 meV depending on the values of the Majorana phases. This region is sometimes referred to as the atmospheric mass scale region. Exploring this region requires a sensitivity to half-lives exceeding 10^{27} years. This is a challenging

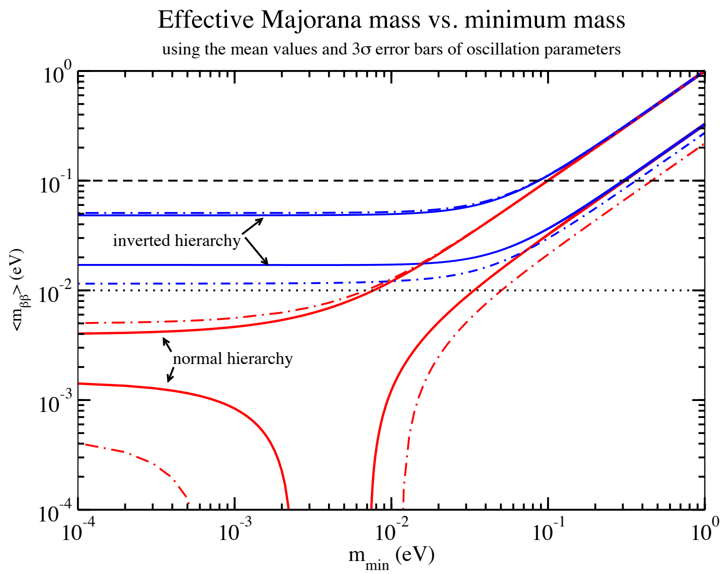

Figure 1-13. *Allowed values of $\langle m_{\beta\beta}\rangle$ as a function of the lightest neutrino mass for the inverted and normal hierarchies. The regions defined by the solid curves correspond to the best-fit neutrino mixing parameters from [116] and account for the degeneracy due to the unknown Majorana phases. The regions defined by the dashed-dotted curves correspond to the maximal allowed regions including mixing parameter uncertainties as evaluated in [116]. The dashed line shows expected sensitivity of next-generation ∼100 kg class experiments and the dotted line shows potential reach of multi-ton scale future experiments.*

goal requiring several ton-years of exposure and very low backgrounds. The accomplishment of this goal requires a detector at the ton scale of enriched material and a background level below 1 count/(ton y) in the spectral region of interest (ROI). Very good energy resolution is also required.

There is one controversial result from a subset of collaborators of the Heidelberg-Moscow experiment, who claim a measurement of the process in ^{76}Ge, with 70 kg-years of data [118]. These authors interpret the observation as giving an $\langle m_{\beta\beta}\rangle$ of 440 meV. Recent limits using the isotope ^{136}Xe from EXO-200 and KamLAND-Zen (see below) are in tension with this $\langle m_{\beta\beta}\rangle$ regime.

There is a large number of current neutrinoless double-beta decay search efforts, employing very different techniques; a recent review is [119]. Here we will highlight some for which there is a component of effort from physicists based in the U.S.. These represent different kinds of detectors and experimental approaches [120, 121, 122, 123, 124, 125, 126, 127, 128, 129].

The Majorana [130, 131, 132, 126] experiment employs the germanium isotope ^{76}Ge. The current phase of the experiment is the "Demonstrator", which will employ 30 kg of Ge enriched to 86% ^{76}Ge and 10 kg of Ge P-type point contact detectors, is being constructed underground at the Sanford Underground Research Facility (SURF). It will have first data in 2013 with data from enriched detectors in 2014. The Majorana collaboration is planning a ton-scale effort in collaboration with its European counterpart GERDA [133].

The "bolometric" CUORE experiment [134, 125], located at Gran Sasso National Laboratory in Italy, employs ^{130}Te in the form of natural TeO_2 crystals. This is a cryogenic setup, operated at temperatures around 10 mK, that determines the energy deposit via temperature rise measured with thermistors. The prototype of this experiment, Cuoricino, ran from 2003-2008 with 11.3 kg of ^{130}Te mass. The first stage of CUORE, CUORE-0, is currently operating with a ^{130}Te mass of 11 kg, and the full CUORE detector plans commencing operations in 2014 with 206 kg. CUORE aims at the sensitivity to the $0\nu\beta\beta$ lifetime of 2×10^{26} after five years of operation.

The EXO experiment [128] makes use of ^{136}Xe, which double-beta decays as $^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Ba}^{++} + \mathrm{e}^- + \mathrm{e}^-$. The first version of EXO, EXO-200, is currently taking data at the Waste Isolation Pilot Plant in New Mexico with 200 kg of xenon enriched to 80% in the isotope 136. A time projection chamber is used to detect both scintillation light from the interaction and ionization energy deposited by the electrons in the xenon, which is used in the liquid phase. EXO-200 reported the first observation of the two-neutrino double-beta decay [135] in ^{136}Xe (later improved [136]) as well as a limit on the neutrinoless double beta decay [137] in ^{136}Xe. The EXO collaboration is planning a 5-ton detector called nEXO that builds on the success of the EXO-200 detector. The expected nEXO sensitivity to the $0\nu\beta\beta$ half-life is 2.5×10^{27} years after 10 years of operation. The EXO collaboration's novel idea for an upgrade is the use of barium tagging: the principle is to reduce backgrounds by identifying the resulting nucleus by laser spectroscopy [138].

Another ambitious idea for a double-beta decay experiment is SNO+ [36, 120]. SNO+ is an experiment at SNOLAB in Canada which plans to refill the acrylic vessel of SNO with liquid scintillator. This experiment would in addition provide a rich physics program of solar, supernova, and geo-neutrino physics (see Sec. 1.10). SNO+ plans to load the scintillator with 0.3% Te, which after one year of data should give them a 90% C.L. sensitivity of approximately 4×10^{25} years (neutrino mass sensitivity of $\sim$140 meV).

KamLAND-Zen [139] (the Kamioka Liquid Anti-Neutrino Detector, ZEro Neutrino double-beta decay experiment) is an extension of the KamLAND [140] liquid scintillator experiment. In 2011, the collaboration added an additional low-background miniballoon into the inner sphere that contains 13 tons of liquid scintillator loaded with 330 kg of dissolved Xe gas enriched to 91% in ^{136}Xe. The initial results include an improved limit on neutrinoless double-beta decay for ^{136}Xe and a measurement of two-neutrino double-beta decay that agrees with the recent EXO-200 result [141]. The collaboration has an additional 400 kg of enriched Xe in hand and is considering options to upgrade the detector with a larger-size internal balloon.

NEXT [142, 143, 122] (Neutrino Experiment with Xenon TPC) intends to use >100 kg of Xe enriched to $\sim$90% in ^{136}Xe. The detector will be a moderate-density gas TPC that will detect primary and secondary scintillation light. By operating at low pressures ($\sim$15 bar), the design should not only provide good energy resolution, but also permit tracking that allows fairly detailed track reconstruction to confirm that candidate events involve two electrons moving in opposite directions. Construction started in 2012 with commissioning scheduled to start in 2014. It will operate at the Laboratorio Subterráneo de Canfranc in Spain.

The LUX-ZEPLIN (LZ) experiment is a proposed two-phase (liquid/gas) Xe detector, containing 7 tons of natural Xe instrumented as a time projection chamber, with readout of direct scintillation and readout of charge via proportional scintillation. While LZ is primarily designed to perform a world-leading direct dark matter search, it is also sensitive to the neutrinoless double beta decay of ^{136}Xe. LZ will replace the currently operating LUX experiment [144] at SURF, and is planned to be commissioned in 2017. After three years of LZ operation, the $0\nu\beta\beta$ half-life sensitivity is projected to be 2.2×10^{26} years.

The SuperNEMO [145, 121] proposal builds on the great success of the NEMO-3 (Neutrino Ettore Majorana Observatory) experiment, which measured two-neutrino double-beta decay rates and set some of the most stringent constraints for zero-neutrino double beta transitions for seven isotopes [146]. The design uses calorimetry to measure energies and timing, and tracking to provide topological and kinematical information about the individual electrons. SuperNEMO will improve on NEMO-3 by using a larger mass of isotope, lowering backgrounds, and improving the energy resolution. The complete experiment will be ready by the end of the decade in a recently-approved extension of the Modane laboratory in the Fréjus Tunnel in France. Its design sensitivity for the $0\nu\beta\beta$ half-life of ^{82}Se is 10^{26} yr, in a 500 kg·yr exposure.

The current and next-generation experiments are of 10-100 kg masses; these have sensitivities down to about 100 meV. Further ton-scale experiments are planned for the generation beyond that: these should have sensitivities reaching the 10 meV or smaller scale. Reaching this regime will be very interesting in its complementarity with oscillation experiments: if the mass hierarchy is independently determined to be inverted, and there is no $0\nu\beta\beta$ decay signal at the 10 meV scale, then neutrinos must be Dirac (assuming Nature has not been so diabolical as to contrive a fine-tuned suppression from e.g., nuclear matrix elements). If a signal is observed at the few meV scale, then not only will we know that neutrinos are Majorana, but we will also know that the hierarchy must be normal, even in the absence of an independent determination.

Experiment	Isotope	Mass	Technique	Status	Location
AMoRE[147, 148]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Devel.	Yangyang
CANDLES[149]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL[150]	^{48}Ca	1 ton	CaF_2 scint. crystals	Devel.	Solotvina
COBRA[151]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[134]	^{130}Te	11 kg	TeO_2 bolometers	Constr. (2013)	Gran Sasso
CUORE[134]	^{130}Te	206 kg	TeO_2 bolometers	Constr. (2014)	Gran Sasso
DCBA[152]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Devel.	Kamioka
EXO-200[135, 137, 136]	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Op. (2011)	WIPP
nEXO[138]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SNOLAB
GERDA[153][133]	^{76}Ge	$\sim$35 kg	^{enr}Ge semicond. det.	Op. (2011)	Gran Sasso
GSO[154]	^{160}Gd	2 t	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Devel.	
KamLAND-Zen[139, 141]	^{136}Xe	400 kg	^{enr}Xe dissolved in liq. scint.	Op. (2011)	Kamioka
LUCIFER[155, 156]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Devel.	Gran Sasso
MAJORANA [130, 131, 132]	^{76}Ge	30 kg	^{enr}Ge semicond. det.	Constr. (2013)	SURF
MOON [157]	^{100}Mo	1 t	^{enr}Mo foils/scint.	Devel.	
SuperNEMO-Dem[145]	^{82}Se	7 kg	^{enr}Se foils/tracking	Constr. (2014)	Fréjus
SuperNEMO[145]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal (2019)	Fréjus
NEXT [142, 143]	^{136}Xe	100 kg	gas TPC	Devel. (2014)	Canfranc
LZ [144]	^{136}Xe	600 kg	Two-phase ^{nat}Xe TPC/scint	Proposal	SURF
SNO+[158, 159, 36]	^{130}Te	800 kg	Te-loaded liq. scint.	Constr. (2013)	SNOLAB

Table 1-5. *A summary list of neutrinoless double-beta decay proposals and experiments.*

A key point is that several experiments using different isotopes are in order, at each step of sensitivity. First, different isotopes involve different matrix elements with their uncertainties. In addition, unknown small-probability γ transitions may occur at or near the endpoint of a particular isotope, but it is very unlikely that they occur for *every* double-beta-decay emitter. Finally, and maybe most importantly, different isotopes generally correspond to radically different techniques, and since $0\nu\beta\beta$ searches require exceedingly low backgrounds, it is virtually impossible to decide *a priori* which technique will truly produce a background-free measurement. The long-term future for $0\nu\beta\beta$ experiments will depend on what is observed: if no experiments, or only some experiments, see a signal at the 100-kg scale, then ton-scale experiments are in order. If a signal is confirmed, the next generation of detectors will need to better investigate the $0\nu\beta\beta$ mechanism by separately measuring the energies of each electron as well as their angular correlations.

1.7 Absolute Neutrino Mass

1.7.1 Kinematic Neutrino Mass Measurements

The neutrino's absolute mass cannot be determined by oscillation experiments, which give information only on mass differences. The neutrino's rest mass has a small but potentially measurable effect on its kinematics, in particular on the phase space available in low-energy nuclear beta decay. The effect is indifferent to the distinction between Majorana and Dirac masses, and independent of nuclear matrix element calculations.

Two nuclides are of major importance to current experiments: tritium (^{3}H or T) and ^{187}Re. The particle physics is the same in both cases, but the experiments differ greatly. Consider the superallowed decay $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$. The electron energy spectrum has the form:

$$dN/dE \propto F(Z,E) p_e (E + m_e)(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2} \tag{1.14}$$

where E, p_e are the electron energy and momentum, E_0 is the Q-value, and $F(Z,E)$ is the Fermi function. If the neutrino is massless, the spectrum near the endpoint is approximately parabolic around E_0. A finite neutrino mass makes the parabola "steeper", then cuts it off m_ν before the zero-mass endpoint. The value of m_ν can be extracted from the shape without knowing E_0 precisely, and without resolving the cutoff.

The flavor state ν_e is an admixture of three mass states ν_1, ν_2, and ν_3. Beta decay yields a superposition of three spectra, with three different endpoint shapes and cutoffs, whose relative weights depend on the magnitude of elements of the mixing matrix. Unless the three endpoint steps are fully resolved, the spectrum is well approximated by the single-neutrino spectrum with an effective mass $m_\beta^2 = \Sigma_i U_{ei}^2 m_i^2$. Past tritium experiments have determined $m_\beta < 2.0$ eV [160, 161, 162].

To measure this spectrum distortion, any experiment must have the following properties. First, it must have high energy resolution–in particular, a resolution function lacking high-energy tails–to isolate the near-endpoint electrons from the more numerous low-energy electrons. Second, it must have extremely well-known spectrometer resolution. The observed neutrino mass parameter depends very strongly on the detector resolution. Finally, it must have the ability to observe a very large number of decays, with high-acceptance spectrometers and/or ultra-intense sources, in order to collect adequate statistics in the extreme tail of a rapidly-falling spectrum.

1.7.2 Upcoming Experiments

KATRIN: The KATRIN experiment [163, 164, 165], now under construction, will attempt to extract the neutrino mass from decays of gaseous T_2. KATRIN achieves high energy resolution using a MAC-E (Magnetic Adiabatic Collimation-Electrostatic) filter. In this technique, the T_2 source is held at high magnetic field. Beta-decay electrons within a broad acceptance cone are magnetically guided towards a low-field region; the guiding is adiabatic and forces the electrons' momenta nearly parallel to B field lines. In the parallel region, an electrostatic field serves as a sharp energy filter. Only the highest-energy electrons can pass the filter and reach the detector, so MAC-E filters can tolerate huge low-energy decay rates without encountering detector rate problems. In order to achieve high statistics, KATRIN needs a very strong source, supplying 10^{11} e$^-/s$ to the spectrometer acceptance. This cannot be done by increasing the source thickness, which is limited by self-scattering, so the cross-sectional area of the source and spectrometer must be very large– 53 cm^2 and

65 m^2 respectively. KATRIN anticipates achieving a neutrino mass exclusion limit down to 0.2 eV at 90% confidence, or 0.35 eV for a 5-sigma discovery. Data-taking for KATRIN is expected to begin in late 2015.

Project 8: Project 8 is a new technology for pursuing the tritium endpoint [166]; it anticipates providing a roadmap towards a large tritium experiment with new neutrino mass sensitivity, via a method with systematic errors largely independent of the MAC-E filter method. In Project 8, a low-pressure gaseous tritium source is stored in a magnetic bottle. Magnetically-trapped decay electrons undergo cyclotron motion for $\sim 10^6$ orbits. This motion emits microwave radiation at frequency $\omega = qB/\gamma m$, where γ is the Lorentz factor. A measurement of the frequency can be translated into an electron energy. A prototype, now operating at the University of Washington, is attempting to detect and characterize single conversion electrons from a ^{83m}Kr conversion electron calibration source. The prototype is intended to help answer a number of technical questions, including the merits of various magnetic-trap configurations for the electrons, waveguide vs. cavity configurations for the microwaves, and questions about data analysis techniques. A first experiment would aim for few-eV neutrino mass sensitivity while precisely measuring other parameters of the decay spectrum. A larger followup experiment would extend the sensitivity down to the limits of the technique.

Microcalorimeter methods: While most of the neutrino-mass community is focused on tritium, there are several other nuclides of potential experimental interest. Tritium is the only low-energy beta decay nuclide whose decay rate (and low atomic number) permits the creation of thin, high-rate sources. If one can detect decays in a cryogenic microcalorimeter, the requirement of a thin source is removed, and one can explore lower-energy decays. For a neutrino mass m_ν and a beta-decay energy E_0, the fraction of decays in the signal region scales as $(m_\nu/E_0)^3$. The best-known candidate is ^{187}Re, whose beta-decay endpoint is unusually low at 2.469 keV. However, the long lifetime of ^{187}Re forces any such experiment to instrument a very large total target mass, and the low-temperature properties of Re are unfavorable. Another candidate, ^{163}Ho, is somewhat more promising. In the electron-capture decay $^{163}\text{Ho} \rightarrow {}^{163}\text{Dy}$, the inner bremsstrahlung spectrum is sensitive to the neutrino mass. Speculation [167] that atomic effects might enhance the endpoint phase space has been largely resolved. At the moment, however, microcalorimeter proposals require long data-taking periods to accumulate statistics with sub-eV sensitivity, and the systematic errors are underexplored.

PTOLEMY: The PTOLEMY experiment [168] at Princeton is attempting to combine many different technologies in a single tritium-endpoint spectrometer. While its primary goal is the detection of relic neutrinos, as discussed in Sec. 1.10.1, its measurements would certainly be relevant to a direct search for neutrino masses. PTOLEMY installed a small technology-validation prototype at the Princeton Plasma Physics Laboratory in February 2013. Several of PTOLEMY's methods are untested and may present serious practical challenges. The use of their solid-state source will require a careful roadmap towards answering systematic-error questions.

Cosmological probes: Another way of addressing the question of absolute neutrino masses connects to the Cosmic Frontier. The field of observational cosmology now has a wealth of data. Global fits to the data – large-scale structure, high-redshift supernovae, cosmic microwave background, and Lyman α forest measurements – yield limits on the sum of the three neutrino masses of less than about 0.3-0.6 eV, although specific results depend on assumptions. Future cosmological measurements will further constrain the absolute mass scale. References [169, 170, 171] are recent reviews. The Planck experiment has very recently published new global cosmology fits, including strong neutrino mass constraints [172].

1.7.3 The Future of Absolute Mass Measurements, and Implications

There is substantial complementarity between kinematic measurements, $0\nu\beta\beta$ measurements, and cosmological constraints. Kinematic measurements are sensitive to m_β, a simple mixing-weighted sum with a nonzero lower bound. $0\nu\beta\beta$ is either (a) insensitive to $m_{\beta\beta}$, if neutrinos are Dirac particles, or (b) if neutrinos are Majorana, sensitive to $m_{\beta\beta}$, a quantity which incorporates masses, mixing angles, and complex phases, and may in certain cases be zero. Cosmological probes are sensitive to the simple sum of masses, independent of mixing angles and symmetries, but this sensitivity correlates with changes to the cosmological assumptions, including (but not limited to) new fundamental physics.

One worthwhile question is, under what circumstances do direct measurements resolve the neutrino mass hierarchy? See Fig. 1-14. Direct measurements based on β-decay are capable of unambiguous determination of the hierarchy because they can identify the three masses weighted by their electron-flavor content. However, such a measurement is well beyond present capabilities for any choice of mass or hierarchy. A measurement at the achievable sensitivity represented by KATRIN, 200 meV, would show that neutrinos have a nearly-degenerate hierarchy, perhaps even more interesting from the theoretical standpoint than the level ordering. In the foreseeable future, new ideas such as Project 8 may be able to reach the 50 meV level. Non-observation of the mass at this level would show that the hierarchy is normal.

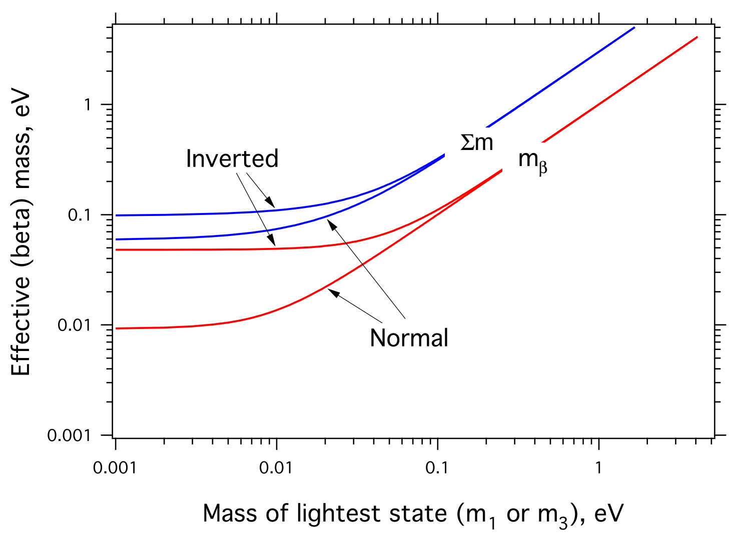

Figure 1-14. *Dependence of the effective mass m_β on the mass of the lightest eigenstate m_1 or m_3 for the normal and inverted hierarchies. Also shown are the sums of the eigenmasses. The oscillation parameters are $\Delta m^2_{21} = 7.54 \times 10^{-5}$ eV^2, $|\Delta m^2_{32}| = 2.42 \times 10^{-3}$ eV^2, $\theta_{12} = 34.1$ degrees, and $\theta_{13} = 9.1$ degrees [64].*

The field of direct neutrino mass determination, with KATRIN leading the push to $\sim$0.2 eV sensitivity, is balancing both statistical and systematic errors. Experiments aiming for lower masses, including Project 8 and PTOLEMY, take it for granted that large statistical power is needed. However, attention must be paid to systematics. One systematic error in particular, the molecular excited-state distribution of the daughter ion (in $T_2 \rightarrow (T\ ^3He)^{+*} + e^- + \bar{\nu}_e$) produces an irreducible smearing of all T_2 decay spectra; this smearing is presently unmeasured, and known (with an uncertainty difficulty to quantify) from quantum theory. The effect is present in common in KATRIN, Project 8, and any future T_2-based experiment. The field would benefit from an experimental verification or a theory cross-check on these excited-state spectra. Technologies allowing high-purity atomic tritium sources would remove this uncertainty. Most other systematic errors in T_2 experiments are technology-specific, which is important for robust comparisons between experiments.

1.8 Neutrino Scattering

Predictions for the rates and topologies of neutrino interactions with matter are a crucial component in many current investigations within nuclear and astroparticle physics. Ultimately, we need to measure neutrino-matter interactions precisely to enable adequate understanding of high-priority physics including neutrino oscillations, supernova dynamics, and dark matter searches. Precise knowledge of such neutrino interactions is an absolute necessity for future measurements of the masses and mixings mediating neutrino oscillations. To enable further progress in neutrino physics, we eventually need to understand, fairly completely, the underlying physics of the neutrino weak interaction within a nuclear environment. This completeness is required so that we can reliably apply the relevant model calculations across the wide energy ranges and varying nuclei necessary for our neutrino investigations.

Neutrino cross-section uncertainties are already becoming a limiting factor in the determination of neutrino oscillation parameters in many experiments. Furthermore, experiments using heavier nuclear targets to increase their signal yields have to contend with the presence of significant nuclear effects impacting both the interaction cross sections and observed final states. Such nuclear effects also impact the reconstruction of the incoming neutrino energy, a key quantity in the determination of neutrino oscillation parameters. Understanding these neutrino-nucleus scattering processes directly affects how well one can separate signal from background. Uncertainties in both the neutrino interaction cross sections and associated nuclear effects must be understood to maximize the sensitivity of an experiment to neutrino oscillations. Of course, depending on the detector, the scientific question being asked, and the oscillation parameters, different cross-section uncertainties can take on different levels of importance. For example, careful control of neutrino/antineutrino cross section differences will be particularly important in establishing CP violation in the neutrino sector [173]. In fact, since $|U_{e3}|$ is larger than minimal assumptions, such systematic uncertainties become even more important because the expected neutrino/antineutrino asymmetry becomes increasingly smaller for larger $|U_{e3}|$.

In addition, we need better understanding of neutrino-nucleus interactions for understanding the dynamics of supernovae. The physics of core-collapse supernova is not yet well-understood, and neutrinos are valuable probes into their inner workings. Furthermore, we will need understand neutrino-nucleus interactions in the few-tens-of-MeV regime in order to interpret a supernova neutrino burst observation.

These and related physics topics are most easily categorized according to the energy of the incident neutrino. The 0.2-10 GeV energy range (called "intermediate-energy" here) is of most relevance to current and planned meson decay-in-flight (DIF) neutrino beams such as those being used currently for long-baseline experiments. In addition, a beam from stored muons (e.g., the proposed nuSTORM facility [174]) would also elucidate this regime. The 10-100 MeV range ("low-energy") is relevant for supernova neutrino studies. A summary of current and future experiments relevant for these topics are listed in Table 1-6.

1.8.1 Intermediate-Energy Regime

In the 0.2-10 GeV neutrino energy regime, neutrino interactions are a complex combination of quasi-elastic (QE) scattering, resonance production, and deep inelastic scattering processes, each of which has its own model and associated uncertainties. Solar and reactor oscillation experiments operating at very low neutrino energies and scattering experiments at very high energies have enjoyed very precise knowledge of their respective neutrino interaction cross sections (at the few-percent level) for the detection channels of interest. However, the same is not true for the relevant intermediate energy regime. In this region, the cross sections even off free nucleons are not very well measured (at the $10-40\%$ level) and the data are in frequent conflict

Table 1-6. *Current and proposed experiments with significant ν cross section measurements. The upper (lower) part of table summarizes the intermediate- (low-) energy regime.*

Experiment	Physics topics[1]	ν Source	Energy (GeV)	Target nuclei	Detector type[2]	Host	Status
MiniBooNE	medE	π DIF	0.4-2	CH_2	Ch/calo	Fermilab	current
T2K	medE	π DIF	0.3-2	CH	scitrk/ TPC/calo	JPARC	current
MINERvA	medE	π DIF	1-20	many[3]	scitrk/calo	Fermilab	current
NOvA NDOS	medE	π DIF	1	CH	scitrk	Fermilab	current
NOvA near	medE	π DIF	1.5-2.5	CH	scitrk	Fermilab	in constr.
MicroBooNE	medE	π DIF	0.2-2	Ar	TPC	Fermilab	in constr.
MINERvA	medE, PDFs	π DIF	1-10	H,D	scitrk/calo	Fermilab	proposed
nuSTORM	medE, ν_e xs	π DIF	0.5-3.5	TBD	TBD	Fermilab	proposed
SciNOvA	medE	π DIF	1.5-2.5	CH	scitrk	Fermilab	proposed
MiniBooNE+	medE	π DIF	0.3-0.5	CH_2	Ch/calo	Fermilab	proposed
CAPTAIN	medE	π DIF	1-10	Ar	TPC	Fermilab	proposed
LBNE near	medE	π DIF	0.5-5	TBD	TBD	Fermilab	proposed
CAPTAIN	lowE	π DAR	0.01-0.05	Ar	TPC	ORNL	proposed
OscSNS	lowE	π DAR	0.01-0.05	CH_2	Ch/calo	ORNL	proposed
IsoDAR	lowE	π,^{8}Li DAR	0.002-0.05	TBD	TBD	TBD	proposed
CENNS	νN coh.	π DAR	0.01-0.05	Ar	calo	Fermilab	proposed
CSI	νN coh.	π DAR	0.01-0.05	TBD	TBD	ORNL	proposed

[1] Physics topics: "medE" = quasi-elastic scattering, π production, etc; "lowE" = ν-nucleus inelastic scattering and processes relevant for supernovae; "νN coh." = νN coherent scattering
[2] Detector types: "Ch" = Cherenkov, "scitrk" = scintillation tracker; "calo" = calorimeter; "TPC" = time projection chamber
[3] many = He, CH, H_2O, Pb, Fe

with theoretical predictions. Furthermore, the nuclear effects ranging from multi-nucleon-target initial states to complex final-state interactions are still quite poorly known. Figure 1-15 shows existing measurements of CC neutrino cross sections in the relevant energy range. Such measurements form the foundation of our knowledge of neutrino interactions and provide the basis for simulations in present use.

There has been renewed interest and progress in neutrino interaction physics in the last ten years because of recent efforts to understand and predict signal and background rates in neutrino oscillation searches in few-GeV beams. One of several intriguing results from these new data comes from recent measurements of QE scattering. QE scattering is a simple reaction historically thought to have a well-known cross section; this is one reason why it is chosen as the signal channel in many neutrino oscillation experiments. Interestingly, the neutrino QE cross section recently measured on carbon at low energy by the MiniBooNE experiment is about 40% higher than the most widely used predictions [176] and is even larger than the free nucleon scattering cross section in some energy regions [177]. Similar effects are seen for antineutrinos [178]. These results are surprising because nuclear effects have always been expected to reduce the cross section, not enhance it. A recent QE cross section measurement from NOMAD at higher energies does not exhibit such an enhancement [179]. A possible reconciliation between the two classes of measurements has suggested that previously-neglected nuclear effects could in fact significantly increase the QE cross section on nuclei at low

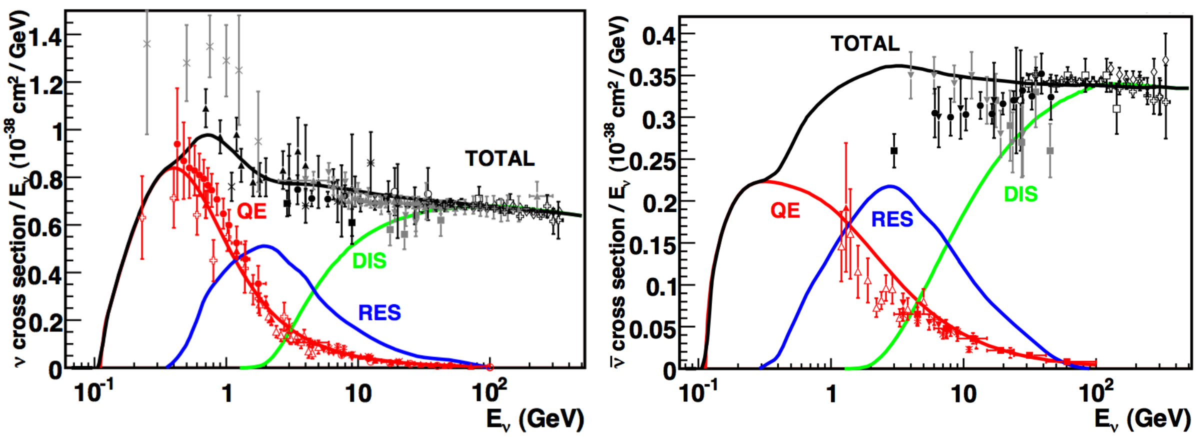

Figure 1-15. *Existing muon neutrino (left) and antineutrino (right) CC cross section measurements [1] and predictions [175] as a function of neutrino energy. The contributing processes in this energy region include quasi-elastic (QE) scattering, resonance production (RES), and deep inelastic scattering (DIS). The error bars in the intermediate energy range reflect the uncertainties in these cross sections (typically* $10-40\%$*, depending on the channel).*

energy [180]. A similar enhancement has been observed in electron-nucleus scattering [181]. If true, this radically changes our thinking on nuclear effects and their impact on low-energy neutrino interactions. This revelation has been the subject of intense theoretical scrutiny and experimental investigation over the past year or more (see for example, [182, 183, 184, 185]).

In the so-called resonance/transition region, the channels of interest are mainly hadronic resonances with the most important being the $\Delta(1232)$. Typical final states are those with a single pion. During the last five years, several new pion production measurements have been performed. In all of them, the targets were nuclei (most often carbon). As one example, the MiniBooNE experiment recently measured a comprehensive suite of CC $1\pi^+$, CC $1\pi^0$, and NC $1\pi^0$ production cross sections [186]. A variety of flux-integrated differential cross sections, often double differential, were reported for various final state particle kinematics. The cross-section results differ from widely-used predictions at the 20% level or more.

There are several efforts currently producing results that will add significantly to the available data and to the underlying physics understanding. The MINERvA experiment in the 1-10 GeV NuMI beam at Fermilab has very recently published results on QE scattering measured with a precise tracking detector from both neutrino and antineutrinos on carbon [184, 185]. The near detectors of the T2K [187] experiment are also measuring neutrino-nucleus interactions as part of their oscillation measurement program. T2K has recently reported total cross sections for neutrino CC inclusive scattering [187]. Additional results on exclusive channels from MINERvA and the T2K and NOvA near detectors will be forthcoming in the near future. The MINERvA experiment will also perform the first studies of nuclear effects in neutrino interactions using a suite of nuclear targets including He, C, O (water), Fe, and Pb in addition to a large quantity of scintillator CH. Analysis of neutrino scattering processes from these varying nuclei are already underway. Another possible step in the MINERvA program is the addition of a deuterium target [188] which is currently under review. This is an intriguing, albeit challenging, possibility as it will allow nuclear effects in these processes to be separated from the bare-nucleon behavior.

All current accelerator-based neutrino experiments use a meson-decay beam either on-axis or off-axis to narrow the energy spread of the beam. The uncertainty in the neutrino flux normalization and spectral shape will ultimately limit our understanding of the underlying physics of neutrino interactions and the ability to conduct precision neutrino oscillation measurements. Because of these uncertainties, an improved understanding of our neutrino beams is paramount. For these beams, some improvement in the knowledge of the neutrino flux is possible through meson-production experiments that determine the underlying meson momentum and angular distributions. These can then be combined with detailed simulations of the neutrino beamline optics. This procedure has been performed for the MiniBooNE [189], K2K [190], and T2K [191] experiments yielding predicted fluxes with $\sim 10\%$ errors. New experiments will require similar efforts with associated hadroproduction experiments [192] to push to a goal of 5% errors.

Additional experiments in beams of different energies provide a valuable cross-check on the underlying energy dependence of physics models as well as the background calculations of the experiments. For example, the NOvA experiment, which will soon run in the NuMI off-axis neutrino beam, offers a unique opportunity to add to the world's neutrino interaction data by measuring cross sections with its near detector as well as with a possible upgrade to a relatively-inexpensive fine-grained detector such as the proposed SciNOvA experiment [193, 194].

A potentially transformative next step would be the use of circulating muon beams. The muons may be either uncooled and unaccelerated as in the case of nuSTORM [174] or both cooled and accelerated as in the case of a Neutrino Factory. These facilities will yield a flux of neutrinos known to better than 1%. Another significant advantage of these muon-decay-based neutrino sources would be the availability, for the first time, of an intense and well-known source of electron-(anti)neutrinos. Such beams would allow the measurement of ν_e-nucleus cross sections, which are not measured and are of great importance to future $\nu_\mu \to \nu_e$ oscillation experiments since lepton universality may be broken due to nuclear effects in nuclei.

In addition to beam improvements, up-and-coming detector technologies such as LAr TPCs will both provide increased tracking precision for better final-state exclusivity as well as measurements specifically on argon. Understanding interactions on argon is obviously crucial for oscillation measurements in LBNE given that the far detector of choice is a LAr TPC. New neutrino scattering measurements on argon are already being reported by ArgoNeuT which ran in the NuMI beam in 2009–2010 [195]. The near-future MicroBooNE experiment, which will begin taking data starting in 2014, will further boost this effort in the next few years. In addition, other efforts with imminent, ~ 10 ton LAr TPCs [196] in an existing beam such as NuMI, can also provide more information on reconstruction and final-state topology to further this effort.

However, in order to adequately map out the complete nuclear dependence of the physics, there is need to have multiple nuclear targets to measure the nuclear effects combined with a precision tracker. For this an attractive follow-on to MINERvA would be a straw-tube/transition-radiation detector that employs multiple nuclear targets (including argon) simultaneously in the same beam such as that proposed for one of the LBNE near-detector options [80].

1.8.2 Low-Energy Regime

The 10-100 MeV neutrino energy range addresses a varied set of topics at the forefront of particle physics such as supernovae, dark matter, and nuclear structure. Low-energy neutrino scattering experiments are possibilities at currently-existing high-intensity proton sources such as the ORNL SNS or the Fermilab Booster neutrino beam line. They should also be considered at future facilities such as Project-X at Fermilab.

Supernova neutrino physics: The multiple physics signatures and expected neutrino fluxes from a core-collapse signature are described in Secs. 1.5.1.1, 1.10.2.1. To get the most from the next supernova neutrino observation, it will be critical to understand the interactions of neutrinos with matter in the tens-of-MeV energy range [197, 196].

A stopped-pion source provides a monochromatic source of 30 MeV ν_μ's from pion decay at rest, followed on a 2.2 μs timescale by $\bar{\nu}_\mu$ and ν_e with a few tens of MeV from μ decay. The ν spectrum matches the expected supernova spectrum reasonably well. A ~ 1 GeV, high-intensity, short-pulse-width, proton beam is desirable for creating such a ν source. Prior examples used for neutrino physics include LANSCE and ISIS. A rich program of physics is possible with such a stopped-pion ν source, including measurement of neutrino-nucleus cross sections in the few tens of MeV range in a variety of targets relevant for supernova neutrino physics. This territory is almost completely unexplored: so far only ^{12}C has been measured at the 10% level. A pion DAR neutrino source such as that currently available at the ORNL SNS neutron spallation target would be an excellent source of neutrinos for this physics on a variety of nuclei relevant for supernova [198, 199]. In addition, this source would allow specific studies to better understand the potential of a large LAr detector such as that proposed for LBNE. In particular, low-energy neutrino-argon cross sections, required for supernova detection in a large LAr detector could be measured with a near-future prototype LAr detector (CAPTAIN) [196]. In the farther future, the high-intensity FNAL Project-X 1-3 GeV Linac would also provide a potential site for these experiments.

Coherent elastic neutrino-nucleus scattering (CENNS): CENNS is a process in which the target nucleus recoils coherently via a collective neutral current exchange amplitude with a neutrino or antineutrino, is a long-sought prediction of the standard model. Although the process is well predicted by the standard model and has a comparatively large cross section (10^{-39} cm^2) in the relevant energy region ($0-50$ MeV), CENNS has never been observed before as the low-energy nuclear recoil signature is difficult to observe. Numerous groups world-wide are now working to detect this elusive process [200]. Only a few sources, in particular nuclear reactors spallation neutrino sources [199, 201] (as well as potential existing sources, such as the FNAL 8 GeV proton source at a far off-axis location [202]) produce the required 1-50 MeV energies of the neutrinos in sufficient quantities for a definitive first measurement. A modest sample of a few hundred events collected with a keV-scale-sensitive dark-matter-style detector could improve upon existing non standard neutrino interaction parameter sensitivities by an order of magnitude or more. A deviation from the $\sim$5% predicted cross section could be an indication of new physics [203, 204]. The cross section is relevant for understanding the evolution of core-collapse supernovae, characterizing future burst supernova neutrino events collected with terrestrial detectors, and a measurement of the process will ultimately set the background limit to direct WIMP searches with detectors at approximately the ten-ton scale [205, 206]. Proposals have arisen to probe nuclear structure [207] owing to the sensitivity of the coherent scatter process to the number of neutrons in the nucleus, and to search for sterile neutrinos [208, 209] by exploiting the flavor-blind nature of the process. There are also potentially practical applications, as described in Sec. 1.11.1.2.

1.8.3 Required Theoretical/Phenomenological Work

A strong effort in theory/phenomenology/modeling is requisite to profit from improved measurements in neutrino experiments. While there is a healthy community working on the subject of neutrino-nucleus interactions in Europe, there is a dearth of phenomenologists in the U.S. able to address the pressing theoretical questions needed to fully understand this subject and apply it to the interpretation of experimental data. There is a critical need within the U.S. physics community to devote time and resources to a theoretical/phenomenological understanding of neutrino-nucleus scattering. This naturally directly calls for a united effort of both the particle and nuclear physics communities to better support these efforts [210]. There are numerous ideas that have been put forth by both experimentalists and theorists for how best to proceed [211, 212]. They include suggestions for improvements to neutrino event generators with more sophisticated underlying calculations for neutrino interactions on nucleons within nuclei, as well as considerations of the formation length of pions and nucleons and final-state interactions of the hadronic shower.

1.9 Beyond the Standard Paradigm – Anomalies and New Physics

Neutrinos moved beyond the standard model years ago with the discovery of neutrino oscillations, which implied the existence of neutrino mass. Much of the oscillation data can be described by a three-neutrino paradigm. However, there are intriguing anomalies that cannot be accommodated within this paradigm, and suggest new physics beyond it. In particular, the marginal yet persistent evidence of oscillation phenomena around $\Delta m^2 \sim 1$ eV^2, which is not consistent with the well-established solar and atmospheric Δm^2 scales, is often interpreted as evidence for one or more additional neutrino states, known as sterile neutrinos. Beyond the sterile neutrino, new physics may appear through a broad array of mechanisms collectively known as non-standard interactions (NSI). Typically, searches for these effects occur in experiments designed to study standard phenomena. One type of NSI that has been the subject of dedicated searches in the past and may play a role in the future program is the neutrino magnetic moment. There are other ways that neutrino experiments can probe exotic physics. For example, the possibility that neutrino oscillations may violate, to some degree, the very fundamental principles of Lorentz and CPT invariance has been considered; see e.g., [213]. In the following subsections we will discuss the prospects for neutrino experiments sensitive to anomalies and new physics over the next several years.

1.9.1 Sterile Neutrinos

Data from a variety of short-baseline experiments, as well as astrophysical observations and cosmology, hint at the existence of additional neutrino mass states beyond the three active species in the standard model (see for example [65]). The implications of these putative sterile neutrino states would be profound, and would change the paradigm of the standard model of particle physics. As a result, great interest has developed in testing the hypothesis of sterile neutrinos and providing a definitive resolution to the question: do light sterile neutrinos exist?

Recently, a number of tantalizing results (anomalies) have emerged from short-baseline neutrino oscillation experiments that cannot be explained by the current three-neutrino paradigm. These anomalies, which are not directly ruled out by other experiments, include the excess of $\bar{\nu}_e$ events (3.8σ) observed by the LSND experiment [214], the ν_e ($3.4\ \sigma$) and $\bar{\nu}_e$ (2.8σ) excesses observed by MiniBooNE [215] particularly at low-energy in ν_e mode [216], the deficit of $\bar{\nu}_e$ events (0.937 ± 0.027) observed by reactor neutrino experiments [217], and the deficit of ν_e events (0.86 ± 0.05) observed in the SAGE and GALLEX radioactive source experiments [218].

Although there may be several possible ways to explain these anomalies, a simple explanation is the $3 + N$ sterile neutrino model, in which there are three light, mostly active neutrinos and N, mostly sterile neutrinos which mix with the active flavors. For $N > 1$, these models allow for CP-violating effects in short-baseline appearance experiments. The world's oscillation data can be fit to these 3+N models resulting in allowed regions that close at 95% CL or better, as shown in Fig. 1-16 and 1-17 for the 3+1 model. Still, significant tension exists between the appearance and disappearance data [219], particularly due to the absence of ν_μ disappearance in the $\Delta m^2 \sim 1$ eV^2 region [220, 221], a key prediction of the 3+N models.

Beyond particle physics, there are hints of additional neutrinos coming from cosmology. Fits to astrophysical data sets (including the cosmic microwave background (CMB), large scale structure, baryon acoustic oscillations and Big Bang nucleosynthesis) are sensitive to the effective number of light degrees of freedom ($N_{\rm eff}$) (which in the standard model is equivalent to saying the effective number of neutrino families, although in principle this could include other types of light, weakly-coupled states). Prior to the release of the Planck data in 2013, there was an astonishing trend that such fits, conducted by different groups and involving differing mixes of data sets and assumptions, tended to favor N_{eff} closer to 4 than 3 [65]. With the release of Planck data [172] new more precise fits to N_{eff} are now more consistent with 3. The Planck collaboration fit values range from 3.30 ± 0.52 (95% CL) to 3.62 ± 0.49 (95% CL) depending on which other data sets are included in the fit. The pre-Planck fits used the full-sky WMAP [222] data set for the first three peaks of the the CMB angular power spectrum, but typically relied on narrow-sky, high angular resolution observations by the South Pole Telescope [223], or the Atacama Cosmology Telescope [224] for the next four peaks. The Planck mission combined a full-sky survey with high angular resolution, and was, for the first time, able to measure the first seven peaks in the spectrum with one apparatus. The Planck Collaboration believes that a miscalibration in the stitched together spectra was responsible for the anomalously high value of N_{eff} found in the earlier fits [172], but the issue is not yet resolved. There is tension between the value of the Hubble constant extracted from Planck data, and that measured by the Hubble Space Telescope. The resolution of this issue may impact the extracted value of N_{eff}. Nonetheless, while the new fits to N_{eff} are now more consistent with three light degrees of freedom, they are still high and allow $N_{\text{eff}} = 4$ at less than, at most, the two sigma level. Finally, it is important to keep in mind that cosmological constraints on the existence of light sterile neutrinos depend on the masses of the mostly sterile states, and on whether they are in thermal equilibrium with the rest of the Universe. Even at face value, the Planck data are still consistent with one or more massless sterile neutrino states that were not fully thermalized [172].

For a comprehensive review of light sterile neutrinos including the theory, the cosmological evidence, and the particle physics data see Ref. [65].

In order to determine if these short-baseline anomalies are due to neutrino oscillations in a $3 + N$ sterile neutrino model, future short-baseline experiments are needed. Table 1-7 lists many proposals for such experiments. These experiments should have robust signatures for electron and/or muon neutrino interactions and they should be capable of measuring the L/E dependence of the appearance or disappearance effect. Several ways of measuring L/E dependence have been proposed including: 1) placing a large detector close to a source of low-energy neutrinos from a reactor, cyclotron or intense radioactive source and measuring the L/E dependence of the $\overset{(-)}{\nu}_e$ disappearance with a single detector, 2) positioning detectors at two or more baselines from the neutrino source, and 3) measuring the L/E dependence of high energy atmospheric neutrinos, where strong matter effects are expected, in particular close to the matter resonance expected for the sterile Δm^2 in the Earth's core. In addition, experiments sensitive to neutral current interactions, in which active flavor disappearance would be a direct test of the sterile hypothesis, are needed.

Finally, it is important to note that satisfactorily resolving these short-baseline anomalies, even if unrelated to sterile neutrinos, is very important for carrying out the three-flavor neutrino oscillation program described earlier. The 2 to 3 σ effects reported at the sub-percent to the several-percent level are similar in scale and effect to the CP-violation and mass hierarchy signals being pursued in long-baseline experiments.

Independent from the short-baseline anomalies, new, mostly sterile, neutrino mass eigenstates with different masses can be searched in a variety of different ways, ranging from weak decays of hadrons and nuclei, charged-lepton flavor violating processes, to searches at lepton and hadron colliders. For details, see, for example, [225, 226, 227, 228]. In particular, a next-generation e^-e^+ collider would provide very stringent bounds on sterile neutrinos with masses around tens of GeV and other new neutrino phenomena (see, e.g., [229]).

1.9.1.1 Projects and Proposals with Radioactive Neutrino Sources

Proposals to use radioactive neutrino sources to search for sterile neutrino oscillations actually predate the "gallium anomaly" [241]. Perhaps the most intriguing opportunity with the source experiments is the possibility of precision oscillometry – the imaging, within one detector, the oscillation over multiple

Table 1-7. *Proposed sterile neutrino searches.*

Experiment	ν Source	ν Type	Channel	Host	Cost Category[1]
Ce-LAND [230]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	Kamioka, Japan	small[2]
Daya Bay Source [231]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	China	small
SOX [232]	^{51}Cr	ν_e	disapp.	LNGS, Italy	small[2]
	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.		
US Reactor [233]	Reactor	$\bar{\nu}_e$	disapp.	US[3]	small
Stereo	Reactor	$\bar{\nu}_e$	disapp.	ILL, France	NA[4]
DANSS [234]	Reactor	$\bar{\nu}_e$	disapp.	Russia	NA[4]
OscSNS [235]	π-DAR	$\bar{\nu}_\mu$	$\bar{\nu}_e$ app.	ORNL, U.S.	medium
LAr1 [236]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
MiniBooNE+ [237]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	small
MiniBooNE II [238]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
ICARUS/NESSiE [239]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	CERN	NA[4]
IsoDAR [113]	^{8}Li-DAR	$\bar{\nu}_e$	disapp.	Kamioka, Japan	medium
νSTORM [174]	μ Storage Ring	$\overset{(-)}{\nu}_e$	$\overset{(-)}{\nu}_\mu$ app.	Fermilab/CERN	large

[1] Rough recost categories: small: <\$5M, medium: \$5M-\$50M, large: \$50M-\$300M.
[2] U.S. scope only.
[3] Multiple sites are under consideration [240].
[4] No U.S. participation proposed.

wavelengths in L/E. Therefore this approach would likely be the best way to deconvolve the multiple frequencies expected if there are two or more sterile neutrino states. Typically these proposals are built around existing detectors with well-measured backgrounds, where the new effort involves creating a source and delivering it to the detector. There are two types of sources actively under consideration: 1) ^{51}Cr, an electron capture isotope which produces ν_e of 750 keV, and 2) ^{144}Ce-^{144}Pr, where the long-lived ^{144}Ce ($\tau_{1/2} = 285$ days) β-decays producing a low energy $\bar{\nu}_e$ of no interest, while the daughter isotope, ^{144}Pr, rapidly β-decays producing a $\bar{\nu}_e$ with a 3 MeV endpoint. Since ^{51}Cr neutrinos are monoenergetic, with no need to reconstruct the neutrino energy, they can be detected by CC, NC or elastic scattering interactions. ^{144}Pr neutrinos, on the other hand, are emitted with a β spectrum and must be detected via a charged-current process such as inverse β-decay.

Proposals actively under consideration include SOX [232] based on the Borexino detector, Ce-LAND [230] based on the KamLAND detector, and a Daya Bay Source experiment [231]. SOX is considering both ^{51}Cr and ^{144}Ce-^{144}Pr phases. In the ^{51}Cr phase, a source of up to 10 MCi is placed about 8 m from the center of the detector. This phase takes advantage of Borexino's demonstrated ability to see the $\nu_e - e$ elastic scattering of 861 keV, ^{7}Be solar neutrino [242]. Later phases may involve a ^{144}Ce-^{144}Pr source which could be located either inside or outside the detector, the former requiring major modifications to the Borexino detector. The Ce-LAND and the Daya Bay Source proposals are both based on ^{144}Ce-^{144}Pr. In the Daya Bay Source proposal, a 500 kCi source is placed in between the four 20-ton antineutrino detectors at the Daya Bay far site. With Ce-LAND, a 75 kCi source could be placed either outside the detector, 9.5 m from the center, or inside the detector (only after the KamLAND-Zen $\beta\beta_{0\nu}$ run is complete). The sensitivity for these proposals is shown in Fig. 1-16a.

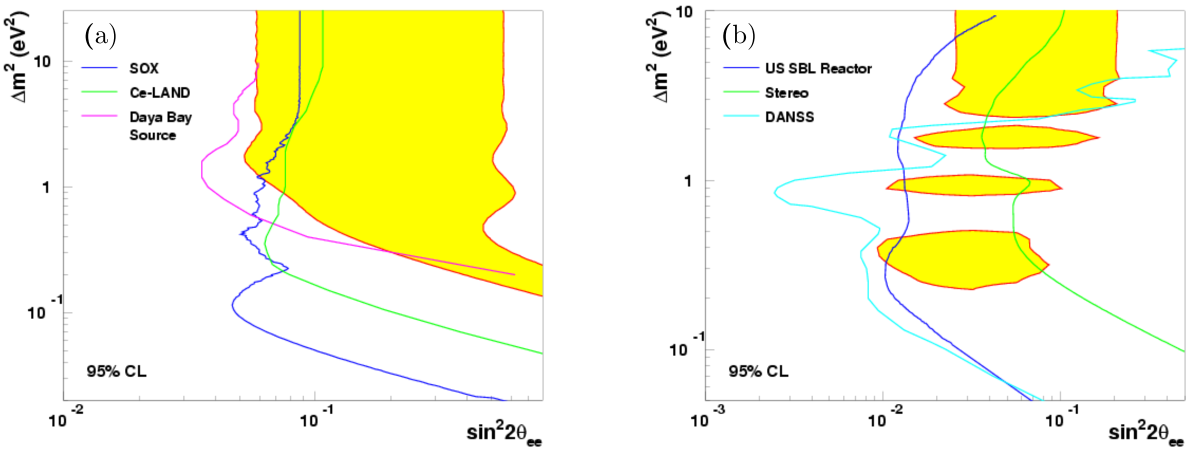

Figure 1-16. *Collaboration-reported sensitivity curves for proposed source (a) and reactor (b) experiments plotted against the global fits [219] for the gallium anomaly and reactor anomaly respectively.*

There is also the possibility of a sterile neutrino measurement based on the combination of a ^{51}Cr source with cryogenic solid state bolometers, to detect all active neutrino flavors through neutral current CENNS [208] (see Sec. 1.8.2). This proposal, known as RICOCHET, would be a direct test of the sterile hypothesis since the neutral current is equally sensitive to all active flavors, but blind to sterile neutrinos.

1.9.1.2 Projects and Proposals that Directly Address the Reactor Anomaly

The apparent deficit of neutrinos in short-baseline reactor neutrino experiments, known as the reactor anomaly, is result of two distinct lines of analysis: the theoretical calculations of the reactor antineutrino flux [243, 244, 245, 246], which are based on measurements of the β-spectra from the relevant fission isotopes [243, 244], and the reactor antineutrino measurements [247, 248, 249, 250, 251, 252, 253, 254, 255]. The anomaly [217] emerges in the comparison of these two analyses, and as such, both improved flux calculations (and the underlying β-spectra measurements) and new reactor antineutrino measurements are needed.

The most direct proof of a sterile neutrino solution to the reactor anomaly would be to observe a spectral distortion in the antineutrino rate that varies as a function of distance from the reactor core. There are several projects and proposals from all over the world to search for this effect, including: Stereo [65] at ILL in France and DANSS [234] at the Kalinin Power Plant in Russia, to name two. In the U.S., the parties interested in this measurement have organized into a single collaboration [233] that is investigating several potential sites [240] and detector technologies [256]. A compact reactor core is highly desirable to reduce the smearing and uncertainty in L, which makes power reactors less attractive. In addition, new detector designs with better spatial resolution, improved background rejection and better neutron tagging may be needed.

On the antineutrino flux side, the existing reactor θ_{13} experiments, such as Daya Bay [257], with their high-statistics near detectors, at baselines far enough to average out any spectral distortions from sterile oscillations, will provide the world's best data on reactor fluxes, ensuring that the uncertainty on the reactor anomaly is dominated by the flux calculation. New measurements of the β-spectra of the fission isotopes [258] would be helpful in further reducing the uncertainty on the flux calculation, but theoretical uncertainties from effects such as weak magnetism [246] will ultimately limit this approach.

1.9.1.3 Projects and Proposals with Accelerator-Induced Neutrinos

There are a number of proposals involving Fermilab's Booster Neutrino Beam (BNB) which are relevant to the sterile neutrino question. The MicroBooNE experiment [259], which is currently under construction just upstream of MiniBooNE, will use the fine grain tracking of its 170-ton LAr TPC to study, in detail, the interaction region of events corresponding to the MiniBooNE low-energy excess, and may help to determine if these $\nu_\mu \to \nu_e$ oscillation candidates are really ν_e charged current quasielastic events as assumed by MiniBooNE. Similarly, the proposed MiniBooNE+ [237] would look for neutron captures following ν_e candidate events. In the MiniBooNE energy range, the production of free neutrons in a neutrino interaction is five times more likely for charged-current than neutral-current events. MiniBooNE+ would attempt to detect these neutrons by adding scintillator to the MiniBooNE detector making it sensitive to the 2.2 MeV gammas produced when a neutron captured on hydrogen. This neutron tagging capability would be used to study whether the MiniBooNE low-energy excess events are truly ν_e events as the oscillation hypothesis requires. The MiniBooNE II proposal [238], to either build a new near detector or move the existing MiniBooNE detector to a near location, is also intended as a test of MiniBooNE excess. The presence of a near detector may help to confirm or refute the baseline dependence of the excess. The LAr1 proposal [236] is a multi-baseline proposal for the BNB which is based on LAr. It would add a 25-ton, "MicroLAr" detector at 100 m and a 3-kt, "LAr1", detector at 700 m to the existing MicroBooNE detector, which is at a baseline of 470 m. The projected sensitivity of this three detector combination is shown in Fig. 1-17b. There is also a less ambitious proposal to add just the MicroLAr near detector [260]. In Fermilab's NuMI beam line the MINOS+ experiment [74] will search for muon neutrino disappearance caused by oscillations to ν_s.

There is also a proposal at CERN for a two detector LAr TPC known as ICARUS/NESSiE [239]. In this proposal, the ICARUS T600 LAr TPC would be moved from Gran Sasso and set 1600 m downstream from a new neutrino beam extracted from the CERN-SPS. A second, smaller LAr TPC would be built at 300 m. Additionally a muon spectrometer would be installed behind each TPC. The projected sensitivity of ICARUS/NESSiE is shown in Fig. 1-17b.

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory is also an intense and well-understood source of neutrinos from π^+ and μ^+ decays-at-rest in much the same way that LAMPF produced neutrinos for LSND [261]. As such it is an excellent place to make a direct test of LSND. The OscSNS [235] proposal would build an 800-ton detector approximately 60 m from the SNS beam dump. OscSNS could improve upon LSND in at least three specific ways: 1) the lower duty factor of the SNS significantly reduces cosmic backgrounds, 2) the detector would be placed upstream of the beam lowering the possibility of non-neutrino, beam-correlated backgrounds, and 3) gadolinium-doped scintillator may be used to capture neutrons, providing a more robust tag of inverse β-decay. In addition to $\bar{\nu}_e$ appearance, OscSNS would search for ν_μ and ν_e disappearance. The projected sensitivity of the OscSNS $\bar{\nu}_e$ appearance search is shown in Fig. 1-17b.

IsoDAR [113] is a proposal to use a low-energy, high-power cyclotron to produce ^{8}Li, which β-decays producing a $\bar{\nu}_e$ with an endpoint of 13 MeV; it is potentially a precursor to DAEδALUS [113]. This cyclotron would be placed near the KamLAND detector which would detect the $\bar{\nu}_e$ via inverse β-decay. This arrangement would be sensitive to the disappearance of $\bar{\nu}_e$, and, given the low energy of the neutrinos and 13-m diameter detector, it should be capable of precision oscillometry. The projected sensitivity of IsoDAR is shown in Fig. 1-17a.

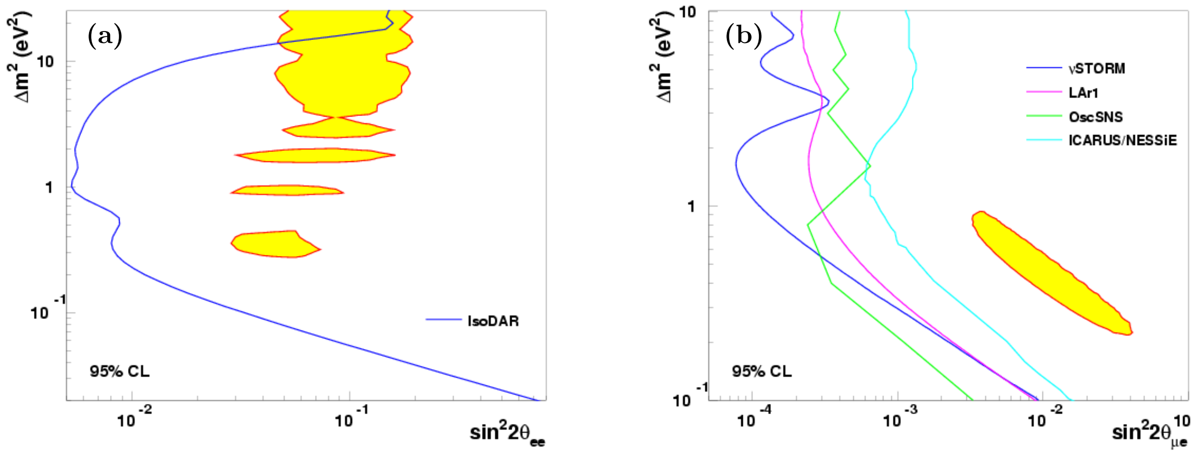

Figure 1-17. *Collaboration-reported sensitivity curves for proposed accelerator-based experiments sensitive to (a) ν_e and $\bar{\nu}_e$ disappearance (IsoDAR) [113] and (b) appearance which includes $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$ in both neutrinos and antineutrinos, plotted against the global fits [219].*

The nuSTORM [174] proposal is to build a racetrack-shaped muon storage ring, to provide clean and well-characterized beams of ν_e and $\bar{\nu}_\mu$ (or $\bar{\nu}_e$ and ν_μ if μ^- are stored). These beams would enable extremely precise searches for sterile neutrino oscillations in four neutrino types, in both appearance and disappearance channels. The most powerful and unprecedented capability of nuSTORM would be to search for $\overset{(-)}{\nu}_\mu$ appearance. The nuSTORM beams are essentially free of intrinsically-produced wrong sign/wrong flavor neutrinos which are unavoidable in pion decay-in-flight beams. On the other hand muon storage rings simultaneously produce ν_e and $\bar{\nu}_\mu$, so it essential to have magnetic detectors to distinguish between $\bar{\nu}_\mu$ from oscillation and ν_μ from the beam. The proposed nuSTORM project has near and far magnetized iron detectors, but future upgrades could include magnetized LAr TPCs. NuSTORM is a facility which, in addition to sterile neutrino searches, would make neutrino cross-section measurements critical to the long-baseline program (see Sec. 1.8) and conduct neutrino factory R&D, yet it is based on existing accelerator technology. Proposals for nuSTORM are currently being considered by both Fermilab [262] and CERN [263]. The projected sensitivity of the nuSTORM $\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu$ search is shown in Fig. 1-17b.

1.9.1.4 Sensitivity from Atmospheric Neutrinos

The disappearance of atmospheric ν_μ in the 0.5 to 10 TeV energy range can be enhanced by matter effects in the Earth's core for the case of a sterile neutrino with $\Delta m^2 \sim 1$ eV^2 [264, 265]. Such neutrinos are observed by the IceCube experiment [266, 267] at the South Pole, which can measure or set limits on the muon to sterile mixing amplitude by studying the zenith angle (effectively L) and energy dependence of any disappearance effect.

1.9.2 Non-Standard Interactions

Neutrino experiments in general, and neutrino oscillation experiments in particular, are also very sensitive to new, heavy degrees of freedom that mediate new "weaker-than-weak" neutral current interactions. These so-called non-standard interactions (NSI) between neutrinos and charged fermions modify not only neutrino production and detection, but also neutrino propagation through matter effects.

Different types of new physics lead to NSI (see, e.g., [268, 269], and references therein). These can be parameterized in terms of the effective operators

$$G_F \epsilon^f_{\alpha\beta} \nu_\alpha \gamma_\mu \nu_\beta \bar{f} \gamma^\mu f, \tag{1.15}$$

where $\nu_{\alpha,\beta} = \nu_{e,\mu,\tau}$, f are charged fermions $(e, u, d, \mu, s, \dots)$, G_F is the Fermi constant, and ϵ are dimensionless couplings.[7] When f is a first-generation fermion, the NSI contribute to neutrino detection and production at order ϵ^2 (ignoring potential interference effects between the standard model and the NSI). On the other hand, the NSI also contribute to the forward-scattering amplitude for neutrinos propagating in matter, modifying the neutrino dispersion relation and hence its oscillation length and mixing parameters. These modified matter effects are of order ϵ^1 and potentially more important than the NSI effects at production or detection. Furthermore, for $\alpha \neq \beta$, the NSI-related matter effects lead to $P_{\alpha\beta} \neq \delta_{\alpha\beta}$ in the very short baseline limit ($L \to 0$); these are not present in the standard model case. More information – including relations to charged-lepton processes – current bounds, and prospects using different neutrino sources are discussed in detail in, for example, [268, 269], and references therein.

1.9.3 Neutrino Magnetic Moment

In the minimally-extended standard model, the neutrino magnetic moment (NMM) is expected to be very small ($\mu_\nu \sim 10^{-19} - 10^{-20}\ \mu_B$) [270, 271]. This makes the NMM an attractive place to look for new physics. The current best terrestrial limit of $\mu_\nu < 2.9 \times 10^{-11}\ \mu_B$ at 90% CL comes from the GEMMA experiment [272]. Many models for new physics allow for a NMM just below the current limit. The NMM can be related to the Dirac neutrino mass scale by naturalness arguments such that the mass scale is proportional to the product of μ_ν and the energy scale of new physics, which implies that $|\mu_\nu| \leq 10^{-14}\ \mu_B$ for Dirac neutrinos [273]. NMM for Majorana neutrinos (which can have transition magnetic moments) suffer from no such constraint. Therefore a discovery of NMM of as much as a few orders of magnitude below the current limit would imply that neutrinos are Majorana particles. Laboratory searches for NMM are based on neutrino-electron elastic scattering [274]. Future reactor and radioactive source experiments for sterile searches, such as those discussed in Secs. 1.9.1.1 and 1.9.1.2, can in many cases push the NMM bounds further. Astrophysical processes also provide very stringent bounds to neutrino electromagnetic properties [275]. Majorana neutrino transition magnetic moments in the oscillation of supernova neutrinos reveal that moments as small as $10^{-24}\mu_B$ may leave a potentially observable imprint on the energy spectra of neutrinos and antineutrinos from supernovae [276],[277].

[7] $\epsilon \sim 1$ ($\ll 1$) implies that the new physics effects are on the order of (much weaker than) those of the weak interactions.

1.10 Neutrinos in Cosmology and Astrophysics

Neutrinos come from astrophysical sources as close as the Earth and Sun, to as far away as distant galaxies, and even as remnants from the Big Bang. They range in kinetic energy from less than one meV to greater than one PeV, and can be used to study properties of the astrophysical sources they come from, the nature of neutrinos themselves, and cosmology.

1.10.1 Ultra-low-energy Neutrinos

The Concordance Cosmological Model predicts the existence of a relic neutrino background, currently somewhat colder than the cosmic microwave background, $T_\nu = 1.95$ K. While relic neutrinos have never been directly observed, their presence is corroborated by several cosmological observables that are sensitive to the amount of radiation in the universe at different epochs. For example, precision measurements of the cosmic microwave background, and measurements of the relic abundances of light elements, independently require relativistic degrees of freedom other than photons, that are compatible with the three known neutrino species of the standard model of particle physics [278, 279]. Interestingly, a number of recent measurements – although well consistent with the standard model – seem to slightly favor a larger amount of radiation, compatible with four light neutrinos. This suggests a connection with the fact that a number of anomalies at neutrino experiments also favor the existence of a fourth "sterile" light neutrino (see Sec. 1.9). While any conclusion is premature, the question of a possible excess of cosmic radiation will be clarified by future, more precise, measurements of this quantity.

The cosmological relic neutrinos constitute a component of the dark matter, and their properties determine the way they contribute, with the rest of the dark matter, to the formation of large-scale structures such as galactic halos. In particular, their mass has a strong impact on structure formation. This is because, being so light, neutrinos are relativistic at the time of decoupling and their presence dampens the formation of structure at small distance scales. The heavier the neutrinos, the more they influence structure formation, and the less structure is expected at small scales. Data are consistent with 100% cold dark matter and therefore give an upper bound on the total mass of the three neutrino species: $\sum m_i < 0.7$ eV, approximately (see e.g., [279]). This bound should be combined with the lower limit from oscillation experiments: $\sum m_i > 0.05$ eV (Sec. 1.5), which sets the level of precision that next-generation cosmological probes must have to observe effects of the relic neutrino masses. At this time, prospects are encouraging for answering this question.

The "holy grail" of neutrino astrophysics/cosmology is the direct detection of the relic neutrino background. This is extremely cold ($1.95 \text{ K} = 1.7 \times 10^{-5}$ eV) and today, at least two of the neutrino species are nonrelativistic. Several ideas have been pursued, and a clear path towards successfully measuring relic neutrinos has yet to emerge. Recently, the idea, first discussed in [280], of detecting relic neutrinos through threshold-less inverse beta decay – e.g., $\nu_e + {}^3\text{H} \to {}^3\text{He} + e^-$ – has received some attention (e.g., [281]). Specific experimental setups have been proposed recently (e.g., PTOLEMY [168]; also see Sec. 1.7.2).

1.10.2 Low-energy Neutrinos

Sources of low energy (MeV to tens-of-MeV range) astrophysical neutrinos include the Earth, the Sun, and core-collapse supernovae. Since neutrinos only interact weakly, they are unique messengers from these sources allowing us to probe deep into the astrophysical body. The following three distinct detector types proposed in the near future would be broadly sensitive to low-energy neutrino physics: liquid-scintillator detectors, water-Cherenkov detectors, and liquid argon time projection chambers. Each detector type has particular advantages. Especially in the case of supernova neutrinos, a combination of all types would allow for a better determination of all the potential science.

1.10.2.1 Physics and Astrophysics with Low-Energy Neutrinos

Solar neutrinos: Despite the tremendous success of previous solar-neutrino experiments there are still many unanswered questions, e.g., such as: What is the total luminosity in neutrinos [32]? What is the metallicity of the Sun's core [282]? The answers to these questions could change our understanding of the formation of the Solar System and the evolution of the Sun. Precise measurements of solar *pep* or *pp* neutrinos are required to answer the first question, and precise measurements of CNO neutrinos could answer the second question. Solar neutrinos are also ideal probes for studying neutrino oscillation properties. The importance of previous solar neutrino experiments for understanding neutrino properties has been described in Sec. 1.5. New experiments, particularly at the energy of the *pep* neutrinos, would be very sensitive to nonstandard physics. An observation of a day-versus-night difference in the solar neutrino rate would conclusively demonstrate the so-called MSW effect [31, 33].

Geoneutrinos: Closer to home, the Earth is also a potent source of low-energy neutrinos produced in the decay of U, Th, K. Precise measurements of the flux of these neutrinos would allow for the determination of the amount of heat-producing elements in the Earth (see, for example, [283]), which is currently only estimated through indirect means. Knowing the amount of heat-producing elements is important for our understanding of convection within the Earth, which is ultimately responsible for earthquakes and volcanoes. The most recent measurements from KamLAND [284] and Borexino [285] are reaching the precision where they can start to constrain Earth models. However, these detectors are not sensitive to the neutrino direction and are therefore sensitive to local variations. Ultimately, we are interested in knowing the amount of heat-producing elements in the Earth's mantle, and hence a detector located on the ocean floor away from neutrinos produced in continental crust would be ideal.

Supernova neutrinos: Supernovae are thought to play a key role in the history of the Universe and in shaping our world. For example, modern simulations of galaxy formation cannot reproduce the structure of the galactic disk without taking the supernova feedback into account. Shock waves from ancient supernovae triggered further rounds of star formation and dispersed heavy elements, enabling the formation of stars like our Sun. Approximately 99% of the energy released in the explosion of a core-collapse supernova is emitted in the form of neutrinos. The mechanism for supernova explosion is still not understood. Supernova neutrinos record the information about the physical processes in the center of the explosion during the first several seconds, as the collapse happens. Extracting the neutrino luminosities, energy spectra, and cooling timescale would also allow us to study the equation of state of the nuclear/quark matter in the extreme conditions at the core of the collapse.

Supernovae also provide an incredibly rich source for the understanding of neutrino interactions and oscillations. As neutrinos stream out of the collapse core, their number densities are so large that their flavor states become coupled due to the mutual coherent scattering. This "self-MSW" phenomenon results in non-linear, many-body flavor evolution and has been under active exploration for the last five years, as supercomputers caught up with the physics demands of the problem (see, for example [286, 287, 288, 289, 290, 291, 292, 293, 294].) While the full picture is yet to be established, it is already clear that the spectra of neutrinos reaching Earth will have spectacular nonthermal features. Neutrino flavor evolution is also affected by the moving front shock and by stochastic density fluctuations behind it, which may also imprint unique signatures on the signal. All of these features will give new large detectors a chance to observe neutrino oscillations in qualitatively new regimes, inaccessible on Earth, and will very likely yield information on the neutrino mass hierarchy (see Sec. 1.5.1.1). Last but not least, the future data will allow us to place significant constraints on many extensions of particle physics beyond the standard model. This includes scenarios with weakly interacting particles, such as axions, Majorons, Kaluza-Klein gravitons, and others (see, for example [295, 296]). These new particles could be produced in the extreme conditions in the core of the star and could modify how it evolves and cools.

Compared to the 1987A event, when only two dozen neutrinos were observed, future detectors may register tens – or even hundreds – of thousands of neutrino interactions from a core-collapse supernova in or nearby the Milky Way. The burst will consist of neutrinos of all flavors with energies in the few tens of MeV range [87]. Because of their weak interactions, the neutrinos are able to escape on a timescale of a few tens of seconds after core collapse (the promptness enabling a supernova early warning for astronomers [297]). From the point of view of maximizing physics harvest from a burst observation, flavor sensitivity – not only interaction rate but the ability to tag different interaction channels– is critical.

While a single supernova in our Galaxy could be expected to produce a large signal in a next-generation neutrino detector, such events are relatively rare (1-3 per century). However, it could also be possible to measure the flux of neutrinos from all the supernovae in cosmic history. The flux of these "diffuse supernova neutrino background" (DSNB) depends on the historical rate of core collapse, average neutrino production, cosmological redshift effects and neutrino oscillation effects [298, 299].

1.10.2.2 Low-energy Neutrino Detectors

In this subsection we describe the leading large-detector technologies for detection of low-energy neutrinos.

Liquid scintillator detectors: Depending on the depth, radiogenic purity, and location, large liquid scintillator detectors could be sensitive to geoneutrinos, *pep*, *pp*, CNO, ^{8}B solar neutrinos, and supernova neutrinos. The majority of the liquid scintillator experiments consist of large scintillator volumes surrounded by light detectors. The Borexino [35] and KamLAND [300] experiments continue to operate. The SNO+ experiment [36] is currently under construction at SNOLAB, in Sudbury, Canada, and the JUNO experiment [44] is currently approved in China. The Hanohano experiment [301] to be located on the ocean floor, and the LENA experiment [115] to be located in Europe have been proposed.

The Borexino Collaboration recently announced the first positive measurement of *pep* neutrinos [302], along with a nontrivial upper bound on neutrinos from the CNO cycle, which are yet to be observed. Because of its greater depth, the SNO+ experiment could make a precise measurement of the *pep* neutrinos [36]. Unlike the other experiments, the LENS experiment [303] currently being planned consists of a segmented detector doped with In, which would allow precise measurement of the entire solar neutrino energy spectrum. Geoneutrinos were first observed in liquid scintillator detectors [304, 305] and all planned scintillator experiments would be sensitive to geoneutrinos, although the location of the JUNO experiment next to nuclear power plants would make such a measurement very difficult. The Hanohano experiment located on the ocean floor would be the ideal geoneutrino experiment.

All of the scintillator detectors would be sensitive to supernova neutrinos, primarily $\bar{\nu}_e$ through inverse beta decay (IBD), $\bar{\nu}_e + p \to e^+ + n$, but also ν_x neutrinos through proton scattering provided their thresholds are low enough [306]. The Hanohano and LENA detectors would also allow a measurement of the DSNB.

Water Cherenkov detectors: Depending on the depth and radiogenic purity, large water-Cherenkov detectors could be sensitive to ^{8}B solar neutrinos and supernova neutrinos. The Super-K [307] ($\sim 50,000$ tons, still operating) and SNO [34] experiments ($\sim 1,000$ tons, completed operation) have measured ^{8}B solar neutrinos flux to better than 5% and measured neutrino oscillations with a precision of better than 5%. A measurement of the day versus night asymmetry would require increased statistics. The proposed Hyper-K detector [83] ($\sim 990,000$ tons) would allow for a measurement of the day versus night asymmetry with a significance better than 4σ.

The tremendous size of the Hyper-K detector would result in $\sim 250,000$ interactions from a core-collapse supernova at the galactic center, and ~ 25 interactions from a core-collapse supernova at Andromeda. The large number of events in a galactic supernova would allow for very sensitive study of the time evolution of the neutrino signal. Although the IceCube detector could not detect individual events from a core-collapse supernova, the large volume of ice visible to the photomultiplier tubes would result in a detectable change in the photomultiplier hit rates, allowing for a study of the time evolution of a supernova [83, 308]. The addition of Gd to the Super-K [308] or Hyper-K detectors would allow for the study of the DSNB within the range of most predictions for the total flux.

Liquid argon time projection chambers: A liquid argon time projection chamber located underground could provide invaluable information about a galactic core-collapse supernova. Unlike other detectors, which are primarily sensitive to $\bar{\nu}_e$, the principal signal would be due only to ν_e interactions, for which unique physics and astrophysics signatures are expected [106, 93]. For a supernova at 10 kpc approximately 1000 events would be expected per 10 kt of liquid argon [309]. It will be critical to site LBNE underground in order to take advantage of the exciting and unique physics a core-collapse supernova will bring [80].

Table 1-8. *Summary of low-energy neutrino astrophysics detectors. ** indicates significant potential, and * indicates some potential but may depend on configuration. Here total mass is given; fiducial mass may be smaller.*

Detector Type	Experiment	Location	Size (kt)	Status	Solar	Geo	Supernova
Liquid scintillator	Borexino	Italy	0.3	Operating	**	**	*
Liquid scintillator	KamLAND	Japan	1.0	Operating	**	**	*
Liquid scintillator	SNO+	Canada	1.0	Construction	**	**	*
Liquid scintillator	RENO-50	South Korea	10	Design/R&D	*	*	**
Liquid scintillator	JUNO	China	20	Design/R&D	*	*	**
Liquid scintillator	Hanohano	TBD (USA)	20	Design/R&D	*	**	**
Liquid scintillator	LENA	TBD (Europe)	50	Design/R&D	*	**	**
Liquid scintillator	LENS	USA	0.12	Design/R&D	**		*
Water Cherenkov	Super-K	Japan	50	Operating	**		**
Water Cherenkov	IceCube	South Pole	2000	Operating			**
Water Cherenkov	Hyper-K	Japan	990	Design/R&D	**		**
Liquid argon	LBNE	USA	35	Design/R&D	*		**

1.10.3 Neutrinos of GeV to PeV Energies

One of the most tantalizing questions in astronomy and astrophysics, namely the origin and the evolution of the cosmic accelerators that produce the observed spectrum of cosmic rays, which extends to astonishingly high energies, may be best addressed through the observation of neutrinos. Because neutrinos only interact via the weak force, neutrinos travel from their source undeflected by magnetic fields and unimpeded by interactions with the cosmic microwave background, unlike photons and charged particles. Due to the low fluxes expected, the construction of high-energy neutrino telescopes requires the instrumentation of large natural reservoirs, a concept demonstrated by AMANDA, Baikal and ANTARES. With the completion of the IceCube Neutrino Telescope [310] in the South Polar icecap in 2010, the era of kilometer scale neutrino telescopes has dawned, and plans for a complementary telescope in the Mediterranean are under development. Already, IceCube has demonstrated astrophysical sensitivity by placing severe constraints on favored mechanisms for gamma-ray bursts [311]. Cascade events exceeding 1 PeV have been observed [312]; these may be a first glimpse of either a new source, or new physics. Physics and astrophysics from future IceCube measurements are detailed in [313].

As with previous generations of neutrino telescopes, these instruments are expected to provide insight into the nature of the messengers themselves. The backgrounds for the astrophysical fluxes sought include atmospheric neutrinos, which are collected by IceCube at a rate of about 100,000 per year in the 0.1 to 100 TeV range. Atmospheric neutrinos provide a probe of neutrino physics and interactions at energies that have been previously unexplored. At TeV energies, the sensitivity of IceCube data to sterile neutrinos in the eV mass range potentially exceeds that of any other experiment and is only limited by systematic errors (see Sec. 1.9). With the addition of IceCube's low-energy infill array, Deep Core [314], which extended its energy sensitivity down to 10 GeV, conventional neutrino oscillations have been observed at the 1 sigma level, and it is hoped that such instruments could provide competitive precision measurements of neutrino oscillation parameters. The copious atmospheric neutrino flux may some day also provide a glimpse into our Earth via neutrino radiography.

These instruments may also shed light on one of the most puzzling questions facing particle physics and cosmology: the nature of the dark matter. Dark matter annihilations in the Sun and the Galactic center could be indirectly detected in neutrino telescopes, covering a region of parameter space that is inaccessible at the LHC, and masses inaccessible to direct detection experiments. Neutrino telescopes have also been active in the search for other exotica, such as magnetic monopoles.

1.10.4 Neutrinos at Energies Over 1 PeV

At ultra high energies, neutrinos could be detected in dense, radio frequency (RF) transparent media via the Askaryan effect [315, 316]. The abundant cold ice covering the geographic South Pole, with its exceptional RF clarity, has been host to several pioneering efforts to develop this approach, including RICE [317] and ANITA [318]. Currently, two discovery-scale instruments are in the prototyping phase: the Askaryan Radio Array (ARA) [319], which is envisioned to instrument a 100-square-km area near the South Pole with 200-m deep antenna clusters, and ARIANNA [320], which would be installed on the surface of the Ross Ice Shelf. Efforts are underway to characterize the ice in Greenland, to determine its suitability as a site for a future cosmogenic neutrino telescope.

The fact that cosmic rays have been observed at energies in excess of 10^{20} eV makes the search for neutrinos at these energies particularly tantalizing. These energies are above the threshhold for pion photoproduction on the cosmic microwave background, which would seem to guarantee a flux of ultra-high-energy (UHE) neutrinos. However, the neutrino flux expectations are sensitive to the composition of the UHE cosmic rays, making the spectrum of UHE cosmic rays a sensitive probe of the heavy ion content. In addition, if a sufficient sample of UHE neutrinos were amassed, it would be possible to measure the neutrino cross section at high energies from the zenith angle spectrum.

1.11 Neutrinos and Society

In this section we discuss the direct and spin-off applications, and the rich opportunities for outreach and education offered by fundamental and applied antineutrino science.

1.11.1 Applied Antineutrino Physics

Direct application of neutrinos to other domains falls into two categories. In geology, they may enable study of Earth's composition on largest scales (see Sec. 1.10), and in nonproliferation, they offer the prospect of improved monitoring or discovery of operating nuclear reactors. Since the signal in both cases arises from antineutrinos only, it is appropriate to refer to these studies as "Applied Antineutrino Physics".

Concerning nonproliferation, the main likely user of antineutrino-based reactor monitoring is the International Atomic Energy Agency (IAEA). IAEA is responsible for monitoring the international fuel cycle, to detect attempts to divert fissile materials and production technologies to nuclear weapons programs. The international monitoring regime administered by the IAEA is referred to as the Safeguards regime [321]. Antineutrino detectors may play a role in this regime, which focuses on timely detection of illicit removal of fissile material from known and declared reactors and other fuel cycle facilities. They may also be useful in future expanded regimes, such as the proposed Fissile Material Cutoff Treaty [322], which will seek to verify the non-existence of an undeclared fissile material production capability in a country or geographical region. In a recent report, the IAEA encouraged continued research into antineutrino-detection-based applications for safeguards and other cooperative monitoring of nuclear reactors [323]. In addition, the U.S. National Nuclear Security Administration has included a demonstration of remote reactor monitoring (1 km and beyond) as an element of its 2011 Strategic Plan [324].

Nonproliferation applications are enabled by three features of reactor antineutrinos. First, reactors emit a copious flux of ~ 0–10 MeV electron antineutrinos resulting from beta decay of neutron-rich fission fragments. Second, the antineutrino IBD cross section is high enough to allow detectors of tractable (cubic meter) sizes to be deployed at tens-of-meter standoff from a reactor. Third, the detected antineutrino flux and energy spectrum both correlate with the core-wide content of fission fragments, and therefore bring information on the inventories of the main fissile isotopes used in weapons.

Concerning applications for existing or future reactor safeguards, cubic-meter-scale antineutrino detectors now make it possible to monitor the operational status, power levels, and fissile content of nuclear power reactors in near-real-time with stand-off distances of roughly 100 meters from the reactor core. This capability has been demonstrated at civil power reactors in Russia and the United States, using antineutrino detectors designed specifically for reactor monitoring and safeguards [325, 326]. This near-field monitoring capability may be of use within the International Atomic Energy Agency's (IAEA) Safeguards Regime, and other cooperative monitoring regimes.

With respect to future missions related to remote discovery or exclusion of reactors, current kt-scale antineutrino detectors, exemplified by the KamLAND and Borexino liquid-scintillator detectors, can allow monitoring, discovery or exclusion of small (few MegaWatt thermal, MWt) reactors at standoff distances up to 10 kilometers. In principle, reactor discovery and exclusion is also possible at longer ranges. More information on this topic may be found at [327].

1.11.1.1 IBD Detectors for Near-Field Safeguards, and for Short-Baseline Experiments

As discussed in section 1.9, and in numerous Snowmass white papers [328], short-baseline neutrino oscillation experiments are being planned by US and overseas groups. These experiments seek to deploy 1–10 ton scale antineutrino detectors from 5–15 meters from a nuclear reactor core. The purpose of the experiments is to search for a possible sterile neutrino signal, and to measure the reactor antineutrino energy spectrum as precisely as possible. The physics goals greatly constrain the experimental configuration. The need for close proximity to the reactor requires that the detector overburden is necessarily minimal, at most ∼45 meters water equivalent (mwe). The physical dimension of the core must be as small as possible, to avoid smearing the oscillation-related spectral distortions with multiple baselines arising from different locations in the core. To be competitive with experiments using strong single-element radioactive sources, this requires that a relatively low power (∼20-50 MWt) research reactor be used for the experiment, greatly constraining the number of possible sites. The above requirements impose stringent constraints on detector design as well. The technology goals for reactor short-baseline experiments and for nonproliferation applications are similar in many respects. In both cases, R & D is required to improve background rejection at shallow depths, while maintaining high efficiency and good energy resolution. To improve specificity for the two-step IBD signature, segmented designs [329] are being contemplated for both cooperative monitoring and short-baseline detectors, as well as the use of Li-doped plastic or liquid scintillator technologies [330]. A key difference between the fundamental and applied technology needs is that the detectors for nonproliferation must also be simple to operate, and may have additional cost constraints compared to the single-use detectors needed for the short-baseline physics experiments.

1.11.1.2 CENNS Detection for Nonproliferation and Fundamental Science

Numerous physics motivations for the measurement of coherent elastic neutrino-nucleus scattering (CENNS) are described in Sec. 1.8.2 (and ' see [331, 332, 200]). For monitoring applications, the process holds considerable interest, since the 100-1000 fold increase in cross section compared with the next most competitive antineutrino interaction may enable a ten-fold or more reduction in detector volume, even with shielding accounted for. This could simplify and expand the prospects for deployment of these detectors in a range of cooperative monitoring contexts. Furthermore, CENNS has important connections to the searches for WIMPs, due to similarity in the nuclear-recoil event signature. Advances in CENNS technology will potentially improve the prospects for WIMP detection, and CENNS backgrounds from natural neutrino sources will eventually limit dark matter searches.

For CENNS detection, both phonon and ionization channel approaches are being pursued. Detector thresholds must be made sufficiently low, while maintaining effective background suppression, so as to allow good collection statistics above background in tractably-sized detectors. In the last few years, several groups worldwide have made significant progress in reducing thresholds in noble liquid [333, 334], and germanium detectors [335], with the intent of improving both coherent scatter and dark matter detectors.

1.11.1.3 Large IBD Detectors and Remote Reactor Monitoring

One-hundred-kt to Mt-scale liquid scintillator and water detectors have been proposed as far detectors for long-baseline accelerator-based neutrino oscillation and CP-violation experiments [83, 336]. If they can be made sensitive to few-MeV antineutrinos, such giant detectors offer an even more diverse physics program, including sensitivity to extra-galactic supernovae, measurement of the diffuse supernova background (see Sec. 1.10), proton decay, and in the case of liquid scintillator detectors, sensitivity to reactor neutrino oscillations at several tens-of-kilometer baseline. The same types of detector could enable discovery, exclusion, or monitoring of nuclear reactors at standoff distances from one to as many as several hundred kilometers. With sufficient suppression of backgrounds, remote detectors (25-500 km standoff) on the 50-kt to one-Mt scale would provide a 25% statistically accurate measurement of the power of a 10-MWt reactor in several months to a year [337]. Water Cherenkov detectors are one promising approach to achieving detector masses on the scale required to meet the above physics and nonproliferation goals. While the water Cherenkov approach is currently disfavored in the United States' LBNE planning process, it nonetheless retains considerable interest for the global community, in particular in Japan [83]. To allow sensitivity to low energy antineutrinos through the IBD process, the water would be doped with gadolinium, so that final-state neutrons can be detected by the $\sim$4 MeV of measurable Cherenkov energy deposited in the gamma-ray cascade that follows capture of neutrons on gadolinium [338, 339]. A kt-scale demonstration of this detector type is now being proposed by the WATCHMAN collaboration in the United States [340]. Scaling of pure liquid-scintillator designs such as KamLAND or Borexino is another approach to megaton class detectors. This approach is exemplified by the LENA collaboration in Europe [336, 115].

1.11.1.4 Applications of Neutrino-related Technologies

A high degree of synergy is evident in technology developments related to neutrino physics experiments. Close collaboration between laboratory, university and industry has been fruitful, solving immediate needs of the neutrino community, and providing spinoff applications in quite different fields with broad societal impact. Examples are provided here.

Detectors: Neutrino/antineutrino detection has motivated significant work on detection technology, the benefits of which extend well beyond the physics community. Examples include plastic and liquid scintillator doped with neutron-capture agents, high-flashpoint scintillators with reduced toxic hazards compared to previous generators of scintillator, and low-cost flat-panel photomultiplier tubes. Doped organic plastic and liquid scintillator detectors are now being pursued in the United States [341], as a means to improve sensitivity to the reactor antineutrino signal. In a similar way, companies such as Bicron Technologies and Eljen Technologies have devoted resources to reducing the biohazards and improving the optical clarity of their scintillation cocktails, in order to facilitate neutrino detection. These improvements clearly benefit other customers, such as the medical and pharmaceutical communities, which use scintillator detectors for radio-assay in nuclear medicine applications. The overall product lines of these companies have benefited considerably from research that has focused on making better neutrino detectors. Another area of research with important spinoff potential is the development of low cost, high efficiency photomultiplier tubes. Cutting-edge research that focused on low-cost PMTs is exemplified by the Large Area Pico-second Photo-Detectors project [342, 343]. Beyond enabling lower-cost neutrino detectors at every scale, such detectors would lower costs and improve performance of medical imaging devices such as Positron Emission Tomography systems, for which the photo-detector element is often a dominant cost and critical component. Emerging nuclear security applications that demand PMT-based imaging, such as three-dimensional reconstruction of the locations and inventories of fissile material in a reprocessing or enrichment plant, also greatly benefit from lower-cost PMTs.

Accelerators: The National Academy of Engineering (NAE) declared one of the Grand Challenges for the new century to be, "the Engineering of Tools for Scientific Discovery" [344] then muses, "Perhaps engineers will be able to devise smaller, cheaper, but more powerful atom smashers, enabling physicist to explore realms beyond the reach of current technology" [344]. The current generation of high-power accelerators have rapidly advanced the boundary of "current technology" and are accomplishing many breakthroughs in these new realms. In the particular case of the rapidly-evolving field of neutrino studies, sources produced from the FNAL Main Injector, CERN's SPS, and J-PARC are enabling very rapid progress. Future experiments with the SNS, and new capabilities at ESS-Lund, Project X, and the high-power DAEδALUS cyclotrons will go a long way towards realizing the visions of the NAE. But, as important are the understandings in fundamental science, even greater are the societal impacts of the technologies being developed for these new accelerators. The indirect spinoffs are numerous: advances in engineering with superconducting materials and magnets, high-volume cryogenics, sophisticated control systems and power converters, and many more. A very direct connection with neutrinos is provided by the DAEδALUS project, which is based on a cascade of compact cyclotrons capable of sending multi-megawatt beams onto neutrino-producing targets for CP-violation studies and searches for sterile neutrinos. Development of this technology, based on accelerating H_2^+ ions, pushes the performance of cyclotrons to new levels, and is being pursued by a broad collaboration of U.S. and foreign laboratories, universities, and industry [46, 111]. As new, cost-effective sources of high-power beams, these cyclotrons will have a significant impact on ADS (Accelerator-Driven Systems) technology for critical nuclear energy-related applications such as driving thorium reactors and burning nuclear waste [345]. On a nearer timescale, industry is quite interested in the application of this technology for isotope production. One of the test prototypes being developed with the assistance of Best Cyclotron Systems Inc. is a 28-MeV cyclotron designed for H_2^+ injection studies. This cyclotron is also suitable for acceleration of He^{++}, and is directly applicable to the production of ^{211}At, a powerful therapeutic agent whose "...use for [targeted α particle therapy] is constrained by its limited availability" [346].

1.11.2 Education and Outreach

Educating Physicists about Nonproliferation: In order to reach out to the public effectively, physicists themselves should be made aware of the potential utility of neutrinos for nuclear security. As revealed by the growing field of applied antineutrino physics, awareness of these connections has grown over the last ten years in the physics community. However, relatively few physicists – including many actively engaged in applied research – have much, if any, formal education in the structure of the global nonproliferation regime, or in the history of the atomic era that led to the current state of affairs in nuclear security. This is especially unfortunate, since at least in the U.S., as this history is closely intertwined with the development of the large-scale accelerator and underground experiments that employ many of these same physicists. In the last five years or so, a few physics departments have worked to develop courses that introduce physicists to both the relevant technology and policy of nonproliferation and nuclear security. Nuclear Engineering departments have a closer connection to the nonproliferation regime, and have developed explicit course elements targeting the connection between nuclear security and nuclear science. These developments and connections should be nurtured.

Educating the General Public about Neutrino Science: An aware and enthusiastic general public is the best way to ensure support and funding for basic research. Each one of us should accept our responsibility for conveying the message whenever possible that investments in our field are of benefit to the nation. Neutrino physics offers a wealth of fascinating and counter-intuitive concepts (e.g., oscillations, high fraction of the Sun's energy emitted as neutrinos, and extremely low cross sections enabling neutrinos to easily penetrate the Earth). In addition, our field sports some highly photogenic experiments (e.g., IceCube, Borexino, Super-K). A suggestion could be made that a reservoir of material be collected, updated and made available for persons to use in outreach talks and activities: lecture outlines, lists of talking points, graphics, etc. The interesting practical applications of neutrinos described earlier provide highly relevant and compelling topics to be communicated to the public.

The importance of Education and Outreach is recognized in the establishment of a whole (Snowmass) "Frontier" dedicated to this topic. Our community should embrace this effort, looking for ways of coordinating and contributing to their activities for furtherance of our mutually compatible goals.

.1 Glossary

Below is a glossary of acronyms and experiment names:

- $0\nu\beta\beta$ – neutrinoless double beta decay
- ADS: Accelerator-Driven Systems – technology for driving nuclear reactors with beams
- AMANDA: Antarctic Muon and Neutrino Detector Array – first-generation neutrino telescope experiment in Antarctica
- ANITA: Antarctic Transient Antenna – neutrino radio antenna balloon experiment in Antarctica
- ANTARES: Astronomy with a Neutrino Telescope and Abyss environmental RESearch – neutrino telescope experiment in the Mediterranean sea
- ARA: Askaryan Radio Array – radiofrequency neutrino antenna experiment at the South Pole
- ARIANNA: Antarctic Ross Ice-shelf ANtenna Neutrino Array – radiofrequency neutrino antenna experiment in Antarctica
- BNB: Booster Neutrino Beam – neutrino beamline at Fermilab using the Booster
- Borexino: scintillator solar neutrino experiment in Gran Sasso National Laboratory
- CAPTAIN: Cryogenic Apparatus for Precision Tests of Argon INteractions – LAr R&D detector
- CC: Charged Current
- Ce-LAND: ^{144}Ce source to be placed in KamLAND to study the reactor neutrino anomaly
- CENNS: Coherent Elastic Neutrino-Nucleus Scattering – refers to the process as well as a proposed experiment to be sited at the BNB
- CHiPS: CHerenkov detectors in mine PitS – proposed experiment to use the Fermilab NuMI beam and a massive Cherenkov detector in a flooded mine pit
- CHOOZ: first-generation reactor neutrino experiment in France
- CKM: Cabibbo-Kobayashi-Maskawa matrix
- CL: Confidence Level
- CMB: Cosmic Microwave Background
- CP: Charge Parity
- CSISNS: Coherent Scattering Investigations at the SNS – proposed CENNS search experiment for the SNS
- CUORE: Cryogenic Underground Observatory for Rare Events – neutrinoless double beta decay search experiment at Gran Sasso National Laboratory
- DAEδALUS: Decay At rest Experiment for δ_{CP} studies At the Laboratory for Underground Science – proposed cyclotron-based neutrino oscillation experiment

- DANSS: Detector of the reactor AntiNeutrino based on Solid-state plastic Scintillator – reactor neutrino experiment in Russia
- DAR: Decay At Rest
- Daya Bay: reactor neutrino experiment in Daya Bay, China
- DIF: Decay In Flight
- DIS: Deep Inelastic Scattering
- Deep Core: PMT infill for low-energy extension to the IceCube experiment
- Double Chooz: reactor neutrino experiment in Chooz, France
- DSNB: Diffuse Supernova Neutrino Background
- ECHo: Electron Capture ^{163}Ho experiment – proposed neutrino mass microcalorimeter experiment
- ESS: European Spallation Source – future facility in Lund, Sweden
- ESSνSB: European Spallation Source Neutrino Super Beam – proposal to use the European Spallation Source (ESS) proton linac to generate a neutrino super beam
- EXO: Enriched Xenon Observatory – neutrinoless double beta decay experiment at WIPP (Waste Isolation Pilot Plant) in Carlsbad, New Mexico
- EVA: ExaVolt Antenna – balloon-based neutrino antenna experiment in Antarctica
- FNAL: Fermi National Accelerator Laboratory
- GALLEX: Gallium-based radiochemical neutrino detector – radiochemical solar neutrino experiment at Gran Sasso National Laboratory
- GEMMA: Germanium Experiment for measurement of the Magnetic Moment of Antineutrino) – neutrino magnetic moment experiment at the Kalinin nuclear power plant in Russia
- GERDA: Ge experiment searching for neutrinoless double beta decay
- GNO: Gallium Neutrino Observatory – radiochemical solar neutrino experiment at Gran Sasso National Laboratory (successor to GALLEX)
- HALO: Helium and Lead Observatory – supernova neutrino detector under construction at SNOLAB
- Hyper-K: Hyper-Kamiokande – proposed large water Cherenkov detector in Japan
- IAEA: International Atomic Energy Agency
- IBD: Inverse Beta Decay (usually refers to $\bar{\nu}_e + p \rightarrow e^+ + n$)
- ICARUS: Imaging Cosmic And Rare Underground Signals – LAr TPC-based neutrino oscillation experiment at Gran Sasso National Laboratory
- IceCube: neutrino telescope located at the Amundsen Scott South Pole station in Antarctica
- ICAL: iron calorimeter atmospheric neutrino experiment at INO
- IDS: International Design Study (for the Neutrino Factory)

- INO: India-based Neutrino Observatory – future underground laboratory in India
- ISIS: research center at Rutherford Appleton Laboratory near Oxford
- IsoDAR: Isotope Decay At Rest experiment – proposed cyclotron-based sterile neutrino experiment
- J-PARC: Japan Proton Accelerator Research Complex
- JUNO: Jiangmen Underground Neutrino Observatory – proposed reactor-based large scintillator experiment to measure the neutrino mass hierarchy in China
- K2K: KEK to Kamioka – first-generation long-baseline oscillation experiment using beam from KEK to Super-K
- KamLAND: Kamioka Liquid scintillator ANtineutrino Detector – reactor neutrino experiment in Japan
- KamLAND-Zen: Zero neutrino double beta decay search – neutrinolesss double beta decay experiment in Japan (Xe-doped balloon deployed in KamLAND).
- KATRIN: KArlsruhe TRitium Neutrino experiment – neutrino mass spectrometer in Germany
- KEK: accelerator laboratory in Tsukuba, Japan
- KM3NET: multi-km^3 Neutrino Telescope – future deep sea neutrino telescope in the Mediterranean sea
- kt: kilotonne (metric unit; 10^3 kilograms)
- LAGUNA: Large Apparatus studying Grand Unification and Neutrino Astrophysics – collaborative project to assess the possibilities for a deep underground neutrino observatory in Europe
- LANSCE: Los Alamos Neutron Science Center
- LAr1: proposal to add additional liquid argon TPCs to the Fermilab Booster neutrino beamline
- LAr1-ND: proposal to add a liquid argon TPC near detector in the Fermilab Booster neutrino beamline
- LAr TPC: Liquid Argon Time Projection Chamber
- LBNE: Long-Baseline Neutrino Experiment – proposed accelerator-based neutrino oscillation experiment in the U.S.
- LBNO: Long-Baseline Neutrino Oscillation experiment – proposed accelerator-based neutrino oscillation experiment in Europe
- LENA: Low Energy Neutrino Astronomy – proposed next-generation liquid scintillator detector
- LENS: Low Energy Neutrino Spectroscopy – low-energy solar neutrino experiment
- LSND: Liquid Scintillator Neutrino Detector – sterile neutrino experiment at Los Alamos National Laboratory
- LUX: Large Underground Xenon – dark matter detector
- LVD: Large Volume Detector – neutrino observatory in Gran Sasso National Laboratory studying low-energy neutrinos from gravitational stellar collapse
- MAJORANA: Ge experiment searching for neutrinoless double beta decay

- MicroBooNE: liquid argon TPC experiment in the Booster neutrino beamline at Fermilab
- MINERνA: Main Injector Experiment for ν-A – neutrino scattering experiment in the NuMI beamline at Fermilab
- MiniBooNE: short-baseline neutrino oscillation experiment using a mineral oil-based Cerenkov detector in the Booster neutrino beamline at Fermilab
- MINOS: Main Injector Neutrino Oscillation Search – neutrino oscillation experiment in the NuMI beamline at Fermilab
- NC: Neutral Current
- NESSiE: Neutrino Experiment with SpectrometerS in Europe – proposed experiment to search for sterile neutrinos using the CERN SPS beam and the ICARUS detector
- NEXT: Neutrino Experiment with Xenon TPC – neutrinoless double beta decay experiment at the Canfranc Underground Laboratory
- NF: common abbreviation for the Neutrino Factory
- NMM: Neutrino Magnetic Moment
- NOMAD: Neutrino Oscillation MAgnetic Detector – neutrino oscillation experiment at CERN
- NOvA: NuMI Off-Axis electron-neutrino Appearance experiment – neutrino oscillation experiment in the NuMI beamline at Fermilab
- NSI: Non-Standard Interactions (of neutrinos)
- NuMAX: Neutrinos from Muon Accelerators at Project X – proposed neutrino oscillation experiment using a muon-storage ring as a source of neutrinos
- NuMI: Neutrinos at the Main Injector – neutrino beamline at Fermilab using the Main Injector
- nuSTORM: neutrino from STORed Muons – proposed short-baseline neutrino experiment to study sterile neutrinos using a muon storage ring as a source of neutrinos
- OPERA: Oscillation Project with Emulsion-tRacking Apparatus – emulsion-based neutrino oscillation experiment in Gran Sasso National Laboratory
- ORCA: Oscillation Research with Cosmics in the Abyss – proposed experiment to measure the neutrino mass hierarchy using the KM3NeT neutrino telescope
- OscSNS: oscillations at the Spallation Neutrino Source – proposed sterile neutrino search using the SNS facility
- PINGU: Precision Icecube Next Generation Upgrade – proposed experiment to measure the neutrino mass hierchy using a low-energy extension to IceCube
- PMNS: Pontecorvo-Maki-Nakagawa-Sakata matrix
- PMT: photomultiplier tube
- PREM: Preliminary Reference Earth Model – model for Earth density distribution
- Project 8: proposed tritium-based neutrino mass experiment

- Project X: proposed proton accelerator complex at Fermilab
- PTOLEMY: Princeton Tritium Observatory for Light Early-universe Massive neutrino Yield – proposed relic Big Bang neutrino background experiment
- QCD: Quantum chromodynamics
- QE: Quasi-Elastic
- RADAR: R&D Argon Detector at Ash River – proposal to add a LAr TPC to the NOvA far detector building in Ash River, Minnesota
- RENO: Reactor Experiment for Neutrino Oscillations – reactor neutrino experiment in South Korea
- RENO-50: proposed reactor-based experiment to measure the neutrino mass hierarchy with a large scintillator detector
- RICE: Radio Ice Cherenkov Experiment – neutrino telescope experiment in Antarctica
- RICOCHET: proposed bolometric sterile neutrino search using CENNS
- SAGE: Soviet American Gallium Experiment – solar neutrino experiment in the Baksan Neutrino Observatory in Russia
- SciNOvA: proposed neutrino scattering experiment adding a fine-grained scintillator detector at the NOvA near site
- SOX: chromium and/or cesium source at Borexino to study the reactor neutrino anomaly
- SNO: Sudbury Neutrino Observatory – solar neutrino experiment at SNOLAB in Canada
- SNO+: solar, geoneutrino, and neutrinoless double beta decay experiment at SNOLAB in Canada
- SNOLAB: underground science laboratory in the Vale Creighton Mine located near Sudbury Ontario Canada
- SNS: Spallation Neutron Source – facility at Oak Ridge National Laboratory
- Stereo: search for sterile neutrinos at the ILL reactor
- SPS: Super Proton Synchotron at CERN
- Super-K: Super-Kamiokande experiment – water Cherenkov detector in the Kamiokande mine in Japan studying proton decay as well as solar, atmospheric, and accelerator-based (T2K) neutrinos
- Super-NEMO: super Neutrino Ettore Majorana Observatory – neutrinoless double beta decay experiment in Europe
- SURF: Sanford Underground Research Laboratory – underground reasearch laboratory in Lead, South Dakota
- T2K: Tokai to Kamiokande experiment – neutrino oscillation experiment using the JPARC beam in Japan
- TPC: Time Projection Chamber
- UHE: Ultra High Energy

- WATCHMAN: WATer CHerenkov Monitoring of Anti-Neutrinos – collaboration of U.S.-based universities and laboratories conducting a site search for a kton scale advanced water detector demonstration
- WIMP: Weakly Interacting Massive Particle – dark matter candidate particle

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