1

Neutrino Physics

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1.1 Introduction

Neutrinos are the most elusive of the known fundamental particles. They are color- and charge- neutral spin one-half fermions, and, to the best of our knowledge, 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. The third neutrino flavor eigenstate, the tau-type neutrino ν_τ, was the last of the fundamental particles to be observed [1], eluding direct observation six years longer than the top quark [2, 3].

More relevant to this Chapter, 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 [4, 5, 6, 7, 8, 9], atmospheric [10, 11], reactor [12, 13] and accelerator neutrinos [14, 15] have established, beyond reasonable doubt, that a neutrino produced in a well-defined flavor state (say, a muon-type neutrino ν_μ) has a non-zero 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 that neutrinos have mass and neutrino mass eigenstates are different from neutrino weak eigenstates, *i.e.*, leptons mix. The neutrino flavor-change is a consequence of so-called neutrino oscillations.

Massive neutrinos imply that a neutrino produced as a coherent superposition of mass-eigenstates, such as a neutrino ν_α with a well-defined flavor, has a non-zero probability to be measured as a neutrino ν_β of a different flavor ($\alpha, \beta = e, \mu, \tau$). This 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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. \tag{1.1}$$

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 parametrize U in Eq. (1.1) with three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ and three complex phases, δ, ξ, ζ, defined by

$$\frac{|U_{e2}|^2}{|U_{e1}|^2} \equiv \tan^2\theta_{12}; \qquad \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} \equiv \tan^2\theta_{23}; \qquad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}, \tag{1.2}$$

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 essentially no effect in flavor-changing phenomena.

In order to relate the mixing elements to experimental observables, it is necessary to 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 $m^2_3 > m^2_2$ ($m^2_3 < m^2_1$) and characterizes a so-called normal (inverted) neutrino mass hierarchy. The two mass hierarchies are depicted in Fig. 1-1.

Our knowledge of neutrino oscillation parameters can be summarized as [16, 17, **?**]

$$\Delta m^2_{21} = 7.59^{+0.20}_{-0.18} \times 10^{-5}\ \text{eV}^2,\ \Delta m^2_{31} = 2.50^{+0.09}_{-0.16} \times 10^{-3}\ \text{eV}^2\ (-2.40^{+0.08}_{-0.09} \times 10^{-3}\ \text{eV}^2), \tag{1.3}$$

$$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}, \qquad \sin^2\theta_{23} = 0.52 \pm 0.06, \qquad \sin^2\theta_{13} = 0.023 \pm 0.004. \tag{1.4}$$

We have virtually no information concerning δ (and, for that matter, ξ and ζ) or the sign of Δm^2_{31}. Indications by T2K [18], MINOS [19] and Double Chooz [20] in 2011 pointed to $\sin^2 2\theta_{13} \simeq 0.08$. In combination, these results excluded $\sin^2 2\theta_{13} = 0$ at more than three sigma without direct reference to solar or atmospheric data, as was required prior to the result from Double Chooz [21]. Very recently, the Daya Bay collaboration, after analyzing 55 days of data, claimed five sigma evidence that $\sin^2\theta_{13}$ is not zero. Their best fit result

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

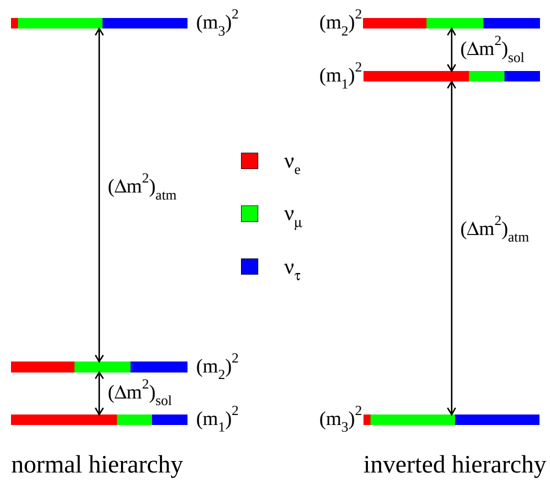

Figure 1-1. *Cartoon of the two distinct neutrino mass hierarchies that fit all of the current neutrino data, for fixed values of all mixing angles and mass-squared differences. The color coding (shading) indicates the fraction* $|U_{\alpha i}|^2$ *of each distinct flavor* ν_α, $\alpha = e, \mu, \tau$ *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*').*

is $\sin^2 2\theta_{13} = 0.092 \pm 0.017$ [**?**]. It is clear that our knowledge of the smallest of the lepton mixing angles is quickly evolving. In the immediate future, reactor neutrino experiments [22, 23, 24] will soon provide improved results, T2K will resume full operation, and MINOS and NOνA are expected to add very useful information.

The main goal of next-generation neutrino oscillation experiments is to test whether the scenario outlined above, the standard three-massive-neutrinos paradigm, is correct and complete. This is to be achieved by not simply determining all of the parameters above, but "over-constraining" the parameter space in order to identify potential inconsistencies. This is not a simple task, and the data collected thus far, albeit invaluable, allow for only the simplest consistency checks. In the future, precision measurements, as will be discussed in Sec. 1.2, will be required.

Large, qualitative modifications to the standard paradigm are allowed. Furthermore, there are several, none too significant, hints in the world neutrino data that point to a neutrino sector that is more complex than what was outlined above. These will be discussed in Sec. 1.6. Possible surprises include new, gauge singlet fermion states that only manifest themselves by mixing with the known neutrinos, and new, weaker-than-weak interactions.

In the standard model, neutrinos were predicted to be exactly massless. The discovery of neutrino masses, hence, qualifies as the first concrete instance where the standard model failed. This is true even if the three-massive-neutrino paradigm described above turns out to be the whole story. More important is the fact that all modifications to the standard model that lead to massive neutrinos change it qualitatively. For a more detailed discussion of this point see, for example, [25].

Neutrino masses, while non-zero, are tiny when compared to all other known mass scales in the standard model,[2] as depicted in Fig. 1-2. Two features readily stand out: (i) neutrino masses are at least six orders of magnitude smaller than the electron mass, and (ii) there is, to be best of our knowledge, a "gap" between the largest allowed neutrino mass and the electron mass. We don't know why neutrino masses are so small

[2]Except, perhaps, for the mysterious cosmological constant.

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."

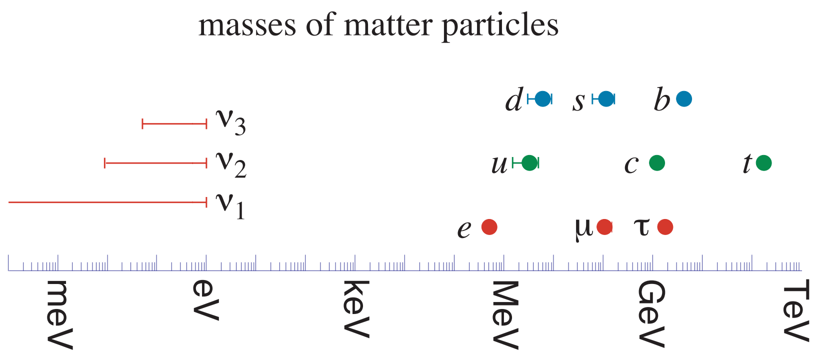

Figure 1-2. *Standard model fermion masses. For the neutrino masses, the normal mass hierarchy was assumed, and a loose upper bound $m_i < 1$ eV, for all $i = 1, 2, 3$ was imposed.*

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 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. 1.3, is to look for neutrinoless double-beta decay, a lepton-number violating nuclear process. The observation of a non-zero 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 non-zero 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 are all 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 answer lies in next-generation experiments, which will be described throughout this Chapter.

For concreteness 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 to the standard model higher-dimensional operators. As first pointed out in [26], 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:

$$\frac{1}{\Lambda}\,(LH)(LH) + h.c. \quad \Rightarrow \quad \frac{v^2}{\Lambda}\nu\nu + h.c., \tag{1.5}$$

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. (1.5). If the new physics is strongly coupled and Eq. (1.5) is generated at the tree-level, the new degrees of freedom are super-heavy: $M_{\rm new} \sim 10^{15}$ GeV. If, however, the new physics is weakly coupled or Eq. (1.5) is generated at the loop level, virtually any value for $M_{\rm new} \gtrsim 1$ eV is allowed. In summary, if Eq. (1.5) 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.

At the tree-level, there are only three renormalizable extensions of the standard model that lead to Eq. (1.5). They are referred to as the three "Types" of seesaw mechanisms, and are summarized as follows. For more details, see, for example, [27, 28].

- *Type I* [29, 30, 31, 32, 33]: The fermion sector of the standard model is augmented by at least two gauge singlets N_i which couple to the lepton and Higgs scalar doublets via a new Yukawa coupling y_ν. These so-called right-handed neutrinos are allowed to have Majorana masses M_N. After electroweak symmetry breaking, assuming $M_N \gg y_\nu v$, one generates Eq. (1.5). Here $\Lambda = M_N/y_\nu^2$.
- *Type II* [34, 35, 36, 37, 38]: The Higgs sector of the standard model is extended by one $SU(2)_L$ Higgs triplet Δ. The neutrino masses are $m_\nu \approx Y_\nu v_\Delta$, where v_Δ is the vacuum expectation value (vev) of the neutral component of the triplet and Y_ν is the Yukawa coupling that describes the strength of the Δ coupling to two lepton doublets. If the doublet and triplet mix via a dimensionful parameter μ, electroweak symmetry breaking can translate into $v_\Delta \sim \mu v^2/M_\Delta^2$, where M_Δ is the mass of the triplet. In this case, after one integrates out the Δ states, Eq. (1.5) is generated, and $\Lambda = M_\Delta^2/(\mu Y_\nu)$. Small neutrino masses require either $M_\Delta \gg v$ or $\mu \ll v$.
- *Type III* [39]: The fermion sector of the standard model is augmented by at least two $SU(2)_L$ triplets T_i with zero hypercharge. As in the Type I case, if these triplets couple to the lepton and Higgs scalar doublets via a new Yukawa coupling y_T, and are endowed with Majorana masses M_T, after electroweak symmetry breaking, assuming $M_T \gg y_T v$, one generates Eq. (1.5). Here $\Lambda = M_T/y_T^2$.

We will refer to different manifestations of these scenarios throughout this Chapter. Some predict new physics at scales that can be probed at the Energy Frontier or elsewhere in the Intensity Frontier, while others predict new physics scales that are way beyond the reach of laboratory experiments. 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. The synergy of neutrino physics with other fundamental physics is discussed in Sec. 1.7.

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, qualitatively, given by

$$|V_{\rm CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}, \tag{1.6}$$

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

$$|U_{\rm PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}. \tag{1.7}$$

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, for example, [27, 40]). Typical results include predictions for the currently unknown neutrino mass and mixing parameters ($\sin^2\theta_{13}$, $\cos 2\theta_{23}$, the mass hierarchy, etc) and the establishment of "sum rules" involving different parameters.

From the flavor physics perspective, the goals of precision neutrino oscillation physics can be broken down into the following questions: is the atmospheric mixing angle maximal ($\theta_{23} = \pi/4$)?, is there leptonic CP violation (or what is the value of δ)?, what is the ordering of mass eigenstates (sign of Δm^2_{31})?, what is the value of the "reactor" angle, θ_{13}?

Precision neutrino oscillation measurements are required in order 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 discussed in Sec. 1.8. 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. 1.5. 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 probe 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.

1.2 Testing the Standard Oscillation Paradigm

Physical effects of nonzero neutrino masses, to date, have only been observed 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.

1.2.1 Overview of Neutrino Oscillations

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 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 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 with 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 cancellation of systematic uncertainties.

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 $\Delta m^2_{21,31}$, defined in the Introduction. 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

$$A_{\alpha\beta} = \delta_{\alpha\beta} + U_{\alpha 2}U^*_{\beta 2}\left(\exp\left(-i\frac{\Delta m^2_{21}L}{2E}\right) - 1\right) + U_{\alpha 3}U^*_{\beta 3}\left(\exp\left(-i\frac{\Delta m^2_{31}L}{2E}\right) - 1\right), \quad (1.8)$$

$$\bar{A}_{\alpha\beta} = \delta_{\alpha\beta} + U^*_{\alpha 2}U_{\beta 2}\left(\exp\left(-i\frac{\Delta m^2_{21}L}{2E}\right) - 1\right) + U^*_{\alpha 3}U_{\beta 3}\left(\exp\left(-i\frac{\Delta m^2_{31}L}{2E}\right) - 1\right), \quad (1.9)$$

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 Figure 1-3. 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. (1.8,1.9) properly describe neutrino flavor-changing phenomena.

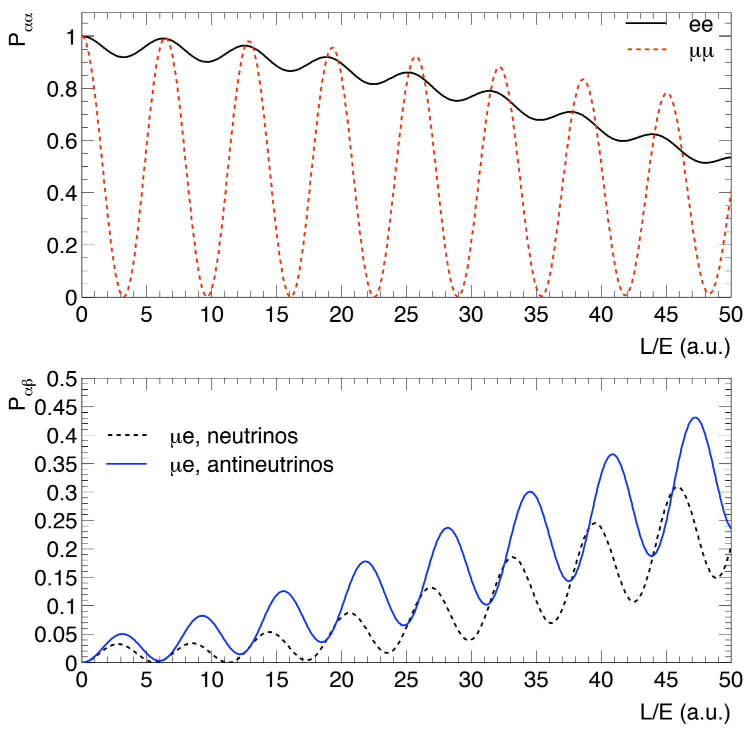

Figure 1-3. *Top: P_{ee} and $P_{\mu\mu}$ in vacuum as a function of L/E (in arbitrary units), for representative values of the neutrino oscillation parameters, including a nonzero value of δ. Bottom: $P_{\mu e}$ and $\bar{P}_{\mu e}$ in vacuum as a function of L/E, for representative values of the neutrino oscillation parameters.*

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 all measurements of $P_{\mu\mu}$ performed to date are, effectively, only sensitive to $|\Delta m^2_{31}|$ and $|U_{\mu 3}|$ – 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 $|U_{e3}|$ turns out to be much smaller than that of the other entries of U. For this reason, measurements of $\bar{P}_{ee}$ have only been precise enough to definitively observe Δm^2_{21}-driven oscillations and hence determine its magnitude, along with that of U_{e2}. The same is true of solar neutrino experiments. The current generation of reactor neutrino experiments is expected to measure $|U_{e3}|$ via precision measurements of $\bar{P}_{ee}$ governed by Δm^2_{31}. These results are expected to be insensitive to all other oscillation parameters.

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 most 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, [41, 42, 43]). 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 validity. For example, one would like to precisely measure θ_{13} in different channels, for different values of L and E in order 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 $\bar{P}_{\mu e}$,[3] as depicted in Fig. 1-3 (bottom), if the following conditions are met, as one can readily confirm by studying Eqs. (1.8,1.9): (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.

The fact that neutrino oscillation experiments might be sensitive to a directly CP-violating effect cannot be overemphasized. To date, all observed CP-invariance violating effects have occurred in experiments involving strange and B-mesons [44], along with tantalizing new hints from the charm sector (see, for example, [45, 46]). Furthermore, in spite of several decades of experimental searches, all of these are explained by the CKM paradigm – the three-flavor mixing paradigm in the quark sector – and all are functions of a unique CP-odd parameter in the standard model Lagrangian: the phase δ_{CKM} in the quark mixing matrix. Neutrino oscillations provide a unique opportunity to probe a brand new CP-violating sector of nature.

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

All neutrino data accumulated so far provide only hints for nonzero $P_{\mu\tau}$ [47, 48] and $P_{\mu e}$ [18, 19].[4] Both results are only sensitive to one mass-square difference ($|\Delta m^2_{31}|$) and to $|U_{\mu 3}U_{\tau 3}|$ and $|U_{\mu 3}U_{e3}|$, respectively. The goal of the current neutrino oscillation experiments NOνA 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. (1.8,1.9) are only valid when the neutrinos propagate in a vacuum. When neutrinos propagate through a medium, the oscillation physics is modified by so-called matter effects [49]. These are due to the coherent forward scattering of neutrinos with the electrons present in the medium and 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.[5] 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 may be observable in the Δm^2_{31} sector, as long as $|U_{e3}|$ 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 $A \ll \Delta m^2_{21,31}/E$. For $\Delta m^2_{31(21)}$ matter effects in the Earth's crust are significant for $E \gtrsim 1$ GeV (20 MeV).

1.2.2 Neutrino Experiments: Sources and Detectors

Next-generation experiments have at their disposal a handful of different 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. 1-4. Associated with each experiment is an appropriate detector. The nature and the capabilities of 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 a mostly unique opportunity to improve on the precision with which $\sin^2\theta_{12}$ is known [51]. 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 [49, 52]. Indeed, data from the SNO experiment seem to hint at potential deviations from standard model expectations [53]. During this decade, more (neutrino) light is expected to shine on this potentially very important matter, from the Borexino [54] and the SNO+ [55] 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 $\bar{\nu}_e$

[4] 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.

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

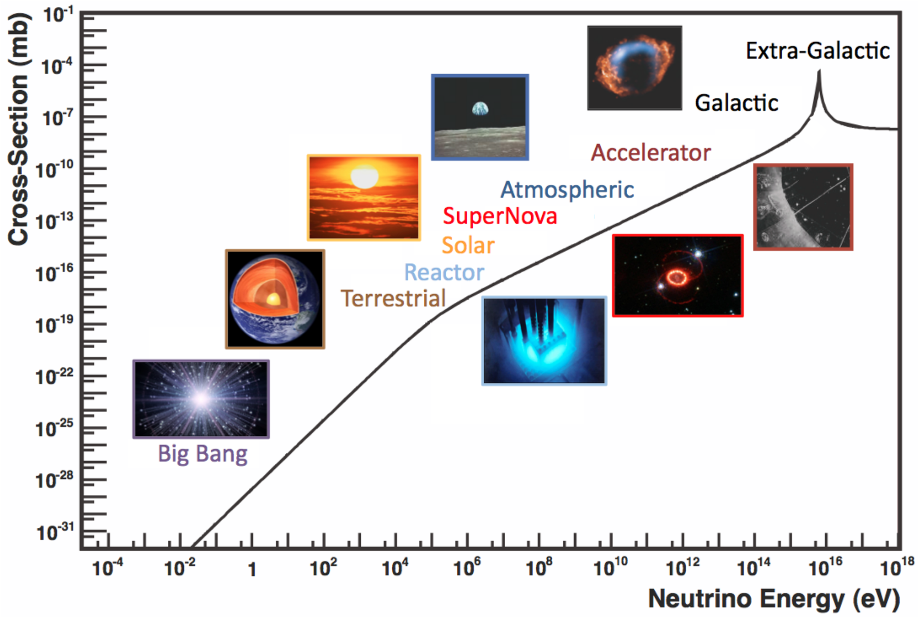

Figure 1-4. *Neutrino interaction cross section as a function of energy, showing typical energy regimes for different sources. The scattering cross section for $\bar{\nu}_e\, e^- \to e^-\, \bar{\nu}_e$ on free electrons is shown for comparison. Plot is reproduced from [50].*

spectrum, one or two kilometers away from the source. At these distances and energies one is only sensitive to Δm^2_{31}-driven oscillations. The necessary precision is expected to be achieved through the comparison 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 [56]. Reactor neutrino experiments with much longer baselines (say, 50 km) have been considered: see, for example, [57, 58]. These would be sensitive to both Δm^2_{31} and Δm^2_{21}-driven oscillations, and, in principle, would allow much more precise measurements of Δm^2_{21} and $|U_{e2}|$. A detector with exquisite energy resolution may also be sensitive to the neutrino mass hierarchy (see, for example, [59]).

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 in order 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 $\bar{P}_{\mu e}$ [60]. 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[6] and hence very intense neutrino sources and very large detectors. Intense neutrino sources, in turn, require very intense proton sources, of the type described in Sec. 1.8. 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." As far as challenges are concerned, 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 the next decade [61]. 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, [62]). 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 [63, 64, 65].

Muon decays are also an excellent source 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 [66], 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" [67].

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

1.2.3 Neutrino Oscillation Experiments: Achievements and Opportunities

The experimental achievements of the past fifteen years that have filled in the three-flavor neutrino picture have been astonishing. In both the "atmospheric" and "solar" sectors, an effect first observed with natural neutrinos was explored by several experiments and confirmed independently with artificial sources of neutrinos. In the atmospheric case, the ν_μ disappearance was confirmed by long-baseline beam experiments, K2K and MINOS. Solar neutrino oscillations measured by radiochemical experiments, Super-Kamiokande and SNO, were confirmed by, and the parameters constrained by, reactor $\bar{\nu}_e$ with KamLAND. A decade ago, the space of allowed oscillation parameters spanned many orders of magnitude; allowed regions have now shrunk to better than the 10% precision level.

The current generation of detectors on the hunt to measure θ_{13} are employing both reactor and boosted-pion-decay beam sources of neutrinos. The known natural sources of neutrinos used for oscillation experiments– solar and atmospheric neutrinos– still have information to be gained from them, both for understanding of neutrino properties and for studies of the sources themselves; furthermore a core collapse supernova will produce an enormous burst of neutrinos of all flavors that can be exploited for both neutrino oscillation physics and core collapse astrophysics. By the end of this decade, we anticipate new invaluable information from the current generation of neutrino oscillation experiments, namely the long-baseline beam experiments MINOS, T2K, and NOνA, and the reactor experiments Double Chooz, Daya Bay and RENO. In the language of the standard paradigm, these are very likely to measure θ_{13}, θ_{23}, and $|\Delta m^2_{31}|$ much more precisely, and may provide nontrivial hints regarding the neutrino mass hierarchy. While the possibility of surprises cannot, and certainly should not, be discarded, it is expected that the neutrino data accumulated until the end of the decade will be unable to definitively test the standard three-neutrino paradigm or observe CP-invariance violation in the lepton sector. That will be the task of next-generation experiments.

Future opportunities for testing the paradigm and probing new physics for next-generation neutrino oscillation experiments are broad and exciting. We will outline in detail the challenges in Section 1.8, and describe there both the global context and opportunities for the United States, but we briefly mention a few highlights here. The next focus for the U.S. is the Long-Baseline Neutrino Experiment (LBNE), which will employ a new beam from Fermilab and a large liquid argon time projection chamber at the Homestake mine in South Dakota, 1300 km away. LBNE will make use of a new beam from Fermilab of 700 kW power; the detector will be on the beam axis. Figure 1-5 shows the expected event spectrum with oscillation probabilities for a representative value of the mixing parameters superimposed.

Figure 1-6 shows the expected sensitivity of NOνA, T2K, and LBNE [68] to oscillation parameters of relevance. These plots are given in terms of "fraction of δ_{CP}": as a function of $\sin^2 2\theta_{13}$, they show the fraction of δ_{CP} values from 0 to 2π for which a 3σ discovery could be made (measurement of non-zero value for the cases of θ_{13} and δ_{CP}, or determination of the hierarchy). If $\sin^2 2\theta_{13}$ is indeed very close to ~ 0.1, as current data seem to prefer, these plots show that the prospects for determining the mass hierarchy are excellent, and chances for measurement of δ_{CP} are also very good. We note that sensitivity of LBNE will be enhanced with the addition of precision $\sin^2 2\theta_{13}$ measurements from other experiments (notably Daya Bay).

Beyond LBNE, Project X will sharply extend the reach for neutrino physics, in concert with diverse Intensity Frontier physics programs. The community's ideas for future physics measurements do not stop with these: there is an abundance of creative concepts for sources and detectors, many currently being explored. We describe some of those in more detail in Section 1.8. Tables 1-1 and 1-2 summarize the capabilities of current and future neutrino oscillation experiments.

Table 1-1. *Different 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, 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. 'Coherent ν-A' stands for very low-energy neutrino experiments, usually from spallation sources, aiming at measuring coherent neutrino–nucleus scattering. See text for more details.*

Expt. Type	ν_e disapp	ν_μ disapp	$\nu_\mu \leftrightarrow \nu_e$	ν_τ app[1]	Examples
Reactor	$\surd\surd$	–	–	–	KamLAND, Daya Bay, Double Chooz, RENO
Solar[2]	$\surd\surd$	–	$\surd$	–	Super-K, Borexino, SNO+, Hyper-K (prop)
Supernova[3]	$\surd\surd$	$\surd$	$\surd\surd$	–	Super-K, KamLAND, Borexino, IceCube, LBNE (prop), Hyper-K (prop)
Atmospheric	$\surd$	$\surd\surd$	$\surd$	$\surd$	Super-K, LBNE (prop), INO (prop), IceCube, Hyper-K (prop)
Pion DAR	$\surd$	–	$\surd\surd$	–	DAEδALUS
Pion DIF	–	$\surd\surd$	$\surd\surd$	$\surd$	MiniBooNE, MINERνA[4], MINOS(+, prop), T2K NOνA, MicroBooNE, LBNE (prop), Hyper-K (prop)
Coherent $\nu-$A[5]	–	–	–	–	CLEAR (prop), Ricochet (prop)
μ DIF[6]	$\surd$	$\surd\surd$	$\surd\surd$	$\surd$	VLENF, NuFact
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]MINERνA measures neutrino cross sections with the aim of reducing systematics for oscillation experiments. [5]Coherent elastic neutrino-nucleus scattering is purely NC and not sensitive to oscillation between active flavors. [6]The "standard" high-energy neutrino factory setups are not sensitive to electron appearance or disappearance.

Table 1-2. *Different types of current or proposed neutrino oscillation experiments and their abilitiy 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. '$\star\star\star$' 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 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	$\star\star\star$	$\star$	–	–	$\star$	$\star\star$	$\star\star$	–	$\star\star$
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	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star$	$\star$	$\star$	$\star\star$	$\star\star$
Coherent $\nu-$A	–	–	–	–	–	–	–	$\star\star\star$	$\star\star$
μ DIF	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star$	$\star$	$\star\star$	$\star\star$
β Beam	$\star\star\star$	–	$\star\star\star$	$\star\star$	$\star\star$	$\star$	$\star$	–	$\star\star$

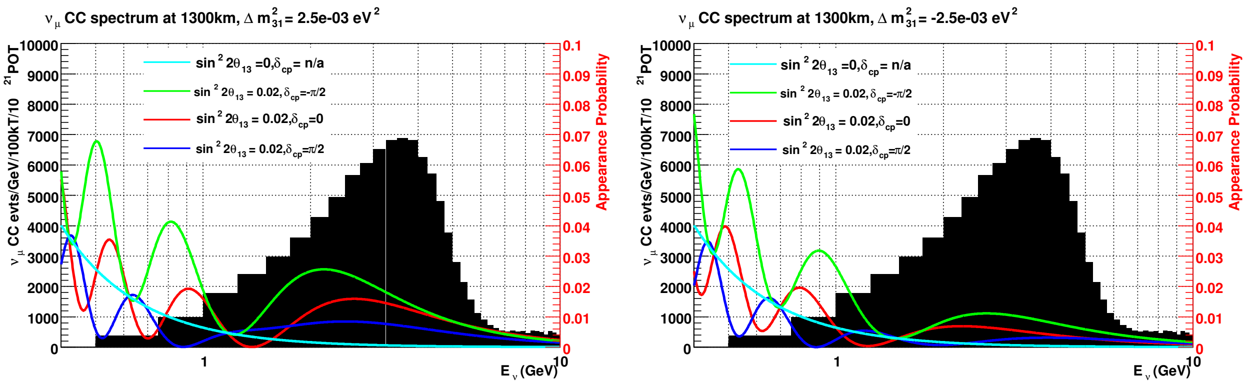

Figure 1-5. *The $\nu_\mu \to \nu_e$ oscillation probability for the LBNE to Homestake baseline of 1300 km for different mixing parameters with normal hierarchy (left) and inverted hierarchy (right), is shown as colored curves. The unoscillated CC ν_μ spectrum from an LBNE candidate beam is shown as the solid black histogram. From reference [68].*

1.3 The Nature of the Neutrino – Majorana versus Dirac

With the realization that neutrinos are massive, there is an increased interest in investigating their intrinsic properties. Understanding the neutrino mass generation mechanism, the absolute neutrino mass scale, and the neutrino mass spectrum are some of the main focuses of 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 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 anti-particle $\overline{\nu}_i$, 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 is mono-energetic. 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

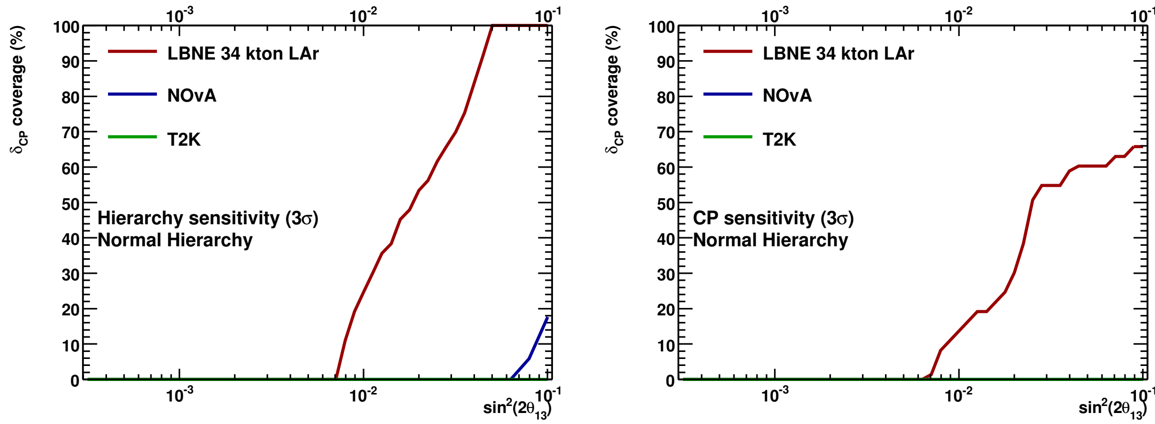

Figure 1-6. *3σ discovery potential of LBNE for determining the mass hierarchy (left), and CP violation (right) as function of $\sin^2 2\theta_{13}$ and the fraction of $\delta_{\rm CP}$ coverage. Here the fraction of $\delta_{\rm CP}$ reflects the fraction of all true values of δ_{CP} for which the corresponding quantity can be measured. Sensitivities are shown for normal mass hierarchy. Results for 5+5 years of ν+$\bar{\nu}$ running in a 700 kW beam for LBNE 34 kt LAr, NOνA (3+3 years of $\nu + \bar{\nu}$ running in a 700 kW beam), and T2K (3+3 years of $\nu + \bar{\nu}$ running in a 770 kW beam) are shown. Note that NOνA and T2K have no sensitivity to CP violation, and T2K has no sensitivity to hierarchy, at 3σ for this range of $\sin^2 2\theta_{13}$ using GLoBES model projections. From [69].*

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,

$$\langle m_{\beta\beta}\rangle = |\cos^2\theta_{12}\cos^2\theta_{13}e^{-2i\xi}m_1 + \sin^2\theta_{12}\cos^2\theta_{13}e^{-2i\zeta}m_2 + \sin^2\theta_{13}e^{-2i\delta}m_3|. \qquad (1.10)$$

If none of the neutrino masses vanish, $\langle m_{\beta\beta}\rangle$ is a function of not only the oscillation parameters $\theta_{12,13}, \delta$ and the neutrino masses $m_{1,2,3}$ but also the two Majorana phases ξ, ζ. Neutrino oscillation experiments indicate that at least one neutrino has a mass of $\sim$ 45 meV or more. As a result and as shown in Fig. 1-7, 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 is sometimes referred to as the atmospheric mass scale. Exploring this region requires a sensitivity to half-lives exceeding 10^{27} years. This is a challenging 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 [71]. These authors interpret the observation as giving an $\langle m_{\beta\beta}\rangle$ of 440 meV. Recent limits from NEMO-3 and Cuoricino (see below) are impinging on this $\langle m_{\beta\beta}\rangle$ regime, for ^{100}Mo and ^{130}Te respectively.

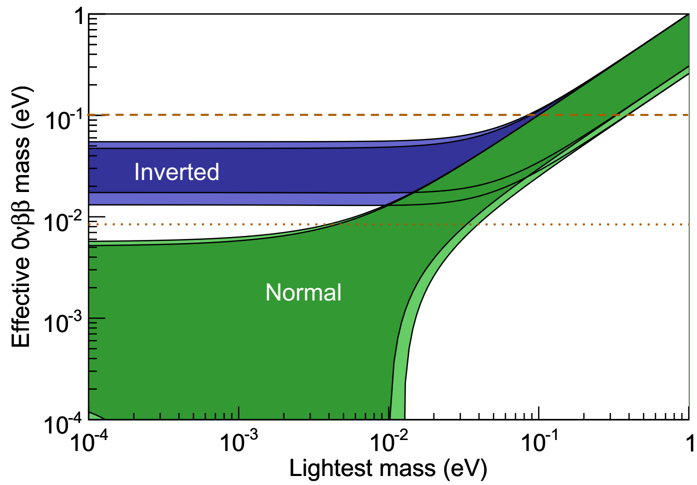

Figure 1-7. *Allowed values of $\langle m_{\beta\beta}\rangle$ as a function of the lightest neutrino mass for the inverted and normal hierarchies. The dark shaded regions correspond to the best-fit neutrino mixing parameters from [70] and account for the degeneracy due to the unknown Majorana phases. The lighter shading corresponds to the maximal allowed regions including mixing parameter uncertainties as evaluated in [70]. 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.*

There is a large number of current neutrinoless double beta decay search efforts, employing very different techniques; a recent review is [72]. 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.

The MAJORANA [73, 74, 75] experiment employs the germanium isotope ^{76}Ge, to be enriched. 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, with an aim of being underground at the Sanford Underground Research Facility (SURF) in 2013. The MAJORANA collaboration is planning a ton-scale effort in collaboration with its European counterpart GERDA.

The "bolometric" CUORE experiment [76], located at Gran Sasso National Laboratory in Italy, employs ^{130}Te in the form of TeO_2 crystals. This is a cryogenic setup which determines energy loss via temperature rise measured with thermistors. The first phase of this experiment, Cuoricino, ran from 2003-2008 with 11.3 kg of ^{130}Te mass. The current version of the experiment, CUORE-0, has 11 kg, and the plan for full CUORE starting in 2014 will have 206 kg.

The EXO experiment 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 175 kg of xenon enriched to 80% in the isotope 136. Both scintillation light from the interaction and ionization energy deposited by the electrons is detected in the xenon which is used in the liquid phase. 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 [77]. This ambitious plan– to tag a single ion in as much as ten tons of xenon – is currently under development, and there are several schemes under investigation, including gaseous versions of EXO. EXO-200 has recently reported the first observation of two-neutrino double-beta decay [78] in ^{136}Xe.

Another ambitious idea for a double-beta decay experiment is SNO+ [55]. 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 neutrino, geoneutrino and supernova neutrino physics. It may also be possible to add 0.1% Nd (possibly enriched with ^{150}Nd, the $0\nu\beta\beta$ decay isotope of interest) to the scintillator. Although typically the energy resolution of such a large detector would not naively be expected to meet the stringent standards of a neutrinoless double-beta decay search, the quantity of dissolved Nd would be so large that the neutrinoless signal would be visible as a clear feature in the spectrum.

KamLAND-Zen [79] (Kamioka Liquid Anti-Neutrino Detector, ZEro Neutrino double-beta decay) is an extension of the KamLAND[80] experiment. KamLAND is a 6.5-m radius balloon filled with 1000 tons of liquid scintillator, submerged inside a 9-m radius stainless-steel sphere filled with 3000 tons of mineral oil with PMTs mounted on the wall. The cavity outside this sphere is filled with water also instrumented with PMTs. KamLAND was built to search for reactor anti-neutrinos and the extension is intended as a search for neutrinoless double-beta decay. 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. This detector at the Kamioka mine in Japan began operation in September 2011, and 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 [81].

NEXT [82, 83] (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 $\sim$0.08 g/cm^3 that will also detect scintillation light. By operating at low pressures ($\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. The collaboration has recently demonstrated impressive 1% FWHM resolution in a limited fiducial volume device. Construction is scheduled to start in 2012 with commissioning to start in 2014. It will operate at the Laboratorio Subterráneo de Canfranc in Spain (LSC).

The SuperNEMO [84] proposal builds on the great success of the NEMO-3 (Neutrino Ettore Majorana Observatory) experiment, which measured two-neutrino double-beta decay rates in seven isotopes [85]. NEMO-3 has provided the best two-neutrino double-beta decay data to date including information on single-electron energy distributions and opening angles. The design uses calorimetry to measure energies and tracking to gather 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 present design is for 100 kg of ^{82}Se, but other isotopes are being considered. It will have a modular design of 20 thin-source planes of 40 mg/cm^2 thickness. Each source will be contained within a geiger-mode drift chamber enclosed by scintillator and phototubes. Timing measurements from digitization of the scintillator and drift chamber signals will provide topological information such as the event vertex and particle directionality. The modules will be surrounded by water and passive shielding. A one-module demonstrator with 7 kg of ^{82}Se is planned to be in operation by 2014. This Demonstrator will have only passive shielding. The complete experiment will be ready by the end of the decade in an extension of the LSM Modane in the Fréjus Tunnel in France.

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 independent oscillation experiments (or data from supernovae or colliders) determine the mass hierarchy 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 is not too diabolical). 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[86, 87]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Devel.	Yangyang
CANDLES[88]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL[89]	^{48}Ca	1 ton	CaF_2 scint. crystals	Devel.	Solotvina
COBRA[90]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[76]	^{130}Te	11 kg	TeO_2 bolometers	Constr. (2012)	Gran Sasso
CUORE[76]	^{130}Te	203 kg	TeO_2 bolometers	Constr. (2013)	Gran Sasso
DCBA[91]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Devel.	Kamioka
EXO-200[78]	^{136}Xe	160 kg	Liq. ^{enr}Xe TPC/scint.	Op. (2011)	WIPP
EXO[77]	^{136}Xe	1-10 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SURF
GERDA[92]	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Op. (2011)	Gran Sasso
GSO[93]	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Devel.	
KamLAND-Zen[94]	^{136}Xe	400 kg	^{enr}Xe disolved in liq. scint.	Op. (2011)	Kamioka
LUCIFER[95, 96]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Devel.	Gran Sasso
MAJORANA [73, 74, 75]	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Constr. (2013)	SURF
MOON [97]	^{100}Mo	1 t	^{enr}Mofoils/scint.	Devel.	
SuperNEMO-Dem[84]	^{82}Se	7 kg	^{enr}Se foils/tracking	Constr. (2014)	Fréjus
SuperNEMO[84]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal (2019)	Fréjus
NEXT [82, 83]	^{136}Xe	100 kg	gas TPC	Devel. (2014)	Canfranc
SNO+[98, 99, 55]	^{150}Nd	55 kg	Nd loaded liq. scint.	Constr. (2013)	SNOLab

Table 1-3. *A summary list of neutrinoless double-beta decay proposals and experiments.*

It is important to understand that several experiments using different isotopes are in order, at each step of sensitivity. This is because different isotopes involve different matrix elements with their uncertainties. In addition, unknown small-probability gamma transitions may happen to occur at or near the end point 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 neutrinoless double-beta decay 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 double-beta decay 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 may be low-energy trackers, in order to better investigate the $0\nu\beta\beta$ mechanism by measuring the energies of each electron separately as well as their angular correlations.

1.4 Weighing Neutrinos

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 to the phase space available in low-energy nuclear beta decay. The effect is indifferent to the distinction between Majorana and Dirac masses, and hence its observation would provide information complementary to neutrinoless double-beta decay.

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:

$$dN/dE \propto F(Z,E) p_e (E + m_e)(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2} \tag{1.11}$$

where E, p_e are the electron energy and momentum, E_0 the Q-value, and $F(Z,E)$ 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. 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.

In order to measure this spectrum distortion, any experiment must have the following properties:

- 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.
- an extremely well-known spectrometer resolution. The neutrino mass parameter covaries very strongly with the detector resolution.
- 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.

The KATRIN experiment [100, 101], 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 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 made very large, 53 cm^2 and 65 m^2 respectively. KATRIN anticipates achieving neutrino mass exclusion limit down to 0.2 eV at 95% confidence, or 0.35 eV for a 3-sigma discovery.

The MARE [102, 103] experiment attempts to extract the neutrino endpoint from the endpoint of ^{187}Re. Rhenium's extremely low endpoint, 2.6 keV, is seven times lower than tritium's; all else being equal, a ^{187}Re endpoint measurement has 7^3 times as much statistical power as a tritium measurement. However, because the ^{187}Re half-life is so long, it is impossible to make a strong transparent source; the decay energy is always self-absorbed. MARE attempts to capture this energy in a microcalorimeter with 1–3 eV energy resolution. To amass high statistics without pileup, MARE needs a large number of individual counters.

MARE is made possible by microbolometer-array technology pioneered in the x-ray astronomy community. MARE's arrays might include, on each of thousands of pixels: a rhenium source/absorber/calorimeter, a transition-edge sensor including readout wiring, and a weak thermal link to a cold support, all fabricated using lithographic techniques. A future implementation of MARE might include 10^5–10^6 microcalorimeters and achieve neutrino mass sensitivity comparable to KATRIN, with independent systematics.

Project 8 is a new technology for pursuing the tritium endpoint [104]; it is currently running proof-of-concept experiments, but anticipates providing a roadmap towards a large tritium experiment with new neutrino mass sensitivity. 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 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. If this is successful, Project 8 offers a tritium measurement strategy with very different scaling laws and systematics than KATRIN.

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 [105, 106, 107] are recent reviews, and see also Sec. 1.7.1.4.

1.5 Neutrino Scattering

While the initial discovery of neutrino oscillations was established using natural (solar and atmospheric) neutrino sources, much of the high precision investigations in the future will be performed with artificial neutrinos. In particular, long-baseline accelerator neutrino beams will play a fundamental role. Such long-baseline experiments will rely on intense neutrino sources to reduce statistical uncertainties and on very careful control of systematic errors. As such, these efforts will require detailed understanding of the interaction of few-GeV neutrinos to complete their experimental programs (the energy region being dictated by the baseline). One of the main sources of systematic uncertainty has and will continue to be poor knowledge of the underlying neutrino interaction cross sections. Figure 1-8 shows existing measurements of charged current 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.

In this energy regime, neutrino interactions are a complex combination of quasi-elastic scattering, resonance production, and deep inelastic scattering processes, each of which has its own model and associated uncertainties. While solar and reactor experiments operating at very low neutrino energies (10's of MeV) and scattering experiments at very high energies (100's of GeV) have enjoyed very precise knowledge of their respective neutrino interaction cross sections (at the few-% level), the same is not true for this intermediate energy regime. In this region, the cross sections are not very well known (at the $10-40\%$ level) and the data are in frequent conflict with theoretical predictions.

Neutrino cross section uncertainties are already becoming a limiting factor in the determination of neutrino oscillation parameters in many experiments. Understanding the underlying neutrino processes directly affects how well one can separate signal from background. Furthermore, experiments using heavier nuclear targets to increase their signal yields have to deal with the presence of significant nuclear effects impacting both the interaction cross sections and final state topologies. Such nuclear effects also impact one's ability to

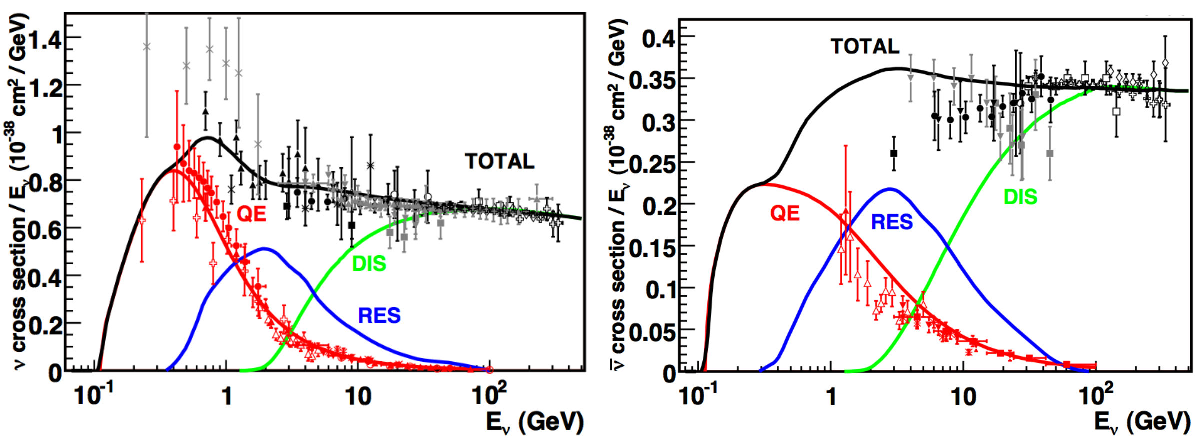

Figure 1-8. *Existing muon neutrino (left) and antineutrino (right) charged current cross section measurements [50] and predictions [108] as a function of neutrino energy. The contributing processes in this energy region include quasi-elastic (QE) scattering, resonance production (RES), and deep inelastic scattering (DIS). The error bars in the intermediate energy range reflect the uncertainties in these cross sections (typically* $10-40\%$ *depending on the channel).*

reconstruct the incoming neutrino energy, a key parameter in the determination of neutrino oscillation parameters. 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 have 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 [109]. In fact, if $|U_{e3}|$ is large, such systematic uncertainties become even more important because the expected neutrino/antineutrino asymmetry becomes increasingly smaller for larger $|U_{e3}|$.

Interest in neutrino interaction physics has recently surged due, in large part, to the demand for accurately predicting signal and background rates in such neutrino oscillation searches. Despite the presence of existing measurements from past experiments (which were pioneering at the time), these data sets are decades old, were not collected on the type of targets relevant for modern oscillation experiments, and generally are not of the precision needed for neutrino oscillation physics. Taking advantage of new intense sources of neutrinos, modern experiments have begun to remeasure these neutrino interaction cross sections, most importantly, on nuclear targets relevant to the neutrino oscillation program. This includes programs at the ArgoNeuT [110], K2K [111, 112, 113, 114, 115], MINERνA [116], MiniBooNE [117, 118, 119, 120, 121, 122, 123, 124, 125, 126], MINOS [127, 128, 129, 130], NOMAD [131, 132, 133, 134], and SciBooNE [135, 136, 137, 138] experiments. One of several intriguing results from these new data comes from recent measurements of quasi-elastic (QE) scattering. QE scattering is a simple reaction historically thought to have a well-known cross section; hence, one reason why it is chosen as the signal channel in many neutrino oscillation experiments. Interestingly, the QE cross section recently measured on carbon at low energy is about 30% higher than the most widely-used predictions [139] and is even larger than the free nucleon scattering cross section in some energy regions [122]. This is surprising because nuclear effects have always been expected to reduce the cross section, not enhance it. A recent QE cross section measurement at higher energies does not exhibit such an enhancement [133]. 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 energy [140]. A similar enhancement has been observed in electron scattering [141]. Significant discrepancies have also been noted in non-QE neutrino data sets [119, 120, 123]. If true, this radically changes our thinking of 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 (for some examples, see [142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162]. These recent discoveries emphasize that neutrino interactions on nuclei are quite complex, especially in the energy regime where we are conducting our neutrino oscillation measurements. Modern data is uncovering new and unexpected phenomena, but more data are surely needed to understand them.

In the near future, significant advances in our understanding of neutrino interactions are expected as new data arrive and are analyzed. New information will include neutrino and antineutrino data expected on a variety of nuclear targets and across a broad energy range from MINERνA, MicroBooNE, and the T2K and NOνA near detectors in the upcoming years. Beyond this, the proposed LBNE near detector complex will be able to add to this wealth of knowledge as well as supply the constraints needed for the long-baseline oscillation program in that experiment. Given the increasing importance of neutrino interaction physics and some surprising discrepancies being unearthed by recent experimental results, people have already started to think beyond this planned program and how we might add to it in both the short and long term. Such ideas include instrumenting the existing MINERνA detector with either hydrogen or deuterium targets [163], construction of a fine-grained detector in the NOνA narrow-band beam (SciNOνA) [164], design of a very low energy neutrino factory (VLENF) to provide precision ν_e and $\overline{\nu}_e$ cross section measurements [165], and installation of a magnetized, high resolution neutrino detector (HiResMν) to explore a host of neutrino interaction physics in the Project X neutrino beams [**?**].

We note also that for neutrino interactions for which cross sections are very well predicted in the context of the standard model, precision measurements provide means of determining standard model parameters such as the weak mixing angle, and enable searches for new physics. Included in this category are neutrino-electron elastic scattering and neutrino-nucleus coherent elastic scattering [166]. Stopped-pion sources are particularly promising for this kind of measurement; large detectors are needed for ν-e scattering experiments, for which cross section is quite small; however for very high-rate neutrino-nucleus coherent scattering, relatively small but very low-threshold dark matter WIMP-style detectors are suitable. (*e.g.* [167, 168]). A recent proposal is to use the far off-axis Fermilab Booster neutrino beam as a source of neutrinos for this measurement [169].

1.6 Beyond the Standard Paradigm – Anomalies and New Physics

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. The possible implications of additional sterile neutrino states would be profound and 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 sterile neutrinos exist?

Recently, a number of tantalizing results (anomalies) have emerged from short-baseline neutrino experiments that cannot be explained by the current three-neutrino paradigm. These anomalies are not directly ruled out by other experiments and include the excess of electron-antineutrino events (3.8σ) observed by the LSND experiment [170], the excess of electron-neutrino events (3.0σ) observed by the MiniBooNE experiment in neutrino mode [171], the excess of electron antineutrino events (2.3σ) observed by the MiniBooNE experiment in antineutrino mode [172], the deficit of electron-antineutrino events (0.937 ± 0.027) observed by reactor neutrino experiments [173], and the deficit of electron neutrino events (0.86 ± 0.05) observed by the SAGE and GALLEX gallium calibration experiments (see [174]).

How can we explain these anomalies? Although there are several possibilities (e.g., Lorentz invariance violation), one of the simplest explanations is the $3 + N$ sterile neutrino model, where there are 3 light, mostly active neutrinos and N heavy, mostly sterile neutrinos. For $N > 1$, these models allow for CP violation in short-baseline experiments. These $3 + N$ models fit the world's neutrino and antineutrino data fairly well [175, 176], albeit it in a not too convincing fashion.One key test of these $3 + N$ models is the existence of muon-neutrino disappearance ($\sin^2 2\theta > 10\%$) at a $\Delta m^2 \sim 1$ eV^2. Several workshops have been held over the past year to critically review the evidence for and against sterile neutrinos and the need to pursue new experiments and strategies to address the experimental observations [177, 178].

In order to determine whether these short-baseline anomalies are due to neutrino oscillations in a $3 + N$ sterile neutrino model and not to some other process or background, future short-baseline experiments with good electron and muon identification will need to measure (with precision) the L/E dependence of neutrino appearance and disappearance at L/E values of order 1. Various ways of measuring the L/E dependence have been proposed. These include: (1) positioning two or more detectors at different distances in an accelerator-induced neutrino beam in order to reduce systematic errors, (2) placing a large detector close to a source of low-energy neutrinos from a reactor or intense radioactive source and measuring the L/E distribution of neutrino events in the single detector, and (3) measuring the L/E distribution of high-energy (TeV) atmospheric-induced neutrinos, where strong matter effects are expected at particular values of L/E.

Diverse experiments, spanning vastly different energy scales, have been proposed or are being built to test the $3+N$ models and resolve the present anomalies. The MicroBooNE experiment is building a liquid-argon (LAr) TPC just upstream of the MiniBooNE detector that will be able to determine whether the event excesses observed by MiniBooNE are due to electron events, as expected from $3 + N$ models, or are simply due to unmodeled photon backgrounds (see Fig. 1-9). Another LAr TPC proposal is to move the ICARUS detector, now taking data in the Gran Sasso Laboratory, to the PS neutrino beamline at CERN and to build a second, smaller LAr TPC [179]. Similar options also exist in the Booster neutrino beamline at Fermilab. With two detectors at different distances, many of the associated systematic errors cancel, which will allow a definitive test of the LSND neutrino oscillation signal. Other accelerator neutrino experiments at Fermilab include the MINOS+ experiment [180], which will search with high sensitivity for muon neutrino to sterile disappearance, and the BooNE experiment [181], which proposes the construction of a second MiniBooNE-like detector at a different distance (200m) than the original MiniBooNE detector (541m). BooNE would have the potential to measure electron neutrino and electron antineutrino appearance, muon neutrino and muon antineutrino disappearance, and CP violation in the lepton sector, as well as demonstrating the existence of sterile neutrinos from the comparison of neutral current π^0 scattering at different distances. Fermilab already has world-class neutrino beams (the Booster neutrino beamline and NuMI); however, future facilities could significantly enhance these capabilities. These future facilities include Project-X, which would increase present proton intensities by an order of magnitude or more, and a muon storage ring, which would enable an extremely precise search for electron neutrino and electron antineutrino disappearance.

Besides at Fermilab and CERN, there are also several other opportunities for pursuing short-baseline neutrino physics. The Spallation Neutron Source (SNS) facility at ORNL produces an intense and well-understood flux of neutrinos from π^+ and μ^+ decay at rest. An idea has been put forward, OscSNS [182], for building a MiniBooNE-like detector approximately 60m from the SNS beam dump. OscSNS would be capable of making precision measurements of electron antineutrino appearance and muon neutrino disappearance. Also, the Southern California Reactor Antineutrino Anomaly Monitor (SCRAAM) [183] experiment could be built at the San Onofre nuclear generating station in California or at the Advanced Test Reactor, a research reactor at the Idaho National Laboratory. SCRAAM would have less baseline spread than previous reactor neutrino experiments and would be able to measure oscillations by looking for a spectral distortion in the reactor neutrino energy spectrum. In addition, neutrino radioactive source experiments could be mounted in either the Borexino, Daya Bay, KamLAND, or SNO+ detectors [184, 185]. The advantage of radioactive source experiments is that, due to the low neutrino energies, oscillations could be observed in a single detector or in several closely-separated detectors. There are also possibilties for performing sterile neutrino measurements

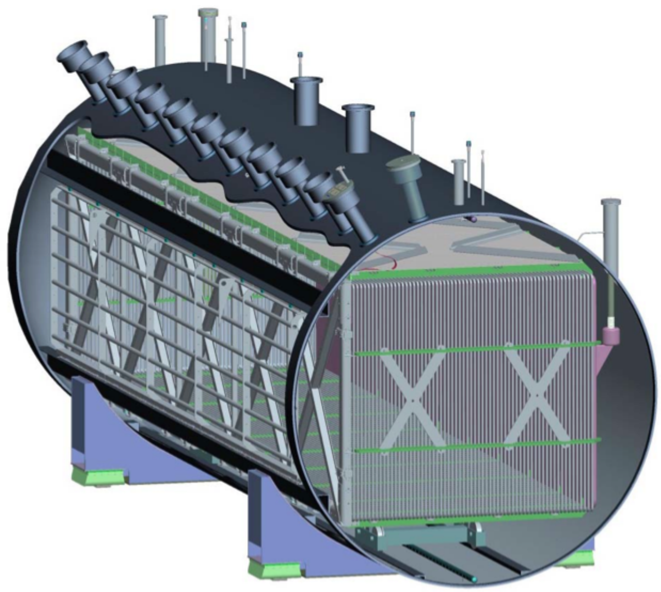

Figure 1-9. *Cutaway view of the MicroBooNE detector.*

in neutral current coherent neutrino-nucleon scattering using cryogenic solid state bolometers [168]. A final opportunity for measuring short-baseline oscillations is to search for atmospheric muon antineutrino disappearance with the IceCube experiment at the South Pole [186]. With a typical atmospheric neutrino energy of a few TeV and a typical distance of a few thousand km, IceCube is very sensitive to oscillations at the roughly 1 eV mass scale, especially because these oscillations would be matter-enhanced via the MSW mechanism.

Finally, we emphasize that satisfactorily resolving these short-baseline anomalies is very important for carrying the neutrino oscillation program described earlier. The two to three sigma effects reported, even if unrelated to sterile neutrinos, are at the sub-percent to the several percent level, similar to, for example, the $|U_{e3}|$ and CP-violating signals being pursued in long-baseline experiments.

Other than new light neutrino degrees of freedom – sterile neutrinos – neutrino experiments are sensitive to several other manifestations of new physics. For example, many proposals for new physics beyond the standard model predict novel, weakly interacting, light scalar or vector particles. Classical examples of such particles include Majorons, axions, Kaluza-Klein modes in the Randall-Sundrum scenarios with extra dimensions, and many others. As discussed over the years, novel light particles could be responsible, among other things, for solving the strong CP problem in QCD, giving neutrinos their mass, or even explaining the origin of Dark Energy. These new particles can be produced by proton bremsstrahlung and detected, assuming they are long-lived, by particle decays or scatters in the center of neutrino detectors, if the proton beam is on-axis.

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 modify neutrino propagation through matter effects. In a little more detail, NSI are described by effective operators proportional to, for example, $G_F \epsilon^f_{\alpha\beta} \nu_\alpha \gamma_\mu \nu_\beta \bar{f} \gamma^\mu f$, where $\nu_{\alpha,\beta} = \nu_{e,\mu,\tau}$, f are charged fermions $(e, u, d, \mu, s, \ldots)$, 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 ($L \to 0$), which are not present in the standard model case. More information – including relations to charged-lepton processes – current bounds, and prospects are discussed in detail in, for example, [187, 188], and references therein.

Very recently, the OPERA Collaboration observed that ν_μ produced at CERN and detected in Gran Sasso arrive at the detector before expected [189]. Interpreted as an anomalous velocity, the neutrinos travel faster than c with fractional difference $(v-c)/c = (2.37 \pm 0.32(\text{stat.})^{+0.34}_{-0.24}(\text{sys.})) \times 10^{-5}$. This result has caused much discussion and needs to be tested, although recent reports indicate some problems with the measurement. Similar long-baseline beam experiments will repeat the measurement, and similar measurements can be done by future long-baseline experiments discussed in this document. If the result holds up, independent experiments using different methods will be critical: for example, an experiment to measure neutrinos in coincidence with their "siblings" from the same parent mesons could be done at Fermilab [190]. Such experiments may be part of the Intensity Frontier.

1.7 Synergy with Other Fundamental Physics Efforts

The study of neutrino properties and interactions is truly interdisciplinary. For example, neutrino scattering provides information to, and requires input from, nuclear physics, low-energy strong interactions, and perturbative QCD, as discussed in Sec. 1.5. The very large detectors required for detecting beam neutrinos are also ideal for searching for nucleon decay, and the very intense proton sources required to produce the different neutrino beams are also necessary when it comes to searching for rare muon or kaon properties. The measurement of astrophysical neutrinos reveals a great deal about their sources and different neutrino properties shape the observable universe in different ways. Conversely, we may be able to infer elusive neutrino properties by observing astrophysical neutrinos or precisely understanding the energy budget and distribution of the universe.

Theoretically, one of the key questions is revealing the mechanism behind neutrino masses and lepton mixing. Regardless of the mechanism, one generically expects new degrees of freedom. We are not sure what those might be but, depending on the energy scale of this new physics, we expect to produce and detect new particles and phenomena through a variety of fundamental physics observables.

1.7.1 Neutrinos in Cosmology and Astrophysics

Neutrinos are copiously produced in astrophysical objects, including the Earth, the sun, and supernova explosions. Neutrinos are also predicted to be relics from the big bang. Finally, the physics behind neutrino masses may provide the answer to one of the most ambitious fundamental physics questions we are allowed to ask: why is there so much matter in the universe?

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

1.7.1.1 Geo- and solar neutrinos

The importance of solar neutrinos for understanding neutrino properties has been emphasized in Sec. 1.2. One of the original motivations for studying solar neutrinos, however, was to understand how the sun works. Neutrinos are produced deep inside the sun and exit effortlessly, hence carrying information that is not accessible through the solar photons. Neutrinos are still revealing details concerning the inner workings of the sun, and future measurements of the *pep* and CNO neutrinos appear very promising [51, 191]. For example, the Borexino collaboration recently announced the first positive measurement of *pep* neutrinos [192], along with a nontrivial upper bound on neutrinos from the CNO cycle, which are yet to be observed. Real-time *pp* neutrino observation is still a future goal, which may be within reach with next-generation very low energy threshold detectors.

Closer to home, the Earth is also a potent source of low-energy antineutrinos and neutrinos, thought to be mostly produced in the decay of uranium, thorium and potassium in the crust. Geoneutrinos were first observed in KamLAND [193] and Borexino [194], experiments designed to study reactor antineutrinos and solar neutrinos. More detailed studies of geoneutrinos, which can be made, for example, with next-generation liquid scintillator detectors, are expected to shine more light on the Earth as a heat source and on the Earth's composition (see, for example, [195]).

The center of the Earth, and especially that of the sun, is expected to act as a gravitational attractor for dark matter. The self-annihilation of dark matter inside these astrophysical bodies may yield high energy ($E \gtrsim 1$ GeV) neutrinos. Those, in turn, might be seen in large neutrino detectors, including IceCube (especially with the DeepCore "infill") [196]. The absence of a flux of high energy neutrinos from the sun provides the most stringent constraint on a class of dark matter models. In the future, the search for high energy solar and terrestrial neutrinos is expected to be among the most promising dark matter search channels [197].

1.7.1.2 Neutrinos from Core Collapse Supernovae

Approximately 99% of the energy released in the explosion of a core collapse supernova is emitted in the form of neutrinos. While these events are somewhat rare in our corner of the universe, the large neutrino detectors of the next generation can operate for decades. On this time scale, there is a significant likelihood of a core-collapse supernova exploding in our galaxy.

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. Furthermore, flavor sensitivity –not only interaction rate but ability to tag different interaction channels– is critical for maximizing the science harvest from a burst observation. Current-generation large detectors made of water and scintillator are primarily sensitive to $\bar{\nu}_e$; however next-generation detectors will expand worldwide flavor sensitivity; for example, liquid argon detectors are primarily sensitive to ν_e [198, 68]. If future Mton-scale detectors are built, prospects are excellent for a vast yield of information from a nearby burst, and we hope even for a reach extending well beyond the Milky Way [199]. With such tremendous rates, it will be possible to precisely measure not only the time-integrated spectra, but also their second-by-second evolution.

We quickly summarize what physics might be gleaned from this data. The first item is the mechanism of the explosion, which has been an unsolved issue in astrophysics for over half a century. Supernova neutrinos record the information about the physical processes in the center of the explosion during the first several seconds, as it happens. Next, the neutrino oscillation physics in a supernova is incredibly rich. 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 [200, 201, 202, 203, 204, 205, 206, 207, 208].) While the full picture is yet to be established, it is already clear that the spectra of neutrinos arriving on 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 this 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. Last but not least, the future data will allow 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 [209, 210]). These new particles could be produced in the extreme conditions in the core of the star and modify how it evolves and cools. The problem thus is very rich and truly multidisciplinary, with neutrino physics and astrophysics going hand-in-hand.

Looking even farther out for sources of neutrinos, one can imagine measuring the flux of neutrinos from all the supernovae in cosmic history. This "diffuse supernova neutrino background" (DSNB) is sometimes referred to as the "relic" supernova neutrino flux. The physics of the DSNB is reviewed in [211, 212]. The DSNB flux depends on the historical rate of core collapse, average neutrino production, cosmological redshift effects and neutrino oscillation effects. For neutrino energies above about 19 MeV, estimates for the $\bar{\nu}_e$ component of the DSNB range from about 0.1 to 1 $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The detection interactions remain the same as for burst neutrinos; however the experimental issues become entirely background-dominated, as there is no external trigger and events will be measured singly. Large gadolinium-doped water and scintillator detectors are especially promising for measuring this flux.

1.7.1.3 Ultra-High Energy Neutrinos from Cosmic Sources

The topic of ultra-high energy cosmic neutrinos is also at the intersection of the Intensity and Cosmic Frontiers. Thanks to their weak interactions, neutrinos are able to traverse very long distances free of impediment, unlike photons or charged particles. They are able to bring unique information about exotic astrophysical objects such as active galactic nuclei and gamma ray bursters, and in addition test neutrino oscillations and fundamental physics. Because the flux of neutrinos from such cosmic sources is expected to be very small, detectors must be extremely large: the current detectors searching for them are the cubic kilometer scale IceCube and ANTARES; upgraded versions of these are also planned. These detectors are also sensitive to atmospheric and supernova neutrinos as discussed elsewhere in this document. The physics and astrophysics reach of such searches is reviewed in [213, 214, 215].

1.7.1.4 Neutrinos and the early universe

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 and are safely consistent with the three known light neutrino species; see, for example, [216]. It is curious that the current data are also consistent with four light neutrinos. Future cosmological data are expected to provide precision measurements of the number of relativistic species and have the potential to not only probe the concordance cosmological model but also help reveal whether there are more very light degrees of freedom (more neutrinos?).

Neutrino properties directly impact the dynamics of the relic neutrinos, which in turn impact cosmological observables. Nonzero neutrino masses, for example, modify the dynamics of structure formation in the early universe. In a nutshell, massive neutrinos constitute a small part of the dark matter. However, given what is known about neutrino masses, neutrinos are relativistic at the time of decoupling – neutrinos are hot dark matter – and their presence dampens the formation of structure at small distance scales. The heavier the neutrinos, the more they influence structure formation, and less structure is expected at small scales. They are consistent with 100% cold dark matter and allow one to place an upper bound on the neutrino masses. Current data constrain, assuming the concordance cosmological model, the sum of the neutrino masses to be less than around 0.5 eV. In the future, it is expected that cosmological observables will be sensitive to the sum of neutrino masses if it is larger than 0.05 eV, perhaps smaller [106]. It is worthwhile pointing out that the current neutrino oscillation data require $\sum m_i > 0.05$ eV, meaning that, assuming the concordance cosmological model, next-generation cosmological observations are expected to observe effects of the relic neutrino masses.

Deviations from the concordance cosmological model or new physics beyond the standard model of fundamental particles can dramatically modify the relation between cosmological observables and neutrino properties. The extraction of neutrino properties from cosmological observables is, in some sense, complementary to that from terrestrial experiments. By comparing the results from these two different classes of experimental efforts, we can not only determine different properties of the massive neutrinos, including exotic ones, but also hope to test and, perhaps, move beyond the concordance cosmological model.

The "holy grail" of neutrino astrophysics/cosmology is the direct detection of the relic neutrino background. These are extremely cold (1.95 K $= 1.7 \times 10^{-5}$ eV) and today, at least two of the neutrino species are nonrelativistic. Several different ideas have been pursued, and a clear path towards successfully measuring relic neutrinos is yet to emerge. Recently, the idea, first discussed in [217], of detecting relic neutrinos through threshold-less inverse-beta decay – e.g., $\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$ – has received some attention [218]. In a nutshell, the β-rays produced by the relic neutrino capture have energies above the end point of the β-rays produced by the ordinary nuclear decay. The expected number of interactions turns out to be accessible for intense enough nuclear samples, such that with enough energy resolution, one can aim at directly determining the existence of the relic neutrinos.

1.7.1.5 Leptogenesis

The right-handed neutrinos in the Type I seesaw mechanism are Majorana fermions and hence do not have a well-defined lepton number. This means that right-handed neutrinos, assuming these are heavy enough, can decay into final states with positive lepton number and final states with negative lepton number. If these decays are CP-violating, right-handed neutrino decays in the early universe can, under the right conditions, generate a lepton-number asymmetry. As the universe cools, part of this lepton asymmetry gets converted into a baryon asymmetry, which translates into a universe with more matter than antimatter and hence a "large" matter density – like the universe we find ourselves in. This process of generating a baryon asymmetry through a lepton asymmetry is referred to as leptogenesis [219].[8] In straightforward versions of leptogenesis, these heavy neutrinos must have masses of 10^9 GeV or more, so that, at least for a long time to come, we will not be able to confirm their existence directly by producing them at an Energy Frontier collider. Instead, the hypothesis of leptogenesis must be explored indirectly through Intensity Frontier experiments with the light neutrinos ν related to the heavy neutrinos N through the seesaw mechanism.

A major motivation to look for CP violation in neutrino oscillations is that its observation would make it more plausible that the baryon-antibaryon asymmetry of the universe arose, at least in part, through leptogenesis.

[8]Similar mechanisms can also be realized in several other neutrino mass models, including the Type II and III seesaws.

To be sure, it can be shown that if all the heavy neutrino masses exceed 10^{12} GeV, then the phases that drive leptogenesis are independent of those in the neutrino mixing matrix [220, 221, 222, 223]. However, there is no need for the heavy neutrino masses to be this large. Indeed, supersymmetry suggests that the mass of the lightest N must be $\sim 10^9$ GeV [224]. It has been shown that when the smallest N mass is below 10^{12} GeV, CP-violating phases in the neutrino mixing matrix, which produce CP violation in light-neutrino oscillation and influence the rate for neutrinoless double-beta decay, lead also, barring accidental cancellations, to a baryon-antibaryon asymmetry [225]. Assuming the seesaw picture, leptogenesis and light-neutrino CP violation generically do imply each other.

1.7.2 Neutrinos and the Energy Frontier

The new degrees of freedom associated with nonzero but small neutrino masses can be directly produced and detected in fundamental physics experiments as long as $M_{\rm new}$ is not exceedingly large. In the Type I seesaw, for example, the right-handed neutrinos can be produced and detected in neutrino oscillation experiments if $M_{\rm new} \lesssim 10$ eV (see, for example, [226]). They look like sterile neutrinos. If $M_{\rm new} \gg 10$ eV, these may still manifest themselves in medium ($M_{\rm new} \lesssim 1$ GeV) and high energy experiments ($M_{\rm new} \lesssim 1000$ GeV). We note, however, that, realistically, any signal of a heavyish N would indicate a more subtle manifestation of the Type I seesaw [227, 228], for the following reason. A generic prediction of the Type I seesaw is that the induced mixing between active and sterile states, which governs right-handed neutrino production, is $U^2_{N\ell} \sim m_\nu/M_N$ and hence unobservably small for $M_N \gg 100$ keV.

In the case of the Type II and III versions of the seesaw mechanism, the situation is markedly different. We comment on those in more detail. Most important, here the new degrees of freedom – extra Higgs scalars or extra charged fermions – can be produced via electroweak interactions at, for example, the LHC, as long as the new states are not too heavy. Furthermore, by studying the production and decay properties of the new states one can both verify that they are connected with the neutrino mass generating mechanism and, perhaps, measure properties of the neutrino oscillation parameters, like the neutrino mass hierarchy.

Several earlier studies for certain aspects of the Type II seesaw model at the LHC exist [229, 230, 231, 232, 233, 234]. The couplings of the new states in the Higgs sector to the standard model fermions are directly proportional to the neutrino masses and the lepton mixing angles. According to the current understanding of neutrino oscillation parameters, Fig. 1-10 depicts the different branching ratios of the $H^{\pm\pm}$ states into leptonic final states [235]. The synergy is apparent: by identifying the flavor structure of the lepton number violating decays of the charged Higgs bosons at the LHC, one can establish the neutrino mass pattern: normal mass hierarchy, inverted mass hierarchy or a quasi-degenerate neutrino mass spectrum.

In the case of the Type III seesaw, the different components of the lepton triplet can be produced via electroweak interactions at the LHC. Furthermore, similar to the Type II seesaw model, some versions of the Type III seesaw model (e.g., [236]) also predict a clear correlation [237] between the neutrino mass matrix and the couplings of the new heavy lepton triplet $T^\pm$ and T^0,

$$m_\nu^{ij} \sim -v^2 \frac{y_T^i y_T^j}{M_T}, \quad BR(T^{\pm,0} \to W^\pm \ell,\ Z\ell) \sim y_T^2 \sim U^2\ \frac{M_T m_\nu}{v^2}, \tag{1.12}$$

where U is the familiar neutrino mixing matrix. The collider search for the production of, say, $T^+ + T^0 \to \ell^+ Z(h) + \ell^+ W^- \to \ell^+ jj(b\bar{b}) + \ell^+ jj$ directly probes, as long as M_T is within reach, the underlying neutrino mass generation mechanism via the lepton flavor correlations governed by the ν mass pattern.

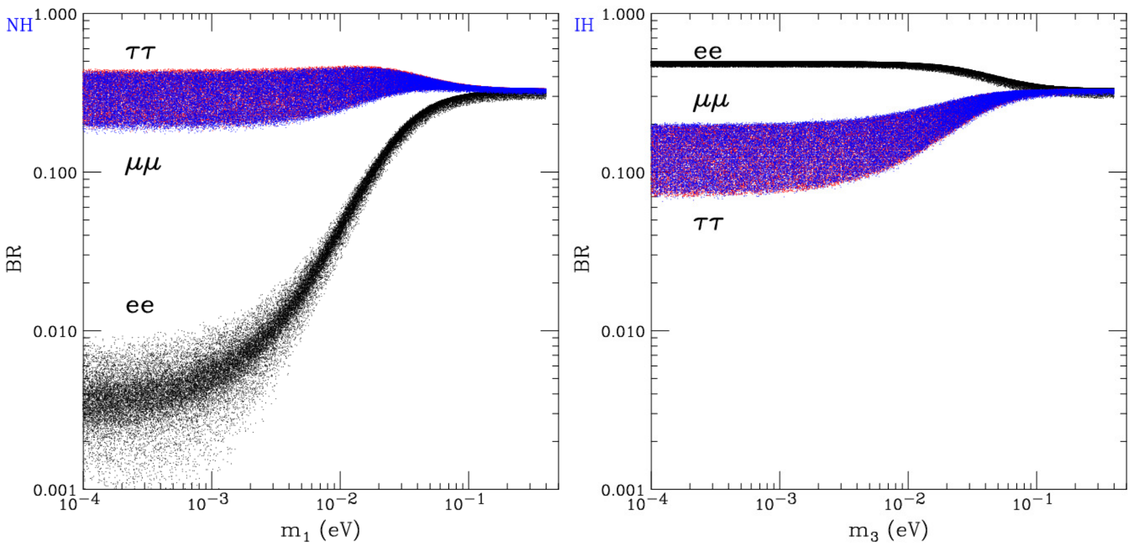

Figure 1-10. *$H^{\pm\pm}$ decay branching fractions as a function of the lightest neutrino mass, assuming a normal (left) or inverted (right) neutrino mass hierarchy. See [235] for details.*

1.7.3 Neutrinos and the "Other" Intensity Frontier

Our understanding of neutrinos stands to increase significantly through the efforts of Intensity Frontier research outside of those discussed in this Chapter. Moreover, as already mentioned in passing, several Intensity Frontier efforts share facility and detector needs with neutrino physics efforts. The most transparent examples include searches for nucleon decay, which also require very massive detectors capable of detecting O(1 GeV) muons and electrons, and searches for rare meson and muon processes, which also require very intense proton sources. There is also strong experimental synergy between between neutrinoless double-beta decay and dark matter direct search detectors.

1.7.3.1 Charged lepton properties

Experiments related to determining the properties and interactions of charged leptons, including precision measurements of the muon magnetic dipole moment, searches for a nonzero muon or electron electric dipole moment, and searches for rare processes that violate charged-lepton flavor ($\mu \to e$ conversion in nuclei, $\ell \to \ell' \gamma$, etc), are potentially very sensitive to the physics responsible for neutrino masses. Conversely, precision measurements of muon properties and other rare charged-lepton processes may not only help reveal the mechanism behind neutrino masses but also play a role in determining neutrino oscillation parameters. The general argument is as follows. The new physics that has manifested itself in the neutrino sector in the form of nonzero neutrino masses is likely to leave its largest imprint in the charged-lepton sector, given the stringent connection between charged leptons and neutrinos. Charged-lepton flavor violation searches have the ability to help determine the flavor structure of the new physics, while searches for electric dipole moments may help establish the relationship between the new physics and CP invariance.

As a more concrete example, neutrino oscillation data already reveal that charged-lepton flavor-violating processes must happen. The reason is simple. Neutrino oscillation experiments reveal that individual lepton-flavor numbers (electron-number, muon-number, tau-number) are not conserved. On the other hand, individual lepton-flavor number conservation was the only symmetry preventing, e.g., $\mu \to e\gamma$ decays from happening. Because the mechanism behind neutrino masses is unknown, the expected "neutrino induced" contribution is unknown. If the neutrinos are Dirac fermions, for example, or if neutrino masses are a consequence of the Type-I seesaw and the new physics scale is very high (say, $M_N \sim 10^{14}$ GeV), the expected rates for charged-lepton flavor violating processes are exceedingly small.[9] If the new physics scale $M_{\rm new}$ is closer by, however, the situation can be markedly different.

There are abundant examples in the literature. Fig. 1-11 depicts the rate for different muon-flavor violating processes as a function of $|U_{e3}|\cos\delta$, in the case of the Type-II seesaw [238]. The overall expectation for the transition rates depends on parameters external to the neutrino mass matrix, like the triplet mass and vacuum expectation value. The combination of data from neutrino oscillation experiments, the Energy Frontier (say, the LHC) and charged lepton flavor violating searches in the Intensity Frontier should ultimately allow one to thoroughly test particular Higgs triplet models and, if these turn out to be correct, unambiguously reveal the physics behind neutrino masses.

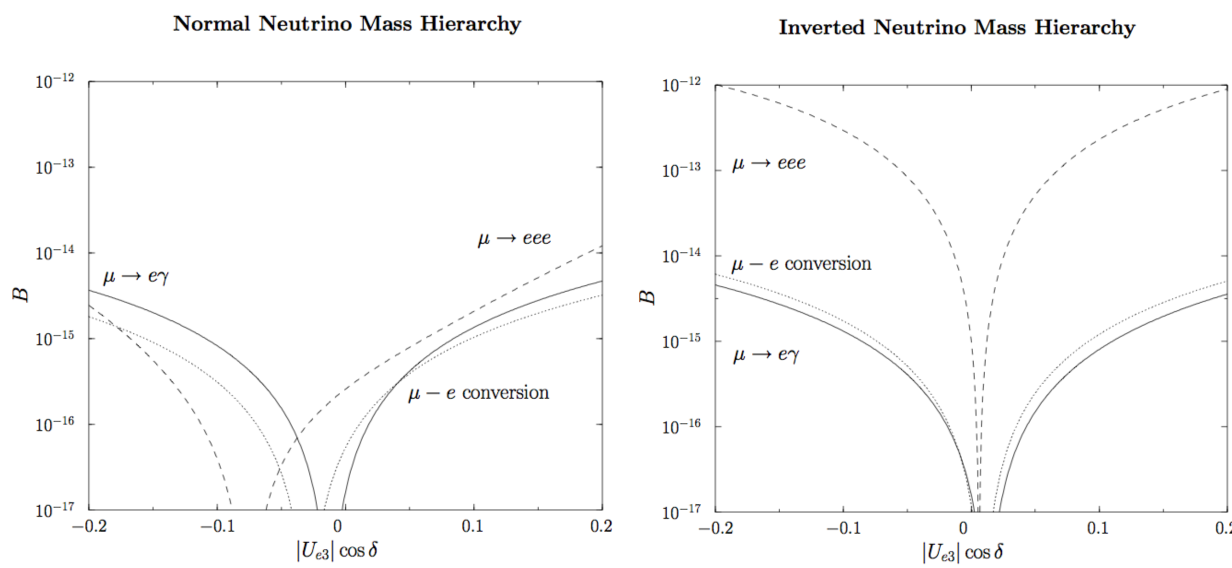

Figure 1-11. *The branching ratios B for $\mu \to e\gamma$ (solid line) and $\mu \to eee$ (dashed line), and the normalized capture rate B for $\mu \to e$-conversion in Ti (dotted line) as a function of $|U_{e3}|\cos\delta$ in a scenario where neutrino masses arise as a consequence of the presence of a triplet Higgs field with a small vacuum expectation value. The lightest neutrino mass is assumed to be negligible while the neutrino mass hierarchy is assumed to be normal (left) and inverted (right). See [238] for details.*

Another important example of the potential interplay between the Energy Frontier, the Cosmic Frontier, and the Intensity Frontier, via experiments with charged leptons and neutrinos, is the possibility to test the leptogenesis hypothesis. If all the new physics associated with generating the baryon asymmetry of the universe is very heavy, it won't be tested directly at the Energy Frontier. If, however, the LHC uncovers new particles at the TeV scale, it is likely that these new degrees of freedom will also be imprinted, just like the neutrinos, with information from very high energy scales. This information, most likely, can only be revealed through searches for charged lepton flavor violation, which are closely related to the flavor properties of the few TeV scale degrees of freedom. All this information, combined with precision measurements of neutrino oscillation parameters – including CP-invariance violating observables – and the confirmation that neutrinos are Majorana fermions, should allow a very powerful, albeit still indirect, test of the leptogenesis hypothesis.

[9] For example, if the neutrinos are Dirac fermions and there is no other new physics, one can compute $B(\mu \to e\gamma) \lesssim 10^{-54}$.

For concrete realizations, see, e.g., [239, 240]. If the seed for the baryon asymmetry is planted when the universe was 10^{-30} seconds old, an indirect test of the mechanism may be as good as it gets.

1.7.3.2 Lepton-number violation in rare meson decays

The relation between neutrinos and quarks is not as straightforward as the one between neutrinos and charged leptons, but the synergy between neutrino physics and meson properties and processes is also significant. As an example, rare meson decays offer several channels for the exploration of lepton-number violation and, as already emphasized, whether lepton number is an exact symmetry of nature is among the most important anticipated pieces of the neutrino mass puzzle. Some of the most stringent constraints on lepton-number violation, other than searches for neutrinoless double-beta decay, come from the meson decay processes

$$M^{\pm} \to \ell^{\pm}\ell'^{\pm}M^{\mp}, \tag{1.13}$$

where $M^{\pm}$ are charged mesons, e.g., $\pi^{\pm}$, $K^{\pm}$, $D^{\pm}$, or $B^{\pm}$, while $\ell, \ell' = e, \mu, \tau$. The searches for these very rare decay processes can be carried out at a variety of Intensity Frontier facilities, from dedicated kaon experiments to B-factories to the LHCb detector. They currently provide the strongest constraints on MeV-scale new, mostly sterile, Majorana neutrinos. For details see, for example, [241]. These states, if discovered, would reveal that lepton number is not a fundamental symmetry of nature and would provide precious information regarding the origin of neutrino masses.

1.8 Facilities and Instrumentation Challenges

In this section we will describe the basic approaches for future experimental steps, and then describe specific programs globally and in the United States.

1.8.1 Experimental Approaches

As described in Section 1.2, the basic approach for measuring oscillation parameters and testing the three-flavor paradigm is to observe either appearance or disappearance of flavors in well-understood neutrino fluxes, as a function of energy and baseline. Well-understood neutrino sources can also be used for cross section measurements and other physics.

1.8.1.1 Neutrino Source Development Challenges

Sources of neutrinos for oscillation experiments can be either natural or artificial. As described in the previous sections, experiments will continue to exploit natural sources of neutrinos– solar, geo-, supernova, and atmospheric neutrinos – for both particle physics and astrophysics. Of course, natural neutrinos require no source development; the experimental challenges in these cases are in the detection technology.

In contrast, development of artificial sources of neutrinos present significant challenges for experimentalists. For the forseeable future, nuclear power reactors [22, 23, 24], which will be exploited over the next ten years for different experiments, are not really candidates for neutrino source R&D: high-power reactors are of course typically designed to optimize electrical power generation, and neutrino experimentalists benefit from the inevitable neutrino by-products. However radioactive sources of low-energy neutrinos have been proposed for some experiments, and creation of high-intensity sources of radioactive isotopes (in reactors or with cyclotrons) requires technical development.

Stopped pion (and muon) neutrino beams (really, isotropic sources) have been employed in the past [242, 243] and can be employed for different oscillation studies, cross section measurements and standard model tests. High-intensity sources such as the Spallation Neutron Source exist but as yet have not been used for neutrino experiments. Recently, there have been proposals to use this type of neutrino source alone or in combination with conventional beams to study CP violation; see [244, 245] and Section 1.8.2.2. A high-intensity stopped-pion source employing novel cyclotrons requires some significant work, but there are connections with applications in industry.

For the "standard" boosted-pion-decay beam of the type used at KEK, FNAL and J-PARC, in which pions are produced by proton irradiation of a thick target, focused forward with a "magnetic horn", and allowed to decay in a long evacuated pipe, design issues are relatively well understood. There are indeed challenges to achieve the proton intensities required for MW "superbeam"-scale beams; however the difficulties seem relatively straightforward to surmount and there are several future proposals for superbeams. There are several challenges associated with measuring neutrino oscillations in superbeam experiments. The beam flavor composition is not simple. Kaon decays and the decays of daughter muons lead to a nonzero flux of ν_e, while a subdominant population of "wrong sign" ν_μ survives the pion charge-selection mechanism. Furthermore, the energy dependence of the neutrino flux is not very well characterized, and near detectors are necessary in order to "measure" the different neutrino fluxes. Furthermore, the charged-current scattering cross section for GeV-scale neutrinos is very hard to model and is yet to be measured with the required precision. This fundamentally important issue is subject of ongoing research and is expected to play a central role in next-generation neutrino experiments. This issue was discussed in some detail in Sec. 1.5. Finally, the measurement of ν_e charged current events is challenging due to beam-induced backgrounds, mostly from neutral pions produced in neutral current ν_μ events. Ultimately, it is fair to say that sub-percent measurements of oscillation probabilities using neutrino superbeams appear to be, at the very best, very challenging.

Farther-future oscillation neutrino sources include neutrino factories and β-beams. The potential high intensity, boost tunability, and lepton sign selection are highly desirable. The technical challenges, however, are large. In particular, for a neutrino factory, methods for "cooling" the muon transverse momentum still require further development. An international design study for a neutrino factory is currently underway [246]. It aims at identifying in detail the steps necessary to demonstrate that a neutrino factory can be built, and at laying out a plan for doing it. The challenges associated with the production of β-beams are also many but well-known. The international design study for a neutrino factory is also charged with assessing the challenges and the virtues of β-beams.

1.8.1.2 Large Detector Development Challenges

Because of the tiny neutrino interaction cross section, detectors for neutrino experiments must typically be very large. Although for some short-baseline oscillation (and other neutrino) experiments, relatively modest scale (kTon or less) detectors can be used, for long-baseline oscillation experiments and for astrophysical neutrinos, detector masses of multi-kTon and upwards scale are required.

There are three main kinds of detector technology under consideration for the next generation of multi-kTon detectors: water Cherenkov, liquid argon and liquid scintillator. See Figure 1-12. Of these, water and liquid argon are the most suitable for long-baseline oscillation experiments, due to better high-energy event reconstruction capabilities.

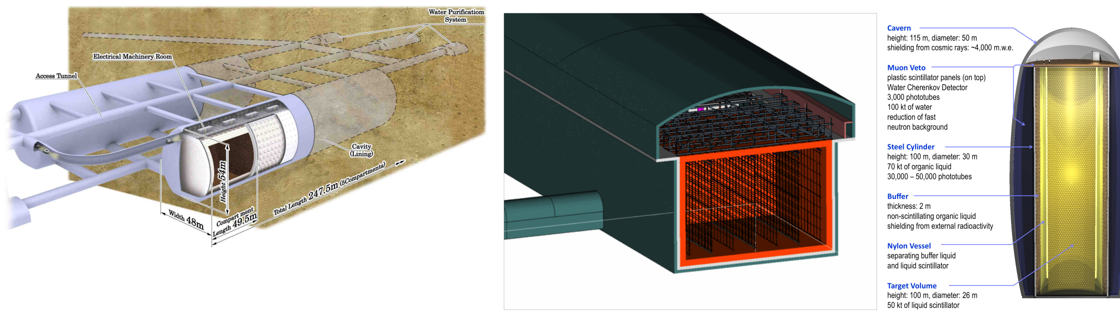

Figure 1-12. *Left: example of a large water detector concept (Hyper-Kamiokande). Center: example of a large liquid argon detector concept (LBNE). Right: example of a large scintillator detector concept (LENA).*

Water Cherenkov Detectors Water Cherenkov detectors, in the form of large volumes of ultrapure water surrounded by photomultiplier tubes (PMTs), are sensitive to the charged particles produced by interactions of neutrinos with energies greater than a few MeV. Charged particles moving faster than the speed of light in a medium produce Cherenkov photons if $\beta > 1/n$, where n is the refractive index of the medium. Water is a convenient and cheap detector material, suitable for neutrino detection because very large volumes can be deployed cheaply, even though light yields are typically much lower than for scintillator. However, due to the Cherenkov threshold, heavy particles are invisible, and signals from low energy electrons, positrons and gammas (which are detected via Compton-scattered electrons) may be lost. Both low (few to few tens of MeV, relevant for solar, supernova and stopped-pion neutrinos) and high ($\gtrsim$ GeV, relevant for beam and atmospheric neutrinos as well as proton decay) neutrino detection are possible in large water Cherenkov detectors. In Cherenkov detectors, particle direction information is available using the angular information from the Cherenkov ring. This is helpful both for reconstructing multiple particles in high energy interactions, and for reconstructing neutrino-electron elastic scattering events at low energy. Particle type can be determined by evaluating the "fuzziness" of a track: electrons and gammas scatter and shower, whereas muons and pions have sharp tracks; the Cherenkov angle can also be of use for particle identification. Low energy event detection may potentially be enhanced in water using Gd doping [247], for which neutrons are captured on gadolinium nuclei, producing a cascade of gammas with $\sim$4 MeV visible energy; this allows tagging of interactions which produce neutrons, such as inverse beta decay. There are also ideas for developing a large area picosecond photosensor-based detector filled with water-based liquid scintillator to expand the capabilities of these detectors to low energy particles and for improved particle identification [**?**].

Past water Cherenkov detectors include IMB [248] and Kamiokande [249]. The successful use of the technology for a wide range of physics topics is well proven at the few-tens-of-kTon scale: Super-Kamiokande [250] has been running for more than fifteen years and has demonstrated a broad range of physics capabilities over several orders of magnitude in energy. Proposed next-generation water Cherenkov detectors include Hyper-Kamiokande [251] in Japan and MEMPHYS [252] in Europe.

Phototubes can also be embedded in ice or suspended in water in long-string configurations. This kind of configuration is primarily sensitive to high energy (greater than multi-GeV) neutrinos, although there is also some sensitivity to supernova neutrinos [253]. The science goals of existing long-string detectors are primarily to study astrophysical objects, although there is oscillation sensitivity with atmospheric (or cosmic) neutrinos as well. Examples are IceCube, ANTARES, and Lake Baikal; planned next generation efforts are KM3NET and ideas for denser infill of Antarctic ice, possibly with enhanced photosensors (PINGU [254]).

In the much farther future, such an enhanced detector could conceivably serve as a target for a long-baseline beam [255].

Liquid Argon Time Projection Chambers Liquid argon (LAr) time projection chambers do not suffer from the Cherenkov threshold issue, and in principle extremely high quality particle reconstruction is possible. The ionization charge from the passage of particles through argon is drifted with an electric field and collected on readout wire planes; a 3D track can be reconstructed using charge arrival time information. Furthermore scintillation light signals in argon detected by photomultiplier tubes can allow fast timing of signals and enhance event localization. Very high purity cryogenic argon is required. Track granularity is determined by wire spacing, and in principle very fine-grained tracking can be achieved. Particle identification is possible by measuring ionization energy loss along a track [256].

Because of the excellent, full-particle tracking capability of liquid argon, very high-efficiency particle reconstruction allows a smaller LAr detector to match the efficiency of a water detector of a given mass, with an approximate ratio of 1 : 6. In principle, low energy physics (< 100 MeV, *e.g.* for supernova neutrinos) is possible in LAr as well, assuming adequate triggering capability.

The current largest liquid argon detector instance is ICARUS [257] in Europe. In the U.S., a dedicated program of development towards large liquid argon detectors has begun at Fermilab with ArgoNeuT [256], the material test stand program, liquid argon purity demonstrator, and reconstruction software development. This path forward in the U.S. will continue with MicroBooNE [258], a 35 ton membrane cryostat, testbeam studies, and an 800 ton LAr TPC (LAr1) [**?**]. Farther future possibilities will include a future LAr detector for LBNE [68], GLACIER [259] in Europe, and detectors in Japan [260].The LAr technique is as yet unproven at multi-kTon scale, but R&D has so far yielded promising results.

Liquid Scintillator Detectors Liquid scintillator detectors consist of large volumes of clear hydrocarbon, in a homogeneous or segmented volume viewed by photomultiplier tubes. Light yield can be very high– typically 50 times more light per energy loss than Cherenkov detectors. This enables both low energy thresholds and good energy resolution. However, in order to detect neutrinos at low energy, extremely good radioactive purity is also required. Particle energy loss is proportional to number of photoelectrons detected, and particle interaction vertices can be reconstructed by timing; to a lesser extent direction and other properties can be reconstructed. Unfortunately because of the isotropy of scintillation light, directionality and tracking capabilities are relatively weak. Nevertheless, some high-energy particle reconstruction may be possible (*e.g.* [261]) using photon timing. This kind of detector excels for detection of low energy (tens of MeV) signals, such as reactor, geo- and solar neutrinos; furthermore $0\nu\beta\beta$ candidate isotopes can be added for high-mass searches (see Section 1.3). There is a long history of successful kTon-scale scintillation detectors, starting with the segmented Baksan [262], MACRO [263] and LVD [264] detectors, and followed by KamLAND [12] and Borexino [54]. The near-future SNO+[55] will be next. Proposed large future detectors include HanoHano [265] and LENA [266].

1.8.1.3 Underground Facilities

Some neutrino experiments can be sited on or near the surface by employing beams with sharply pulsed timing to separate signal events from cosmogenic background, or by using other strong background rejection techniques; and some are not especially sensitive to cosmogenic background (*e.g.* kinematic experiments for absolute neutrino mass). However it is highly desirable, and in some cases mandatory, to site next-generation detectors in deep underground laboratories. For neutrinoless double-beta decay searches, low rates of cosmic rays and very deep locations are absolutely essential. These detectors furthermore have very stringent requirements on rates of natural radioactivity from both surroundings and detector materials, so very clean underground facilities are also important. Such requirements are shared with dark matter WIMP search detectors as well.

It is also desirable to site large detectors designed to be targets for long-baseline beams at deep locations, as these detectors can address a much broader range of physics topics when protected from cosmogenic background. The depth required depends both on physics topic and on detector technology, as the specific nature of the background will vary according to the particular signal. For natural sources of neutrinos, the depth requirements may be fairly stringent. Reference [267] explores depth requirements for physics sensitivity to different topics.

For these reasons, plans for next-generation experimental programs focus primarily on deep underground laboratory facilities. Infrastructure at a common site can furthermore be shared between different experiments.

1.8.2 Opportunities for Experimental Programs

1.8.2.1 Global context

Worldwide there are multiple existing and planned programs of beams and detectors at surface and underground sites. We present a brief survey of international projects here.

In Canada, the premier underground laboratory is SNOLAB, in Sudbury, Ontario, at a great 2070 m depth. This laboratory hosted the SNO heavy water experiment, soon to be converted to the SNO+ scintillator experiment, which will be doped with ^{150}Nd for a neutrinoless double-beta decay search. SNOLAB hosts, or is preparing to host, a variety of dark matter search experiments and neutrinoless double-beta decay search experiments. Some underground space remains unallocated at this time, although perhaps not for long.

In Japan, the Super-Kamiokande experiment near Kamioka, Japan, has been operational since 1996, and has produced a very broad range of results using solar and atmospheric neutrinos, and has the world's best limits on proton decay. It also served as the target for the first long-baseline neutrino experiment K2K (KEK to Kamioka), and is currently the target for the T2K (Tokai to Kamioka) off-axis beam from J-PARC near Tokai. The beam will be upgraded over the next several years. Japan also hosts the KamLAND experiment, which measured long-baseline reactor $\bar{\nu}_e$ disappearance and is now focusing on a neutrinoless double-beta decay search using dissolved xenon. Other underground experiments are sited in the Kamioka mine.

A prominent proposed new experiment in Japan is Hyper-Kamiokande, to be sited near the Super-K detector [251]. Two sites in the Tochibora mine (1500-1750 meters water equivalent depth) are under study. The proposed detector has a fiducial mass of 560 kTon and 10-20% Super-K-equivalent photomultiplier coverage. The plan is for an eventual upgrade of the T2K beam to 1.7 MW. There are also ideas for Japan-based liquid argon detectors, including a 100 kTon facility at Okinoshima island halfway between Japan and Korea [260].

A future underground large detector optimized for atmospheric neutrinos is the planned 50-kTon ICAL iron calorimeter detector for the India-based Neutrino Observatory [268]. This detector has lepton sign-selection capability using a magnetic field to enable separation of neutrinos and antineutrinos. If θ_{13} is large, ICAL will have reasonable sensitivity to the neutrino mass hierarchy via the $P_{\mu\mu}$ channel [269]. At the same laboratory site, other experiments are also planned.

Europe currently hosts the world's highest-power conventional boosted meson-decay beam, the 510 kW CNGS (Cern Neutrinos to Gran Sasso) beam, sent 730 km from CERN to the experiments at the Gran Sasso laboratory, including OPERA and Icarus. There is some potential for upgrade of CNGS to 750 kW, but no practical near detector location for this beam. A number of future beam, detector and siting possibilities are being explored by the LAGUNA study [270]. The envisioned EUROnu superbeam from CERN would be a 4 MW beam to Fréjus. Detectors under consideration for LAGUNA include a 0.5 Mt water Cherenkov detector (MEMPHYS [252]), a 100 kt LAr detector (GLACIER [259]) and a 50 kTon scintillator detector (LENA [266]). Beam options from CERN sending neutrinos to these sites include also beta beams or a neutrino factory in the farther future. Top sites under consideration are Pyhäsalmi in Finland (2300 km from CERN), Fréjus (130 km from CERN) and Umbria (665 km from CERN, off-axis from the existing CNGS beam). A possible staged program is described in [271]. Europe is also a major participant in the international neutrino factory and β-beam design studies and associated R&D experiments (MERIT, MICE and EMMA).

This survey of proposed programs globally is far from exhaustive: a number of smaller-scale laboratory facilities exist or are planned at various European locations [272, 273]. Efforts in other parts of the world include the JinPing underground laboratory in China, and the proposed ANDES facility in South America.

1.8.2.2 U.S. Contributions and Facilities

Current and Near-Future Programs Existing facilities in the U.S. dedicated to neutrinos are centered at Fermilab. The NuMI (Neutrinos at the Main Injector) beam facility [274] employs 120 GeV/c protons impinging on a graphite target, and two magnetic horns and a 675-m decay pipe; beam power is approximately 400 kW. Neutrinos are sent to MINOS, a 5 kTon iron tracker detector at the Soudan mine 734 km away in Minnesota, located on the beam axis. The MINOS experiment includes a near detector facility at Fermilab. Since January 2005, NuMI has delivered more than 10^{21} protons on target. This beam also serves the MINERνA experiment. The MiniBooNE experiment employs a separate Booster beam, which delivers 8 GeV protons on target to a secondary beamline with a focusing horn and 50-m decay region. In both MINOS and MiniBooNE cases, the polarity of the horns can be reversed to produce a flux which is primarily ν_μ or $\bar{\nu}_\mu$.

Highlights of the U.S. neutrino program of the past $\sim$15 years include the most precise measurements of ν_μ disappearance $|\Delta m^2|$ from MINOS [275, **?**], $|U_{e3}|$ results [19], as well as numerous searches for new physics. MINOS has plans for extended running (MINOS+ [180].) The MiniBooNE program has also produced several important neutrino oscillation searches (Sec. 1.6) in addition to multiple neutrino interaction measurements as described in Sec. 1.5.

The NOνA experiment will employ an upgraded 700 kW off-axis NuMI beam. The 14-kTon liquid scintillator detector is under construction at Ash River (see Fig. 1-13), at an 810-km baseline; this location is off the beam axis, where the beam neutrino spectrum is narrower. The NOνA program will improve the measurements of $|U_{e3}|$ and parameters related to ν_μ disappearance for both neutrinos and antineutrinos. In particular, NOνA will have a chance to determine the mass hierarchy, thanks to its long baseline.

A number of proposals for small experiments and extensions to existing experiments could enhance the U.S. program, *e.g.* [**?**]. Several of these described in various sections of this Chapter.

U.S. physicists have also made significant contributions to offshore neutrino experiments. These include longstanding contributions to the Super-K and T2K programs, which will continue to run through this decade. The U.S. has been a major participant in the Double Chooz (in France) and Daya Bay (in China)

Figure 1-13. *NOνA schematic with timeline (left) and site (right).*

reactor $|U_{e3}|$ experiments, both of which have recently started production running. The physics runs of these experiments planned over the next several years will have high impact.

LBNE The next major planned neutrino program in the U.S. is the Long-Baseline Neutrino Experiment (LBNE). The experiment as currently envisioned comprises a new 700 kW beam at Fermilab, a near detector complex, and a large far detector at the Homestake mine in South Dakota, at a baseline of 1300 km. Extensive design work and physics sensitivity studies were done over the past few years for two detector options for LBNE: a 200-kTon single-module water Cherenkov detector and a 34-kTon dual-module liquid argon TPC [68]: although a configuration with both technologies would be preferable for physics, the cost was prohibitive. After an exhaustive decision-making process, the LAr detector option was selected (see Fig. 1-14). The deep site at 4850 ft is strongly favored for this program, thanks to improved cosmogenic background rejection for astrophysical neutrino and proton decay studies, as well as possibility for shared infrastructure with a broader underground program.

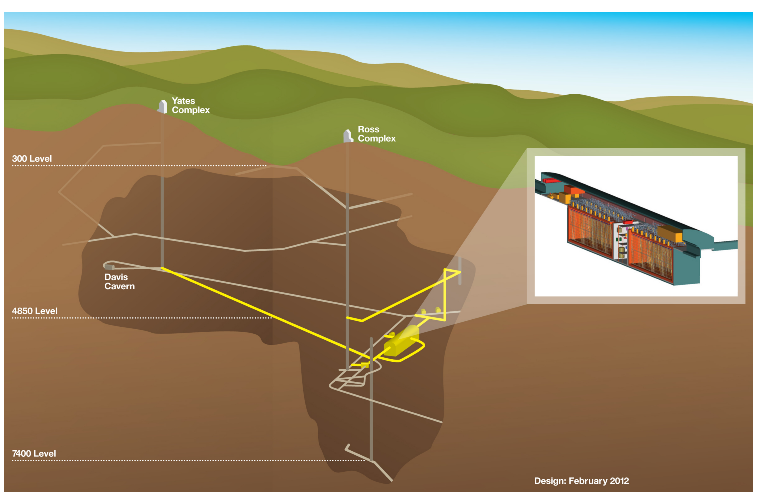

Figure 1-14. *The proposed LBNE LAr detector at the 4850 ft level of the Homestake mine.*

The sensitivity of LBNE was discussed in Sec. 1.2 (see Fig. 1-6). At the proposed deep site, the LBNE program will be enriched by additional sensitivity to proton decay and atmospheric and supernova neutrino physics.

Homestake The site currently under consideration for the LBNE far detector is the Homestake mine in Lead, South Dakota, the former site of the Davis chlorine solar neutrino experiment. This site could also host a suite of other underground experiments with both Intensity and Cosmic Frontier impacts. The facility currently at this site is known as the Sanford Underground Research Facility (SURF). The facility will host its first dark matter (LUX) and neutrinoless double-beta (Majorana Demonstrator) experiments early in 2012. The State of South Dakota established the South Dakota Science Technology Authority (SDSTA) to oversee the conversion of the former mine into a research facility. The SDSTA has accomplished rehabilitation of the facility assuring safe redundant access from the surface to the 4850 level (feet below ground). The pumping system has been restored and the accumulated water pool has been lowered below the 5800 foot level. The 7400 foot level is anticipated being reached by early 2014. Two shafts require upgrading to enable experimental activity underground: the Ross shaft is being refurbished to restore rock hoisting capacity necessary for major construction activities. It will serve as the primary operations and maintenance access for facility operations personal and materials. The Yates shaft is being upgraded to primary access capability and will serve as the principal scientific access underground. This upgraded Yates shaft is anticipated to be completed early in 2012 to support the new physics experiments. Conceptual designs for the excavations and outfitting necessary for the LBNE 34 kT liquid argon detector either at the 800L or the 4850L are well underway. The plans using the 4850L maximize the synergies of collocating the experiments and sharing facility infrastructure and access.

Project X Project X [276] is a U.S.-led accelerator initiative with strong international participation that aims to realize a next generation proton source that will dramatically extend the reach of Intensity Frontier research. The state of the art in superconducting RF has advanced to a point where it can be considered and implemented as the core enabling technology for a next-generation multi-megawatt proton source–reliably delivering unprecedented beam power at duty factors ranging from 10^{-5} to 100%. The base Super-Conducting RF technology also supports flexible beam-timing configurations among simultaneous experiments, allowing a broad range of experiments to develop and operate in parallel. The DOE Office of High Energy Physics and its advisory bodies have recognized this potential and are supporting R&D for Project X that could lead to a construction start as early as 2016. Project X has leadership potential in the future landscape of proton sources, and can enable new lines of research including neutrino interaction and oscillation experiments: Project X is a multi-megawatt proton source with proton kinetic energies of 3, 8, and 120 GeV which can drive intense simultaneous neutrino beams directed toward near detectors on the Fermilab site and massive detectors at distant underground laboratories. In addition there are possibilities for kaon, muon, nuclear and neutron precision experiments, as described elsewhere in this document. Furthermore, neutrino factory, and beyond that, muon-collider concepts depend critically on developing multi-megawatt proton source technologies. A technology roadmap has been developed that will directly leverage the Project X infrastructure into a platform for these future concepts. Initial review of the potential research program has identified 25+ world-class and world-leading experimental programs which can be driven by Project X. Many of these programs are underway now and can serve as cost-effective day-one beneficiaries of Project X beam power.

Notable in the Project X program is the deep reach in neutrino physics. The direct scope of Project X includes 2000-2400 kW of beam power at 60-120 GeV and 50-190 kW at 8 GeV, corresponding to three times the initial beam power of the Long Baseline Neutrino Experiment (LBNE) and three to twelve times the beam power delivered to the MiniBooNE experiment. This extraordinary beam power is particularly important to long-baseline experiments where the sensitivity is ruled by the product of beam power and detector mass, where detectors are pushed to the limit of massive scale. The benefits of Project X to neutrino physics can be expressed both in terms of beam power and in terms of its ability to bring new physics within reach sooner. Project X beam intensities allow the long-baseline oscillation physics program to be accomplished three times faster (i.e., oscillation measurements made in 10 years with Project X would take more than 30 years without). More importantly, searches for CP violation in the neutrino sector quickly become potential "discovery" level measurements with Project X (a 3σ measurement of CP violation in a 10 year exposure of LBNE in a 700 kW beam becomes 5σ in the same time with Project X). Figure 1-16 gives an example of the extended reach that will result from Project X's beam power. With the increased beam intensity, a much larger fraction of phase space can be probed at high significance, thus ensuring more complete coverage of whatever possible value of δ_{CP} Nature has chosen. In addition, Project X uniquely enables high intensity running at lower neutrino energies. For example, a step beyond the direct scope of Project X is an upgrade of the 8 GeV pulsed beam power to 4000 kW simultaneous with 2000 kW at 60 GeV. This joint beam power can enable precise tuning of the neutrino energy spectrum to simultaneously illuminate both the first and second interference maxima, which greatly enhances the sensitivity of LBNE to matter-antimatter asymmetries among neutrinos.

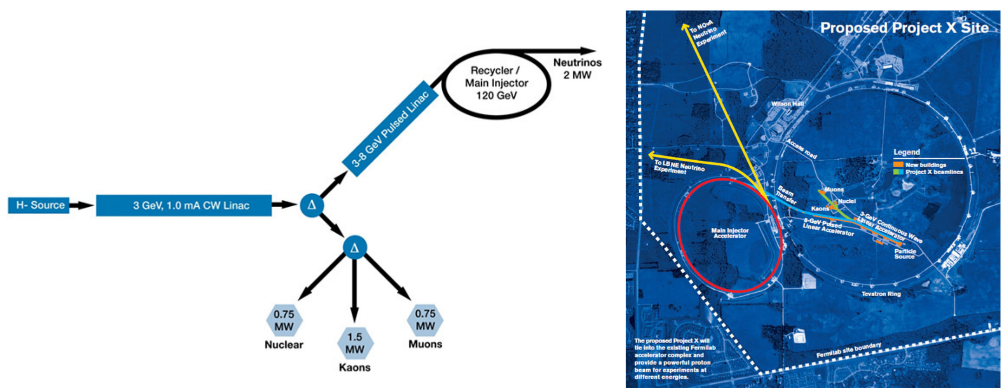

Figure 1-15. *Left: Project X reference design. Right: Project X proposed site at Fermilab.*

Other Ideas for Future Experiments Neutrino factories remain an interesting potential source of neutrinos for the farther future. The International Design Study for a Neutrino Factory (the IDS-NF)[246] has a baseline neutrino factory design, involving a high-energy (E_μ=25 GeV) two-baseline facility. It remains the best facility to accurately measure the remaining parameters in the 3 ν mixing parameter space, if it turns out that the value of $\sin^2 2\theta_{13}$ is actually 3σ below the central value of the latest global fit ($\sin^2 2\theta_{13} > 0.005$). In the case of large $\sin^2 2\theta_{13}$ ($\sin^2 2\theta_{13} > 0.01$), another possibility could be more effective: this would be a single baseline (L = 2000 km), lower energy facility (E_μ=10 GeV), termed the LENF that uses a 100 kT magnetized iron detector (MIND) as the far detector. A recently-developed strategy (again in the context of $\sin^2 \theta_{13}$ being large) is for a phased or staged approach for the LENF - the low-luminosity-low-energy Neutrino Factory, L^{3}ENF. This facility would require neither a proton driver to begin the physics program, nor muon ionization cooling. The facility could enable an earlier start and presents an obvious upgrade path.

The Very-Low-Energy Neutrino Factory (VLENF) [165] is another idea for a near-term, relatively inexpensive facility that could address large Δm^2 neutrino oscillations, make precision neutrino cross section measurements in the few GeV range with a well-known beam, and also serve as a technology test demonstration. The facility is very simple and consists of a conventional target station, a capture and transport section, and injection into a race track ring with a straight length of between 50-75 m.

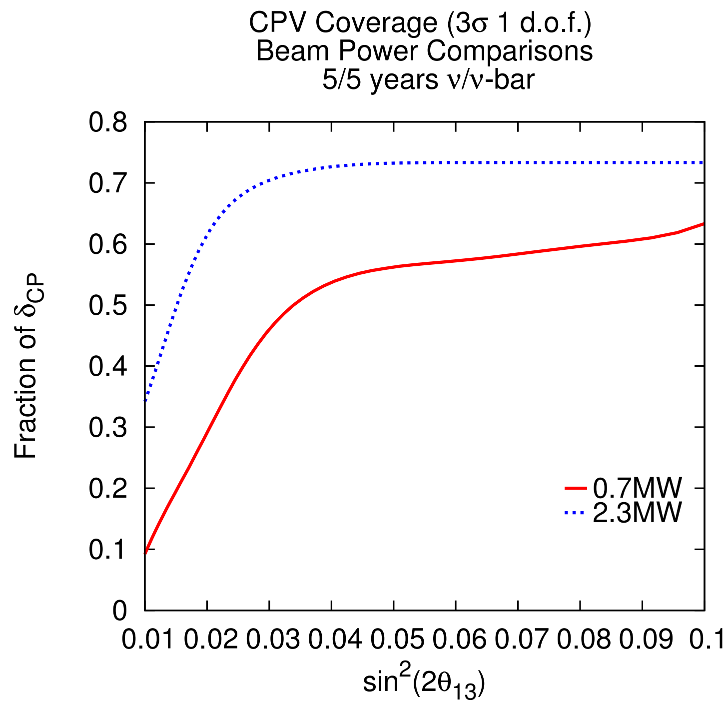

Figure 1-16. *Comparison of the fraction of δ_{CP} values for which a 3σ discovery of CP violation would be possible, for 10 years of LBNE running with 0.7 MW and with the beam power enhancement to 2.3 MW that would be enabled by Project X. Plot is from M. Bass.*

An additional idea to improve CP violation sensitivity is DAEδALUS [244], which is complementary to LBNE and which may be possible for an inverse-beta-decay-sensitive far detector. DAEδALUS combines multiple pion decay-at-rest neutrino sources with a water Cherenkov detector doped with gadolinium, or possibly a scintillator detector. The experimental configuration includes multiple cyclotron complexes at baselines ranging from 1-20 km. The experiment uses only $\bar{\nu}_e$ appearance, comparing oscillation probabilities at different L/E and exploiting the L-dependence of the CP-violating interference terms in the three-neutrino oscillation probability. This experimental setup allows for a powerful search for CP violation in three-neutrino mixing. Furthermore, there are further improvements in combination with a conventional long-baseline measurement [277]. This kind of stopped-pion source is also valuable for other kinds of physics, including sterile neutrino searches. DAEδALUS requires development of new high-power cyclotrons (which we note may have industrial applications). A promising concept [278] involves acceleration of H_2^+ ions which offers excellent prospects for meeting the ambitious requirements.

1.9 Conclusions

The standard model has been one of the most successful theoretical descriptions of nature in the history of humankind. Decades of precision tests have revealed only one concrete violation of the standard model: the existence of nonzero neutrino mass. While many experiments continue to look for other standard-model-violating processes, it is clear that continued study of the neutrino sector is of the upmost importance.

Compared to the other fermions, the elusive nature of the neutrino has made it extremely difficult to study in detail. While the field of neutrino physics has been making continuous progress over many decades, the rate of progress in recent years has been impressive. The current generation of neutrino experiments is producing important results that help us to better understand the neutrino sector. In some cases, these experiments have uncovered intriguing anomalies that require additional study and will prompt future experiments. Furthermore, the current generation of neutrino experiments are providing advances in detector technology and analytical techniques that will be necessary for the next generation of neutrino experiments.

This synergy, the physics of the neutrino as a key to understanding the fundamental nature of the physical world along with technological advances in experimental techniques, make this an exciting time for neutrino physics. The coming decade will provide us with an opportunity to answer some of the most fundamental and important questions of our time: Are neutrinos Majorana or Dirac particles? Is there CP violation in the lepton sector? Does the small, but nonzero neutrino mass couple to a mass scale that is far beyond what we can hope to reach in colliders? Although these questions have been in existence for many years, we now have opportunities to finally answer some of them.

The coming decade promises significant experimental progress around the world. In the search for neutrinoless double-beta decay, a number of experiments rely on complementary isotopes and experimental techniques. The next generation of $\sim$100 kg-class $0\nu\beta\beta$ experiments should reach effective masses in the 100 meV range; beyond that, there are opportunites for multi-ton-class experiments which will reach $<$10 meV effective mass sensitivity, pushing below the inverted hierarchy region. The next-generation tritium beta decay kinematic experiment, KATRIN, will push limits a factor of ten beyond the current best ones; innovative new ideas may help to go beyond. Long-baseline neutrino oscillation experiments will clarify the neutrino mass hierarchy and search for CP violation: these require new high-power beams and large underground detectors. Both T2K and MINOS are currently running, with NOνA expected to begin in 2014. Reactor experiments will also continue to take data this decade. There is vigorous world-wide activity towards planning for large-scale next-generation long-baseline efforts. There are exciting opportunities for the U.S. to take leadership in this arena with LBNE, and beyond that, Project X for increased neutrino intensity at several beam energies. Given the challenges associated with precision measurements in the neutrino sector, complementary baselines, sources and detector techniques will be needed to help further understand the nature of CP violation in the neutrino sector. Smaller experiments will also help address some of the remaining anomalies and hints for new physics beyond the three-flavor paradigm.

The diversity of physics topics that can be probed through the neutrino sector is significant and the interplay between neutrino physics and other fields is vast. Neutrinos can and will 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. In other words, the neutrino sector sits at the nexus of the worldwide effort in Energy Frontier, Intensity Frontier and Cosmic Frontier physics.

Finally, the unique physics potential and technological advancements have conspired to produce a fertile environment for new ideas for improved measurements and new techniques. This provides an important training ground for the next generation of scientists and engineers, motivated and excited about groundbreaking experiments that can benefit from their contributions.

References

[1] K. Kodama et al. Observation of tau neutrino interactions. *Phys. Lett.*, B504:218–224, 2001.

[2] F. Abe et al. Observation of top quark production in $\bar{p}p$ collisions. *Phys. Rev. Lett.*, 74:2626–2631, 1995.

[3] S. Abachi et al. Observation of the top quark. *Phys. Rev. Lett.*, 74:2632–2637, 1995.

[4] B.T. Cleveland, Timothy Daily, Jr. Davis, Raymond, James R. Distel, Kenneth Lande, et al. Measurement of the solar electron neutrino flux with the Homestake chlorine detector. *Astrophys. J.*, 496:505–526, 1998.

[5] W. Hampel et al. GALLEX solar neutrino observations: Results for GALLEX IV. *Phys. Lett.*, B447:127–133, 1999.

[6] Q.R. Ahmad et al. Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory. *Phys. Rev. Lett.*, 89:011301, 2002.

[7] J.N. Abdurashitov et al. Solar neutrino flux measurements by the Soviet-American Gallium Experiment (SAGE) for half the 22 year solar cycle. *J. Exp. Theor. Phys.*, 95:181–193, 2002.

[8] S. Fukuda et al. Solar B-8 and hep neutrino measurements from 1258 days of Super-Kamiokande data. *Phys. Rev. Lett.*, 86:5651–5655, 2001.

[9] S.N. Ahmed et al. Measurement of the total active B-8 solar neutrino flux at the Sudbury Neutrino Observatory with enhanced neutral current sensitivity. *Phys. Rev. Lett.*, 92:181301, 2004.

[10] Y. Fukuda et al. Evidence for oscillation of atmospheric neutrinos. *Phys. Rev. Lett.*, 81:1562–1567, 1998.

[11] Y. Ashie et al. Evidence for an oscillatory signature in atmospheric neutrino oscillation. *Phys. Rev. Lett.*, 93:101801, 2004.

[12] K. Eguchi et al. First results from KamLAND: Evidence for reactor anti- neutrino disappearance. *Phys. Rev. Lett.*, 90:021802, 2003.

[13] T. Araki et al. Measurement of neutrino oscillation with KamLAND: Evidence of spectral distortion. *Phys. Rev. Lett.*, 94:081801, 2005.

[14] M.H. Ahn et al. Indications of neutrino oscillation in a 250 km long baseline experiment. *Phys. Rev. Lett.*, 90:041801, 2003.

[15] D.G. Michael et al. Observation of muon neutrino disappearance with the MINOS detectors and the NuMI neutrino beam. *Phys. Rev. Lett.*, 97:191801, 2006.

[16] Thomas Schwetz, Mariam Tortola, and J.W.F. Valle. Where we are on θ_{13}: addendum to 'Global neutrino data and recent reactor fluxes: status of three-flavour oscillation parameters'. *New J. Phys.*, 13:109401, 2011.

[17] P.A.N. Machado, H. Minakata, H. Nunokawa, and R.Zukanovich Funchal. Combining Accelerator and Reactor Measurements of θ_{13}: The First Result. 2011.

[18] K. Abe et al. Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam. *Phys. Rev. Lett.*, 107:041801, 2011.

[19] P. Adamson et al. Improved search for muon-neutrino to electron-neutrino oscillations in MINOS. *Phys. Rev. Lett.*, 107, 2011.

[20] Y. Abe et al. Indication for the disappearance of reactor electron antineutrinos in the Double Chooz experiment. 2011.

[21] G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo, and A. M. Rotunno. Evidence of $theta_{13} > 0$ from global neutrino data analysis. *Phys. Rev.*, D84:053007, 2011.

[22] F. Ardellier et al. Double Chooz: A search for the neutrino mixing angle theta(13). 2006.

[23] Xinheng Guo et al. A precision measurement of the neutrino mixing angle theta(13) using reactor antineutrinos at Daya Bay. 2007.

[24] J. K. Ahn et al. RENO: An Experiment for Neutrino Oscillation Parameter θ_{13} Using Reactor Neutrinos at Yonggwang. 2010.

[25] Andre de Gouvea. Neutrinos have mass: So what? *Mod. Phys. Lett.*, A19:2799–2813, 2004.

[26] Steven Weinberg. Baryon and Lepton Nonconserving Processes. *Phys. Rev. Lett.*, 43:1566–1570, 1979.

[27] R.N. Mohapatra, S. Antusch, K.S. Babu, G. Barenboim, Mu-Chun Chen, et al. Theory of neutrinos: A White paper. *Rept. Prog. Phys.*, 70:1757–1867, 2007.

[28] Paul Langacker. Neutrino Masses from the Top Down. 2011.

[29] Peter Minkowski. $\mu \to e\gamma$ at a Rate of One Out of 1-Billion Muon Decays? *Phys. Lett.*, B67:421, 1977.

[30] Tsutomu Yanagida. Horizontal symmetry and masses of neutrinos. *Conf. Proc.*, C7902131:95, 1979.

[31] Murray Gell-Mann, Pierre Ramond, and Richard Slansky. Complex spinors and unified theories. *Conf. Proc.*, C790927:315–321, 1979. To be published in Supergravity, P. van Nieuwenhuizen & D.Z. Freedman (eds.), North Holland Publ. Co., 1979.

[32] S.L. Glashow. In M. Lévy et al., editor, *Quarks and Leptons at Cargèse*, page 707. Plenum, 1980.

[33] Rabindra N. Mohapatra and Goran Senjanovic. Neutrino Mass and Spontaneous Parity Violation. *Phys. Rev. Lett.*, 44:912, 1980.

[34] W. Konetschny and W. Kummer. Nonconservation of Total Lepton Number with Scalar Bosons. *Phys. Lett.*, B70:433, 1977.

[35] T.P. Cheng and Ling-Fong Li. Neutrino Masses, Mixings and Oscillations in SU(2) x U(1) Models of Electroweak Interactions. *Phys. Rev.*, D22:2860, 1980.

[36] George Lazarides, Q. Shafi, and C. Wetterich. Proton Lifetime and Fermion Masses in an SO(10) Model. *Nucl. Phys.*, B181:287, 1981.

[37] J. Schechter and J.W.F. Valle. Neutrino Masses in SU(2) x U(1) Theories. *Phys. Rev.*, D22:2227, 1980.

[38] Rabindra N. Mohapatra and Goran Senjanovic. Neutrino Masses and Mixings in Gauge Models with Spontaneous Parity Violation. *Phys. Rev.*, D23:165, 1981.

[39] Robert Foot, H. Lew, X.G. He, and Girish C. Joshi. Seesaw neutrino masses induced by a triplet of leptons. *Z. Phys.*, C44:441, 1989.

[40] Carl H. Albright and Mu-Chun Chen. Model Predictions for Neutrino Oscillation Parameters. *Phys. Rev.*, D74:113006, 2006.

[41] A. Cervera, A. Donini, M.B. Gavela, J.J. Gomez Cadenas, P. Hernandez, et al. Golden measurements at a neutrino factory. *Nucl. Phys.*, B579:17–55, 2000.

[42] J. Burguet-Castell, M.B. Gavela, J.J. Gomez-Cadenas, P. Hernandez, and Olga Mena. On the Measurement of leptonic CP violation. *Nucl. Phys.*, B608:301–318, 2001.

[43] V. Barger, D. Marfatia, and K. Whisnant. Breaking eight fold degeneracies in neutrino CP violation, mixing, and mass hierarchy. *Phys. Rev.*, D65:073023, 2002.

[44] K. Nakamura et al. Review of particle physics. *J. Phys. G*, G37:075021, 2010.

[45] T. Aaltonen et al. Measurement of CP–violating asymmetries in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays at CDF. *Phys.Rev.*, D85:012009, 2012. 29 pages, 20 figures, 3 tables. Submitted to Phys. Rev. D.

[46] R. Aaij et al. Evidence for CP violation in time-integrated $D^0 \to h^-h^+$ decay rates. 2011.

[47] K. Abe et al. A Measurement of atmospheric neutrino flux consistent with tau neutrino appearance. *Phys. Rev. Lett.*, 97:171801, 2006.

[48] N. Agafonova et al. Observation of a first ν_τ candidate in the OPERA experiment in the CNGS beam. *Phys. Lett.*, B691:138–145, 2010.

[49] L. Wolfenstein. Neutrino Oscillations in Matter. *Phys. Rev.*, D17:2369–2374, 1978.

[50] F Formaggio and G. P. Zeller. From eV to EeV: Neutrino Cross Sections Across Energy Scales. 2012. to be published in Rev. Mod. Phys.

[51] John N. Bahcall and Carlos Pena-Garay. Global analyses as a road map to solar neutrino fluxes and oscillation parameters. *JHEP*, 0311:004, 2003.

[52] S.P. Mikheev and A.Yu. Smirnov. Resonance Amplification of Oscillations in Matter and Spectroscopy of Solar Neutrinos. *Sov. J. Nucl. Phys.*, 42:913–917, 1985.

[53] B. Aharmim et al. Combined Analysis of all Three Phases of Solar Neutrino Data from the Sudbury Neutrino Observatory. 2011.

[54] G. Alimonti et al. The Borexino detector at the Laboratori Nazionali del Gran Sasso. *Nucl. Instrum. Meth.*, A600:568–593, 2009.

[55] Christine Kraus and Simon J. M. Peeters. The rich neutrino programme of the SNO+ experiment. *Prog. Part. Nucl. Phys.*, 64:273–277, 2010.

[56] K. Anderson, J.C. Anjos, D. Ayres, J. Beacom, I. Bediaga, et al. White paper report on Using Nuclear Reactors to Search for a value of θ_{13}. 2004.

[57] H. Minakata, H. Nunokawa, W.J.C. Teves, and R. Zukanovich Funchal. Reactor measurement of theta(12): Principles, accuracies and physics potentials. *Phys. Rev.*, D71:013005, 2005.

[58] S.T. Petcov and T. Schwetz. Precision measurement of solar neutrino oscillation parameters by a long-baseline reactor neutrino experiment in Europe. *Phys. Lett.*, B642:487–494, 2006.

[59] Pomita Ghoshal and S.T. Petcov. Neutrino Mass Hierarchy Determination Using Reactor Antineutrinos. *JHEP*, 1103:058, 2011.

[60] J.M. Conrad and M.H. Shaevitz. Multiple Cyclotron Method to Search for CP Violation in the Neutrino Sector. *Phys. Rev. Lett.*, 104:141802, 2010.

[61] Enrique Fernandez-Martinez, Gerardo Giordano, Olga Mena, and Irina Mocioiu. Atmospheric neutrinos in ice and measurement of neutrino oscillation parameters. *Phys. Rev.*, D82:093011, 2010.

[62] M. C. Gonzalez-Garcia, Michele Maltoni, and Jordi Salvado. Testing matter effects in propagation of atmospheric and long-baseline neutrinos. *JHEP*, 05:075, 2011.

[63] T. K. Gaisser and M. Honda. Flux of atmospheric neutrinos. *Ann. Rev. Nucl. Part. Sci.*, 52:153–199, 2002.

[64] M. C. Gonzalez-Garcia, M. Maltoni, and J. Rojo. Determination of the atmospheric neutrino fluxes from atmospheric neutrino data. *JHEP*, 10:075, 2006.

[65] R. Abbasi et al. Measurement of the atmospheric neutrino energy spectrum from 100 GeV to 400 TeV with IceCube. *Phys. Rev.*, D83:012001, 2011.

[66] S. Choubey et al. Interim Design Report for the International Design Study for a Neutrino Factory. FERMILAB-DESIGN-2011-01.

[67] P. Zucchelli. A novel concept for a anti-ν_e / ν_e neutrino factory: The beta beam. *Phys. Lett.*, B532:166–172, 2002.

[68] T. Akiri et al. The 2010 Interim Report of the Long-Baseline Neutrino Experiment Collaboration Physics Working Groups. 2011.

[69] LBNE collaboration. Internal document.

[70] Claude Amsler et al. Review of particle physics. *Phys. Lett.*, B667:1–1340, 2008.

[71] H. V. Klapdor-Kleingrothaus, A. Dietz, H. L. Harney, and I. V. Krivosheina. Evidence for Neutrinoless Double Beta Decay. *Mod. Phys. Lett.*, A16:2409–2420, 2001.

[72] III Avignone, Frank T., Steven R. Elliott, and Jonathan Engel. Double Beta Decay, Majorana Neutrinos, and Neutrino Mass. *Rev. Mod. Phys.*, 80:481–516, 2008.

[73] E. Aguayo et al., 2011. Presented at the American Physical Society Division of Particles and Fields 2011, Providence RI, USA, August 2011.

[74] D. G. II Phillips et al., 2011. Presentation for the Rutherford Centennial Conference on Nuclear Physics, Manchester UK, August 2011.

[75] A. G. Schubert et al., 2011. Submitted to AIP Conference Proceedings, 19th Particles and Nuclei International Conference (PANIC 2011), Massachusetts Institute of Technology, Cambridge, MA, USA, July 24-29, 2011.

[76] F. Alessandria et al., 2011. Submitted to Astropart. Phys.

[77] M. Danilov et al. Detection of very small neutrino masses in double-beta decay using laser tagging. *Phys. Lett.*, B480:12–18, 2000.

[78] N. Ackerman et al. Observation of Two-Neutrino Double-Beta Decay in ^{136}Xe with EXO-200. *Phys. Rev. Lett.*, 107:212501, 2011.

[79] A. Gando et al., 2012.

[80] S. Abe et al. *Phys. Rev. Lett.*, 100:221803, 2008.

[81] Measurement of the Double-Beta Decay Half-life of ^{136}Xe in KamLAND-Zen. 2012.

[82] E. Gómez et al., 2011.

[83] Nadia Yahlali et al. *Nucl. Instrum. Meth. Phys. A*, 617:520, 2010.

[84] R. Arnold et al. *Eur. Phys. J. C*, 70:927, 2010.

[85] M. Bongrand et al., 2011. to be published in Proceedings 22nd Rencontres de Blois, July, 2010.

[86] Sun Kee Kim, 2011. Presentation at MEDEX 2011, Prague, Czech Republic.

[87] S. J. Lee et al. *Astropart. Phys.*, 34:732, 2011.

[88] Tadafumi Kishimoto. *Int. J. Mod. Phys. E*, 18:2129, 2009.

[89] Yu G. Zdesenko et al. *Astropart. Phys.*, 23:249, 2005.

[90] K. Zuber. *Phys. Lett. B*, 519:1, 2001.

[91] N. Ishihara et al. *Nucl. Instrum. Meth. A*, 443:101, 2000.

[92] S. Schönert et al. *Nucl. Phys. Proc. Suppl.*, 145:242, 2005.

[93] F. A. Danevich. *Nucl. Phys. A*, 694:375, 2001.

[94] Yu. Efremenko, 2011. Presentation at MEDEX 2011, Prague, Czech Republic.

[95] Andrea Giuliani, 2010. presentation at Beyond 2010, Cape Town, South Africa, February 2010.

[96] C. Arnaboldi et al. *Astropart. Phys.*, 34:344, 2011.

[97] Hiroyasu Ejiri. *Mod. Phys. Lett. A*, 22:1277, 2007.

[98] M. C. Chen. *Nucl. Phys. Proc. Suppl.*, 145:65, 2005.

[99] M. C. Chen et al. *eConf*, page C080730, 2008.

[100] A. Osipowicz et al. 2001. arXiv:hep-ex/0109033.

[101] R. G. H. Robertson. *J. Phys. Conf. Ser.*, 120:052028, 2008.

[102] E. Andreotti et al. MARE, Microcalorimeter Arrays for a Rhenium Experiment: A detector overview. *Nucl. Instrum. Meth.*, A572:208–210, 2007.

[103] A. Nucciotti and for the MARE Collaboration. Neutrino mass calorimetric searches in the MARE experiment. 2010.

[104] Benjamin Monreal and Joseph A. Formaggio. Relativistic Cyclotron Radiation Detection of Tritium Decay Electrons as a New Technique for Measuring the Neutrino Mass. *Phys. Rev.*, D80:051301, 2009.

[105] Julien Lesgourgues and Sergio Pastor. Massive neutrinos and cosmology. *Phys. Rept.*, 429:307–379, 2006.

[106] K. N. Abazajian et al. Cosmological and Astrophysical Neutrino Mass Measurements. *Astropart. Phys.*, 35:177–184, 2011.

[107] Yvonne Y. Y. Wong. Neutrino mass in cosmology: status and prospects. *Ann. Rev. Nucl. Part. Sci.*, 61:69–98, 2011.

[108] D. Casper. The nuance neutrino physics simulation, and the future. *Nucl. Phys. Proc. Suppl.*, 112:161–170, 2002.

[109] J. Morfin. `http://if-neutrino.fnal.gov/neutrino1-pagers.pdf`.

[110] C. Anderson et al. First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon. 2011.

[111] C. Mariani et al. Measurement of inclusive π^0 production in the Charged-Current Interactions of Neutrinos in a 1.3-GeV wide band beam. *Phys. Rev.*, D83:054023, 2011.

[112] A. Rodriguez et al. Measurement of single charged pion production in the charged-current interactions of neutrinos in a 1.3-GeV wide band beam. *Phys. Rev.*, D78:032003, 2008.

[113] R. Gran et al. Measurement of the quasi-elastic axial vector mass in neutrino-oxygen interactions. *Phys. Rev.*, D74:052002, 2006.

[114] M. Hasegawa et al. Search for coherent charged pion production in neutrino-carbon interactions. *Phys. Rev. Lett.*, 95:252301, 2005.

[115] S. Nakayama et al. Measurement of single pi0 production in neutral current neutrino interactions with water by a 1.3-GeV wide band muon neutrino beam. *Phys. Lett.*, B619:255–262, 2005.

[116] Deborah A. Harris. Preliminary results from the MINERvA experiment. 2011.

[117] Joseph Grange. New Results from MiniBooNE Charged-Current Quasi-Elastic Anti-Neutrino Data. *AIP Conf.Proc.*, 1405:83–88, 2011.

[118] Ranjan Dharmapalan. Neutral Current Elastic Interactions in MiniBooNE. *AIP Conf.Proc.*, 1405:89–94, 2011.

[119] A.A. Aguilar-Arevalo et al. Measurement of Neutrino-Induced Charged-Current Charged Pion Production Cross Sections on Mineral Oil at $\mathrm{E}_\nu \sim 1$ GeV. *Phys. Rev.*, D83:052007, 2011.

[120] A.A. Aguilar-Arevalo et al. Measurement of ν_μ-induced charged-current neutral pion production cross sections on mineral oil at $E_\nu \in 0.5 - 2.0$ GeV. *Phys. Rev.*, D83:052009, 2011.

[121] A.A. Aguilar-Arevalo et al. Measurement of the Neutrino Neutral-Current Elastic Differential Cross Section on Mineral Oil at $E_\nu \sim 1$ GeV. *Phys. Rev.*, D82:092005, 2010.

[122] A.A. Aguilar-Arevalo et al. First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section. *Phys. Rev.*, D81:092005, 2010.

[123] Alexis A. Aguilar-Arevalo et al. Measurement of nu(mu) and anti-nu(mu) induced neutral current single pi0 production cross sections on mineral oil at E(nu) O(1- GeV). *Phys. Rev.*, D81:013005, 2010.

[124] A.A. Aguilar-Arevalo et al. Measurement of the ν_μ charged current π^+ to quasi-elastic cross section ratio on mineral oil in a 0.8-GeV neutrino beam. *Phys. Rev. Lett.*, 103:081801, 2009.

[125] A.A. Aguilar-Arevalo et al. First Observation of Coherent π^0 Production in Neutrino Nucleus Interactions with E_ν <2 GeV. *Phys. Lett.*, B664:41–46, 2008.

[126] A.A. Aguilar-Arevalo et al. Measurement of muon neutrino quasi-elastic scattering on carbon. *Phys. Rev. Lett.*, 100:032301, 2008.

[127] Nathan Mayer and Nicholas Graf. Improvements to MINOS CCQE analysis. *AIP Conf.Proc.*, 1405:41–46, 2011.

[128] Daniel Cherdack. Neutrino-nucleus coherent NC(pi0) scattering in the MINOS Near Detector. *AIP Conf.Proc.*, 1405:115–120, 2011.

[129] M. Dorman. Preliminary results for CCQE scattering with the MINOS near detector. *AIP Conf.Proc.*, 1189:133–138, 2009.

[130] P. Adamson et al. Neutrino and Antineutrino Inclusive Charged-current Cross Section Measurements with the MINOS Near Detector. *Phys. Rev.*, D81:072002, 2010.

[131] C.T. Kullenberg et al. A Search for Single Photon Events in Neutrino Interactions in NOMAD. *Phys. Lett.*, B706:268–275, 2012.

[132] C.T. Kullenberg et al. A Measurement of Coherent Neutral Pion Production in Neutrino Neutral Current Interactions in NOMAD. *Phys. Lett.*, B682:177–184, 2009.

[133] V Lyubushkin et al. A Study of quasi-elastic muon neutrino and antineutrino scattering in the NOMAD experiment. *Eur.Phys.J.*, C63:355–381, 2009.

[134] Q. Wu et al. A Precise measurement of the muon neutrino-nucleon inclusive charged current cross-section off an isoscalar target in the energy range $2.5 < E_\nu < 40$-GeV by NOMAD. *Phys. Lett.*, B660:19–25, 2008.

[135] Y. Nakajima et al. Measurement of inclusive charged current interactions on carbon in a few-GeV neutrino beam. *Phys. Rev.*, D83:012005, 2011.

[136] Y. Kurimoto et al. Improved measurement of neutral current coherent π^0 production on carbon in a few-GeV neutrino beam. *Phys. Rev.*, D81:111102, 2010.

[137] Y. Kurimoto et al. Measurement of Inclusive Neutral Current Neutral pi0 Production on Carbon in a Few-GeV Neutrino Beam. *Phys. Rev.*, D81:033004, 2010.

[138] K. Hiraide et al. Search for Charged Current Coherent Pion Production on Carbon in a Few-GeV Neutrino Beam. *Phys. Rev.*, D78:112004, 2008.

[139] R.A. Smith and E.J. Moniz. Neutrino reactions on nuclear targets. *Nucl. Phys.*, B43:605, 1972.

[140] M. Martini, M. Ericson, G. Chanfray, and J. Marteau. A Unified approach for nucleon knock-out, coherent and incoherent pion production in neutrino interactions with nuclei. *Phys. Rev.*, C80:065501, 2009.

[141] J. Carlson, J. Jourdan, R. Schiavilla, and I. Sick. Longitudinal and transverse quasielastic response functions of light nuclei. *Phys. Rev.*, C65:024002, 2002.

[142] Jan T. Sobczyk. Multinucleon ejection model for Meson Exchange Current neutrino interactions. 2012.

[143] J.E. Amaro, M.B. Barbaro, J.A. Caballero, and T.W. Donnelly. Meson-exchange currents and quasielastic antineutrino cross sections in the SuperScaling Approximation. 2011.

[144] Ulrich Mosel. Neutrino-Nucleus Interactions around 1 GeV. 2011.

[145] Andrea Meucci, Carlotta Giusti, and Franco Davide Pacati. Relativistic descriptions of final-state interactions in neutral-current neutrino-nucleus scattering at MiniBooNE kinematics. *Phys. Rev.*, D84:113003, 2011.

[146] Omar Benhar. Confronting electron- and neutrino-nucleus scattering. 2011.

[147] J. Nieves, I.Ruiz Simo, and M.J.Vicente Vacas. The nucleon axial mass and the MiniBooNE Quasielastic Neutrino-Nucleus Scattering problem. *Phys. Lett.*, B707:72–75, 2012.

[148] M. Martini, M. Ericson, and G. Chanfray. Neutrino quasielastic interaction and nuclear dynamics. *Phys. Rev.*, C84:055502, 2011.

[149] Jan T. Sobczyk. Transverse Enhancement Model and MiniBooNE Charge Current Quasi-Elastic Neutrino Scattering Data. 2012.

[150] Bhubanjyoti Bhattacharya, Richard J. Hill, and Gil Paz. Model independent determination of the axial mass parameter in quasielastic neutrino-nucleon scattering. *Phys. Rev.*, D84:073006, 2011.

[151] Arie Bodek and Howard Budd. Neutrino Quasielastic Scattering on Nuclear Targets: Parametrizing Transverse Enhancement (Meson Exchange Currents). *Eur. Phys. J.*, C71:1726, 2011.

[152] J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly, and J.M. Udias. Relativistic analyses of quasielastic neutrino cross sections at MiniBooNE kinematics. *Phys. Rev.*, D84:033004, 2011.

[153] Omar Benhar and Giovanni Veneziano. Nuclear effects in neutral current quasi-elastic neutrino interactions. *Phys. Lett.*, B702:433–437, 2011.

[154] Artur M. Ankowski and Omar Benhar. Electroweak nuclear response at moderate momentum transfer. *Phys. Rev.*, C83:054616, 2011.

[155] J. Nieves, I. Ruiz Simo, and M.J. Vicente Vacas. Inclusive Charged–Current Neutrino–Nucleus Reactions. *Phys. Rev.*, C83:045501, 2011.

[156] Luis Alvarez-Ruso. Neutrino interactions: challenges in the current theoretical picture. 2010.

[157] Omar Benhar. Modeling neutrino-nucleus interactions. Do we need a new paradigm? 2010.

[158] J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly, and C.F. Williamson. Meson-exchange currents and quasielastic neutrino cross sections in the SuperScaling Approximation model. *Phys. Lett.*, B696:151–155, 2011.

[159] Cezary Juszczak, Jan T. Sobczyk, and Jakub Zmuda. On extraction of value of axial mass from MiniBooNE neutrino quasi-elastic double differential cross section data. *Phys. Rev.*, C82:045502, 2010.

[160] Omar Benhar, Pietro Coletti, and Davide Meloni. Electroweak nuclear response in quasi-elastic regime. *Phys. Rev. Lett.*, 105:132301, 2010.

[161] A.V. Butkevich. Analysis of flux-integrated cross sections for quasi-elastic neutrino charged-current scattering off ^{12}C at MiniBooNE energies. *Phys. Rev.*, C82:055501, 2010.

[162] M. Martini, M. Ericson, G. Chanfray, and J. Marteau. Neutrino and antineutrino quasielastic interactions with nuclei. *Phys. Rev.*, C81:045502, 2010.

[163] R. Tayloe. `http://if-neutrino.fnal.gov/neutrino1-pagers.pdf`.

[164] M.E. Christy. `http://if-neutrino.fnal.gov/neutrino1-pagers.pdf`.

[165] A Bross. http://if-neutrino.fnal.gov/neutrino1-pagers.pdf.

[166] J.L. Orrell. http://if-neutrino.fnal.gov/neutrino1-pagers.pdf.

[167] K. Scholberg et al. The CLEAR Experiment. 2009.

[168] Joseph A. Formaggio, E. Figueroa-Feliciano, and A.J. Anderson. Sterile Neutrinos, Coherent Scattering and Oscillometry Measurements with Low-temperature Bolometers. *Phys. Rev.*, D85:013009, 2012. 14 pages, 10 figures. Version 2: Temperature dependence on alpha fixed from earlier version.

[169] J. Yoo. http://if-neutrino.fnal.gov/neutrino1-pagers.pdf.

[170] A. Aguilar-Arevalo et al. Evidence for neutrino oscillations from the observation of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam. *Phys. Rev.*, D64:112007, 2001.

[171] A.A. Aguilar-Arevalo et al. Unexplained Excess of Electron-Like Events From a 1-GeV Neutrino Beam. *Phys. Rev. Lett.*, 102:101802, 2009.

[172] A.A. Aguilar-Arevalo et al. Event Excess in the MiniBooNE Search for $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations. *Phys. Rev. Lett.*, 105:181801, 2010.

[173] G. Mention, M. Fechner, Th. Lasserre, Th.A. Mueller, D. Lhuillier, et al. The Reactor Antineutrino Anomaly. *Phys. Rev.*, D83:073006, 2011.

[174] Carlo Giunti and Marco Laveder. Statistical Significance of the Gallium Anomaly. *Phys. Rev.*, C83:065504, 2011.

[175] Carlo Giunti and Marco Laveder. Implications of 3+1 Short-Baseline Neutrino Oscillations. *Phys. Lett.*, B706:200–207, 2011.

[176] Joachim Kopp, Michele Maltoni, and Thomas Schwetz. Are there sterile neutrinos at the eV scale? *Phys. Rev. Lett.*, 107:091801, 2011.

[177] https://indico.fnal.gov/conferenceDisplay.py?confId=4157.

[178] http://www.cpe.vt.edu/snac/.

[179] E. Calligarich, S. Centro, D. Gibin, A. Guglielmi, F. Pietropaolo, et al. A search for sterile neutrinos at CERN-PS. *J. Phys. Conf. Ser.*, 203:012110, 2010.

[180] G. Tzanankos et al. MINOS+: a Proposal to FNAL to run MINOS with the medium energy NuMI beam. FERMILAB-PROPOSAL-1016.

[181] I. Stancu, Z. Djurcic, D. Smith, R. Ford, T. Kobilarcik, et al. Letter of Intent to Build a MiniBooNE Near Detector:BooNE. 2009.

[182] http://physics.calumet.purdue.edu/~oscsns/sns_proposal.pdf.

[183] https://www-pls.llnl.gov/data/docs/about_pls/office_of_science_programs/hep/bowden_DOE_110209.pdf.

[184] Michel Cribier, Maximilien Fechner, Thierry Lasserre, Alain Letourneau, David Lhuillier, et al. A proposed search for a fourth neutrino with a PBq antineutrino source. *Phys. Rev. Lett.*, 107:201801, 2011.

[185] D.A. Dwyer, K.M. Heeger, B.R. Littlejohn, and P. Vogel. Search for Sterile Neutrinos with a Radioactive Source at Daya Bay. 2011.

[186] V. Barger, Y. Gao, and D. Marfatia. Is there evidence for sterile neutrinos in IceCube data? *Phys. Rev.*, D85:011302, 2012.

[187] M. B. Gavela, D. Hernandez, T. Ota, and W. Winter. Large gauge invariant non-standard neutrino interactions. *Phys. Rev.*, D79:013007, 2009.

[188] Carla Biggio, Mattias Blennow, and Enrique Fernandez-Martinez. General bounds on non-standard neutrino interactions. *JHEP*, 08:090, 2009.

[189] T. Adam et al. Measurement of the neutrino velocity with the OPERA detector in the CNGS beam. 2011.

[190] M. Schmitt and M. Velasco. `http://if-neutrino.fnal.gov/neutrino1-pagers.pdf`.

[191] Aldo M. Serenelli, W.C. Haxton, and Carlos Pena-Garay. Solar models with accretion. I. Application to the solar abundance problem. *Astrophys. J.*, 743:24, 2011.

[192] The Borexino Collaboration. First evidence of pep solar neutrinos by direct detection in Borexino. 2011.

[193] T. Araki, S. Enomoto, K. Furuno, Y. Gando, K. Ichimura, et al. Experimental investigation of geologically produced antineutrinos with KamLAND. *Nature*, 436:499–503, 2005.

[194] G. Bellini, J. Benziger, S. Bonetti, M.Buizza Avanzini, B. Caccianiga, et al. Observation of Geo-Neutrinos. *Phys. Lett.*, B687:299–304, 2010.

[195] Gianni Fiorentini, Marcello Lissia, and Fabio Mantovani. Geo-neutrinos and Earth's interior. *Phys. Rept.*, 453:117–172, 2007.

[196] C. Rott. `http://if-neutrino.fnal.gov/neutrino1-pagers.pdf`.

[197] Gianfranco Bertone, Dan Hooper, and Joseph Silk. Particle dark matter: Evidence, candidates and constraints. *Phys. Rept.*, 405:279–390, 2005.

[198] Kate Scholberg. Supernova neutrino detection. 2007.

[199] Shin'ichiro Ando, John F. Beacom, and Hasan Yuksel. Detection of neutrinos from supernovae in nearby galaxies. *Phys. Rev. Lett.*, 95:171101, 2005.

[200] Huaiyu Duan, George M. Fuller, and Yong-Zhong Qian. Collective neutrino flavor transformation in supernovae. *Phys. Rev.*, D74:123004, 2006.

[201] Gianluigi L. Fogli, Eligio Lisi, Antonio Marrone, and Alessandro Mirizzi. Collective neutrino flavor transitions in supernovae and the role of trajectory averaging. *JCAP*, 0712:010, 2007.

[202] Georg G. Raffelt and Alexei Yu. Smirnov. Self-induced spectral splits in supernova neutrino fluxes. *Phys. Rev.*, D76:081301, 2007.

[203] Georg G. Raffelt and Alexei Yu. Smirnov. Adiabaticity and spectral splits in collective neutrino transformations. *Phys. Rev.*, D76:125008, 2007.

[204] A. Esteban-Pretel, A. Mirizzi, S. Pastor, R. Tomas, G.G. Raffelt, et al. Role of dense matter in collective supernova neutrino transformations. *Phys. Rev.*, D78:085012, 2008.

[205] Huaiyu Duan and James P Kneller. Neutrino flavour transformation in supernovae. *J. Phys. G*, G36:113201, 2009.

[206] Basudeb Dasgupta, Amol Dighe, Georg G. Raffelt, and Alexei Yu. Smirnov. Multiple Spectral Splits of Supernova Neutrinos. 2009.

[207] Huaiyu Duan, George M. Fuller, and Yong-Zhong Qian. Collective Neutrino Oscillations. *Ann. Rev. Nucl. Part. Sci.*, 60:569–594, 2010.

[208] Huaiyu Duan and Alexander Friedland. Self-induced suppression of collective neutrino oscillations in a supernova. *Phys. Rev. Lett.*, 106:091101, 2011.

[209] Georg G. Raffelt. Particle Physics from Stars. *Ann. Rev. Nucl. Part. Sci.*, 49:163–216, 1999.

[210] Steen Hannestad and Georg Raffelt. New supernova limit on large extra dimensions. *Phys. Rev. Lett.*, 87:051301, 2001.

[211] John F. Beacom. The Diffuse Supernova Neutrino Background. *Ann. Rev. Nucl. Part. Sci.*, 60:439–462, 2010.

[212] Cecilia Lunardini. Diffuse supernova neutrinos at underground laboratories. 2010.

[213] Thomas K. Gaisser, Francis Halzen, and Todor Stanev. Particle astrophysics with high-energy neutrinos. *Phys. Rept.*, 258:173–236, 1995.

[214] F. Halzen. High-energy neutrino astronomy. *Phys. Rept.*, 333:349–364, 2000.

[215] Luis A. Anchordoqui and Teresa Montaruli. In Search for Extraterrestrial High Energy Neutrinos. *Ann. Rev. Nucl. Part. Sci.*, 60:129–162, 2010.

[216] Jan Hamann, Steen Hannestad, Georg G. Raffelt, and Yvonne Y.Y. Wong. Sterile neutrinos with eV masses in cosmology: How disfavoured exactly? *JCAP*, 1109:034, 2011.

[217] Steven Weinberg. Universal Neutrino Degeneracy. *Phys. Rev.*, 128:1457–1473, 1962.

[218] Alfredo G. Cocco, Gianpiero Mangano, and Marcello Messina. Probing low energy neutrino backgrounds with neutrino capture on beta decaying nuclei. *JCAP*, 0706:015, 2007.

[219] M. Fukugita and T. Yanagida. Baryogenesis Without Grand Unification. *Phys. Lett.*, B174:45, 1986.

[220] J.A. Casas and A. Ibarra. Oscillating neutrinos and muon to e gamma. *Nucl. Phys.*, B618:171–204, 2001.

[221] Asmaa Abada, Sacha Davidson, Francois-Xavier Josse-Michaux, Marta Losada, and Antonio Riotto. Flavor issues in leptogenesis. *JCAP*, 0604:004, 2006.

[222] Enrico Nardi, Yosef Nir, Esteban Roulet, and Juan Racker. The Importance of flavor in leptogenesis. *JHEP*, 0601:164, 2006.

[223] A. Abada, S. Davidson, A. Ibarra, F.-X. Josse-Michaux, M. Losada, et al. Flavour Matters in Leptogenesis. *JHEP*, 0609:010, 2006.

[224] Kazunori Kohri, Takeo Moroi, and Akira Yotsuyanagi. Big-bang nucleosynthesis with unstable gravitino and upper bound on the reheating temperature. *Phys. Rev.*, D73:123511, 2006.

[225] S. Pascoli, S.T. Petcov, and Antonio Riotto. Connecting low energy leptonic CP-violation to leptogenesis. *Phys. Rev.*, D75:083511, 2007.

[226] Andre de Gouvea and Wei-Chih Huang. Constraining the (Low-Energy) Type-I Seesaw. 2011.

[227] Andre de Gouvea, James Jenkins, and Nirmala Vasudevan. Neutrino Phenomenology of Very Low-Energy Seesaws. *Phys. Rev.*, D75:013003, 2007.

[228] Andre de Gouvea. GeV seesaw, accidentally small neutrino masses, and Higgs decays to neutrinos. 2007.

[229] Eung Jin Chun, Kang Young Lee, and Seong Chan Park. Testing Higgs triplet model and neutrino mass patterns. *Phys. Lett.*, B566:142–151, 2003.

[230] Tao Han, Heather E. Logan, Biswarup Mukhopadhyaya, and Raghavendra Srikanth. Neutrino masses and lepton-number violation in the littlest Higgs scenario. *Phys. Rev.*, D72:053007, 2005.

[231] A. Hektor, M. Kadastik, M. Muntel, M. Raidal, and L. Rebane. Testing neutrino masses in little Higgs models via discovery of doubly charged Higgs at LHC. *Nucl. Phys.*, B787:198–210, 2007.

[232] Tao Han, Biswarup Mukhopadhyaya, Zongguo Si, and Kai Wang. Pair production of doubly-charged scalars: Neutrino mass constraints and signals at the LHC. *Phys. Rev.*, D76:075013, 2007.

[233] M. Kadastik, M. Raidal, and L. Rebane. Direct determination of neutrino mass parameters at future colliders. *Phys. Rev.*, D77:115023, 2008.

[234] A.G. Akeroyd, Mayumi Aoki, and Hiroaki Sugiyama. Probing Majorana Phases and Neutrino Mass Spectrum in the Higgs Triplet Model at the CERN LHC. *Phys. Rev.*, D77:075010, 2008.

[235] Pavel Fileviez Perez, Tao Han, Gui-yu Huang, Tong Li, and Kai Wang. Neutrino Masses and the CERN LHC: Testing Type II Seesaw. *Phys. Rev.*, D78:015018, 2008.

[236] Borut Bajc and Goran Senjanovic. Seesaw at LHC. *JHEP*, 0708:014, 2007.

[237] Abdesslam Arhrib, Borut Bajc, Dilip Kumar Ghosh, Tao Han, Gui-Yu Huang, et al. Collider Signatures for Heavy Lepton Triplet in Type I+III Seesaw. *Phys. Rev.*, D82:053004, 2010.

[238] Mitsuru Kakizaki, Yoshiteru Ogura, and Fumitaka Shima. Lepton flavor violation in the triplet Higgs model. *Phys. Lett.*, B566:210–216, 2003.

[239] S. Pascoli, S.T. Petcov, and W. Rodejohann. On the connection of leptogenesis with low-energy CP violation and LFV charged lepton decays. *Phys. Rev.*, D68:093007, 2003.

[240] Matthew R. Buckley and Hitoshi Murayama. How can we test seesaw experimentally? *Phys. Rev. Lett.*, 97:231801, 2006.

[241] Anupama Atre, Tao Han, Silvia Pascoli, and Bin Zhang. The Search for Heavy Majorana Neutrinos. *JHEP*, 0905:030, 2009.

[242] C. Athanassopoulos et al. The Liquid Scintillator Neutrino Detector and LAMPF Neutrino Source. *Nucl. Instrum. Meth.*, A388:149–172, 1997.

[243] B. Armbruster et al. Upper limits for neutrino oscillations muon-antineutrino to electron-antineutrino from muon decay at rest. *Phys. Rev.*, D65:112001, 2002.

[244] J. Alonso, F.T. Avignone, W.A. Barletta, R. Barlow, H.T. Baumgartner, et al. Expression of Interest for a Novel Search for CP Violation in the Neutrino Sector: DAEdALUS. 2010.

[245] Sanjib K. Agarwalla, Patrick Huber, Jonathan M. Link, and Debabrata Mohapatra. A new approach to anti-neutrino running in long baseline neutrino oscillation experiments. *JHEP*, 1104:099, 2011.

[246] S. Choubey et al. Interim Design Report. 2011.

[247] John F. Beacom and Mark R. Vagins. GADZOOKS! Antineutrino spectroscopy with large water Cherenkov detectors. *Phys. Rev. Lett.*, 93:171101, 2004.

[248] R. Becker-Szendy et al. IMB-3: A Large water Cherenkov detector for nucleon decay and neutrino interactions. *Nucl. Instrum. Meth.*, A324:363–382, 1993.

[249] K. S. Hirata et al. Real time, directional measurement of B-8 solar neutrinos in the Kamiokande-II detector. *Phys. Rev.*, D44:2241–2260, 1991.

[250] Y. Fukuda et al. The Super-Kamiokande detector. *Nucl. Instrum. Meth.*, A501:418–462, 2003.

[251] K. Abe, T. Abe, H. Aihara, Y. Fukuda, Y. Hayato, et al. Letter of Intent: The Hyper-Kamiokande Experiment — Detector Design and Physics Potential —. 2011.

[252] J. L. Borne et al. The MEMPHYS project. *Nucl. Instrum. Meth.*, A639:287–289, 2011.

[253] R. Abbasi et al. IceCube Sensitivity for Low-Energy Neutrinos from Nearby Supernovae. 2011.

[254] Tyce and DeYoung. Particle physics in ice with icecube deepcore. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, (0):–, 2011.

[255] Jian Tang and Walter Winter. Requirements for a New Detector at the South Pole Receiving an Accelerator Neutrino Beam. 2011.

[256] O. Palamara. The ArgoNeuT LAr-TPC: A dedicated experiment for neutrino cross section measurement at FNAL. *Nucl. Phys. Proc. Suppl.*, 217:189–192, 2011.

[257] S. Amerio et al. Design, construction and tests of the ICARUS T600 detector. *Nucl. Instrum. Meth.*, A527:329–410, 2004.

[258] C. M. Ignarra. MicroBooNE. 2011.

[259] Alessandro Curioni. GLACIER and related R&D. *J. Phys. Conf. Ser.*, 309:012012, 2011.

[260] Takuya Hasegawa. Introductory remark on the First International Workshop towards the Giant Liquid Argon Charge Imaging Experiment (GLA2010). *J. Phys. Conf. Ser.*, 308:012001, 2011.

[261] R. Mollenberg et al. Reconstruction of GeV neutrino events in LENA. *AIP Conf. Proc.*, 1382:141–143, 2011.

[262] A. A. Pomansky. Underground low background laboratories of the baksan neutrino observatory. *Nucl. Instrum. Meth.*, B17:406–410, 1986.

[263] M. Ambrosio et al. The MACRO detector at Gran Sasso. *Nucl. Instrum. Meth.*, A486:663–707, 2002.

[264] G. Bari et al. The Large Volume Detector (LVD): a multipurpose underground detector at Gran Sasso. *Nucl. Instrum. Meth.*, A277:11–16, 1989.

[265] John G. Learned, Stephen T. Dye, and Sandip Pakvasa. Hanohano: A Deep ocean anti-neutrino detector for unique neutrino physics and geophysics studies. 2007.

[266] Michael Wurm et al. The next-generation liquid-scintillator neutrino observatory LENA. 2011.

[267] Adam Bernstein et al. Report on the Depth Requirements for a Massive Detector at Homestake. 2009.

[268] M.Sajjad Athar et al. India-based Neutrino Observatory: Project Report. Volume I. 2006.

[269] Raj Gandhi, Pomita Ghoshal, Srubabati Goswami, Poonam Mehta, S.Uma Sankar, et al. Mass Hierarchy Determination via future Atmospheric Neutrino Detectors. *Phys. Rev.*, D76:073012, 2007.

[270] A. Rubbia. The LAGUNA design study: Towards giant liquid based underground detectors for neutrino physics and astrophysics and proton decay searches. *Acta Phys. Polon.*, B41:1727–1732, 2010.

[271] Sanjib Kumar Agarwalla, Tracey Li, and Andre Rubbia. An Incremental approach to unravel the neutrino mass hierarchy and CP violation with a long-baseline Superbeam for large θ_{13}. 2011.

[272] Alessandro Bettini. The world underground scientific facilities. A compendium. 2007.

[273] A. Bettini. Underground laboratories. *Nucl. Instrum. Meth.*, A626-627:S64–S68, 2011.

[274] J. Hylen et al. Conceptual design for the technical components of the neutrino beam for the main injector (NuMI). FERMILAB-TM-2018.

[275] P. Adamson et al. Measurement of the neutrino mass splitting and flavor mixing by MINOS. *Phys. Rev. Lett.*, 106:181801, 2011.

[276] `http://projectx.fnal.gov`.

[277] J. Alonso et al. A Study of Detector Configurations for the DUSEL CP Violation Searches Combining LBNE and DAEdALUS. 2010.

[278] L. Calabretta et al. Preliminary Design Study of High-Power H2+ Cyclotrons for the DAEdALUS Experiment. 2011.