The DNP/DPF/DAP/DPB

Joint Study on the Future of Neutrino Physics

The Neutrino Matrix

The Neutrino Matrix
Draft v2.0

The Writing Committee

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matrix *n:*
1 : something within or from which something else originates, develops, or takes form
2 : the natural material in which something is embedded
3 : womb
4 : a rectangular array of mathematical elements

Contents

Executive Summary

Neutrinos are everywhere, an ancient relic of the Big Bang. Millions fill every cubic meter of space throughout the universe, unobserved, a neutrino matrix that seemingly influences nothing but in fact has influenced everything. Now, remarkable new experiments on these elusive particles are prompting a revolution in physics.

The first hint of the true nature of neutrinos was Nobel Prize winner Ray Davis's extraordinary discovery that fewer neutrinos come from the sun than were expected from our understanding of how the sun produces its energy. We now know that this is due to "neutrino oscillations," a macroscopic consequence of the laws of quantum mechanics that govern the sub-atomic realm. Oscillations, in turn, require that neutrinos have mass, finally confirming a long-held suspicion. Since Davis's discovery, we have verified the existence of neutrino oscillations and neutrino mass using neutrinos produced in our atmosphere, in nuclear reactors, and by accelerators.

We see the future of neutrino physics as framed by three overarching themes:

- **Neutrinos and the New Paradigm:** Neutrinos have provided us with the first tangible evidence of phenomena beyond the reach of our theory of the laws of particle physics, the remarkably predictive "Standard Model". In the Standard Model, neutrinos do not have mass and do not oscillate. Through this crack in the edifice we are now peering, with no small excitement, to see the physics that lies beyond. It appears to be a glimpse of what physics is like at energies not seen since the Big Bang. Questions crowd upon us. The neutrino masses are known to be nonzero, but their values are uncertain by a factor of 100—what, exactly, are the masses? How much do neutrinos mix with each other, allowing one "flavor" to change into another? Neutrinos, alone among matter particles, could be their own antiparticles. Are they? Our understanding of nature has been enormously enriched by the study of symmetry. Perhaps the most baffling symmetry is the 'CP' symmetry (change particle to antiparticle and interchange left and right; everything should behave the same as before). Nature seems to have a bias here. Do neutrinos respect CP perfectly, a little, or not at all? We recommend the experimental program needed to build the foundations of the new paradigm.
- **Neutrinos and the Unexpected:** The surprises of the last decade have reminded us, if any reminder were needed, that discovery comes from careful comparison of what is observed to what is expected. Neutrino physics has been marked by "anomalous", unexpected results that have proved to be absolutely correct and to have deep significance. Neutrinos may have even more extraordinary properties than those already seen. We have evidence for exactly three types or flavors of neutrinos with normal interactions. Are there others with even weaker interactions? We describe an experimental program designed to be open to the unexpected.
- **Neutrinos and the Cosmos:** Neutrinos originating from the Big Bang and the depths of exploding stars prompt us to search for connections between the greatest and tiniest distance scales. Neutrinos allow us to probe the origin and future of solar energy, upon which all life on earth depends. Understanding neutrinos is necessary to comprehend supernova explosions, perhaps the origin of the heaviest elements on earth. The mass of neutrinos may influence the large-scale structure of the universe. Nature's bias with respect to CP is essential to

explain why the universe contains matter and no antimatter. However, the bias seen in laboratory experiments outside the neutrino realm is much too small. Perhaps neutrinos violate CP enough to explain this mystery. We describe an experimental program to map out the connections between the neutrino and the cosmos.

While the directions are clear, the best strategy for exploration demands thoughtful planning. Developing the strategy is made more challenging by the fact that it spans the studies of particle physics, nuclear physics, astrophysics, and particle beams. Drawing on the wide-ranging expertise of members of the neutrino community in these areas, we report the results of our study on the future of neutrino physics, organized by four Divisions of the American Physical Society. Among our group, consensus has emerged on three recommendations:

- **We recommend, as a high priority, a phased program of sensitive searches for neutrinoless nuclear double beta decay.** Our present theoretical perspective, and the evidence from neutrino oscillation, lead us to believe that this rare process, in which one atomic nucleus turns into another by emitting two electrons, may be experimentally observable. Although the experiments are extremely challenging, the question of whether the neutrino is its own antiparticle can only be addressed via this technique.The answer to this question is of central importance, not only to our understanding of neutrinos, but also to our understanding of the origin of mass.

- **We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum and to search for CP violation among neutrinos.** This comprehensive program would have several components: an experiment built a few kilometers from a nuclear reactor, an accelerator beaming neutrinos to a detector hundreds of kilometers away, and, in the future, a neutrino 'superbeam' program utilizing a multi-megawatt proton accelerator. The interplay of the components makes possible a decisive separation of neutrino physics features that would otherwise be commingled and ambiguous. This program is also valuable for the tools it will provide to the larger community. For example, the proton accelerator can sustain a wide range of research well beyond neutrino physics.

  On the horizon is the promise of a neutrino factory, which will produce extraordinarily pure, well defined neutrino beams. Similarly challenging are the ideas for massive new detectors that will yield the largest and most precise samples of neutrino data ever recorded. At the same time, these multipurpose detectors can be used for fundamental and vitally important studies beyond the field of neutrino physics, such as the search for proton decay. The development of new facilities must go hand-in-hand with the development of new technologies. We emphasize the need for underground laboratory facilities that will provide the necessary shelter for the most sensitive probes of neutrino properties, as well as allowing studies in a wide variety of other exciting areas of science.

- **We recommend further development of a neutrino experimental program that can measure the present energy production of the sun.** A precise measurement of the total number of neutrinos radiated by the sun will test the fundamental question of whether the sun shines only through nuclear fusion reactions. In addition, the neutrinos we observe were created just 8 minutes earlier in the sun's core, but the heat from those same reactions will not reach the sun's surface for another roughly 40,000 years. That the sun's energy production does not vary on this time scale is thus testable by comparing the total neutrino flux to the sun's present energy output.

These recommendations are made in the context of certain assumptions about features of the current and ongoing program which have led to the breakthroughs and placed the new paradigm within reach. These include:

- **Continuation and strong support of the existing program.** The vigorous U.S. program of neutrino physics has the potential to become the best worldwide. Its contributions have been well balanced between notable recent breakthroughs, the search for rare properties, and creative use of the connections to astrophysics. We are justifiably proud of our recent accomplishments. The full potential of the program, however, will not be reached without making optimal use of the investments already made. We have identified four areas to address: increasing proton intensity for neutrino experiments at Fermilab, resolution of the third experimental hint of oscillations (the "LSND" result), support for measurement of ^{7}Be solar neutrinos and continued support for R&D for detection of ultra-high energy astrophysical neutrinos. With these and other modest improvements, the results can be maximized.

- **Determination of the neutrino reaction and production cross sections required for a precise understanding of neutrino-oscillation physics and the neutrino astronomy of astrophysical and cosmological sources.** Our broad and exacting program of neutrino physics is built upon precise knowledge of particle interactions with matter, a subfield known as cross-section physics. This report supports an expansion of the existing program of determining the neutrino cross sections. Symbiotic with other programs as they are, these experiments maximize our physics gain at modest cost.

- **Research and development to assure the practical and timely realization of accelerator and detector technologies critical to the recommended program.** In addition, new techniques are needed to detect the highest energy neutrinos, which could be used to open a new window on the cosmos. To ensure continued progress in understanding several aspects of the neutrino matrix, research into new technologies must begin today.

- **International Cooperation.** We advocate that a strong U.S. and international program be maintained far into the future. The U.S. contribution should include both experiments within the U.S. and American participation in key experiments located throughout the world. The history of progress in science depends on both competition and cooperation.

The experimental program described in this study is intended to be a very fruitful investment in fundamental physics. The selection is physics-rich, diverse, and cost-effective. A time line has been developed to synchronize aspects of the program and to be integrated with the worldwide effort to reach an understanding of the neutrino. The program components are chosen to provide unique information and thereby enhance companion studies in high energy physics, nuclear physics, and astrophysics. There are rare moments in science when a clear road to discovery lies ahead and there is broad consensus about the steps to take along that path. This is one such moment.

1 Introduction

We live within a matrix of neutrinos. They flit by, unnoticed by us, and pass through us with equal disregard. Their number far exceeds the count of all the atoms in the entire universe. Although they hardly interact with matter at all, they helped forge the elements in the early universe, they tell us how the sun shines, they cause the titanic explosion of a dying star. They may even be the reason we live in a universe filled with matter – in other words, the reason for our being here.

Much of what we know about neutrinos we have learned in just the last six years. Neutrino discoveries have come so fast we have barely had time to rebuild the conceptual matrix by which we hope to understand them.

The new discoveries have taught us two important things: that neutrinos can change from one type to another; and that, like other fundamental particles of matter, they can approach, but never reach, the speed of light. The implications of these new facts reach well beyond just neutrinos, and affect our understanding of the Sun, our theory of the evolution of the Universe, and our hope of finding a more fundamental theory of the subatomic world. We now have so many new questions, our task in this Study has been especially difficult. We are most certain of one thing, neutrinos will continue to surprise us.

The Story:

A crisis loomed at the end of the 1920's – a decade already filled with revolutions. One of physics' most sacred principles – the conservation of energy – appeared not to hold within the subatomic world. For certain radioactive nuclei, energy just seemed to disappear, leaving no trace of its existence.

In 1930, Wolfgang Pauli suggested what he called a "desperate remedy." Pauli postulated that the missing energy was being carried away by a new particle, whose properties were such that it would not yet have been seen: it carried no electric charge and scarcely interacted with matter at all.

Luckily, Enrico Fermi was able to show that while the new particles would be hard to observe, seeing them would not be impossible. What was needed was an enormous number of them, and a very large detector. Fermi named Pauli's particle the neutrino, which means 'little neutral one'. More than two decades after Pauli's letter proposing the neutrino, Clyde Cowan and Fred Reines finally observed (anti)neutrinos emitted by a nuclear reactor. Further studies over the course of the next 35 years taught us that there were three kinds, or 'flavors,' of neutrinos (electron neutrinos, muon neutrinos, and tau neutrinos) and that, as far as we could tell, they had no mass at all. The neutrino story (Fig. 1) might have ended there, but developments in solar physics changed everything.

In 1919, Sir Arthur Eddington had suggested that the sun's multi-billion year age could be explained if its power source was the "well-nigh inexhaustible" energy stored in atomic nuclei. With Fermi's neutrino theory, Hans Bethe and Charles Critchfield in 1938 created the first detailed theory of the nuclear furnace burning in the sun's core.

Neutrinos are produced in great numbers by nuclear reactions, and they can pass from the solar center to us completely undisturbed. While the light we see from the sun represents energy created in the core tens of thousands of years ago, a neutrino created in the sun right now will reach us in just over eight minutes. But if neutrinos can pass easily through the sun, how could we possibly detect them on Earth? In the mid-1960's experimentalist Raymond Davis, Jr. and theorist John Bahcall thought about this prob-

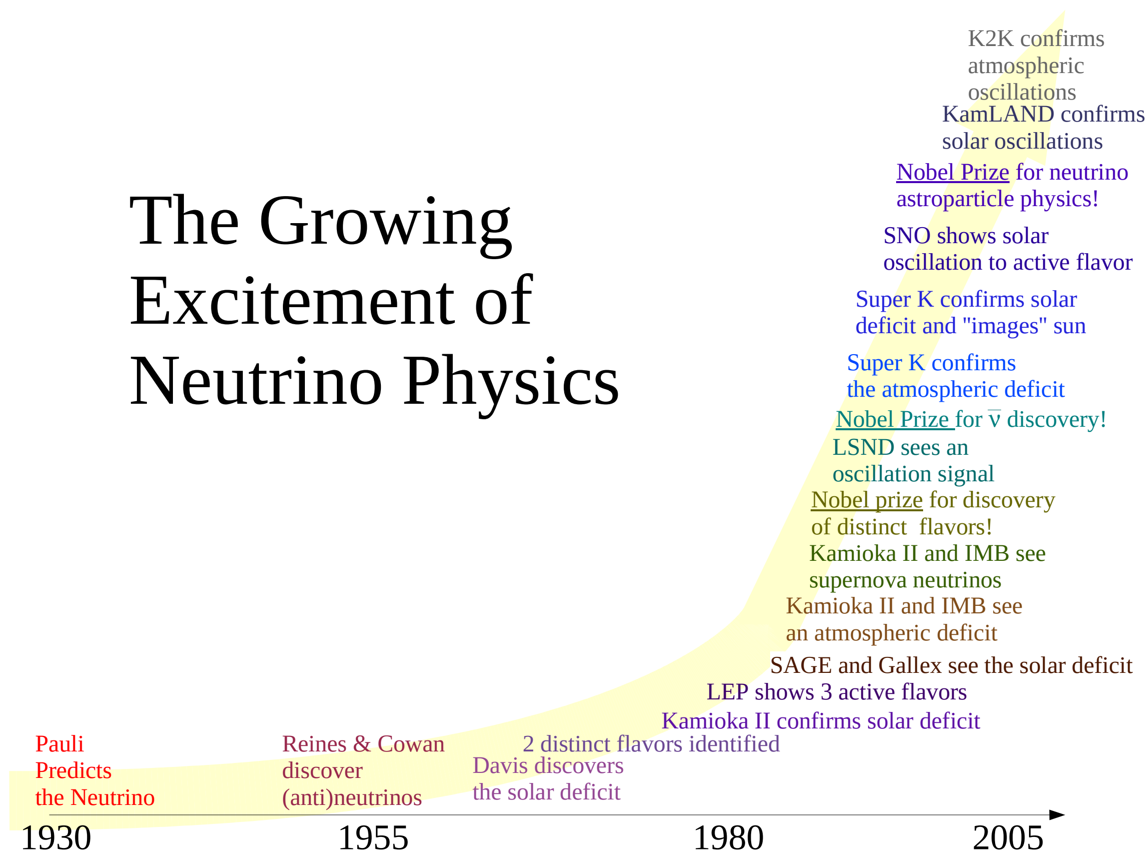

Figure 1: A brief history of the neutrino.

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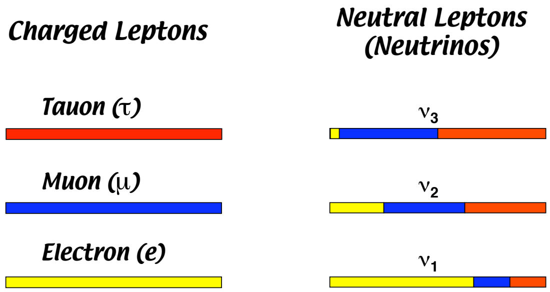
lem. Bahcall's detailed calculations showed that there might just be enough neutrinos produced in the sun that they could be observed on earth, and Davis set out to build a detector that could see the neutrinos. His detector weighed hundreds of tons, and he had to be able to detect the few atoms each week that had been transformed by neutrinos. What Davis saw surprised everyone.

While he did observe neutrinos, Davis found only roughly 1/3 the number Bahcall had predicted. Davis' experiment was exceedingly difficult, and Bahcall's calculations equally so. Many physicists believed that it was likely that either, or perhaps both, were in error. But over the next three decades, solar neutrino predictions became more refined, and new experiments invariably saw fewer than predicted. The mystery would not go away.

Neutrinos in a Nutshell

Neutrinos are the most abundant matter particles, called "fermions," in the universe. Unlike their relatives, the electron and the quarks, they have no electrical charge.

There are three different types (or 'flavors') of electron-like particles, each with a different mass: the electron (e) itself, the muon (μ) weighing 200 times more than the electron, and the tau (τ) which weighs 18 times more than the muon. For each of these charged particles there is also a neutrino. Collectively, these six particles (e, μ, τ, ν_1, ν_2 and ν_3) are known as the 'leptons', which comes from the Greek word meaning 'thin', 'subtle', or 'weak'.



The leptons. The colors indicate the 'flavors' of the charged leptons, electron, mu, and tau. The flavors determine what happens when a lepton collides with another particle.

Neutrino masses are exceedingly tiny, compared to the masses of their charged brethren. It is only from discoveries made in the last six years that we know that these masses are not exactly zero, and that the heaviest of them must weigh at least one ten-millionth as much as an electron. Moreover, we know that the masses are all different.

Like all the other particles of matter, neutrinos have antimatter partners, denoted with a bar on top: *e.g.* $\bar{\nu}_1$, $\bar{\nu}_2$, $\bar{\nu}_3$. Unlike any other fermion, though, the ν and $\bar{\nu}$ may in fact be the same particle!

Drawn six years ago, the figure above would have the neutrinos each with a single, different flavor, like the charged leptons. Neutrinos are created with other particles through a force appropriately named the 'weak interaction,' and the weak interaction does not change flavor. For example, in the beta decay studied by Pauli in 1930 the weak interaction makes an antielectron and an 'electron neutrino,' ν_e. A weak interaction that made an antimuon would also make a 'mu neutrino,' ν_μ, and so forth. But what are those 'particles'? The only way nature can construct a neutrino that is totally electron flavored is to form a quantum-mechanical mixture of exactly the appropriate amounts of the mixed-flavor particles ν_1, ν_2 and ν_3. What had always been thought of as a simple particle, ν_e is actually a quantum-mechanical Neapolitan of the 3 neutrinos with definite masses.

As time passes, or the neutrino travels, the quantum waves that accompany the different parts get out of step because the masses are different. Depending on the distance travelled, what was originally produced as an electron flavored 'neutrino' can become mu flavored or tau flavored as the components shift. This is the phenomenon called neutrino oscillations, and it provides our best evidence that neutrinos have distinct, nonzero masses.

There is a lot still to learn about the masses and flavors! We are now trying to measure the flavor contents of each neutrino, and we represent them by 3 trigonometric angles called θ_{12}, θ_{13}, and θ_{23}. The masses themselves are only known within broad ranges, although oscillations tell us quite a lot about the differences.

The best explanation that encompassed both the theoretical prediction and the experimental results was that the neutrinos produced in the Sun were changing from one flavor to another. Experiments like Davis' were sensitive only to electron neutrinos, the only kind the sun can produce. If on their way from the sun to the earth some of the electron neutrinos changed into the other flavors, they could sail through the detectors completely unobserved. Such an idea was very far from our vanilla concept of neutrinos. For one thing, the ability to change flavor meant neutrinos had to have mass.

While physicists puzzled over the solar neutrino experiments, a new neutrino mystery arose in the mid 1980s. When cosmic rays hit the earth's atmosphere, they create showers of other particles, including neutrinos. The Kamiokande and IMB experiments, built to search for proton decay, found that the number of mu neutrinos created in the atmosphere appeared to be smaller than expected. The experimenters pointed out that, like the solar neutrinos, this could be true if the mu neutrinos were actually changing into tau neutrinos. But the experiments were very difficult, and many physicists again attributed the deficit to error.

Now the explanation is clear. In 1998, the Super-Kamiokande experiment showed that neutrinos changing flavor as they traveled through space was the only way to explain the missing 'atmospheric' neutrinos. A few years later, the Sudbury Neutrino Observatory (SNO) collaboration built a detector sensitive to Davis' missing neutrinos, finding them all there but in different flavors. Physicists have now also observed transformation of man-made neutrinos. The KamLAND experiment has observed reactor antineutrino disappearance that is consistent with solar neutrino disappearance, and the K2K accelerator-based experiment observed muon-neutrino disappearance that is consistent with the atmospheric deficit.

Not all the neutrino mysteries have been solved. One that remains is the observation in the LSND experiment of neutrinos changing flavor, but in a way unlike either solar neutrinos or atmospheric neutrinos.

The discovery of neutrino oscillations and mass has answered questions that had endured for decades. As those veils have lifted, burning new questions about the physical and mathematical neutrino matrix challenge us. We have started down the road to a new understanding of the physics of matter.

2 Neutrinos: Discovery in Action

The story of neutrinos continues to be written. As the narrative unfolds, three themes have crystallized that broadly define the science. Within each of these themes, we are confronted by basic questions. Understanding the nature of neutrinos has become a critical issue at the frontiers of physics, astrophysics, and cosmology. There is universal agreement about the questions that must be answered. It is only the difficulty of obtaining the answers that demands strategy and planning.

2.1 Neutrinos and the New Paradigm

The neutrino discoveries of the last decade are bringing about a revolutionary New Standard Model, which modifies the basic picture of the elementary particles and poses a set of well-defined but presently unanswered questions. These questions are so fundamental it is as if the neutrino were a newly discovered particle.

- **What are the masses of the neutrinos?**

The Mass that Roared

The discovery that neutrinos have mass is a profound revolution in particle physics. For 30 years we have had a robust, trustworthy, "Standard" model that has unfailingly been able to describe anything in the particle world we asked of it, in some cases to 10 decimal places. That basic model predicted that neutrinos have no mass. We always expected that one day the model would fail, even hoped for it, because it must be a simplification of some grander description. Now we simply do not know what nature is telling us, but a key must be the anomalously tiny size of the neutrino's mass.

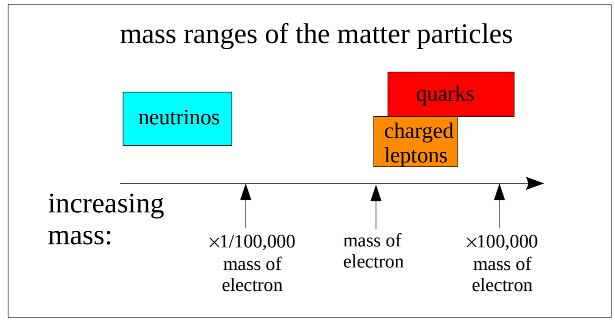


Figure 2: The masses of the fundamental fermions, the particles of matter. The masses are shown on a log scale. The individual neutrino masses are not well known, and the average is only known to within two orders of magnitude. There is a surprisingly large difference between the neutrino masses and the masses of the quarks and charged leptons.

The combination of solar, atmospheric, accelerator, and reactor neutrino data reveals unambiguously that at least two neutrinos have nonzero, distinct masses. This naively simple fact turns out to be revolutionary, and has forced us to modify our fundamental description of particle physics. Furthermore, these data, which provide evidence for neutrino oscillations, allow the precise determination of the difference between the squares of two neutrino masses. If there are three neutrinos with masses m_1, m_2, and m_3, oscillation experiments are capable of measuring the mass-squared differences. We express these as Δm^2_{12}, which is $m_2^2 - m_1^2$, Δm^2_{23}, which is $m_3^2 - m_2^2$, and Δm^2_{13} which is $m_3^2 - m_1^2$. One can see from this that only two of these mass-squared differences are independent; the third is known by definition once the first two are measured.

Oscillations tell us about the differences of mass, but what can we say about the masses themselves? In the laboratory, precise measurements of the tritium beta-decay spectrum constrain the average of the three neutrino masses to be less than 2.2 eV. For comparison (Fig. 2), the electron, the lightest of the charged elementary particles, has a mass of 511,000 eV. But the oscillation results point to an average mass not smaller than 0.02 eV. The mass is boxed in to the range 0.02 to 2.2 eV.

Interestingly, studies of the large-scale structure of the visible universe combined with the precise determination of the cosmic microwave background radiation from experiment tell us that the average neutrino mass is in the vicinity of 0.5 eV or less. Now we must pin it down. There are three types of experiments poised to increase our sensitivity to the absolute value of the neutrino masses by about another one or two orders of magnitude over the next 10 to 20 years:

1. more precise, state-of-the-art tritium beta decay experiments, seeking to directly measure the average neutrino mass.
2. neutrinoless double-beta-decay experiments, which have sensitivity to another linear combination of neutrino masses, provided that neutrinos are their own antiparticle; and
3. precision studies of the distribution of the cosmic microwave background across the

sky and the large-scale structure of the universe revealed by clusters of galaxies.

The two possible orderings of the masses, or hierarchies, are depicted in Fig. 3, and are often referred to as "normal" and "inverted." We currently have no information regarding which is correct. Knowing the ordering of the neutrino masses is of the utmost importance. For example, in the case of an inverted hierarchy, there are at least two neutrinos that have almost the same mass to the one percent level. We have never encountered two different fundamental particles with quasi-degenerate masses – understanding this will prove to be a challenge and will tell us something fundamental about the workings of Nature.

Future neutrino experiments can potentially determine the neutrino mass hierarchy. The most promising ways of obtaining this information include

1. accelerator-based long-baseline oscillation experiments with baselines in the vicinity of 1000 km or more; and
2. very large atmospheric neutrino experiments which can independently measure the oscillation of neutrinos and antineutrinos.

• What is the pattern of mixing among the different types of neutrinos?

Double Identity

Neutrinos exist with a dual identity – what you see depends on how you look at them. The physical neutrinos are simply not the objects we thought we knew, ν_e, ν_μ, and ν_τ. They are objects, ν_1, ν_2, and ν_3, each with a rainbow of the three flavors. Understanding the connection between the dual identities, which we gain by watching the neutrino flavor change with time, is central to defining these mysterious particles and key to the beyond-the-Standard-Model physics that can produce this strange behavior.

As described in the section Neutrinos in a Nutshell, the "physical" neutrinos, as we shall call neutrinos with definite mass, are mixtures of the electron, muon, and tau flavors. Mathematically, we relate the physical neutrinos to the flavors via a mixing matrix. The same phenomenon is observed in the quark sector, and several decades of research have gone into measuring and interpreting the elements of what is referred to as the CKM matrix.

Like the neutrinos, the quarks have physical mass states that are mixtures of their flavor states. Unlike neutrinos, these mixtures are well measured. One would think that we could look to the quarks to understand the neutrinos, but the theoretical analogy fails completely. Unlike the numbers that describe quark mixings, which are rather small, the mixing of the neutrinos turns out to be large. The mixing in the leptonic sector is very different from mixing in the quark sector, and we have no idea why.

We can describe the mixing in "matrix notation:"

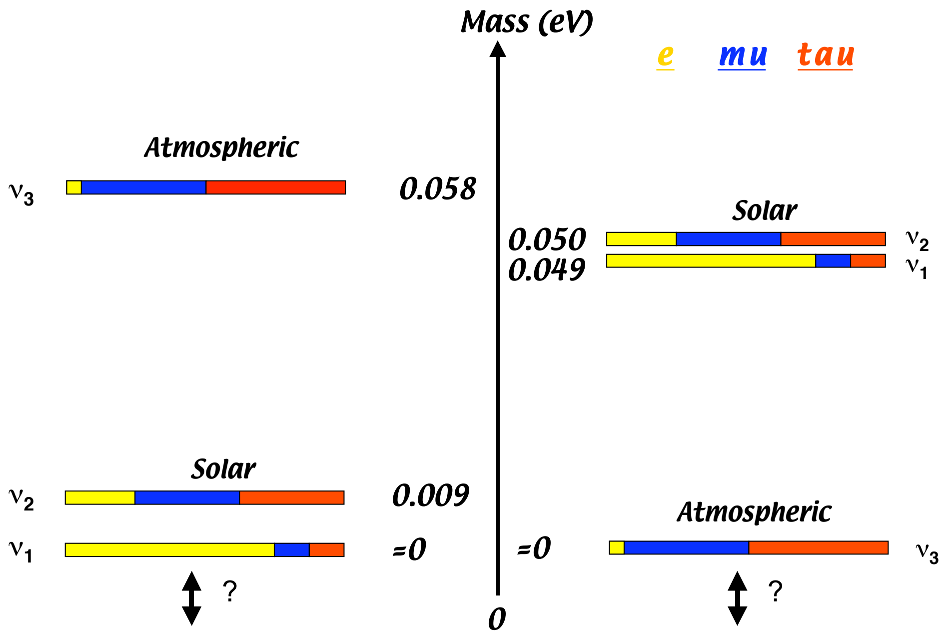


Figure 3: The two possible arrangements (hierarchies) of the masses of the three known neutrinos, based on oscillation data. The picture shows the situation for the mass of the lightest neutrino being zero; but in fact, from experiment, the average mass of the neutrinos may be as large as 2.2 eV.

Neutrinos

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

The difference between the large numbers that dominate the neutrino matrix, just approximate here, and the small values of the quark matrix is dramatic.

Determining all the elements of the neutrino mixing matrix is important because it is likely that, in a way we do not yet understand, they encode fundamental information about the structure of matter. We see mixing in other contexts in physics, and it generally is a result of the interaction of simpler, more primitive, systems. The mu and tau flavors, for example, appear to be mixed as much as they can possibly be – is it so, and, if so, why?

For three neutrino species, the neutrino mixing matrix **U** has nine elements, but only either four or six are independent; six if neutrinos are their own antiparticles, four otherwise. These are usually chosen to be three mixing angles: the "solar angle" θ_{12}, the "atmospheric angle" θ_{23}, and θ_{13}; and one or three complex phases. Neutrino mixing and mass together lead to neutrino oscillations – this is how we learned that neutrinos have mass – and the detailed study of the oscillation phenomenon allows us to measure the three mixing angles and one of the CP-violating phases, referred to as δ.

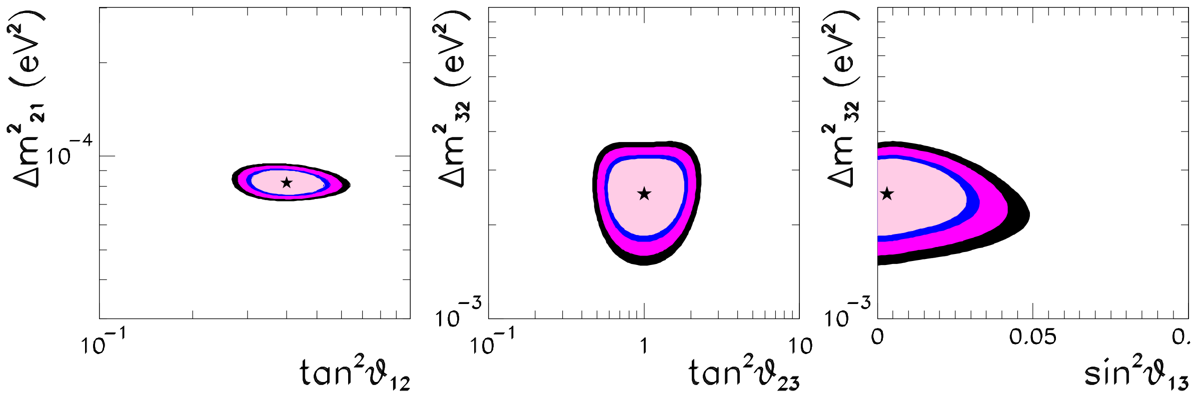


Figure 4: Current experimental constraints on the three mixing angles, θ_{12}, θ_{13}, and θ_{23}, and their dependence on the two known mass-squared differences, Δm^2_{12} and Δm^2_{23}. The star indicates the most likely solution. The contours correspond to certain confidence levels of finding the parameters within.

We can describe the mass states and neutrino mixings using the set of bars in Fig. 3. Each bar represents a physical neutrino of a given mass, ν_1, ν_2, and ν_3. We use mixing angles to describe how much of each flavor (electron, mu, or tau) can be found in the physical neutrino. In this diagram we denote the fractional flavors by the color in the bar. Yellow is electron flavor, blue is muon flavor, and red is tau flavor. For concreteness we have picked certain flavor fractions for each bar, but in some cases, the exact fractional amount is not well known.

We can now connect the diagram of Fig. 3 to the mixing angles we measure:

- $\sin^2\theta_{13}$ is equal to the amount of ν_e contained in the ν_3 state (the yellow in the ν_3 bar).
- $\tan^2\theta_{12}$ is equal to the amount of ν_e in ν_2 divided by the amount of ν_e in ν_1, *i.e.*, the ratio of the yellow fraction of the ν_2 bar to the yellow fraction of the ν_1 bar in Fig. 3. We currently know that $\tan^2\theta_{12} < 1$, which means that there is more ν_e in ν_1 than in ν_2.
- $\tan^2\theta_{23}$ is the ratio of ν_μ to ν_τ content in ν_3, *i.e.*, the fraction of the ν_3 bar in Fig. 3 colored blue divided by the fraction colored red. We currently do not know whether the ν_3 state contains more ν_μ or more ν_τ, or an equal mixture.

Figure 4 summarizes our experimental knowledge of the 3 mixing angles.

The mixing can be measured by

1. Precision solar neutrino experiments;
2. Very precise measurements, at the 1% level or better, of the flux and spectrum of electron-flavor antineutrinos produced in nuclear reactors and observed a few kilometers away from the source;
3. Accelerator-based long-baseline oscillation experiments with baselines of several hundred km or more.

- **Are neutrinos their own antiparticles?**

> **The Oddest Couple**
> *Particles have antiparticles that are identical in every respect except charge. Their charges have opposite signs. What are we to make of neutrinos, which have no charge? Is there anything that requires a distinction between neutrinos and antineutrinos? If there is not, perhaps neutrinos and antineutrinos are really the same particle. This possibility can explain why neutrinos are so light, yet not completely massless, and it also points to the existence of neutrinos so heavy we cannot possibly make them in the laboratory. Intriguingly, their mass-energy happens to be about the same as the energy where the known forces (except gravity) may unite as one. We must find out if neutrinos are their own antiparticles.*

The requirement that Albert Einstein's theory of special relativity also be applicable to the weird world of quantum mechanics led to the remarkable prediction, by Paul A. M. Dirac, that for every particle there exists an antiparticle. The particle and the antiparticle have identical mass and spin but have exactly opposite internal quantum numbers, like electric charge. Neutral particles are special in the following sense: they can be their own antiparticles. This is true of several neutral bosons, including the photon, the neutral pion, and the Higgs boson, which as yet is only theorized.

Neutrinos are the only elementary neutral fermions known to exist, and could also be their own antiparticles. Now that we know neutrinos have mass, we can address this most fundamental question. Determining whether neutrinos are their own antiparticles is the number one requirement for understanding the New Standard Model. There are two completely different ways of "adding" massive neutrinos to the old Standard Model – one that allows neutrinos to be their own antiparticle, and one that does not – and we must know which one is correct in order to proceed. As things stand, we no longer know the equations that describe all experimentally observed phenomena in particle physics.

In practice, we attack this problem by asking what must be true if the neutrinos are *not* their own antiparticles. If the neutrino and antineutrino are distinct particles, they must possess some new fundamental "charge" which distinguishes the neutrino from the antineutrino. This charge is called "lepton number." We assign the neutrinos and the negatively charged leptons lepton number +1, and the antineutrinos and the positively charged leptons lepton number -1. If lepton number is violated by *any* physical process, it would not be a conserved charge. This necessarily would imply that the neutrinos *are* their own antiparticles. If, on the other hand, lepton number is always conserved, it reveals a new fundamental symmetry of Nature, one we did not know existed before. [1]

Currently, we have no concrete experimental evidence that lepton number is violated. By far the most sensitive probe of lepton number violation is neutrinoless double beta decay. This is a process related to the beta decay process discussed earlier, where a neutron decays to a proton, an electron, and a neutrino. In a nucleus with multiple neutrons, it may be energetically favorable for two neutrons to beta decay simultaneuosly. This process, called double beta decay, occurs rarely; it results in two neutrinos, two electrons and two protons. If neutrinos are their own antiparticle, then, in principle, the

[1] Note to experts: lepton number is known to be violated in the Standard Model by nonperturbative effects. One should replace everywhere 'lepton number' by 'baryon number minus lepton number' ($B-L$), which is the non-anomalous global symmetry of the old Standard Model Lagrangian. If it turns out that neutrinos are not their own antiparticles, we are required to "upgrade" $B-L$ from an accidental symmetry to a fundamental one.

neutrino pair could annihilate, resulting in neutrinoless double beta decay. In this process, a nucleus ^{A}Z decays into another nucleus $^{A}(Z+2)$ plus two electrons, thereby violating lepton number by two units.

The outcomes of future searches for neutrinoless double beta decay, combined with results from neutrino oscillation experiments and direct searches for neutrino masses, may not only unambiguously determine whether the neutrino is its own antiparticle, but may also allow for a precise determination of the neutrino masses themselves.

• Do neutrinos violate the symmetry CP?

Figure 5: A neutrino physicist seen in a CP Mirror, which inverts spatially and maps matter to antimatter. CP invariance implies the same behavior for both sides of the mirror.

The Mirror Cracked

When you look at yourself in a mirror, you see a perfect spatial reflection that behaves just as you do, only in reverse. Nature's particle mirror, which we call "CP," is one that reflects not only in space, but from matter to antimatter. This particle mirror is known to have a tiny flaw: at a very small level quarks don't behave like their looking-glass partners. But what is small for quarks could be large for neutrinos, and through this crack in Nature's mirror, we may see physics far beyond the present energy scales.

CP invariance says that when matter is mirrored spatially and then converted to antimatter, the result should behave identically to the original particle (see Fig. 5). Guided by the quark sector, though, we expect CP-invariance to be violated in the neutrino sector at a small level. We are also led to conclude that, as in the quark sector, several CP-invariance violating phenomena in neutrino physics should be described in terms of the same fundamental parameter – the CP-violating phase δ contained in the mixing matrix. We have learned, however, that the guidance provided by the quark sector and other "theoretical prejudices" can lead us astray. There is no fundamental reason to believe that the mechanism for neutrino CP-invariance violation is the same as the one observed in the quark sector, and the only way to verify it is to study it experimentally in detail.

The best, and only practical, way of studying CP-invariance violation in the neutrino sector is via accelerator-based long-baseline oscillation experiments. Ideally, we should be able to compare electron-flavor to muon-flavor neutrino oscillations to electron-flavor to muon-flavor antineutrino oscillations and decide whether the oscillation probabilities differ. That can show that CP-invariance is violated, although in practice the presence of matter can counterfeit the effect. One can correct for that, but only if the neutrino mass hierarchy is known. Moreover, CP violation is not observable at all unless the flavor conversion caused by the mixing angle θ_{13} is also observable.

As in the quark sector, the experimental verification and detailed study of CP-invariance violation will require significant resources, ingenuity, and patience. We recommend a program to resolve the question. In general terms, sorting out the three unknowns of neutrino mixing, namely θ_{13}, δ_{rmCP}, and the mass hierarchy, can be accomplished with a combination of:

1. Long-baseline accelerator experiments in which

sufficient matter is present in the beam to provide sensitivity to the mass hierarchy via the Mikheyev-Smirnov-Wolfenstein matter enhancement effect.

2. Long-baseline accelerator experiments in which flavor conversion develops through the action of all three mixing angles, a prerequisite for observing CP violation.

3. Medium-baseline (a few km) experiments with reactors or accelerators to determine the magnitude of θ_{13} independent of the influence of CP violation and the mass hierarchy.

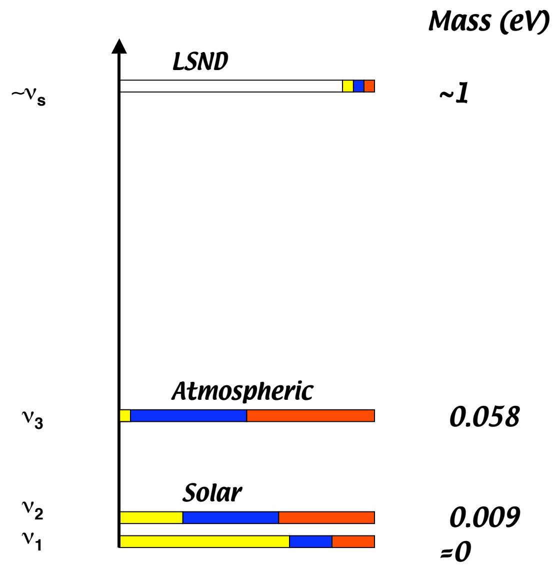


Figure 6: A possible arrangement (hierarchy) of the masses of the neutrinos, based on oscillation data, with the additional input of evidence of a fourth type of neutrino from LSND.

2.2 Neutrinos and the Unexpected

"Curiouser and curiouser," neutrinos may have properties beyond even our new paradigm. Such properties would again force a profound revision in our thinking.

- **Are there 'sterile' neutrinos?**

The Small, Silent Type
Neutrinos interact with other particles through the quiet language of the weak force. This makes them elegant probes for new physics, because their voice is uncluttered by exchanges via the strong and electromagnetic interaction, unlike the gregarious quarks and charged leptons. But the neutrinos that speak to us through the weak interactions may be accompanied by companions who are even quieter. There are indications from experiments that these faint partners may exist.

Elegant experiments at the world's largest electron-positron collider indicate that there are three and only three light neutrinos that interact with matter. Other neutral fermions, lacking the universal weak interaction that characterizes the known neutrinos, would evade the inventory of species made in collider experiments.

Precision studies of muon-flavor antineutrinos produced by antimuon decay at the Liquid Scintillator Neutrino Detector (LSND), located at the Los Alamos National Laboratory, combined with the rest of existing neutrino data, hint at the possibility that this new type of matter may exist, and that it mixes ever so slightly with the neutrinos. If this is indeed the case, a more appropriate description of "neutrinos" may be best represented by something like Fig. 6.

The mysterious light neutral fermions capable of mixing with neutrinos are known as 'sterile neutrinos'; while the electron-flavor, the muon-flavor and the tau-flavor neutrinos are referred to as 'active neutrinos.' The existence of sterile neutrinos mixed with the active neutrinos would change our understanding of the evolution of the universe, might help us understand some peculiar properties of pulsars, and might help explain why elements heavier than iron are as abundant as we observe them here on earth. The consequences of light sterile neutrinos are far from sterile.

They would, moreover, completely alter our understanding of the particle world. Light neutrinos are not "standard features" of many of the theoretical exercises to extend our New Standard Model. The fact that they are light is the conundrum, so their discovery would place an important condition on extensions of our theory.

It is important that all neutrino oscillation experiments look for small admixtures of sterile neutrinos. Of utmost importance is the confirmation by another independent experimental effort of the puzzle posed by the LSND result. This is the purpose of the MiniBooNE experiment, currently running at Fermilab. We look forward to its results, which will help us understand whether the population of the particle world is more diverse than expected.

- **Do neutrinos have exotic properties?**

The Accidental Neutrino

To our surprise, we have found that neutrinos have complex properties. This hard-won discovery ended the 70-year old picture of neutrinos as simple, massless objects. Particles with mass can have other properties, too. How do we find out more? We can gain guidance by considering the properties of other particles, and by looking carefully, as Ray Davis did years ago, to see if what we observe is always what we expect.

A wide range of exotic properties are possible in the neutrino sector. These include magnetic and electric dipole moments, unexpected neutrino decays, and even violation of our most sacred fundamental symmetries. We would be remiss not to search for these, since neutrinos have a long history of surprising us with their bizarre behavior.

Despite being electrically neutral, neutrinos may have distributions of charge and magnetism called electric and magnetic dipole moments. This can only happen with massive particles. In the New Standard model, the neutrino magnetic moment is expected to be tiny, at least eight orders of magnitude away from current experimental bounds. Reactor and accelerator experiments in the next 10 to 15 years hope to improve the sensitivity to neutrino magnetic moments by two orders of magnitude. The observation of a nonzero effect would indicate the existence of nonstandard physical effects mediated by new particles at or above the electroweak symmetry breaking scale (about 100 GeV).

Massive particles may decay to lighter particles, so it is theoretically possible for neutrinos to decay. In the New Standard Model, neutrinos decay to even lighter neutrinos and/or photons, and the lifetime is expected to be absurdly long: $\tau_\nu > 10^{38}$ years. Despite this, we should still search for much shorter neutrino lifetimes, because that would be evidence that our new paradigm is wrong. Stringent bounds have been set for neutrino decay into photons – longer than billions of years. But bounds on neutrinos decaying into new exotic matter are surprisingly weak.

There are many other deep physics principles which can be tested through neutrino studies. The discovery of effects such as the violation of Lorentz invariance, of the equivalence principle, or of CPT-invariance, to name only a few, would force us to redefine the basic tools – relativity, quantum mechanics – we use in order to describe Nature. Physics and astrophysics would be led to the very challenging but rewarding path of fundamental revision.

• **What do neutrinos have to tell us about the intriguing proposals for new models of fundamental physics?**

Journey to a Grand Unified Theory

Like paleontologists, who must infer the behavior of dinosaurs from a few remaining bones and fossils, physicists must reconstruct the behavior of particles at the high energies of the Big Bang from the clues provided by the low energy interactions we produce in the laboratory today. Our recent new discoveries of the properties of neutrinos belong in the skeleton of a larger "Grand Unified" theory. It is a strange looking beast, and further experimentation will be required before we can understand its full form.

The discoveries about neutrinos have forced us to revise our robust and durable theory of physics, the Standard Model. Until the question of whether neutrinos are their own antiparticles is sorted out, a clear path to the new Standard Model cannot be seen. There are other tantalizing hints for physics beyond the New Standard Model. The "running coupling constants" seem to unify at some very large energy scale, leading to the strong belief that Nature can be described in terms of a simpler grand unified theory (GUT) that manifests itself as the Standard Model at lower, more accessible energies.

Neutrinos may turn out to play a major role in improving our understanding of GUTs. Some GUTs provide all the elements required to understand small neutrino masses – if they are their own antiparticle – and the matter-antimatter asymmetry of the universe via leptogenesis. GUTs also provide relations among the quark mixing matrix, the lepton mixing matrix, the quark masses, and the lepton masses, in such a way that detailed, precise studies of the leptonic mixing angles and the neutrino mass hierarchy teach us about the nature of GUTs. In particular, the large mixing angles of the leptonic mixing matrix provide an interesting challenge for GUTs. The study of neutrino masses and mixing provides a privileged window into Nature at a much more fundamental level.

Of course, several other neutrino probes may end up serving as the ultimate guide towards a deeper understanding of the universe, its constituents, and their interactions. One example: the confirmation of the LSND anomaly would require a deep re-examination of the New Standard Model, independent of the nature of the mechanism responsible for the effect. If this turns out to be the case, new accelerator and low-energy solar neutrino experiments will be required to understand this new physics, and it is possible that neutrino experiments may be the *only* probes of these phenomena.

2.3 Neutrinos and the Cosmos

In the last few years the evidence for cold dark matter and dark energy in the cosmos have brought us face to face with the uncomfortable fact that we have no idea what 90% of the universe is made of. Neutrinos, oddly, *are* a component of dark matter, but a minor ingredient by mass. Exactly how much, we do not know yet. On the other hand, despite being at a chilly 2K today, they were "hot" until cosmos was billions of years old. They may have played a very significant role in the formation of the vast skeins of galaxies in superclusters throughout the universe.

• **What is the role of neutrinos in shaping the universe?**

Neutrinos are Forever

Neutrinos were created in the cauldron of the Big Bang. They are the progenitors of the matter that is within us. Their total mass outweighs the stars. They played a role in the framing of the gossamer strands of galaxies. We see in them the imprint of the cool matrix of neutrinos that fills and shapes the universe.

The development of structure in the universe is determined by its constituents and their abundances. Neutrinos, due to their tiny masses, have streamed freely away from developing aggregations of matter until quite recently (in cosmological terms), when they finally cooled and their average speeds have decreased to significantly less than the speed of light. What is their role in shaping the universe? The answer to this question will not be known until the neutrino masses are known.

A stringent but model-dependent upper bound on the neutrino mass is provided by a combination of neutrino oscillation experiments, detailed studies of the cosmic microwave background radiation, and "full sky" galactic surveys, that measure the amount of structure in the observed universe at very large scales. It is a testament to the precision of current cosmological theory that the fraction of the universe's density contributed by neutrinos is only 5% or less in this analysis. Laboratory measurements currently bound this number from above at 18%, and atmospheric neutrino oscillations set a lower limit of 0.2%. A unique test of our current understanding of the history of the universe will come from new experiments that directly determine the neutrino mass.

Several experimental probes of astrophysics and cosmology will help build a coherent picture of the universe at the largest scales, including

1. Precision studies of the spectrum of the cosmic microwave background radiation;
2. Galactic surveys;
3. Studies of gravitational weak lensing effects at extragalactic scales;
4. Precision determination of the primordial abundance of light elements; and
5. Studies of the nature of dark energy, such as surveys of distant type-Ia supernovae.

• **Are neutrinos the key to the understanding of the matter-antimatter asymmetry of the universe?**

Neutrinos Matter

All around us, for as far as we can see, the universe is made of matter. Lucky for us, for otherwise we would be annihilated and disappear in a flash of energy. But why? In the initial fireball of the big bang, equal amounts of matter and antimatter were surely created. What gave the slight edge to matter in the race for total annihilation? Surprisingly heavy members of the neutrino family could explain this asymmetry. The light neutrinos we see today, the descendants of the heavy family, may hold the archaeological key.

It is remarkable that lepton number and CP-invariance violation in the neutrino sector may be the answer to one of the most basic questions we think we are allowed to ask – why does the universe we have observed so far contain (much, much) more matter than antimatter? In more detail, we would like to understand the following issue: in the distant past, the universe is very well described by a "gas" of ultra-relativistic matter and force carriers in thermal equilibrium. This thermal bath contained a very tiny asymmetry, around one extra proton or neutron, or 'baryons,' for every 10^{10} baryons and antibaryons.

As the universe cooled down, almost all matter and antimatter annihilated into light, and this tiny "left-over" matter makes up all of the observable universe. It is widely believed that the fact that the primordial asymmetry was so small indicates that in even earlier times the universe was described by a symmetric gas of matter and antimatter, and that the asymmetry arose dynamically as the universe evolved. This dynamical generation of a matter-antimatter asymmetry is referred to as 'baryogenesis,' and the ingredients it must contain were identified long ago: violation of C-invariance – invariance of nature when particles are replaced by antiparticles – and CP-invariance – equivalent to time-reversal invariance; baryon-number violation; and the presence, in the early universe, of physical processes that occur out of thermal equilibrium. More than just a matter of taste, baryogenesis is required in almost all models for the universe that contain inflation, as the inflationary state of the universe erases any finely-tuned matter-antimatter asymmetry one could have postulated as present since the beginning of time. Without baryogenesis, inflationary models predict a very boring, matter-antimatter symmetric universe.

In the Standard Model with massless neutrinos, it is not possible to dynamically generate the matter-antimatter asymmetry of the universe, for a few reasons, including: (i) the CP-invariance violation present in the quark sector is "too small" to generate a large enough baryon asymmetry; and (ii) there are no physical processes that occur significantly out of thermal equilibrium in a Standard Model gas, at very high temperatures. We only learned this recently, when it became clear that the Higgs boson is not light enough.

Neutrino masses may come to the rescue. Not only do they provide new sources of CP-invariance violation, they also provide new mechanisms for generating the matter-antimatter asymmetry of the universe. The most popular mechanism for generating the matter antimatter-asymmetry of the universe with the help of neutrino masses is called 'leptogenesis.' What is remarkable about several realizations of leptogenesis is that they relate the observed matter-antimatter asymmetry of the universe to combinations of neutrino masses, mixing angles and other free parameters. Hence, we may learn, by performing low-energy experiments, about whether neutrino masses and mixing have something to do with the fact that the universe is made of matter.

This is no simple matter, so to speak, and it may turn out that one can never completely learn whether the answer is 'yes' or 'no.' The main reason for the potential lack of information is the presence of the "other free parameters" mentioned above. It is often the case that the baryon asymmetry depends on parameters that describe Nature at very high energy scales. This may occur at the lepton-number-breaking scale, which could be as high as 10^{15} GeV, an energy we simply cannot access by direct experiment. Under these circumstances, low-energy experiments can only probe particular combinations of the leptogenesis parameters, and these may end up severely underconstrained.

We have a plan for attacking this difficult problem. First, we must determine whether CP-invariance is violated in the leptonic sector. Second, we must learn whether neutrinos are their own antiparticles, and determine as well as possible the overall scale of neutrino masses. It may turn out, then, that several realizations of leptogenesis will be ruled out, or, perhaps, some very simple model may fit all data particularly well. Further help may be provided by "non-neutrino experiments," including probes of the physics responsible for electroweak symmetry breaking (is there low-energy supersymmetry?, etc.) and searches for charged-lepton flavor violating processes like $\mu \to e\gamma$. At that point, even if one cannot prove whether leptogenesis is responsible for the matter-antimatter asymmetry, we should have enough circumstantial evidence to believe it or to refute it.

• What can neutrinos disclose about the deep interior of astrophysical objects, like the sun and the earth, and about the mysterious sources of very high energy cosmic rays?

> **Neutrino Odyssey**
> *While the main focus of this story is on the physics of neutrinos themselves, it must not be forgotten that neutrinos can be used to probe both inner structure and outer limits. They are messengers that come from deep in the heart of exploding stars and cataclysmic centers of galactic nuclei. Through observation of these neutrinos, the fields of astrophysics and neutrino physics have illuminated each other in the past and will continue to in the future.*

Neutrinos are the ultimate probe of astrophysical objects and phenomena. Neutrinos are deeply penetrating. Observing astrophysical neutrinos is the only way to look at the interiors of objects like the sun or the earth, and provides the only means of obtaining detailed information about the cataclysmic death of large stars (supernova explosions).

The only way to determine the source of very high energy cosmic rays is to study the very high energy neutrinos produced in these yet unknown extreme environments. Unlike photons and protons, which, along with heavier nuclei, are bent around by galactic and extra-galactic magnetic fields and absorbed by the cosmic microwave background, neutrinos are produced at the source and travel straight to us, undeflected and unabsorbed. Several probes of astrophysical neutrinos are being built, developed, and studied, including

1. Under-ice and underwater kilometer-size detectors of very high energy neutrinos, such as Ice Cube, in Antarctica;
2. Kilometer-size cosmic ray detector arrays, like the Auger experiment in Argentina;
3. New detectors sensitive to coherent radio and acoustic waves produced by neutrino–matter interactions at extremely high energies, above 10^{15} eV, like the RICE and ANITA experiments; and
4. Efforts to observe galactic supernova explosions and the supernova neutrino background, expected to permeate space as a witness to all supernova explosions of the past.

3 Current Program and International Context

The astonishing discoveries in neutrinos over the last decade promise to revolutionize our understanding of nature at the most fundamental level. These discoveries have resulted from a broad range of experiments, many which were originally justified for different purposes. Some of these experiments continue, along with other new experiments which have been designed to provide yet more precise study of neutrino properties and perhaps offering even more revolutionary discoveries.

Neutrino physics enjoys a strong partnership between theorists and experimentalists, a relationship that drives the field forward. The cross-cultural nature of the topic brings fresh ideas from astrophysics, cosmology, particle physics, and nuclear physics. International collaboration (see Table 1) and competition has led to a healthy exchange of fresh ideas. The range of experiments, in size and years of running, has allowed

AMANDA	Belgium, Germany, Japan, Netherlands, Sweden, United Kingdom, United States, Venezuela
KamLAND	China, Japan, United States
MiniBooNE	United States
SNO	Canada, United Kingdom, United States
Super-Kamiokande and K2K	Japan, Korea, Poland, United States
ANITA	United States
Auger	Argentina, Armenia, Australia, Bolivia, Brazil, the Czech Republic, France, Germany, Italy, Mexico, Poland, Slovenia, Spain, United Kingdom, United States, Vietnam
Borexino	Belgium, Germany, Hungary, Italy, Poland, Russia, United States
Ice Cube	Belgium, Germany, Japan, Netherlands, New Zealand, Sweden, United Kingdom, United States, Venezuela
KATRIN	Czech Republic, Germany, Russia, United Kingdom, United States
MINOS	Brazil, France, Greece, Russia, United Kingdom, United States
RICE	United States

Table 1: Countries collaborating with the U.S. in our current and near-future experiments.

for both in-depth study and quick turnaround in investigating anomalies. Neutrino physics covers a broad range of experimental techniques and needs, and the existing program is already strong and rich in promise of new discovery. It is critical that, while future initiatives are undertaken, the current experimental programs be exploited as fully as possible. Furthermore, it is essential that the future program take account of the existing domestic and international efforts which are either already underway or planned for the next several years. With full use of the existing program, the future program outlined in this report has great potential for exciting new discoveries, even beyond the presently defined questions.

The existing U.S. experimental program (Fig. 7) is in the process of addressing a substantial fraction of the important topics we have just described. It is critical that we provide strong support to the current efforts, and where possible provide modest additional investment in order to realize the best return from this investment. Some of the important ongoing experiments either in the U.S. or with substantial U.S. participation are:

- **AMANDA:** AMANDA has pioneered the use of the Antarctic Ice for use as a neutrino telescope. It is currently taking data and will be integrating with the km^3-sized Ice Cube over the next year or so.
- **KamLAND:** Recent results from the KamLAND experiment, located in Japan, show a clear energy dependent oscillation effect which not only clearly agrees and confirms solar neutrino oscillations but also strongly constrains the possible range of Δm^2_{12}. Kamland continues to collect data and we anticipate that the final results will provide a precision measurement of this parameter for which we do not expect any improvement for the foreseeable future.
- **MiniBooNE:** This U.S.-based experiment is running in neutrino mode, and benefiting from continuous improvements in Booster

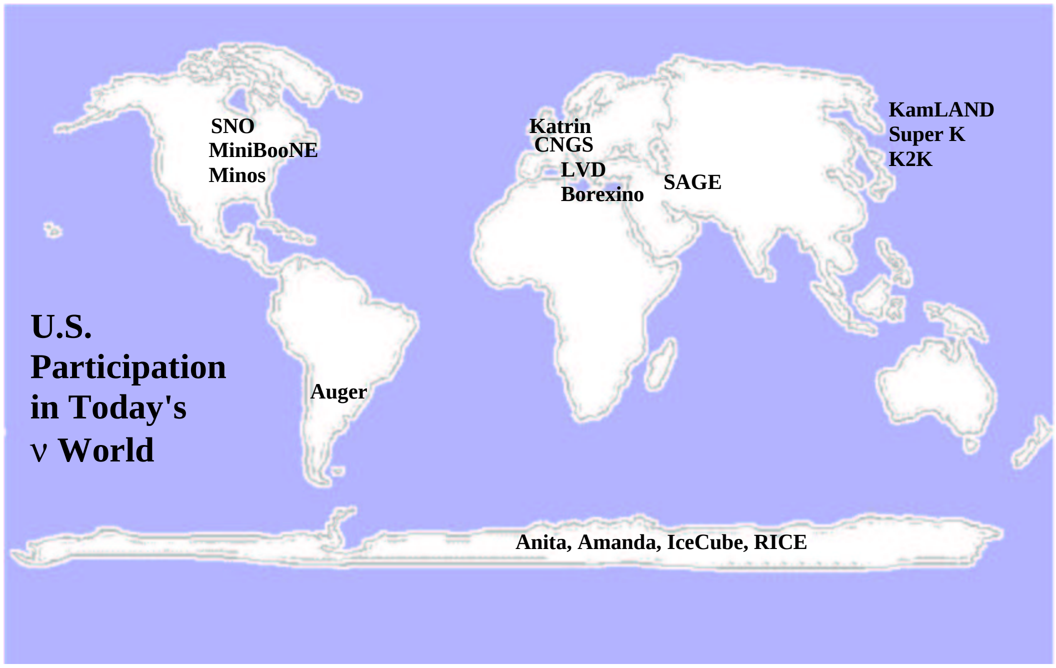


Figure 7: Neutrino experiments around the world. The ones shown have significant US involvement.

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delivery of beam. Should the LSND $\bar{\nu}_\mu$ to $\bar{\nu}_e$ transition signal be confirmed, important additional experiments, described in the superbeams working group report, will be required. If the neutrino running does not confirm the LSND, it is important to also check the result using an antineutrino beam.

- **SNO:** The SNO experiment, in Canada, has provided crucial experimental evidence contributing to the proof that the solar neutrino deficit results from flavor transitions from ν_e to some combination of ν_μ and ν_τ. SNO is now preparing the detector for operations with ^{3}He neutron counters in order to improve sensitivity to the mixing angles θ_{12} and θ_{13}, and complete its physics program.

- **Super-Kamiokande and K2K:** Decisive evidence of oscillations in atmospheric neutrinos has come from Super-Kamiokande, and the oscillation phenomenon is now also seen in K2K with neutrinos from the KEK accelerator. These experiments, located in Japan, are impressive for the breadth and quality of results on atmospheric, accelerator, and solar neutrinos. Super-Kamiokande is currently operating with about 1/2 its full photomultiplier complement, and will undergo refurbishment to the full coverage in 2005.

Recognizing the deep importance of neutrino studies, the U.S. is already committed to several new experiments which are well into the construction phase:

- **ANITA:** This balloon-born radio telescope, to be launched in the Antarctic, is designed to detect very high energy neutrinos resulting from the GZK effect. A characteristic pulse of radio energy is produced by the intense shower of particles when such neutrinos interact in the ice. ANITA is expected to provide the first sensitivity to these putative neutrinos.
- **Auger:** Auger is a 10-km^2 air shower array currently under construction in Argentina with substantial U.S. involvement. Auger's primary goal is the study of very high energy air showers, including those produced by neutrinos at and above the GZK cutoff.
- **Borexino:** This experiment, at the Gran Sasso Laboratory in Italy, is aimed at a measurement of solar neutrinos with energy spectrum sensitivity and ability to measure the flux from ^{7}Be decays. Construction is essentially complete, but operations have been delayed. It is hoped that operations can begin in 2005. The goals of this experiment remain very relevant and we support bringing this experiment into operation.
- **Ice Cube:** This is a km^3 high-energy neutrino observatory being built in the ice cap at the South Pole. It is an international collaboration with primary support coming from the NSF. It will very substantially extend sensitivity to possible astrophysical point sources of neutrinos.
- **KamLAND Solar Neutrinos:** Plans are developing to upgrade the KamLAND detector in Japan to permit a lower energy threshold in order to detect solar neutrinos from ^{7}Be decay. Both Japan and the U.S. are participating. Because the measurement of ^{7}Be neutrinos represents a substantial experimental challenge, it is likely that two independent experiments will be necessary to reach the desired 5% accuracy.
- **KATRIN:** The KATRIN experiment is under construction in Germany. It has an international collaboration focused on improving the sensitivity to direct neutrino mass measurement in tritium beta decay. KATRIN represents an excellent example where U.S. groups are working together with international collaborators to build a single facility with unique capabilities.
- **MINOS:** The NuMI beamline will be complete late in 2004 and MINOS beam operations will begin. This U.S.-based experiment will offer precision measurements of oscillation parameters and extension in sensitivity to ν_e appearance. The sensitivity of MINOS depends on the number of protons which can be delivered. Investments in the Main Injector proton intensity will be important to best exploit the investment in MINOS and extend its discovery reach. We endorse such investment.
- **RICE:** RICE has pioneered the use of an array of radio antennas on the surface of the Antarctic ice which seeks to observe neutrinos at the highest energies. It is currently taking data. Theoretical estimates of neutrino fluxes suggest that substantially larger arrays may be required for positive observation of ultra-high energy neutrinos.

In addition to the existing or soon-to-exist experiments with significant U.S. involvement there are important new experiments being planned or built abroad which must inform the planning for a future U.S. program. In discussing these future prospects, we do not include all possible future activities but take some account of the relative advancement of the proposal or status of construction. Some of the major experiments being planned/built of which our proposed U.S. program has taken explicit account are:

- **CNGS:** Two experiments, ICARUS, and OPERA, are in construction at the Gran Sasso Laboratory in Italy for use with the CERN-Gran Sasso neutrino beam which will start operation in 2006. These experiments will search for evidence of ν_τ appearance and along with MINOS will extend the sensitivity to ν_e appearance. CERN, located in Switzerland, is working to increase SPS proton intensity in order to maximize the physics output.

- **Indian Neutrino Observatory (INO):** A large magnetized atmospheric neutrino detector is being proposed for construction in India. This detector may provide sensitivity to the neutrino mass hierarchy.

- **LVD:** LVD is an 800-ton liquid scintillator detector at Gran Sasso Laboratory in Italy, which continues running with sensitivity to a galactic supernova.

- **Mediterranean Neutrino Observatory:** There are three underwater neutrino telescopes currently under development in the Mediterranean, NESTOR, NEMO, and ANTARES. It is anticipated that these development projects will result in a final project to build a single km^3 size detector. This will add a northern complement to the Ice Cube Detector. No U.S. competitor is proposed for the northern hemisphere, and modest U.S. collaboration may develop on the effort in the Mediterranean.

- **Neutrinoless double beta decay:** There are many R&D programs worldwide in double beta decay, some of which include operating experiments. Among isotopes receiving the most attention are ^{76}Ge, ^{100}Mo, ^{130}Te and ^{136}Xe. The NEMO III experiment in the Modane Laboratory in France is collecting data with kilogram quantities of several enriched isotopes, and features particle tracking for event identification. Cuoricino is a calorimetric experiment operating with kilogram quantities of natural Te. Both experiments plan expansions. A controversial analysis of data from the Heidelberg-Moscow experiment that used approximately 10 kg of enriched ^{76}Ge reports evidence for an effective neutrino mass greater than 0.1 eV.

- **Reactor experiments:** Double CHOOZ, KASKA. The proposed Double CHOOZ experiment in France will use the existing underground space where the first CHOOZ experiment was performed along with a near detector to reduce the systematic uncertainty. A proposal has been submitted and is in the approval process. KASKA is an experiment being planned for the Kashiwazaki reactor site in Japan. Both of these experiments have a sensitivity goal of $\sin^2 2\theta_{13} \leq 0.03$ at 90% CL for $\Delta m^2 = 0.002$ eV^2.

- **SAGE:** The SAGE gallium experiment in Russia is unique in its sensitivity to neutrinos from the proton-proton (pp) interaction and ^{7}Be decays in the sun. With termination of the GNO gallium experiment at Gran Sasso, discussions have commenced about combining the SAGE and GNO collaborations. Formal participation by U.S. groups in SAGE has ended, but cooperation in this important experiment continues.

- **T2K:** T2K will use the new 50 GeV accelerator, starting in 2009 at Tokai, along with the Super-Kamiokande Detector to improve sensitivity to ν_e appearance about a factor of 5-10 beyond MINOS and CNGS. Due to the 295-km baseline, T2K is almost insensitive to matter effects. This makes relatively cleaner measurements for θ_{13} and δ_{CP} but does not provide sensitivity to the mass hierarchy. For that reason, that type of experiment is a good complement to a longer-baseline experiment with sensitivity to matter effects, such that the combination of the two provides clean separation of all of the associated parameters. There is

U.S. participation in T2K with developing plans on the scope of that participation. T2K is an important part of a coherent international effort necessary to measure all of these oscillation parameters.

In addition to explicit neutrino physics experiments, there are several related experimental programs that provide crucial data for better understanding results from the neutrino experiments. Some of these include:

- **Nuclear Physics Cross Sections:** Nuclear physics cross section measurements are critical to understanding the Sun and supernovae processes. We support a program of relevant measurements.
- **Cosmic-Ray and Astrophysics Measurements:** Better understanding of cosmic rays and astrophysics measurements are important to atmospheric neutrinos and to eventual understanding and prediction of observed neutrino sources.
- **Cosmology connections to neutrinos:** Measurements of the cosmic microwave background (CMB) and large scale structure continue to offer very interesting promise of placing limits or even observation of an effect resulting from neutrino mass in the range of 0.1 eV.

A final consideration is support for a strong theory effort on the broad set of issues in neutrino physics. Theoretical efforts in neutrino physics have played a fundamental role in interpreting the wide range of revolutionary experimental results and building a coherent, yet still incomplete, picture of the new physics uncovered by the discovery of neutrino flavor transitions. Among the triumphs of such efforts are computations of the solar neutrino flux, development of the neutrino oscillation formalism including the effects of neutrino propagation in matter, and determination of the effects of neutrinos in big-bang nucleosynthesis, large scale structure formation, and the distortions of the cosmic microwave background radiation.

It is also part of the theoretical efforts to establish connections between the new discoveries in neutrino physics and our most fundamental understanding of matter, time, and energy. Significant advances have been made in several arenas, including establishing connections between neutrino masses and leptonic mixing with the concept of grand unification, establishing a relationship between neutrino masses and the matter-antimatter asymmetry of the Universe (through leptogenesis), and developing different predictive mechanisms for understanding the origin of neutrino masses in a more satisfying and relevant way.

Finally, due to the particular interdisciplinary nature of neutrino physics, theory has played the absolutely essential role of integrating results and developments in astronomy, astrophysics, cosmology, high-energy and low-energy particle physics, and nuclear physics. As new discoveries arise in all of these disciplines, theoretical guidance and “integration” will continue to be indispensable.

4 Recommendations

Our recommendations for a strong future U.S. neutrino physics program are predicated on fully capitalizing on our investments in the current program. The present program includes the longest baseline neutrino beam and a high-flux short baseline beam, both in the U.S. Elsewhere, American scientists and support are contributing in important ways to the burgeoning world program in neutrino physics, including a long-baseline reactor experiment in Japan, solar and atmospheric neutrino experiments in Canada, Italy, Japan, and Russia, a direct mass measurement in Germany, ultra high energy astrophysics experiments in Antarctica and Argentina, and other experiments. We congratulate not only the scientists involved but also the Agencies for their perceptive support of this developing program, which has been so spectacularly fruitful.

Four issues deserve special mention:

1. Support for continued increases of proton intensity for Fermilab neutrino experiments, as is necessary for the present experiments to meet their physics goals.
2. Support for decisive resolution of the high-Δm^2 puzzle. This issue is currently addressed by a single experiment now running in a neutrino beam at Fermilab. Ultimately, a decisive resolution of the puzzle may require additional studies with beams of antineutrinos.
3. Support for determination of the ^{7}Be solar neutrino flux. Measurements of the ^{7}Be solar neutrino flux are currently in the program of two underground detectors, one in Italy and the other in Japan.
4. Continued support for enhanced R&D focusing on new techniques for detecting neutrinos above 10^{15} eV from astrophysical sources. This capability would open a new window to astrophysics with significant discovery potential.

Turning to the recommendations for the future, we preface our remarks by drawing attention to some basic elements in common:

1. In every instance the need for suitable underground detector facilities emerges. A successful neutrino program depends on the availability of such underground space.
2. The precise determination of neutrino cross sections is an essential ingredient in the interpretation of neutrino experiments and is, in addition, capable of revealing exotic and unexpected phenomena, such as the existence of a neutrino magnetic or electric dipole moment. Interpretation of atmospheric and long-baseline accelerator-based neutrino experiments, understanding the role of neutrinos in supernova explosions, and predicting the abundances of the elements produced in those explosions all require knowledge of neutrino cross sections. New facilities, such as the Spallation Neutron Source, and existing neutrino beams can be used to meet this essential need.
3. It is important that worldwide at least two detectors should be operational which, in addition to their other physics roles, are continuously sensitive to a galactic supernova.

Our recommendations have their genesis in central questions in neutrino physics: What are the masses of the neutrinos? How and why do they mix? Are neutrinos their own antiparticles? Is CP symmetry broken by neutrinos? Upon the answers to these questions rests a comprehensive understanding of fundamental physics and of the universe.

• **We recommend, as a high priority, that a phased program of sensitive searches**

for neutrinoless nuclear double beta decay be initiated as soon as possible.

Neutrinoless double beta decay is the only practical way to discover if neutrinos are their own antiparticles and, thus, a new form of matter. Without this information, the construction of the New Standard Model cannot be completed. The lifetime for neutrinoless double beta decay is inversely proportional to an effective neutrino mass. Hence, in order to observe a signal not only must the neutrinos be their own antiparticles, they must also be heavy enough.

We recommend a phased approach with successively larger detectors and lower backgrounds. The first experiments should address masses of a few tenths of an eV. This is the 'degenerate' mass scale in which the three neutrino masses are nearly equal, and it is the range in which the large-scale structure of the universe would be affected. From cosmological and existing double beta decay data, controversial arguments have been made that the neutrino mass is actually of this size. For this mass range, neutrinoless double beta decay can be discovered and precisely measured with isotopic samples of approximately 200 kg in a period of 3 to 5 years.

If neutrinoless double beta decay is not observed in the 200-kg experiments, then a second phase of experimentation with 1-ton isotopic samples should be initiated to search in the 20 to 55 meV mass range. That is the range given by the observed atmospheric neutrino oscillation signal if the mass hierarchy is non-degenerate and inverted. A non-degenerate, *normal* mass hierarchy with effective masses below 20 meV requires sample sizes of hundreds of tons. For that scale of experiment substantially more R&D will be necessary.

Difficult as these experiments are, it is prudent to pursue more than a single scalable technique with different isotopes and an expanded R&D effort. Worldwide, only four collaborations (two predominantly European and two predominantly U.S.) are likely to propose viable 200-kg experiments (with ^{76}Ge, ^{130}Te, and ^{136}Xe) in the near future. It is conceivable that two of the groups will merge, leaving three efforts among which the U.S. will play a major role in two, and a secondary role in the third.

The U.S. is well positioned to make a significant contribution to this program. However, these experiments all require that appropriate underground facilities at moderate to substantial depth be available.

• **We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos. This program should have the following components:**

- **A rapidly deployed multi-detector reactor experiment with sensitivity to $\overline{\nu}_e$ disappearance down to $\sin^2 2\theta_{13} = 0.01$, an order of magnitude below present limits.**
- **A timely accelerator experiment with comparable $\sin^2 2\theta_{13}$ sensitivity and sensitivity to the mass-hierarchy through matter effects.**
- **A proton driver in the megawatt class or above and neutrino superbeam with an appropriate very large detector capable of observing CP violation and measuring the neutrino mass-squared differences and mixing parameters with high precision.**

The discovery of neutrino oscillations has provided completely new information about neutrino masses and mixing. To complete our understanding of mixing and the mass hierarchy, to discover whether or not the CP symmetry is violated by neutrinos, and to be sensitive to unanticipated new physics, a flexible program with several complementary experiments is necessary.

Knowledge of the presently unknown value of the mixing angle θ_{13} is a key factor in all of these objectives. Determination of this important parameter, or at least a stringent limit on it down to $\sin^2 2\theta_{13} = 0.01$, can be established with a relatively modest scale reactor experiment in a timely manner. We strongly urge the initiation of a reactor based multi-detector experiment with this sensitivity as soon as possible.

A new long-baseline experiment using the existing NuMI beamline at Fermilab and a beam upgraded to 0.4 MW would be sensitive to combinations of the mixing angles θ_{13} and θ_{23}, the phase δ, and the mass-squared difference Δm^2_{23}. Furthermore, if $\sin^2 2\theta_{13}$ is large enough, such an experiment in concert with other experiments can potentially determine the neutrino mass hierarchy through matter effects. Such an experiment should be roughly 10 times more sensitive to ν_e appearance than the long baseline experiment currently underway at Fermilab and, if done in a timely manner, would capitalize on the considerable investment in NuMI.

Given that the value of θ_{13} is presently unknown, should the accelerator and reactor experiments should be done in sequence or contemporaneously? According to most theoretically motivated estimates, the chance that $\sin^2 2\theta_{13}$ is less than 0.01 is small, but not zero. Notwithstanding that risk, we strongly recommend the contemporaneous strategy. First, accurate determinations of the values of θ_{23}, Δm^2_{23} and a stringent upper limit on θ_{13} are of central importance to an understanding of the origin of neutrino masses and mixing. Second, we draw attention to the unique and time-sensitive opportunity for the U.S. to build a strong accelerator-based neutrino physics program, with real discovery potential, that will be a major contributor in the rapidly advancing world program.

Even without knowing the outcome of the initial steps in the program, it is clear that very large-scale, long-baseline experiments will provide the best sensitivity to all the oscillation parameters as well as to possible unanticipated new physics. They also provide the only possibility for quantitatively exploring CP-invariance violation in the neutrino sector. A proton driver in the megawatt class or above used to produce a neutrino superbeam, together with a detector of more than 100 kilotons mass should be able to probe all aspects of three-generation neutrino mixing, unambiguously determine the mass hierarchy, and provide definitive information on the amount of CP-invariance violation, as long as $\sin^2 2\theta_{13}$ is larger than about 0.01. If $\sin^2 2\theta_{13}$ is smaller still, a neutrino factory will be required, because of its potential freedom from backgrounds. Such a facility likewise requires the , such as the driver described above. The intense proton driver and detector would each also provide benefits across a wide spectrum of fundamental physics in addition to neutrino physics.

Because of the long lead time in designing a new intense proton driver, a decision as to whether to embark on such a program should be made as soon as practicable. With their existing accelerator infrastructures and capabilities, either Brookhaven or Fermilab would be natural sites, and both laboratories have been working on designs. A comprehensive study of the scientific, technical, cost, and strategic issues will be necessary.

Massive detectors have been key to the recent revolution in neutrino physics. Their significant cost is more appropriately justified by the diverse physics program made possible by a multipurpose detector. Such a detector should be capable of addressing problems in nucleon decay, solar neutrinos, supernova neutrinos, and atmospheric neutrinos in addition to long-baseline neutrino physics. The broad range of capabilities, however, can only be realized if it is built deep enough underground. If one is to be sited in the U.S., new appropriate underground facilities have to be developed.

A high-intensity neutrino factory or a 'beta-beam' facility is the ultimate tool in neutrino physics for the long term, and may be the only facility capable of definitively addressing some of the physics issues. Neutrino factories and beta beams require, respectively, development of a muon storage ring or a radioactive-ion storage ring, which provides intense, high energy muon and/or electron neutrino beams with well understood energy spectra and very low background levels. Neutrino factories are presently the focus of the U.S. development program, and there is a significant collaboration with Europe and Japan. The neutrino factory R&D program needs substantial levels of support if the facility is to be realized in the long term.

The overall program must be considered in an international context. Reactor experiments less sensitive than the one recommended here are being considered in France and Japan. An interesting and extensive off-axis superbeam program is under construction in Japan. Like the recommended U.S. program, it is sensitive to a combination of parameters. The programs are complementary because only the U.S. program has sufficiently long baselines to provide good sensitivity to the mass hierarchy through matter enhancement. With both the U.S. and international programs we may confidently hope for complete understanding of neutrino mixing.

• **We recommend the development of a spectroscopic solar neutrino experiment capable of measuring the energy spectrum of neutrinos from the primary *pp* fusion process in the sun.**

The experiments that first established neutrino flavor transformation exploited neutrinos from the sun and neutrinos produced in the earth's atmosphere. These sources continue to be used in the present program of neutrino experiments. Natural neutrino sources are an important component of a program seeking to better understand the neutrino and at the same time aiming to use neutrinos to better understand astrophysical sources.

A measurement of the solar neutrino flux due to *pp* fusion, in comparison with the existing precision measurements of the higher-energy ^{8}B neutrino flux, will demonstrate the transition between vacuum and matter-dominated oscillations, known as the Mikheyev-Smirnov-Wolfenstein effect. In combination with the essential prerequisite experiments that will measure the ^{7}Be solar neutrino flux with an accuracy of 5%, a measurement of the *pp* solar neutrino flux will allow a sensitive test of whether or not the Sun shines exclusively through the fusion of light elements. Moreover, the neutrino luminosity of the Sun today is predictive of the Sun's surface temperature some 10,000 years in the future because neutrinos, unlike photons, travel directly from the center of the Sun to the earth.

Low-energy solar neutrino experiments need to be located in very deep underground sites in order to achieve the required reduced levels of background. If one is to be located in the U.S., adequate underground facilities are required.

A coordinated program such as we recommend has enormous discovery potential, and builds naturally upon the successes already achieved in the U.S. program. It is a rare and wonderful circumstance that the questions of fundamental science can be so clearly formulated and so directly addressed.

5 Timeline and Branch Points

How will the program we have recommended here evolve with time, what are the branch points at which new information will illuminate the course ahead, and how do the U.S. and world programs move forward in mutual cooperation? In Fig. 8, a schematic timeline illustrates a feasible and appropriate schedule for the research.

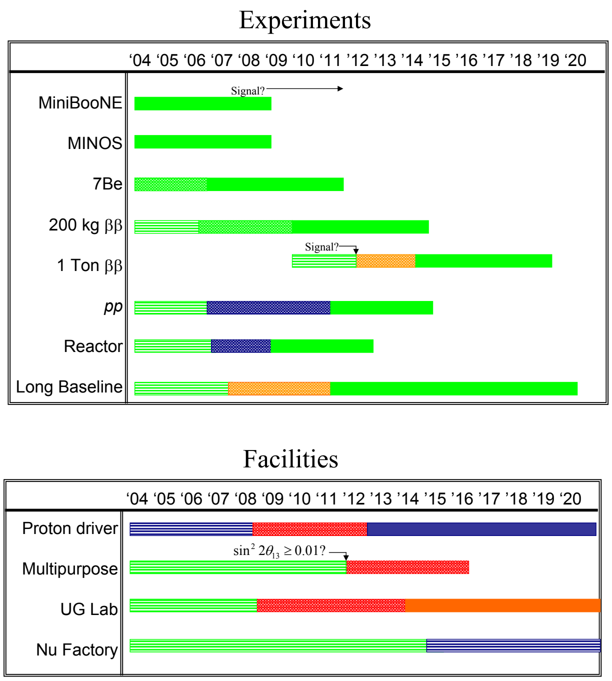

Figure 8: An approximate indication of the development of our recommended neutrino program with time. Some branchpoints are also indicated. Green: $\leq$ 10 M per year. Blue: 10 - 30 M per year. Orange: 40 - 100 M per year. Red: $\geq$ 100M per year. Barred: R&D. Hatched: Design and construction. Solid: operations.

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Because of the richness of the physics, a number of experimental programs have branch points. It is difficult to predict all of the possible future branches. Here we note those that are clearly discernible.

The neutrinoless double beta decay program will reach a decision point after the results of the 200 kg experiments are known. In the event that no signal is seen, the likely branch is to larger detectors sensitive to the 'atmospheric mass' range. A positive signal at any stage will require experiments with other isotopes to confirm such a fundamental scientific observation and to reduce the influence of theoretical uncertainties in the quantitative result for the effective neutrino mass; because the experiments take many years, it is necessary to initiate more than one at each branch.

The direction that the comprehensive program of oscillation parameter measurements takes in the future depends on the value of the parameter $\sin^2 2\theta_{13}$. If this parameter is larger than 1%, the program we have outlined will accurately determine some of the underlying physics, while the recommended proton driver and very large detector will be necessary for a quantitative understanding of the extent of CP violation among the neutrinos. If, on the other hand, this parameter is less than 1%, information on neutrino mixing will be provided by the proton driver and appropriate very large detector, but the search for CP violation would likely have to await the neutrino factory.

The resolution of the LSND question also represents an important branch point, although in this case, observation of a signal would call for augmentation of the program presented in this document. The current program would continue as presented, but with additional goals and accompanied by a suite of appropriate new experiments to further explore this dramatic new phenomenon.

6 Conclusions of the Study

In this study, neutrino physicists, accelerator physicists, and astrophysicists have worked together to identify the most exciting scientific opportunities for the future of neutrino physics. We have prioritized these needs, dividing our findings into two high priority recommendations that we concluded are crucial for the continued advancement of the field, and one that would substantially enhance the U.S. program through its added discovery potential. We note, however, that these represent a small subset of the interesting ideas that emerged from the study, ideas reported in the appendix of Working Group Reports. This collection, which we believe represents the future in each study area, underlines the intellectual richness of the field.

Out of this activity has emerged a program for which the whole will be far greater than the sum of its parts. This is assured in a number of ways. We have coordinated the program to maximize results and minimize duplication, taking into account the worldwide program. Our recommendations encourage international cooperation, in order to leverage U.S. investment. Our choices are interdisciplinary, exploiting the excitement of connecting results from wide-ranging disciplines. Just as the science represents the convergence of many disciplines, so too will the continued support of many Agency Divisions and Offices be needed to bring it to fruition.

With implementation of these recommendations, U.S. scientists will begin to illuminate the neutrino matrix to see its true character, form, and role in the universe.

A Working Group Reports

In this Appendix, only the Executive Summaries of the Working Groups are presented. The full text can be found at **www.interactions.org/neutrinostudy**.

A.1 Executive Summary of Solar and Atmospheric Experiments Working Group

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A.1.1 Introduction

Both the first evidence and the first discoveries of neutrino flavor transformation have come from experiments which use neutrino beams provided by Nature. These discoveries were remarkable not only because they were unexpected—they were discoveries in the purest sense—but that they were made initially by experiments designed to do different physics. Ray Davis's solar neutrino experiment was created to study solar astrophysics, not the particle physics of neutrinos. The Kamiokande experiments were hoping to observe proton decay, rather than study the (ostensibly relatively uninteresting) atmospheric neutrino flux. That these experiments and their successors have had such a great impact upon our view of neutrinos and the Standard Model underscores two of the most important motivations for continuing current and creating future solar and atmospheric neutrino experiments: they are naturally sensitive to a broad range of physics (beyond even neutrino physics), and they therefore have a great potential for the discovery of what is truly new and unexpected.

The fact that solar and atmospheric neutrino experiments use naturally created neutrino beams raises the third important motivation—the beams themselves are intrinsically interesting. Studying atmospheric neutrinos can tell us about the primary cosmic ray flux, and at high energies it may bring us information about astrophysical sources of neutrinos (see Report of Astrophysics Working Group) or perhaps even something about particle interactions in regimes still inaccessible to accelerators. For solar neutrinos, the interest of the beam is even greater: as the only particles which can travel undisturbed from the solar core to us, neutrinos tell us details about the inner workings of the Sun. The recent striking confirmation of the predictions of the Standard Solar Model (SSM) are virtually the tip of the iceberg: we have not yet examined in an exclusive way more than 99% of the solar neutrino flux. The discovery and understanding of neutrino flavor transformation now allows us to return to the original solar neutrino project—using neutrinos to understand the Sun.

The fourth and perhaps strongest motivation for solar and atmospheric neutrino experiments is that they have a vital role yet to play in exploring the new physics of neutrinos. The beams used in these experiments give them unique sensitivity to some of the most interesting new phenomena. The solar beam is energetically broadband, free of flavor backgrounds, and passes through quantities of matter obviously unavailable to terrestrial experiments. The atmospheric beam is also broadband, but unlike the solar beam it has the additional advantage of a baseline which varies from tens of kilometers to many thousands.

The Solar and Atmospheric Neutrino Experiments Working Group has chosen to focus on the following primary physics questions:

- *Is our model of neutrino mixing and oscillation complete, or are there other mechanisms at work?*

  To test the oscillation model, we must search for sub-dominant effects such as non-standard interactions, make precision comparisons to the measurements of other experiments in different regimes, and verify the predictions of both the matter effect and vacuum oscillation. The breadth of the energy spectrum, the extremely long baselines, and the matter densities traversed by solar and atmospheric neutrinos make them very different than terrestrial experiments, and hence measurements in all three mixing sectors—including limits on θ_{13}—can be compared to terrestrial measurements and thus potentially uncover new physics.

- *Is nuclear fusion the only source of the Sun's energy?*

  Comparison of the total energy output of the Sun measured in neutrinos must agree with the total measured in photons, if nuclear fusion is the only energy generation mechanism at work.

- *What is the correct hierarchical ordering of the neutrino masses?*

  Atmospheric neutrinos which pass through the Earth's core and mantle will have their transformation altered due to the matter effect, dependent upon the sign of the Δm^2_{32} mass difference. Future large scale water Cerenkov experiments may be able to observe this difference in the ratio of μ-like to e-like neutrino interactions, while magnetized atmospheric neutrino experiments may be able to see the effect simply by comparing the number of detected ν_μ to $\bar{\nu_\mu}$ events.

A.1.2 Recommendations

The highest priority of the Solar and Atmospheric Neutrino Experiment Working Group is the development of a real-time, precision experiment that measures the *pp* solar neutrino flux. A measurement of the *pp* solar neutrino flux, in comparison with the existing precision measurements of the high energy ^{8}B neutrino flux, will demonstrate the transition between vacuum and matter-dominated oscillations, thereby quantitatively testing a fundamental prediction of the standard scenario of neutrino flavor transformation. The initial solar neutrino beam is pure ν_e, which also permits sensitive tests for sterile neutrinos. The *pp* experiment will also permit a significantly improved determination of θ_{12} and, together with other solar neutrino measurements, either a measurement of θ_{13} or a constraint a factor of two lower than existing bounds.

In combination with the essential pre-requisite experiments that will measure the ^{7}Be solar neutrino flux with a precision of 5%, a measurement of the *pp* solar neutrino flux will constitute a sensitive test for non-standard energy generation mechanisms within the Sun. The Standard Solar Model predicts that the *pp* and ^{7}Be neutrinos together constitute more than 98% of the solar neutrino flux. The comparison of the solar luminosity measured via neutrinos to that measured via photons will test for any unknown energy generation mechanisms within the nearest star. A precise measurement of the *pp* neutrino flux (predicted to be 92% of the total flux) will also test stringently the theory of stellar evolution since the Standard Solar Model predicts the *pp* flux with a theoretical uncertainty of 1%.

We also find that an atmospheric neutrino experiment capable of resolving the mass hierarchy is a high priority. Atmospheric neutrino experiments may be the only alternative to very long baseline accelerator experiments as a way of resolving this fundamental question. Such an experiment could be a very large scale water Cerenkov detector, or a magnetized detector with flavor and antiflavor sensitivity.

Additional priorities are nuclear physics measurements which will reduce the uncertainties in the predictions of the Standard Solar Model, and similar supporting measurements for atmospheric neutrinos (cosmic ray fluxes, magnetic fields, etc.). We note as well that the detectors for both solar and atmospheric neutrino measurements can serve as multipurpose detectors, with capabilities of discovering dark matter, relic supernova neutrinos, proton decay, or as targets for long baseline accelerator neutrino experiments.

A.2 Executive Summary of the Reactor Working Group

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A.2.1 Introduction

The worldwide program to understand neutrino oscillations and determine the mixing parameters, CP violating effects, and mass hierarchy will require a broad combination of measurements. Our group believes that a key element of this future neutrino program is a multi-detector neutrino experiment (with baselines of $\sim$ 200 m and $\sim$ 1.5 km) with a sensitivity of $\sin^2 2\theta_{13} = 0.01$. In addition to oscillation physics, the reactor experiment may provide interesting measurements of $\sin^2 \theta_W$ at $Q^2 = 0$, neutrino couplings, magnetic moments, and mixing with sterile neutrino states.

θ_{13} is one of the twenty six parameters of the standard model, the best model of electroweak interactions for energies below 100 GeV and, as such, is worthy of a precision measurement independent of other considerations. A reactor experiment of the proposed sensitivity will allow a measurement of θ_{13} with no ambiguities and significantly better precision than any other proposed experiment, or will set limits indicating the scale of future experiments required to make progress. Figure 9 shows a comparison of the sensitivity of reactor experiments of different scales with accelerator experiments for setting limits on $\sin^2 2\theta_{13}$ if the mixing angle is very small, or for making a measurement of $\sin^2 2\theta_{13}$ if the angle is observable. A reactor experiment with a 1% precision may also resolve the degeneracy in the θ_{23} parameter when combined with long-baseline accelerator experiments (see Fig. 9).

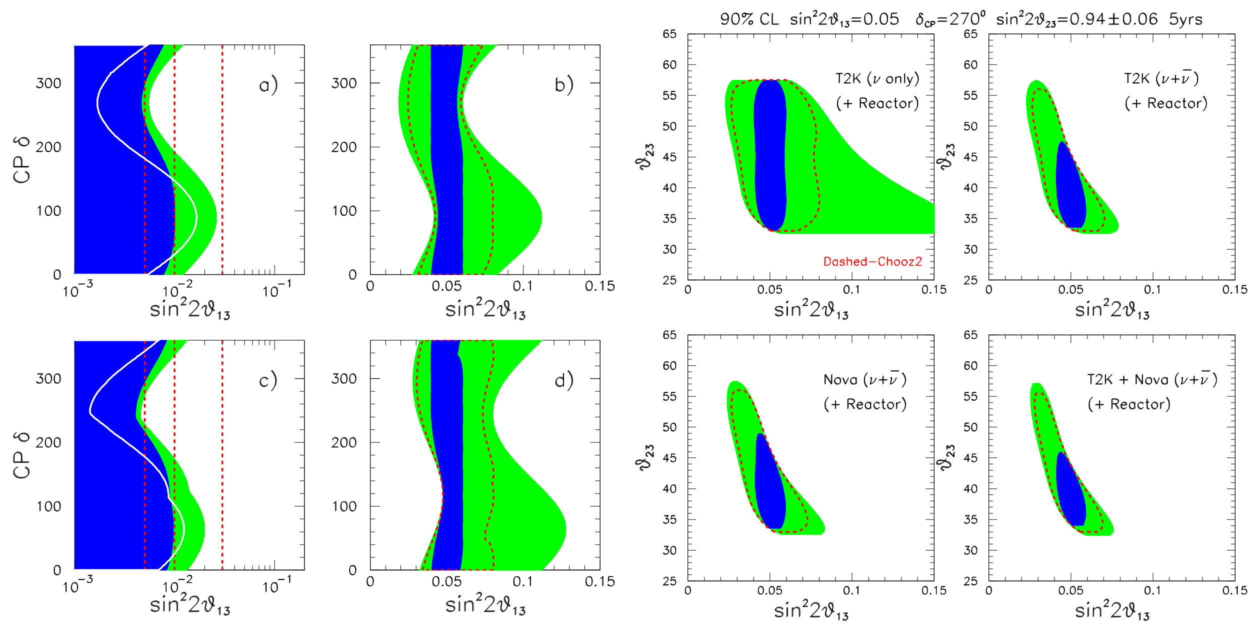

Figure 9: **Left 4 Panels:** 90% C.L. regions and upper limits for various oscillation measurements for (a,c) $\sin^2 2\theta_{13} = 0$ and (b,d) $\sin^2 2\theta_{13} = 0.05$. The top (bottom) plots are for the T2K (Nova) long-baseline experiments. The three vertical dashed lines in (a) and (c) correspond to the 90% C.L. upper limits of 0.005, 0.01, and 0.03 possible with different scales of reactor experiments. The green region (white curve) is the 90% C.L. allowed region for the two long-baseline experiments for a five year neutrino-only run with nominal ($\times 5$) beam rate, and the blue region gives the combination of the five year long-baseline measurement with a reactor experiment with sensitivity of $\sin^2 2\theta_{13} = 0.01$; in (b) and (d), the dashed curves show how the combined measurement would be degraded with a reactor experiment with sensitivity of $\sin^2 2\theta_{13} = 0.03$. **Right 4 Panels:** 90% C.L. allowed regions for simulated data with oscillation parameters of $\sin^2 2\theta_{13} = 0.05$, $\theta_{23} = 38^o$, $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 and $\delta_{CP} = 270^o$. The analysis includes the restriction that $\sin^2 2\theta_{23} = 0.94 \pm 0.06$. The green regions are for various combinations of the T2K and/or Nova experiments for five years of running periods. The blue regions are the 90% C.L. allowed regions for the combination of a reactor experiment with experiment. The dashed red lines show how the combined measurement would be degraded with a reactor experiment with 3 times worse sensitivity.

In combination with long-baseline measurements, a reactor experiment may give early indications of CP violation and the mass hierarchy. The combination of the T2K and Nova long-baseline experiments will be able to make significant measurements of these effects if $\sin^2 2\theta_{13} > 0.05$ and with enhanced beam rates can improve their reach to the $\sin^2 2\theta_{13} > 0.02$ level. If θ_{13} turns out to be smaller than these values, one will need other strategies for getting to the physics. Thus, an unambiguous reactor measurement of θ_{13} is an important ingredient in planning the strategy for the future neutrino program.

A.2.2 Recommendations

Our group has one highest priority recommendation:

- We recommend the rapid construction of a multi-detector reactor experiment with a sensitivity of 0.01 for $\sin^2 2\theta_{13}$.

Our other recommendations are the following:

- To help accomplish our highest priority recommendation, we recommend R&D support necessary to prepare a full proposal.
- We recommend continued support for the KAMLAND experiment. KAMLAND has made the best determination of Δm^2_{12} to date, and will provide the best measurement for the foreseeable future. As the deepest running reactor experiment, it also provides critical information about cosmic-ray related backgrounds for future experiments.
- We recommend the exploration of potential sites for a next-generation experiment at a distance of 70 km from an isolated reactor complex to make high precision measurements of θ_{12} and Δm^2_{12}.
- We recommend support for development of future large-scale reactor θ_{13} experiments that fully exploit energy spectrum information.

A.3 Executive Summary of the Superbeams Working Group

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A.3.1 Introduction

As we seek the answers to the central questions in neutrino physics, accelerator-based experiments will be crucial for providing the necessary precision and sensitivity. There are several physics questions which accelerator superbeam experiments will address:

- *What is the mixing pattern among the neutrinos? Do the mixings suggest some new fundamental mechanism which causes them to have unusual values?*
- *What is the mass hierarchy for the three known neutrinos?*
- *Do neutrinos violate the symmetry CP?*
- *Are there additional light neutrinos and do they participate in oscillations with the three known neutrinos?*
- *Do we understand the basic mechanism of neutrino oscillations?*
- *Do neutrinos have measurable magnetic moments or other exotic properties?*

Shorter-term experiments will depend on existing accelerator capabilities. However, in the longer term it is now clear that we will require new or upgraded proton accelerators capable of providing greater than a mega-Watt of proton power for a neutrino superbeam. With such a driver, a rich new program of neutrino oscillation and other physics measurements will be possible.

A.3.2 Recommendations

I. Highest Priority Recommendation:

- **Build a new MW+ class proton driver, neutrino superbeam and very massive detector in the United States.**

These are the necessary components for a complete set of precision measurements on the oscillation parameters of interest. The key feature of these experiments is that they will provide 1% measurement of $\sin^2 2\theta_{23}$ and Δm^2_{23} and sensitivity to $\sin^2 2\theta_{13}$ below 0.01 (depends on the other parameters). Should $\sin^2 2\theta_{13}$ be greater than about .01 these experiments will also provide discovery and measurement capability for CP violation and due to the long baselines unique measurement capability of the mass hierarchy. A very large multi-purpose detector located at an underground site will permit not just long-baseline oscillation measurements but also measurements on solar and atmospheric neutrinos, a search for supernova neutrinos and a search for proton decay. The new proton driver will enable both long and short baseline oscillation experiments as well as a variety of other neutrino experiments. It will also permit new precise muon and hadron experiments as well as act as the essential first stage of a possible future neutrino factory.

II. Short-term Recommendations:

- **Significant design studies for a new proton driver facility have been completed over the last few years. We urge a rapid decision on this facility.**

  We expect that it will take roughly 8 years from now before a new proton driver could be completed, if the decision to proceed and selection of the site is done soon. Moving now to decide on this machine will permit the U.S. to have the leading program of neutrino measurements in the following decade.

- **Increase proton intensity at Fermilab, roughly by about a factor of 2 in both the Booster and Main Injector neutrino beamlines over the next few years.**

  Both the MINOS and Mini-BooNE experiments offer exciting discovery and measurement potential in the next few years but their capabilities depend critically on proton intensity. Roughly, we encourage investment with a goal of delivering about 4×10^{20} protons per year at both 8 GeV and 120 GeV.

- **We recommend the LSND result be tested with both neutrinos and anti-neutrinos.**

  Mini-BooNE is currently using neutrinos to test the LSND result (which is $\overline{\nu_e}$ appearance in an initial beam of $\overline{\nu_\mu}$). It is essential that this test be conclusive. Should Mini-BooNE not confirm LSND with neutrinos, testing the result with anti-neutrinos will be important. Improvements in proton intensity as discussed in the preceding recommendation would permit Mini-BooNE to also test LSND with anti-neutrinos.

- **We endorse the physics goals of a long-baseline ν_e appearance experiment using the existing NuMI beamline. We recommend development of this experimental program. A reactor neutrino experiment running in parallel will be complementary.**

  Such an experiment should be roughly 10 times more sensitive than MINOS to ν_e appearance and being done in a timely manner would capitalize on the considerable investment in NuMI. With a suitable detector, a properly optimized appearance experiment could have good sensitivity to θ_{13} and provide a unique relatively short-term opportunity to determine the neutrino mass hierarchy via matter effects. That determination would have important implications for fundamental neutrino properties as well as the requirements for future neutrinoless double beta decay experiments.

III. Long Term Strategy and Priorities:

- **Pursue a long-baseline neutrino program. The U.S. should focus on longer baseline experiments than are being considered in Japan or Europe (at present at least). The overall U.S. program (domestic and participation in experiments abroad) should form a coherent part of an international effort.**

  Neutrino Superbeam experiments being planned in Japan and Europe have baselines sufficiently short so that it is difficult to measure the matter effects which can identify the mass hierarchy. This is a unique measurement capability which we believe the U.S. experiment(s) should offer. In addition, the U.S. experiments have the potential for providing the best sensitivity to the oscillation parameters, including first measurement of ν_e appearance and discovery and measurement of CP violation in neutrino oscillations.

- **A massive detector will be necessary for the future long-baseline experiments. We recommend a study of the possible eventual connection between a neutrino superbeam with a massive multi-purpose detector.**

  One can probably build the very large detector needed just for long baseline experiments alone on the surface. However, the capabilities which such a detector must have can permit a broad range of physics measurement capabilities if located underground. We think it is essential to study the technology and possible connections between the superbeam and multi-purpose underground detector.

- **If LSND is confirmed, a whole new range of experiments should follow with possible programs at a variety of laboratories.**

  If the LSND observation is correct, then there are light sterile neutrinos which also participate in oscillations, or something even stranger yet. This modifies the model of neutrino mixings in a way that requires us to provide measurements to both establish the very nature of the mixing as well as specific values of parameters. Long baseline experiments with the capabilities we describe here will still be essential, but the interpretation of their results may be different. In addition, new short (or possibly medium) baseline experiments will be essential to study the new physics phenomena in detail and build a new picture of neutrino physics.

- **Searches for exotic neutrino properties should be pursued with new superbeam experiments.**

  Due to their special properties, neutrinos can be particularly sensitive to a range of possible new physics from extra dimensions to violation of equivalence principle to new very weak interactions. Relatively small new short-baseline experiments are able to extend sensitivity to possible exotic physics associated with neutrinos and such experiments will become better as higher intensity neutrino beams are available. A good example of such a measurement is to search for an anomalously large neutrino magnetic moment induced (in example) by effects of extra dimensions. Experiments extending such sensitivity by a factor of 10-100 are foreseen.

- **New high-precision cross-section experiments should be undertaken.**

  Detailed understanding of neutrino interaction cross sections is important for future oscillation measurements. Such measurements can also provide interesting insight to QCD effects and effects of nuclear matter. Current understanding of cross-sections (total, differential and exclusive final states) in the GeV range, so important to oscillation experiments, is only at the tens of percent level. Although near detectors can help to cancel some of the uncertainty in cross sections, the better and more precise solution is to actually measure the cross sections better than currently known once and for all! We encourage that the experiments necessary for this be carried out.

A.4 Executive Summary of the Neutrino Factory and Beta Beam Experiments and Development Working Group

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and
The Neutrino Factory and Muon Collider Collaboration

A.4.1 Introduction

Two new types of facility have been proposed that could have a tremendous impact on future neutrino experiments—the Neutrino Factory and the Beta Beam facility. In contrast to conventional muon-neutrino beams, Neutrino Factory and Beta Beam facilities would provide a source of electron-neutrinos (ν_e) and -antineutrinos ($\bar{\nu}_e$), with very low systematic uncertainties on the associated beam fluxes and spectra. The experimental signature for $\nu_e \rightarrow \nu_\mu$ transitions is extremely clean, with very low background rates. Hence, Neutrino Factories and Beta Beams would enable very sensitive oscillation measurements to be made. This is particularly true at a Neutrino Factory which not only provides very intense beams at high energy, but also provides muon-neutrinos (ν_μ) and -antineutrinos ($\bar{\nu}_\mu$) in addition to electron-neutrinos (ν_e) and -antineutrinos ($\bar{\nu}_e$). This would facilitate a large variety of complementary oscillation measurements in a single detector, and dramatically improve our ability to test the three-flavor mixing framework, measure *CP* violation in the lepton sector (and perhaps determine the neutrino mass hierarchy), and, if necessary, probe extremely small values of the mixing angle θ_{13}.

At this time, we do not know the value of θ_{13}. If $\sin^2 2\theta_{13} < 0.01$, much of the basic neutrino oscillation physics program will be beyond the reach of conventional neutrino beams. In this case Neutrino Factories and Beta Beams offer the only known way to pursue the desired physics program.

The sensitivity that could be achieved at a Beta Beam facility presently looks very promising, but is still being explored. In particular, the optimum Beta Beam energy is under discussion. Low energy Beta Beam measurements would complement Superbeam measurements, but would achieve a θ_{13} sensitivity that does not appear to be competitive with that of a Neutrino Factory. Higher energy Beta Beams may approach the sensitivity possible with a Neutrino Factory, although systematics issues need further study. Thus, while a Beta Beam facility may have a significant role to play in the future global neutrino program, more work must be done on its design, development, cost estimate, and physics sensitivity to validate its potential. We note that, due to very limited resources, there has been no significant activity in the U.S. on Beta Beams. Progress on Beta Beam development being made in Europe should be followed, especially if the higher energy solution continues to look favorable.

An impressive Neutrino Factory R&D effort has been ongoing in the U.S. and elsewhere over the last few years, and significant progress has been made toward optimizing the design, developing and testing the required accelerator components, and significantly reducing the cost, even during the current Study. (Although a full engineering study is required, we have preliminary indications that the unloaded cost of a Neutrino Factory facility based on an existing Superbeam proton driver and target station can be reduced substantially compared with previous estimates.) Neutrino Factory R&D has reached a critical stage in which support is required for two key international experiments (MICE and Targetry) and a third-generation international design study. If this support is forthcoming, a Neutrino Factory could be added to the Neutrino Physics roadmap in about a decade.

Given the present uncertainty about the size of θ_{13}, *it is critical to support an ongoing and increased U.S. investment in Neutrino Factory accelerator R&D to maintain this technical option.* A Neutrino Factory cannot be built without continued and increased support for its development. We note that the 2001 HEPAP Report advocated an annual U.S. investment of $8M on Neutrino Factory R&D. The present support is much less than this. Since R&D on the design of frontier accelerator facilities takes many years, support must be provided *now* to have an impact in about a decade.

A.4.2 Recommendations

Accelerator R&D is an essential part of the ongoing global neutrino program. Limited beam intensity is already constraining the neutrino physics program, and will continue to do so in the future. More intense and new types of neutrino beams would have a big impact on the future neutrino program. A Neutrino Factory would require a Superbeam-type MW-scale proton source. We thus encourage the rapid development of a Superbeam-type proton source.

The Neutrino Factory and Beta Beam Working Group's specific recommendations are:

- ***We recommend that the ongoing Neutrino Factory R&D in the U.S. be given continued encouragement and financial support.*** We note that the HEPAP Report of 2001 recommended an annual support level of $8M for Neutrino Factory R&D, and this level was considered minimal to keep the R&D effort viable.

  In addition, and consistent with the above recommendation,

  1. ***We recommend that the U.S. funding agencies find a way to support the international Muon Ionization Cooling Experiment (MICE), in collaboration with European and Japanese partners.*** We note that MICE now has scientific approval at the Rutherford Appleton Laboratory in the UK, and will require significant U.S. participation. This has been identified as an important experiment for the global Neutrino Factory R&D program. A timely indication of U.S. support for MICE is needed to move the experiment forward.
  2. ***We recommend that support be found to ensure that the international Targetry R&D experiment proceeds as planned.*** We note that this R&D activity is

crucial for the short-, medium-, and long-term neutrino programs, and for other physics requiring high-intensity beams.

3. ***We recommend that a World Design Study, aimed at solidly establishing the cost of a cost-effective Neutrino Factory, be supported at the same level as Studies I and II.*** We note that the studies done here suggest that the cost of a Neutrino Factory would be significantly less than estimated for Studies I and II. This makes a Neutrino Factory a very attractive ingredient in the global neutrino roadmap.

- ***We recommend that progress on Beta Beam development be monitored, and that our U.S. colleagues cooperate fully with their EU counterparts in assessing how U.S. facilities might play a role in such a program.*** We note that there is no significant U.S. R&D effort on Beta Beams due to our limited R&D resources. Insofar as an intermediate energy solution is desirable, however, the Beta Beam idea is potentially of interest to the U.S. physics community.

A.5 Executive Summary of the Neutrinoless double beta decay and direct searches for neutrino mass

A.5.1 Introduction

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The physics addressed by this research program seeks to answer many of the Study's questions:

1. Are neutrinos their own anti-particles?
2. What are the masses of the neutrinos?
3. Do neutrinos violate the symmetry CP?
4. Are neutrinos the key to the understanding of the matter-antimatter asymmetry of the Universe?
5. What do neutrinos have to tell us about the intriguing proposals for new models of physics?

Only the research covered within this working group can answer the first and second of these fundamental questions. Among the ways to measure the neutrino mass, three are notable because they are especially sensitive: double-beta decay, tritium beta decay, and cosmology. Consequently, we have focused our report and recommendations on them.

• Observation of the neutrinoless double-beta decay ($0\nu\beta\beta$) would prove that the total lepton number is not conserved and would establish a non vanishing neutrino mass of Majorana nature.

In other words, observation of the $0\nu\beta\beta$ decay, independent of its rate, would show that neutrinos, unlike all the other constituents of matter, are their own antiparticles. There is no other realistic way to determine the nature - Dirac or Majorana, of massive neutrinos. This would be a discovery of major importance, with impact not only on this fundamental question, but also on the determination of the absolute neutrino mass scale, and on the pattern of neutrino masses, and possibly on the problem of CP violation in the lepton sector, associated with Majorana neutrinos. There is a consensus on this basic point which we translate into the recommendations how to proceed with experiments dedicated to the search of the $0\nu\beta\beta$ decay, and how to fund them.

• To reach our conclusion, we have to consider past achievements, the size of previous experiments, and the existing proposals. There is a considerable community of physicists worldwide as well as in the US interested in pursuing the search for the $0\nu\beta\beta$ decay. Past experiments were of relatively modest size. Clearly, the scope of future experiments should be considerably larger, and will require advances in experimental techniques, larger collaborations and additional funding. In terms of $\langle m_{\beta\beta}\rangle$, the effective neutrino Majorana mass that can be extracted from the observed $0\nu\beta\beta$ decay rate, there are three ranges of increasing sensitivity, related to known neutrino-mass scales of neutrino oscillations.

• The ~100-500 meV $\langle m_{\beta\beta}\rangle$ range corresponds to the quasi-degenerate spectrum of neutrino masses. The motivation for reaching this scale has been strengthened by the recent claim of an observation of $0\nu\beta\beta$ decay in ^{76}Ge; a claim that obviously requires further investigation. To reach this scale and perform reliable measurements, the size of the experiment should be approximately 200 kg of the decaying isotope, with a corresponding reduction of the background.

This quasi-degenerate scale is achievable in the relatively near term, ~ 3-5 years. Several groups with considerable US participation have well established plans to build ~ 200-kg devices that could scale straight-forwardly to 1 ton (Majorana using ^{76}Ge, Cuore using ^{130}Te, and EXO using ^{136}Xe). There are also other proposed experiments worldwide which offer to study a number of other isotopes and could reach similar sensitivity after further R&D. Several among them (*e.g.* Super-NEMO, MOON) have US participation.

By making measurements in several nuclei the uncertainty arising from the nuclear matrix elements would be reduced. The development of different detection techniques, and measurements in several nuclei, is invaluable for establishing the existence (or lack thereof) of the $0\nu\beta\beta$ decay at this effective neutrino mass range.

• The ~20-55 meV range arises from the atmospheric neutrino oscillation results. Observation of $\langle m_{\beta\beta}\rangle$ at this mass scale would imply the inverted neutrino mass hierarchy or the normal-hierarchy ν mass spectrum very near the quasi-degenerate region. If either this or the quasi-degenerate spectrum is established, it would be invaluable not only for the understanding of the origin of neutrino mass, but also as input to the overall neutrino physics program (long baseline oscillations, search for CP violations, search for neutrino mass in tritium beta decay and astrophysics/cosmology, etc.)

To study the 20-50 meV mass range will require about 1 ton of the isotope mass, a challenge of its own. Given the importance, and the points discussed above, more than one experiment of that size is desirable.

• The ~2-5 meV range arises from the solar neutrino oscillation results and will almost certainly lead to the $0\nu\beta\beta$ decay, provided neutrinos are Majorana particles. To reach this goal will require ~100 tons of the decaying isotope, and no current technique provides such a leap in sensitivity.

• The qualitative physics results that arise from an observation of $0\nu\beta\beta$ decay are profound. Hence, the program described above is vital and fundamentally important even if the resulting $\langle m_{\beta\beta}\rangle$ would be rather uncertain in value. However, by making measurements in several nuclei the uncertainty arising from the nuclear matrix elements would be reduced.

• Unlike double-beta decay, beta-decay endpoint measurements search for a kinematic effect due to neutrino mass and thus are "direct searches" for neutrino mass. This technique, which is essentially free of theoretical assumptions about neutrino properties, is not just complementary. In fact, both types of measurements will be required to fully untangle the nature of the neutrino mass. Excitingly, a very large new beta spectrometer is being built in Germany. This KATRIN experiment has a design sensitivity approaching 200 meV. If the neutrino masses are quasi-degenerate, as would be the case if the recent double-beta decay claim proves true, KATRIN will see the effect. In this case the $0\nu\beta\beta$-decay experiments can provide, in principle, unique information about CP-violation in the lepton sector, associated with Majorana neutrinos.

• Cosmology can also provide crucial information on the sum of the neutrino masses. This topic is summarized in a different section of the report, but it should be mentioned here that the next generation of measurements hope to be able to observe a sum of neutrino masses as small as 40 meV. We would like to emphasize the complementarity of the three approaches, $0\nu\beta\beta$, β decay, and cosmology.

A.5.2 Recommendations

We conclude that such a double-beta-decay program can be summarized as having three components and our recommendations can be summarized as follows:

1. A substantial number (preferably more than two) of 200-kg scale experiments (providing the capability to make a precision measurement at the quasi-degenerate mass scale) with large US participation should be supported as soon as possible.
   ◦ Each such experiment will cost approximately $10M-$20M and take 3-5 years to implement.
2. Concurrently, the development toward ~1-ton experiments (*i.e.* sensitive to $\sqrt{\Delta m^2_{\rm atm}}$) should be supported, primarily as expansions of the 200-kg experiments. The corresponding plans for the procurement of the enriched isotopes, as well as for the development of a suitable underground facility, should be carried out. The US funding agencies should set up in a timely manner a mechanism to review and compare the various proposals for such experiments which span research supported by the High Energy and Nuclear Physics offices of DOE as well as by NSF.

◦ Each such experiment will cost approximately $50M-$100M and take 5-10 years to implement.

3. A diverse R&D program developing additional techniques should be supported.
   The total cost of this described program will be approximately $250M over a 10 year period.

• In addition to double-beta decay, other techniques for exploring the neutrino mass need to be pursued also. We summarize these recommendations as follows.

1. Although KATRIN is predominately a European effort, there is significant US participation. The design and construction of this experiment is proceeding well and the program should continue to be strongly supported.
2. Research and development of other techniques for observing the neutrino mass kinematically should be encouraged.

A.6 Executive Summary of the Neutrino Astrophysics and Cosmology Working Group

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A.6.1 Introduction

In 2002, Ray Davis and Masatoshi Koshiba were awarded the Nobel Prize in Physics "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos." However, while astronomy has undergone a revolution in understanding by synthesizing data taken at many wavelengths, the universe has only barely been glimpsed in neutrinos, just the Sun and the nearby SN 1987A. An entire universe awaits, and since neutrinos can probe astrophysical objects at densities, energies, and distances that are otherwise inaccessible, the results are expected to be particularly exciting. Similarly, the revolution in quantitative cosmology has heightened the need for very precise tests that are possible only with neutrinos, and prominent among them is the search for the effects of neutrino mass, since neutrinos are a small but known component of the dark matter.

The Neutrino Astrophysics and Cosmology Working Group put special emphasis on the following primary questions of the Neutrino Study; there are also strong connections to the other questions as well.

- *What is the role of neutrinos in shaping the universe?*
- *Are neutrinos the key to the understanding of the matter-antimatter asymmetry of the universe?*
- *What can neutrinos disclose about the deep interiors of stars?*

A.6.2 Recommendations

Our principal recommendations are:

- **We strongly recommend the development of experimental techniques that focus on the detection of astrophysical neutrinos, especially in the energy range above 10^{16} eV.**

  We estimate that the appropriate cost is less than $10 million to enhance radio-based technologies or develop new technologies for high energy neutrino detection. The technical goal of the next generation detector should be to increase the sensitivity by factor of 10, which may be adequate to measure the energy spectrum of the expected GZK (Greisen-Zatsepin-Kuzmin) neutrinos, produced by the interactions of ultra-high energy cosmic ray protons with the cosmic microwave background (Fig. 10). The research and development phase for these experiments is likely to require 3-5 years.

- **We recommend support for new precision measurements of neutrino-nucleus cross sections in the energy range of a few tens of MeV.**

  We estimate that measurements of neutrino cross-section recommended by this working group can be accomplished for less than $10 million, with R&D requiring $0.5 million for one year. Construction will require two additional years.

- **We recommend that adequate resources be provided to allow existing large-volume solar, reactor, proton decay, and high energy neutrino telescopes to observe neutrinos from the next supernova explosion and participate in a worldwide monitoring system. Furthermore, future large-volume detectors should consider the detection of supernova neutrinos an important science goal and plan accordingly.**

  We anticipate that the investment to insure that large volume detectors maintain sensitivity to galactic supernovae, as well as the diffuse supernova neutrino background from all supernovae, will be less than $10 million over the next 5 years. New large volume detectors expected for long-baseline, reactor, proton-decay, solar, and high energy neutrino detectors should consider new ideas to enhance the capabilities for the detection of supernova neutrinos. The cost is not possible to determine at this time.

Our principal endorsements are:

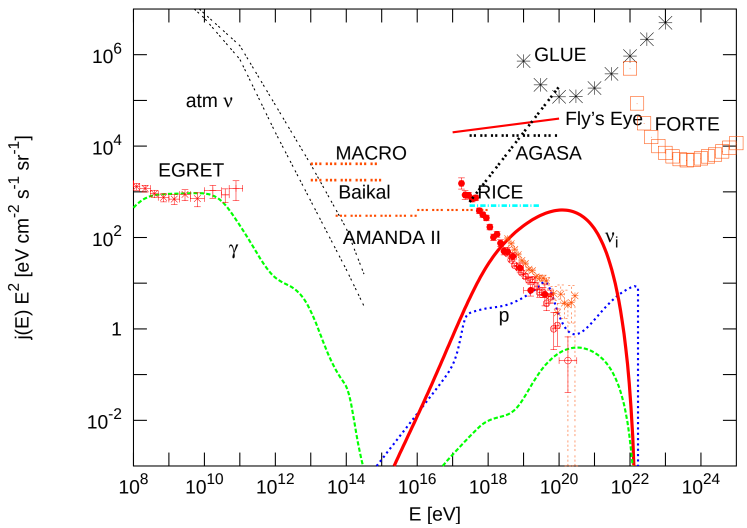

Figure 10: Results are shown for the neutrino flux (solid red line) predicted by a model of D.V. Semikoz and G. Sigl (JCAP 0404:003 (2004) [hep-ph/0309328]), compared to existing limits (horizontal lines labeled by the experiments). This model is chosen to produce the largest neutrino flux compatible with both the cosmic ray (red data points, blue dotted lines) and gamma ray data (red data points, green dashed lines), yet it remains beyond the reach of current experiments. A new generation of experiments is needed to test these very important predictions, as well as to begin to survey the ultra-high energy universe for new sources.

- **We enthusiastically support continued investment in a vigorous and multi-faceted effort to precisely (but indirectly) measure the cosmological *neutrino* background through its effects on big-bang nucleosynthesis, the cosmic microwave background, and the large-scale structure of galaxies; in particular, weak gravitational lensing techniques offer a very realistic and exciting possibility measuring neutrino masses down to the scale indicated by neutrino oscillations.**

- **We enthusiastically support theoretical and computational efforts that integrate the latest results in astronomy, astrophysics, cosmology, particle physics, and nuclear physics to constrain the properties of neutrinos and elucidate their role in the universe.**

- **We enthusiastically support the scientific goals of the current program in galactic and extra-galactic neutrino astrophysics experiments, including Super-Kamiokande, AMANDA, and NT-200 deployed in Lake Baikal. Furthermore, we endorse the timely completion of projects under construction, such as IceCube, undersea programs in the Mediterranean, ANITA, and AUGER.**

- **Though solar neutrinos were not in our purview, we endorse the conclusion of the Solar/Atmospheric Working Group that it is important to precisely measure solar neutrinos, and strongly support the development of techniques which could also be used for direct dark matter detection.**

A.7 Executive Summary of the Theory Discussion Group

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A.7.1 Introduction

Various oscillation experiments, from solar and atmospheric to reactor and accelerator neutrinos have conclusively established that neutrinos have mass and mix. Thanks to these experiments, we now know: (i) the rough magnitude of the leptonic mixing angles (two of the three are large and a third one relatively small) and (ii) that the masses of all three neutrino species are exceedingly small compared to charged fermion masses. This very small amount of information has already served as source of great excitement as it provides the first (and currently only) evidence of physics beyond the standard model. The discovery of neutrino masses also raises hope that the one of the fundamental mysteries of the cosmos – why there is more matter than anti-matter? – may be eventually resolved through a better understanding of neutrinos.

There are, however, other fundamental neutrino properties, related to their masses, about which we do not have information yet. To elevate our knowledge of neutrinos to the same level as that of the quarks, the theory discussion group has attempted to provide a prioritized list of the essential properties of neutrinos needed for this purpose. This would surely shed essential light on the nature of the new physics beyond the standard model as well as, perhaps, the origin of matter.

The key questions whose answers we do not know are:

1. Are neutrinos their own anti-particles?
2. What is the pattern of neutrino masses ?
3. Is there CP violation in the leptonic sector?
4. Are there additional neutrino species as may be hinted by the LSND experiment?

On the theoretical side, while there are several different ways to understand small neutrino masses, the seesaw mechanism, which introduces a set of heavy "right-handed neutrinos," appears to be the most appealing. Existing data do not provide any way to verify if this idea is correct. A key question here is whether the seesaw scale is near the grand unification scale where all forces are expected to unify or much lower.

Before listing our recommendations, we very briefly discuss some of what we should learn from the results of various future neutrino experiments:

(i) Searches for neutrinoless double beta decay:

A positive signal would teach us that lepton number (or more precisely the $B-L$ quantum number), which is an accidental symmetry of the standard model in the absence of neutrino masses, is violated. This would provide fundamental information, and would serve as a crucial milestone in searches for new physics.

The popular seesaw mechanism predicts that neutrinos are their own antiparticles, and the observation of neutrinoless double beta decay would solidify it as the leading candidate explanation for the origin of neutrino masses.

The observation of a positive signal in the foreseeable future would also also imply the quasi-degenerate or inverted hierarchy for the neutrino masses. The quasi-degenerate pattern would suggest some special mechanism for mass generation, possibly type II (Higgs triplet) seesaw, such as can emerge in SO(10) grand unified theories (GUTs).

On the other hand, the absence of evidence for neutrinoless double beta decay would rule out the inverted and quasi-degenerate mass-hierarchies, if the experiments reach an ultimate sensitivity of $< m_{ee} > \simeq 15-50$ meV and if neutrinos are Majorana particles. Furthermore, if at the same time KATRIN observes a positive signal, we would learn that neutrinos are Dirac fermions. This fact would have far reaching implications for theory. It would, for example, contradict the predictions of the seesaw theory.

(ii) Determination of the mass hierarchy:

This can obtained, for example, from long baseline oscillation experiments An inverted mass hierarchy ($m_3^2 \ll m_1^2, m_2^2$), may interpreted to mean that leptons obey a new (only slightly broken) symmetry: $L_e - L_\mu - L_\tau$, which would raise doubts about quark-lepton symmetry, which is a fundamental ingredient of GUTs, such as SO(10). A normal mass hierarchy ($m_3^2 \gg m_1^2, m_2^2$), on the other hand, is expected in generic seesaw models, including most SO(10) GUT that address fermion masses and mixing.

(iii) Measurement of θ_{13}:

The next most important search item is the magnitude of θ_{13}, which can be obtained, for example, from reactor neutrino experiments as well as long baseline accelerator neutrino experiments. θ_{13} turns out to be one of the most clear discriminators among various models of neutrino masses. Simple symmetry arguments suggest that there are two possible ranges for θ_{13}: $\theta_{13} \simeq \sqrt{\Delta m_\odot^2/\Delta m_{\rm atm}^2} \geq 0.1$ or $\theta_{13} \simeq \Delta m_\odot^2/\Delta m_{\rm atm}^2 \simeq 0.04$. Of course, the magnitude of θ_{13} also determines whether other fundamental questions (including "is there leptonic CP violation?" and "what is the neutrino mass hierarchy?") can be experimentally addressed via neutrino oscillations.

(iv) CP violation and origin of matter:

One may argue that CP violation in the leptonic sector is expected, as strongly suggested by the presence of a large CP phase in the quark sector. We believe, however, that detailed experimental studies are required in order to determine the mechanism for leptonic CP-violation (assuming it exists!).

The observation of leptonic CP-violation would enhance the possibility that the matter asymmetry of the Universe was generated in the lepton sector by demonstrating the CP violation exists among leptons. However, there is no unambiguous connection: the absence of CP-invariance violation in the light neutrino sector, for example, would *not* imply that enough baryon asymmetry cannot be generated via the leptogenesis mechanism. It turns out, however, that models for leptogenesis generically imply observable CP-invariance violation in the leptonic sector.

(v) Extra neutrinos:

If the LSND anomaly is confirmed by MiniBooNE, a substantial change in our understanding of high energy physics will be required. One potential interpretation of the LSND anomaly is to postulate the existence of (at least one) extra, "sterile" neutrino. This would be a very concrete hint for new physics, beyond the traditional seesaw, GUTs, etc. If MiniBoone confirms the LSND anomaly, the most important task will be to explore the nature of this phenomenon. It may turn out that LSND (and MiniBooNE) have uncovered some even more exotic phenomenon.

(vi) Other issues:

Precision measurements of solar neutrino spectrum can also provide useful information about the detailed nature of matter effect on neutrino propagation in the Sun as well as sources of energy generation there. Similarly reactor searches for magnetic moment of neutrinos can also provide signals of physics beyond the standard model such as possible extra dimensions or new physics at TeV scale.

In this Working Group, approaches that focus on the following primary physics questions are addressed:

- *Is our model of neutrino mixing and oscillation complete, or are there other mechanisms at work?*

  To test the oscillation model, we must search for sub-dominant effects such as non-standard interactions, make precision comparisons to the measurements of other experiments in different regimes, and verify the predictions of both the matter effect and vacuum oscillation. The breadth of the energy spectrum, the extremely long baselines, and the matter densities traversed by solar and atmospheric neutrinos make them very different than terrestrial experiments, and hence measurements in all three mixing sectors—including limits on θ_{13}—can be compared to terrestrial measurements and thus potentially uncover new physics.

- *Is nuclear fusion the only source of the Sun's energy, and is it a steady state system?*

  Comparison of the total energy output of the Sun measured in neutrinos must agree with the total measured in photons, if nuclear fusion is the only energy generation mechanism at work. In addition, the comparison of neutrino to photon luminosities will tell us whether the Sun is in an approximately steady state by telling us whether the rate of energy generation in the core is equal to that radiated through the solar surface—the heat and light we see today at the solar surface was created in the interior $\sim$ 40,000 years ago, while the neutrinos are just over eight minutes old.

- *What is the correct hierarchical ordering of the neutrino masses?*

  Atmospheric neutrinos which pass through the Earth's core and mantle will have their transformation altered due to the matter effect, dependent upon the sign of the Δm^2_{32} mass difference. Future large scale water Cerenkov experiments may be able to observe this difference in the ratio of μ-like to e-like neutrino interactions, while magnetized atmospheric neutrino experiments may be able to see the effect simply by comparing the number of detected ν_μ to $\bar{\nu_\mu}$ events.

A.7.2 Recommendations

We very strongly recommend the following experiments, that will shed light on the issues discussed above. We make the conservative assumption that MiniBooNE will not confirm the LSND anomaly:

1. Double beta decay searches, which will shed light on whether neutrinos are their own antiparticles;
2. Oscillation experiments capable of precisely measuring all oscillation parameters, including the neutrino mass hierarchy, θ_{13} and, ultimately, CP-violation;
3. Finally, we recommend that all resources be provided to Mini-Boone until a satisfactory resolution of the LSND puzzle is obtained.

B APS Study Origins, Committees, Glossary

B.1 APS neutrino Study, Justification and Scope

The American Physical Society Divisions of Particles and Fields and of Nuclear Physics, together with the APS Divisions of Astrophysics and the Physics of Beams, sponsored a year-long Study on the Physics of Neutrinos. The overarching purpose of the study was for a diverse community of scientists to examine the broad sweep of neutrino physics, and if possible, to move toward agreement on the next steps toward answering the questions that drive the field. The study is intended to lay the scientific groundwork for the choices that must be made during the next few years.

The study had its kickoff meeting in December 2003 at Argonne, and a final plenary meeting in June 2004 at Snowmass. The working groups and committees had a number of other meetings as well. This report is the product of that process, along with reports from each of the working groups. A web site with links to the documents and to working pages for each working group was maintained at:
http://www.interactions.org/neutrinostudy. Committees are listed in Table 2.

B.2 Charge of the Study

The APS Divisions of Particles and Fields and of Nuclear Physics, together with the APS Divisions of Astrophysics and the Physics of Beams, is organizing a year-long Study on the Physics of Neutrinos, beginning in the fall of 2003. The Study is in response to the remarkable recent series of discoveries in neutrino physics and to the wealth of experimental opportunities on the horizon. It will build on the extensive work done in this area in preparation for the 2002 long range plans developed by NSAC and HEPAP, as well as more recent activities, by identifying the key scientific questions driving the field and analyzing the most promising experimental approaches to answering them. The results of the Study will inform efforts to create a scientific roadmap for neutrino physics.

The Study is being carried out by four APS Divisions because neutrino physics is inherently interdisciplinary in nature. The Study will consider the field in all its richness and diversity. It will examine physics issues, such as neutrino mass and mixing, the number and types of neutrinos, their unique assets as probes of hadron structure, and their roles in astrophysics and cosmology. It will also study a series of experimental approaches, including long and short baseline accelerator experiments, reactor experiments, nuclear beta-decay and double beta-decay experiments, as well as cosmic rays and cosmological and astrophysical observations. In addition, the study will explore theoretical connections between the neutrino sector and physics in extra dimensions or at much higher scales.

The Study will be led by an Organizing Committee and carried out by Working Groups. The Organizing Committee will function as an interdisciplinary team, reporting to the four Divisions, with significant international participation. The Study will be inclusive, with all interested parties and collaborations welcome to participate. The final product of the Study will be a book (or e-book) *containing reports from each Working Group, as well as contributed papers by the Working Group participants. The Organizing Committee and Working Group leaders will integrate the findings of the Working Groups into a coherent summary statement about the future. The Working Groups will meet as necessary, with a goal of producing the final report by August 2004.*

The overarching purpose of the Study is for a diverse community of scientists to examine the broad sweep of neutrino physics, and if possible, to move toward agreement on the next steps toward answering the questions that drive the field. The Study will lay scientific groundwork for the choices that must be made during the next few years.

B.3 Sponsors for domestic neutrino science

⊙ Department of Energy Office of High Energy Physics The mission of the High Energy Physics (HEP) program is to explore the fundamental nature of matter, energy, space, and time.

⊙ Department of Energy Office of Nuclear Physics The DOE Nuclear Physics (NP) program aims to understand the composition, structure, and properties of atomic nuclei, the processes of nuclear astrophysics and the nature of the cosmos.

⊙ Department of Energy, National Nuclear Security Administration

⊙ National Science Foundation

⊙ National Aeronautics and Space Administration

B.4 Context: Related Studies and Reports

<> The Nuclear Science Advisory Committee's long-range plan, "Opportunities in Nuclear Science: A Long-Range Plan for the Next Decade."
www.sc.doe.gov/henp/np/nsac/nsac.html

<> The High-Energy Physics Advisory Panel subpanel report on long-range planning, "The Science Ahead: The Way to Discovery," lays out a roadmap for the U.S. particle physics program over the next 20 years, also known as the "Bagger-Barish" report.
doe-hep.hep.net/lrp_panel/index.html

<> The DOE "Office of Science Strategic Plan" and the 20-year facilities roadmap, "Facilities for the Future of Science: A Twenty-Year Outlook."
www.sc.doe.gov/Sub/Mission/Mission_Strategic.htm

<> The National Research Council (NRC) laid out 11 key scientific questions at the intersection of physics and astronomy in a report entitled "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century."
www.nationalacademies.org/bpa/projects/cpu/report.

<> The OSTP report entitled "The Physics of the Universe: A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy" is the response of the White House to the NRC

Organizing Committee:

Stuart J. Freedman	University of California, Berkeley	Co-chair
Boris F. Kayser	Fermilab	Co-chair
Janet Conrad	Columbia University	
Guido Drexlin	University of Karlsruhe	
Belen Gavela	University Autonoma de Madrid	
Takaaki Kajita	University of Tokyo	
Paul Langacker	University of Pennsylvania	
Keith Olive	University of Minnesota	
Bob Palmer	Brookhaven National Lab	
Georg Raffelt	Max Planck Institute for Physics	
Hamish Robertson	University of Washington	
Stan Wojcicki	Stanford University	
Lincoln Wolfenstein	Carnegie-Mellon University	

Working Groups and Group Leaders:

Solar and atmospheric neutrino experiments:

John N. Bahcall	Institute for Advanced Study
Joshua R. Klein	University of Texas, Austin

Reactor neutrino experiments:

Gabriela Barenboim	University of Valencia
Ed Blucher	University of Chicago

Superbeam experiments and development:

William Marciano	Brookhaven National Laboratory
Douglas Michael	California Institute of Technology

Neutrino factory and beta beam experiments and development:

Steven Geer	Fermilab
Michael Zisman	Lawrence Berkeley National Laboratory

Neutrinoless double beta decay and direct searches for neutrino mass:

Steven R. Elliott	Los Alamos National Laboratory
Petr Vogel	California Institute of Technology

Neutrino Astrophysics and Cosmology:

Steven Barwick	University of California, Irvine
John Beacom	Ohio State University

Theory:

Rabi Mohapatra	University of Maryland

Writing Committee

Janet Conrad	Columbia University	
Steve Elliott	Los Alamos National Laboratory	
Stuart J. Freedman	University of California, Berkeley	
Maury Goodman	Argonne National Laboratory	
André de Gouvéa	Northwestern University	
Boris F. Kayser	Fermilab	
Joshua R. Klein	University of Texas, Austin	
Douglas Michael	California Institute of Technology	
Hamish Robertson	University of Washington	Chair

Table 2: Committees

Report “Connecting Quarks with the Cosmos.” One of its recommendations is that NSF and DOE should collaborate to “identify a core suite of physics experiments” for research into Dark Matter, neutrinos, and proton decay; and that NSF should take the lead on conceptual development and formulation of a scientific roadmap for an underground laboratory facility.
www.ostp.gov/html/physicsoftheuniverse2.pdf

<> A National Research Council Report, “Neutrinos and Beyond: New Windows on Nature,” addresses the scientific motivation for the Ice Cube project at the South Pole and for a multipurpose national underground laboratory.
books.nap.edu/catalog/10583.html

<> A HEPAP Subpanel Report, “Quantum Universe: The Revolution in 21st Century Particle Physics” identifies nine questions for particle physics.
interactions.org/cms/?pid=1012346.

<> A White Paper Report on Using Reactors to search for a value of θ_{13}.
www.hep.anl.gov/minos/reactor13/reactor13.pdf

<> A Fermilab Report, “The Coming Revolution in Particle Physics ” Report of the Fermilab Long Range Planning Committee.
www.fnal.gov/pub/today/directors_corner/lrpreportfinal.pdf

B.5 Glossary of acronyms

- AGS - Alternating Gradient Synchrotron, accelerator at Brookhaven
- AMANDA - Antarctic Muon And Neutrino Detector Array
- ANITA - ANtarctic Impulse Transient Antenna
- ANTARES - Astronomy with a Neutrino Telescope and Abyss environmental RESearch
- APS - American Physical Society
- BBN - Big Bang Nucleosynthesis
- BOONE - BOOster Neutrino Experiment
- CC - Charged Current neutrino event
- CDF - Collider Detector Facility
- CERN - European Laboratory for Particle Physics
- CKM - Cabbibo Kobayashi Maskawa 3x3 mixing matrix
- CMB - Cosmic Microwave Background
- CHORUS - Cern Hybrid Oscillation Research apparatUS
- CNGS - Neutrinos to Gran Sasso
- CPT - Charge conjugation - Parity - Time reversal invariance
- CUORE - Cryogenic Underground Observatory for Rare Events
- D0 - (D-zero) collider experiment at Fermilab intersection region D0
- DOE - Department of Energy
- EDF - Electricite de France (manager of CHOOZ reactor)
- EXO - Enriched Xenon beta-beta decay Observatory
- FNAL - Fermi National Accelerator Lab
- GALLEX - GALLium EXperiment
- GENIUS - GErmanium liquid NItrogen Underground Study
- GNO - Germanium Neutrino Observatory
- GUT - Grand Unified Theory
- GZK - Greisen Zatsepin Kuzmin cutoff in cosmic ray energy spectrum
- HELLAZ - HElium at Liquid AZzote temperature
- HEPAP - High Energy Physics Advisory Panel
- ICARUS - Imaging Cosmic and Rare Underground Signals
- INO - Indian Neutrino Observatory (proposal)
- JPARC - Japanese PArticle Research Center
- K2K - KEK to Super-Kamiokande
- KamLAND - Kamioka Liquid scintillator Anti-Neutrino Detector
- KASKA - Kashiwazaki-Kariwa Reactor Neutrino (proposal)
- KATRIN - KArlsruhe TRItium Neutrino Experiment
- LENS - Low Energy Neutrino Spectroscopy
- LEP - Large Electron Proton collider
- LMA - Large Mixing Angle Solution of the Solar neutrino problem
- LSND - Liquid Scintillator Neutrino Detector
- MINERvA - Main INjector ExpeRiment (neutrino)-A

- MINOS - Main Injector Neutrino Oscillation Search
- MOON - MOlybdenum Observatory for Neutrinos
- MNSP - Maki Nakagawa Sakata Pontecorvo 3x3 mixing matrix
- MSW - Mikheyev-Smirnov-Wolfenstein matter-enhancement effect for neutrino oscillations
- MWE -Meters of Water Equivalent
- NC - Neutral Current neutrino event
- NEMO - Neutrino Ettore Majorana Observatory
- NOvA - NuMI Off-axis (neutrino) Appearance
- NOMAD - Neutrino Oscillation MAgnetic Detector (CERN)
- NSF - National Science Foundation
- NuMI - Neutrinos at the Main Injector
- NuTeV - Neutrinos at the TeVatron
- OMB - Office of Management and Budget
- OPERA - Oscillation Project with Emulsion-tRacking Apparatus
- OSTP - Office of Science and Technology Policy
- QCD - Quantum ChromoDynamics
- P5 - Particle Physics Project Prioritization Panel
- QE - Quasi-Elastic neutrino event
- R&D - Research and Development
- RICE - Radio Ice Cerenkov Experiment
- SAGE - (Soviet) russian American Gallium Experiment
- SAGENAP - Scientific Assessment Group for Experimental Non-Accelerator Physics
- SLC - Stanford Linear Collider
- SM - Standard Model of particles and fields
- SMA - Small Mixing Angle Solution of the Solar Neutrino Problem
- SN(e) - Supernova(e)
- SNO - Sudbury Neutrino Observatory
- SPS - CERN Super Proton Synchrotron
- SSM - Standard Solar Model
- Super-Kamiokande - Super-Kamioka Nucleon Decay Experiment
- SUSY - SUper SYmmetry
- T2K - Tokai to Kamiokande long-baseline experiment at JPARC
- WMAP - Wilkinson Microwave Anisotropy Probe