In this talk, I review the framework that explains our experimental observations in neutrino physics. I will explain how a set of measurements in the last few years have filled in remaining gaps in this picture, and layout the remaining outstanding questions along with techniques for addressing them in the coming decade.

1. INTRODUCTION

It’s been a remarkable decade in neutrino physics. Ten years ago this summer, at the 1998 neutrino conference in Takayama, the Super-Kamiokande collaboration reported the observation of neutrinos changing flavor [1], thereby establishing the existence of neutrino mass. A few years later, the SNO experiment solved the long-standing solar neutrino problem [2] demonstrating that it too was due to neutrino oscillation. Just a few years after that, these effects were confirmed and the oscillation parameters were measured with man-made neutrino sources [3, 4]. Now, just in this last year, the same neutrinos which were the source of the 30 year old solar neutrino problem were measured for the first time in a real-time experiment.

In this talk, I will explain how a set of experiments, especially ones in the last few years, have established a consistent framework of neutrino physics and also explain some outstanding questions. Finally, I will cover how a set of upcoming experiments hope to address these questions in the coming decade.

1.1. Framework

First, I would like to briefly review our current understanding of the properties of neutrinos. As far as we know, there are three light neutrinos which interact via the weak force. Since there are three neutrinos, there are two mass splittings that separate them, and two possible configurations or “hierarchies” which are presently consistent with the experimental data. The first, known as the “normal” hierarchy is where the two lowest mass states are separated by the small solar splitting and then the highest mass state is separated from those two by the much larger atmospheric mass splitting. The so called “inverted” hierarchy reverses this configuration and the two highest mass states share the smaller splitting [5].

The eigenstates that travel through space are not the flavor states that we measure through the weak force, but rather the mass states. Since each flavor state is a quantum mechanical combination of mass states, there is some probability to measure a different flavor state then the original one after some time and distance.

The oscillations of atmospheric $\nu_{\mu}$ and solar $\nu_{e}$ can be explained separately by considering each as a two neutrino system. However, both phenomena can be explained together if we consider a 3 neutrino mass system. The relationship between the flavor and mass states of the neutrinos can be expressed with the following matrix equation:

$$
\begin{pmatrix}
\nu_{e} \\
\nu_{\mu} \\
\nu_{\tau}
\end{pmatrix}
=
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_{1} \\
\nu_{2} \\
\nu_{3}
\end{pmatrix},
$$

(1)

where the probability for a transition from flavor $a$ to flavor $b$ is given by:

$$
P(\nu_{a} \rightarrow \nu_{b}) = \delta_{ab} - 4 \sum_{j>i} \text{Re}(U_{ai}^{*}U_{bi}U_{aj}U_{bj}^{*}) \sin^{2}(1.27\Delta m_{ij}^{2}L/E)
$$

(2)
\[ \pm 2 \sum_{j>i} \text{Im}(U_{ai}^* U_{bj} U_{aj}^* U_{bi}) \sin^2 \left( 2 \Delta m_{ij}^2 L/E \right). \]  

(3)

with \( L \) in km, \( E \) in GeV, and \( \Delta m^2 \) in eV\(^2\). The minus sign refers to neutrinos and the plus sign to anti-neutrinos. The familiar two-flavor oscillation formula is a limiting case when considering only a single \( \Delta m^2 \) between the two states.

With three neutrino masses, there are two neutrino mass differences (\( \Delta m_{12}^2, \Delta m_{23}^2 \)), three mixing angles (\( \theta_{13}, \theta_{23}, \theta_{12} \)) and one CP violating phase. From our current understanding of atmospheric and solar oscillations, we know the two mass differences, and two of the mixing angles. The \( 3 \times 3 \) matrix from Eqn. (4) can be expressed in terms of these angles as:

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix},
\]

(4)

where “s” represents the sine of each mixing angle and “c” represents the cosine. In the decomposition above, the disappearance of solar neutrinos is driven by the oscillations of the 1-2 mass states, which are mixed by the matrix with the \( \theta_{12} \) terms, and observed atmospheric disappearance is driven by the matrix with the \( \theta_{23} \) terms. The middle mixing matrix, contains the as yet unmeasured \( \theta_{13} \), which we hope to soon measure. It should be noted that the \( \delta \) in this equation causes CP violation. There are two additional diagonal phases in the mixing matrix which adjust the rate of neutrinoless double beta-decay if neutrinos are their own anti-particles. These phases do not effect oscillations as only non-diagonal elements are present in equation (4).

1.2. Questions

There are a set of remaining questions we hope to address in the set of experiments which will be running in coming decade and beyond. The most important of these are:

1. What is the absolute mass of the neutrinos?
2. What is the pattern, or “hierarchy”, of neutrino masses?
3. Are neutrinos their own anti-particles?
4. Is there CP violation in the neutrino sector? If so, is it big enough to drive lepto-genesis and is it related to the quark sector?
5. What is the value of the final unmeasured mixing angle and is the atmospheric angle maximal?

2. ATMOSPHERIC AND SOLAR NEUTRINO EXPERIMENTS

I would like to start by discussing recent results from atmospheric and solar neutrino experiments. Not only did these experiments give us our first definitive evidence for neutrino oscillations but they are continuing to add important information about neutrino properties. The best constraints on one of the mixing angles comes from atmospheric neutrinos and the only measurement in a critical region of oscillation transition comes from solar neutrinos.
2.1. Atmospheric neutrino results

2.1.1. Super-Kamiokande

The Super-K experiment has taken data in three phases and is now starting a fourth phase to prepare for the upcoming T2K beam. New updated analyses were presented at this conference. In preparing these results the Super-K collaboration made improvements to the flux calculations, reconstruction algorithms, Monte Carlo and detector simulator, and also reevaluated their systematic errors.

These analyses exclude neutrino de-coherence and decay models at the four and five sigma level, constrain oscillations into admixtures of sterile neutrinos to be less than 23%, and most crucially constrain the atmospheric mixing angle $\theta_{23}$ to $45^\circ \pm 4^\circ$, a 10% accuracy. This is the most stringent current constraint on $\theta_{23}$.

2.2. Solar neutrino results

2.2.1. Borexino

One of the most important results in the last year came from the Borexino experiment [6]. For the first time, solar neutrinos in the energy region in the transition between vacuum oscillations and matter-enhanced resonance oscillations have been observed in real time. Previously, these low energy solar neutrinos in the 1 MeV range had only been seen by radio-chemical experiments. As seen in Figure 1 taken from [7],

![Figure 1: The realtime observation of $^7$Be solar neutrinos taken from [7].](image)

a clear shoulder from the low-energy $^7$Be neutrino scattering can be seen on top of the low-energy radioactive background. By using 192 days of data they were able to accurately measure the flux and show it is consistent with the solar large mixing angle (LMA) solution. This is important because previously the large errors on the measurements in this energy region from the gallium and chlorine experiments allowed for exotic non-standard oscillation scenarios. This is shown in Figure 2 where the effect of the Borexino measurement can be seen.

Before Borexino, on the plot on the left, the two low energy points are counting experiments using gallium and chlorine. Since these are integral measurements, the solar neutrino flux at any energy must be calculated by subtracting the measured flux from higher energy measurements from the measured flux. When the higher energy chlorine data is replaced by the Borexino measurement in the plot on the right, the measurement from the gallium data also changes since the contribution to the measurement from the higher energy flux is now seen to be higher than previously assumed. The effect of this is to now have two data points with smaller error bars which fall nicely
on the LMA prediction. A beautiful result! This result directly confirms our standard picture of neutrino oscillations using low-energy neutrinos from the sun.

2.2.2. Super-Kamiokande

The search for direct evidence of LMA oscillations is also the goal of the next phase of the Super-K solar analysis. The Super-K collaboration has worked hard during the SK-III phase to lower the radioactive background in the central region of the detector. If this background rejection factor can be achieved in SK-IV along with lower statistical errors and a lower correlated energy systematic error it should be possible to see the turn-up in survival probability as predicted by the LMA solution. This should be on the order of a 10% effect in Super-K, and the plan for SK-IV is to lower the energy threshold to 4.0 MeV to make this measurement possible.

2.2.3. SNO Phase III

The SNO experiment was the experiment that first conclusively demonstrated that the deficit of solar neutrinos seen on the earth was also due to neutrino oscillations. They did this by measuring both the flavor-blind neutral-current reaction, and the electron-neutrino only charged current reaction off of deuterium. Although the number of measured charged current reactions was less than expectation, the number of neutral current reactions was as expected, showing that the electron neutrinos were not disappearing but rather just transforming into a flavor for which the detector had no sensitivity.

Doing this measurement requires tagging the neutron that is produced in the neutral current reaction:

$$\nu_x + d \rightarrow p + n + \nu_x.$$  \hspace{1cm} (5)

There were three ways to see this neutron and they corresponded to the three running phases of SNO. In the first phase the neutron was captured on pure $D_2O$. In the second phase, salt was added to the water increasing the neutron capture cross-section and resulting in the production of higher energy gamma-rays which were easier to detect. In the third and final phase, for which we saw results at this conference, $^3$He neutron counters were added to the detector. Where as before, the energy from both the charge and neutral current reactions was measured via Cherenkov light, now the NC signal was measured in the neutron counters thereby breaking a degeneracy of the systematic errors and adding confidence to the measurements.
2.2.4. Kamland 2008

Finally, I want to mention the recent results from the Kamland experiment which probe the same oscillation parameters as the solar experiments but use neutrinos from reactors. This year, we saw exciting new results from Kamland where they increased the size of their data set and also, by improving their analysis techniques, were able to both lower the energy threshold to 1 MeV and use data closer to the wall. The combined effect of this was an increase of almost a factor of 20 in exposure. The result can be seen in Figure 3 taken from [8] which shows a clear sinusoidal oscillation pattern over almost two full cycles!

![Figure 3: New results from the Kamland experiment. This figure is taken from [8] and shows almost two full cycles of oscillation.](image)

Covering such a large range in L/E means that the fit to the mass squared difference can be very precise and these results allow Kamland to measure the solar mass splitting to the level of 2.7%.

3. OSCILLATION SEARCHES AT ACCELERATORS

I would now like to turn to searches for neutrino oscillation using accelerators. Before I do, I would like to explain the two main classes of accelerator searches. There are two types of searches that can be undertaken at accelerators. There are both **appearance** and **disappearance** searches. The differences comes down to whether or not the neutrinos produced in the beam that is being used have enough energy to produce their associated lepton via a charged-current reaction. For example, if a muon neutrino has 2 GeV of energy, there is no problem to produce a muon when it interacts off of a nucleus. If, on the other hand, a muon neutrino has only 5 MeV of energy there isn’t enough energy available to produce a muon.

So, if we were to start with an electron neutrino which later oscillated into a muon neutrino, in the first case there would be no problem creating the muon and we could (for example) look for muons to appear from our electron beam. In the second case however, the charged current reaction couldn’t happen and the neutrinos will have seemed to have disappeared. It should be noted that in both of these cases the neutral current interactions are flavor blind. Examples of appearance analyses and experiments that I am presenting today include the Miniboone, T2K, Nu$
u$a and OPERA experiments. Examples of disappearance experiments include MINOS, K2K, and the Super-K atmospheric analysis.
3.1. MiniBooNE Results

In the beginning of this talk I pointed out that there appear to be three neutrinos and two mass differences. Until very recently however, there was a piece of evidence which challenged this picture. The LSND experiment had presented evidence of a third mass splitting [9] when they saw evidence for $\nu_e$ appearance from a muon beam coming from stopped pions. If this result was true it would mean either that there were more neutrinos than we knew about (which is hard to accommodate with other data) or that our “simple” picture of neutrino oscillation was too naive. So, a new experiment, MiniBooNE was build to test the same region of L/E as the LSND experiment but at a different baseline and energy so as to have difference systematic errors.

Approximately a year ago, the MiniBooNE collaboration reported it’s first results [10] reporting that there was no appearance signal where one would expect if the LSND result was correct in the model of “simple” two or three flavor oscillations. Puzzlingly however, an unexpected excess of data over Monte Carlo was seen in the lowest energy part of their sample below where the LSND signal was expected.

The collaboration spent this last year intensively studying this anomaly. They included more data in their search, included new backgrounds in their analysis, and re-evaluated the backgrounds they had already included. We saw those results for the first time in this meeting. The collaboration concluded that the excess was still significant. The results of their oscillation search remains unchanged, they still rule out the previous LSND results in a standard two flavor oscillation scenario but they cannot yet explain the low-energy excess.

The collaboration is undertaking some important (and impressive!) cross-checks now. First of all, we will hopefully soon see results from their anti-neutrino running which should shed light on whether this is a cross-section effect (and even more directly test the LSND result which was performed with anti-neutrinos). Secondly, and most impressively they are also looking at highly off-axis neutrinos from the NuMi neutrino beam used by the MINOS experiment. This beam is at a very different energy and baseline then their beam so if this effect is an oscillation effect it should appear at a different energy than what is being seen now.

3.2. MINOS Results

The MINOS collaboration uses the muon neutrino beam produced at the NuMi facility at Fermilab to shoot neutrinos over 700 km away to their detector in northern Minnesota. MINOS has now measured the $\Delta m^2_{23}$ parameter to approximately 5%, the best measurement on the parameter to date. They have also excluded decay and decoherence models at the 4-6 sigma level and ruled out oscillation into admixtures sterile states to a fraction of less than 68%. MINOS will continue to take data resulting in a further tightening on the measurement of $\Delta m^2_{23}$ along with a chance to measure $\theta_{13}$ through $\nu_e$ appearance if the value of the parameter is close to the current limit.

4. FUTURE ACCELERATOR OSCILLATION PROSPECTS

There are three accelerator based oscillation experiments that are either starting or planning on starting soon. All three look for the appearance of a neutrino flavor that was not in the original beam.

4.0.1. OPERA

The first of these experiments is the OPERA experiment which has already begun operation. The OPERA experiment aims to see the direct appearance of tau neutrinos in a beam of muon neutrinos produced over 700 km away at CERN. They hope to do this by looking for the tell-tale kink of the tau decay in a emulsion block.

OPERA is a hybrid electronic/emulsion detector. Electronic trackers including drift chambers point tracks back to emulsion blocks which are removed by robots and scanned by a network of automatic scanning stations. After 1.5 years, the installation of the blocks is now complete. Depending on the exact value of the atmospheric mixing parameter the experiment expects to measure on the order of 10 events on a background of less than 1 event after 5
years of running. The full beam is expected in 2009 and the experiment is on track to see their first tau interaction next year.

4.0.2. T2K

The T2K experiment is one of two new so-called “off-axis” experiments. Unlike K2K and then MINOS, the neutrino beam is aimed a few degrees away from the far detector. By aiming the beam off-axis the far detector sees fewer total neutrinos but a sharper narrow band beam with more neutrinos at the energy of interest. Due to the kinematics of pion decay, most of the neutrinos at a particular angle from the beam direction give the same neutrino energy. This allows the experiments to probe neutrino appearance and disappearance at the particular energy that is predicted by the oscillation model.

The main goal of the T2K experiment is to observe the appearance of $\nu_e$ in a almost pure $\nu_\mu$ beam after traveling the 295 km between the JPARC accelerator center and the Super-K detector. Detection of electron appearance would allow a measurement of the unknown $\theta_{13}$ mixing angle. The expected sensitivity is ten to twenty times better than the current limit from the CHOOZ experiment \[11\]. Additionally, the T2K experiment hopes to measure the two atmospheric mixing parameters $\Delta m_{23}^2$ and $\theta_{23}$ to a few percent accuracy hopefully determining whether or not the atmospheric mixing angle is maximal.

T2K employs both on-axis and off-axis near detectors located 280 m from the neutrino source along with the Super-Kamiokande detector 295 km away. The off-axis near detector uses the refurbished UA1 magnet along with FGDs, TPCs, and a water/scintillator detector for measuring the neutrino interactions before the neutrinos have a chance to oscillate.

The T2K neutrino beam will start in April of 2009 and the on-axis detectors along with Super-K will be operational at that time. In the fall of 2009 the off-axis detector will be installed and full running will begin in the winter.

4.0.3. Nova

The Nova experiment is also an off-axis experiment optimized for the search for $\nu_e$ appearance. Nova will make use of a 700 kW upgraded version of the already existing NuMi beam-line. The detector will be located over 700 km away in northern Minnesota at Ash River near the Canadian border.

The Nova far detector is a 15 kton totally active liquid scintillator detector. It, and its matching off-axis near detector, function as a low-Z calorimeter allowing time for electromagnetic showers to develop over a long distance to help distinguish showers initiated by electrons or pizero decays. Nova is unique in the current generation of long-baseline experiments in that its 700 km long baseline will allow it to address question of the mass hierarchy if the value of $\theta_{13}$ is large enough. It will be do this by comparing the $\nu_\mu$ to $\nu_e$ oscillation probability for both neutrino and anti-neutrino beams.

The Nova collaboration plans to start construction of their far detector in April of 2009, with the first 2.5 kton of data taking in August of 2012. The detector should be complete in January of 2014. Like T2K it has an expected sensitivity to $\theta_{13}$ of 10 to 20 times lower than the present limit.

5. $\theta_{13}$ AT REACTORS

There is another complimentary way to measure $\theta_{13}$ by using neutrinos from reactors. Unlike the accelerator based experiments, these are disappearance experiments and use the same inverse beta decay capture reaction as used by the Kamland experiment. Neutrinos from a powerful reactor are measured just a few kilometers away from the cores and monitored for a distortion in the energy spectrum. This technique is complimentary to the accelerator experiments since they are measuring slightly different things. Unlike the long baseline appearance probability the disappearance probability has no dependence on the atmospheric mixing angle or CP violating phase. In the first few kilometers from the reactor core the disappearance probability is given by:
\[ P(\bar{\nu}_e \rightarrow x) \approx \sin^2 \theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right). \]  

(6)

This is the technique that was by the CHOOZ collaboration \cite{11} when it set the current best limit on the \( \theta_{13} \) parameter. Several collaborations hope to redo this measurement with a much tighter control of the systematic errors, allowing them to achieve substantially lower sensitivity than before. Current and planned experiments include the Double CHOOZ experiment in France (8.7 GW reactor), Daya Bay in China (11.6 GW), Reno in Korea (17.3 GW) and Angra (6 GW) in Brazil.

5.0.4. Double CHOOZ

In order to achieve a much lower sensitivity than the previous version of the experiment, the Double CHOOZ experiment will reuse the previous CHOOZ site 1051 m from the reactor core but add a second site 300m from the reactor core. By using two identical detectors the first detector will be used to normalize the results in the farther detector much as in the accelerator experiments.

The key to these new class of reactor experiments is to rely on relative measurements. By also building more robust veto and calibration systems they can lower the expected backgrounds. They hope to decrease the statistical error on the experiment from 2.7% in CHOOZ to be .5% in the new configuration.

The far lab is being built now and they plan to have the far detector running in early 2009. The near detector lab construction should begin in late 2008 with assembly of the near lab completed in late 2009. After approximately 1.5 years of running the Double CHOOZ experiment should achieve a sensitivity on \( \sin^2 2\theta_{13} \) of approximately 0.6. Then, the near detector should become operational reaching a sensitivity of 0.03 after a few more years or running.

5.0.5. Daya Bay

The Daya Bay collaboration has the impressive goal of measuring \( \sin^2 2\theta_{13} \) to the 0.01 level, similar to the accelerator based experiments. In order to achieve this difficult task they need to keep both the statistical and systematic errors very low. To achieve this they are taking a multi-prong approach.

First off, they are optimizing the distance of their detectors to maximize the oscillation signal and they are placing the detectors as deep as possible to try to reduce cosmogenic backgrounds. To further reduce backgrounds they are making a multi-level comprehensive veto. They will leverage their high power reactor with a large detector mass spread over multiple near and far detectors. They plan for 160 tons of target distributed in 8 detectors and may swap detectors between the positions.

The surface building assembly began in summer of 2008 and they expect data running in all eight detectors in three halls by December 2010. If all goes according to plan they will reach a sensitivity of 0.01 in 2013 or 2014.

6. DIRECT MASS MEASUREMENTS

All of my talk up-to-now has been concerned with oscillation studies. These studies probe the mass splittings and mixing angles but tell us nothing about the absolute mass scale of neutrinos. Along with cosmological techniques, which I will not cover here, there are two main techniques for studying the absolute neutrino mass.

6.1. KATRIN

The first technique is the direct measurement of kinematic parameters in beta decays. This is an old idea and the two experiments which have the best current limits on the absolute mass of the neutrino (Mainz \cite{12} and Troisk \cite{13}) have come together to form a new collaboration known as Katrin.

In direct mass experiments, a radioactive beta source such as \(^3\)He is used and the energy spectrum of the outgoing electron is examined. If the neutrino has mass, then the end point of the spectrum will be distorted.
limits are on the order of 2 eV and Katrin hopes to push them to 0.2 eV. In order to be sensitive to distortions in the end point in the last eV you need both very high statistics and good energy resolution.

High statistics are necessary because only $2 \times 10^{-13}$ of all decays take place in the last 1 eV. So, in order to measure this shape you need a huge number of decays. Energy resolution is important because the small distortion in the end-point energy will be washed out if the energy resolution is not less than this difference. Katrin addresses these two issues with an impressive 70 m detector. A high intensity tritium source produces electrons which are transported first through a pre-spectrometer and then into a large volume spectrometer which acts as a high-pass filter with an adjustable threshold. The electrons which pass through the spectrometer are then brought to impinge on a multi-pixel silicon semiconductor detector which has very high energy resolution and a very thin entrance window.

6.2. Double Beta Decay

There is another approach to measuring absolute neutrino mass that has the added advantage that it has the potential to also tell us something about the mass hierarchy and the Majorana nature of the neutrino. In some nuclei, normal beta-decay can’t happen because it is energetically disfavored. In these cases, it is still possible for two beta decays to happen simultaneously. This process is known as double beta-decay and happens at a much lower rate then normal beta-decay. When double beta-decay takes place two electrons and two neutrinos are emitted and if one looks at the sum the energies of the electrons you get a beta-decay like spectrum.

If, however, neutrinos are their own anti-particles (Majorana particles) then something special can happen. The two neutrinos can annihilate with each-other in a process known as neutrinoless double beta-decay (as opposed to the normal neutrinofull double beta-decay. When this happens the kinematics of the outgoing particles are constrained and the sum of the two electron energies is no longer continuous but rather monochromatic. In order to see neutrinoless double beta-decay one must find the monochromatic line at the end of the continuous neutrino full double beta-decay spectrum.

If this process can be measured, it tells you a lot. First of all, it tells you that neutrinos are Majorana, that they are their own anti-particles. This has very serious implications for models of neutrino mass generation. Secondly, it tells you about the absolute mass of the neutrinos. What you actually measure in double beta-decay is a rate of the double beta-decay process. This rate is proportional to three important quantities: a phase space factor, a nuclear matrix element, and the effective mass. The effective mass can be written as:

$$< m_{\beta\beta} > = |\Sigma_i U_{ei}^2 m_i|.$$  \hspace{1cm} (7)

Where the $U_{ij}$ are the elements of the mixing matrix in Equation 1 and include two diagonal Majorana phases. The electron coupling is mostly to the first two mass states and so the hierarchy is extremely important. In an inverted hierarchy the first two mass states have a minimum mass of the atmospheric neutrino splitting while in the normal hierarchy the lowest mass state could have an absolute mass as low as zero. This is demonstrated in the following figure taken from [14] which shows the effective mass verses the minimum mass of the lowest mass state.

For the current and upcoming generation of experiments we can hope to probe the 10s to 100s of meV range of mass if we have an inverted hierarchy. If however, the hierarchy is normal we will have to wait for even larger experiments.

6.2.1. The relationship to accelerator experiments

Non-accelerator and accelerator based neutrino experiments are often thought of separately but there are very important connections between them. The case of the mass hierarchy is an important example. If neutrinoless double beta decay is seen in this next generation of experiments we will know that neutrinos are Majorana and that we are dealing with an inverted hierarchy. This in turn tell us we should expect to measure an inverted hierarchy in long-baseline experiments. If we didn’t, then there would be an important flaw in our theory. Conversely, if
we measure the normal hierarchy in our long-baseline experiments we should not expect to be able to measure neutrinoless double beta-decay in the near future.

What are we to think if absent evidence from long-baseline experiments we measure nothing in the upcoming round of double beta-decay experiments? It could mean several things: Neutrinos might be Dirac particles which would preclude the process from taking place, we might be dealing with a normal hierarchy, the mass might be just below our reach, or most depressingly, we might be unlucky enough that the Majorana phases have conspired to cancel out and reduce our expected rate to near zero.

6.3. Experimental Techniques

There are very many collaborations active in this field and many proposed experimental techniques. I will just touch on a few here that presented talks at this conference and serve as examples of some of the major classes of experiments.

6.3.1. Gerda/ Majorana

The Gerda and Majorana collaborations both use solid state germanium detectors. They are using enriched Ge-76 diodes which have excellent resolution. They are using somewhat different techniques, Gerda suspends bare Ge in a cryogenic bath, while Majorana uses a more traditional cryostat approach. The two collaborations are working together to characterize detectors and build common Monte Carlo tools. The Gerda collaboration plans on finishing construction of their phase-I experiment by spring of 2009.

6.3.2. EXO

The EXO experiment uses cryogenic liquid xenon and measures both the scintillation light and charge in a TPC. The gas is easily repurified and recycled and heavy R&D is taking place for future extremely large volumes which would attempt to tag the remaining Ba daughter isotope so as to remove background. A 200 kg prototype has been installed in the WIPP underground facility and cool-down is expected to be complete in early 2009.
6.3.3. SNO+

The SNO+ experiment aims to build a very large self shielding mass of scintillator for the purposes of double beta-decay searches in addition to solar, reactor, geo and supernova neutrino studies. They hope to do this by refilling the old SNO vessel with scintillator. By doping the scintillator with $^{150}$Nd which has an endpoint energy above most known low energy backgrounds, they hope to fit the endpoint spectrum plus neutrinoless beta-decay signal. Now they are doing R&D to determine the best way to dope the scintillator and are working to fill the vessel soon.

7. SUMMARY AND FUTURE

I hope this talk has given you an overview of the experimental neutrino picture. Putting all of the information together, the following two figures taken from [8] and prepared by E. Kearns respectively show the current state of the art for measuring the solar and atmospheric oscillation parameters.

![Figure 5: The solar mixing parameters as measured by the Kamland and and solar neutrino experiments. This figure taken from [8].](image)

We now have a consistent set of experiments with measurements at the 2 - 10% level. The best measurements of $\Delta m^2_{12}$ come from Kamland, on $\theta_{12}$ from the solar experiments, on $\Delta m^2_{23}$ from MINOS and on $\theta_{23}$ from Super-K. They all point to the same places in parameter space. The new results from Borexino and MiniBoone further cement our understanding of the situation.

The next set of experiments will hopefully get us close to the 1% level in accuracy. The period of precision neutrino experiments has begun. We also hope to add info on absolute mass of the neutrino to the picture along with the nature of the mass pattern and whether the neutrino is a Dirac or Majorana particle. All of the experiments I mentioned above must be considered together for a complete understanding of the situation.
7.1. Future Facilities

It is also worth spending a moment to discuss even farther future ideas and plans. Many groups in the US, EU and Asia are thinking about how to measure the CP violating phase $\delta$ if $\theta_{13}$ is seen in the next generation of experiments. The technique for measuring $\delta$ is to compare the rate of neutrino and anti-neutrino oscillation. Unfortunately, it turns out that this measurement will only give measurable results of $\theta_{13}$ is large enough, which is why the next generation of long-baseline experiments are so critical to this question.

There is more than one approach to producing the neutrino and anti-neutrino beams used in these studies. First of all, there are the so called “super-beams”. These are more powerful versions of the conventional pion decay based beams we are utilizing in long-baseline experiments now. Next there are beta-beams. These beams of very pure electron neutrino or anti-neutrino beams are made by allowing accelerated radioactive ions to decay in a storage ring. Finally, there are neutrino factories. In a neutrino factory muons are produced from pion decay, cooled, injected into a storage ring and allowed to decay in long straight sections.

When possible, future facilities should be incorporated into a larger program of particle physics. A nice example of this idea is the proposed Project-X facility at Fermilab. Project-X is a super-beam which would send a very high intensity conventional neutrino beam to the proposed Deep Underground Science and Engineering Laboratory in South Dakota. This facility would also provide a high intensity muon source for other lepton physics and could be the first stage of a future neutrino factory or muon collider.

Finally, I want to mention that there is a large world-wide R&D program taking place on future large detectors to serve as targets for these beams. The work now is on designing extremely large water Cherenkov and liquid argon detectors.

7.2. Things I skipped

In covering such a large field there are many items I regrettably had to skip in this talk. I have prepared backup information for some of them which you can find in my slides. In this conference we heard about future experimental
atmospheric neutrino prospects from the INO experiment in India which will utilize RPCs and a magnetic field to measure first atmospheric neutrinos, and then hopefully neutrinos from a neutrino factory.

We also had nice reviews and results on both hadron production experiments and neutrino interactions. Both of these topics are vital to understanding precision neutrino oscillation results from long-baseline experiments. Finally, we heard nice results on low energy scattering experiments and saw a beautiful set of measurements on normal two neutrino beta decay from the NEMO-III experiment along with their plans for the Super-Nemo facility.

There is a large list of other topics which I might have covered if I had time and I would have particularly liked to have said something about supernova and how the neutrinos measured on Earth from one could tell us about particle physics and neutrino properties in addition to astrophysics.

8. CONCLUSIONS

The last ten years have seen the discovery of neutrino mass, the solution to the solar neutrino problem and the start of precision neutrino measurements. So far, everything fits together well. If we are lucky, in the next decade we will measure the remaining mixing angle, learn the nature and absolute mass of the neutrino along with its mass pattern. This information coupled with new knowledge gained at the LHC will let us plan our next steps.

What I outlined above is an ambitious program that will take many groups working in concert over many years to achieve. Preparing for this talk let me see that there are indeed large numbers of excited people working on these problems. Because of this I am quite hopeful that the person who is lucky enough to talk to you ten years from now will have as many good results to report to you as I did today.

On this note I’d like to close with the end of a poem written by B. Nolty and K. Scholberg from our days together as graduate students on the MACRO experiment:

“So gladly we march to mines, tunnels or seas:
New physics or not, we get PhDs –
Condensed to a preprint we’ll mail to our mothers
Of one page of physics (two pages of authors).

(Full text at http://www.cithep.caltech.edu/macro/songs/sad.html)

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