Eur Phys J C **33**, s01, s43–s50 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-03-1693-8

EPJ C direct
electronic only

Neutrino experiments

K.T. Lesko[a]

Institute for Nuclear and Particle Astrophysics, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Received: 13 January 2004 / Accepted: 4 February 2004 /

Abstract. This review examines a wide variety of experiments investigating neutrino interactions and neutrino properties from a variety of neutrino sources. We have witnessed remarkable progress in the past two years in settling long standing problems in neutrino physics and uncovering the first evidence for physics beyond the Standard Model in nearly 30 years. This manuscript briefly reviews this recent progress in the field of neutrino physics and highlights several significant experimental arenas and topics for the coming decade of particular interest. These highlighted experiments include the precision determination of oscillation parameters including θ_{13}, θ_{12}, Δm_{12}^2 and Δm_{23}^2 as well as a number of fundamental properties are likely to be probed included nature of the neutrino (Majorana versus Dirac), the number of neutrino families and the neutrino's absolute mass.

PACS. 14.60.Pq Neutrino mass and mixing – 26.65.+t Solar neutrinos – 95.85.Ry Neutrino, muon, pion, and other elementary particles; cosmic rays – 23.40.Bw Weak-interaction and lepton (including neutrino) aspects of beta decay – 13.15.+g Neutrino interactions – 14.60.St Non-standard-model neutrinos, right-handed neutrinos, etc. – 14.60.Lm Ordinary neutrinos (nue, numu, nutau) – 95.55.Vj Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors

1 Introduction

There as been tremendous progress in the past two years in our understanding of neutrino properties and interactions. It will be challenging to adequately incorporate all of the experimental results and interpretations into a single review. Fortunately many of the details describing these important developments are included elsewhere within this journal in the contributed papers. These contain many more of the experimental details and thorough discussions of the analyses. This paper serves as broad-brush overview of the recent neutrino experiments and a roadmap for the most interesting (and sometimes the most challenging) experiments in the coming decade.

For the past thirty years there has been intriguing hints that neutrinos were not correctly described in the Standard Model. A variety of experiments using accelerator, solar, and atmospheric neutrinos indicated that fewer neutrinos were detected than would have been expected from knowledge of the source. These "disappearance" experiments gained in statistical and systematic significance as the experiments matured and as there appeared multiple experiments discovering consist neutrino suppression from the same neutrino sources. During the same period the neutrino source models have significantly advanced, matured, and became truly robust. Increasingly, it appeared that neutrino flavor oscillations was the most straightforward method to explain this collection of experiments. In this decade we have witnessed a handful of experiments that have effectively answered this three decade old problem, convincingly demonstrated that neutrinos are massive, and that neutrino undergo flavor transformations. Rapidly the field is advancing from the discovery phase into precision determination of neutrino oscillation parameters. However, despite this progress there are still fundamental neutrino properties that are only poorly known or completely undetermined. These little-known properties and parameters present the physics community with great opportunities to continue the quest to finally understand the neutrino.

Neutrino experiments are typically discussed and group-ed based on the source of the neutrinos. Thus we have the classifications of experiments that primarily concentrate on neutrino oscillations from:

- solar neutrinos,
- atmospheric neutrinos,
- reactor neutrinos,
  and
- accelerator neutrinos.

Complementing these oscillation experiments there are several experiments that probe aspects of neutrinos relating to the absolute mass of a neutrino and whether the neutrino is a Dirac or Majorana particle. We will next examine the progress in all these areas.

---

[a] This work supported by the U.S. Department of Energy under Contract DE-AC03-76SF00098.

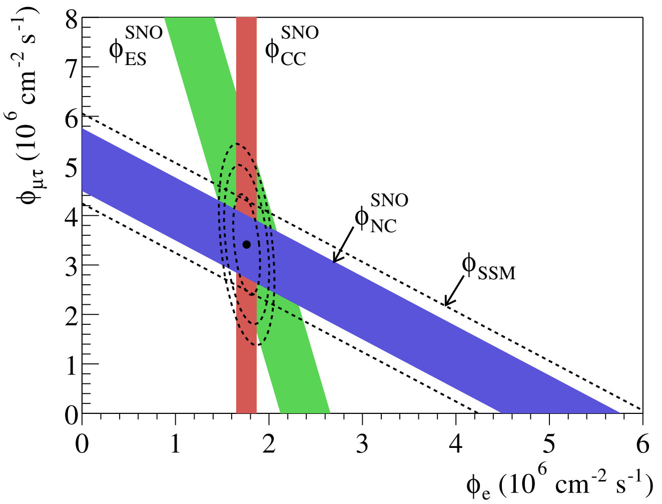

Fig. 1. Flux of solar ν_μ or ν_τ *vs.* flux of ν_e deduced from the three neutrino reactions in SNO. The *diagonal bands* show the total ^{8}B flux as predicted by the Standard Solar Model [11] (*dashed lines*) and that measured with the NC reaction (*solid band*). The intercepts of these bands with the axes represent the $\pm 1\sigma$ errors. The bands intersect at the fit values for ϕ_e and $\phi_{\mu\tau}$, indicating that the combined flux results are consistent with flavor transformation

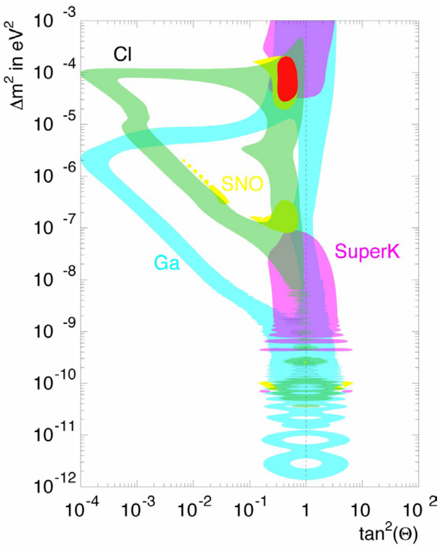

Fig. 2. A global analysis of the solar neutrino experiments presented in the text. Only the LMA solution remains as a viable solution to this group of experiments. This figure is courtesy of H. Murayama.

2 Solar neutrino and recent reactor neutrinos experiments

The most dramatic progress in understanding neutrinos and neutrino oscillations occurred in the field of solar neutrinos. The Sun is a prodigious source of electron-neutrinos, ν_e, a by-product of the nuclear fusion reactions in the core of the Sun. The description of these reactions and experiments to detect them have developed remarkable since it was first proposed in 1963 [1] [2] that these neutrinos could be used to probe the nuclear origins of solar energy into a thorough model of several complex nuclear reaction chains. The Standard Solar Model describes the nuclear reactions and the matter and thermal distributions within the Sun. In the decade following these proposals and as solar models were being developed, the Solar Neutrino Problem was formulated as experiments found significantly lower than predicted fluxes of neutrinos.

2.1 The sudbury neutrino observatory

This thirty-year-old dilemma was recently and convincingly solved by the Sudbury Neutrino Observatory (SNO) [3] [4]. SNO is a 1 kilotonne heavy water, D_2O, Čerenkov detector located $\sim$ 2-km underground in Sudbury Ontario Canada in INCO's Creighton mine. SNO's measurement of the total neutrino flux, independent of flavor, and of the electron-neutrino flux, with the use of Charged Current (CC), Neutral Current (NC), and Elastic Scattering (ES) reactions produced very strong evidence, in an appearance experiment, of neutrino flavor transformation. When combined with the other experiments comprising the Solar Neutrino Problem – the radio-chemical experiments Homestake Chlorine experiment [5], SAGE [6] and Gallex [7] (and GNO [8]), and the water Čerenkov experiments Kamiokande [9] and Super-Kamiokande [10] – the neutrino oscillation parameter space is now restricted to a single region, the Large Mixing Angle (LMA) solution. This solution invokes matter enhanced neutrino oscillations (the MSW mechanism). Thus, SNO has observed flavor transformation as the electron-neutrinos created in the solar core transform into other flavors. These results are presented in Fig. 1.

From the global analyses of these seven experiments we can draw even more conclusions about neutrino oscillations. The LMA solution significantly favors non-maximal mixing of neutrino flavors; that the ordering of the massive neutrino eigenstates is normal, $m_{\nu_1} < m_{\nu_2}$, and there is no “dark side” [12]; there there is now strong support for matter affects in the Sun to explain the magnitude of the electron-neutrino suppression. Directly comparing the total neutrino flux to solar model predictions improved limits were also obtained for sterile neutrinos and even some proton-decay channels. A global analysis of the solar neutrino experiments is presented in Fig. 2.

2.2 KamLAND

Within a few months of SNO's first NC publication, KamLAND's first publication was released [13]. KamLAND is a $\sim$ 1 kilotonne liquid scintillator detector located in the cavity that formerly sited the Kamiokande experiment. Using Japan's nuclear power reactors with a flux-weighted mean distance of $\sim$ 180 km, the KamLAND collaboration reported a suppression of reactor neutrinos in good agreement wtih and uniquely determined by the LMA solution of the solar neutrino problem. Assuming CPT conservation, this is good evidence, making use of an entirely dif-

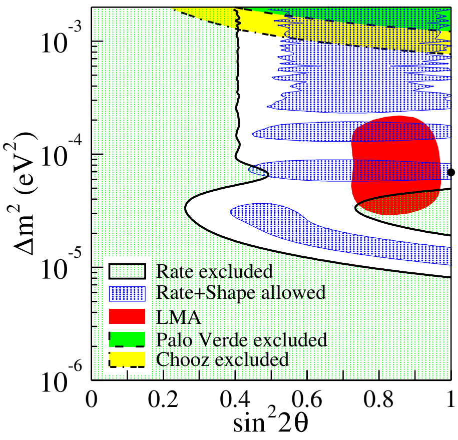

Fig. 3. Excluded regions of neutrino oscillation parameters for the rate analysis and allowed regions for the combined rate and shape analysis from KamLAND at 95% C.L.The 95% C.L. allowed region of the Large Mixing Angle solution of solar neutrino experiments is shown. The *thick dot* indicates the best fit to the KamLAND data in the physical region: $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 6.9 \times 10^{-5}\text{eV}^2$. All regions look identical under $\theta \leftrightarrow (\pi/2 - \theta)$ except for the solar neutrino experiment determined LMA region

ferent source of neutrinos and with a well characterized source and spectrum of neutrinos, that the Solar Neutrino Problem is answered by neutrino flavor oscillations and with LMA parameters (Δm$^2 \sim 0.7$ x 10^{-5} , $\sin^2(2\theta) \sim 0.8$). An analysis of the reactor spectrum in addition to the flux rate bifurcates the LMA solution into two regions a higher mass region, LMA2 and a lower mass region LMA1. The results of the solar experiments and KamLAND are presented in Fig. 3

2.3 Future experiments and improvements in solar and reactor experiments

In the near term we anticipate significant improvements in the determination of the LMA parameters and some hope for the observation of an oscillation pattern. SNO has nearly completed its analysis of its enhanced NC mode, using 2 tonnes of NaCl dissolved in the D_2O to improve its NC sensitivity. With improved NC and CC flux measurements this will further refine the mixing angles. Following this measurement SNO plans include the deployment of an array of ^{3}He counters to complement the NaCl measurement with a method with very different systematics and further improved sensitivity. In addition observation by SNO of spectral distortions or day/night affects (matter affects due to the earth) would be important confirmations of the MSW hypothesis. While with increased statistics and improved systematics KamLAND may be able to significantly better define Δm^2 if Δm^2 is below $\sim$ 1 x 10^{-4} eV^2. So we see that solar neutrinos has rapidly evolved from discovery mode to precision determination of oscillation parameters.

Longer term efforts are aimed at lower energy solar neutrinos, primarily ^{7}Be and p-p neutrinos. The ^{7}Be flux is known to approximately 7-10% dominated by solar model uncertainties, but the observation of these neutrinos would provide valuable confirmation of solar physics and a slight increase in the precision of the determination of the mixing angle. Several liquid scintillator experiments are aimed at the ^{7}Be flux, the conversion of KamLAND and Borexino being constructed in Gran Sasso. The primary flux of solar neutrinos, the p-p neutrinos, is known with 1 - 2% precision. This higher degree of certainty in flux and their lower energy open a wider pallet of physics, which includes 1) an improvement of θ_{12} by a factor of 2 to 3 and the associated precision inputs to The Maki, Nakagawa, Sakata, and Pontecorvo matrix (MNSP) that describes the mixing of neutrino flavors, 2) tests of the unitary of the MNSP matrix and in reducing covariances in future experiments such as long baseline measurements of θ_{13}, 3) tests for sterile neutrinos, 4) searches for neutrino magnetic moments, and 5) probes of fundamental solar physics. These future experiments are faced with even more challenging reduction of the radioactive background species including ^{85}Kr, ^{210}Pb, ^{210}Bi and radon.

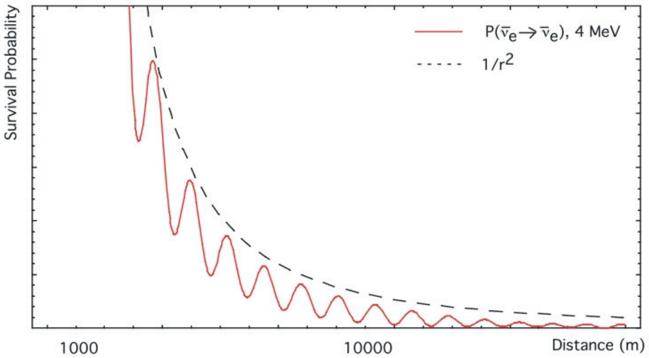

Fig. 4. Subdominate oscillation patterns characteristic of θ_{13} terms superimposed on the dominate θ_{12} neutrino suppression. Figure courtesy of K. Heeger

For the longer term nuclear power reactors provide a promising source of neutrinos to probe the last unknown element of the MNSP matrix, θ_{13}. By probing for subdominate oscillation patterns superimposed on the primary oscillations, it may be possible to measure θ_{13}. This determination would provide valuable and complementary information to future accelerator neutrino measurements and important removal of parameter degeneracies faced by the accelerator sources. If the systematics of the measurements can be controlled to the 0.5 - 1 % level then it may be possible to improve our limits (or measure) θ_{13} by 1 to 1.5 orders of magnitude. The experiment signature for such a long baseline, high precision reactor experiment is presented in Fig. 4.

3 Atmospheric neutrino experiments

High energy cosmic rays striking the earth's atmosphere produce pions and muons. These particles subsequent decay producing electron- and muon-neutrinos with energies extending into GeV. By observing neutrinos coming from around the earth a variety of different path lengths can be examined. These path lengths are directly mapped into zenith angle distributions for the neutrinos in detectors. A number of experiments have examined atmospheric neutrinos over the past decade, including Kamiokande, Super-Kamiokande, MACRO, Soudan, IMB, and others.

3.1 MACRO

The MACRO detector, decommissioned several years ago was a composite detector (streamer tubes, nuclear track detectors, liquid scintillator and rock absorber). The detector was sited in Gran Sasso Underground Laboratory. The collaboration recently reanalyzed their through-going muon data. They improved their analysis by estimating the event energy using multiple Coulomb scattering in the detector. Combining these data with their existing angular distribution analyses they find a suppression of atmospheric neutrinos consistent with neutrino oscillations ($\nu_\mu \rightarrow \nu_\tau$) with maximal mixing and a preferred $\Delta\mathrm{m}^2$ of 0.0023 at a level of greater than 5 σ.

3.2 Super-Kamiokande

Super-Kamiokande is a massive water Čerenkov detector (23 kilotonne fiducial volume) located 2700 m.w.e. underground in Mt Ikenoyama Japan. They reported a new analysis of 1489 days of data from Super-K I. This analysis probes neumu to neutau oscillations and used fully contained and partially contained events, upward going muons, and multi-ring events. The collaboration has updated their Monte Carlo simulations of their detector, improved their fitters and data reduction algorithms and coupled this to their new atmospheric neutrino flux calculations. The best fit to their data is for a neutrino oscillation hypothesis with maximal mixing and $\Delta\mathrm{m}^2$ - 2.0 x 10^{-3} eV^2. Their data favor ν_μ to ν_τ oscillations over ν_μ to ν_e. And there is not hint for electron neutrino appearance in their data. Importantly for many proposed or experiments being developed this favored solution is slightly lower in $\Delta\mathrm{m}^2$ than previous solutions. While being statistically consistent with earlier analyses, this lower value reduces τ appear signals for several experiments. Super-K's results presented at this conference are presented in Fig. 5.

4 Accelerator and long baseline neutrino experiments

The fourth source of neutrinos used for oscillation experiments are man-made neutrinos from accelerators. The third experiment reporting evidence for neutrino oscillations was LSND a liquid scintillator detector at LAMPF at Los Alamos National Laboratory. These results are difficult to reconcile with highly significant oscillations signatures from solar and atmospheric neutrino experiments and the three known species of light neutrinos, which are also indicated by LEP and SLC measurements of the decay of the Z-boson. The three neutrinos introduce two separate differences in neutrino masses. LSND apparently found a third, higher $\Delta\mathrm{m}^2$ than solar and atmospheric neutrinos. This has lead to the conjecture that the LSND signal involves sterile neutrinos, that is neutrinos that do not couple to matter in the same fashion as the other three neutrino species.

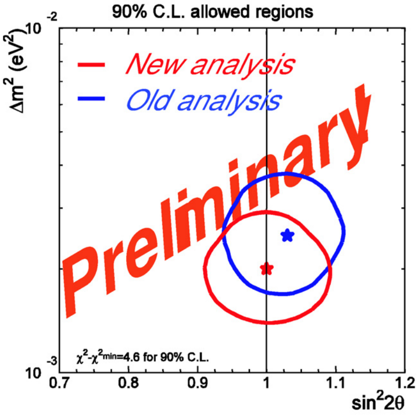

Fig. 5. Revised analysis of Super-K's 1489 day data set including fully contained and partially contained events, upward going muons, and multi-ring events. Improving the Monte Carlo simulations, event reconstruction and using updated flux calculations resulted in a slight lowering of the preferred value for $\Delta\mathrm{m}^2$ that is consistent with early determinations but affects a number of experiments probing this region of parameter space

4.1 MiniBooNE

To examine this solution and produce a convincing rebuttal or confirmation the MiniBooNE experiment at Fermi Lab is probing the ν_μ to $\nu_{sterile}$ to ν_e signal championed by the LSND collaboration to explain their results. MiniBooNE is a oil-based dual mode (scintillating and Čerenkov) liquid detector. The detector was recently completed and commissioned and is collecting data. They are pursuing a blind analysis of their data and should have a statistically adequate sample to report results in 2005.

4.2 K2K

The K2K experiment combines an accelerator source of neutrinos from KEK directed at the Super-K detector. The experiment is aimed at probing the same region of parameter space indicated by the atmospheric neutrino experiments, including Super-K. The collaboration reported improvements to the near detector used to analyze the momentum and angular distributions of the beam. These upgrades include the replacement of the Pb-glass calorimeter with SciBar elements to improve tracking and energy response and to provide better particle identification. The SciBars also have enabled studies of low energy neutrino interactions. The K2K collaboration presented an updated analysis excludes the null hypothesis (no oscillations) to

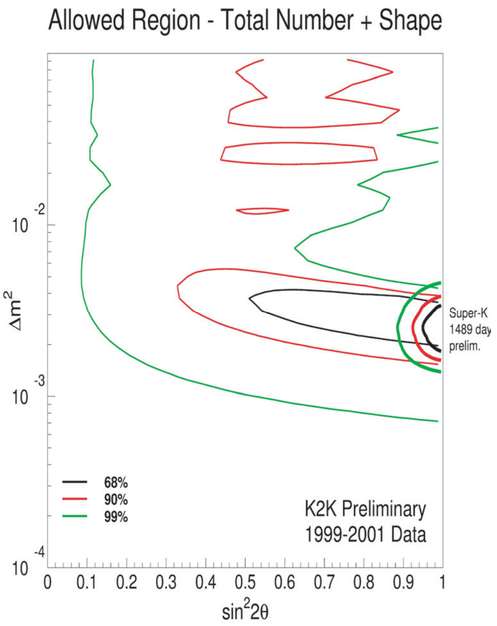

Fig. 6. The recent K2K analysis overlayed with Super-K atmospheric neutrino analysis both reported at this conference

be less than 1% best fit at maximal mixing 1.5 - 3.9 x 10^{-3} eV^2 consistent with atmospheric neutrino experiments. These results are presented in Fig. 6.

4.3 ICARUS, OPERA, and CNGS

In the near term a program of beams and detectors is being developed in Europe. CERN will be a source of high energy neutrinos and several detectors will be sited underground at Gran Sasso (732 km baseline). These experiments will principally probe for tau-neutrino appearance from the accelerator neutrino beams. The recent best fit Δm^2 solutions from Super-K present rate challenges to these appearance experiments as the rates of τ appearance may be significantly reduced.

The ICARUS experiment is a liquid argon imaging Time Projection Chamber. Using a beam from CERN, the CNGS program, ICARUS will seek τ appearances in the TPC. They have successfully operated a 300T module and plan on having 600 tonnes at Gran Sasso by the end of 2003. By 2006 they plan on installing two additional 1200 tonne modules. This mass will produce tens of events. In addition to neutrino oscillations, they plan simultaneous programs in solar, atmospheric neutrino experiments and nucleon decay searches.

Also planning on using the CGNS beams in 2006 is OPERA. This is a hybrid emulsion experiment, again seeking tau appearance in the beam. OPERA is building on extensive previous experience with emulsions from the DO-NUT experiment to produce a reliable and robust detector.

4.4 NuMI-MINOS

In the US the NuMI-MINOS program is being developed at FermiLAB with detectors sited at Soudan (750 km baseline) and ultimately other sites are being considered for additional measurements. Again this program is aimed at testing solutions of atmospheric neutrinos anomaly with accelerator beams. If $\Delta m^2_{23} \leq 2$ x 10^{-3} the steel and scintillator detector in the Soudan Underground Laboratory will detect an oscillation dip and can determine Δm^2_{23} to $\sim$ 1 x 10^{-3} eV^2, but will have little affect on the determination of $\sin^2(2\theta_{23})$. There is the possibility of τ appearance, but again Super-K's recent results make this experiment more challenging. The detector has been completed and is undergoing cosmic ray calibration. the beam will be commissioned through December 2004. The near detector plans are completed and they anticipate the start of physics in 2005 with a five year run planned.

4.5 Future facilities

In Japan J-PARC-Kamioka program proposes to generate a neutrino beam using the J-PARC facility at Jaeri. This accelerator will initially be a source of 1 GeV ν_μ from 0.75 MW 50 GeV PS (10^{12} ppp, 0.275 hz,). Ultimately this accelerator will be upgraded to 4MW at 50 GeV. Construction is scheduled for Japanese fiscal years 2001 through 2006.

The first phase of the program will use Super-K as the detector and promises roughly 100 times the statistics as the K2K experiment. It will probe neutrino oscillations with two channels: 1) μ to x disappearance and should resolve $\delta \sin^2(\theta) \sim 0.01$ and Δm^2 to 1 x 10^{-4} in 5 years and 2) μ to e appearance with approximately a 20 times improvement over existing reactor experiments determining $\sin^2(2\theta_{13})$ at 90 % C.L. to 0.006. They will include a neutral current measurement as well. In the second phase with the increased neutrino flux and a significantly larger detector they will pursue CP violation measurements and nucleon decay studies.

The NuMI off-axis proposal includes the development of a new detector to make use of existing neutrino beam. Off-axis positioning of the detector produces a kinematically focused beam of neutrinos with an energy of $\sim$ 2 GeV. This energy is below the τ production threshold and produces relatively high rates per proton especially for antineutrinos. Baselines of 700 to 1000 km are being investigated. Thus, matter affects are anticipated to amplify mass hierarchy sensitivity. Phase I, 2008-2014, will make use of 4 x 10^{20} Protons On Target/year coupled to a 50 kton fiducial detector running a proposed 1.5 year neutrinos and 5 years anti-neutrinos. Phase II, 2014-2020, would increase the POT by a factor of 25 and will run a similar length of time in neutrino and antineutrino modes as phase I. When combined with JPARC-Super-K and NUMI on-axis data might reveal neutrino mixing parameters, masses and hierarchy, angles, CP phase.

As mentioned above the primary European focus combines several detectors at Gran Sasso using neutrino beams from CERN- the CNGS program. These beam are anticipated to begin in 2006. Future improvements in the beam include a possible 2 GeV 4MW H^- accelerator after 2010 with a run plan of 2 years of neutrinos, 10 years of anti-neutrinos coupled to a long baseline detector sited in Frejus (130-km baseline). The detector is being discussed as 400 kT water Čerenkov detector. This combination will measure $\sin^2(2\theta_{13})$ to 0.0025

Neutrino Factories are further in the future and are beyond the scope of this review. This omission is not meant to reflect on or diminish the critical neutrino physics that ultimately will require such neutrino facilities to fully probe neutrino properties.

5 Neutrinoless double beta decay

Double beta decay is one of the rarest decay modes known in nature. In its usual form it is a second order weak process with the conversion of two neutrons to two protons accompanied by two betas and two neutrinos. The final nucleus, removed by two nuclear charge units, must be more deeply bound than the initial nucleus and the intermediate nucleus (separated by a single nuclear charge), must be less bound than either the initial or the final nucleus. If the neutrino is Majorana in nature rather than Dirac (being its own antiparticle) it is possible the two betas to share the full decay energy with the emission of no neutrinos. In contrast to the neutrino oscillation experiments presented above, which measure the differences between mass eigenstates, neutrinoless double beta decay measures effective neutrino mass. A comprehensive review can be found in [14].

If the $\beta\beta(0\nu)$ decay is mediated by a light massive Majorana neutrino, the half-life for this decay is:

$$[T^{0\nu}_{1/2}(0^+ \rightarrow 0^+)]^{-1} = G^{0\nu}(E_0, Z)\left|M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2}M^{0\nu}_F\right|^2 \langle m_\nu\rangle^2, \tag{1}$$

where $G^{0\nu}$ is the exactly calculable phase space integral, $\langle m_\nu\rangle$ is the effective neutrino mass and $M^{0\nu}_{GT}$, $M^{0\nu}_F$ are the nuclear matrix elements, defined in

$$|M_{0\nu}| \equiv M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2}M^{0\nu}_F = \tag{2}$$

$$\langle f| \sum_{lk} H(r_{lk}, \bar{A})\tau_l^+\tau_k^+ \left(\sigma_l \cdot \sigma_k - \frac{g_V^2}{g_A^2}\right)|i\rangle\ . \tag{3}$$

In the usual sense any neutrino species (or flavor) can be expressed as a superposition of mass eigenstates as described by the MNSP matrix. For example, the electron neutrinos are superpositions,

$$\nu_e = \sum_i^N U_{ei}\nu_i\ , \tag{4}$$

and the rate of the $\beta\beta(0\nu)$ decay is proportional to the effective neutrino mass

$$\langle m_\nu\rangle^2 = \left|\sum_i^N U_{ei}^2 m_i\right|^2 = \left|\sum_i^N |U_{ei}|^2 e^{\alpha_i} m_i\right|^2, (\text{all} \quad m_i \geq 0). \tag{5}$$

This quantity depends, as indicated, on the $N-1$ Majorana phases $\alpha_i/2$ of the matrix U which are irrelevant in neutrino oscillation experiments that do not change the total lepton number.

There are several indicators and experiments that suggest that the next generation of neutrinoless double beta decay experiments are well positioned to access the neutrino mass range of interest. The neutrino oscillation experiments presented above indicate the difference in neutrino masses, however if we assume the lightest mass is small we can estimate the mass range of interest from the atmospheric neutrino experiments, $\mathrm{M}^2 \sim \Delta\mathrm{m}^2 \sim 2 \text{ x } 10^{-3}\ \mathrm{eV}^2$. While the solar neutrino experiments suggest $\mathrm{M}^2 \sim \Delta\mathrm{m}^2 \sim 7 \text{ x } 10^{-5}\ \mathrm{eV}^2$. The WMAP observations favor massive neutrinos of M $\sim$ 0.2 eV. Importantly, the solar neutrino experiments measure the mixing angle, θ_{12} to be less than maximal so there can not be accidental cancellation of solar neutrino phases.

To distinguish normal two neutrino from neutrino-less double beta decay in practice, energy resolution is critical experimental consideration in addition to the ubiquitous concerns over backgrounds and contamination. Some experiments are exploring additional experimental handles including imaging the charge and paths of the betas. So far there exist limits on this process (and one much discussed observation). In addition to the semi-conductor diode approach used for many years, new technologies are being approached including cryogenic calorimeters. Several new experiments are in final commissioning phases and there are a variety of proposals and collaborations forming to pursue this next frontier in neutrinos.

5.1 NEMO

The NEMO experiment is currently undergoing commissioning in the Frejus Underground Laboratory with 4800 m.w.e. over burden. Their target consists of 6.9 kg of enriched ^{100}Mo and they employ both event tracking and calorimetry. The tracking is provided by 6180 drift cells operating in Geiger mode with an external magnetic field. They obtain calorimetry information from 1940 plastic scintillators coupled to low activity PMTs. In addition there are extensive shields for magnetic fields, radon, neutrons and cosmic rays. After five years of operation they hope to reach $\mathrm{t}_{1/2} < 8 \text{ x } 10^{24}$ years or $\langle \mathrm{m}_\nu\rangle < 0.1$ to 0.4 eV for ^{100}Mo and $\langle \mathrm{m}_\nu\rangle < 0.6$ to 1.2 eV for ^{182}Se. The collaboration has plans for introducing a variety of double beta decay targets into NEMO to obtain multiple simultaneous measurements of nuclei such as ^{82}Se, ^{116}Cd, ^{130,nat}Te, ^{150}Nd, ^{96}Zr, and ^{48}Ca. They anticipate $\beta\beta(0\nu)$ results in 2004.

5.2 Cuoricino

The Cuoricino experiment is an innovative cryogenic experiment pursuing $\beta\beta(0\nu)$ physics. The initial detector, Cuoricino, consists of 42 kg of TeO detectors. The detectors are divided into 14 modules in each tower with four 760 g detectors in each module operating at a temperature of 50 mK. The decay energy contained in each module is detected by NTD Ge thermistors. Several modules with nine detectors are included to investigate surface contamination issues. After successful operation of the Cuoricino detector the collaboration plans upgrades and increasing detector mass by adding additional detector towers until a final mass of 760 kg is reached for the CUORE experiment. With the Cuoricino detector, assuming contamination can be controlled sensitivity of $\langle \mathrm{m}_\nu \rangle < 0.24$ to 0.4 eV may be obtained. This range of sensitivity would significantly overlap the claim by [15]. Assuming bulk and surface contamination are adequately controlled the final CUORE sensitivity for $\beta\beta(0\nu)$ would be $\langle \mathrm{m}_\nu \rangle < 37$ to 140 meV x $(\mathrm{T[y]})^{1/4}$, where T is the running time of the full experiment.

5.3 C0BRA

C0BRA is another innovative approach to double beta decay. Concentrating on double electron-capture nuclei rather than double beta decay the collaboration hopes to combine several interesting isotopes in a single detector. Pursuing room temperature semi-conductors, they are assembling CdTe (CdZeTe) detectors. Thus a single detector would permit multiple measurements of $^{(}106, 108)$Cd, ^{64}Zn, and ^{120}Te EC modes and ^{70}Zn, ^{116}Cd, and ^{130}Te double beta decay studies. The collaboration has installed prototype detectors in Gran Sasso (having established several world records for limits on EC decay modes), and are developing a proposal for a more ambitious detector. The proposal is planned for 2004.

5.4 Majorana and genius

Pursuing well developed semi-conductor technology and innovative shielding concepts there are two proposals to build large arrays of Ge detectors. The Majorana collaboration is developing a proposal to build an array of $\sim$ 500 kg of isotopically enriched ^{76}Ge detectors. These detectors would be highly segmented and mounted in ultra-low background cryostats in a deep underground laboratory. Sites at SNOLAB in Canada and possible National Underground Scientific and Engineering Laboratory in the U.S. are being investigated. The GENIUS proposal is also centered on $\sim$ 500 kg of enriched Ge, but would submerge the diodes in a large cryogenic bath to reduce external backgrounds. Both collaborations are forming and developing comprehensive proposals.

6 Tritium endpoint measurements

Precise measurements of beta-spectra permit, to date, the most accurate direct limits to be set on neutrino masses. In particular, tritium beta decay has provided the most accurate limits on ν_e. Experiments spanning nearly twenty years and using both magnetic and electrostatic spectrometers have reduced the limit on the mass of ν_e from $\sim$ 40 eV down to the current limit of $\sim$ 2 eV. Heroic efforts to overcome experimental difficulties, the development of a variety targets (frozen, gaseous atomic and molecular targets) and elegant spectrometer designs have made these advances possible. The Mainz experiment has collected tritium data from 1994 through 2001. Since 1998 they significantly improved their signal to background and eliminated or reduced many of their systematics. These improvements have eliminated the negative m^2 problems that plagued earlier experiments. A new analysis of the 1998/99 data plus the 2001 data looking specifically in the last 70 eV interval yield the following limits: $\mathrm{m}_\nu^2 = -0.7 \pm 2.2 \pm 2.1$ eV^2 and $\mathrm{m}_\nu \leq 2.3$ eV at 95% C.L. With this limit the intrinsic sensitivity limit of the Mainz spectrometer is reached.

A new collaboration based at Karlsruhe is developing a new experiment, KATRIN. The proposal includes a pre-spectrometer with a fixed retarding potential followed by transport solenoids and ending in a main spectrometer with variable retarding potentials. The pre-spectrometer would be 1.7 m in diameter and 3.5 m long with an energy acceptance of $\sim$ 70 eV. The main spectrometer would be 10 m in diameter and 22 m long with an energy acceptance of 1 eV. By using a stronger tritium source, longer experimental runs, improved energy resolution, and better experimental calibration the KATRIN collaboration hopes to improve the limit on m_ν from 2 eV to 0.2 eV with 5 σ discovery potential to $\mathrm{m}_\nu \leq 0.35$ eV^2. Funding proposals are current being advanced. Commissioning of the main spectrometer is anticipated in 2006 while the first measurements would begin in 2007.

7 Other neutrino properties

There are additional neutrino properties that are currently be addressed including fundamental quantities such as the magnetic moment of the neutrino. The Texono collaboration using the Kuo-Sheng reactor have recently derived direct experimental limits of $\mu_\nu < 1.3$ x $10^{-10}\mu_B$ at 90 % C.L.

8 Conclusions

As this review briefly presents, the progress in understanding neutrino properties has made tremendous advances in the past two years. The solar neutrino problem has been solved. We have very convincing evidence from SNO's appearance experiment that neutrinos undergo flavor transformations and are massive. While their mass is not enough to comprise the entire Dark Matter, neutrinos are the first confirmed source of this intriguing material in the universe. The solar neutrino experiments have converged on the Large Mixing Angle solution to matter enhanced oscillations – in contrast to the quark sector leptons appear to mix with at least two large angles. This

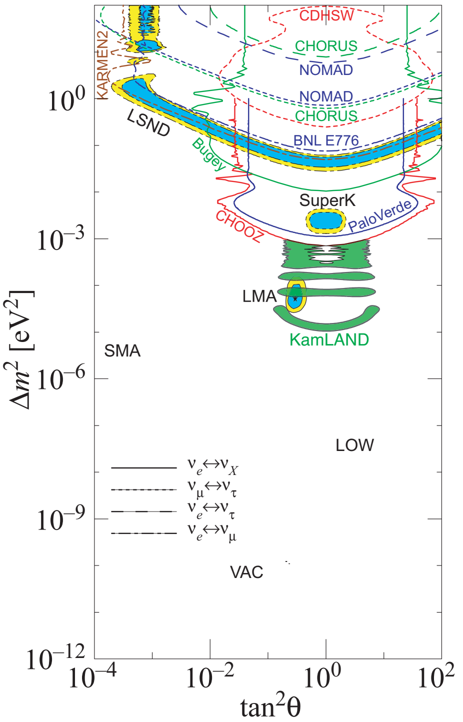

Fig. 7. This figure, courtesy of H. Murayama, indicates the different experimental signatures for neutrino oscillations: the solar and reactor neutrino region, atmospheric neutrino experiments and recent long base line accelerator experiments, and finally the LSND results. Limits for other oscillation modes are also presented. The region labeled LMA is the preferred region obtained by a global analysis of all solar radiochemical experiments, Super-K, and SNO

solution was confirmed by a reactor experiment, KamLAND, assuming CPT conservation. The evidence from atmospheric neutrinos and long base line experiments provide a consistent picture of oscillations between ν_μ and ν_τ with maximal mixing between these flavors. In the brief span of two years these experiments have advanced from the discovery phase in convincing demonstrating that neutrinos are massive and transform between species to the phase of precision determination of neutrino oscillation and mixing parameters. A global compilation of results of these oscillation experiments are illustrated in Fig. 7. This figure highlights the positive signatures for oscillations seen by the solar neutrino experiments and recently by a long baseline reactor experiment, the atmospheric neutrino anomaly recently confirmed by K2K, the LSND experiment, and a number of searches with different modes of oscillations that did not detected flavor transformations.

In spite of these rapid advances there remain fundamental questions about neutrinos, some of which near term experiments are well positioned to address.

– **Is θ_{13} finite? If so, what is its magnitude?**
  A number of proposals using long base line reactor experiments are being developed to address this in the near in parallel with longer term accelerator proposals. The reactor and accelerator experiments provide complementary information necessary to begin analyzing potential CP violation effects with leptons. Ultimately neutrino factories and intensive neutrino sources may be required to fully address the issue of CP violation with neutrinos.
– **Is the neutrino Dirac or Majorana in nature?**
  Again a number of near term experiments are being developed and proposed to address this issue by pushing the limits of $\beta\beta(0\nu)$ down by several orders of magnitude.
– **What is the absolute mass of a neutrino?**
  Both direct endpoint measurements and $\beta\beta(0\nu)$ experiments are being developed to address this question.
– **Are there sterile neutrinos?**
  Solar neutrino experiments are beginning to place interesting bounds on possible sterile neutrinos. In addition the miniBooNE experiment will specifically address the LSND results that appear to require the presence of sterile neutrinos.
– **Is the MNSP matrix unitary? What are the precise determination of its elements? Are there more neutrinos than the three known species?**
  In the very near term SNO and KamLAND should significantly refine $\sin^2(2\theta_{12})$ and Δm^2_{12}. The atmospheric neutrino oscillation parameters, $\sin^2(2\theta_{23})$ and Δm^2_{23} are being addressed both by more refined analyses of existing data and by a new generation of long base line experiments in the U.S., Japan, and Europe.

Acknowledgements. A thorough understanding of neutrino mixing, neutrino oscillations and possible CP violation may well require the development of new accelerator facilities and experimental techniques. However, we are currently presented with an exciting frontier to explore with even more dramatic discoveries and new physics potentially with our reach in the coming decade.

References

1. J.N. Bahcall: Phys. Rev. Lett. **12**, 300 (1964);
2. R. Davis: Phys. Rev. Lett. **12**, 303 (1964)
3. Q.R. Ahmad et al. (the SNO Collaboration): Phys. Rev. Lett. **89**, 011301 (2002)
4. Q.R. Ahmad et al. (the SNO Collaboration): Phys. Rev. Lett. **89**, 011302 (2002)
5. B.T. Cleveland et al.: Astrophys. J. **496**, 505 (1998)
6. J.N. Abdurashitov et al.: J. Exp. Theor. Phys. **95**, 181 (2002)
7. W. Hampel et al.: Phys. Lett. B **447**, 127 (1999)
8. M. Altmann et al.: Phys. Lett. B **490**, 16 (2000)
9. Y. Fukuda et al.: Phys. Rev. Lett. **77**, 1683 (1996)
10. S. Fukuda et al.: Phys. Lett. B **539**, 179 (2002)
11. J.N. Bahcall, M.H. Pinsonneault, and S. Basu: Astrophys. J. **555**, 990 (2001)
12. A. de Gouvea, A. Friedland, and H. Murayama: Phys. Lett. B **490**, 125 (2000)
13. Eguchi et al.: Phys. Rev. Lett. **90**, 021802-1 (2003)
14. S. Elliott and P. Vogel: Annu. Rev. Nucl. Part. Sci. **52**, (2002)
15. H.V. Klapdor et al.: Mod. Phys. Lett. A **16**, 2409 (2001)