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SEARCH FOR NEUTRINO OSCILLATIONS*

R. Maschuw

Institut f. Strahlen- u. Kernphysik, Universität Bonn
Nussallee 14–16, 53115 Bonn, Germany

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Neutrino oscillations provide the most sensitive method to explore the mass of neutrinos. Within the two component mixing scheme the current status of the search for neutrino oscillations is presented. Claimed evidence for oscillations of atmospheric and solar neutrinos need further experimental confirmation. An oscillation $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ as found by the LSND experiment could not be confirmed by the KARMEN experiment.

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1. Introduction

Whether or not neutrinos are massive particles is one of the most interesting questions of current elementary particle physics. In the minimum standard model of electroweak interaction the mass of the neutrino is assumed to be zero in accordance with having negative helicity only. Grand Unified Theories (GUT's) however, very much would like the neutrino to be massive and having Majorana character *i.e.* for the two helicity states the particle would be identical to its antiparticle. Furthermore, due to their large abundance in the universe neutrinos with mass unequal zero would be of great importance in astrophysics and cosmology.

It is therefore not surprising that enormous effort has been made in recent years to test experimentally the hypothesis of a massive neutrino. From precision measurements of the kinematics of the reactions ${}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $e^+e^- \rightarrow \tau^+\tau^- \rightarrow l\nu_l\nu_\tau + 5\pi\nu_\tau$, only upper limits have been deduced to be

$$m_{\bar{\nu}_e} < 4\ \mathrm{eV}/c^2\,[1]\,, m_{\nu_\mu} < 170\ \mathrm{keV}/c^2\,[2]\,, \mathrm{and}\ m_{\nu_\tau} < 18\ \mathrm{MeV}/c^2\,[3]\,,$$

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respectively. Observation of neutrinoless double beta decay would prove the neutrino to be a massive Majorana particle. From the nonobservation of the $\beta\beta^{0\nu}$-decay ^{76}Ge $\rightarrow$ ^{76}Se + $2e^-$ again only an upper limit of an effective Majorana mass has been deduced to be $\langle m_{\nu_{\rm M}} \rangle < 0.5 {\rm eV}/c^2$ [4].

Much more sensitive even to very small neutrino masses would be the search for neutrino oscillations as it is a quantummechanical interference effect. For neutrino oscillations to occur neutrinos not only have to have mass but also to undergo mass mixing. This means that the flavour eigenstates $\nu_e,\ \nu_\mu,\ \nu_\tau$ as created in weak interaction processes not necessarily are also the mass eigenstates of the mass operator in the Lagrangian but in fact are certain compositions of nondegenerate mass eigenstates $\nu_1,\ \nu_2$ and ν_3.

$$|\nu_l\rangle = \sum_l U_{l,i}\,|\nu_i\rangle; \qquad l = e, \mu, \tau;\ i = 1,2,3$$

This neutrino mixing would be equivalent to the well known Kobayashi Maskawa mixing scheme in the quark sector and is therefore a quite reasonable suggestion. In the time development of a once created flavor neutrino the mass eigenstate components due to their different masses pick up different phases ${\rm e}^{-iE_it}$; $E_i = \sqrt{p^2 + m_i^2}$. At some flight distance L or flight time t the composition might then be equivalent to that of some other flavor neutrino and changing even further. That is what one calls neutrino flavor oscillation. Restricting for simplicity to two neutrino components only the mass mixing is expressed by just one mixing angle Θ equivalent to the Cabbibo mixing in the quark sector. The appearance oscillation probability for say a muon neutrino ν_μ of energy E(MeV) to have mutated after some travel distance $L(m)$ into say an electron neutrino ν_e, is given by the expression

$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\Theta \times \sin^2\left(\frac{1.27\Delta m^2(ev^2) * L(m)}{E({\rm MeV})}\right)$$

with mixing parameters Θ being the mixing angle and $\Delta m^2 = |m_2^2 - m_1^2|$ being the difference of the squared eigenstate masses. An oscillation probability unequal zero therefore does not determine the absolute value of a neutrino mass however it would be a clear signature of neutrinos having nonzero mass. Whereas the $\sin^2 2\Theta$ term determines the oscillation amplitude the second $\sin^2$-term represents the oscillating character when for a given Δm^2 , the ratio L/E is varied. The argument of this term being π defines the oscillation length $L_\nu(m) = \frac{\pi}{1.27 * \Delta m^2({\rm eV}^2)} * E({\rm MeV})$.

Whereas for large Δm^2 averaging over realistic source and detector sizes and energy spreads the oscillation probability is entirely determined by the mixing angle, small Δm^2 values can only be tested with the experimental parameter L/E to be in the order of $1/\Delta m^2$. To be sensitive to very low values of Δm^2 one either has to choose a neutrino source of very low energy or a very large source-detector distance or preferably both. Correspondingly the different neutrino sources available — accelerators, reactors, the atmosphere, the sun — will cover different sensitivity regions of decreasing magnitude of Δm^2 respectively going down to values as low as $10^{-11}\,\mathrm{eV}^2$.

The primary result of an oscillation experiment is the measurement of an oscillation probability which for each experiment due to its statistical and systematic uncertainties is restricted to some minimum value. The corresponding values of mixing parameters determine the sensitivity curve in the two dimensional plot of Δm^2 vs. $\sin^2 2\Theta$. With no oscillation probability found to be significantly different from zero, exclusion limits of oscillation parameters are deduced from its upper bound normally given with a 90% confidence level (C.L.). A definitely positive oscillation probability however is transformed into an evidence plot *i.e.* assigning areas of possible oscillation parameters again within 90% C.L.

2. Current status of neutrino oscillations

The current experimental status of the search for neutrino oscillations is sketched in Fig. 1 in terms of a two flavour mixing scheme. The solid lines represent exclusion limits, the dashed lines are sensitivity curves of currently ongoing or planned experiments whereas for the hatched areas of oscillation parameters evidence of neutrino oscillations has been claimed.

2.1. Reactor neutrinos

The solid line assigned to BUGEY/CHOOZ denotes the current exclusion limits from reactor neutrino disappearance experiments $\bar{\nu}_e \rightarrow x$. The most recent one, CHOOZ [5], employs a 5t Gd-loaded liquid scintillator detector at about 1 km from a 8.5 GW nuclear power station in the Ardennes (France). Like all other reactor experiments performed so far it has found no deficit of $\bar{\nu}_e$ which were detected by the inverse beta decay reaction $^1\mathrm{H}\,(\,\bar{\nu}_e\,, e^+\,)\,n$. However being the first long baseline oscillation experiment it is the most sensitive one with respect to Δm^2 reaching down as low as 10^{-3} eV^2 for full mixing. It already covers part of the very interesting sensitivity region of atmospheric neutrinos to be described later (see Fig. 1). Another long baseline reactor experiment with similar sensitivity, PALO VERDE [6], is just becoming operational.

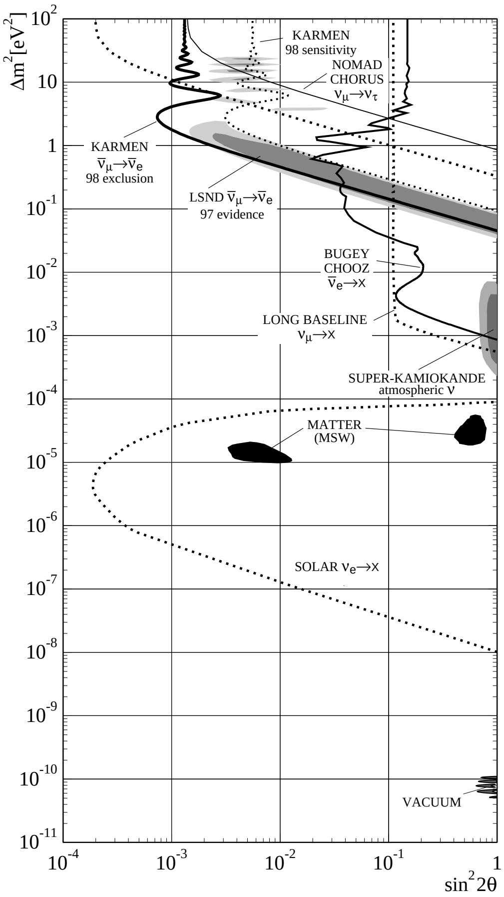

Fig. 1. Sensitivities, Exclusions and Evidences for Neutrino Oscillations

2.2. Accelerator neutrinos

The exclusion limits from accelerator neutrino oscillation experiments, looking for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_\tau$ appearance are given by the other two solid lines. Due to their much higher energies these experiments are less sensitive to low Δm^2 , only of the order of 10^{-1} eV^2. But having the ability to detect the appearance of a new neutrino flavour their sensitivity to the mixing angle reaches down to $\sin^2 2\Theta \approx 2 \times 10^{-3}$. In this region there is one experiment, LSND, which has claimed evidence for neutrino oscillations in the channel $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (hatched area) contradicted by the KARMEN experiment which uses the same π^+-decay at rest (DAR) neutrino source as LSND providing $\bar{\nu}_\mu$ with energies up to 53 MeV. This problem will be discussed in more detail at the end of the paper.

The oscillation channel $\nu_\mu \rightarrow \nu_\tau$ is currently looked for by two experiments at CERN, CHORUS and NOMAD [7], trying to detect ν_τ via the reaction $\nu_\tau N \rightarrow \tau^- X$ and the subsequent decay $\tau^- \rightarrow \pi^- \nu_\tau$ and other decay channels. Whereas CHORUS is looking for the τ^--decay kink in emulsion stacks, NOMAD, as an electronic detector, is analysing the missing transverse momentum p_t of the ν_τ. So far these experiments have reached exclusion limits for $\sin^2 2\Theta > 1.3$ and 2.2×10^{-3} respectively at large Δm^2 with prospects to come down to limits in the order of 2×10^{-4} (dotted line parallel to the solid one). There is a proposal to improve this by even an order of magnitude in a new experiment TOSCA. The motivation is to be sensitive to cosmological relevant values of $\Delta m^2 > 10$ eV^2 at low mixing angles with respect to the dark matter problem.

2.3. Atmospheric neutrinos

A region of mixing parameters Δm^2 between 10^{-3} eV^{2}and 10^{-2} eV^2 at almost full mixing has been claimed for evidence of oscillations of atmospheric neutrinos (dot-hatched area in Fig. 1). These emerge from the decay chain of positive and negative pions $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ and $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$, $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$. They are produced by spallation processes in the high atmosphere induced by the hadronic component of cosmic radiation. The energies of atmospheric neutrinos range from a few 100 MeV up to 40 GeV with a maximum intensity at about 1 GeV. Due to the production process the ratio of μ-like to e-like neutrinos should be in the order of two, increasing with energy as less muons decay before they reach the earth. Compared to this only a fraction of ≈ 0.6 of the expected μ/e ratio has been found by different underground detectors IMB, SOUDAN, KAMIOKANDE [8]. This deficit of muon neutrinos has been interpreted in terms of neutrino oscillations either of $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\tau$. A $\nu_\mu \rightarrow \nu_e$ oscillation with $\Delta m^2 \approx 10^{-2}$ eV^2 is ruled out by the recent CHOOZ reactor experiment assuming CP conservation. Therefore the result points towards a $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_{\text{sterile}}$ interpretation. Since 1996 the SUPERKAMIOKANDE (SK) detector, a 50 kt water Cherenkov counter viewed by 11,200 20" phototubes is operating and has confirmed the above result with much higher statistics. The Cherenkov rings, quite clear ones for μ-tracks from charged current (ν_μ,μ)-transitions, more washed out ones for slightly showering electrons from (ν_e,e)-transitions allow good particle identification. In addition they also provide directionality and thus also allowed to measure angular distributions of atmospheric neutrinos in the sub-GeV and multi-GeV region. With the distance source-detector varying from about 20 km to 12 000 km with the zenith angle for the first time the L/E-dependence of the oscillation probability could be tested. The angular distributions clearly favour the interpretation of neutrino oscillations with Δm^2 between $(1\div5) \times 10^{-3}$ eV^2 at mixing angles $\sin^2 2\Theta > 0.8$ [9]. This result is backed by the analysis of upgoing muons having been created by ν_μ on their way through the earth from underneath the detector.

However, taking the different results of all atmospheric neutrino experiments and analyses they are not entirely conclusive in all aspects and it is obvious that the SK claim of ν-oscillation evidence has to be confirmed by other, terrestrical experiments where the ν-beam is completely under control. This is the domain of the accelerator long baseline experiments now being under intense investigation at CERN, KEK and FNL [10]. Their sensitivities are indicated by the dashed line in Fig. 1. Probably the first one to come into operation will be the K2K-experiment where the KEK ν-beam of 1.4 GeV average energy is directed towards the SK-detector about 250 km away in the Kamioka mine. Whether this is already sufficient to confirm the ν_μ-deficit of atmospheric neutrinos is left to be seen. In either case the MINOS project of Fermilab with an 8 kt detector in the Soudan mine at 732 km from the source or one or the other of various proposals for CERN long baseline experiments in the 732 km distant Gran Sasso laboratory needs to be realized before a definite answer can be given. In each of these experiments which preferably should have ν_τ detection capability, apart from the far distance detector, a short distance detector will be employed to be at least sensitive to a ν_μ deficit. As the sensitivities of these experiments so far just match the evidence region of SK some more thoughts might be necessary to put into these proposals as to fully cover the SK evidence claim.

2.4. Solar neutrinos

The next most interesting region of oscillation parameters indicated by the remaining three hatched areas and the dotted line in the low Δm^2 — region of Fig. 1 denote the results and the sensitivities of solar neutrino experiments. The well known solar neutrino problem arises from the measured deficit of electron neutrinos from the sun compared to the expectations from the Standard Solar Model (SSM). The deficit fractions (experimental errors only) as compared to the SSM of BP95 [11] are listed in the following table [12, for reference]. These values differ from each other as due to their threshold energy the different experiments measure different fractions of the solar neutrino spectrum. One possible explanation compatible with the results of all experiments would be the assumption of so called vacuum oscillations. This would be a disappearance oscillation $\nu_e \to$ x with Δm^2 as low as $\approx 7\times10^{-11}$eV^2 due to the large distance earth-sun of 1.5×10^{11} m but at rather large mixing angles of about $\sin^2 2\Theta = 0.8$.

TABLE I

Measured solar neutrino deficit fractions

HOMESTAKE,(Chlorine) ^{8}B + ^{7}Be	^{37}Cl(ν_e,e^-)^{37}Ar	0.27 ± 0.02
GALLEX, (Gallium) pp-ν's	^{71}Ga(ν_e,e^-)^{71}Ga	0.56 ± 0.04
SAGE, (Gallium) pp-ν's	^{71}Ga(ν_e,e^-)^{71}Ga	0.48 ± 0.1
KAMIOKANDE, (water Ch) ^{8}B only	(ν_e,e^-)-scattering	0.42 ± 0.06
SUPERKAMIOKANDE, (Ch)) ^{8}B only	(ν_e,e^-)-scattering	0.37 ± 0.01

Another interpretation can be given in terms of the Mikheyev–Smirnov–Wolfenstein effect (MSW). This denotes a resonant transition of electron neutrinos into other neutrino species on their way through the sun due the different interactions of the fractional flavour components of the mass eigenstates with matter. Whereas for ν_e both, Charge Current (CC) and Neutral Current (NC) interaction is involved in (ν,e)-scattering only the NC Z^0-exchange can contribute for ν_μ and ν_τ. This influences dramatically the propagation of the effective matter eigenstates. For certain ν-energies and electron densities varying with the radial distance in the sun it can lead to resonant ν_e transitions sometimes also called matter oscillations. The region of mixing parameters for this phenomenon to occur is indicated by the dotted line in Fig. 1. As the different experiments have slightly different sensitivities only two smaller areas of mixing parameters are left to be compatible with the results of all experiments (hatched areas in Fig. 1). The recent data from SuperKamiokande with 6800 solar neutrino events for the first time also allowed shape analysis of the B^8 ν_e-energy spectrum. Although compatible, the results so far are not fully conclusive in all aspects compared to the results of the other experiments.

Improvements are expected from SK with even better statistics. For final conclusions the next generation of solar neutrino experiments has to be awaited. The recently inaugurated Sudbury Neutrino Observatory SNO [13] with a 1 kt heavy water Cherenkov detector for the first time will be able to look for both, CC and NC processes. Looking for NC deuteron disintegration, d$\nu \rightarrow$ npν with corresponding neutron detection, ν_μ and ν_τ possibly oscillated from ν_e can thus be detected. Together with ν_e, measured separately by CC interaction, this will check the total neutrino flux for ^{8}B-neutrinos. BOREXINO, [14] at the Gran Sasso Laboratory, will be a 300 t liquid scintillation detector viewed at by a sphere of 1600 phototubes. Looking for ν_e-scattering with a threshold as low as $E_{\rm th} = 250$ keV (compared to 6 MeV of SK) it will particularly be sensitive to the monoenergetic 861 keV neutrinos from ^{7}Be which are expected to be strongly suppressed in the MSW scheme.

3. LSND *vs* KARMEN

The highest Δm^2 -values for neutrino oscillation evidence has been claimed by the LSND experiment [15] at Los Alamos indicated as cross-hatched area in Fig. 1 (see also contribution of G. Garvey). Starting with $\bar{\nu}_\mu$ of up to 53 MeV energy from the pion decay at rest sequence (DAR) this experiment is looking for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with a 157 t mineral oil/scintillator tank viewed by 1220 phototubes. Detection of both, Cherenkov light from minimum ionizing electrons and scintillation light from strongly ionizing particles, provides particle identification necessary for background suppression. $\bar{\nu}_e$ would be detected via the inverse beta decay process $^1\mathrm{H}\,(\,\bar{\nu}_e\,, e^+\,)\,n$ requiring a delayed coincidence signature from the positron followed by 2.2 MeV gammas from (n,p)-capture. Fitting the ratio R of Likelyhoods of correlated and accidental gammas LSND claimed to have found 83 $\pm$ 24 excess ν_e-events due to oscillations. With a reasonable cut at $R > 30$, 33.9 $\pm$ 8.0 "goldplated" events provide a positron energy spectrum above 20 MeV. However direct cuts on the positron energy can reliably only be made at above 36 MeV as to distinguish unambiguously $\bar{\nu}_e$-events from ν_e-events with a similar coincidence signature by the reaction $^{12}\mathrm{C}\,(\,\nu_e\,, e^-\,)\,^{12}\mathrm{N}_{\mathrm{g.s.}}$. With an oscillation probability $P_{\mathrm{osc}} = (0.31 \pm 0.09 \pm 0.05)$ % resulting from an R-distribution fit, LSND claims a 90 % CL evidence region of oscillation parameters as indicated in Fig. 1.

As mentioned above, this result had not been confirmed by the competitive KARMEN [17] experiment. KARMEN is performed at the neutron spallation facility ISIS of the Rutherford Appleton Laboratory providing a pulsed source (50 Hz) of neutrinos ν_μ , ν_e and $\bar{\nu}_\mu$ with energies up to 52.8 MeV from the successive decay of stopped pions and muons, $\pi^+ \xrightarrow{26\mathrm{ns}} \mu^+ + \nu_\mu$ and $\mu^+ \xrightarrow{2.2\mu\mathrm{s}} e^+ + \nu_e + \bar{\nu}_\mu$. Neutrino induced reactions are detected in a high resolution segmented scintillation calorimeter of 56 ton fiducial mass looked at by 1024 phototubes. Compared to LSND the most important feature of KARMEN apart from its much better energy resolution is the time structure of the ISIS neutrino beam due to the short proton bursts of ISIS (2$\times$100 ns, 50 Hz). This time structure has to be reflected in any measured time distribution of ν-induced events. Particularly ν_e- and $\bar{\nu}_\mu$-events would have to follow the 2.2 μs slope of its parent muon decay providing a very stringent signature.

Extensively exploiting these features, KARMEN, from 1990 to 1995 has performed an entire experimental program of neutrino physics investigating quantitatively several charged current (CC) as well as neutral current (NC) neutrino nucleus interactions with implications on specific weak couplings, weak nuclear formfactors, exotic decay and interaction modes and others [18]. One of the main topics of the KARMEN experiment has also been the search for neutrino oscillations particularly the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance oscillation. An excess of $\bar{\nu}_e$ as at LSND, would have been detected via the classical inverse β-decay reaction $^1\mathrm{H}\,(\,\bar{\nu}_e\,, e^+\,)\,n$ followed by (n,γ)-capture but in this case either on Gd or ^{1}H. Spatially correlated delayed coincidences within proper time and energy windows would be the candidates for possible neutrino oscillation events. Although about 140 of those $\bar{\nu}_e$-like events have been found in the 1990-95 data a careful Maximum Likelihood analysis using the precise knowledge of the energy and time distribution of the neutrinos and its reaction products did not yield a positive evidence for any ν-oscillation. However the KARMEN1 exclusion limits on the oscillation parameters Δm^2 and $\sin^2 2\Theta$ could not rule out the entire area of oscillation parameters compatible with the LSND findings. The sensitivity was governed by an irreducible background intensity caused by fast neutrons from μ-capture and μ-induced spallation processes in the 7000 steel shielding surrounding the liquid scintillation calorimeter. Entering the detector unidentified, these neutrons cause a prompt signal by (n,p)-scattering followed by a (n,γ)-process of the scattered and thermalized neutrons thus providing the same signature as $\bar{\nu}_e$ oscillated from $\bar{\nu}_\mu$. To cure this problem an additional layer of veto counters (5 cm plastic scintillator) had been implemented in the shielding with still about 4.5 attenuation lengths of steel ($\lambda_n^{\mathrm{Fe}} = 21.6$ cm) towards the detector. Neutrons created within the enclosure of the veto shield and causing a detector signal are thus identified by the veto of having been induced by muons. This did reduce the relevant background to oscillation signals by a factor of 40.

With this new KARMEN2 setup data have been taken in 97/98. Whereas only 2.88 ± 0.13 mostly neutrino induced background events could have been expected, KARMEN2 has seen no $\bar{\nu}_e$-event so far. Using the unified approach as recommended by the Particle Data Group PDG [16] an oscillation signal of > 1.1 events can thus be excluded at a 90 % CL. With 811 ± 89 events expected for full oscillation the upper limit for the mixing angle at large Δm^2 is $\sin^2 2\Theta < 1.3 \times 10^{-3}$ at 90 % CL. The corresponding exclusion curve in Fig. 1 already covers almost completely the entire LSND evidence region thus contradicting any claim for neutrino oscilattions in this channel. The fact that no event has been found although 2.9 events should at least have been seen from background is of course an accidental fluctuation. Nevertheless by the rules of statistics it provides a sound exclusion curve. As KARMEN continues to take more data in 1998/99 the current sensitivity curve on the basis of estimated backround (dotted line) will move towards and meet this exclusion limit even if those background events are found as they should.

4. Summary

The current experimental status of neutrino oscillations is quite exciting. Obviously for two nonterrestrical sources — atmospheric and solar neutrinos — there are experimental effects that could be explained in terms of ν-oscillations. However it would be too early to state that this interpretation is already fully conclusive. New dedicated solar neutrino experiments have to decide whether solar neutrino oscillations, if at all existing, follow the MSW scheme of resonant matter transitions or the scheme of "just so"-vacuum oscillations with much lower Δm^2 -values. The recent SK oscillation claim for atmospheric neutrinos requires confirmation by terrestrial long baseline experiments which are currently planned or even under construction at various laboratories. Finally the LSND/KARMEN controversy has to be resolved.

Taken the mixing parameters from the different neutrino oscillation claims a variety of even very speculative scenarios for massive neutrinos are on the market. However, from an experimentalists point of view it seems to be premature to draw any serious conclusions on the mass of the neutrino. At the current stage the observed phenomena have to be confirmed, their origin due to oscillations has to be settled and the mixing parameters have to be fixed by experiment. Nevertheless, another interesting five years of neutrino physics is lying ahead of us.

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