A Review on Neutrino Physics, Mass and Oscillations.

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Abstract

We present a short review of the present status of the problem of neutrino masses and mixing including a survey of theoretical motivations and models, experimental searches and implications of recently appeared solar and atmospheric neutrino data, which strongly indicate nonzero neutrino masses. Such data apparently requires the existence of light sterile neutrino in addition to the three active ones and two-generation nearly maximal mixing.
1 Introduction

Among all the fundamental particles the neutrino occupies a unique place in many ways and as such it has shed light on many important aspects of our present understanding of nature and is believed to hold the key to the physics beyond the Standard Model. Presently, the question of whether the neutrino has mass is one of the outstanding issues in particle physics, astrophysics, cosmology and theoretical physics in general. There are several theoretical, observational and experimental motivations which justify the searching for possible non-zero neutrino masses (see i.e. [1, 2] for excellent older reviews on this matter).

Fermion masses in general are one of the major problems of the Standard Model. Observation or non-observation of neutrino masses could introduce an useful new perspective on the subject. If massless they would be the only fermions with this property. A property which is not dictated by a fundamental underlying principle (at least one which is known presently), such as gauge invariance in the case of the photon. If massive the question is why are their masses so much smaller than those of their charged partners. Although theory alone can not predict neutrino masses, it is certainly true that they are strongly suggested by present theoretical models of elementary particles and most extensions of the Standard Model definitively require neutrinos to be massive. They therefore constitute a powerful probe of new physics at a scale larger than the electroweak scale.

Some hints at accelerator experiments as the the observed indications of spectral distortion and deficit of solar neutrinos and the ratio of atmospheric $\nu_e/\nu_\mu$ neutrinos and their zenith distribution are naturally accounted by the oscillations of a massive neutrino. Recent claims of the High-statistics high precision SuperKamiokande experiment are unambiguous and left little room for the scepticism.

Neutrinos are basic ingredients of astrophysics and cosmology. There may be a hot dark matter component (HDM) to the Universe: simulations of structure formation fit the observations only when one has some 20 % of HDM, the best fit being two neutrinos with a total mass of 4.7 eV. If so, neutrinos would be, at least in quantity, one of the most important ingredients in the Universe. There seems to be however some kind of conflict within cosmology itself: observations of distant objects favor a large cosmological constant instead of HDM.

Regardless of mass and oscillations, astrophysical interest in the neutrino and their properties arises from the fact that it is copiously produced in high temperature and/or high density environment and it often dominates the physics of those astrophysical objects. The interactions of the neutrino with matter is so weak that it passes freely through any ordinary matter existing in the Universe. This makes neutrinos to be a very efficient carrier of energy drain from optically thick objects. At the same time they give a good probe for the interior of such dense objects. For example, the solar neutrino flux is, together with heliosysmology, one of the two known probes of the solar core. A similar statement applies to the type-II supernovas: The most interesting questions around supernovas, the explosion dynamics itself with the shock revival, and, the synthesis of the heaviest elements by r-process, could be positively affected by changes in the neutrino flux, e.g. by MSW active or sterile conversions. Finally, ultra high energy neutrinos are called to be useful probes of diverse distant astrophysical objects. Active Galactic Nuclei (AGN) should be copious emitters of $\nu$’s, providing both detectable point sources and an
observable diffuse background which is larger in fact than the atmospheric neutrino background in the very high energy range.

2 The neutrinos in the Standard Model.

The standard model (SM) contains three left-handed neutrinos. The three neutrinos are represented by two-component Weyl spinors $\nu_i, i = e, \mu, \tau$ each describing a left-handed fermion. They are upper components of weak isodoublets $L_i$, they have $I_{3W} = 1/2$ and an unit of the global $i$th lepton number. These standard model neutrinos are strictly massless. The only Lorenz scalar made out of them is the Majorana mass, of the form $\nu^\dagger_i \nu_i$; it has the quantum number of a weak isotriplet, with $I_{3W} = 1$ as well as two units of total lepton number. Thus to generate a renormalizable Majorana mass term at the tree level one needs a Higgs isotriplet with two units of lepton number. Since in the strict standard model Higgs is a weak isodoublet Higgs, there are no tree-level neutrino masses. If we want to consider quantum corrections we should consider effective terms where a weak isotriplet is made out of two isodoublets and which are not invariant under lepton number symmetry. The conclusion is that the standard model neutrinos are kept massless by global chiral lepton number symmetry (and more general properties as renormalizability of the theory). However this is a rather formal conclusion, there is no any other independent, compelling theoretical argument in favor of such symmetry. Or, with other words, there is not any reason why we would like to keep it intact.

Independent from mass oddities in any other respect neutrinos are very well behaved particles within the SM framework. Some properties are unambiguously known about neutrinos. The LEP line-shape measurement imply that are only three ordinary light neutrinos. Big Bang Nucleosynthesis (BBN) constrains the parameters of possible sterile neutrinos (which interact and are produced only by mixing). All the existing data on the the weak interaction processes in which neutrinos take part are perfectly described by the Standard Model charged-current (CC) and neutral-current (NC) Lagrangians:

$$L_{i}^{CC} = -\frac{g}{\sqrt{2}} \sum_{l=e,\mu,\tau} \bar{\nu}_l \gamma_\alpha \nu_l L^\alpha + h.c.$$  
$$L_{i}^{NC} = -\frac{g}{2 \cos \theta_W} \sum_{l=e,\mu,\tau} \bar{\nu}_l \gamma_\alpha \nu_l Z^\alpha + h.c.$$  

The CC and NC interaction Lagrangians conserve the total three lepton numbers $L_{e,\mu,\tau}$ while CC interactions determine the notion of flavor neutrinos $\nu_{e,\mu,\tau}$. There are no indications in favor of violation of lepton numbers in weak processes. From the existing experiments very strong bounds on branching ratios of rare, lepton number violating, processes are obtained, for example: $R(\mu \to e\gamma) < 5 \times 10^{-11}$ and $R(\mu \to 3e) < 10^{-12}$ ($\mathbb{B}$, $90\%$ CL).

3 Neutrino mass terms and models.

Any satisfactory model that generates neutrino masses must contain a natural mechanism that explains their small value, relative to that of their charged partners. Given the latest experimental indications it would also be desirable that includes justification for light sterile neutrinos.
and near maximal mixing. To generate neutrino masses without new fermions, we must break lepton number by adding to the SM Higgs Fields carrying lepton numbers, one can arrange then to break lepton number explicitly or spontaneously through their interactions. Possibly, the most familiar approach to give neutrino masses is, however, to introduce for each one an electroweak neutral singlet. This happens naturally in left-right symmetric models where the origin of SM parity violation is ascribed to the Spontaneous breaking of a B-L symmetry. In the SO(10) GUT the Majorana neutral particle N enters in a natural way in order to complete the matter multiplet, the neutral N is a SU(3) × SU(2) × U(1) singlet. According to the scale where they have relevant effects, Unification (i.e. the aforementioned SO(10) GUT) and weak-scale approaches (i.e. radiative models) can be distinguished.

Phenomenologically, mass terms can be viewed as describing transitions between right (R) and left (L)-handed states. For a set of four fields: $\psi_L, \psi_R, (\psi^c)_L, (\psi^c)_R$, the most general mass part of the free-field Lagrangian can be written as:

$$-L = m_D (\overline{\psi}_L \psi_R) + \frac{1}{2} m_T (\overline{(\psi_L)^c} \psi_L) + \frac{1}{2} m_S (\overline{(\psi_R)^c} \psi_R) + \text{h.c.}$$

(3)

In terms of the new Majorana fields: $\nu = (1/\sqrt{2})(\psi_L + (\psi_L)^c)$, $N = (1/\sqrt{2})(\psi_R + (\psi_R)^c)$, the Lagrangian becomes:

$$-L = (\overline{\nu}, \overline{N}) \begin{pmatrix} \nu & N \end{pmatrix} \begin{pmatrix} m_T & m_D \\ m_D & m_S \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

(4)

where the neutrino mass matrix is evident. Diagonalizing this matrix one finds that the physical particle content is given by two Majorana mass eigenstates: The inclusion of the Majorana mass splits the four degenerate states of the Dirac field into two non-degenerate Majorana pairs. If we assume that the states $\nu, N$ are respectively active and sterile, the "Majorana masses" $m_T$ and $m_S$ transform as weak triplets and singlets respectively. $m_D$ is an standard Dirac mass term. The neutrino mass matrix can easily be generalized to three or more families, in which case the masses become matrices themselves. The complete flavor mixing comes from two different parts, the diagonalization of the charged lepton Yukawa couplings and that of the neutrino masses. In most simple extensions of the standard model, this CKM-like leptonic mixing is totally arbitrary with parameters only to be determined by experiment. Their prediction, as for for the quark hierarchies and mixing, needs further theoretical assumptions (i.e. Ref.[4] predicting $\nu_\mu - \nu_\tau$ maximal mixing).

The case $m_T, m_S \equiv 0$ in Eq.(4) corresponds to a purely Dirac mass term. In this case $\nu, N$ are degenerate with mass $m_D$ and a four component Dirac field can be recovered as $\nu \equiv \nu + N$. The Dirac mass term allows a conserved lepton number $L = L_\nu + L_N$. For an ordinary Dirac neutrino the $\nu_L$ is active and $\nu_R$ is weak sterile, an SU(2) singlet, the mass term describes then a $\Delta I = 1/2$ transition and is generated from SU(2) breaking with a Yukawa coupling:

$$-L_{Yuk} = h_\nu \overline{(\nu_L, l)} \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} N_R + \text{h.c.}$$

(5)

One has $m_D = h_\nu v/2$ where $v$ is the vacuum expectation value of the Higgs doublet and $h_\nu$ is the corresponding Yukawa coupling. A neutrino Dirac mass is qualitatively just like any other fermion masses, but that leads to the question of why it is so small in comparison with the rest
of fermion masses: one would require $h_{\nu_e} < 10^{-10}$ in order to have $m_{\nu_e} < 10$ eV. Or in other words: $h_{\nu_e}/h_e \sim 10^{-5}$ while for the hadronic sector we have $h_{up}/h_{down} \sim O(1)$.

A pure Majorana mass transition term, $m_T$ or $m_S$ terms in Lagrangian (3), describes in fact a particle-antiparticle transition violating lepton number by two units ($\Delta L = \pm 2$). It can be viewed as the creation or annihilation of two neutrinos leading therefore to neutrinoless double beta decay.

For $N$ a gauge singlet, a renormalizable mass term of the type $L_N = m_S N^T N$ is allowed by SM SU(3)$\times$SU(2)$\times$U(1) symmetry. However, it would not be consistent in general with unified symmetries, i.e. with a full SO(10) symmetry. In such theory the most straightforward possibility for generating a term like it in the full theory would be to include a 126 Higgs and a Yukawa coupling. Alternatively, one can imagine more complicated interactions containing products of several simpler Higgs fields. Whatever the concrete model, the main point to have into account is that, it is strongly suggested that $m_S$ is associated with breaking of some unified symmetry, the expected scale for it should be in a large range covering from $\sim$ TeV (left-right models) to GUT scales $\sim 10^{15} - 10^{17}$ GeV (from couplings unification).

If $\nu_L$ is active then $\Delta I=1$ and $m_T$ must be generated by either an elementary Higgs triplet or by an effective operator involving two Higgs doublets arranged to transform as a triplet.

For an elementary triplet $m_T \sim h_T v_T$, where $h_T$ is a Yukawa coupling and $v_T$ is the triplet VEV. The simplest implementation (the old Gelmini-Roncadelli model) is excluded by the LEP data on the Z width: the corresponding Majoron couples to the Z boson increasing significantly its width. Variant models involving explicit lepton number violation or in which the Majoron is mainly a weak singlet (invisible Majoron models) could still be possible.

For an effective operator originated mass, one expects $m_T \sim 1/M$ where $M$ is the scale of the new physics which generates the operator. One can see this easily in the see-saw scheme: The $N$’s communicate with the familiar fermions through the Yukawa interactions (Eq.(5). If $N$ were massless the effect of Eq.(3) would be to generate masses of the same order as ordinary quark and lepton masses. If $N$ are massive enough Yukawa and mass terms could be integrated out to generate an effective term of the type $(L, \text{lepton doublet})$:

$$L_{\text{eff}} \sim h^2/m_S LL\phi\phi + h.c.$$ 

In the seesaw limit in Eq.(3), taking $m_T \sim 1/m_S \sim 0, m_D << m_S \sim GUT$, the two Majorana neutrinos acquire respectively masses $m_1 \sim m_D^2/m_S << m_D, m_2 \sim m_S$. There is one heavy neutrino and one neutrino much lighter than the typical Dirac fermion mass. This is a natural way of generating two well separated mass scales.

Now we come again to the Majorana mass $m_S$ for the sterile neutral $N$: $m_S$ can vary anywhere from the TeV scale to the Planck Scale among the large quantity of proposed concrete seesaw and related models. The TeV scale models are motivated, i.e., by left-right symmetric models. With typical $m_D$'s, one expects masses of order $10^{-1}$ eV, 10 keV, and 1 MeV for the $\nu_{e,\mu,\tau}$ respectively violating cosmological bounds unless heavy neutrinos decay rapidly and invisibly. GUT motivated intermediate scales ($10^{12} - 10^{16}$ GeV) yield typical masses in the range relevant to hot dark matter, and solar and atmospheric neutrino oscillations. For $m_S \sim 10^{12}$ GeV (some superstring models, GUT with multiple breaking stages) one can obtain light neutrino masses.
of the order \((10^{-7} \text{ eV}, 10^{-3} \text{ eV}, 10 \text{ eV})\). Such range of masses would allow the interpretation of the Solar and atmospheric deficits as, respectively, \(\nu_e \rightarrow \nu_\mu \), \(\nu_\mu \rightarrow \nu_\tau\) oscillations. \(\nu_\tau\) could be considered as a dark matter candidate. For \(m_S \sim 10^{16}\) (grand unified seesaw with large Higgs representations) one typically finds smaller masses around \((10^{-11}, 10^{-7}, 10^{-2}) \text{ eV}\) somehow more difficult to fit into the present known experimental facts.

Models have been proposed where small tree level neutrino masses are obtained without making use of large scales. The model proposed by \cite{6} (inspired by previous superstring models) offers an example of the possibility of having neutrino mass matrices more general than that given by Eq.\(\text{(4)}\). The incorporation of additional iso-singlet neutral fermions \(N_i\) leads to a matrix of the type:

\[
\begin{pmatrix}
0 & m_D & 0 \\
0 & 0 & M \\
0 & M & \mu
\end{pmatrix},
\]

(6)

The smallness of neutrino masses is explained directly from the, otherwise left unexplained, smallness of the parameter \(\mu\) in such a model. Moreover, there would be neutrino mixing even if the light neutrino remains strictly massless \((\mu \equiv 0)\).

The anomalies observed in the solar neutrino flux, atmospheric flux and low energy accelerator experiments cannot all be explained consistently without introducing a light, then necessarily sterile, neutrino. If all the Majorana masses are small, active neutrinos can oscillate into the sterile right handed fields. Light sterile neutrinos can appear in particular see-saw mechanisms if additional assumptions are considered ("singular see-saw " models) with some unavoidable fine tuning. The alternative to such fine tuning would be seesaw-like suppression for sterile neutrinos involving new unknown interactions, i.e. family symmetries, resulting in substantial additions to the SM, (i.e. some sophisticated superstring-inspired models, Ref.\cite{5}).

Finally, weak scale, radiative generated mass models where the neutrino masses are zero at tree level constitute a very different class of models: they explain in principle the smallness of \(m_\nu\) for both active and sterile neutrinos. Different mass scales are generated naturally by different number of loops involved in generating each of them. The actual implementation generally requires however the ad-hoc introduction of new Higgs particles with nonstandard electroweak quantum numbers and lepton number-violating couplings \cite{6}.

The magnetic dipole moment is another probe of possible new interactions. Majorana neutrinos have identically zero magnetic and electric dipole moments. Flavor transition magnetic moments are allowed however in general for both Dirac and Majorana neutrinos. Limits obtained from laboratory experiments are of the order of a few \(\times 10^{-10}\mu_B\) and those from stellar physics or cosmology are \(O(10^{-11} - 10^{-13})\mu_B\). In the SM electroweak theory, extended to allow for Dirac neutrino masses, the neutrino magnetic dipole moment is nonzero and given, as \cite{6} and references therein):

\[
\mu_\nu = \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} = 3 \times 10^{-19}(m_\nu/1 \text{ eV})\mu_B
\]

(7)

where \(\mu_B\) is the Bohr magneton. The proportionality of \(\mu_\nu\) to the neutrino mass is due to the absence of any interaction of \(\nu_R\) other than its Yukawa coupling which generates its mass. In left-right symmetric theories \(\mu_\nu\) is proportional to the charged lepton mass: a value of \(\mu_\nu \sim 10^{-13} - 10^{-14}\mu_B\) can be reached still too small to have practical astrophysical consequences.
Magnetic moment interactions arise in any renormalizable gauge theory only as finite radiative corrections. The diagrams which generate a magnetic moment will also contribute to the neutrino mass once the external photon line is removed. In the absence of additional symmetries a large magnetic moment is incompatible with a small neutrino mass. The way out suggested by Voloshin consists in defining a SU(2)$_\nu$ symmetry acting on the space $(\nu, \nu^c)$, magnetic moment terms are singlets under this symmetry. In the limit of exact SU(2)$_\nu$ the neutrino mass is forbidden but $\mu$ is allowed. Diverse concrete models have been proposed where such symmetry is embedded into an extension of the SM (left-right symmetries, SUSY with horizontal gauge symmetries [8]).

4 Experimental considerations.

4.1 Laboratory, reactor and accelerator results.

No indications in favor of non-zero neutrino masses were found in direct kinematical searches:

1. From the measurement of the high energy part of the $\beta$ spectrum in the tritium decay: The Troitsk and Mainz experiments obtain respectively $m_{\nu e} < 3.4$ eV [9] and Mainz $m_{\nu e} < 2.7$ eV [10]. Both measurements are plagued by interpretation ambiguities: apparition of negative mass squared and bumps at the end of the spectrum.

2. Limits for the muon neutrino mass have been derived using the decay channel $\pi^+ \rightarrow \mu^+\nu_\mu$ at intermediate energy accelerators (PSI, LANL). The present limits are $m_{\nu\mu} \lesssim 160$ keV [11].

3. A tau neutrino mass of less than 30 MeV is well established and confirmed by several experiments: limits of 28, 30 and 31 MeV have also been obtained by the OPAL, CLEO and ARGUS experiments respectively [12]. The best upper limit for the $\tau$ neutrino mass has been derived using the decay mode $\tau \rightarrow 5\pi^\pm\nu_\tau$ by the ALEPH collaboration [13]: $m_{\nu\tau} < 18$ MeV (95% CL).

Many experiments on the search for neutrinoless double-beta decay $[(\beta\beta)_{0\nu}]$,

$$(A, Z) \rightarrow (A, Z + 2) \rightarrow 2 e^-, $$

have been done. This process is possible only if neutrinos are massive and Majorana particles. The matrix element of the process is proportional to the effective Majorana mass $\langle m \rangle = \sum_i \eta_i U_{\alpha i}^2 m_i$. Uncertainties in the precise value of upper limits are important since they depend on theoretical calculations of nuclear matrix elements. From the non-observation of $(\beta\beta)_{0\nu}$ the Heidelberg-Moscow Ge experiment [14] draws the limit $|\langle m \rangle| < 0.5 - 1.5$ eV (90% CL). In the next years it is expected an increase in sensitivity allowing limits down the $|\langle m \rangle| \sim 0.1$ eV level.

Many short-baseline (SBL) neutrino oscillation experiments with reactor and accelerator neutrinos did not find any evidence of neutrino oscillations. For example experiments looking for $\bar{\nu}_e \rightarrow \bar{\nu}_e$ or $\nu_\mu \rightarrow \nu_\mu$ dissapereace [15, 16] or oscillations $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ [17, 18].
The first reactor long-baseline neutrino oscillation experiment CHOOZ found no evidence for neutrino oscillations in the $\bar{\nu}_e$ disappearance mode [18]. Their results imply an exclusion region in the plane of the two-generation mixing parameters (with normal or sterile neutrinos) given approximately by $\Delta m^2 > 0.9 \times 10^{-5} eV^2$ for maximum mixing and $\sin^2 2\theta > 0.18$ for large $\Delta m^2$, as shown in Fig. (1). CHOOZ results are important for the atmospheric deficit problem: as it is seen in Fig. (1) they are incompatible with an $\nu_e \rightarrow \nu_\mu$ oscillation hypothesis for the solution of the atmospheric problem.

![Figure 1: The 90% C.L. exclusion plot for CHOOZ, compared with previous experimental limits and with the KAMIOKANDE allowed region.](image)

Los Alamos LSND experiment has reported indications of possible $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations [19]. They search for $\bar{\nu}_e$'s in excess of the number expected from conventional sources at a liquid scintillator detector located 30 m from a proton beam dump at LAMPF. A $\bar{\nu}_e$ signal has been detected via the reaction $\bar{\nu}_e p \rightarrow e^+ n$ with $e^+$ energy between 36 and 60 MeV, followed by a $\gamma$ from $np \rightarrow d\gamma$ (2.2 MeV). A total $\bar{\nu}_e$ excess of $51.8^{+18.7}_{-16.9} \pm 8.0$ events has been obtained. If this excess is attributed to neutrino oscillations of the type $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, it corresponds to an oscillation probability of $3.1 \pm 1.0 \pm 0.5 \times 10^{-3}$. The results of a similar search for $\nu_\mu \rightarrow \nu_e$ oscillations where the $\nu_e$ are detected via the CC reaction $C(\nu_e,e^-)X$ provide a value for the corresponding oscillation probability of $2.6 \pm 1.0 \pm 0.5 \times 10^{-3}$.

The LSND result has not been confirmed by the KARMEN experiment. The KARMEN experiment (Rutherford Laboratories), following a similar experimental setup as LSND, searches for $\bar{\nu}_e$ produced by $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at a mean distance of 17.6 m. The time structure of the neutrino beam is important for the identification of the neutrino induced reactions and for the suppression of the cosmic ray background. Systematic time anomalies not completely understood has been reported. The 1990-1995 and the latest 1997-1998 KARMEN data showed inconclusive results. They found no events, with an expected background of $2.88 \pm 0.13$ events, for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, however the positive LSND result in this channel could not be excluded in total either [20]. At the end of 1999, the KARMEN sensitivity is expected to be able to exclude the whole parameter region of evidence suggested by LSND if no oscillation signal were found (Fig. 2). The first phase of a third pion beam dump experiment designed to set the LSND-
KARMEN controversy has been approved to run at Fermilab. Phase I of "BooNe" (MiniBooNe) expects a $10 \sigma$ signal ($\sim 1000$ events) and thus will make a decisive statement either proving or ruling it out. Plans are to run early 2001. Additionally, there is a letter of intent of a similar experiment to be carried out at the CERN PS \cite{21,22}.

![Figure 2: The LSND 1993-97 likelihood regions along with KARMEN2 limits (unified approach) together with a priori sensitivity.](image)

4.2 Solar neutrinos

Indications in the favor of neutrino oscillations were found in "all" solar neutrino experiments: The Homestake Cl radiochemical experiment with sensitivity down to the lower energy parts of the $^8$B neutrino spectrum and to the higher $^7$Be line. The two radiochemical $^{71}$Ga experiments, SAGE and GALLEX, which are sensitive to the low energy pp neutrinos and above and the water Cerenkov experiments Kamiokande and Super-Kamiokande (SK) which can observe only the highest energy $^8$B neutrinos. Water Cerenkov experiments in addition demonstrate directly that the neutrinos come from the Sun showing that recoil electrons are scattered in the direction along the sun-earth axis.

Two important points to remark are: a) The prediction of the existence of a global neutrino deficit is hard to modify due to the constraint of the solar luminosity on pp neutrinos detected at SAGE-GALLEX. b) The different experiments are sensitive to neutrinos with different energy ranges and combined yield spectroscopic information on the neutrino flux. Intermediate
energy neutrinos arise from intermediate steps of the thermonuclear solar cycle. It may not be impossible to reduce the flux from the last step ($^8\text{B}$), for example by reducing temperature of the center of the Sun, but it seems extremely hard to reduce neutrinos from $^7\text{Be}$ to a large extent, while keeping a reduction of $^8\text{B}$ neutrinos production to a modest amount. If minimal standard electroweak theory is correct, the shape of the $^8\text{B}$ neutrino energy spectrum is independent of all solar influences to very high accuracy.

Unless the experiments are seriously in error, there must be some problems with either our understanding of the Sun or neutrinos. Clearly, the SSM cannot account for the data (see Fig.3) and possible highly nonstandard solar models are strongly constrained by heliosysmology studies (See Fig.(4)).

There are at least two reasonable particle physics explanations that could account for the suppression of intermediate energy neutrinos. The first one, neutrino oscillations in vacuum, requires a large mixing angle and a seemingly unnatural fine tuning of neutrino oscillation length with the Sun-Earth distance for intermediate energy neutrinos. The second possibility, level-crossing effect oscillations in presence of solar matter and/or magnetic fields of regular and/or chaotic nature (MSW, RSFP), requires no fine tuning either for mixing parameter or neutrino mass difference to cause a selective large reduction of the neutrino flux. This mechanism explains naturally the suppression of intermediate energy neutrinos, leaving the low energy pp neutrino flux intact and high energy $^8\text{B}$ neutrinos only loosely suppressed. Concrete range of parameters obtained including the latest SK data will be showed in the next section.

![Figure 3: The severity of the problem with astrophysical solutions. The constraints on $^8\text{B}$ and $^7\text{Be}$ fluxes (considered as free parameters) from the combined Cl, Ga, and Čerenkov experiments (90, 95, and 99% C.L.) are shown. The best fit solutions are obtained for unphysical values. Diverse standard and nonstandard solar models are shown. [From Hata and Langacker, Ref. (23) and references therein.]](image-url)
Figure 4: The excellent agreement between the calculated (solar model BP98) and the measured (Sun) sound speeds. The fractional error is much smaller than generic fractional changes in the model, 0.03 to 0.08, that might significantly affect the solar neutrino predictions. [Adapted from Christensen-Dalsgaard, Ref.[24], as it appears in [25].]

4.3 The SK detector and Results.

The high precision and high statistics Super-Kamiokande (SK) experiment initiated operation in April 1996. A few words about the detector itself. SK is a 50-kiloton water Cerenkov detector located near the old Kamiokande detector under a mean overburden of 2700 meter-water-equivalent. The effective fiducial volume is 22.5 kt. It is a well understood, well calibrated detector. The accuracy of the absolute energy scale is estimated to be ±2.4% based on several independent calibration sources: cosmic ray through-going and stopping muons, muon decay electrons, the invariant mass of π0’s produced by neutrino interactions, radioactive source calibration, and, as a novelty in neutrino experiments, a 5-16 MeV electron LINAC. In addition to the ability of recording higher statistics in less time, due to the much larger dimensions of the detector, SK can contain multi-GeV muon events making possible for the first time a measurement of the spectrum of μ-like events up to ∼8 − 10 GeV/c.

The results from the first 504 days of data from SK (results presented recently at the Neutrino98 conference [24]), combined with data from earlier experiments provide important constraints on the MSW and vacuum oscillation solutions for the solar neutrino problem (SNP). In the next paragraphs we will present a summary of the results presented in that conference together with initial analysis in the framework of neutrino oscillations.

The most robust results of the solar neutrino experiments so far are the total observed rates. The most recent data on rates are summarized in table (1). Total rates alone indicate that the νe energy spectrum from the Sun is distorted. The SSM flux predictions are inconsistent with the observed rates in solar neutrino experiments at approximately the 20σ level. Furtherly, there is no linear combination of neutrino fluxes that can fit the available data at the 3σ level (Fig.(3)).

From a two-flavor analysis of the total event rates in the ClAr, SAGE,GALLEX and SK experiments the best χ² fit considering active neutrino oscillations is obtained for Δm² =
| Experiment      | Target | E. Th. (MeV) | $S_{Data}/S_{SSM}$ (1σ) |
|-----------------|--------|-------------|-------------------------|
| Homestake       | $^{37}$Cl | 0.8         | 0.33 ± 0.029            |
| Kamiokande      | $^{1}H_{2}O$ | $\sim 7.5$ | 0.54 ± 0.07             |
| SAGE            | $^{71}$Ga | 0.2         | 0.52 ± 0.06             |
| GALLEX          | $^{71}$Ga | 0.2         | 0.60 ± 0.06             |
| SK (504 days)   | $^{1}H_{2}O$ | $\sim 6.5$ | 0.474 ± 0.020           |

Table 1: Neutrino event rates measured by solar neutrino experiments, and corresponding predictions from the SSM (see Ref. [27] and references therein, we take the INT normalization for the SSM data (1σ errors).

$5.4 \times 10^{-6}$ eV$^2$, $\sin^2 2\theta = 6.0 \times 10^{-3}$ (the so called small mixing angle solution, SMA). Other local $\chi^2$ minima exist. The large mixing angle solution (LMA) occurs at $\Delta m^2 = 1.8 \times 10^{-5}$ eV$^2$, $\sin^2 2\theta = 0.76$, the LOW solution (lower probability, low mass), at $\Delta m^2 = 7.9 \times 10^{-8}$ eV$^2$, $\sin^2 2\theta = 0.96$. The vacuum oscillation solution occurs at $\Delta m^2 = 8.0 \times 10^{-11}$ eV$^2$, $\sin^2 2\theta = 0.75$. At this extremely low value for the mass difference the MSW effect is inoperant.

For oscillations involving sterile neutrinos (the matter effective potential is modified in this case) the LMA and LOW solutions are not allowed and only the (only slightly modified) SMA solution together with the vacuum solution are still possible.

More sophisticated analysis including more than two neutrino species are not available but they would not change so much the previous picture while introducing a much larger technical difficulty. Analysis which consider neutrino oscillations in presence of magnetic fields, the RSFP effect, have also been presented. Typically, they yield solutions with $\Delta m^2 \sim 10^{-7} - 10^{-8}$ eV$^2$ for both small and large mixing angles. RSFP solutions are much more ambiguous than pure MSW solutions because of necessity to introduce additional free parameters in order to model the largely unknown intensity and profile of solar magnetic fields. The recognition of the random nature of solar convective fields and recent theoretical developments in the treatment of Schroedinger random equations have partially alleviated this situation, allowing the obtention of SNP solutions without the necessity of a detailed model description (see recent analysis in [28, 29, 30]). In addition, random RSFP models predict the production of a sizeable quantity of electron antineutrinos. Presently, antineutrino searches with negative results in Kamiokande and SK are welcome because restrict significantly the, uncomfortably large, parameter space of RSFP models. In the future such antineutrinos could be identified both in SK or in SNO setting the Majorana nature of the neutrino ([28, 29, 30]).

If MSW oscillations are effective, for a certain range of neutrino parameters the observed event rate will depend upon the zenith angle of the Sun (Earth matter regeneration effect). After 504 days of data still, due to lack of statistics, the most robust estimator of zenith angle dependence by now is the Day-night (or up-down) asymmetry, A. The experimental estimation is:

$$A \equiv \frac{D - N}{D + N} = -0.023 \pm 0.020 \pm 0.014, \quad (E_{recoil} > 6.5 \text{ MeV}).$$  \hspace{1cm} (8)

The difference is small and not statistically significant but it is in the direction that would be expected from regeneration at Earth (the Sun is apparently neutrino brighter at night).
alone the small value observed for $A$ excludes a large part of the parameter region that is allowed if only the total rates would be considered (see Fig. 3).

From the independence from astrophysical causes, the shape of the neutrino spectrum determines the shape of the recoil electron energy spectrum produced by neutrino-electron scattering in the detector. All the neutrino oscillation solutions (SMA, LMA, LOW and Vacuum) provide acceptable, although indeed not excellent fits to the recoil energy spectrum. The simplest test is to investigate whether the ratio, $R$, of the observed to the standard energy spectrum is a constant. The fit of the ratio $R$ to a linear function yields slope values which are incompatible at 99% CL with the hypothesis of no distortion (see Figs. 5, 6).

In the case where all data, the total rates, the zenith-angle dependence and the recoil energy spectrum, is combined the best-fit solution is almost identical to what is obtained for the rates only case. For other solutions, only the SMA and vacuum solution survives (at the 99% CL). The LMA and the LOW solutions are, albeit marginally, ruled out [27].

A small but significant discrepancy appears when comparing the predictions from the global best fits for the energy spectrum at high energies ($E_\nu \gtrsim 13$ MeV) with the SK results presented in Neutrino98 [26]. From this discrepancy it has been speculated that hep neutrinos may affect the solar neutrino energy spectrum. Presently low energy nuclear physics calculations of the rate of the hep reaction are highly uncertain (a factor of six is allowed). Coincidence between expected and measured ratios is improved when the hep flux is allowed to vary as a free parameter (see Fig. 7).
Figure 5: The result of the MSW parameter space (shaded regions) allowed by the combined observations at 95% C.L. assuming the Bahcall-Pinsonneault SSM with He diffusion. The constraints from Homestake, combined Kamiokande and Super-Kamiokande, and combined SAGE and GALLEX are shown by the dot-dashed, solid, and dashed lines, respectively. Also shown are the regions excluded by the Kamiokande spectrum and day-night data (dotted lines). [From Hata and Langacker, Ref.([23] and references therein.)]

Figure 6: Deviation from an undistorted energy spectrum. The $1, 2, 3\sigma$ allowed regions are shown in the figure. The ratio of the observed counting rate as a function of electron recoil energy $E_p$ to the expected undistorted energy spectrum was fit to a linear function of energy, with intercept $R_0$ and slope $S_0$. The five oscillation solutions SMA active and sterile, LMA, LOW, and vacuum oscillations, all provide acceptable fits to the data, although the fits are not particularly good. [From Bahcall and Krastev, Ref.(27)].
Figure 7: Nuclear physics calculations of the rate of the hep reaction are uncertain. The figure show the results for the predicted energy spectrum that is measured by SK ([26]). The total flux of hep neutrinos was varied to obtain the best-fit for each scenario. The calculated curves are global fits to all of the data, the chlorine, GALLEX, SAGE, and SK total event rates, the SK energy spectrum and Day-Night asymmetry. [Figure reproduced from Ref.([42])].

Figure 8: The SK multi-GeV data sample. The ratio of the number of FC (fully contained) data events to FC Monte Carlo events versus reconstructed $L/E_\nu$. Points: absence of oscillations. Dashed lines: expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3} \text{eV}^2$ and $\sin^2 2\theta = 1$. The slight $L/E_\nu$ dependence for $e$-like events is due to contamination (2-7\%) of $\nu_\mu$ CC interactions. [From Ref.[33]]
4.4 Atmospheric neutrinos

Atmospheric neutrinos are the decay products of hadronic showers produced by cosmic ray interactions in the atmosphere. The experimental ratio $R$

$$R \equiv \frac{\langle \mu/e \rangle_{DATA}}{\langle \mu/e \rangle_{MC}}$$

where $\mu/e$ denotes the ratio of the numbers of $\mu$-like to $e$-like neutrino interactions observed in the data or predicted by the simulation has been measured as an estimator of the atmospheric neutrino flavor ratio $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$. The individual absolute neutrino flux calculation has a 20% uncertainty. The flux ratio has been calculated however to an accuracy of better then 5% in the range $0.1-10$ GeV. The calculated flux ratio has a value of about 2 for energies $< 1$ GeV and increases with increasing neutrino energy. For neutrino energies higher than a few GeV, the fluxes of upward and downward going neutrinos are expected to be nearly equal; geomagnetic field effects at these energies are expected to be small because of the relative large geomagnetic rigidity of the primary cosmic rays that produce these neutrinos.

Anomalous, statistically significant, low values of the ratio $R$ has been obtained previously in the water Cerenkov detectors Kamiokande and IMB-3 and the Soudan-2 for “sub-GeV” events ($E_{vis} < 1$ GeV). The NUSEX and Frejus experiments have reported results consistent with no deviation from unity with smaller data samples. Kamiokande experiment observed a value of $R$ smaller than unity in the multi-GeV ($E_{vis} > 1$ GeV) energy region as well as a dependence of this ratio on the zenith angle. IMB-3, with a smaller data sample, reported inconclusive results in a similar energy range but they are not in contradiction with Kamiokande observations.

SuperKamiokande (SK) recent results are completely consistent with previous results but they are more accurate than before. Specially significant improvements in accuracy have been obtained in measuring the zenith angular dependence of the neutrino events. They see that the flux of muon neutrinos going up is smaller than that of downgoing neutrinos: In the sub-GeV range ($E_{vis} < 1.33$ GeV), from an exposure of 22.5 Kiloton-years of the SK detector the measured ratio $R$ is:

$$R = 0.61 \pm 0.03 \pm 0.05.$$  

It is not possible to determine from data, whether the observed deviation of $R$ is due to an electron excess of a muon deficit. The distribution of $R$ with momentum in the sub-GeV range is consistent with a flat distribution within the statistical error as it happens with zenith angle distributions (see right plots in Fig.9). In the multi-GeV range, it has been obtained (for a similar exposure) a ratio $R$ which is slightly higher than at lower energies $R = 0.66 \pm 0.06 \pm 0.08$. For e-like events, the data is apparently consistent with MC. For $\mu$-like events there is a clear discrepancy between measurement and simulation.

A strong distortion in the shape of the $\mu$-like event zenith angle distribution was observed (Plots 89). The angular correlation between the neutrino direction and the produced charged lepton direction is much better at higher energies ( $\sim 15^0 - 20^0$): the zenith angle distribution of leptons reflects rather accurately that of the neutrinos in this case. The ratio of the number of upward to downward $\mu$-like events was found to be

$$(N_{up}/N_{down})^\mu_{Data} = 0.52^{+0.07}_{-0.06} \pm 0.01$$
while the expected value is practically one: \( \frac{N_{\text{up}}}{N_{\text{down}}}^{\text{MC}} = 0.98 \pm 0.03 \pm 0.2 \). The validity of the results has been tested by measuring the azimuth angle distribution of the incoming neutrinos, which is insensitive to a possible influence from neutrino oscillations. This shape agreed with MC predictions which were nearly flat.

The most obvious solution to the observed discrepancy is \( \nu_\mu \rightarrow \nu_\tau \) flavor neutrino oscillations. This fits well to the angular distribution, since there is a large difference in the neutrino path-length between upward-going (\( \sim 10^4 \) Km) and downward-going (\( \sim 20 \) Km), a zenith angle dependence of \( R \) can be interpreted as evidence for neutrino oscillations. Oscillation into sterile neutrinos, \( \nu_\mu \rightarrow \nu_s \), is also a good explanation consistent with data. \( \nu_\mu - \nu_e \) oscillations does not fit however so well, they would also conflict laboratory measurements (CHOOZ,Figs.(1-10)). Apart from neutrino oscillation, no other consistent explanation has been proposed.

Evidence for oscillations equals evidence for non-zero neutrino mass within the standard neutrino theory. The allowed neutrino oscillation parameter regions obtained by Kamiokande and SK from different analysis are shown in Fig.(10). The best fit is obtained for squared mass differences in the range \( 10^{-2} - 10^{-3} \text{ eV}^2 \), and very large mixing. Unless there is no fine tuning, this suggests a neutrino mass of the order of 0.1 eV. Such a mass implies the neutrino energy density in the universe to be 0.001 of the critical density which is too small to have cosmological consequences. This is of course a very rough argument: specific models, however, may allow larger neutrino masses quite naturally.

Figure 9: Angular distribution for Super-Kamiokande electron-like and muon-like sub-GeV and multi-GeV events. Predictions in the absence of oscillation (thick solid line), \( \nu_\mu \rightarrow \nu_e \) (thin solid line), \( \nu_\mu \rightarrow \nu_s \) (dashed line) and \( \nu_\mu \rightarrow \nu_\tau \) (dotted line). The errors displayed in the experimental points is only statistical. [From Ref.[34]]
Figure 10: The allowed neutrino oscillation parameter regions obtained by Kamiokande and SK (90% C.L.). (1) and (2): the regions obtained by contained event analyses from Super-Kamiokande and Kamiokande, respectively. (3) and (4): upward through-going muons from SK and Kamiokande, respectively. (5) stopping/through-going ratio analysis of upward going muons from SK. [From Ref. 35]

Figure 11: Conclusive probes of lepton number violation in solar neutrino experiments. Iso-sigma contours for the SNO for the combined CC-shape and CC/NC test, for the representative oscillation cases. Iso-sigma contours for the combined CC-shape and CC/NC test, for representative oscillation cases. STD = standard (no oscillation); SMA = small mixing angle (MSW); LMA = large mixing angle (MSW); VAC = vacuum oscillation. [From Ref. 32]
4.5 Global multi-fold analysis and the necessity for sterile neutrinos.

From the individual analysis of the data available from neutrino experiments, it follows that there exist three different scales of neutrino mass squared differences and two different ranges of small and maximal mixing angles, namely:

\[ \Delta m^2_{\text{sun}} \sim 10^{-5} - 10^{-8} \ \text{eV}^2, \quad \sin^2 2\theta \sim 7 \times 10^{-3} (\text{MSW, RSFP}), \]
\[ \sim 10^{-10} \ \text{eV}^2, \quad \sin^2 2\theta \sim 0.8 - 0.9 (\text{Vac.}); \] (9)

\[ \Delta m^2_{\text{Atm}} \sim 5 \times 10^{-3} \ \text{eV}^2, \quad \sin^2 2\theta \sim 1 \] (10)

\[ \Delta m^2_{\text{LSND}} \sim 3 \times 10^{-1} - 2 \ \text{eV}^2 \quad \sin^2 2\theta \sim 10^{-3} - 10^{-2}. \] (11)

Fortunately for the sake of simplicity the neutrino mass scale relevant for HDM is roughly similar to the LSND one. The introduction of the former would not change any further conclusion. But for the same reason, the definitive refutation of LSND results by KARMEN or future experiments does not help completely in simplifying the task of finding a consistent framework for all the neutrino phenomenology.

Any combination of experimental data which involves only of the two mass scales can be fitted within a three family scenario, but solving simultaneously the solar and atmospheric problems requires generally some unwelcome fine tuning of parameters at the $10^{-2}$ level. The detailed analysis of Ref.[36] obtains for example that solutions with 3 neutrino families which are compatible with the results from SBL inclusive experiments, LSND and solar neutrino experiments are possible. The problem arises when one add the results from CHOOZ, which rule out large atmospheric $\nu_{\mu}\nu_{e}$ transitions and zenith dependence from SK atmospheric data one comes to the necessity of consideration of schemes with four massive neutrinos including a light sterile neutrino. Among the numerous possibilities, complete mass hierarchy of four neutrinos is not favored by existing data [36] nor four-neutrino mass spectra with one neutrino mass separated from the group of the three close masses by the "LSND gap" ($\sim 1$) eV. One is left with two possible options where two double-folded groups of close masses are separated by a $\sim 1$ eV gap:

(A) \[
\begin{align*}
\nu_e \rightarrow \nu_s : & \quad m_1 < m_2 << m_3 < m_4 \\
\nu_{\mu} \rightarrow \nu_{\tau} : & \quad \text{LSND}\sim 1 \text{eV}
\end{align*}
\]

(B) \[
\begin{align*}
\nu_e \rightarrow \nu_{\tau} : & \quad m_1 < m_2 << m_3 < m_4 \\
\nu_{\mu} \rightarrow \nu_s : & \quad \text{LSND}\sim 1 \text{eV}
\end{align*}
\]

The two models would be distinguishable from the detailed analysis of future solar and atmospheric experiments. For example they may be tested combining future precise recoil electron spectrum in $\nu e \rightarrow \nu e$ measured in SK and SNO [36] with the SNO spectrum measured in CC absorption. The SNO experiment (a 1000 t heavy water under-mine detector) will measure the rates of the charged (CC) and neutral (NC) current reactions induced by solar neutrinos in deuterium:

\[ \nu_e + d \rightarrow p + p + e^- \quad (\text{CC absorption}), \quad \nu_x + d \rightarrow p + n + \nu_x \quad (\text{NC dissociation}). \] (15)

including the determination of the electron recoil energy in the CC reaction. Only the more energetic $^8$B solar neutrinos are expected to be detected since the expected SNO threshold for
CC events is an electron kinetic energy of about 5 MeV and the physical threshold for NC dissociation is the binding energy of the deuteron, \( E_b = 2.225 \text{ MeV} \). If the (B) model it is true one expects \( \phi^{CC}/\phi^{NC} \sim 0.5 \) while in the (A) model the ratio would be \( \sim 1 \). The schemes (A) and (B) give different predictions for the neutrino mass measured in tritium \( \beta \)-decay and for the effective Majorana mass observed in neutrinoless double \( \beta \) decay. Respectively we have \( |<m| \sim m_4 (A) \) or \( <<m_4 (B) \). Thus, if scheme (A) is realized in nature this kind of experiments can see the effect of the LSND neutrino mass.

From the classical LEP requirement \( N^{act}_\nu = 2.994 \pm 0.012 \) \[3\], it is clear that the fourth neutrino should be a \( SU(2) \otimes U(1) \) singlet in order to ensure that does not affect the invisible \( Z \) decay width. The presence of additional weakly interacting light particles, such as a light sterile \( \nu_s \), is constrained by BBN since it would enter into equilibrium with the active neutrinos via neutrino oscillations. The limit \( \Delta m^2 \sin^2 2\theta < 3 \times 10^{-6} \text{ eV}^2 \) should be fulfilled in principle. However systematical uncertainties in the derivation of the BBN bound make any bound too unreliable to be taken at face value and can eventually be avoided \[8\]. Taking the most restrictive options (giving \( N^{eff}_\nu < 3.5 \)) only the (A) scheme is allowed, one where the sterile neutrino is mainly mixed with the electron neutrino. In the lest restrictive case \( N^{eff}_\nu < 4.5 \) both type of models would be allowed.

## 5 Conclusions and future perspectives.

The theoretical challenges that the present phenomenological situation offers are two at least: to understand origin and, very particularly, the lightness of the sterile neutrino (apparently requiring a radiatively generated mass) and to account for the maximal neutrino mixing indicated by the atmospheric data which is at odd from which one could expect from considerations of the mixing in the quark sector. Actually, the existence of light sterile neutrinos could even be beneficial in diverse astrophysical and cosmological scenarios (supernova nucleosynthesis, hot dark matter, lepton and baryon asymmetries for example).

In the last years different indications in favor of nonzero neutrino masses and mixing angles have been found. These evidences include four solar experiments clearly demonstrating an anomaly compared to the predictions of the Standard Solar Model (SSM) and a number of other atmospheric experiments, including a high statistics, well calibrated one, demonstrating a quite different anomaly at the Earth scale.

One could argue that if we are already beyond the stage of having only ”circumstantial evidence for new physics”, we are still however a long way from having ”conclusive proof of new physics”. Evidence for new physics does not mean the same as evidence for neutrino oscillations but there exists a significant case for neutrino oscillations and hence neutrino masses and mixing as ”one”, indeed the most serious candidate, explanation of the data. One of the possible alternatives is that one or more of the experiments will turn out to be wrong. This is possible and even probable, but it is little probable that with all the evidence accumulated by now all the experiments turn out to be simultaneously wrong.

Many neutrino experiments are taking data, are going to start or are under preparation: solar neutrino experiments (SNO and Borexino are of major interest, also HERON, HELLAZ,
ICARUS, GNO and others); LBL reactor (CHOOZ, Palo Verde, KamLand) and accelerator experiments (K2K, MINOS, ICARUS and others); SBL experiments (LSND, KARMEN, BooNE and many others). The important problem for any next generation experiment is to find specific and unambiguous experimental probe that the "anomalies" which has been found are indeed signals of neutrino oscillations and to distinguish among the different neutrino oscillation possibilities (this is specially important in the Solar case). Among these probes, we could include:

- Perhaps the most direct test of SM deviation: to measure the ratio of the flux of $\nu_e$'s (via a CC interaction) to the flux of neutrinos of all types ($\nu_e + \nu_\mu + \nu_\tau$, determined by NC interactions). This measurement will be done hopefully by the SNO experiment in the near future. See Fig. (11).

- Statistically significant demonstration of an energy-dependent modification of the shape of the electron neutrino spectrum arriving at Earth. Besides observing distortion in the shape of $^8$B neutrinos, it will be very important to make direct measurements of the $^7$Be (Borexino experiment) and pp (HERON,HELLAZ) neutrinos.

- Improved observation of a zenith angle effect in atmospheric experiments or their equivalent, a day-night effect in solar experiments.

- And least, but by no means the least, independent confirmation by one or more accelerator experiments.

There is a high probability that in the near future we should know much more than now about the fundamental properties of neutrinos and their masses, mixing and their own nature whether Dirac or Majorana.

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