Neutrinos: Heralds of New Physics

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The central role of neutrinos in the determination of fundamental interactions is reviewed. The recent SuperKamiokande discovery of neutrino mass gives an \textit{aperçu} of physics at short distances, and tests theories of flavor. Quark-lepton symmetries, derived from grand unification and/or string theories, can help determine the standard model parameters in the neutrino sector.

1. A Neutrino Story

Over the last seventy years, neutrinos have proved to be of central importance for our understanding of fundamental interactions. From their existence which led to Fermi’s theory of $\beta$ decay, to their chiral nature which held the key to parity violation, and again today it is no surprise that it is their masses that give the first indication of new interactions beyond the standard model.

Once it became apparent that the spectrum of $\beta$ electrons was continuous \cite{1,2}, something drastic had to be done! In December 1930, in a letter that starts with typical panache, “Dear Radioactive Ladies and Gentlemen…” W. Pauli puts forward a “desperate” way out: there is a companion neutral particle to the $\beta$ electron. Thus earthlings became aware of the neutrino, so named in 1933 by Fermi (Pauli’s original name, neutron, superseded by Chadwick’s discovery of a heavy neutral particle), implying that there is something small about it, specifically its mass, although nobody at that time thought it was that small.

Fifteen years later, B. Pontecorvo \cite{3} proposes the unthinkable, that neutrinos can be detected: an electron neutrino that hits a $^{37}$Cl atom will transform it into the inert radioactive gas $^{37}$Ar, which can be stored and then detected through radioactive decay. Pontecorvo did not publish the report, perhaps because of the times, or because Fermi thought the idea ingenious but not immediately relevant.

In 1956, using a scintillation counter experiment they had proposed three years earlier \cite{4}, Cowan and Reines \cite{5} discover electron antineutrinos through the reaction $\nu_e + p \rightarrow e^+ + n$. Cowan passed away before 1995, the year Fred Reines was awarded the Nobel Prize for their discovery. There emerge two lessons in neutrino physics: not only is patience required but also longevity: it took 26 years from birth to detection and then another 39 for the Nobel Committee to recognize the achievement! This should encourage physicists to train their children at the earliest age to follow their footsteps at the earliest possible age, in order to establish dynasties of neutrino physicists. Perhaps then Nobel prizes will be awarded to scientific families?

In 1956, it was rumored that Davis \cite{6}, following Pontecorvo’s proposal, had found evidence for neutrinos coming from a pile, and Pontecorvo \cite{7}, influenced by the recent work of Gell-Mann and Pais, theorized that an antineutrino produced in the Savannah reactor could oscillate into a neutrino and be detected. The rumor went away, but the idea of neutrino oscillations was born; it has remained with us ever since.

Neutrinos give up their secrets very grudgingly: its helicity was measured in 1958 by M. Goldhaber \cite{8}, but it took 40 more years for experimentalists to produce convincing evidence for its mass. The second neutrino, the muon neutrino is detected \cite{9} in 1962, (long anticipated by theorists Inoué and Sakata in 1943 \cite{10}). This time things
went a bit faster as it took only 19 years from theory (1943) to discovery (1962) and 26 years to Nobel recognition (1988).

That same year, Maki, Nakagawa and Sakata [1] introduce two crucial ideas: neutrino flavors can mix, and their mixing can cause one type of neutrino to oscillate into the other (called today flavor oscillation). This is possible only if the two neutrino flavors have different masses.

In 1964, using Bahcall’s result [2] of an enhanced capture rate of $^{8}$B neutrinos through an excited state of $^{37}$Ar, Davis [3] proposes to search for $^{8}$B solar neutrinos using a 100,000 gallon tank of cleaning fluid deep underground. Soon after, R. Davis starts his epochal experiment at the Homestake mine, marking the beginning of the solar neutrino watch which continues to this day. In 1968, Davis et al reported [4] a deficit in the solar neutrino flux, a result that stands to this day as a truly remarkable experimental tour de force. Shortly after, Gribov and Pontecorvo [5] interpreted the deficit as evidence for neutrino oscillations.

In the early 1970’s, with the idea of quark-lepton symmetries [6,7] suggests that the proton could be unstable. This brings about the construction of underground detectors, large enough to monitor many protons, and instrumentalized to detect the Čerenkov light emitted by its decay products. By the middle 1980’s, several such detectors are in place. They fail to detect proton decay, but in a remarkable serendipitous turn of events, 150,000 years earlier, a supernova erupted in the large Magellanic Cloud, and in 1987, its burst of neutrinos was detected in these detectors! All of a sudden, proton decay detectors turn their attention to neutrinos, while to this day still waiting for its protons to decay! Today, these detectors have shown great success in measuring solar and atmospheric neutrinos, culminating in SuperKamiokande’s discovery of evidence for neutrino masses.

2. Standard Model Neutrinos

The standard model of electro-weak and strong interactions contains three left-handed neutrinos. The three neutrinos are represented by two- components Weyl spinors, $\nu_i, i = e, \mu, \tau$, each describing a left-handed fermion (right-handed antifermion). As the upper components of weak isodoublets $L_i$, they have $I_{3W} = 1/2$, and a unit of the global $i$th lepton number.

These standard model neutrinos are strictly massless. The only Lorentz scalar made out of these neutrinos is the Majorana mass, of the form $\nu_i^\dagger \nu_j$; it has the quantum numbers of a weak isodoublet, with third component $I_{3W} = 1$, as well as two units of total lepton number. Thus to generate a Majorana mass term at tree-level, one needs a Higgs isodoublet with two units of lepton number. Since the standard model Higgs is a weak isodoublet Higgs, there are no tree-level neutrino masses.

Quantum corrections, on the other hand, are not limited to renormalizable couplings, and it is easy to make a weak isodoublet out of two isodoublets, yielding the $SU(2) \times U(1)$ invariant $L_i^\dagger L_j \cdot H^\dagger H$, where $H$ is the Higgs doublet. As this term is not invariant under lepton number, it is not be generated in perturbation theory. Thus the important conclusion: The standard model neutrinos are kept massless by global chiral lepton number symmetry. Simply put, neutrino masses offer proof of physics beyond the standard model.

3. Neutrino Masses

Direct experimental limits on neutrino masses are quite impressive, $m_{\nu_e} < 10$ eV, $m_{\nu_\mu} < 170$ keV, $m_{\nu_\tau} < 18$ MeV [8], and neutrinos must be extraordinarily light. Any model that generates neutrino masses must contain a natural mechanism that explains their small value, relative to that of their charged counterparts.

We just mention one way to generate neutrino masses without new fermions: add lepton number carrying Higgs fields to the standard model which break lepton number explicitly or spontaneously through their interactions.

Perhaps the simplest way to give neutrinos masses is to introduce for each one an electroweak singlet Dirac partner, $\overline{N}_i$. These appear naturally in the grand unified group $SO(10)$. Neutrino Dirac masses are generated by the couplings $L_i \overline{N}_j H$ after electroweak breaking. Un-
which are like quark and charged lepton masses

$$m \sim \Delta I_w = 1/2.$$  

Based on recent ideas from string theory, it has been proposed [13] that the world of four dimensions is in fact a “brane” immersed in a higher dimensional space. In this view, all fields with electroweak quantum numbers live on the brane, while standard model singlet fields can live on the “bulk” as well. One such field is the gravitron, others could be the right-handed neutrinos. Their couplings to the brane are reduced by geometrical factors, and the smallness of neutrino masses is due to the naturally small coupling between brane and bulk fields.

In the absence of any credible dynamics for the physics of the bulk, and the belief that “one neutrino on the brane is worth two in the bulk”, we take the more conservative approach where the bulk does opens up, but at much shorter scales. One indication of such a scale is that at which the gauge couplings unify, the other is given by the value of neutrino masses. The situation is remedied by introducing Majorana mass terms $\nu_i \nu_j$ for the right-handed neutrinos. The masses of these new degrees of freedom is arbitrary, since it has no electroweak quantum numbers live on the brane, and the bulk does opens up, but at much shorter scales.

The flavor mixing comes from two different parts, the diagonalization of the charged lepton Yukawa couplings, and that of the neutrino masses. From the charged lepton Yukawas, we obtain $U_e$, the unitary matrix that rotates the lepton doublets $L_i$. From the neutrino Majorana matrix, we obtain $U_\nu$, the matrix that diagonalizes the Majorana mass matrix. The $6 \times 6$ seesaw Majorana matrix can be written in $3 \times 3$ block form

$$M = \mathcal{V}_\nu \mathcal{D} \mathcal{V}_\nu \sim \left( \begin{array}{cc} U_\nu & d_{\nu} U_{\nu}^\dagger \\ d_{\nu} U_{\nu} & U_{\nu} \end{array} \right),$$  

where $\epsilon$ is the tiny rastio of the electroweak to lepton number violating scales, and $\mathcal{D} = \text{diag}(\epsilon^2 D_\nu, D_N)$, is a diagonal matrix. $D_\nu$ contains the three neutrino masses, and $\epsilon^2$ is the seesaw suppression. The weak charged current is then given by

$$j^+ \mu = e_i \sigma_{\mu j} U_{MNS} \nu_j ,$$  

is the matrix first introduced in ref [11], the analog of the CKM matrix in the quark sector.

In the seesaw-augmented standard model, this mixing matrix is totally arbitrary. It contains, as does the CKM matrix, three rotation angles, and one CP-violating phase, and also two additional CP-violating phases which cannot be absorbed in a redefinition of the neutrino fields, because of their Majorana masses (these extra phases can be measured only in $\Delta C = 2$ processes). All these additional parameters await to be determined by experiment, although maximal $\nu_\mu - \nu_\tau$ mixing was anticipated long ago [21,22] on the basis of grand unified ideas.

4. Present Experimental Issues

The best direct limit on the electron neutrino mass come from Tritium $\beta$ decay, but it does not specify its type, Dirac or Majorana-like. An important clue is the absence of neutrinoless double $\beta$ decay, which puts a limit on electron lepton number violation.

Much smaller neutrino masses can be detected through neutrino oscillations. These can be observed using natural sources of neutrinos; some
are somewhat understood and predictable, such as neutrinos produced in cosmic ray secondaries, neutrinos produced in the sun; others, such as neutrinos produced in supernovas close enough to be detected are much rarer. The second type of experiments monitor neutrinos from reactors, and the third type uses accelerator neutrino beams. Below we give a brief description of some of these experiments.

- **Atmospheric Neutrinos**
  Neutrinos produced in the decay of secondaries from cosmic ray collisions with the atmosphere have a definite flavor signature: there are twice as many muon like as electron like neutrinos and antineutrinos, simply because pions decay all the time into muons. It has been known for sometime that this 2:1 ratio differed from observation, hinting at a deficit of muon neutrinos. However last year SuperK [23] was able to correlate this deficit with the length of travel of these neutrinos, and this correlation is the most persuasive evidence for muon neutrino oscillations: after birth, muon neutrinos do not all make it to the detector as muon neutrinos; they oscillate into something else, which in the most conservative view, should be either an electron or a tau neutrino. However, a nuclear reactor experiment, CHOOZ, rules out the electron neutrino as a candidate. Thus there remains two possibilities, the tau neutrino or another type of neutrino that does not interact weakly, a sterile neutrino. The latter possibility is being increasingly disfavored by a careful analyses of matter effects: it seems that muon neutrinos oscillate into tau neutrinos. The oscillation parameters are

\[
(m_{\nu_\mu} - m_{\nu_\tau}) \sim 10^{-3} \text{eV}^2; \quad \sin^2 2\theta_{\nu_\mu-\nu_\tau} \geq .86 . \quad (6)
\]

Although this epochal result stands on its own, it should be confirmed by other experiments. Among these is are experiments that monitor muon neutrino beams, both at short and long baselines.

- **Solar Neutrinos**
  Starting with the pioneering Homestake experiment, there is clearly a deficit in the number of electron neutrinos from the Sun. This has now been verified by many experiments, probing different ranges of neutrino energies and emission processes. This neutrino deficit can be parametrized in three ways

- Vacuum oscillations [24] of the electron neutrino into some other species, sterile or active, can fit the present data, with large mixing angle, \(\sin^2 2\theta_{\nu_e-\nu_\tau} \geq .7\), and

\[
(m_{\nu_e}^2 - m_{\nu_\tau}^2) \sim 10^{-10} - 10^{-11} \text{eV}^2 . \quad (7)
\]

This possibility implies a seasonal variation of the flux, which the present data is so far unable to detect.

- MSW oscillations [23]. In this case, neutrinos produced in the solar core traverse the sun like a beam with an index of refraction. For a large range of parameters, this can result in level crossing region inside the sun. There are two distinct cases, according to which the level crossing is adiabatic or not. These interpretations yield different ranges of fundamental parameters.

  The non-adiabatic layer yields the small angle solution, \(\sin^2 2\theta_{\nu_e-\nu_\tau} \geq 2 \times 10^{-3}\), and

\[
(m_{\nu_e}^2 - m_{\nu_\tau}^2) \sim 5 \times 10^{-6} \text{eV}^2 . \quad (8)
\]

The adiabatic layer transitions yields the large angle solution, \(\sin^2 2\theta_{\nu_e-\nu_\tau} \geq .65\) with,

\[
(m_{\nu_e}^2 - m_{\nu_\tau}^2) \sim 10^{-4} - 10^{-5} \text{eV}^2 . \quad (9)
\]

This solution implies a detectable day-night asymmetry in the flux.

How do we distinguish between these possibilities? Each of these implies different distortions of the Boron spectrum from the laboratory measurements. In addition, the highest energy solar neutrinos may not all come from Boron decay: some are expected to be “hep” neutrinos coming from \(p + ^3He \rightarrow ^4He + e^+ + \nu_e\).

In their measurement of the recoil electron spectrum, SuperK data show an excess of high end events, which would tend to favor vacuum
oscillations. They also see a mild day-night asymmetry effect which would tend to favor the large angle MSW solution. In short, their present data does not allow for any definitive conclusions, as it is self-contradictory.

A new solar neutrino detector, the Solar Neutrino Observatory (SNO) now coming on-line, should be able to distinguish between these scenarios. It contains heavy water, allowing a more precise determination of the electron recoil energy, as it involves the heavier deuterium. Thus we expect a better resolution of the Boron spectrum’s distortion. Also, with neutron detectors in place, SNO will be able to detect all active neutrino species through their neutral current interactions. If successful, this will provide a smoking gun test for neutrino oscillations.

- **Accelerator Oscillations**

These have been reported by the LSND collaboration [26], with large angle mixing between muon and electron antineutrinos. This result has been partially challenged by the KARMEN experiment which sees no such evidence, although they cannot rule out the LSND result. This controversy will be resolved by an upcoming experiment at FermiLab, called MiniBoone. This is a very important issue because, assuming that all experiments are correct, the LSND result requires a sterile neutrino to explain the other experiments, that is both light and mixed with the normal neutrinos. This would require a profound rethinking of our ideas about the low energy content of the standard model.

At the end of this Century, there remains several burning issues in neutrino physics that are likely to be soon settled by experiments:

- **Origin of the Solar Neutrino Deficit**

This is being addressed by SuperK, in their measurement of the shape of the $^8 B$ spectrum, of day-night asymmetry and of the seasonal variation of the neutrino flux. Their reach will soon be improved by lowering their threshold energy.

SNO is joining the hunt, and is expected to provide a more accurate measurement of the Boron flux. Its *raison d'être*, however, is the ability to measure neutral current interactions. If there are no sterile neutrinos, we might have a flavor independent measurement of the solar neutrino flux, while measuring at the same time the electron neutrino flux!

This experiment will be joined by BOREXINO, designed to measure neutrinos from the $^7 Be$ capture. These neutrinos are suppressed in the small angle MSW solution, which could explain the results from the $p − p$ solar neutrino experiments and those that measure the Boron neutrinos.

- **Atmospheric Neutrino Deficit**

Here, there are several long baseline experiments to monitor muon neutrino beams and corroborate the SuperK results. The first, called K2K, already in progress, sends a beam from KEK to SuperK. Another, called MINOS, will monitor a FermiLab neutrino beam at the Soudan mine, 730 km away. A third experiment under consideration would send a CERN beam towards the Gran Sasso laboratory (also about 730 km away!). Eventually, these experiments hope to detect the appearance of a tau neutrino.

This brief survey of upcoming experiments in neutrino physics was intended to give a flavor of things to come. These measurements will not only determine neutrino parameters (masses and mixing angles), but will help us answer fundamental questions about the nature of neutrinos, especially the possible kinship between leptons and quarks. The future of neutrino physics is bright, and with much more to come: the production of intense neutrino beams in muon storage rings, and even the detection of the cosmological neutrino background!

5. **Theories**

On the theory side, it must be said that theoretical predictions of lepton hierarchies and mixings depend very much on hitherto untested theoretical assumptions. In the quark sector, where the bulk of the experimental data resides, the theoretical origin of quark hierarchies and mixings is
a mystery, although there exist many theories, but none so convincing as to offer a definitive answer to the community’s satisfaction. It is therefore no surprise that there are more theories of lepton masses and mixings than there are parameters to be measured. Nevertheless, one can formulate the issues in the form of questions:

- Do the right handed neutrinos have quantum numbers beyond the standard model?

- Are quarks and leptons related by grand unified theories?

- Are quarks and leptons related by anomalies?

- Are there family symmetries for quarks and leptons?

The measured numerical value of the neutrino mass difference (barring any fortuitous degeneracies), suggests through the seesaw mechanism, a mass for the right-handed neutrinos that is consistent with the scale at which the gauge couplings unify. Is this just a numerical coincidence, or should we view this as a hint for grand unification?

Grand unified theories, originally proposed as a way to treat leptons and quarks on the same footing, imply symmetries much larger than the standard model’s. Implementation of these ideas necessitates a desert and supersymmetry, but also a carefully designed contingent of Higgs particles to achieve the desired symmetry breaking. That such models can be built is perhaps more of a testimony to the cleverness of theorists rather than of Nature’s. Indeed with the advent of string theory, we know that the best features of grand unified theories can be preserved, as most of the symmetry breaking is achieved by geometric compactification from higher dimensions [27].

An alternative point of view is that the vanishing of chiral anomalies is necessary for consistent theories, and their cancellation is most easily achieved by assembling matter in representations of anomaly-free groups. Perhaps anomaly cancellation is more important than group structure.

Below, we present two theoretical frameworks of our work, in which one deduces the lepton mixing parameters and masses. One is ancient [22], uses the standard techniques of grand unification, but it had the virtue of predicting the large $\nu_\mu - \nu_\tau$ mixing observed by SuperKamiokande. The other [28] is more recent, and uses extra Abelian family symmetries to explain both quark and lepton hierarchies. It also predicted large $\nu_\mu - \nu_\tau$ mixing, while both schemes predict small $\nu_e - \nu_\mu$ mixings.

5.1. A Grand Unified Model

The seesaw mechanism was born in the context of the grand unified group $SO(10)$, which naturally contains electroweak neutral right-handed neutrinos. Each standard model family appears in two irreducible representations of $SU(5)$. However, the predictions of this theory for Yukawa couplings is not so clear cut, and to reproduce the known quark and charged lepton hierarchies, a special but simple set of Higgs particles had to be included. In the simple scheme proposed by Georgi and Jarlskog [29], the ratios between the charged leptons and quark masses is reproduced, albeit not naturally since two Yukawa couplings, not fixed by group theory, had to be set equal. This motivated us to generalize [22] their scheme to $SO(10)$, where it is (technically) natural, which meant that we had an automatic window into neutrino masses through the seesaw. The Yukawa couplings were of the Higgs-heavy, with 126 representations, but the attitude at the time was “damn the Higgs torpedoes, and see what happens”. A modern treatment would include non-renormalizable operators [30], but with similar conclusion. The model yielded the mass relations

$$m_d - m_s = 3(m_e - m_\mu); \quad m_d m_s = m_e m_\mu; \quad (10)$$

as well as

$$m_h = m_\tau, \quad (11)$$

and mixing angles

$$V_{us} = \tan \theta_c = \sqrt{\frac{m_d}{m_s}}; \quad V_{cb} = \sqrt{\frac{m_c}{m_t}}. \quad (12)$$

While reproducing the well-known lepton and quark mass hierarchies, it predicted a long-lived
b quark, contrary to the lore of the time. It also made predictions in the lepton sector, namely maximal $\nu_\tau - \nu_\mu$ mixing, small $\nu_e - \nu_\mu$ mixing of the order of $(m_e/m_\mu)^{1/2}$, and no $\nu_e - \nu_\tau$ mixing.

The neutral lepton masses came out to be hierarchical, but heavily dependent on the masses of the right-handed neutrinos. The electron neutrino mass came out much lighter than those of $\nu_\mu$ and $\nu_\tau$. Their numerical values depended on the top quark mass, which was then supposed to be in the tens of GeVs!

Given the present knowledge, some of the features are remarkable, such as the long-lived $b$ quark and the maximal $\nu_\tau - \nu_\mu$ mixing. On the other hand, the actual numerical value of the $b$ lifetime was off a bit, and the $\nu_e - \nu_\mu$ mixing was too large to reproduce the small angle MSW solution of the solar neutrino problem.

The lesson should be that the simplest SO(10) model that fits the observed quark and charged lepton hierarchies, reproduces, at least qualitatively, the maximal mixing found by SuperK, and predicts small mixing with the electron neutrino [21].

5.2. A Grand Unified Model

There is another way to generate hierarchies, based on adding extra family symmetries to the standard model, without invoking grand unification. These types of models address only the Cabibbo suppression of the Yukawa couplings, and are not as predictive as specific grand unified models. Still, they predict no Cabibbo suppression between the muon and tau neutrinos. Below, we present a pre-SuperK model [28] with those features.

The Cabibbo suppression is assumed to be an indication of extra family symmetries in the standard model. The idea is that any standard model-invariant operator, such as $Q_i \overline{Q}_j H_d$, cannot be present at tree-level if there are additional symmetries under which the operator is not invariant. Simplicity is to assume an Abelian symmetry, with an electroweak singlet field $\theta$, as its order parameter. Then the interaction

$$Q_i \overline{Q}_j H_d \left( \frac{\theta}{M} \right)^{n_{ij}},$$

(13)

can appear in the potential as long as the family charges balance under the new symmetry. As $\theta$ acquires a vev, this leads to a suppression of the Yukawa couplings of the order of $\lambda^{n_{ij}}$ for each matrix element, with $\lambda = \theta/M$ identified with the Cabibbo angle, and $M$ is the natural cut-off of the effective low energy theory. As a consequence of the charge balance equation

$$X_{ij}^{[d]} + n_{ij} \dot{X}_\theta = 0,$$

(14)

the exponents of the suppression are related to the charge of the standard model-invariant operator [31], the sum of the charges of the fields that make up the the invariant.

This simple Ansatz, together with the seesaw mechanism, implies that the family structure of the neutrino mass matrix is determined by the charges of the left-handed lepton doublet fields.

Each charged lepton Yukawa coupling $L_i \overline{N}_j H_u$, has an extra charge $X_{L_i} + X_{N_j} + X_H$, which gives the Cabibbo suppression of the $ij$ matrix element. Hence, the orders of magnitude of these couplings can be expressed as

$$\left( \frac{\lambda^{p_1} 0 0 \lambda^{p_2} 0}{0 \lambda^{s_1} 0 \lambda^{s_2} 0} \right) \dot{Y} \left( \frac{\lambda^{p_1} 0 0}{0 \lambda^{s_1} 0 \lambda^{s_2} 0} \right),$$

(15)

where $\dot{Y}$ is a Yukawa matrix with no Cabibbo suppressions, $l_i = X_{L_i}/X_\theta$ are the charges of the left-handed doublets, and $p_i = X_{N_i}/X_\theta$, those of the singlets. The first matrix forms half of the MNS matrix. Similarly, the mass matrix for the right-handed neutrinos, $\overline{N}_i \overline{N}_j$ will be written in the form

$$\left( \frac{\lambda^{p_1} 0 0 \lambda^{p_2} 0}{0 \lambda^{s_1} 0 \lambda^{s_2} 0} \right) \mathcal{M} \left( \frac{\lambda^{p_1} 0 0}{0 \lambda^{s_1} 0 \lambda^{s_2} 0} \right),$$

(16)

The diagonalization of the seesaw matrix is of the form

$$L_i H_u \overline{N}_j \left( \frac{1}{\mathcal{N} k \mathcal{N}} \right)_{j\mathcal{k}} \overline{N}_k H_u L_i,$$

(17)

from which the Cabibbo suppression matrix from the $\overline{N}_i$ fields cancels, leaving us with

$$\left( \frac{\lambda^{l_1} 0 0 \lambda^{l_2} 0 \lambda^{l_3}}{0 \lambda^{s_1} 0 \lambda^{s_2} 0 \lambda^{s_3}} \right) \dot{M} \left( \frac{\lambda^{l_1} 0 0 \lambda^{l_2} 0 \lambda^{l_3}}{0 \lambda^{s_1} 0 \lambda^{s_2} 0 \lambda^{s_3}} \right),$$

(18)
where $\hat{\mathcal{M}}$ is a matrix with no Cabibbo suppressions. The Cabibbo structure of the seesaw neutrino matrix is determined solely by the charges of the lepton doublets! As a result, the Cabibbo structure of the MNS mixing matrix is also due entirely to the charges of the three lepton doublets. This general conclusion depends on the existence of at least one Abelian family symmetry, which we argue is implied by the observed structure in the quark sector.

The Wolfenstein parametrization of the CKM matrix [22], and the Cabibbo structure of the quark mass ratios

$$
\frac{m_u}{m_t} \sim \lambda^8 \quad \frac{m_c}{m_t} \sim \lambda^4 \quad \frac{m_d}{m_b} \sim \lambda^4 \quad \frac{m_s}{m_b} \sim \lambda^2 ,
$$

(19)

can be reproduced [28,33] by a simple family-traceless charge assignment for the three quark families, namely

$$
X_{Q,\bar{u},d} = \mathcal{B}(2,-1,-1) + \eta_{Q,\bar{u},d} (1,0,-1) ,
$$

(20)

where $\mathcal{B}$ is baryon number, $\eta_{\bar{u}} = 0$, and $\eta_Q = \eta_{\bar{d}} = 2$. Two striking facts are evident:

- the charges of the down quarks, $\bar{d}$, associated with the second and third families are the same,
- $Q$ and $\bar{\pi}$ have the same value for $\eta$.

To relate these quark charge assignments to those of the leptons, we need to inject some more theoretical prejudices. Assume these family-traceless charges are gauged, and not anomalous. Then to cancel anomalies, the leptons must themselves have family charges.

Anomaly cancellation generically implies group structure. In $SO(10)$, baryon number generalizes to $\mathcal{B} - \mathcal{L}$, where $\mathcal{L}$ is total lepton number, and in $SU(5)$ the fermion assignment is $\bar{5} = \bar{d} + L$, and $10 = Q + \pi + \bar{\pi}$. Thus anomaly cancellation is easily achieved by assigning $\eta = 0$ to the lepton doublet $L_i$, and $\eta = 2$ to the electron singlet $\pi_1$, and by generalizing baryon number to $\mathcal{B} - \mathcal{L}$, leading to the charges of the three chiral families

$$
X = (\mathcal{B} - \mathcal{L})(2,-1,-1) + \eta_{Q,\bar{u},d} (1,0,-1) ,
$$

(21)

where now $\eta_{\bar{u}} = \eta_{L} = 0$, and $\eta_Q = \eta_{\bar{d}} = \eta_{\bar{\pi}} = 2$.

The charges of the lepton doublets are simply $X_{\nu} = -(2,-1,-1)$. We have just argued that these charges determine the Cabibbo structure of the MNS lepton mixing matrix to be

$$
U_{MNS} \sim \begin{pmatrix}
0 & \lambda^3 & \lambda^3 \\
\lambda^3 & 1 & 1 \\
\lambda^3 & 1 & 1
\end{pmatrix} ,
$$

(22)

implying no Cabibbo suppression in the mixing between $\nu_\mu$ and $\nu_\tau$. This is consistent with the SuperK discovery and with the small angle MSW [25] solution to the solar neutrino deficit. One also obtains a much lighter electron neutrino, and Cabibbo-comparable masses for the muon and tau neutrinos. Notice that these predictions are subtly different from those of grand unification, as they yield $\nu_\mu - \nu_\tau$ mixing. It also implies a much lighter electron neutrino, and Cabibbo-comparable masses for the muon and tau neutrinos.

On the other hand, the scale of the neutrino mass values depend on the family trace of the family charge(s). Here we simply quote the results our model [28]. The masses of the right-handed neutrinos are found to be of the following orders of magnitude

$$
m_{\nu_e} \sim M \lambda^3 ; \quad m_{\nu_\mu} \sim M_{\nu_\tau} \sim M \lambda^7 ,
$$

(23)

where $M$ is the scale of the right-handed neutrino mass terms, assumed to be the cut-off. The seesaw mass matrix for the three light neutrinos comes out to be

$$
m_\theta \begin{pmatrix}
a \lambda^6 & b \lambda^3 & c \lambda^3 \\
b \lambda^3 & d & e \\
c \lambda^3 & e & f
\end{pmatrix} ,
$$

(24)

where we have added for future reference the prefactors $a, b, c, d, e, f$, all of order one, and

$$
m_\theta = \frac{v_u^2}{M \lambda^8} ,
$$

(25)

where $v_u$ is the vev of the Higgs doublet. This matrix has one light eigenvalue

$$
m_{\nu_e} \sim m_\theta \lambda^6 .
$$

(26)

Without a detailed analysis of the prefactors, the masses of the other two neutrinos come out to be...
both of order $m_0$. The mass difference announced by superK \cite{23} cannot be reproduced without going beyond the model, by taking into account the prefactors. The two heavier mass eigenstates and their mixing angle are written in terms of

\[ x = \frac{df - e^2}{(d + f)^2}, \quad y = \frac{d - f}{d + f}, \quad (27) \]

as

\[ \frac{m_{\nu_2}}{m_{\nu_3}} = \frac{1 - \sqrt{1 - 4x}}{1 + \sqrt{1 - 4x}}, \quad \sin^2 2\theta_{\mu\tau} = 1 - \frac{y^2}{1 - 4x}, \quad (28) \]

If $4x \sim 1$, the two heaviest neutrinos are nearly degenerate. If $4x \ll 1$, a condition easy to achieve if $d$ and $f$ have the same sign, we can obtain an adequate split between the two mass eigenstates. For illustrative purposes, when $0.03 < x < 0.15$, we find

\[ 4.4 \times 10^{-6} \leq \Delta m^2_{\nu_e - \nu_\mu} \leq 10^{-5} \text{ eV}^2, \quad (29) \]

which yields the correct non-adiabatic MSW \cite{25} effect, and

\[ 5 \times 10^{-4} \leq \Delta m^2_{\nu_\mu - \nu_\tau} \leq 5 \times 10^{-3} \text{ eV}^2, \quad (30) \]

for the atmospheric neutrino effect. These were calculated with a cut-off, $10^{16}$ GeV $< M < 4 \times 10^{17}$ GeV, and a mixing angle, $0.9 < \sin^2 2\theta_{\mu\tau} < 1$. This value of the cut-off is compatible not only with the data but also with the gauge coupling unification scale, a necessary condition for the consistency of our model, and more generally for the basic ideas of grand unification.

6. Outlook

Presently, neutrino physics is being driven by many experimental findings that challenge theoretical expectations. Although all can be explained in terms of neutrino oscillations, it is unlikely that they are correct in their conclusions: one must remember that evidence for neutrino oscillations has often been reported, only to either be withdrawn or else contradicted by other experiments.

The reported anomalies associated with solar neutrinos, neutrinos produced in cosmic ray cascades \cite{23}, and also in low energy reactions \cite{26}, cannot all be correct without introducing a new type of neutrino which does not couple to the $Z$ boson, a sterile neutrino \cite{24}.

Small neutrino masses are naturally generated by the seesaw mechanism, which works because of the weak interactions of the neutrinos. A similar mass suppression for sterile neutrinos involves new hitherto unknown interactions, resulting in substantial additions to the standard model, for which there is no independent evidence. Also, the case for a heavier cosmological neutrino in helping structure formation may not be as pressing, in view of the measurements of a small cosmological constant.

Neutrino physics is extremely exciting as it provides the best opportunities for finding and understanding physics beyond the standard model.

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