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C. R. Physique 6 (2005) 719–728

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Neutrino Physics/Physique des neutrinos

Neutrinos: precursors of new physics

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Abstract

Since neutrinos are the only elementary particles that interact only weakly, the study of their properties, albeit experimentally difficult, reflects the true nature of the Weak Interactions. We begin with a historical review, emphasizing the central role of neutrinos in the formulation of the Standard Model. We review the generalizations of the Standard Model needed to accommodate both Dirac and Majorana neutrino masses. The recent experimental findings which demonstrate that neutrinos have tiny masses are discussed. We argue that small neutrino masses as well as the unexpected mixing patterns between the three neutrino flavors give us a glimpse, through the Seesaw mechanism, of physics at or near the Planck scale. ***To cite this article: P. Ramond, C. R. Physique 6 (2005).***

Résumé

Les neutrinos, précurseurs de nouvelle physique. Puisque les neutrinos sont les seules particules élémentaires interagissant uniquement par interaction faible, l'étude de leurs propriétés, difficile expérimentalement, reflète fidèlement la nature de cette force. Une revue historique souligne leur rôle spécifique dans la formulation du modèle standard de la physique des particules. Nous présentons les généralisations de ce modèle nécessaires pour rendre compte de leurs masses (Dirac et Majorana). Nous discutons ensuite les résultats expérimentaux qui ont démontré leur nature massive. Finalement, nous montrons comment les petites masses et les mélanges des trois saveurs de neutrinos peuvent être interprétés par l'intermédiaire du mécanisme de "Seesaw" comme une fenêtre sur la physique à l'échelle de Planck. ***Pour citer cet article : P. Ramond, C. R. Physique 6 (2005).***

Keywords: Neutrino history; Neutrino mass; Beyond standard model

Mots-clés : Histoire du neutrino ; Masse du neutrino ; Au delà du modèle standard

1. Early neutrino stories

Neutrinos, inextricably linked with the history of Weak Interactions [1], continue to play a central role in understanding the Fundamental Interactions of Nature. The recent discoveries of neutrino mass effects provide, no doubt, another clue as to their structure, were we only able to decipher it. It is in that spirit that we begin with a neutrino-centric account of that history.

By the end of the 1920s, Physics and physicists were riding high. Thanks to the insights of De Broglie, Heisenberg and Schrödinger, Quantum Mechanics had just been formulated, opening a window on the workings of atomic and nuclear processes. Yet there were nagging problems. Foremost among these was β-radioactivity. As early as 1911, Von Baeyer, Hahn, and Meit-

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doi:10.1016/j.crhy.2005.07.006

ner [2] had found the β-process to be like α-radioactivity, a two-particle decay, yielding a product nucleus and ejecting a monoenergetic electron. Their conclusion was challenged by the young Chadwick in 1914, but his internment in the Great War precluded more detailed experiments. It was only in 1927 with the definitive experiment of Ellis and Wooster [3] that the issue was resolved: the ejected electron has only a fraction of the available energy. What happened to the rest? In a daring proposal, Bohr, Kramers, and Slater [4] had surmised earlier that energy was conserved only in an average sense in β-decay. Debye quipped *"I do not want to think about it, like the new taxes ... "*.

In 1928 and 1929 another puzzling result comes to light: Kronig and then Heitler and Herzberg, measure the rotational Raman spectra of Nitrogen [5], and conclude that its nuclear spin is an integer, probably one. This result was very puzzling to the physicists of the time who knew that Nitrogen weighs fourteen times as much as Hydrogen, but with an electric charge (measured by the ubiquitous Chadwick in scattering experiments) that is only seven times the Hydrogen nucleus. At a time when only electrons and protons were known, it meant a Nitrogen nucleus made up of fourteen protons with seven tightly bound 'nuclear electrons'. With twenty one spin one-half particles, it should have half-odd integer spin, contradicting the results of Kronig, Heitler and Herzberg.

In 1930, it took the genius of Pauli to seize upon these two experimental puzzles and offer a common resolution: the nucleus contains a hitherto unknown electrically neutral particle with spin one-half, which is ejected with the electron during the β-process. Pauli surmises that his new 'neutron', as he calls it, is bound to the nucleus through its magnetic moment interaction (the Pauli term), which of course requires his particle to have a (small) mass.

It must have been very daring to propose a new fundamental particle. Had it explained only one puzzle, it is likely that Pauli would not have entertained the idea, but a 'twofer' could not be denied! Indeed in his famous letter, Pauli describes his proposal as *"a desperate remedy ... "*. It is only in 1933 at the seventh Solvay conference that Pauli puts his suggestion in print! Forty years later, Dirac [6] captured the spirit of these times

> *" One finds that it is really remarkable how unwilling people were to postulate a new particle. This applies to both theoretical and experimental workers. It seems that they would look for an explanation rather than postulate a new particle. The climate has completely changed since the early days. People are only too keen to publish evidence for a new particle, whether this evidence comes from experiment or from some ill-established theoretical idea."*

Written more than thirty years ago, this comment has gained even more relevance today, when infinite towers of new particles are shamelessly proposed to explain the slightest experimental discrepancies! *'O Tempore! O Mores!'*

Ironically, Nature explains Pauli's puzzles with two distinct particles. Chadwick soon discovers that nuclei do contain electrically neutral spin 1/2 particles. As massive as a proton, it cannot be Pauli's light companion of β-electrons. There is no further need for nuclear electrons, and the Nitrogen nucleus, with fourteen spin one-half particles, seven protons and seven neutrons, regains integer spin status.

However, the β-decay puzzle remained to be explained. Pauli is half-right: another particle is indeed emitted during β-decay.

Fermi [7] sets the stage for the modern theory of Weak Interactions by incorporating both Chadwick's discovery and Pauli's suggestion. He thought in terms of creation and annihilation operators for particles (second quantized theory). During β-decay a nuclear transition takes place when a neutron is destroyed and a proton is created, at the same time that an electron and a (anti)neutrino are created,

$$n \to p + e^- + \bar{\nu}$$

In Fermi's picture, neither electron nor antineutrino pre-exist in the nucleus; both are created in the decay process. Perrin [8] had already recognized that neutrinos must be much lighter than electrons, but Fermi proposes to find kinematic evidence for its mass by examining the high end of the electron spectrum, a method that survives to this day [9]. The subsequent history of Weak Interactions turns out to be an elaboration of Fermi's great paper, and generalizing it to processes as diverse as μ and K-decays.

Most physicists, however, thought that neutrinos would never be detected since they are neutral and interact so very weakly. In 1946, B. Pontecorvo proposed [10] a practical method for detecting low energy neutrinos based on the reaction

$$\nu_e + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar}$$

It is a nice suggestion, said Fermi, but without practical use; intimidated, Pontecorvo never published it! Neutrinos have a way of humbling even the greatest physicists, since Ray Davis was awarded the Nobel Prize for detecting solar neutrinos by means of Pontecorvo's process!

But it did take a quarter of a century to find them. In 1956, Clyde Cowan and Fred Reines [11] finally detected neutrinos (project 'Poltergeist') through the inverse reaction

$$\bar{\nu} + p \to n + e^+$$

by taking advantage of the large flux of antineutrinos generated by the Savannah River reactor. In this reaction, the positron is immediately annihilated, yielding two photons, while the neutron random walks until it is absorbed by Cadmium, which has a high neutron capture cross section, and produces three photons. An antineutrino hit is triggered by two photons followed by three photons. The antineutrino is the only elementary particle discovered south of the Mason–Dixon line!

The same year, T.D. Lee and C.N. Yang [12] suggested Parity violation in weak decays. Soon after, Salam, Landau, and Lee and Yang independently remarked [13] that parity violation opens the way for a very simple description of neutrinos. The Dirac equation splits up in half, so to speak, and neutrinos produced in π decays could have only one spin degree of freedom, and the accompanying muon would be polarized. In equations, the neutrino field appearing in Fermi's Hamiltonian would be the *chiral* combination

$$\nu_L \equiv \frac{1+\gamma_5}{2}\nu(x)$$

or as we know it, a Weyl fermion. They noted that this implied maximal parity violation. The spin of the neutrino was measured in 1957, in an ingenious experiment by M. Goldhaber [14], by applying resonant X-ray scattering to the aftermath of an S-wave electron capture.

The discovery of the muon in cosmic rays, an unstable heavier version of the electron, had led Sakata and Inouë [15] to speculate, as early as 1943, that it must have its own neutrino, distinct from the one associated with the electron. Theoretical arguments, such as the absence of the decay $\mu \to e + \gamma$, suggested electrons and muons did not share a common neutrino, but it was not until the early 1960s that direct evidence for a second neutrino was produced [16]. Finally, with the detection of the τ lepton a decade later, comes a third species of neutrino.

It did not take very long before this idea was generalized to all weak decays, including nucleons, leading to the famous universal $(V - A)$ theory of Marshak and Sudarshan [17] and of Feynman and Gell-Mann [18]. The Fermi interaction is now viewed as the product of spin-one currents, suggesting that it is mediated by a spin one particle, just like Quantum Electrodynamics. Its gauge-invariant structure had already been generalized by Yang and Mills to non-Abelian symmetries, and in 1961, S.L. Glashow [19] writes a series of Yang–Mills models which unify the weak and electromagnetic interactions, one of which has the $SU(2) \times U(1)$ gauge structure. S. Weinberg [20] and A. Salam [21], independently suggest that this gauge symmetry is spontaneously broken, which has the advantage of generating masses for the elementary fermions. In addition to the yet-to-be-found Higgs boson, the GSW model predicts two new massive spin-one particles, the charged $W^{\pm}$-boson and the neutral Z-boson; both were found near their predicted masses. Their model together with the theory of nuclear interactions, which were included through the quarks of M. Gell-Mann and G. Zweig, is now known as the Standard Model of particle physics.

The Standard Model has met every experimental test over a quarter of a Century, until 1998 when SuperKamiokande [22] announces incontrovertible evidence for massive neutrinos.

2. Neutrinos and the Standard Model

The Standard Model is a relativistic non-Abelian Yang–Mills field theory based on the gauge group $SU(2) \times U(1)$ which presents a unified description of weak and electromagnetic interactions. It describes, in addition to electromagnetic interactions and the charge-changing β-interactions, new charge-conserving weak processes. It includes Quantum Chromodynamics, an $SU(3)^c$ gauge theory, where color-carrying quarks are acted upon by eight gluons, the agents of the strong interactions.

2.1. Lorentz invariance and fermions

Lorentz invariance requires a specific description of fermions in field theory that is crucial for understanding neutrino masses. The generators of the Lorentz group split up into two sets of commuting but non-Hermitian generators, $(\vec{J} + i\vec{K})$ and $(\vec{J} - i\vec{K})$, generating $SU(2)$ and $\overline{SU(2)}$, respectively. $\vec{J}$ are the three rotations and $\vec{K}$ the three boosts. $SU(2)$ is related to $\overline{SU(2)}$, either by Parity $(\vec{J} \to \vec{J}, \vec{K} \to -\vec{K})$, or by Charge Conjugation $(i \to -i)$.

Accordingly, there are two types of spinors, the eigenstates of CP (the combined operation of Charge Conjugation and Parity). The first type are the left-handed Weyl fermions, ψ_L which transform as spinors under the first $SU(2)$, and are mute with respect to the second. The second type are mute under the first and spinors under the second are called right-handed Weyl spinors ψ_R. Electrons and positrons are described by *both* left- and right-handed fields, e_L and e_R, accounting for their four degrees of freedom (spin up and down electrons and positrons). Both are necessary to describe the parity-conserving electrodynamics of charged fermions. Gauge interactions do not change handedness (chirality), and the electromagnetic current is the parity-invariant sum of left-handed and right-handed currents.

2.2. Standard Model currents

The salient features of the Standard Model can best be summarized by listing the currents to which the gauge fields couple. Electromagnetic Interactions of charged fermions stem from the coupling of the photon to the electromagnetic current

$$e\,A^{\mu}J^{\rm em}_{\mu}$$

where e is the electromagnetic coupling constant of QED. The charge-changing weak processes are generated by

$$\frac{e}{\sqrt{2}\sin\theta_{\rm w}}\left(W^{+\mu}J^{-}_{\mu}+W^{-\mu}J^{+}_{\mu}\right)$$

where $W^{\pm}_{\mu}$ represent the massive intermediate vector boson and its antiparticle, and $\theta_{\rm w}$ is the Weinberg angle. These are supplemented by the charge-preserving weak process

$$\frac{e}{\cos\theta_{\rm w}\sin\theta_{\rm w}}Z^{\mu}\left(J^{3}_{\mu}-\sin^{2}\theta_{\rm w}J^{\rm em}_{\mu}\right)$$

where Z_{μ} is the massive neutral vector boson. The electromagnetic current is parity conserving and of course does not contain neutrinos. In terms of Weyl fermions the currents for the first family are the electromagnetic current

$$J^{\rm em}_{\mu}=e^{\dagger}_{L}\sigma_{\mu}e_{L}-\frac{2}{3}\mathbf{u}^{\dagger}_{L}\sigma_{\mu}\mathbf{u}_{L}+\frac{1}{3}\mathbf{d}^{\dagger}_{L}\sigma_{\mu}\mathbf{d}_{L}+(L\leftrightarrow R)$$

the charge-changing weak currents

$$J^{+}_{\mu}=e^{\dagger}_{L}\sigma_{\mu}\nu_{eL}+\mathbf{d}^{\dagger}_{L}\sigma_{\mu}\mathbf{u}_{L}$$

and the neutral current

$$J^{3}_{\mu}=\frac{1}{2}\nu^{\dagger}_{eL}\sigma_{\mu}\nu_{eL}-\frac{1}{2}e^{\dagger}_{L}\sigma_{\mu}e_{L}+\frac{1}{2}\mathbf{u}^{\dagger}_{L}\sigma_{\mu}\mathbf{u}_{L}-\frac{1}{2}\mathbf{d}^{\dagger}_{L}\sigma_{\mu}\mathbf{d}_{L}$$

The other two families of elementary particles contribute the same expressions with $(e,\mathbf{u},\mathbf{d})$, replaced by $(\mu,\mathbf{c},\mathbf{s})$ and $(\tau,\mathbf{t},\mathbf{b})$, respectively. The weak currents are fixed in terms of one parameter, the Weinberg angle $\theta_{\rm w}$, which also relates the masses of the vector bosons

$$M^{2}_{W}=M^{2}_{Z}\cos^{2}\theta_{\rm w}$$

valid at lowest order in perturbation theory (tree level). The $SU(2)$ invariance of the Standard Model links the neutrinos to the left-handed charged leptons in doublets of negative unit hypercharge

$$L_{e,\mu,\tau}\equiv\begin{pmatrix}\nu_{eL}\\ e_{L}\end{pmatrix}_{-1},\quad\begin{pmatrix}\nu_{\mu L}\\ \mu_{L}\end{pmatrix}_{-1},\quad\begin{pmatrix}\nu_{\tau L}\\ \tau_{L}\end{pmatrix}_{-1}$$

In the original version of the Standard Model, neutrinos are the only particles without right-handed partners. Quarks and charged leptons, on the other hand, have $SU(2)$-singlet right-handed components.

The decay width of the Z-boson was measured with great accuracy from its Breit-Wigner signature in $e^{+}e^{-}$ annihilation. As we can see from the coupling of the neutral current, Z decays into all particle–antiparticle pairs of mass less than $M_{Z}/2$, including neutrino–antineutrino pairs. The conclusion is that there are no more than three types of light neutrinos. Hence another momentous conclusion, brought about by studying neutrinos: there are only three chiral families of elementary particles. Any other chiral family, if it exists at all, must contain neutrinos that weigh more than half-a-Z-boson. Nature, like bureaucracies, seems to like triplicate copies!

Finally, we note yet another internal consistency of the Standard Model. Triangle anomalies associated with its $U(1)$ hypercharge gauge symmetry can spoil its renormalizability. Remarkably [23], the contribution of the leptons, including neutrinos, around the triangle loop are exactly cancelled by that of the quarks (only for three colors), and ultraviolet finiteness is restored.

2.3. Standard Model masses

The masses of the charged leptons arise from Yukawa couplings of the type

$$L_{f}\overline{f}'H$$

where $f,f'=e,\mu,\tau$. H is the Higgs doublet, with four degrees of freedom, the only spinless particles of the Standard Model. However, the Higgs potential is arranged so that at its minimum, the doublet acquires a vacuum value. This has two consequences: breaking spontaneously the $SU(2)\times U(1)$ gauge symmetry down to Maxwell's $U(1)$, *and* generating masses for the three charged leptons. Of the four Higgs degrees of freedom, three are 'eaten' to provide the massive $W^{\pm}$- and Z-bosons with their longitudinal partners. The lone survivor is the Higgs boson, which is being relentlessly hunted to this day. Its mass is one of two Standard Model parameter yet to be measured, the other being the strength of CP violation by the Strong Interactions.

It contains also similar Yukawa couplings between the three quark doublets

$$\mathbf{Q}_a \equiv \begin{pmatrix} \mathbf{u}_L \\ \mathbf{d}_L \end{pmatrix}_{1/3}, \begin{pmatrix} \mathbf{c}_L \\ \mathbf{s}_L \end{pmatrix}_{1/3}, \begin{pmatrix} \mathbf{t}_L \\ \mathbf{b}_L \end{pmatrix}_{1/3}$$

$a = 1, 2, 3$, and their right-handed partners $\overline{\mathbf{u}'}$ and $\overline{\mathbf{d}'}$

$$\mathbf{Q}_a \overline{\mathbf{d}'} H + \mathbf{Q} \overline{\mathbf{u}'} H^*$$

where $\overline{\mathbf{u}'} = \bar{\mathbf{u}}, \bar{\mathbf{c}}, \bar{\mathbf{t}}$, and $\overline{\mathbf{d}'} = \bar{\mathbf{d}}, \bar{\mathbf{s}}, \bar{\mathbf{b}}$. The mass operators of charged fermions are all weak isodoublets, the same quantum numbers as the order parameter that breaks electroweak symmetry!

There are no mass terms of this kind for neutrinos, since the original formulation of the Standard Model has no right-handed neutrinos: neutrinos are massless.

3. Neutrino masses

In relativistic field theories, fermion mass terms are simply Lorentz singlets which are bilinear in spinor fields. To construct such invariants, we note two facts: conjugates of left-handed fields transform like right-handed fields, and also that the antisymmetric product of two spinors of the same handedness is an invariant. For example, one can build four bilinear Lorentz-invariants out of the electron spinor fields

$$e_L e_L, \ e_R e_R, \ e_L \overline{e_R}, \ e_R \overline{e_L}$$

The first two require only *one* Weyl spinor, but the last two require both left-and right-handed fields. The first two combinations are not mass terms because both e_L and e_R carry electric charge. The electron mass has to be found in the last two, and appears in the Lagrangian as their real symmetric sum

$$m_e (e_L \overline{e_R} + e_R \overline{e_L})$$

This type of mass, with *both* left-handed and right-handed components, is called a *Dirac mass*. It preserves electron (lepton) number, defined to be one for both e_L and e_R, and thus -1 for their conjugates, $\overline{e_R}$ and $\overline{e_L}$.

The same applies to neutrino fields, with the important caveat that the original Standard Model contains neither right-handed neutrinos nor left-handed antineutrinos. With only one ν_L for each flavor, the choice of mass terms is restricted to

$$m_\nu (\nu_L \nu_L + \text{conj.})$$

allowed since neutrinos carry no electric charge. This is called the *Majorana mass* term. Since ν_L carries unit electron (lepton) number, Majorana masses violate lepton number symmetry. The figure of merit that distinguishes Majorana from Dirac masses is fermion number.

Majorana neutrino mass terms are bilinears in the lepton doublets under the weak $SU(2)$, which transform as one component of a weak isotriplet. Without a Higgs isotriplet, there can be no gauge invariant Yukawa coupling at tree level, and thus no mass. Yet, gauge invariance does not forbid such a coupling from being generated in the full quantum Lagrangian. This is because a scalar weak isotriplet can itself be constructed as a Higgs field bilinear. The resulting gauge invariant interaction would be (schematically) of the form

$$\frac{1}{\Lambda} LLHH$$

where Λ has dimension of mass. Still, it is not generated by quantum effects, *only* because it violates the lepton number symmetry. Standard Model neutrinos are kept massless by a *global* symmetry. Presumably Λ denotes the energy scale at which lepton number would be broken.

With three species of neutrinos, the Standard Model naively has four global symmetries, baryon number B, and three lepton numbers, electron number L_e, muon number L_μ, and tau number L_τ. It is convenient to arrange the last three into one overall lepton number and two relative lepton numbers

$$L = (L_e + L_\mu + L_\tau), \ (L_e - L_\mu), \ (L_\mu - L_\tau)$$

Due to quantum anomalies, neither B nor L are separately conserved, only the combination $(B - L)$.

On theoretical grounds global symmetries are simply book-keeping devices, and are not expected to be exact; for one, black holes do not respect them. Breaking of $(B - L)$ could manifest itself through the detection of as diverse phenomena as proton decay, or neutrinoless double β-decay, where two electrons are produced without their neutrinos, or even oscillations between neutrinos and antineutrinos. None of these have been observed to date.

Violation of the relative lepton number symmetries could manifest itself in decays like $\mu \to e + \gamma$, but also in flavor oscillations, where an electron neutrino '*morphs*' through mixing into another neutrino flavor, a muon or tau neutrino. Mixing between particles of different flavors is observable only if they have different masses, although it does not require the mass to be Majorana or Dirac. Majorana masses violate the $(B - L)$ symmetry, while Dirac masses do not. Flavor mixing breaks only the relative lepton number symmetries.

Experimentally, neutrinos are much lighter than their charged lepton partners. Tritium decay, using Fermi's kinematical method, limits the electron neutrino to be lighter than a few eV, and the precision measurements of the inhomogeneities in the microwave background require [24] the sum of the masses of all neutrino species to be less than an electronvolt [25]!

Yet, as we know now, neutrinos have masses. There is now solid evidence for the flavor oscillations of neutrinos. As a result two of the Standard Model's exact global symmetries are broken. This is the first chink in the armor of this most remarkable model.

4. Neutrino oscillations

Since neutrinos interact so weakly, it is not surprising that those who study them, no matter how carefully, can sometimes be led to wrong conclusions. Even the great Pauli was not immune, as we saw earlier. A case in point is the detection of solar neutrinos (see also [26]).

Ever since the 1960s, Ray Davis had been measuring the number of electron neutrinos coming from the Sun. They provide the only direct information from its core. He used Pontecorvo's reaction, by detecting the Argon produced by the very rare highest energy solar electron neutrinos hitting a tank full of Chlorine. He did detect the solar neutrinos [27], a singular achievement, but the solar neutrino flux in that energy range was less than half theoretical expectations. The significance of the result was met with cynicism; W. Fowler quipped that perhaps the Sun had turned off! However, Pontecorvo and Gribov [28] immediately interpreted the result in terms of *flavor* neutrino oscillations: electron neutrinos produced at the core 'morph' into other neutrino flavors which Davis is not equipped to detect, hence the deficit. Interestingly enough, Pontecorvo himself had suggested in the 1950s neutrino–antineutrino oscillations as the interpretation of Ray Davis' 'rumor of a detection' of a neutrino outside a reactor, using of course, Pontecorvo's reaction! Davis's rumor went away but it gave birth to the idea of oscillations in neutrino physics. Note that flavor oscillations violate the *relative* lepton number symmetries but preserve total lepton number, while particle–antiparticle oscillations violate total lepton number. When the second neutrino was detected [16] in 1962, Maki, Nakagawa and Sakata [29] were the first to propose the idea of oscillations between different flavors of neutrinos. Today we know that Davis's Solar neutrino deficit is real and due to flavor oscillations.

Unlike the numerous 'sightings' of neutrino oscillations effects, for which the evidence was either too flimsy, or else withdrawn, Davis's Solar neutrino anomaly was not going away. On the contrary, it was reinforced by a series of brilliant experiments using the same type of reaction as Pontecorvo's, but applied to Gallium, which detects the vastly more plentiful lowest energy neutrinos produced in the Solar core. They also reported deviations from theoretical expectations [30].

In 1998, SuperKamiokande, the giant water Čerenkov detector in Japan, reported solid evidence [22] for neutrino oscillations, not in solar neutrinos, as some had expected, but in its detection of 'atmospheric' neutrinos, born in cosmic ray showers (see [31] for details). In SuperK, an electron (muon) neutrino can produce by elastic scattering an electron (muon) going so fast as to produce a telltale Čerenkov cone, which is detected by arrays of phototubes. The cone points back to the direction of the incoming neutrino. The vast majority of (anti)neutrinos caught in the detector have much higher energy than the solar neutrinos, as they were born in cosmic ray showers. They enter the detector from all directions, since they can easily traverse the earth. SuperK's surprising result: the number of neutrinos of a given flavor (muon and electron) entering the detector depends on their direction. Since they are created isotropically in the upper atmosphere, their direction is related to the length of their travel. The data fits with the quantum mechanical oscillation formula for the detection probability of a muon neutrino in an electron neutrino beam of energy E (in MeV):

$$P(\nu_e \to \nu_\mu)(t) = \sin^2 2\theta \sin^2\left(\frac{2\pi t \Delta m^2}{2.47E}\right)$$

where θ is the mixing angle, and Δm^2 is the difference of the squared masses (in eV^2) (see [32] for more details on neutrino oscillations).

SuperK catches the much rarer solar neutrinos as well, identified as those whose Čerenkov cones point back to the Sun, and their result confirmed the Davis deficit.

This picture was reinforced by the SNO (Sudbury Neutrino Observatory) experiment [33], a tank filled with heavy water. In this case, in addition to electrons, the neutrinos can hit Deuterium as well. Electron neutrinos can dissociate Deuterium via the reaction $\nu_e + D \to e^- + p + p$, producing an easily identifiable final state with two protons. They can also dissociate Deuterium through the rarer 'neutral current' process $\nu_e + D \to \nu_e + n + p$. Its tagging requires enhanced neutron identification. The *raison d'être* of the Sudbury detector is its ability to detect deuterium dissociation by neutral current, irrespective of the flavor of the neutrino that caused it. The intermediate Z-boson which mediates the reaction, couples equally to all flavors, resulting in equal probabilities for $\nu_\mu + D \to \nu_\mu + n + p$ and $\nu_\tau + D \to \nu_\tau + n + p$. Suppose that electron neutrinos oscillate into muon and tau neutrinos on their way from the Sun. Dissociations by neutral current processes measure the total number of neutrinos produced at the Solar core, even if they morph into muon and tau neutrinos on the way. Remarkably, their results are consistent with theoretical calculations [34], and they detect less charged current dissociations by electron neutrinos, verifying the Davis deficit as a result of flavor oscillations.

SNO's first results (together with those from SuperK [35]) suggest that electron neutrinos from the Sun oscillate mostly into muon neutrinos, but very little into tau neutrinos. This was confirmed by the second phase (direct detection of neutrons after flavoring their tank with salt). There does not appear to be any loss of signal, in the sense that there are no detectable oscillations into a fourth species of neutrinos. To escape the limits imposed by Z-boson decay, these would have to be *sterile*, that is without gauge interactions. The reactor experiment KamLAND [36] confirmed later the electron neutrino oscillation in the range of parameters which interpret the solar neutrino data (for more details on solar neutrinos, see for example [26]).

On the other hand, the atmospheric neutrino data from SuperK [22] and K2K [37], a short baseline accelerators-based experiment in the Kamioka detector, paint a different picture for muon neutrinos: they oscillate mostly into τ neutrinos (see [31] for details).

A clear physical picture emerges from these experiments. Neutrinos produced in various weak decays with e^+, μ^+, and τ^+, denoted by ν_e, ν_μ, and ν_τ, respectively are linear combination of three neutrino mass eigenstates, ν_1 , ν_2 , and ν_3. Oscillations measure only their mass differences,

$$\left|m_{\nu_1}^2 - m_{\nu_2}^2\right| \sim 8 \times 10^{-5}\ \mathrm{eV}^2, \qquad \left|m_{\nu_2}^2 - m_{\nu_3}^2\right| \sim 3 \times 10^{-3}\ \mathrm{eV}^2$$

The most stringent bound on the absolute value of the sum of their masses comes from WMAP [24]

$$\sum_i m_{\nu_i} < 0.71\ \mathrm{eV}$$

The observable mixing coefficients relating weak and mass eigenstates are summarized in the matrix

$$\begin{pmatrix} \cos\theta_\odot & \sin\theta_\odot & \sin\theta_{13} \\ -\cos\theta_\oplus \sin\theta_\odot & \cos\theta_\oplus \cos\theta_\odot & \sin\theta_\oplus \\ \sin\theta_\oplus \sin\theta_\odot & -\sin\theta_\oplus \cos\theta_\odot & \cos\theta_\oplus \end{pmatrix}$$

with

$$\theta_\oplus = 45^{\circ}{}^{+10^\circ}_{-10^\circ}, \quad \theta_{13} < 13^\circ, \quad \theta_\odot = 32.5^{\circ}{}^{+2.4^\circ}_{-2.3^\circ}$$

Solar and atmospheric neutrino oscillations are effectively two-body oscillations. Both the atmospheric angle $\theta_\oplus$ and the solar angle $\theta_\odot$ are 'large'. Accelerator experiments [38] have only set a limit on the third angle, θ_{13}, the only one that is possibly similar to the Cabibbo angle of the quark sector. Neutrinos bring more surprises (at least to most theorists [39]): with two large angles, neutrino mixings are very different from those in the quark sector.

The study of neutrinos is not only surprising; it is difficult. There is one experiment that stands in the path to complete consistency. The LSND detector [40] at Los Alamos has found evidence for mixing between $\bar{\nu}_\mu$ and $\bar{\nu}_e$, with a mass difference that contradicts that obtained by SuperK and SNO. Of course, neutrinos and antineutrinos may not behave the same way (CPT violation), but global analyses [41] suggest otherwise. One experiment has to be wrong.

5. Right-handed neutrinos

When Pati and Salam [42] proposed that quarks and leptons are indistinguishable at very short distances, they noted that since all quarks and charged leptons are represented by distinct left- and right-handed partners, neutrinos should also have right-handed partners. The simplest Grand Unified model based on $SU(5)$ [43] does not require right-handed neutrinos, but at the expense of putting the fermions of each family in separate representations. Grand Unified models which assemble each family of fermions into a single representation include right-handed neutrinos.

In view of the qualitative successes of Grand Unification, it seems natural to include these degrees of freedom, and limit our discussion to their implications for neutrino masses, although there are many ways to generate neutrino masses without them.

The addition of right-handed neutrinos suggests Dirac masses if lepton number is exact, but it can also imply Majorana masses if lepton number is violated, but as gravity would say, a mass is a mass.

The simplest Grand-Unified model that includes one right-handed partner for each neutrino is $SO(10)$ [44], where each family of elementary fermions fits nicely into *one* spinor representation. Under the breakdown $SO(10) \supset SU(2) \times U(1) \times SU(3)^c$,

$$\mathbf{16} = \left[(\mathbf{2}, \mathbf{1}^c) + \left(\mathbf{1}, \bar{\mathbf{3}}^c\right)\right] + \left[(\mathbf{2}, \mathbf{3}^c) + \left(\mathbf{1}, \bar{\mathbf{3}}^c\right) + (\mathbf{1}, \mathbf{1}^c)\right] + (\mathbf{1}, \mathbf{1}^c)$$

with particle content (for the lightest family)

$$\left[\begin{pmatrix} \nu_e \\ e \end{pmatrix} + \bar{\mathbf{d}}\right] + \left[\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix} + \bar{\mathbf{u}} + \bar{e}\right] + \overline{N}$$

Unbarred fields are left-handed, barred fields are right-handed. The last entry is the right-handed neutrino, and is a singlet under $SU(2) \times U(1) \times SU(3)^c$. We note that it is equally natural to consider other Grand Unified models, such as E_6 [45], which contain more than one gauge singlet field per family.

For simplicity, we restrict the rest of the discussion to the '*ν-Standard Model*', that is, the Standard Model augmented by one right-handed neutrino for each family. Having neither electric nor weak charges, they can couple to Standard Model fields through Yukawa couplings of the type

$$\overline{N_R} \begin{pmatrix} \nu_{e_L} \\ e_L \end{pmatrix} H$$

shown here for the lightest family. The Higgs vacuum value generates a Dirac neutrino mass of the form

$$m_{\mathrm{Dir}} \overline{N_R} \nu_L$$

Arising from the same mechanism as for quarks and charged leptons, it does not account for the 'remarkable lightness of neutrinos', and the strength of this Yukawa coupling must be extremely small compared to the others.

Fortunately, right-handed neutrinos can have Majorana masses of their own,

$$M_{\mathrm{Maj}} N_R N_R$$

as allowed by Lorentz invariance. Unless lepton number symmetry is preserved, the value of M_{Maj} is undetermined. Electroweak symmetry breaking generates mixing between right- and left-handed neutrinos, so that the fermion mass terms become

$$m_{\mathrm{Dir}} \nu_L \overline{N_R} + M_{\mathrm{Maj}} N_R N_R + \text{c.c.}$$

where m_{Dir} is the Dirac mass limited in value to the scale of electroweak breaking, while M_{Maj} is unrestricted. The physical fields are determined by diagonalizing this mass matrix.

In the limit where M_{Maj} is large compared to the electroweak breaking scale, the mass eigenstates split into one linear combination with mass of the order of M_{Maj}, and one linear combination

$$\nu_{\mathrm{phys}} \approx \nu_L + \varepsilon \overline{N_R}$$

where

$$\varepsilon = \left(\frac{m_{\mathrm{Dir}}}{M_{\mathrm{Maj}}}\right) < 1$$

is the ratio of the electroweak scale breaking to that of lepton number breaking. This neutrino is mostly the one produced in weak decays, and its mass is naturally suppressed

$$m_{\mathrm{neutrino}} \sim \varepsilon m_{\mathrm{Dir}} < m_{\mathrm{Dir}}$$

compared with that of its charged partner. This mixing [46,47], the Seesaw mechanism, naturally produces lighter neutrino masses.

Using this mechanism, Gell-Mann et al. and Yanagida [47] predicted tiny neutrino masses in the milli-eV range, by identifying M_{Maj} with the Grand Unification scale (a few orders of magnitude below the Planck scale), in remarkable agreement with their recently 'observed' values.

Another salutary effect comes from using such a large scale. The N_Rs decay through their Yukawa couplings to Standard Model particles,

$$N \rightarrow \text{Higgs} + \text{lepton}$$

offering a natural mechanism [48] for generating lepton number asymmetry in the early universe. Leptogenesis is now the prime candidate to explain the baryon asymmetry in our present universe (see [25]).

Today, after decades of precision measurements, the three gauge coupling constants of the Standard Model are well determined. Their extrapolation to very short distances, using the renormalization group, shows that they do unify into one value at a Seesaw-like scale, but only if the Standard Model is generalized to Supersymmetry. This scale, first perceived experimentally from the study of neutrinos, would imply a plethora of new supersymmetric partner particles at the upcoming Large Hadronic Collider at CERN.

The seesaw mechanism and this coincidence of scales may be illusory, but they suggest a concise picture of Physics at the threshold of quantum gravity with definite predictions: neutrinoless double β-decay, and the discovery of Supersymmetry at CERN. As in the past, neutrinos are the *canaris* of new physics, pointing to the much richer structures that await physicists in their quest for the ultimate architecture of the Universe.

Acknowledgement

I wish to thank Dr. L. Everett for many helpful suggestions and conversations.

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