FACT & FANCY IN NEUTRINO PHYSICS II

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ABSTRACT
This brief and opinionated essay evolved from my closing talk at the Tenth International Workshop on Neutrino Telescopes, held in Venice in March 2003. Portions were inspired by several excellent presentations at the Workshop. Other scattered comments about neutrino physics relate to variations of the seesaw model yielding the FGY ansatz, or to those yielding significant suppressive mixing of neutrino amplitudes.

I am honored to have been chosen to give the closing address at this Workshop. The late and beloved Viki Weisskopf described the privilege of being a physicist. Milla Baldo-Ceolin, on ten occasions, has given us the privilege of practicing our art in La Serendissima. Let me begin by thanking Milla and her staff for making these wondrous Venetian workshops possible.

The original F&FiNP was presented as a Harvard Colloquium in the form of a play in December 1973, just after neutral currents were found and just before the dramatic discovery of the curiously called $J/\Psi$ particle. Our play was later published in the Reviews of Modern Physics [1]. The cast consisted of:

Alvaro De Rújula: Moderator, an Experimental Physicist
Howard Georgi: Computer, one that can talk
Helen R. Quinn: Speaker, a Conservative Theorist
and me: Model-Builder, a not-so-conservative Theorist

The plot centered upon the exciting new data then emerging on deep-inelastic lepton scattering, and their interpretation in terms of a naive quark model, but one involving quarks yet undiscovered: those with charm (which do exist) and those with fancy (which do not). It was a heady time in the history of particle physics, somewhat confused by Rubbia’s soon-to-vanish ‘high-y anomaly.’ Milla’s request for a reprise of Fact and Fancy is impossible to fulfil in these more tepid days, but as I attempt to recall its spirit please remember that Facts refer to suppositions that are true, Fancy to those that rest on no solid ground.

Colleagues occasionally ask why I never claimed credit for the invention of the seesaw model of neutrino masses — that is, the scheme by which neutrino masses arise from an interplay between Higgs-induced Dirac masses involving three weak doublet neutrinos and three singlet states, and large bare Majorana masses of the singlets. In lieu of staking a claim, let me offer a chronological list of the earliest published discussions of the seesaw model:

1
In my 1979 Cargèse talks, I wrote: “Consider the effect of [neutrino] mixing on the distribution of neutrinos produced by cosmic rays. Upward directed neutrinos have a trajectory of $\sim 10^4$ km while downward directed neutrinos travel only $\sim 10$ km... It is possible that the next world-shaking developments in particle physics will emerge from such experiments.” Little did I realize that I would wait almost two decades before the anticipated atmospheric neutrino oscillations would be detected. If only Bruno Pontecorvo could had seen how far we have come toward understanding the pattern of neutrino masses and mixings! Way back in 1963 he was among the first have envisaged the possibility of neutrino flavor oscillations. For that reason, the analog to the Cabibbo-Kobayashi-Maskawa matrix pertinent to neutrino oscillations should be known as the PMNS matrix, to honor four neutrino visionaries: Pontecorvo, Maki, Nakagawa, and Sakata.

A plea! The mixing angles appearing in standard parametrizations of both the PMNS matrix and the CKM matrix are usually designated by $\theta_{12}$ (solar/Cabibbo), $\theta_{23}$ (atmospheric/$b \to c$) and $\theta_{13}$ (subdominant/$b \to u$). It is awkward and absurd to use two indices where one would do. Therefore, I prefer, recommend and shall hereafter use a simpler and more compact notation:

$$\theta_1 \equiv \theta_{23}, \quad \theta_2 \equiv \theta_{13}, \quad \theta_3 \equiv \theta_{12}. $$

What we have managed thusfar to learn about these parameters (and the CP violating phases $\delta$) is rather roughly summarized in the following table:

| Parameter | Quarks   | Leptons  |
|-----------|----------|----------|
| $\sin \theta_1$ | 0.04     | $\sim \sqrt{2}/2$ |
| $\sin \theta_2$ | 0.004    | $\leq 0.16$ |
| $\sin \theta_3$ | 0.22     | $\sim 0.55$ |
| $\delta$ | $\sim 1$ | ??       |

A question! How much better must we strive to determine these parameters, about which our theories are so sadly reticent? For the quark sector, the answer primarily involves the two unitarity relations:

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0, \quad \text{and}$$
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \equiv 1 - \Delta = 1.$$
The first of these is usually called the ‘unitarity triangle.’ Current measurements indicate that the triangle inequalities are obeyed with the angle between the latter two legs given by $\sin 2\beta = 0.78 \pm 0.08$. Further data is required to confirm the view that standard-model CP violation, i.e., that implied solely by the complexity of the CKM matrix, offers a correct and complete description of all observable CP-violating phenomena in both the kaon and $B$-meson sectors. (Here we ignore the so-called strong CP problem.)

The second relation poses a small puzzle. Wilkinson [2], from a recent simultaneous analysis of several super-allowed Fermi transitions, obtains

$$\Delta = 0.0004 \pm 0.0017,$$

which is in excellent agreement with CKM universality, whereas Abele [3], from a new measurement of the neutron lifetime, obtains

$$\Delta = 0.0083 \pm 0.0028,$$

which is a 3-sigma discrepancy from theory. At least one of these two estimates must be flawed. Furthermore, I have heard that the long-accepted value $|V_{us}| \simeq 0.22$ may be challenged by high-statistics studies of kaon decay. The current situation is confused. However, a confirmed departure from CKM universality (whether positive or negative), should there be one, would be decisive evidence for physics beyond the standard model.

On that engaging note, let us look to the leptons. First off, we had best verify our three-state description of neutrino oscillations and convince ourselves that the ugly construct of ‘sterile neutrinos’ can be safely abandoned. This done, with what precision must the leptonic mixing angles be determined? I would argue as follows. Being aware of no compelling theoretical reason for any of the leptonic angles $\theta_i$ to assume special values, such as zero or $\pi/4$, I would be satisfied if atmospheric neutrino oscillations (which are known to be nearly maximal) could be measured sufficiently well to bound $\theta_1$ away from $\pi/4$ with reasonable certainty. Similarly, solar oscillations (which are strongly favored to be less than maximal) should be measured sufficiently to bound $\theta_3$ away from $\pi/4$ with 5-sigma certainty. Finally, I would be satisfied if the subdominant angle $\theta_2$ could be bounded away from zero with 5-sigma certainty. Once these benchmarks are met, I would argue that further measurements of neutrino oscillation phenomena would be pointless, until and unless theorists can provide further guidance.

That leaves the question of $\delta$, the parameter governing CP violation in neutrino physics. Discussions at this Conference suggest that the cost of bounding $\delta$ from zero would be enormous. It has been said that a reliable measurement of $\delta$ would require the construction of a multi-billion euro muon factory, for which this task would be the sole raison d’être. I believe that such a facility is not affordable by our presently impoverished discipline. Unless a cheaper route to $\delta$ can be found, there are too many less costly but equally important challenges remaining in neutrino physics that should command our limited funds. Among them are the following:

- Pinning down the leptonic mixing angles, as described above.
• Searching for neutrinoless double beta decay.
• Studying the tritium endpoint so as to constrain neutrino masses.
• Measuring the two squared-mass differences among neutrinos.
• Distinguishing the normal from the inverted neutrino mass spectra.
• Resolving the LSND anomaly and confirming the 3 active neutrino scenario.
• Testing CPT for neutrinos, *e.g.*, by comparing solar and Kamland data.
• Improving the already astonishing cosmological limit on the sum of the neutrino masses, such as was eloquently described by Prof. Pastor at this meeting.

**Seesaws!** Let me return to the wondrous mechanism which is somewhat the theme of my talk. It is a neat way to generate neutrino masses with a minimum of new architecture. At the same time, the seesaw can address the mystery of universal baryon asymmetry. Professor Buchmüller, at this meeting, stressed the virtue of the seesaw to implement leptogenesis and consequent baryogenesis. Indeed, he claimed that such a scheme yields a powerful constraint on the sum of the squares of the light neutrino masses. He works in the context of three heavy singlet neutrino states, where one of them is significantly lighter than the others. Otherwise, the model in an unconstrained seesaw with Dirac masses arising from a single Higgs boson. It is interesting to note that leptogenesis, in this model, occurs entirely independently of the parameters of the PMNS matrix. In particular, the requisite CP violation is controlled by otherwise inaccessible ‘Majorana phases,’ and not by the δ parameter. (Early references to these phases, and indications of their unobservability, may be found in ref. [4].)

The situation is more constrained and perhaps more interesting should we adopt the simple Frampton-Glashow-Yanagida FGY *ansatz* [5] in which there are just two heavy singlets (*N*<sub>i</sub>), and the neutrino mass terms (in an abbreviated notation) take the special form:

\[
(\alpha \nu_e + b \nu_\mu) \langle h \rangle N_2 + (c \nu_\mu + d \nu_\tau) \langle h \rangle N_1 + M_1 N_1 N_1 + M_2 N_2 N_2,
\]

or a related form in which the roles of \(\nu_\mu\) and \(\nu_\tau\) are reversed. The Higgs vev is denoted by \(\langle h \rangle\). The Yukawa couplings \(a, b, c, d\) are arbitrary complex numbers, but we may choose the flavor phases so as to make all but one of them real. Consequently, and for either version of our ansatz, exactly one convention-independent phase controls both leptogenesis (via *N* decay) and CP violation in the neutrino sector. Thus the (unknown) sign characterizing CP violation in the neutrino sector is correlated to the (known) sign of the baryon asymmetry of the universe.

Furthermore, and as noted by Raidal & Strumia [6] (who have dubbed our model “the most minimal seesaw”), the FGY ansatz has four potentially observable consequences at low energy:

1. One of the three neutrino masses must vanish.
2. The inverted neutrino mass hierarchy is excluded.
3. The neutrino flavor-mixing parameters are constrained by the relation:

\[
\sin \theta_2 = \sin 2\theta_3 \left( \tan \theta_1 \right)^{\pm 1} \sqrt{\frac{\Delta_s}{4\Delta_a}},
\]
where the sign ambiguity (linked to the choice of ansatz) is not phenomenologically significant because of the experimental result \( \tan \theta_1 \approx 1 \). The parameters \( \Delta_{a,s} \) are the squared mass differences pertinent to atmospheric and solar neutrino oscillations. Insofar as experiment strongly indicates solar neutrino oscillations to be far from maximal, this relation predicts the subdominant angle \( \theta_2 \) to be large enough to make searches for CP violation in the neutrino sector feasible.

(4) The element of the neutrino mass matrix responsible for neutrinoless double beta decay is given by

\[
M_{ee} = \sin^2 \theta_3 \sqrt{\Delta_s},
\]

which is small enough to pose a formidable challenge to experimenters who would search for this rare or nonexistent process. The importance of this search cannot be overstated. The detection of no-neutrino \( \beta \beta \) decay would prove that lepton number is not conserved, and would thereby exclude the otherwise tolerable possibility (pointedly stressed by Jack Steinberger) that neutrino masses are ludicrously hierarchic but purely Dirac.

The attentive reader will have noted that the elegant and predictive ansatz we proposed is unnatural and unrenormalizable per se. Without further ado, its form is not preserved by divergent radiative corrections. This difficulty can be remedied in several ways. For example, Raby \cite{7} claims to have generated our ansatz naturally in a supersymmetric context such as to preserve the correlation between the baryon asymmetry and observable CP violation in the neutrino sector. Another way to accomplish these goals is sketched below.

We assign a flavor quantum number \( F \) to the light leptons as follows. To the (electron, muon, tau lepton) and its left-handed neutrino, we assign \( F = (1, 0, -1) \), resp. We introduce three Higgs doublets, \( h_i \) to account for lepton masses. Their subscripts are identified with their flavor assignments: \( F \equiv i = (0, -3, -4) \). In a similar fashion, the left-handed singlet neutrino \( N_1 \) is renamed \( N_4 \) and assigned \( F = 4 \), while \( N_2 \) is renamed \( N_3 \) with \( F = 3 \). It will be required that \( F \) be conserved by all dimension-4 terms in the Lagrangian. However, \( F \) is softly broken by the dimension-3 Majorana mass terms, but in such a manner as to conserve \( F \) modulo 2. Thus these terms are constrained to be \( M_3 N_3^2 + M_4 N_4^2 \). The \( M_i \) may be chosen to be real with no loss of generality. I summarize below the other consequences of these flavor assignments:

- The charged lepton masses arise from Yukawa couplings of \( h_0 \) to light lepton states. They are necessarily flavor diagonal in the basis we are using. Note that \( h_0 \) has no \( F \)-conserving couplings involving \( N_i \), and that \( h_i \) (for \( i \neq 0 \)) do not contribute to the charged lepton masses.
- The allowed couplings of the light doublet states to the \( N_i \) are just those required to reproduce the FGY ansatz:

\[
(\hat{a}\langle h_{-4}\rangle \nu_e + \hat{b}\langle h_{-3}\rangle \nu_\mu)N_3 + (\hat{c}\langle h_{-4}\rangle \nu_\mu + \hat{d}\langle h_{-3}\rangle \nu_\tau)N_4.
\]

In this manner, the structure of the FGY ansatz is preserved by radiative corrections (up to small finite terms) because it is protected by the softly-broken flavor symmetry, and so also are all of its observable consequences.
Suppressive neutrino mixing! Two potentially threatening departures from standard-model predictions regarding neutrino physics are the three sigma NuTeV anomaly [8] and the two sigma departure of the $Z^0$ invisible width from its expected value [9]. In the former case, a ratio of neutral-current to charged current cross sections is reported to be less than its predicted value by $1.2 \pm 0.4\%$. In the latter case, the neutrino count is shy of three by $0.016 \pm 0.008$.

Many authors have proposed, considered, criticized or rejected explanations of these ‘anomalies’ involving significant suppressive mixings between light and heavy neutrino states [10]. Finding neither discrepancy convincing, we need make no comment on this issue. Nonetheless, several recent papers [11] address the ancillary question of how this mixing can arise in seesaw models and what would be its observable consequences. The upshot of these analyses is that the effective flavor eigenstates (i.e., the doublet states coupled to $e$, $\mu$ and $\tau$, projected onto the space of light neutrino eigenstates) are neither normalized nor orthogonal. They satisfy the relation:

$$\langle \nu^\dagger_I \cdot \nu_I \rangle = \delta_{ll'} - \Theta_{ll'},$$

where $\Theta$ is a small non-negative hermitean matrix. Ordinarily, the entries of $\Theta$ are given by ratios of mostly doublet light neutrino masses to their mostly singlet heavy counterparts. These are typically less than $10^{-11}$ and therefore entirely negligible. This is the case, for example, for the FGA ansatz discussed previously.

It has been observed [11], however, that carefully chosen values of the seesaw parameters can lead to very much larger (and empirically relevant) $\Theta$’s. For these pathological cases, the diagonal components of $\Theta$ can yield significant suppressions of the various weak-interaction leptonic amplitudes involving neutrinos, such as might ameliorate the above-cited anomalies, or aggravate the previously-discussed disputed departure from CKM universality. Similarly, the off-diagonal components of $\Theta$ can induce, via loop diagrams, otherwise forbidden processes such as $\mu \to e + \gamma$, $\mu \to 3e$, and $\mu-e$ conversion. For these contrived situations the entries of the matrix $\Theta$ are virtually independent of the neutrino masses, although they are not entirely arbitrary. In any event, it would seem worthwhile to set direct experimental upper bounds on these possible departures from neutrino orthonormality and to delineate the theoretical constraints upon them.

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References

[1] A. De Rújula et al., Rev. Mod. Phys. 46(1974)391.
[2] D.H. Wilkinson, J. Phys. G; Nucl. Part. Phys. 29(2003)189.
[3] Helmut Abele, in Rencontres de Moriond 2002, hep-ex/0208048.
[4] A. de Gouvêa, B. Kayser & R.N. Mohapatra, hep-ph/0211394.
[5] P.H. Frampton, S.L. Glashow & T. Yanagida, Phys. Lett. B548(2002)119.
[6] M. Raidal & A. Strumia, Phys. Lett. B553(2003)72.
[7] Stuart Raby, hep-ph/0302027.
[8] K.S McFarland et al., hep-ex/0205081; G.P. Zeller et al., hep-ex/0207037.
[9] The LEP Collaborations, the LEP Electroweak Working Group, and the SLD Heavy Flavor Group, hep-ex/0212036.
[10] E.g., J. Bernardéu et al., Phys. Lett B187(1987)303; A. de Gouvêa et al., Nucl. Phys. B623(2002)395, hep-ph/0107158; K.S. Babu and J.C. Pati, hep-ph/0203029; S. Davidson et al., JHEP 0202(2002)037; Paul Langacker, hep-ph/0211065; T. Takeuchi, hep-ph/0209109; T. Takeuchi et al., 2002 Nagoya Workshop, www.eken.phys.nagoya-u.ac.jp/; W. Loinaz, N. Okamura, T. Takeuchi, et al., hep-ph/0210193, hep-ph/0304004.
[11] S.L. Glashow, hep-ph/0301250; W. Loinaz et al., hep-ph/0304044.