SEE-SAW MECHANISM AND PETER MINKOWSKI

In June 2004 there was a conference SEE-SAW 25 celebrating the "25th" anniversary. June 11-12, 2004 at Institute Henri Poincare immediately before Neutrino 2004 June 14-19 at College de France nearby.

SEESAW 25

International Conference on the Seesaw Mechanism and the Neutrino Mass

10-11 June 2004
Institut Henri Poincaré, Paris

First Bulletin (October 2003)

1. General information

On the occasion of the 25th anniversary of the seesaw mechanism, we are organizing an international conference on the Seesaw Mechanism and the Neutrino Mass at the Institut Henri Poincaré, Paris, on 10 and 11 June 2004. The conference will take place a few days before the XXIst International Conference on Neutrino Physics and Astrophysics (Neutrino 2004), to be held at the Collège de France, Paris, on 14-19 June 2004.

The aim is to assess the progress made since the invention of the seesaw mechanism in 1979 by M. Gell-Mann, P. Ramond, R. Slansky and T. Yanagida, and to review the recent theoretical developments in the understanding of the observed pattern in neutrino masses and mixings. Observable implications of the seesaw mechanism such as leptogenesis or lepton flavour violation in supersymmetric theories will also be addressed, and the key aspects of the vast experimental programme aiming at determining the neutrino parameters and properties will be reviewed.

Information about the conference is available on the conference website:

http://seesaw25.in2p3.fr/

2. Scientific programme

The programme will consist of invited plenary talks only. The following subjects will be covered:

- historical perspective on the seesaw mechanism
- various realizations of the seesaw mechanism
- seesaw mechanism and GUTs
- seesaw mechanism and extra dimensions
- seesaw mechanism and supersymmetry
- textures and flavour models
- seesaw mechanism and renormalization group effects
- CP violation in the seesaw mechanism
- seesaw mechanism and the baryon asymmetry
- alternatives to the seesaw mechanism
- seesaw mechanism beyond neutrino physics
- neutrinos and astrophysics
- the experimental evidence for neutrino mass
- the abolute neutrino mass scale and the nature of neutrinos
- theta_13 and CP violation in the neutrino sector
- multipurpose detectors (low-energy neutrinos and CDM)

FACT & FANCY IN NEUTRINO PHYSICS II

Sheldon Lee Glashow
Physics Department, Boston University
590 Commonwealth Avenue, Boston, MA 02215
Email: slg@bu.edu

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/Ψ 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 beteen 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) Tsutomu Yanagida in *Proc. Workshop on Unified Theories &c.*, [Feb. 13-14, 1979], eds. O. Sawada and A. Sugamoto (Tsukuba,1979) p.95.

2) S.L. Glashow, in *Quarks and Leptons, Cargèse* [July 9-29,1979], eds. M. Lévy, *et al.*, (Plenum, 1980, New York), p. 707.

3) M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity,* [Sept. 27-29 1979], eds. D. Freedman *et al.*, (North Holland, 1980, Amsterdam).

4) R.N. Mohapatra and G. Senjanović, Phys. Rev. Lett. 44 (1980) 912.

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 ~ 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 Cabbibbo-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 θ_{12} (solar/Cabibbo), θ_{23} (atmospheric/$b \to c$) and θ_{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:

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

What we have managed thusfar to learn about these parameters (and the CP violating phases δ) 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	≤ 0.16
$\sin\theta_3$	0.22	~ 0.55
δ	~ 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:

$$V_{ud}\, V_{ub}^* + V_{cd}\, V_{cb}^* + V_{td}\, V_{tb}^* = 0, \quad \text{and}$$
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \equiv 1 - \Delta = 1.$$

During the next week I had dinner
with Harald Fritzsch and Peter Minkowski.

I recalled in Sept 1975 Murray Gell-Mann
telling me: $m_\nu \sim m^2/M$. What happened

between 1975-79?

There is a paper:
H. Fritzsch + M. Gell-Mann + P. Minkowski
PL B59, 256 (1975)
mentions m^2/M but not see-saw.

However, P.M. eventually alluded to:

P. MINKOWSKI

PL B67, 421 (1977)

"Mu → e gamma at a rate of one out of 1 billion muon decays"

fully explains See-saw mechanism.

In 2004 this had 16 cites in 27 years.

Now it has 250 cites.

Well deserved, Peter!!

INTRODUCTION TO LEPTOGENESIS

One of the most profound ideas in particle theory is that of Sakharov (1967). Following the discovery of CP violation in K decay (1964) - a surprise - he enunciated the conditions for baryogenesis:

1. B violation

2. C and CP violation.

3. Out-of thermal equilibrium era.

Early discussions were stated in terms of p decay but calculations gave much too small a baryon number of the universe. Now though we still have no evidence for B violation there is evidence for L violation in Majorana neutrino masses. Leptogenesis where $N \rightarrow e^- H^+$ followed by electroweak sphaleron conversion can give the correct B number.

Note that in $N \to e^- H^+$,
H^+ is massless since $E \gg M_W$.

L is subsequently converted to B through sphalerons which conserve (B - L).

We will study CP violation both at low energy (ξ_L = parameter) in ν oscillations and at high energy (ξ_H = parameter) in leptogenesis.

Can ξ_L and ξ_H be related?

Generally not, but our purpose here is to demonstrate the remarkable fact that in a class of models the answer is positive.

In such a case the sign of CP violation in neutrino oscillations can be predicted from the baryon number of the universe.

Present data on neutrinos:

ATMOSPHERIC NEUTRINOS

$\Delta_a \simeq 3 \times 10^{-3} eV^2$

$\tan^2 \theta_a \simeq 1$

SOLAR NEUTRINOS

$\Delta_S \simeq 5 \times 10^{-5} eV^2$

$0.6 \leq \sin^2 2\theta_3 \leq 0.96$

$\sin^2 2\theta_3 = 0.8$ is best fit

THE THIRD MIXING ANGLE

$\sin^2 2\theta_2 \leq 0.1$ (CHOOZ)

θ_2 is sometimes called θ_{13}

These data must be accommodated successfully in our model.

THE MODEL

In the minimal SM: $m(\nu_i) = 0$.

Simplest extension of minimal SM which allows both $m(\nu) \neq 0$ and successful leptogenesis is:

TWO RIGHT-HANDED NEUTRINOS $N_{1,2}$

This, plus appropriate texture zeroes in the Dirac 3×2 rectangular matrix, is our model.

(Note that $N_{1,2,3}$ model suggested by SO(10) has an ESSENTIAL AMBIGUITY avoided here.)

New terms in the lagrangian are:

$$\mathcal{L} = \frac{1}{2}(N_1, N_2)\begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \end{pmatrix} \tag{4}$$

$$+(N_1, N_2)\begin{pmatrix} a & a' & 0 \\ 0 & b & b' \end{pmatrix}\begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix} + h.c. \tag{5}$$

D_{ij} is a rectangular 3×2 Dirac matrix.

We have assumed a texture

$$D_{ij} = \begin{pmatrix} x & x & 0 \\ 0 & x & x \end{pmatrix}$$

which leaves the exact number of parameters necessary and sufficient to account for the data.

Using the see-saw mechanism we compute:

$$
\begin{aligned}
L &= D^T M^{-1} D \\
&= \begin{pmatrix} a^2/M_1 & aa'/M_1 & 0 \\ aa'/M_1 & [(a')^2/M_1 + b^2/M_2] & bb'/M_2 \\ 0 & bb'/M_2 & (b')^2/M_2 \end{pmatrix}
\end{aligned}
$$

We can choose a basis in which a, b, b' are real and $a' = |a'|e^{i\delta}$.

To check consistency with low-energy data we put $a' = \sqrt{2}a$ and $b' = b$ (all real) whereupon:

whereupon:

putting $a^{'} = \sqrt{2}a$ and $b^{'} = b$ gives

$$L = \begin{pmatrix} a^2/M_1 & \sqrt{2}a^2/M_1 & 0 \\ \sqrt{2}a^2/M_1 & [2a^2/M_1 + b^2/M_2] & b^2/M_2 \\ 0 & b^2/M_2 & b^2/M_2 \end{pmatrix} \tag{6}$$

We diagonalize by rewriting:

$$\frac{1}{2}\nu^T L\nu = \frac{1}{2}\nu^{'T} U^T L U\nu^{'}$$

where U is a real orthogonal matrix
and $\nu^{'}$ are the three mass eigenstates.

We parametrize the unitary diagonalizing matrix as:

$$U = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ -1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & -1/2 & 1/\sqrt{2} \end{pmatrix} \times$$

$$\times \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta & sin\theta \\ 0 & -sin\theta & cos\theta \end{pmatrix}$$

We deduce the mass eigenvalues and θ:

$M(\nu_3^{'}) = 2b^2/M_2 \gg M(\nu_2^{'}) = 2a^2/M_1 \gg M(\nu_1^{'}) \equiv 0$

The vanishing eigenvalue is exact (rank = 2)

This assumes $a^2/M_1 \ll b^2/M_2$. We also find:

$$\theta \simeq \frac{M(\nu_2^{'})}{\sqrt{2}M(\nu_3^{'})} \ll 1$$

For the unitary matrix relevant to neutrino oscillaions:

$U_{e3} = sin\theta/\sqrt{2} \simeq m(\nu_2^{'})/2m(\nu_3^{'})$.

Thus $A^{'} = \sqrt{2}a$ and $b^{'} = b$ adequately fits all the data. These values can be shimmied to improve the fit.

We deduce that:

$$\frac{2b^2}{M_2} \simeq \sqrt{\Delta_a} \simeq 0.05eV$$

and

$$\frac{2a^2}{M_1} \simeq \sqrt{\Delta_S} \simeq 0.007eV$$

These results imply that the N_1 state can satisfy the out-of -equlibrium condition but not N_2. Thus for leptogenesis to succeed it is necessary that $M(N_2) > M(N_1)$ and this resolves a sign ambiguity present in models with three right-handed neutrinos.

THE CONNECTING LINK

In our model (really a class of models) we can calculate the CP violation parameters ξ_L and ξ_H characterizing respectively the low- and high- energy.

THE RELATIVE SIGN OF THESE TWO PARAMETERS IS FIXED.

The magnitude itself is not predicted because it depends on the parameters.

The presence of texture zeroes in L and D implies only one phase, and that is why LE and HE are related. Let us therefore calculate ξ_H and ξ_L explicitly:

BARYON NUMBER THROUGH LEPTOGENESIS.

$$B \sim \xi_H = (ImDD^\dagger)^2_{12}$$

This crucial quantity and B proportional to ξ_H can be evaluated uniquely in the present model:

In the model

$$\xi_H = Im(a^{'}b)^2$$

$$= +Y^2a^2b^2sin^2\delta > 0$$

which has a definite sign.

Here $a^{'} = Yae^{i\delta}$ loosens up the previous assignment $a^{'} = \sqrt{2}a$.

Low-energy CP violation.

The relevant parameter is:

$$\xi_L = Im(h_{12}h_{23}h_{31})$$

where $h = (LL^\dagger)$ and ξ_L is like the Jarlskog determinant for quarks.

Simple algebra give:

$$\xi_L = -\frac{a^6 b^6}{M_1^3 M_2^3} \sin 2\delta Y^2 (2 + Y^2)$$

which has a definite sign (negative).

The predicted sign is robust with respect to varying the phenomenological parameters.

So in a class of models having two right-handed neutrinos and a texture with the minimum number of parameters to accommodate the low-energy phenomenology we find that the

RELATIVE SIGN OF ξ_L and ξ_H IS UNIQUE

The essential ambiguity of normal versus inverted hierarchy for N_R's with three N_R's is evaded by including only two N_R's.

This provides a very interesting link between elementary particles (neutrinos) and the early universe.