Neutrino Masses and Flavor Mixing: An Overview

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Outline

1. Established Anomalies of Solar and Atmospheric Neutrinos
2. Neutrino Oscillations? That is Most Likely!
3. Constraints on the Absolute Neutrino Mass Scale
4. Phenomenology of Lepton Flavor Mixing and CP Violation

Nobel Prize 2002

R. Davis, **R. Giacconi**, **M. Koshiba**

1. Established Anomalies

Solar Neutrinos:

- First observed: R. Davis 1967; Firmly established: SNO 2002
- The measurement of ^{8}B neutrino flux by SNO (and SK):

$$\boxed{\Phi^{\rm CC} = \Phi_e \; , \; \Phi^{\rm ES} = \Phi_e + \frac{1}{6}\Phi_{\mu\tau} \; , \; \Phi^{\rm NC} = \Phi_e + \Phi_{\mu\tau}}$$

Flavor conversion: $\Phi_{\mu\tau} \neq 0$ ($> 5\sigma$)! Consistent with SSM!!

- Mechanism: ◇ Oscillation? ◇ Spin flip? ◇ Exotic interaction?

Atmospheric Neutrinos:

- Observed: Kamiokande *etc* 1980s; Established: SK 1998
- The up-down asymmetries of ν_e and ν_μ measured by SK:

$$\boxed{\frac{\rm U}{\rm D}\langle\nu_e\rangle \sim 1; \frac{\rm U}{\rm D}\langle\nu_\mu\rangle \sim 0.5}$$

ν_μ neutrino deficit ($> 10\sigma$)!

- Mechanism: ◇ Oscillation? ◇ Decay? ◇ Exotic interaction?

2. Neutrino Oscillations

Oscillations are most likely responsible for the observed anomalies:

Neutrinos are massive and lepton flavors are mixed

Some arguments: (a) The SSM works well; (b) $m_\nu = 0$ is not guaranteed by any fundamental laws; (c) $m_\nu \neq 0$ is naturally expected beyond the SM; (d) Oscillations can simultaneously interpret both anomalies; (e) Other possibilities are more complicated or far-fetched in phenomenology, or have no good motivation in theory.

Hopefully, the situation will soon be clarified by KamLAND, further operation of SNO, SK and K2K, and later by Borexino *etc*.

Atmospheric Neutrinos:

ν_μ conversion mostly to ν_τ: $\Delta m^2_{\rm atm} = (1.6 - 3.9) \times 10^{-3}~{\rm eV}^2$, $\sin^2 2\theta_{\rm atm} > 0.92$ (at 90% C.L.).

Solar Neutrinos:

The LMA (large mixing angle) MSW solution is today most favored: $\Delta m^2_{\rm sun} = (3.3 - 17) \times 10^{-5}\ {\rm eV}^2$, $\tan^2\theta_{\rm sun} = (0.30 - 0.58)$ (at 90% C.L.). But, some surprises are not ruled out.

The SMA (small mixing angle) MSW solution is today practically excluded (A.Yu. Smirnov, hep-ph/0209131).

The LOW and VO solutions are accepted at 3 σ level.

Sub-leading effects are possible. Hybrid solutions are not excluded.

LSND Neutrinos:

$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ conversion: $\Delta m^2_{\rm LSND} \sim 1\ {\rm eV}^2$, $\sin^2 2\theta_{\rm LSND} \sim 10^{-2}$.

NOT confirmed by KARMEN. Disfavored by *Global Analysis* (light sterile neutrinos are not welcome). To be clarified by MiniBOONE.

Mass and Mixing:

Three possible patterns of the neutrino mass spectrum:

- Normal Hierarchy: $m_1, \; m_2 \ll m_3$
- Inverted Hierarchy: $m_1 \approx m_2 \gg m_3$
- Approximate Degeneracy: $m_1 \approx m_2 \approx m_3$

In comparison: strong hierarchy of charged lepton and quark masses: $m_e \ll m_\mu \ll m_\tau$ and $m_u \ll m_c \ll m_t$ and $m_d \ll m_s \ll m_b$.

A nearly *bi-maximal* pattern of lepton flavor mixing:

- $\theta_{12} \approx \theta_{\rm sun} \sim 32^\circ$
- $\theta_{23} \approx \theta_{\rm atm} \sim 45^\circ$
- $\theta_{13} \approx \theta_{\rm chooz} < 12^\circ$

In comparison: quark mixing $\theta_{12} \approx 13^\circ$, $\theta_{23} \approx 2.3^\circ$, $\theta_{13} \approx 0.2^\circ$.

3. Absolute Neutrino Masses

PDG 2002 $m^{\rm eff}_{\nu_e} < 2.2$ eV, $m^{\rm eff}_{\nu_\mu} < 170$ keV, $m^{\rm eff}_{\nu_\tau} < 15.5$ MeV.

Three ways to pin down the absolute scale of neutrino masses:

- Tritium β decay experiments: $\boxed{m^{\rm eff}_{\nu_e} = \sum_i \left(m_i |V_{ei}|^2\right)}$

  KATRIN sensitivity 0.3 eV.

- Neutrinoless $\beta\beta$ decay experiments: $\boxed{\langle m\rangle_{ee} = \sum_i \left(m_i V^2_{ei}\right)}$

  Today's upper bound 0.3 eV. Tomorrow's sensitivity 0.03 eV. The only chance to answer: are neutrinos Majorana particles?

- Astrophysical and cosmological constraints: $\sum_i m_i < 3$ eV at 95% C.L. (S. Hannestad, hep-ph/0208567), hence the heaviest neutrino mass in the range (0.05 - 1) eV, contributing only a bit to dark matter of the universe.

4. Phenomenology

Two questions: Why masses so small? Why mixing angles so big?

The seesaw mechanism: smallness of left-handed neutrino masses (0.1 eV) is attributed, compared to the electroweak scale (10^2 GeV), to largeness of right-handed neutrino masses (10^{14} GeV).

$$\boxed{-\mathcal{L}_{\rm Yukawa} = \bar{l}_{\rm L} \tilde{\phi} Y_l e_{\rm R} + \bar{l}_{\rm L} \phi Y_{\rm D} \nu_{\rm R} + \frac{1}{2} \overline{\nu^{\rm c}_{\rm R}} M_{\rm R} \nu_{\rm R} + {\rm h.c.}}$$

After *SSB*, we obtain $M_l = Y_l \langle \phi \rangle$ and $M_{\rm D} = Y_{\rm D} \langle \phi \rangle$. The left-handed (light) neutrino mass matrix turns out to be

$$\boxed{M_\nu = M_{\rm D} \frac{1}{M_{\rm R}} M^T_{\rm D}}$$

If specific textures of $M_{\rm R}$ and $M_{\rm D}$ are given, M_ν can be calculated.

The leptogenesis mechanism: the decays of right-handed (heavy) neutrinos $N_i \to l + \phi^\dagger$ vs $N_i \to l^c + \phi$ occur at both tree and one-loop levels, leading to CP asymmetries ε_i. If $M_1 \ll M_2 \ll M_3$, only ε_1 produced by the out-of-equilibrium decay of N_1 survives,

$$\boxed{\varepsilon_1 = -\frac{3}{16\pi v^2} \cdot \frac{M_1}{[\tilde{M}_\mathrm{D}^\dagger \tilde{M}_\mathrm{D}]_{11}} \cdot \sum_{j=2}^{3} \frac{\mathrm{Im}\left([\tilde{M}_\mathrm{D}^\dagger \tilde{M}_\mathrm{D}]_{1j}\right)^2}{M_j}}$$

and it results in a lepton asymmetry $Y_\mathrm{L} \equiv n_\mathrm{L}/\mathrm{s} = \varepsilon_1 d/g_*$. Finally Y_L is converted into a net baryon asymmetry via (B+L)-violating sphaleron processes (M. Fukugita & T. Yanagida 1986):

$$\boxed{Y_\mathrm{B} \equiv \frac{n_\mathrm{B}}{\mathrm{s}} = \frac{c}{c-1} Y_\mathrm{L} = \frac{c}{c-1} \cdot \frac{d}{g_*} \varepsilon_1}$$

The observed baryon asymmetry of the universe: $Y_\mathrm{B} \sim 5 \times 10^{-11}$.

Flavor mixing and CP violation: The leptonic flavor mixing matrix V arises from the mismatch between diagonalizations of M_l and M_ν:

$$\boxed{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu1} & V_{\mu2} & V_{\mu3} \\ V_{\tau1} & V_{\tau2} & V_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}$$

Three mixing angles (θ_{12}, θ_{23}, θ_{13}) and three CP-violating phases (Dirac δ and Majorana ρ & σ) are required to parametrize V.

- Long-baseline neutrino experiments: to determine θ_{13} and δ
- Neutrinoless $\beta\beta$ decay experiment: to constrain ρ and σ

Speculations on model building to interpret large mixing angles:

- Weak hierarchy or near degeneracy of neutrino masses
- Flavor symmetries such as U(1) symmetry or flavor democracy

Comments on the connection or disconnection between ε_1 and δ:

- Indirect connection via seesaw is possible, but model-dependent
- There is no way to prove/disprove leptogenesis experimentally
- A theoretically meaningful criterion to select low-energy models

Remarks on a possible theory of lepton masses and flavor mixing

- Rare decays of charged leptons might help (completeness)
- Progress in the sector of quarks might help (unification)
- The breakthrough might be beyond flavor physics (up to down)

Conclusion

- A number of questions call for definite answers experimentally.
- E. Witten: "Despite some interesting attempts, there has never been a convincing quantitative model of the neutrino masses".