Neutrinos: masses, mixing and symmetries

~~Amal~~ Amol Dighe
DTP, TIFR

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Outline

1. Neutrinos: a Curriculum Vitae
   - The multifaceted neutrino
   - The knowns and the unknowns
2. $\mathcal{PR}$-neutrino interaction (> 20 years)
   - Light Dirac neutrinos from SUSY GUT
   - Resolving the LSND anomaly
   - Neutrino mass models
   - Oscillation phenomenology
   - Quark-lepton symmetries and their radiative breaking
3. Parting shots

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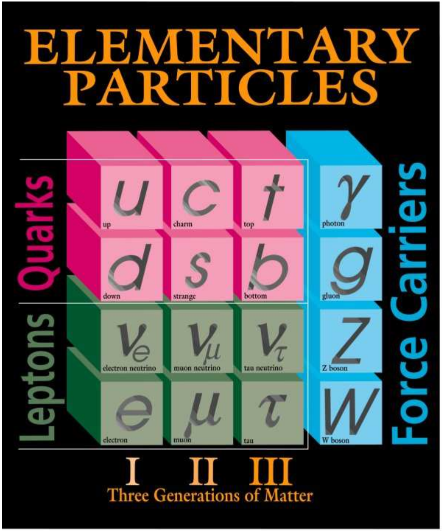
Aspects of neutrinos

- Particles that accompany radioactive β decay
- Byproducts of nuclear reactions
- The most abundant particles
- The most weakly interacting particles
- The lightest massive particles
- Particles that break left-right (mirror) symmetry maximally
- Particles that may be their own antiparticles
- Particles that may have created the matter-antimatter asymmetry

The niche of neutrinos in the Standard Model



Fermilab 95-759

- 3 neutrinos: ν_e, ν_μ, ν_τ
- chargeless
- spin 1/2
- almost massless

A brief history of neutrinos

- Postulated: 1932 (Pauli)
- Discovery of electron neutrino: 1956

  Reines-Cowan: Nobel prize 1995
- Muon neutrino ν_μ: 1962

  Steinberger-Schwartz-Lederman: Nobel prize 1988
- Tau neutrino ν_τ: 2000 (CERN)
- Solar neutrino observations: 1960's –

  Supernova neutrino observation: 1987

  Davis and Koshiba: Nobel prize 2001
- Solar neutrino puzzle: 1960's – 2002

  ν_e mixes with ν_μ and ν_τ
- Atmospheric neutrino problem: 1980's – 1998

  ν_μ and ν_τ mix almost maximally

Outline

Our current knowledge about neutrinos

$$(\nu_e, \nu_\mu, \nu_\tau) \leftrightarrow (\nu_1, \nu_2, \nu_3)$$

Solar, Atmospheric and Reactor neutrino experiments $\Rightarrow$

- Mass squared differences: $\Delta m^2_{21} \ll \Delta m^2_{31} \approx \Delta m^2_{32}$

$$\Delta m^2_{\odot} \approx (7.0 - 9.3) \times 10^{-5} \mathrm{eV}^2 \, , \; \Delta m^2_{\mathrm{atm}} \approx (1.3 - 4.2) \times 10^{-3} \mathrm{eV}^2$$

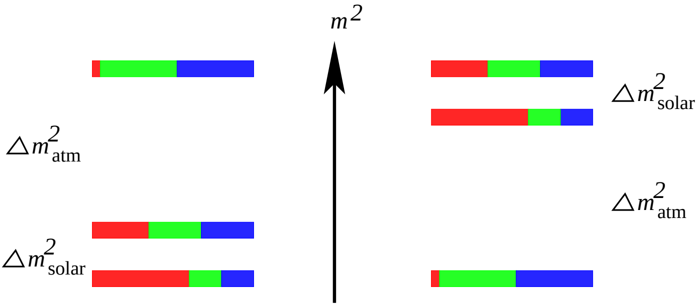
- Mixing matrix: $U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$

$$|U_{e1}|^2 \approx 0.7 \, , \; |U_{e2}|^2 \approx 0.3 \, , \; |U_{\mu 3}|^2 \approx 0.5 \, , \; |U_{e3}|^2 < 0.05$$

Two large angles and one small angle (vanishing ??)

Open questions in neutrino physics

- Mass hierarchy: Normal or Inverted ? (ν_e, ν_μ, ν_τ)



- Absolute neutrino masses
- CP violation $\overset{?}{\Rightarrow}$ Leptogenesis
- Are there more than three neutrinos ?
- Origin of neutrino masses

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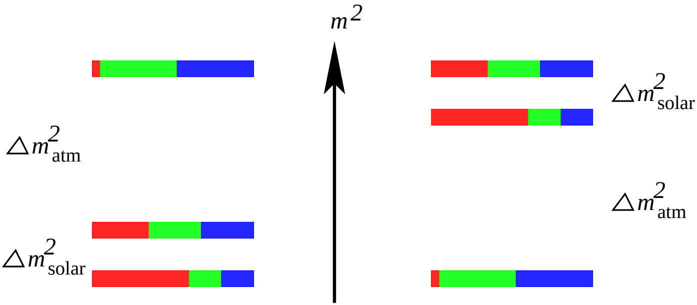

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Need for light Dirac neutrinos

- Seesaw mechanism for generating small neutrino masses:

$$m_\nu \approx m_D \frac{1}{M_R} m_D^T \qquad \Rightarrow \text{ Neutrinos are necessarily Majorana}$$

- Experimental results in 1984:
  - Neutrinoless double beta decay $\Rightarrow m_{ee} < 10$ eV
  - Tritium beta decay $\Rightarrow m_{\bar{\nu}_e} > 20$ eV (Ruled out later)
- The only way to resolve: neutrinos are Dirac particles (no lepton number violation).

Light Dirac neutrinos from SUSY SO(10) GUT

$$SO(10) \xrightarrow{M_{GUT}} SU(2)_L \times SU(2)_R \times SU(4) \qquad (10^{16}\ GeV)$$
$$\xrightarrow{M_{SUSY}} SU(3)_C \times SU(2)_L \times U(1)_Y \qquad (10^{10}\ GeV)$$

- Four chiral neutral fermions $\equiv$ two physical Dirac neutrinos

$$M_\nu \sim \begin{pmatrix} 0 & 0 & A & 0 \\ 0 & 0 & B & C \\ A & B & 0 & 0 \\ 0 & C & 0 & 0 \end{pmatrix}$$

- Global symmetries to restrict Yukawa couplings and keep radiative corrections under control
- The mass relation $m_\nu \sim m_u\, M_{SUSY}/M_{GUT}$
- $m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} = m_u : m_c : m_t$, $\qquad m_{\nu_e} \approx$ 20–55 eV

$\mathcal{PR}$, O. Shanker: PRL 1984, PRD 1984

Explicit construction of a globally SUSY SO(10) superpotential

Anjan S. Joshipura, $\mathcal{PR}$, O. Shanker, Utpal Sarkar: PLB 1985

Outline

The LSND problem

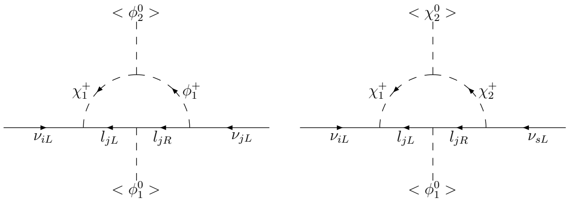
- Solar neutrino experiments $\Rightarrow$ oscillations with $\Delta m^2 \sim 10^{-4}$ eV^2
- Atmospheric neutrino experiments $\Rightarrow$ oscillations with $\Delta m^2 \sim 10^{-3}$ eV^2
- LSND experiment ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) $\Rightarrow$ oscillations with $\Delta m^2 \sim 1$ eV^2
- Only 3 neutrinos $\Rightarrow$ only 2 independent Δm^2
- Fourth neutrino species ? Or any other solution ?

Discrete Z_5 and seesaw

- Three active and one sterile neutrino, each with left and right chiral components
- Discrete Z_5 symmetry to generate hierarchy in elements of neutrino mass matrix
- Atmospheric neutrino solution through $\nu_\mu \leftrightarrow \nu_\tau$
  Maximal $\mu - \tau$ mixing and small mass difference from the pseudo-Dirac structure $\begin{pmatrix} a & b \\ b & a \end{pmatrix}$
- Solar neutrino solution through $\nu_e \leftrightarrow \nu_s \oplus \nu_e \leftrightarrow \nu_\mu$

Ernest Ma, $\mathcal{PR}$: PRD 1995

Radiative neurino mass generation for 4 neutrinos



- An extension of the Zee model: radiative generation of $m_{\text{active}-\text{active}}$ and $m_{\text{active}-\text{sterile}}$ from charged Higgs exchange
- Solar: $\nu_e \leftrightarrow \nu_s$, Atmospheric: $\nu_\mu \leftrightarrow \nu_\tau$ (bimaximal mixing), LSND anomaly: $\nu_e \leftrightarrow \nu_\mu$
- Approximate relationship $\Delta m^2_{atm} \approx 2\sqrt{\Delta m^2_{sol} \Delta m^2_{LSND}}$

Naveen Gaur, Ambar Ghosal, Ernest Ma, $\mathcal{PR}$: PRD 1998

With non-maximal θ_{12}, a modified relation

$$\sin^2 2\theta_{12} \approx 1 - [\Delta m^2_{atm}/(4\Delta m^2_{sol} \Delta m^2_{LSND})^2]^2$$

$\mathcal{PR}$, Sudhir K. Vempati: PRD 2002

Solar, atmospheric and LSND from 3 neutrinos

- Atmospheric neutrinos: $\nu_\mu \leftrightarrow \nu_\tau$ oscillations
  LSND: $\nu_\mu \leftrightarrow \nu_e$ oscillations
- Solar neutrino conversions through new ν_τ-quark neutral current interactions:

$$\mathcal{L}_{\rm new} = -\sqrt{2}\bar{\nu}_{\tau L}\gamma^\mu \nu_{\tau L}(G^q_{\tau\tau V}\bar{q}\gamma^\mu q + G^q_{\tau\tau A}\bar{q}\gamma^\mu\gamma^5 q)$$

- Zenith angle dependence predicted, but smaller for sub-GeV atmospheric data

Ernest Ma, $\mathcal{PR}$: PRL 1998

Outline

Higher dimensional models of light Majorana neutrinos

- ADD models with a “SM” brane inside the 5-d bulk
- No-go theorem, using solar, atmospheric, reactor and cosmological data, for the following class of models:
  - Three or four light Majorana neutrinos on the brane
  - One or more right chiral neutrinos in the bulk
  - Flavour blind bulk - brane couplings
- Extra dimensions, if relevant to neutrino mixing, must discriminate between neutrino flavours

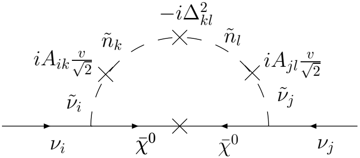
JoAnne L. Hewett, $\mathcal{PR}$, Sourov Roy: PRD 2004

Bilarge neutrino mixing from SUSY

- Nonlinear terms in the hidden sector generate Majorana mass terms for (s)neutrinos

$$\mathcal{L}_{\rm eff} = \frac{1}{M_P}([X_{ij}^\dagger N^i N^j]_D + [X_{ij}^\dagger L^i N^j H_u]_F) + H.c.$$

- Nondiagonal $\Delta L = 2$ mass terms, almost diagonal ~~SUSY~~ A-terms.



- Radiatively induced masses + seesaw $\Rightarrow$ bi-large mixing

Biswarup Mukhopadhyaya, $\mathcal{PR}$, Raghavendra Srikanth: PRD 2006

Outline

CP violation in long baseline experiments

- Disentangling "real" CP violation from "fake" CP violation
- Lowest order analytic calculations of neutrino conversion probabilities for a variable earth density
- For maximal mixing, matter effects on the survival probability $P_{\nu_\mu \to \nu_\mu}$ vanish identically

Biswajoy Brahmachari, Sandhya Choubey, $\mathcal{PR}$: NPB 2003

Deviation of atmospheric mixing angle from maximality

- $\theta_{23} \in (40^\circ, 60^\circ)$ at 3σ, best fit at 45°
- Deviation from maximality: $D \equiv 1/2 - \sin^2\theta_{23}$ x
- In vacuum, $\Delta P \equiv P_{\nu_\mu \to \nu_\mu} - P_{\bar{\nu}_\mu \to \bar{\nu}_\mu} \propto D^2$
- In matter, linear ΔP dependence on D:
  $\Delta P \propto |U_{e3}|^2 (1 - 2|U_{\mu 3}|^2) \propto \theta_{13}^2 D$
- With $\sin^2 2\theta_{13} > 0.08$ and $|D| > 0.1$, sign of D may be determined to 3σ with 1000 kt-yr at INO
- Sign of D $\Rightarrow$ resolution of "octant ambiguity"

Sandhya Choubey and $\mathcal{PR}$, PRL 2004, PRD 2006

Outline

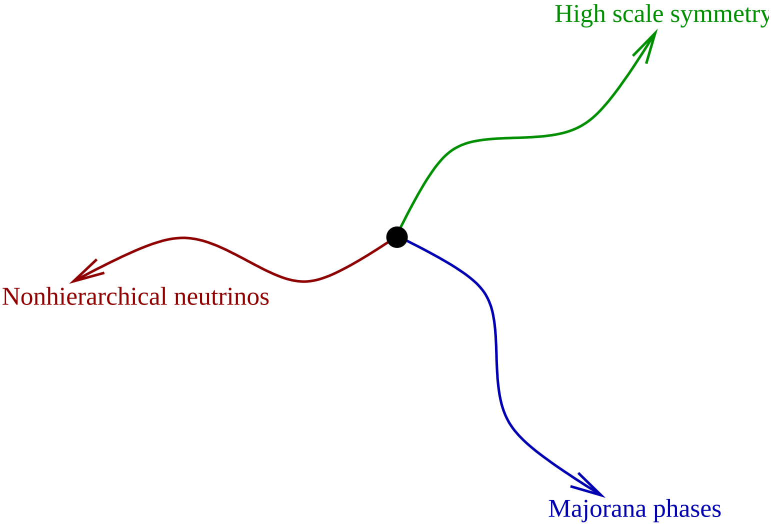
Quark-lepton symmetries

- Quark mixing angles: $\theta_{12}^q \equiv \theta_C \approx 12^\circ, \theta_{23}^q \equiv |V_{cb}| \approx 2^\circ$
- Neutrino mixing angles: $\theta_{12} \approx 34^\circ \pm 1.5^\circ, \theta_{23} \approx 45^\circ \pm 5^\circ$
- A possible relation: "Quark-lepton complementarity (QLC)"

$$\theta_{12}^q + \theta_{12} = 45^\circ \qquad (\text{ Also } \theta_{23}^q + \theta_{23} \approx 45^\circ)$$

- Can be implemented in two steps:
  - Symmetry of neutrino mass matrix:
    ($\mu - \tau$ exchange/ $L_\mu - L_\tau$ gauge/ S_3 permutation) $\Rightarrow$
    $U_\nu \equiv U_{bimax} : \theta_{12} = \theta_{23} = 45^\circ, \theta_{13} = 0^\circ$
  - SO(10) GUT $\Rightarrow U_{PMNS} = U_\nu^\dagger U_\ell$ (QLC2)
- SU(5) GUT $\Rightarrow U_{PMNS} = U_\ell^\dagger U_\nu$ (QLC1)
  $\Rightarrow \theta_{12} + \theta_{12}^q/\sqrt{2} = 45^\circ$
- A_4 or S_3 permutation symmetry $\Rightarrow$
  $U_\nu \equiv U_{tribimax} : \theta_{12} = \sin^{-1}\frac{1}{\sqrt{3}}, \theta_{23} = 45^\circ, \theta_{13} = 0^\circ$
  Tri-bimaximal mixing (TBM)

Interconnections



Radiative corrections to symmetry relations

- QLC and TBM give distinct predictions for neutrino mixing angles, but only at the high scale where the symmetry is unbroken
- Renormalization group evolution can change the predictions, making it impossible to distinguish between the symmetry scenarios, especially for quasidegenerate scenarios
- Symmetries can be preserved with proper choice of Majorana phases, e.g. $m_1 \approx -m_2$
- Correlations between the evolutions of mixing angles help in distinguishing between high scale symmetries in spite of large RG evolution

Amol Dighe, Srubabati Goswami, $\mathcal{PR}$: PRD 2006, PRD 2007

In the words of Mark Antony

Friends, physicists and TIFR-folk, lend me your ears;

I came to review his works, not to just praise him;

The good papers that men write live after them,

The not-so-good ones are interred in the arXiv's

So let it be...

It's said that he is loquacious

But he is (also) an honourable man.

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