Plan of Lectures

I. Standard Neutrino Properties and Mass Terms (Beyond Standard)

II. Neutrino Oscillations

III. The Data and Its Interpretation

IV. Some Missing Pieces and the Meaning of All This

Plan of Lecture IV

Some Missing Pieces and the Meaning of All This

The Future Experimental Program and Its Challenges

Some Lessons:

- The Need of New Physics
- The Possibility of Leptogenesis
- How the Sun Shines

Present and Future of Neutrino Parameters

3-ν parameter	Present knowledge ($\sim 3\sigma$ C. L.)	Near and Not so Near Future
θ_{23}	$0.49 \leq \tan^2\theta_{23} \leq 2.2$	$P(\nu_\mu \to \nu_\mu)$ MINOS, CNGS
θ_{12}	$0.29 \leq \tan^2\theta_{12} \leq 0.64$	SNO NC, KamLAND
θ_{13}	$\sin^2\theta_{13} \leq 0.054$	$P(\bar\nu_e \to \bar\nu_e)$ Reactor, $P(\nu_\mu \to \nu_e)$ LBL
$\|\Delta m^2_{31}\|$	$1.4 \leq \|\Delta m^2_{31}\|/10^{-3}\text{eV}^2 \leq 3.4$	$P(\nu_\mu \to \nu_\mu)$ MINOS, CNGS
$\text{sgn}(\Delta m^2_{31})$	unknown	$P(\nu_\mu \to \nu_e)$, $P(\bar\nu_\mu \to \bar\nu_e)$ LBL
$\|\Delta m^2_{21}\|$	$5.2 \leq \Delta m^2_{21}/10^{-5}\text{eV}^2 \leq 9.8$	$P(\bar\nu_e \to \bar\nu_e)$ KamLAND
$\text{sgn}(\Delta m^2_{21})$	$+$ (MSW)	Done!
δ	unknown	$P(\nu_\mu \to \nu_e)$ versus $P(\bar\nu_\mu \to \bar\nu_e)$ LBL
Majorana	unknown	$0\nu\beta\beta$
m_ν	$\sum m_\nu < \mathcal{O}(1)$ eV	β-decay, $0\nu\beta\beta$, cosmo

Neutrino Parameters: Future Strategies

- Oscillation Probabilities in Earth: $\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$ $B_\pm = \Delta_{31} \pm V_E$ $(V_E \sim 10^{-13}\ \text{eV})$
  $\tilde{J} = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$

$$
\begin{aligned}
P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} \simeq\ & s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) \\
+\ & \tilde{J} \frac{\Delta_{12}}{V_E} \frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\delta \cos\left(\frac{\Delta_{31} L}{2}\right) \\
\pm\ & \tilde{J} \frac{\Delta_{12}}{V_E} \frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \sin\delta \sin\left(\frac{\Delta_{31} L}{2}\right) + \ldots \\
P(\nu_\mu \to \nu_\mu) \simeq\ & 1 - c^2_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta_{31} L}{2}\right) + \mathcal{O}(\Delta_{12}, s^2_{13}) \\
P(\nu_e \to \nu_e) \simeq\ & 1 - \sin^2 2\theta_{31} \sin^2\left(\frac{\Delta_{31} L}{2}\right) - c^4_{31} \sin^2\left(\frac{\Delta_{21} L}{2}\right)
\end{aligned}
$$

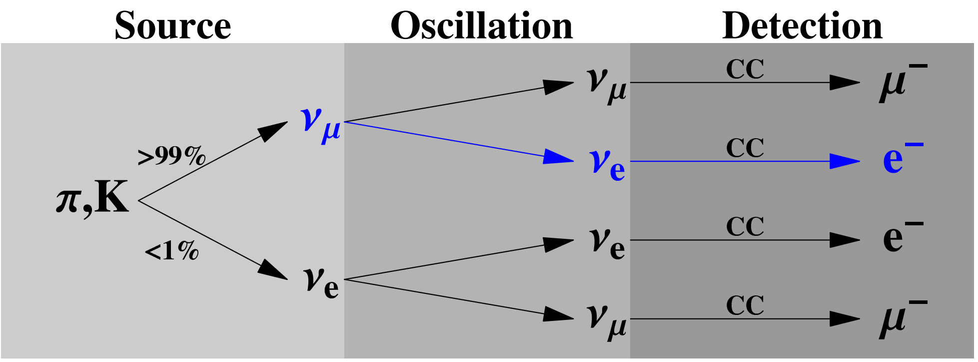
– $\text{sgn}(\Delta m^2_{31})$: Need of matter effects $\Rightarrow$ very long L

– θ_{13}: Very intense ν_μ or ν_e beam with low background

– $\not{C}$P: All angles and Δm^2 non vanishing $\Rightarrow$ Δm^2_{21} in LMA and θ_{13} not too small
Intense beams with exchangeable initial state $(\nu/\bar\nu)$

Experimental Set-ups

- Conventional (=from π decay) Superbeams



Off-Axis	Exp	L	$\langle E\rangle$
	T2K (Japan)	295 km	0.76 GeV
	NuMI (Fermilab)	812 km	2.22 GeV

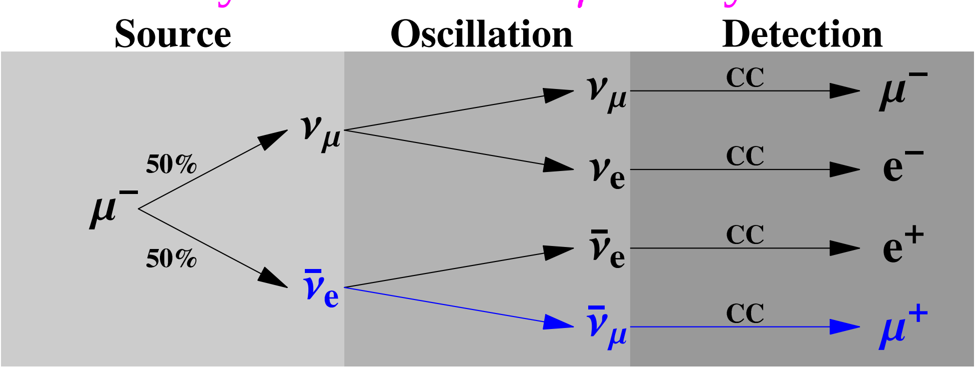
- Reactor Experiment with 2 Detectors [only θ_{13}]

$$P(\nu_e\to\nu_e)\simeq 1-\sin^2 2\theta_{31}\sin^2\left(\frac{\Delta_{31}L}{2}\right)$$

CHOOZII (France), Many proposals

$\langle E\rangle\sim 4$ MeV $\quad L\sim 1$–2 km

- ν-factory: ν beam from μ decay



$\langle E\rangle\sim 20$–50 GeV

$L\sim 700$–7000 km

- β-beam : Beam of pure ν_e or $\overline{\nu}_e$ from heavy-ion decay: ${}^6_2He^{++}\to{}^6_3Li^{++}\,e^-\,\nu_e$

Challenge at Future LBL: Parameter Degeneracies

$$P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right)$$
$$+ \tilde J \frac{\Delta_{12}}{V_E}\frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\delta \cos\left(\frac{\Delta_{31} L}{2}\right)$$
$$\pm \tilde J \frac{\Delta_{12}}{V_E}\frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \sin\delta \sin\left(\frac{\Delta_{31} L}{2}\right) + \dots$$
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - c_{13}^2 \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta_{31} L}{2}\right) + \mathcal{O}(\Delta_{12}, s_{13}^2)$$

$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$ $\quad B_\pm = \Delta_{31} \pm V_E$

$\tilde J = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$

(a) $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ ambiguity:

$$P_{\nu_\mu\nu_\mu} \propto \sin^2 2\theta_{23} \text{ and } P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)}(\theta_{23},\theta_{13},\delta) = P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)}(\tfrac{\pi}{2}-\theta_{23},\theta'_{13},\delta')$$

(b) (θ_{13},δ) ambiguity:

$$P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)}(\theta_{13},\delta) = P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)}(\theta'_{13},\delta')$$

(c) $(\mathrm{sgn}\ \Delta m^2_{31}, \delta)$ ambiguity:

$$P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)}(\mathrm{sgn}\Delta m^2_{31},\delta) = P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)}(-\mathrm{sgn}\Delta m^2_{31},\delta')$$

$$\Downarrow$$

If only total number of ν_e, ν_μ, $\overline\nu_e$ and $\overline\nu_\mu$ at given L are measured $\Rightarrow$ 8-fold degeneracy

Future LBL: Cures of Degeneracies

$$
\begin{aligned}
P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} \simeq\ & s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) \\
+\ & \tilde{J}\, \frac{\Delta_{12}}{V_E} \frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\delta \cos\left(\frac{\Delta_{31} L}{2}\right) \\
\pm\ & \tilde{J}\, \frac{\Delta_{12}}{V_E} \frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \sin\delta \sin\left(\frac{\Delta_{31} L}{2}\right) + \ldots
\end{aligned}
$$

- Go to *magic* baselines:

  At $L = \frac{2\pi}{V_e} \sim 7500$ km $\Rightarrow$ Only first term survives

  Unambiguous determination of θ_{13} but no sensitivity to CP violation (also a bit too long...)

  At $L = \frac{\pi}{4\Delta_{31}} \simeq 560\text{km}\,\frac{E}{\text{GeV}}\,\frac{2.2\times10^{-3}}{\Delta m_{31}^2}$ $\Rightarrow$ $\cos\delta$ term cancels out

  (θ_{13}, δ) ambiguity broken but others remain

- Combine measurements at different L and different E

  Need several detectors and/or several beams

- Wide-band superbeam allowing for spectrum measurements $N_\nu(E_\nu)$

  Need detector with good energy resolution

- Use "silver" oscillation channels $\nu_e \to \nu_\tau$ and $\nu_\mu \to \nu_\tau$

  Need higher beam energy and high resolution detector

Some Lessons: New Physics

A fermion mass can be seen as at a Left-Right transition

$m_f \overline{f_L} f_R$ (this is not $SU(2)_L$ gauge invariant)

If the SM is *the fundamental theory*:

– All terms in lagrangian (including masses) must be $\left\{ \begin{array}{l} \text{gauge invariant} \\ \text{renormalizable } (\dim \leq 4\ ) \end{array} \right.$

– A gauge invariant fermion mass is generated by interaction with the Higgs field $\lambda_f \overline{f_L} \phi f_R \rightarrow m_f = \lambda_f v$

($v \equiv$ Higgs vacuum expectation value ~ 250 GeV)

– But there are no right-handed neutrinos

$\Rightarrow$ No renormalizable gauge-invariant operator for tree level ν mass

– SM gauge invariance also implies the accidental symmetry

$G_{\rm SM}^{\rm global} = U(1)_{\rm B} \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} \Rightarrow m_\nu = 0$ *to all orders*

Thus the most striking implication of ν masses:

There is New Physics Beyond the SM

And it is also the only solid evidence! To go further one has to be cautious...

Lessons: The Scale of New Physics

If SM is an effective low energy theory, for $E \ll \Lambda_{\rm NP}$

– The same particle content as the SM and same pattern of symmetry breaking

– But there can be non-renormalizable (dim$>$ 4) operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_n \frac{1}{\Lambda_{\rm NP}^{n-4}} \mathcal{O}_n$$

First NP effect $\Rightarrow$ dim=5 operator

There is only one!

$$\mathcal{O}_5 = \frac{Z^\nu_{ij}}{\Lambda_{\rm NP}} \left(\overline{\psi_{Li}} \tilde{\phi}\right) \left(\tilde{\phi}^T \psi^C_{Lj}\right)$$

which after symmetry breaking

induces a ν Majorana mass

$$(M_\nu)_{ij} = \frac{Z^\nu_{ij}}{2} \frac{v^2}{\Lambda_{\rm NP}}$$

$\mathcal{O}_5$ breaks total lepton and lepton flavour numbers

Implications:

– It is natural that ν mass is the first evidence of NP

– Naturally $m_\nu \ll$ other fermions masses $\sim \lambda^f v$

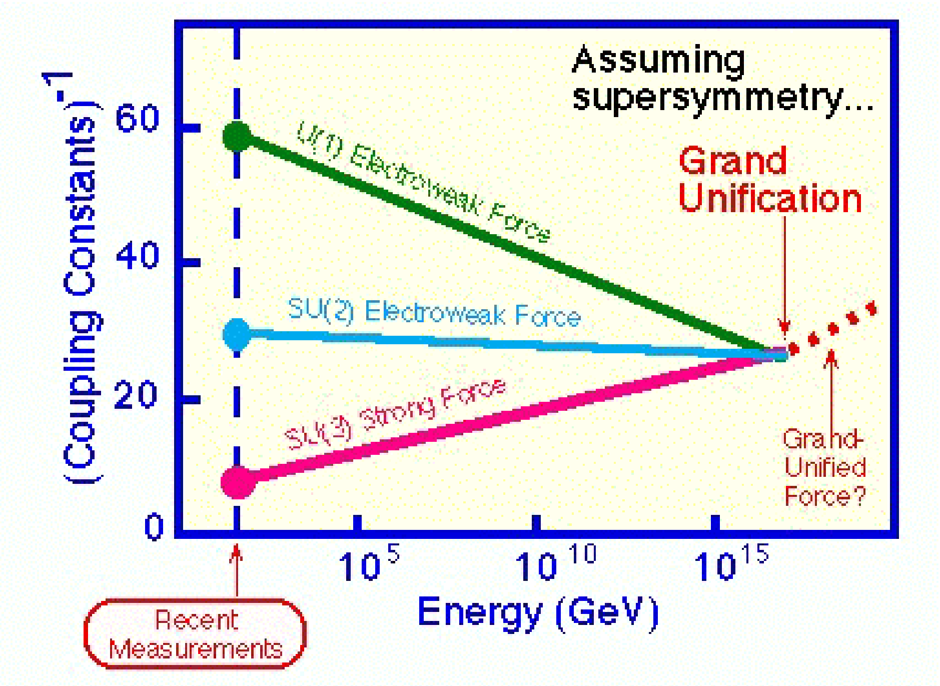
– $m_\nu > \sqrt{\Delta m^2_{atm}} \sim 0.05$ eV $\Rightarrow \Lambda_{\rm NP} < 10^{15}$ GeV

But this is scale was already known to particle physicists...

Lessons: The Scale of New Physics

$m_\nu > \sqrt{\Delta m^2_{\rm atm}} \sim 0.05 {\rm eV} \Rightarrow 10^{10} < \Lambda_{\rm NP} < 10^{15} {\rm GeV}$

New Physics Scale close to Grand Unification scale



Also the generated neutrino mass term is Majorana :

$\Rightarrow$ It violates total lepton number

$$\mathcal{O}_5 = \frac{Z^\nu_{ij}}{\Lambda_{\rm NP}} \left(\overline{\psi_{Li}} \tilde\phi\right)\left(\tilde\phi^T \psi^C_{Lj}\right)$$

The See-Saw

Simplest NP: add right-handed ν_R (=SM singlet) neutrinos

Well above the electroweak (EW) scale

$$-\mathcal{L}_{\rm NP} = \frac{1}{2} M_{Rij}\overline{\nu_{Ri}^c}\nu_{Rj} + \lambda^\nu_{ij}\overline{\psi_{Li}}\tilde{\phi}\nu_{Rj} + \text{h.c..}$$

ν_R is a EW singlet $\Rightarrow M_{Rij} >> $ EW scale

Below EW symmetry breaking scale ($E \ll M_R$):

a) $m_D = \lambda^\nu v \sim$ mass of other fermions is generated

b) ν_R are so heavy that can be "integrated out"

$$\Downarrow \quad E \ll M_R$$

$$\mathcal{L}_{\rm NP} \Rightarrow \mathcal{O}_5 = \frac{(\lambda^{\nu T}\lambda^\nu)_{ij}}{M_{\rm R}}\left(\overline{\psi_{Li}}\tilde{\phi}\right)\left(\tilde{\phi}^T\psi^C_{Lj}\right) \Rightarrow m_\nu = m_D^T\frac{1}{M_R}m_D$$

This is the see-saw

Lessons:

– $\mathcal{L}_{\rm NP}$ contains 18 parameters which we want to know

– $\mathcal{O}_5$ contains 9 parameters which we can measure

$\Rightarrow$ Same $\mathcal{O}_5$ can give very different $\mathcal{L}_{\rm NP}$

$\Rightarrow$ It is *difficult* to "imply" bottom-up (model independently)

Leptogenesis

Baryogenesis and the SM

- From Nucleosytesys and CMBR data $\Rightarrow$ $Y_B = \frac{n_b - n_{\bar{b}}}{s} = \frac{n_b}{s} \sim 10^{-10}$

- Y_B can be dynamically generated if *Three Sakharov Conditions* are verified:
  - Baryon number is violated
  - C and CP are violated
  - Departure from thermal equilibrium

- The SM verifies these conditions:

$\rightarrow$ Conserves $B-L$ but violates $B+L$

$\rightarrow$ CP violation due to δ_{CKM}

$\rightarrow$ Departure from thermal equilibrium *at Electroweak Phase Transition*

- But the SM fails on two points:
  - With the bound of SM Higgs mass the EWPT is not strong first order PT
  - CKM CP violation is too suppressed

$$\Downarrow$$

$$Y_{B,SM} \ll 10^{-10}$$

Leptogenesis

- From the analysis of oscillation data $\Rightarrow$ $m_{\nu_3} \gtrsim 0.05$ eV

- If m_ν is generated via the See-saw mechanism

$$-\mathcal{L}_{\rm NP} = \frac{1}{2} M_{Rij} \overline{\nu_{Ri}^c} \nu_{Rj} + \lambda_{ij} \overline{\psi_{Li}} \tilde{\phi} \nu_{Rj} \Rightarrow m_\nu \sim \frac{\lambda^2 \langle \phi \rangle^2}{M_R}$$

$\Big\}$ $(M_{\nu_{R3}}/\lambda_3^2 \lesssim 10^{15}$ GeV$)$

$\Rightarrow$ Lepton Number is Violated (M_R)

$\Rightarrow$ New Sources of CP violation λ

$\Rightarrow$ Decay of ν_R can be out of equilibrium

(if $\Gamma_{\nu_R} \ll$ Universe expansion rate) $\Rightarrow$ $\Gamma_{\nu_R} \ll H\big|_{T=M_{\nu_R}}$

$$\Downarrow$$

Leptogenesis $\equiv$ generation of lepton asymmetry Y_L

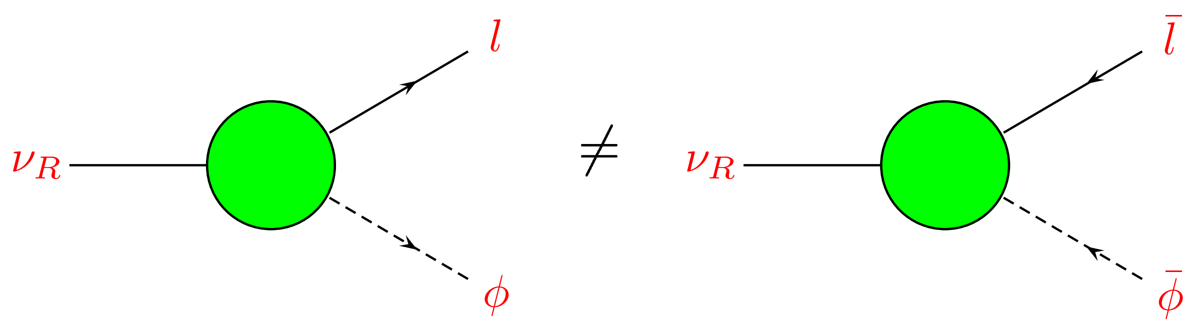
- At the electroweak transition sphaleron processes:

$\Rightarrow$ Y_L is transformed in $Y_B \simeq -\frac{Y_L}{2}$

- In the the See-saw mechanism $-\mathcal{L}_{\rm NP} = \frac{1}{2} M_{Rij} \overline{\nu_{R}{}_i^c} \nu_{Rj} + \lambda_{ij} \overline{\psi_{Li}} \tilde{\phi} \nu_{Rj}$

  – In the Early Universe decay of heavy ν_R: $\Gamma(\nu_R \to \phi\, l_L) = \frac{1}{8\pi} \sum_i (\lambda\lambda^\dagger)^2_{ii} M_{\nu_{Ri}}$

  – CP can be violated at 1-loop



(This requires 3 light generations and at least $2\nu_R$)

$$\epsilon_L = \frac{\Gamma(\nu_R \to \phi\, l_L) - \Gamma(\nu_R \to \overline{\phi}\, \overline{l_L})}{\Gamma(\nu_R \to \phi\, l_L) + \Gamma(\nu_R \to \overline{\phi}\, \overline{l_L})} = -\frac{1}{8\pi} \sum_k \frac{Im[(\lambda\lambda^\dagger)^2_{k1}]}{(\lambda\lambda^\dagger)_{11}} \times f\left(\frac{M_{\nu_{Rk}}}{M_{\nu_{R1}}}\right)$$

$$\Rightarrow \; |\epsilon_L| \lesssim 0.1 \frac{M_{\nu_{R1}}}{\langle\phi\rangle^2} (m_{\nu_3} - m_{\nu_1})$$

$$Y_L = \frac{n_{\nu_R}}{s} \epsilon_L\, d \sim 10^{-3} d\, \epsilon_L$$

$n_{\nu_R} \equiv$ density of ν_R ($d < 1 \equiv$ dilution factor)

Out of Equilibrium condition $\Gamma_{\nu_R} \ll H\big|_{T=M_{\nu_R}} \Rightarrow \tilde{m_1} \equiv \frac{(\lambda\lambda^\dagger)^2_{11} \langle\phi\rangle^2}{M_{\nu_{R1}}} \lesssim 5 \times 10^{-3} eV$

- In the See-saw mechanism $-\mathcal{L}_{\rm NP} = \frac{1}{2} M_{Rij} \overline{\nu_{Ri}^c} \nu_{Rj} + \lambda_{ij} \overline{\psi_{Li}} \tilde{\phi} \nu_{Rj}$

$$M^\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

$m_D = \lambda \langle \phi \rangle$ is a 3×3 matrix

M_R is a 3×3 symmetric matrix

$\Rightarrow$ M^ν has 6 physical phases

$\Rightarrow$ It is easy to generate $\epsilon_L \sim 10^{-6}$

$\Rightarrow$ $m^\nu_{\rm light} = m_D^T M_N^{-1} m_D$ has 3 physical phases

Oscillation experiments can only see one of these three phases

$\Rightarrow$ No direct correspondence between CPV in leptogenesis and CPV in oscillations

- The final Y_B depends on:
  - ϵ_L the CP asymmetry
  - $M_{\nu_{R1}}$ the mass of the lightest ν_R
  - $\tilde{m}_1 \equiv \frac{(\lambda\lambda^\dagger)^2_{11}\langle\phi\rangle^2}{M_{\nu_{R1}}}$ the *effective* neutrino mass
  - $m^2_{\nu_1} + m^2_{\nu_2} + m^2_{\nu_3}$ the sum of the light neutrinos mass squared
- To generate the required Y_B:
  - $M_{\nu_{R1}} \gtrsim 4 \times 10^8$ GeV
  - $m_{\nu_3} \lesssim 0.12$ eV
  - Large CP phases

    The CP violating phase relevant for leptogenesis
    may not be the same as the one relevant for oscillations

Learning How the Sun Shines

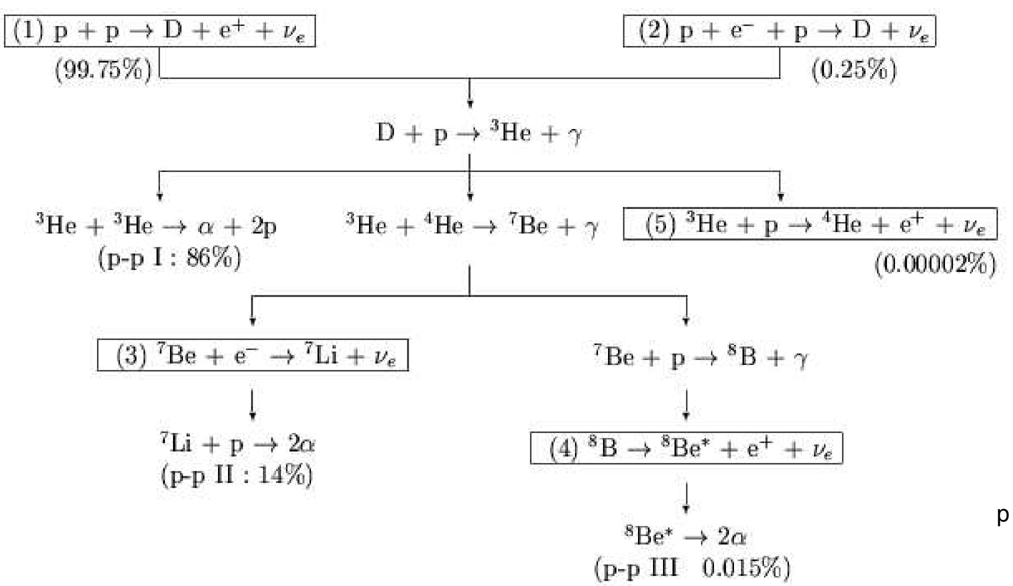
- The Sun shines converting protons into α, e^+ and $\nu' s$

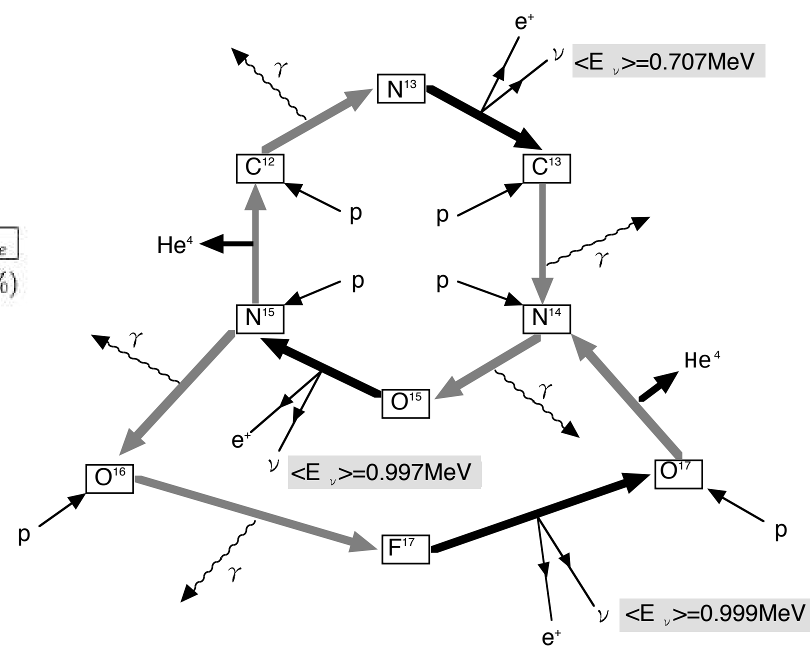
$$4\,p \;\rightarrow\; {}^4He \;+\; 2\,e^+ \;+\; 2\,\nu_e \;+\; \gamma$$

$4m_p - m_{^4He} - 2m_e \simeq 26$ MeV Thermal energy mostly in γ

- Two major chains of nuclear reactions

pp chain: CNO cycle:





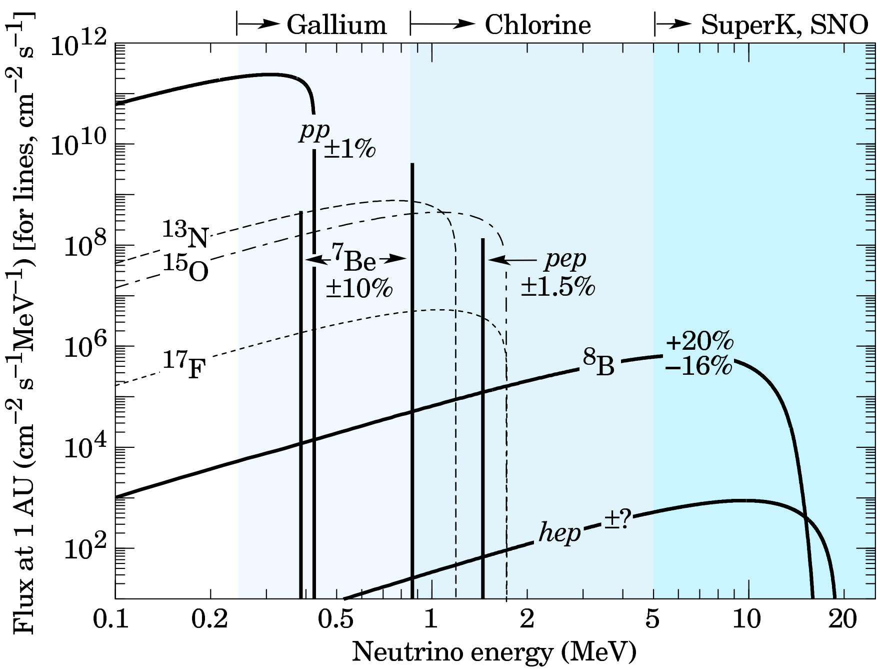
- The ratio pp/CNO very sensitive to T_{core}

- First proposal by Bethe (1939) was that CNO dominated

“It is shown that the most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons.”

- Improved Solar Model& nuclear reaction data $\Rightarrow$ Sun shines primarily by p-p

- BP00 Fluxes



$$\frac{L_{CNO}}{L_\odot} = 1.5\%$$

$$\frac{L_{p-p}}{L_\odot} = 98.5\%$$

- Can this be tested experimentally?

– Radiochemical experiments sensitive to CNO fluxes

But do not measure $E \Rightarrow$ only integrated flux above E_{th}

– Oscillations modify the E dependence of detected fluxes

$\Rightarrow$ Possible suppression of CNO fluxes $\Rightarrow$ no experimental limit

How the Sun Shines? Older Answer

- Before SK and SNO large CNO solutions allowed

  Bahcall, Fukugita, Krastev PLB (1996)

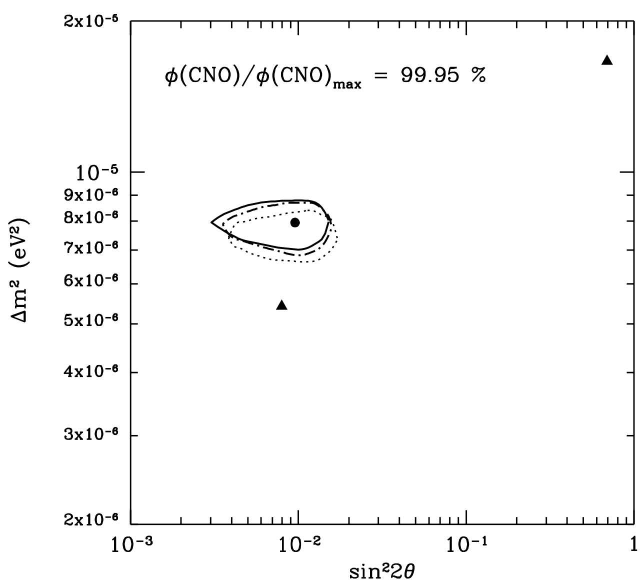
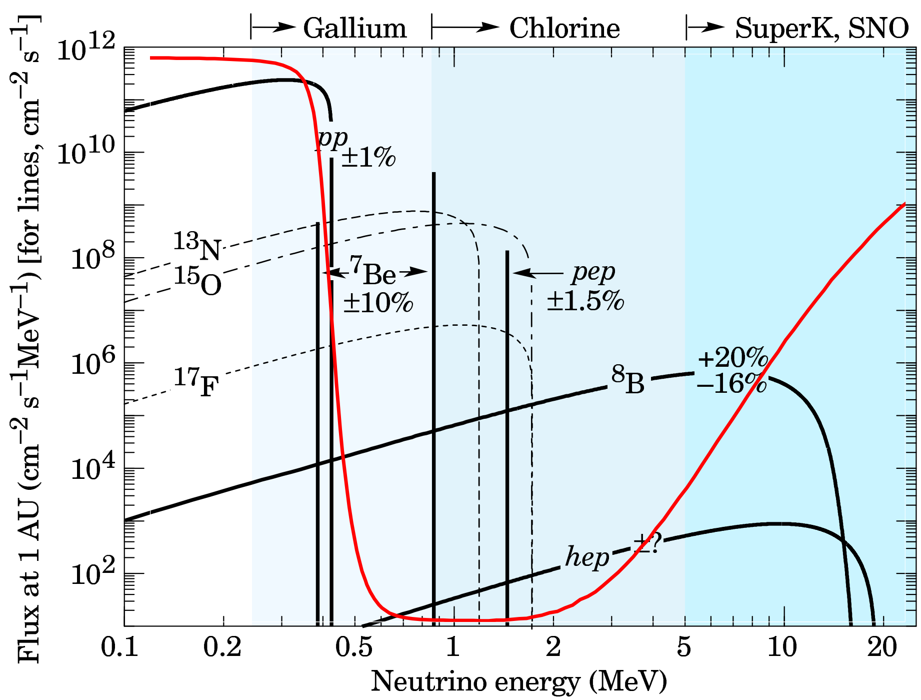


Fig.2



How the Sun Shines? Present Answer

- Fit solar (and KamLAND) data for:
  - 2ν oscillations $\Delta m^2, \tan^2\theta$
  - 8 free solar ν fluxes under conditions:
    * Luminosity constraint

$$\frac{L_\odot}{4\pi(A.U.)^2} = \sum_{i=1}^{8} \alpha_i \Phi_i \;\Rightarrow\; 1 = \sum_{i=1}^{8} \left(\frac{\alpha_i}{10\text{ MeV}}\right) a_i f_i$$

$$f_i \equiv \frac{\Phi_i}{\Phi_i(\mathrm{BP2000})}, \qquad a_i \equiv \frac{\Phi_i(\mathrm{BP2000})}{(8.5272\times 10^{10}\mathrm{cm}^{-2}\mathrm{s}^{-1})}$$

* Nuclear Physics inequalities:

$$\Phi_{^7\mathrm{Be}} + \Phi_{^8\mathrm{B}} \le \Phi_{\mathrm{pp}} + \Phi_{\mathrm{pep}} \qquad \Phi_{^{15}\mathrm{O}} \le \Phi_{^{13}\mathrm{N}}$$

* ^{15}O and ^{17}F fluxes: $\frac{\Phi_{^{15}\mathrm{O}}(\mathrm{BP2000})}{\Phi_{^{13}\mathrm{N}}(\mathrm{BP2000})} < \frac{\Phi_{^{15}\mathrm{O}}}{\Phi_{^{13}\mathrm{N}}} < 1$ and $\frac{\Phi_{^{17}\mathrm{F}}(\mathrm{BP2000})}{\Phi_{^{13}\mathrm{N}}(\mathrm{BP2000})} < \frac{\Phi_{^{17}\mathrm{F}}}{\Phi_{^{13}\mathrm{N}}} \le 1$

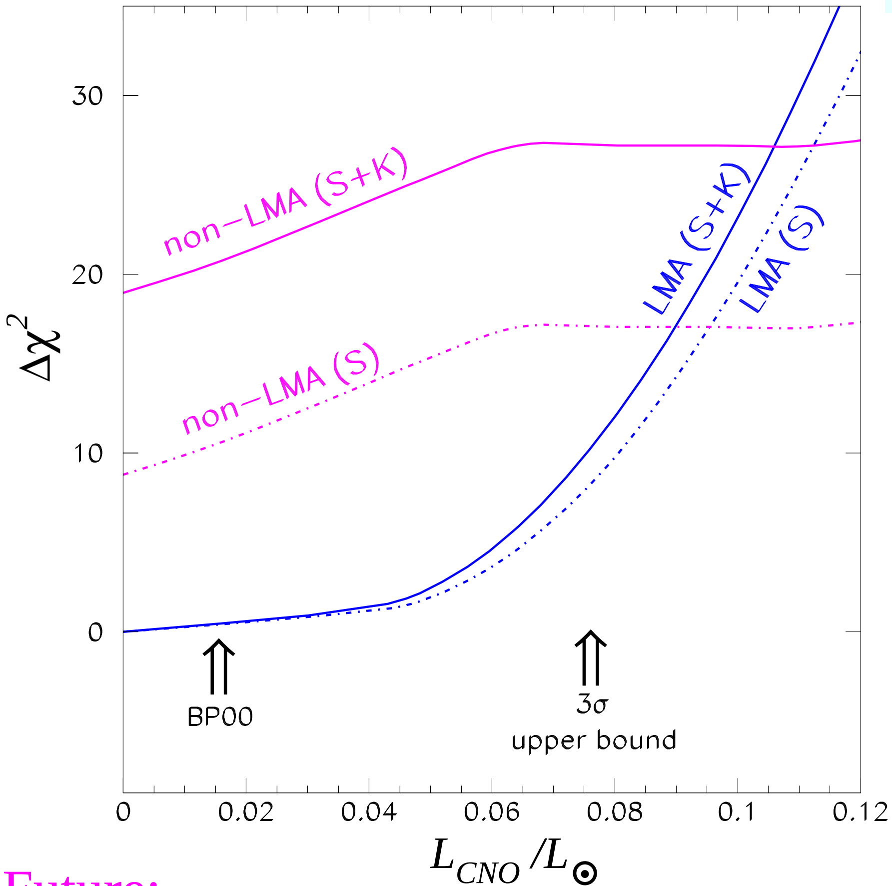
* *pep* flux: $\frac{\Phi_{pep}}{\Phi_{p-p}} = \frac{\Phi_{pep}(\mathrm{BP2000})}{\Phi_{p-p}(\mathrm{BP2000})} \pm 10\%$

* hep flux: within present limits $1 \le f_{hep} \le 8$

How the Sun Shines? Present Answer

Study the quality of fit as a function of:

$$\frac{L_{CNO}}{L_\odot} = \sum_{i=N,O,F} \left(\frac{\alpha_i}{10\text{ MeV}}\right) a_i\, f_i$$



Resulting Limit:

$$\frac{L_{\rm CNO}}{L_\odot} < 7.3\% \ (7.8\%)$$
at 3σ

Old large CNO solutions were SMA-like

$\Rightarrow$ Improvement from SK and SNO data

Future:

– Borexino: $\Rightarrow \frac{L_{\rm CNO}}{L_\odot} < 5.6\% \ [4.9\%]$

– To test BP00 prediction 1.5%: lowE experiment with excellent E resolution

How the Sun Shines? My Show-off Slide

Prof. J. Bahcall 15 May 03

Inst. Adv. Studies

Dear John:

Congratulations! To get the rates of the pp and the CNO reaction from the solar neutrinos is ingenious. I am convinced by your calculation. Sincerely

Hans

Summary IV

- Some Lessons from the Existing Data:
  - There is New Physics
  - Most likely SM is an Effective Low Energy Theory
  - $\Lambda_{NP} \lesssim 10^{15}$ GeV ($\ll M_{\rm Plank}$)
  - Results Fit well with GUT expectations
  - If the seesaw is the origin of $m_\nu \Rightarrow$ Leptogenesis is unavoidable
  - The Sun burns by the pp-chain by more than 90%
- To proceed learning we need more and more precise experiments:

  This is a challenging task

Conclusions

- Neutrino oscillation searches have shown us
  - $\Delta m^2_{31} \sim 2.4 \times 10^{-3}$ eV^2 and $\Delta m^2_{21} \sim 7.1 \times 10^{-5}$ eV^2 $\Rightarrow$ ν's are massive
  - $|U_{\rm LEP}| \simeq \begin{pmatrix} \frac{1}{\sqrt{2}}(1+\mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}}(1-\mathcal{O}(\lambda)) & \epsilon \\ -\frac{1}{2}(1-\mathcal{O}(\lambda)+\epsilon) & \frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \\ \frac{1}{2}(1-\mathcal{O}(\lambda)-\epsilon) & -\frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \end{pmatrix}$ $\lambda \sim 0.2$ $\epsilon \lesssim 0.2$ $\Rightarrow$ Different from U_{CKM}

- $m_\nu \neq 0 \Rightarrow$ Need to extend SM It can be done:

  (a) *breaking* total lepton number $\rightarrow$ Majorana $\nu : \nu = \nu^C$

  (b) *conserving* total lepton number $\rightarrow$ Dirac $\nu : \nu \neq \nu^C$

- Majorana $\nu' s$ are more *Natural*: appear *generically* if SM is a LE effective theory
  - $\Lambda_{NP} \lesssim 10^{15}$ GeV
  - Results Fit well with GUT expectations
  - Leptogenesis may explain the baryon asymmetry

Conclusions

- Still open questions
  - Is $\theta_{13} \neq 0$?
  - Is there CP violation in the leptons (is $\delta \neq 0, \pi$)?
  - Is θ_{23} large or maximal?
  - Normal or Inverted mass ordering?
  - Are neutrino masses:
    - hierarchical: $m_i - m_j \sim m_i + m_j$?
    - degenerated: $m_i - m_j \ll m_i + m_j$?
  - Dirac or Majorana? what about the Majorana Phases?
  - $\ldots$

- To answer:

Proposed new generation ν osc experiments:

– LBL with Conventional Superbeams and/or ν-factory:

– Medium Baseline Reactor Experiment

Also no-oscillation experiments:

– ν-less $\beta\beta$ decay, ^{3}H beta decay

– Interesting input from cosmological data

Rich but *Challenging* Experimental Program

Hope some of you take the challenge!

Other New Physics Sources of ν -Oscillations

- Other New Physics Effects can also lead to ν-Oscillations

$$P_{\alpha\beta} = \sin^2 2\theta \, \sin^2\left(2\pi \frac{L}{\lambda}\right)$$

But in general oscillation wavelength has different E_ν dependence

- Violation of Lorentz Invariance: $\lambda = \frac{2\pi}{E\delta v}$

Non universal asymptotic velocity of neutrinos $v_1 \neq v_2 \Rightarrow E_i = \frac{m_i^2}{2p} + v_i p$

Limit from ATM data $\Rightarrow$ $|\delta v| \leq 8.1 \times 10^{-25}$

- Violation of Weak Equivalence Principle: $\lambda = \frac{\pi}{E|\phi|\delta\gamma}$

Non universal coupling of neutrinos $\gamma_1 \neq \gamma_2$ *to gravitational potential* ϕ

Limit from ATM data $\Rightarrow$ $|\phi \, \Delta\gamma| \leq 4.0 \times 10^{-25}$

A Side Effect: Lepton Flavour Violation

– ν oscillation $\Rightarrow$ Lepton Family Number is not conserved

– Can be seen in charged leptons?

If only $m_\nu \simeq \sqrt{\Delta m^2_{\rm atm}} \Rightarrow Br(\tau \to \mu\gamma) \sim 10^{-41}$ too small!

But if there is an intermediate scale (for example SUSY)
$\Rightarrow Br(\tau \to \mu\gamma)$ or $Br(\mu \to e\gamma)$ could be observable