SOLAR NEUTRINO DATA, NEUTRINO MASS SPECTRUM, CP-VIOLATION AND $(\beta\beta)_{0\nu}$-DECAY

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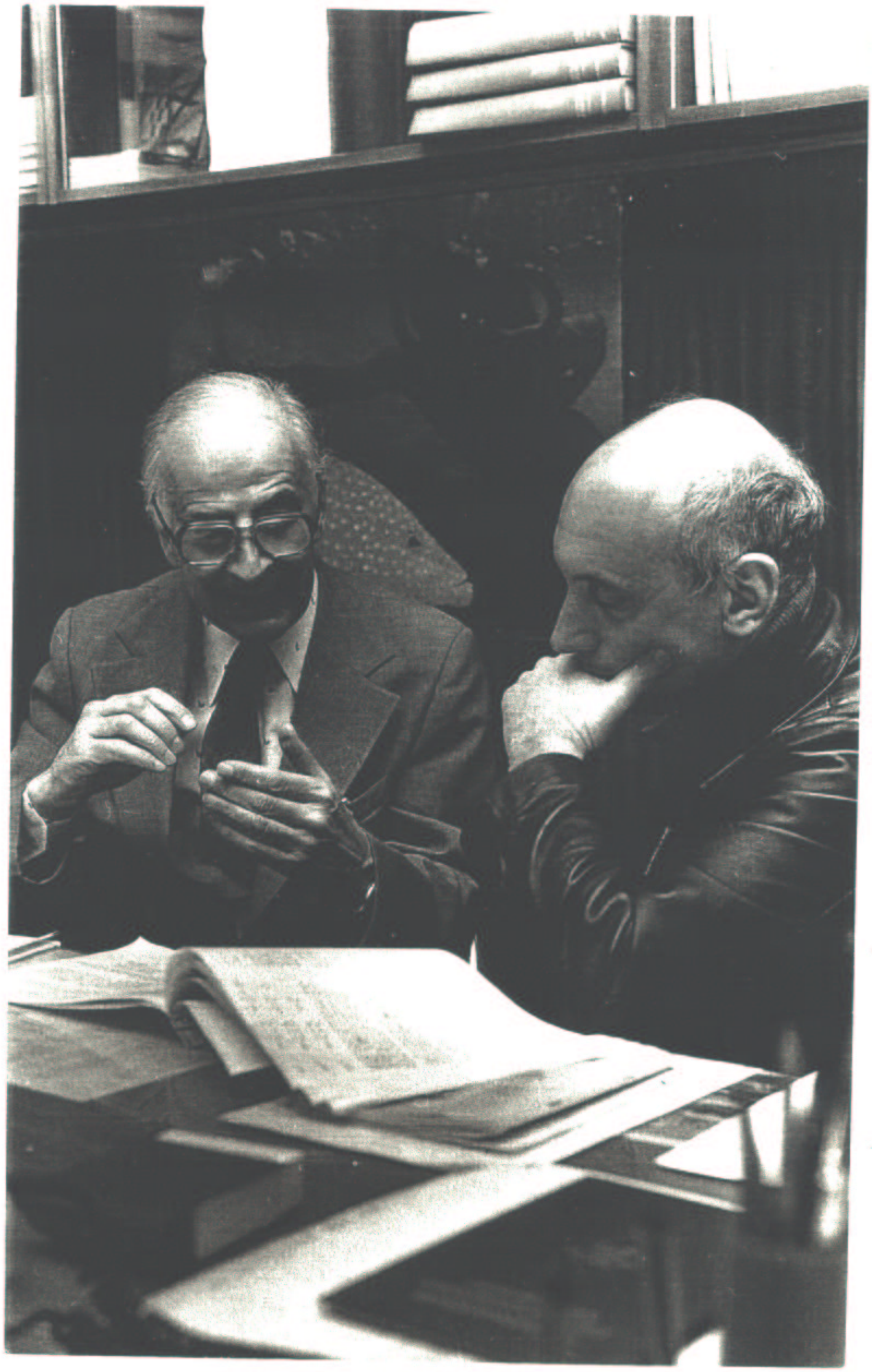

EVIDENCES FOR ν-OSCILLATIONS:

- ν_{ATM} : SK — UP-DOWN ASYMMETRY (ZENITH ANGLE DEPENDENCE) MULTI-GeV μ-LIKE SAMPLE

  DOMINANT $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau$

  K2K, MINOS, CNGS.

- $\nu_\odot$: HOMESTAKE, KAMIOKANDE, SAGE, GALLEX/GNO, SUPER-KAMIOKANDE, SNO

  DOMINANT $\nu_e \to \nu_{\mu,\tau}$

  KamLAND, BOREXINO, ...

- LSND

  $\bar{\nu}_\mu \to \bar{\nu}_e$ MiniBOONE

$$\nu_{\ell L} = \sum_{j=1} U_{\ell j} \nu_{jL}, \quad \ell = e, \mu, \tau$$

ν- FACTORIES : 3-ν MIXING, LMA MSW

$L \sim (3000 - 7000)$ km.

SNO

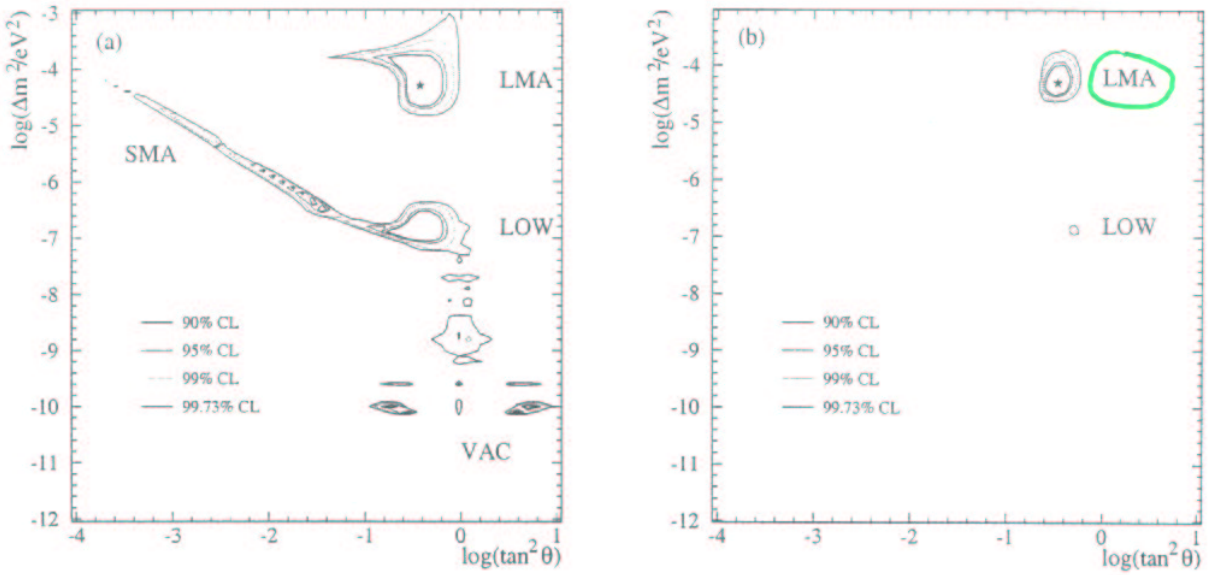

FIG. 4: Allowed regions of the MSW plane determined by a χ^2 fit to (a) SNO day and night energy spectra and (b) with additional experimental and solar model data. The star indicates the best fit. See text for details.

SNO web site: http://sno.phy.queensu.ca

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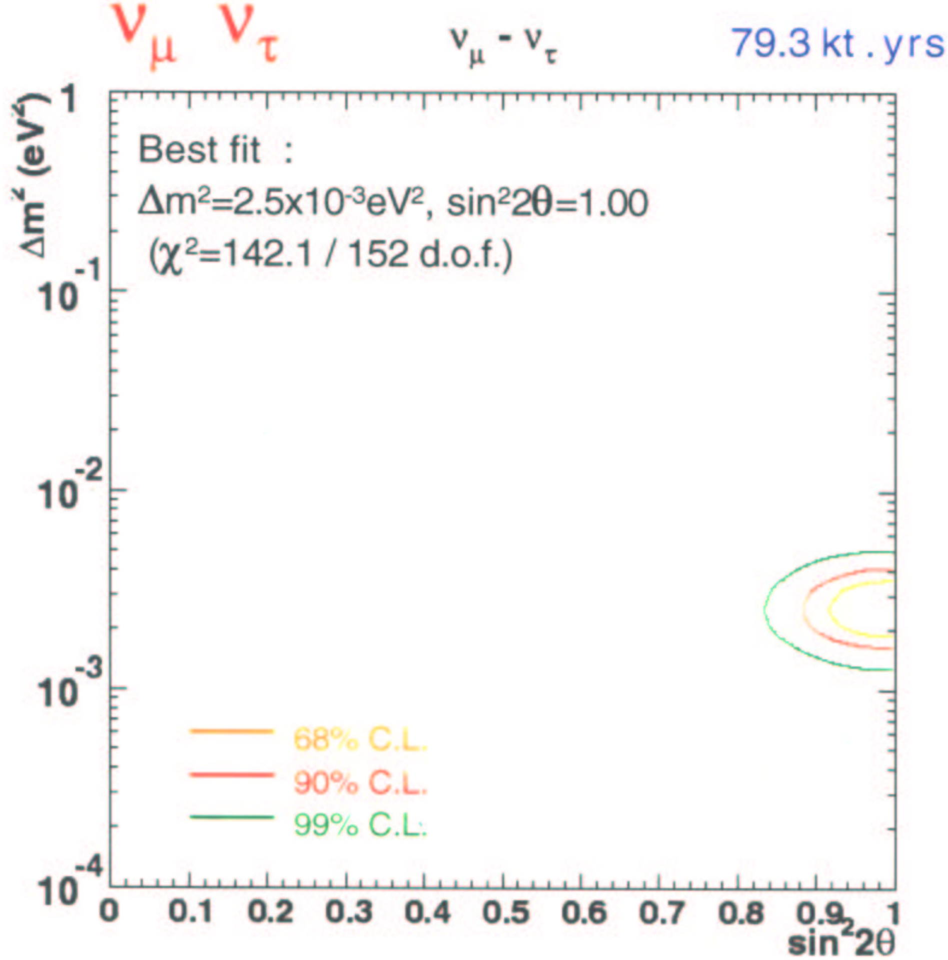
	$\Delta m^2_\odot[eV^2]>0$	$\sin^2 2\theta_\odot$
B. F. V.:	5×10^{-5}	0.75
95% C.L.	$(2.5-10)\times10^{-5}$	0.56-0.89

$\cos 2\theta_\odot \geq 0.26$ AT 99.73% C.L.

Allowed region

(FC + PC + UP-thru + UP-stop)

ν_μ ν_τ



SK combined result

$\Delta m^2 = (1.7\sim4)\times10^{-3}eV^2$

$\sin^2 2\theta > 0.89$ (90% C.L.)

SIGN (Δm^2) - UNDETERMINED

3-ν MIXING : $m_1 < m_2 < m_3$ - NH

OR $m_3 < m_1 < m_2$ - IH

CHOOZ : $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$\sim 1\,km$
$\bar{E}_\nu \sim 2\,MeV$

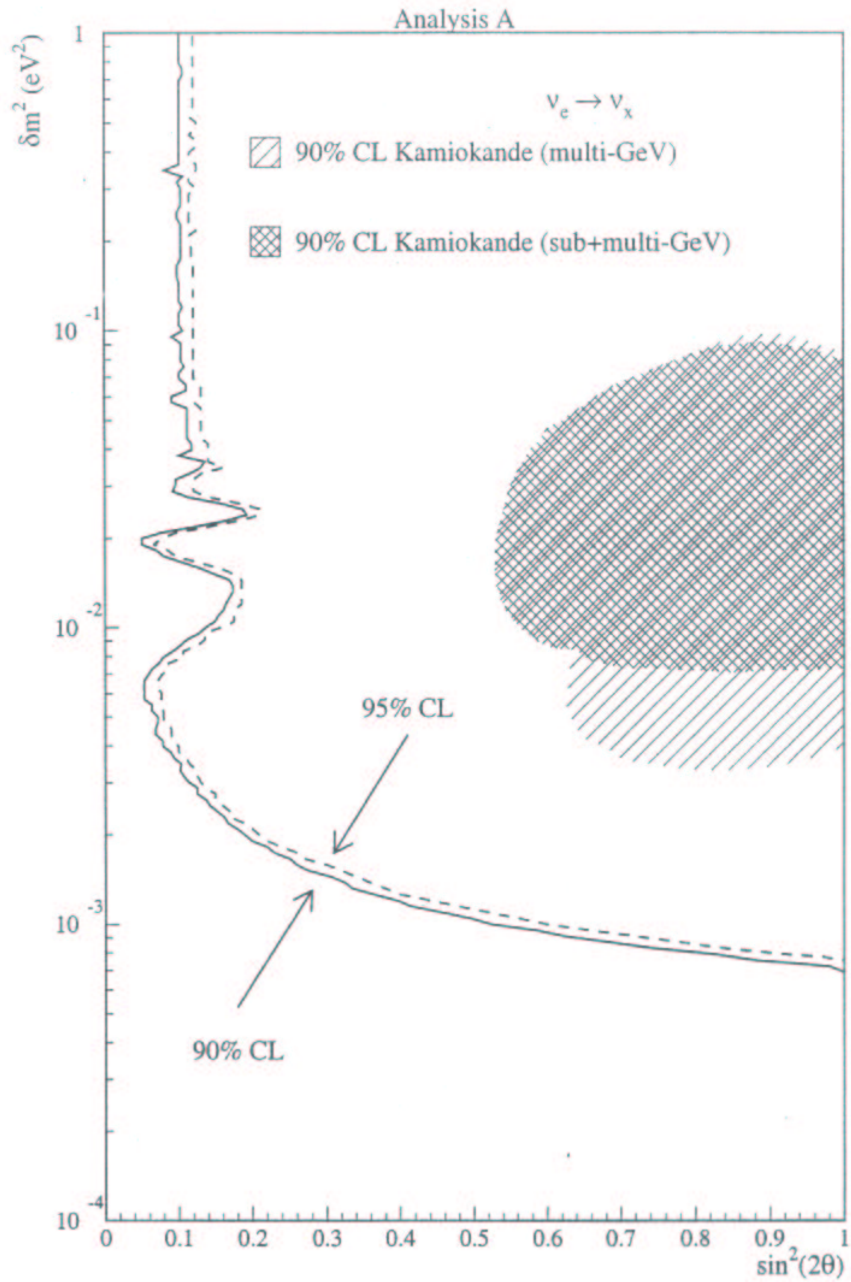


Figure 9: Exclusion plot for the oscillation parameters based on the absolute comparison of measured vs. expected positron yields.

3-ν Mixing:

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

U_{PMNS}

Parameters: U_{PMNS} – $n \times n$

		n	2	3	4
Angles		$\frac{n(n-1)}{2}$	1	3	6
CP-violating phases:					
ν_j – Dirac		$\frac{(n-1)(n-2)}{2}$	0	1	3
ν_j – Majorana		$\frac{n(n-1)}{2}$	1	3	6

Bilenky, Hosek, Petcov '80; Doi et al., '81.

STANDARD PARAMETRIZATION:

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\alpha_{21}/2} & U_{e3}\, e^{i\left(\frac{\alpha_{31}}{2}+\delta\right)} \\ -s_{12}c_{23}-c_{12}s_{23}U_{e3}^{*} & (c_{12}c_{23}-s_{12}s_{23}U_{e3}^{*})e^{\frac{i\alpha_{21}}{2}} & s_{23}c_{13}e^{i(\alpha_{31}/2+\delta)} \\ s_{12}s_{23}-c_{12}c_{23}U_{e3}^{*} & (-c_{12}s_{23}-s_{12}c_{23}U_{e3}^{*})e^{\frac{i\alpha_{21}}{2}} & c_{23}c_{13}e^{i(\alpha_{31}/2+\delta)} \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$. $0 \le \theta_{12}, \theta_{13}, \theta_{23} \le \pi/2$

$U_{e3} = s_{13}e^{-i\delta}$, $\delta \in [0, 2\pi]$ - DIRAC CP-VIOLATING PHASE

α_{21}, α_{31} - MAJORANA CP-VIOLATING PHASES

IF ν_j ARE MAJORANA PARTICLES, (S.M. BILENKY, J. Hosek, S.T.P. '80) CP - SYMMETRY CAN BE VIOLATED EVEN IN THE CASE OF $n = 2$ FAMILIES OF LEPTONS:

$$n_{CP}^{M} = \frac{n(n+1)}{2} - n = \frac{n(n-1)}{2}$$

"PARAMETERS":

$\theta_{12}, \theta_{13}, \theta_{23}$

ν_j DIRAC MAJORANA

δ $\delta, \alpha_{21}, \alpha_{31}$

m_1, m_2, m_3

$m_{1,2,3}$: MEASURED IN ν-OSCILLATION EXPERIMENTS

$$\Delta m^2_{\odot} = \Delta m^2_{21} > 0, \quad |\Delta m^2_{ATM}| = |\Delta m^2_{31}|$$

A. $m_1 < m_2 < m_3$ OR $m_3 < m_1 < m_2$

B. $m_1 < m_2 < m_3$:

$$m_1, m_2, m_3 \Longrightarrow m_1, \Delta m^2_{21} > 0, \Delta m^2_{32} > 0$$

$$m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}$$

$$m_3 = \sqrt{m_1^2 + \Delta m^2_{21} + \Delta m^2_{32}}$$

$$\Delta m^2_{ATM} = \Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$$

TWO POSSIBILITIES:

$$\left.\begin{array}{l} \Delta m^2_{\odot} = \Delta m^2_{21} \text{ - NH} \\ \Delta m^2_{\odot} = \Delta m^2_{32} \text{ - IH} \end{array}\right\} \text{- "DISCRETE" PARAMETER}$$

THE MAIN PROBLEMS IN THE STUDIES OF ν-MIXING:

- DETERMINATION OF $\Delta m^2_{\odot}$, $\theta_{\odot}$, Δm^2_{atm}, θ_{atm} WITH A HIGH PRECISION
- MEASURE, OR IMPROVE BY AT LEAST A FACTOR OF ~10 THE EXISTING LIMITS ON, $|U_{e3}|^2 = \sin^2\theta_{13}$
- DETERMINE THE TYPE OF ν-MASS SPECTRUM,

  $m_1 \ll m_2 \ll m_3$, NH

  $m_1 \ll m_2 \cong m_3$, IH

  $m_1 \cong m_2 \cong m_3$, $m_j^2 \gg \Delta m^2_{atm}$, QD
- DETERMINE, OR OBTAIN CONSTRAINTS ON, THE ABSOLUTE ν-MASS SCALE (LIGHTEST ν MASS)
- DETERMINE THE NATURE OF ν_j (DIRAC VS MAJORANA)
- ESTABLISH WHETHER CP-SYMMETRY IS VIOLATED IN THE LEPTON SECTOR
  1. DUE TO THE DIRAC PHASE, δ,
  2. DUE TO THE MAJORANA PHASES α_{21}, α_{31}, IF ν_j - MAJORANA
- FIND A THEORY WHICH EXPLAINS THE DATA (THE THEORY)

$\nu_\odot$ - DATA : Δm^2_{21}, θ_{12}

SNO : D-N, CC/NC, SPECTRUM CC

$A_{D-N} < 10\%$, $R_{CC/NC} < 0.50$ CAN SIGNIFICANTLY REDUCE THE LMA REGION

$A_{D-N} > 10\%$ - ELLIMINATES LOW-QVO

$A_{D-N} > 1\%$ - ELLIMINATES QVO

KamLAND : LMA $L \cong 180\,km$

IF $\Delta m^2_{21} \gtrsim 2 \times 10^{-4}\,eV^2$, POST KAMLAND $L \sim 20\,km$

BOREXINO : D-N LOW, ...

ν_{ATM} - DATA (SK) : $|\Delta m^2_{31}|$, θ_{23} θ_{13} ?

K2K, MINOS, CNGS

SUPERBEAMS

VLBL (ν-FACTORY) : δ, θ_{13} (θ_{23})

ν - MASS SPECTRUM : ^3H β-DECAY, $(\beta\beta)_{0\nu}$-DECAY

MAJORANA ν_j : $(\beta\beta)_{0\nu}$-DECAY

α_{21}, α_{31}

KAMLAND:

- OBSERVES e^+ - SPECTRUM DISTORTIONS

  $\Delta m^2_\odot \simeq (2\times10^{-5} - 10^{-4})\ eV^2$

- DOES NOT OBSERVE e^+ - SPECTRUM DISTORTION BUT MEASURES JUST A REDUCTION OF THE TOTAL EVENT RATE BY

  $\sim \left(1 - \frac{1}{2}\sin^2 2\theta_\odot \left(1-|U_{e3}|^2\right)^2\right)$

  $\Delta m^2_\odot \gtrsim 2\cdot10^{-4}\ eV^2$

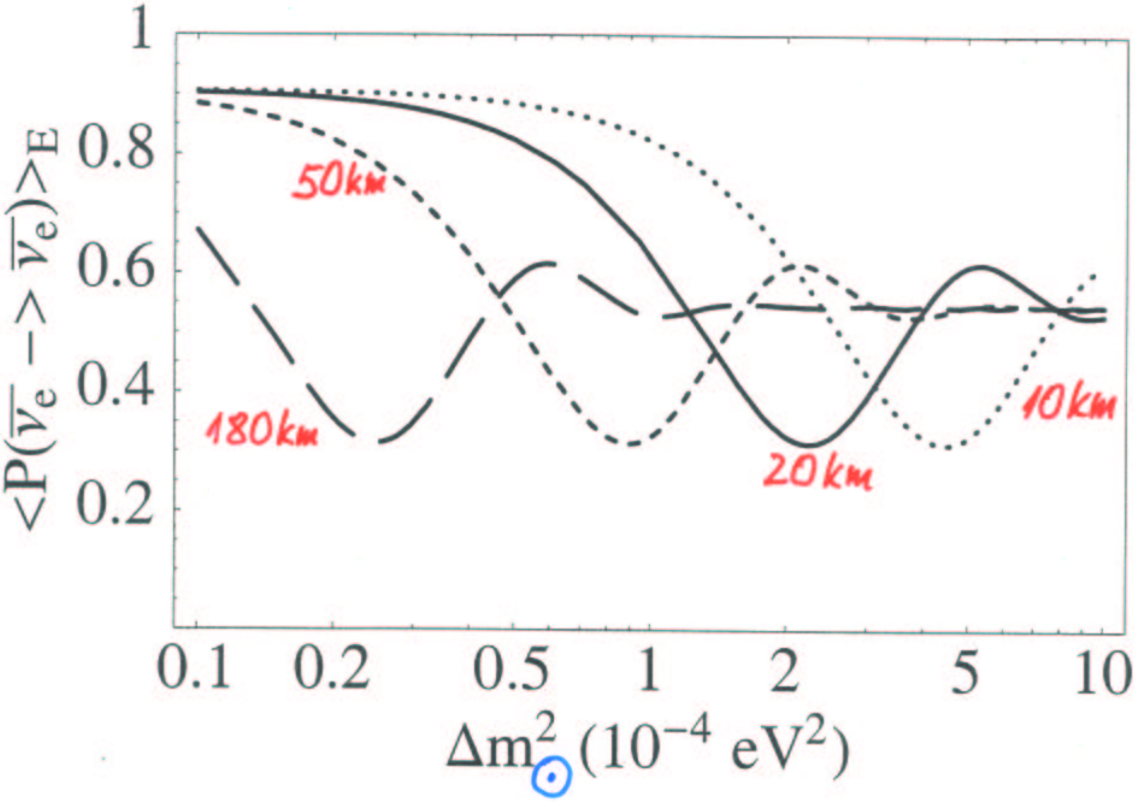
- DOES NOT OBSERVE ANY DEVIATIONS FROM THE ST PREDICTIONS

  PROBLEM WITH LMA!

  LOW, QVO, VO, RSFP, FCNC, ... ?

M. PIAI, S.T.P. '01

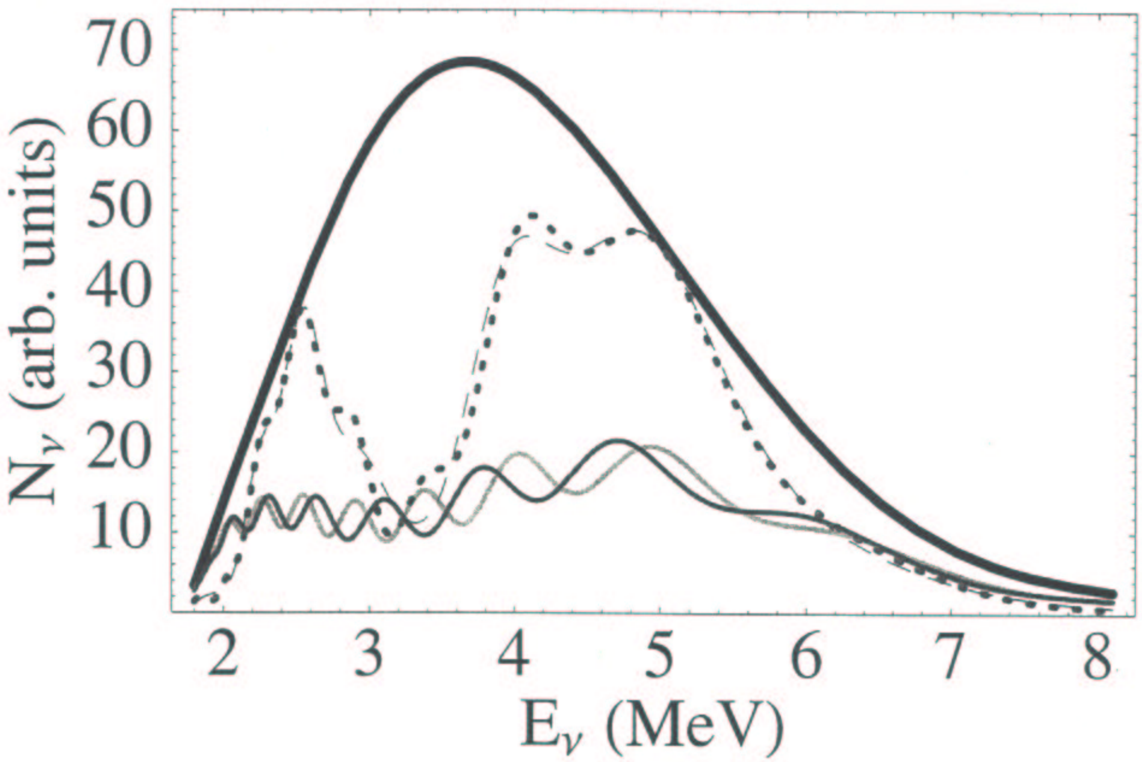
FIGURE N. 1



$\Delta m^2_{31} = 2.5 \cdot 10^{-3}\ eV^2$, $\sin^2 2\theta_{\odot} = 0.8$, $\sin^2 \theta_{CH} = 0.05$

M. PIAI, S.T.P. '01

FIGURE N. 2



$\Delta m^2_\odot = 2 \cdot 10^{-4}\, eV^2 ; \; 6 \cdot 10^{-4}\, eV^2$

$L = 20\, km$

$10^{-4}\, eV^2 \leq \Delta m^2_\odot \leq 8 \cdot 10^{-4}\, eV^2$

CAN BE EXPLORED

M. PIAI, S.T.P '01

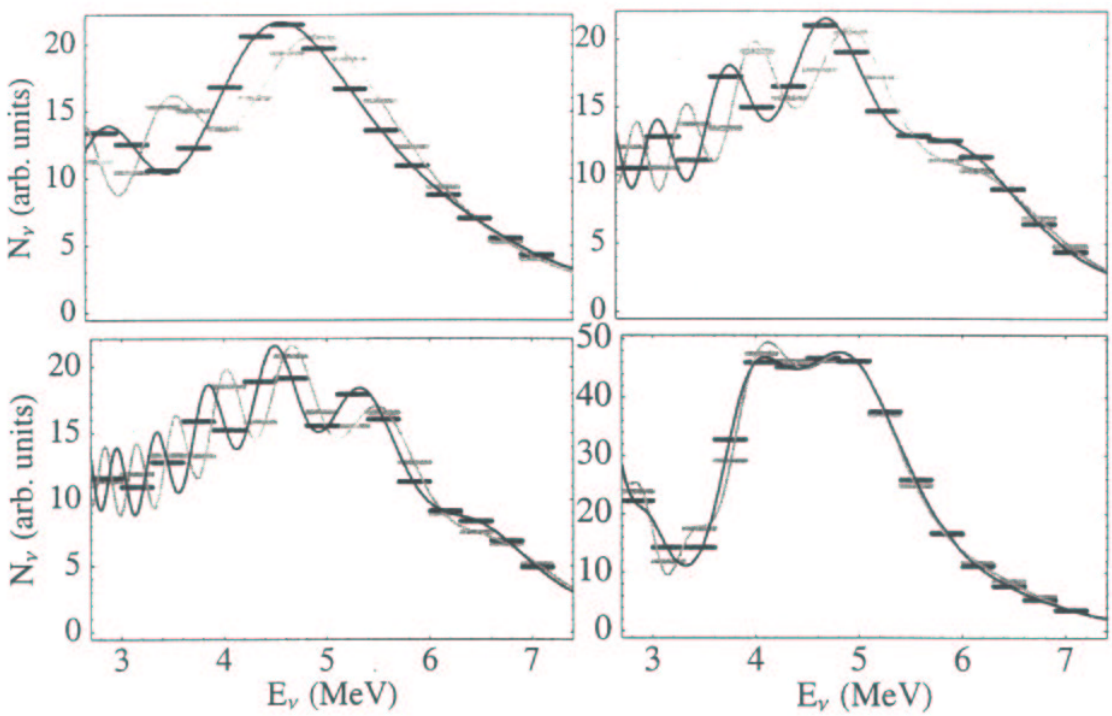


Figure 3: Comparison between the predicted event rate spectrum at $L = 20$ km, measured in energy bins having a width of $\Delta E_\nu = 0.3$ MeV in the cases of normal (light grey) and inverted (dark grey) neutrino mass hierarchy. The two upper and the lower left figures are for $\Delta m^2_\odot = 2 \times 10^{-4}$ eV^2, $\sin^2 2\theta_\odot = 0.8$, $\sin^2\theta = 0.05$, and $\Delta m^2_{31} = 1.3;\ 2.5;\ 3.5 \times 10^{-3}$ eV^2, respectively. The lower right figure was obtained for $\Delta m^2_\odot = 6 \times 10^{-4}$ eV^2 and $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2.

Normal vs. Inverted hierarchy:

$L = 20$ km, KAMLAND LIKE DETECTOR

$$2 \cdot 10^{-4}\,\mathrm{eV}^2 \lesssim \Delta m^2_\odot \lesssim 5 \cdot 10^{-4}\,\mathrm{eV}^2$$

EXTREMELY CHALLENGING!

2 The $\bar{\nu}_e$ Survival Probability

We assume 3-neutrino mixing. The neutrinos with definite mass in vacuum ν_j, $j = 1, 2, 3$, are numbered (without loss of generality) in such a way that their masses obey $m_1 < m_2 < m_3$. We do not assume any of the relations $m_1 \ll m_2 \ll m_3$, or $m_1 \lesssim m_2 \ll m_3$, or $m_1 \ll m_2 \cong m_3$.

In the case of normal hierarchy between the neutrino masses we have:

$$\Delta m^2_\odot = \Delta m^2_{21}, \tag{6}$$

and

$$|U_{\mathrm{e}1}| = \cos\theta_\odot \sqrt{1 - |U_{\mathrm{e}3}|^2}, \;\; |U_{\mathrm{e}2}| = \sin\theta_\odot \sqrt{1 - |U_{\mathrm{e}3}|^2}, \tag{7}$$

where

$$\theta_\odot = \theta_{12}, \;\; |U_{\mathrm{e}3}|^2 = \sin^2\theta \equiv \sin^2\theta_{13}, \tag{8}$$

θ_{12} and θ_{13} being two of the three mixing angles in the standard parameterization of the PMNS matrix. $|U_{e3}|^2$ is constrained by the CHOOZ and Palo Verde results. The $\bar{\nu}_e$ survival probability has the form:

$$\begin{aligned}
&P_{NH}(\bar{\nu}_e \to \bar{\nu}_e)\\
&= \;1 - 2\sin^2\theta\cos^2\theta \left(1 - \cos\frac{\Delta m^2_{31} L}{2\,E_\nu}\right)\\
&- \;\frac{1}{2}\cos^4\theta \sin^2 2\theta_\odot \left(1 - \cos\frac{\Delta m^2_\odot L}{2\,E_\nu}\right)\\
&+ \;2\sin^2\theta\,\cos^2\theta\,\sin^2\theta_\odot \left(\cos\left(\frac{\Delta m^2_{31} L}{2\,E_\nu} - \frac{\Delta m^2_\odot L}{2\,E_\nu}\right) - \cos\frac{\Delta m^2_{31} L}{2\,E_\nu}\right).
\end{aligned} \tag{9}$$

For the neutrino mass spectrum with inverted hierarchy one has:

$$\Delta m^2_\odot = \Delta m^2_{32}, \tag{10}$$

and

$$|U_{\mathrm{e}2}| = \cos\theta_\odot \sqrt{1 - |U_{\mathrm{e}1}|^2}, \;\; |U_{\mathrm{e}3}| = \sin\theta_\odot \sqrt{1 - |U_{\mathrm{e}1}|^2}. \tag{11}$$

The mixing matrix element constrained by the CHOOZ and Palo Verde data is now $|U_{\mathrm{e}1}|^2$:

$$|U_{e1}|^2 = \sin^2\theta. \tag{12}$$

The expression for the $\bar{\nu}_e$ survival probability can be written in the form:

$$\begin{aligned}
&P_{IH}(\bar{\nu}_e \to \bar{\nu}_e) \\
&= 1 - 2\,\sin^2\theta\,\cos^2\theta\,\left(1 - \cos\frac{\Delta m^2_{31}\,L}{2\,E_\nu}\right) \\
&- 12\cos^4\theta\,\sin^2 2\theta_\odot\,\left(1 - \cos\frac{\Delta m^2_\odot\,L}{2\,E_\nu}\right) \qquad (13) \\
&+ 2\,\sin^2\theta\,\cos^2\theta\,\cos^2\theta_\odot\,\left(\cos\left(\frac{\Delta m^2_{31}\,L}{2\,E_\nu} - \frac{\Delta m^2_\odot\,L}{2\,E_\nu}\right) - \cos\frac{\Delta m^2_{31}\,L}{2\,E_\nu}\right) .
\end{aligned}$$

IF ν_j - MAJORANA PARTICLES,

BILENKY ET AL. '80
DOI ET AL. '81

U_{PMNS} - CONTAINS 3ν MIXING

$\begin{cases} \delta \text{ - DIRAC} \\ \alpha_{21}, \alpha_{31} \text{ - MAJORANA} \\ \text{PHYSICAL CP-VIOLATING PHASES} \end{cases}$

ν - OSCILLATIONS $\overset{(-)}{\nu}_l \rightleftarrows \overset{(-)}{\nu}_{l'}$, $l, l' = e, \mu, \tau$

BILENKY, HOSEK, STP '80

- ARE NOT SENSITIVE TO THE NATURE OF ν_j;
- PROVIDE INFORMATION ON $\Delta m^2_{jk} = m_j^2 - m_k^2$, $j > k = 1,2,3$
  BUT NOT ON THE ABSOLUTE VALUES OF NEUTRINO MASSES m_j.

HOW CAN ONE OBTAIN INFORMATION ON

- THE NATURE OF ν_j ?
- m_1, m_2, m_3, i.e., ON THE ν-MASS SPECTRUM ?
- ON THE CP-VIOLATION IN THE LEPTON SECTOR, INDUCED BY THE MAJORANA CP-VIOLATING PHASES ?

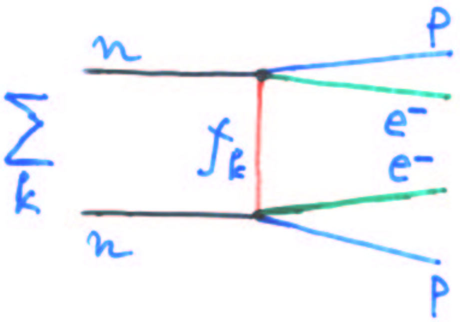
THE MAJORANA NATURE OF ν_j CAN MANIFEST ITSELF IN THE EXISTENCE OF PROCESSES

$\Delta L = \pm 2$: $K^+ \to \pi^- \mu^+ \mu^+$
$\mu^- + (A, Z) \to \mu^+ + (A, Z-2)$, ...

THE MOST SENSITIVE PROCESS - $(\beta\beta)_{0\nu}$ - decay OF CERTAIN EVEN-EVEN NUCLEI :

$(\beta\beta)_{0\nu}$ - decay:

$$(A,Z) \longrightarrow (A, Z+2) + e^- + e^-$$



$$\nu_{eL}(x) = \sum_k U_{ek} \underbrace{\nu_{kL}(x)}_{m_{\nu_k}}$$

$$\mathcal{H}^{\beta}_{W} = \frac{G_F}{\sqrt{2}} 2 \left(\bar{e}_L(x) \gamma_\alpha \nu_{eL}(x)\right) j^{h}_{\alpha}(x) + h.c.$$

$$S^{(2)} = - \frac{(-i)^2}{2} 4 \left(\frac{G_F}{\sqrt{2}}\right)^2 \int dx_1 \, dx_2 \times T^{h}_{\alpha\beta}(x_1, x_2) \times$$

$$\times N \left[\bar{e}_L(x_1) \gamma_\alpha \nu_{eL}(x_1) \nu^T_{eL}(x_2) \gamma^T_\beta \bar{e}^T_L(x_2)\right]$$

$$A(\beta\beta)_{0\nu} \sim \langle m_\nu \rangle ,$$

$$\langle m_\nu \rangle = \sum_k |U_{ek}|^2 \frac{1}{i} \underbrace{\eta^{CP}(\nu_k)} m_k$$

$m_k \lesssim$ few MeV
CP - inv.

Data:
^{76}Ge

$$\boxed{|\langle m_\nu \rangle| < (1 \div 2) \text{ eV}}$$

The Majorana nature of the massive neutrinos can manifest itself in the existence of $L \neq 0$, $\Delta L = 2$, processes. The process most sensitive to the existence of massive Majorana neutrinos (coupled to the electron) is the neutrinoless double β ($(\beta\beta)_{0\nu}-$) decay of certain even-even nuclei

$$(A, Z) \rightarrow (A, Z+2) + e^- + e^-. \tag{1}$$

If the $(\beta\beta)_{0\nu}-$ decay is generated *only by the left-handed (LH) charged current weak interaction through the exchange of virtual massive Majorana neutrinos*, $A((\beta\beta)_{0\nu})$ is proportional to the so-called "effective Majorana mass"

$$A((\beta\beta)_{0\nu}) \quad \sim <m> \equiv \sum_{j=1} U_{\mathrm{e}j}^2\, m_j, \qquad m_j \lesssim \text{ few MeV}, \tag{2}$$

where m_j is the mass of the Majorana neutrino ν_j and U_{ej} is the element of neutrino (lepton) mixing matrix U.

A large number of experiments are searching for $(\beta\beta)_{0\nu}-$decay of different nuclei at present. No indications that this process takes place were found. ^{76}Ge Heidelberg-Moscow experiment:

$$|<m>| \; < 0.35 \text{ eV}, \quad 90\% \text{ C.L.} \tag{3}$$

Taking into account a factor of 3 uncertainty associated with the calculation of the relevant nuclear matrix element

$$|<m>| \; < (0.35 \div 1.05) \text{ eV}, \quad 90\% \text{ C.L.}. \tag{4}$$

The IGEX collaboration has obtained [30]:

$$|<m>| \; < (0.33 \div 1.35) \text{ eV}, \quad 90\% \text{ C.L.} \tag{5}$$

Considerably higher sensitivity to the value of $|<m>|$ is planned to be reached in several $(\beta\beta)_{0\nu}-$decay experiments of a new generation:

- the NEMO3 experiment scheduled to start in 2002, will search for $(\beta\beta)_{0\nu}-$decay of ^{100}Mo and ^{82}Se; will reach a sensitivity to $|<m>| \; \cong 0.1$ eV.

- CUORE: a similar sensitivity is planned to be reached with the cryogenic detector CUORE; will search for the $(\beta\beta)_{0\nu}-$decay of ^{130}Te.

- GENIUS: sensitivity to $|<m>| \; \cong 10^{-2}$ eV, is planned to be achieved utilizing one ton of enriched ^{76}Ge.

- EXO: proposal to study the $(\beta\beta)_{0\nu}-$decay of ^{136}Xe in a background-free experiment with detection of the two e^- and the $^+$Ba atom in the final state; the estimated sensitivity of this experiment is $|<m>| \; \cong (1-5) \times 10^{-2}$ eV.

As is well known, the explanation of the atmospheric and solar neutrino data in terms of neutrino oscillations requires the existence of 3-neutrino mixing in the weak charged lepton current:

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj} \nu_{j\mathrm{L}}, \tag{5}$$

where ν_{lL}, $l = e, \mu, \tau$, are the three left-handed flavour neutrino fields, $\nu_{j\mathrm{L}}$ is the left-handed field of the neutrino ν_j having a mass m_j and U is a 3×3 unitary mixing matrix - the Pontecorvo-Maki-Nakagawa-Sakata neutrino (lepton) mixing matrix. If ν_j are Majorana neutrinos,

$$C(\bar{\nu}_j)^T = \nu_j, \ j = 1, 2, 3,$$

C is the charge conjugation matrix, and for $m_j \lesssim$ few MeV,

$$|<m>| \ = \left|m_1 U_{\mathrm{e}1}^2 + m_2 U_{\mathrm{e}2}^2 + m_3 U_{\mathrm{e}3}^2\right| \tag{6}$$

$$= \left|m_1 |U_{\mathrm{e}1}|^2 + m_2 |U_{\mathrm{e}2}|^2 \ e^{i\alpha_{21}} + m_3 |U_{\mathrm{e}3}|^2 \ e^{i\alpha_{31}}\right| \tag{7}$$

where

$$U_{ej} = |U_{ej}| \ e^{\frac{i\alpha_j}{2}}$$

$$\alpha_{21} \equiv (\alpha_2 - \alpha_1), \quad \alpha_{31} \equiv (\alpha_3 - \alpha_1)$$

are two CP-violating phases. If CP-invariance holds, one has

L. WOLFENSTEIN '81
B. KAYSER '84
BILENKY, NEDELCHEVA, S.T.P. '84

$$\alpha_{21} = k\pi, \quad \alpha_{31} = k'\pi, \qquad k, k' = 0, 1, 2, ...$$

In this case

$$\eta_{21} \equiv e^{i\alpha_{21}} = \pm 1, \quad \eta_{31} \equiv e^{i\alpha_{31}} = \pm 1, \tag{8}$$

represent the relative CP-parities of the neutrinos ν_1 and ν_2, and ν_1 and ν_3, respectively.

We can numerate (without loss of generality) the neutrino masses in such a way that $m_1 < m_2 < m_3$. If we denote by $\theta_\odot$ and θ respectively the mixing angles constrained by the solar neutrino data and the data from the CHOOZ experiment, then depending on the type of the neutrino mass spectrum one has either

$$|U_{\mathrm{e}1}| = \cos\theta_\odot \sqrt{1 - |U_{\mathrm{e}3}|^2}, \quad |U_{\mathrm{e}2}| = \sin\theta_\odot \sqrt{1 - |U_{\mathrm{e}3}|^2}, \quad |U_{\mathrm{e}3}|^2 = \sin^2\theta, \tag{9}$$

or

$$|U_{\mathrm{e}2}| = \cos\theta_\odot \sqrt{1 - |U_{\mathrm{e}1}|^2}, \quad |U_{\mathrm{e}3}| = \sin\theta_\odot \sqrt{1 - |U_{\mathrm{e}1}|^2}, \quad |U_{\mathrm{e}1}|^2 = \sin^2\theta. \tag{10}$$

Relations (9) are valid for the hierarchical neutrino mass spectrum, while those in eq. (10) are realized for the neutrino mass spectrum with inverted hierarchy.

The neutrino oscillation experiments provide information on $\Delta m^2_{jk} = m^2_j - m^2_k$ $(j > k)$. In the case of 3-neutrino mixing as an independent set of three neutrino mass parameters one can choose

$$m_1, \quad \sqrt{\Delta m^2_{21}}, \quad \sqrt{\Delta m^2_{32}}.$$

Then :

$$m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}\ , \tag{11}$$

$$m_3 = \sqrt{m_1^2 + \Delta m^2_{21} + \Delta m^2_{32}}\ . \tag{12}$$

The Δm^2 inferred from the atmospheric neutrino data,

$$\Delta m^2_{\rm atm} = \Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}\ , \tag{13}$$

while for the one deduced from the solar neutrino data, $\Delta m^2_\odot$, we have two possibilities:

$$\Delta m^2_\odot \equiv \Delta m^2_{32} \quad \text{or} \quad \Delta m^2_\odot \equiv \Delta m^2_{21}\ . \tag{14}$$

Depending on the relative magnitudes of m_1, $\sqrt{\Delta m^2_{21}}$ and $\sqrt{\Delta m^2_{32}}$, one recovers the different possible types of neutrino mass spectrum:

1. if $m_1 \ll \sqrt{\Delta m^2_{21}} \ll \sqrt{\Delta m^2_{32}}$, one has $m_1 \ll m_2 \ll m_3$, i.e., hierarchical (H) neutrino mass spectrum;

2. $m_1 \ll \sqrt{\Delta m^2_{32}} \ll \sqrt{\Delta m^2_{21}}$ implies $m_1 \ll m_2 \simeq m_3$, i.e., neutrino mass spectrum with inverted hierarchy (IH);

3. for $\sqrt{\Delta m^2_{21}}, \sqrt{\Delta m^2_{32}} \ll m_1$, we have $m_1 \simeq m_2 \simeq m_3$, i.e., quasi-degenerate (QD) neutrino mass spectrum;

4. if $\sqrt{\Delta m^2_{21}} \ll \sqrt{\Delta m^2_{32}} \sim \boldsymbol{O}(m_1)$, one finds $m_1 \simeq m_2 < m_3$, i.e., spectrum with "partial mass hierarchy"; interpolates between H and QD.

5. for $\sqrt{\Delta m^2_{32}} \ll \sqrt{\Delta m^2_{21}} \sim \boldsymbol{O}(m_1)$, we have $m_1 < m_2 \simeq m_3$, i.e., spectrum with "partial inverted mass hierarchy"; interpolates between IH and QD.

Given the values of $\Delta m^2_\odot$, $\theta_\odot$, $\Delta m^2_{\rm atm}$ and of θ,

$$|{<}m{>}| = |{<}m{>}|\ (m_1, \alpha_{21}, \alpha_{31}; S), \qquad S = H,\ IH$$

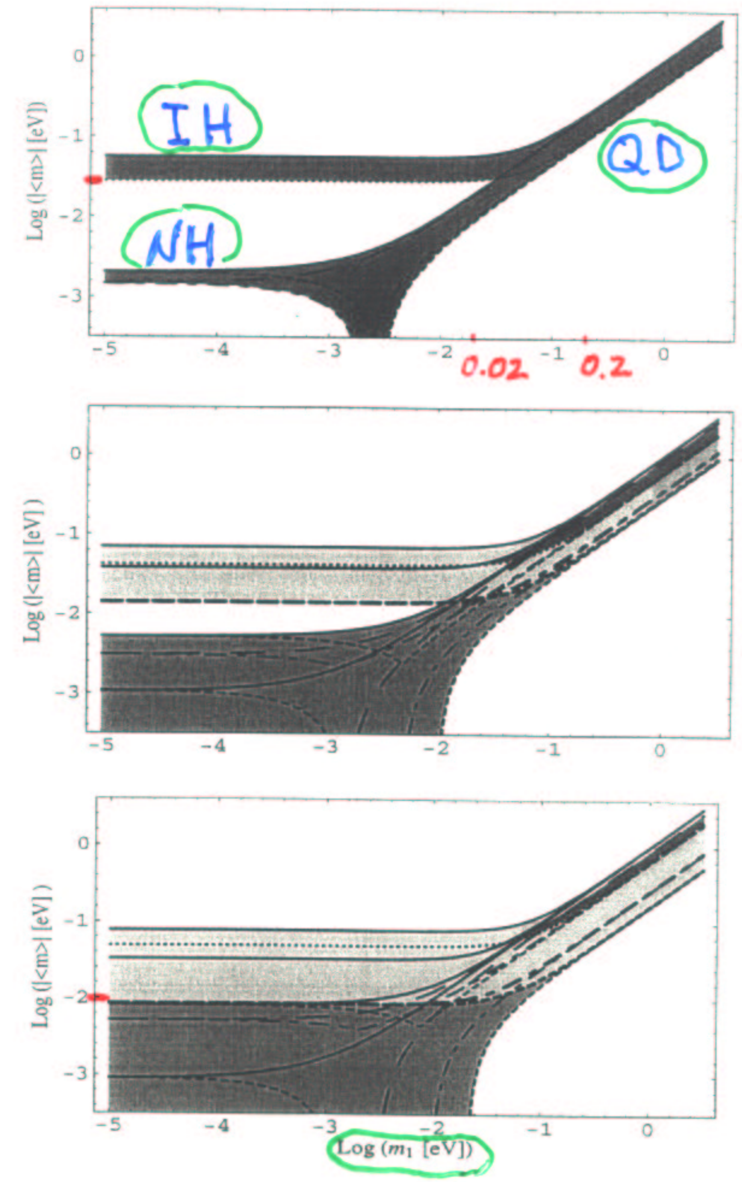
The knowledge of m_1 would allow to determine the neutrino mass spectrum.

GIVEN THE VALUES OF Δm^2_{atm} AND $\Delta m^2_{\odot}$, INFERRED FROM THE DATA, ONE HAS:

- $\underline{m_1 \ll 0.02\,eV}$ - HIERARCHICAL OR INVERTED HIERARCHY
- $\underline{0.02 \lesssim m_1 \lesssim 0.2\,eV}$ - PH OR PIH
- $\underline{m_1 > 0.2\,eV}$ - QD

ν - MASS SPECTRUM

PASCOLI, S.T.P.'02



B.F.V.

90% C.L.

99.73% C.L.

Figure 3: The dependence of $|<m>|$ on m_1 in the case of the LMA solution, for $\Delta m^2_\odot = \Delta m^2_{21}$ and $\Delta m^2_\odot = \Delta m^2_{32}$, and for the best fit values (upper panel) and the 90% C.L. allowed values (middle panel) of the neutrino oscillation parameters found in refs. [1, 41]. The lower panel is obtained by using the 99.73% C.L. allowed values of $\Delta m^2_\odot$ and $\cos 2\theta_\odot$ from [1] and the 99% C.L. allowed values of $\Delta m^2_{\rm atm}$ and $\sin^2\theta$ from [41] (the latter article does not include results at 99.73% C.L.). In the case of CP-conservation, the allowed values of $|<m>|$ are constrained to lie: for i) $\Delta m^2_\odot = \Delta m^2_{21}$ and the middle and lower panels (upper panel) - in the medium-grey and light-grey regions *a)* between the two lower thick solid lines (on the lower thick solid line) if $\eta_{21} = \eta_{31} = 1$, *b)* between the two long-dashed lines and the axes (on the long-dashed line) if $\eta_{21} = -\eta_{31} = 1$, *c)* between the two thick dash-dotted lines and the axes (on the dash-dotted lines) if $\eta_{21} = -\eta_{31} = -1$, *d)* between the three thick short-dashed lines and the axes (on the short-dashed lines) if $\eta_{21} = \eta_{31} = -1$; and for ii) $\Delta m^2_\odot = \Delta m^2_{32}$ and the middle and lower panels (upper panel) - in the light-grey regions *a)* between the two upper thick solid lines (on the upper thick solid line) if $\eta_{21} = \eta_{31} = \pm 1$, *b)* between the dotted and the doubly-thick short-dashed lines (on the dotted line) if $\eta_{21} = -\eta_{31} = -1$, *c)* between the dotted and the doubly-thick dash-dotted lines (on the dotted line) if $\eta_{21} = -\eta_{31} = +1$. In the case of CP-violation, the allowed regions for $|<m>|$ cover all the grey regions. Values of $|<m>|$ in the dark grey regions signal CP-violation.

V. BARGER ET AL.:

"NO-GO FOR CP-VIOLATION IN $(\beta\beta)_{0\nu}$-DECAY"

TOO PESSIMISTIC ... (PASCOLI, S.T.P.)

CONSIDER, FOR EXAMPLE,

IH SPECTRUM ($m_1 < 0.02\,eV$), $|U_{e1}|^2$-NEGLIGIBLE

$$\sqrt{\Delta m^2_{atm}}\cos 2\theta_\odot \le |<m>| \le \sqrt{\Delta m^2_{atm}}$$

"JUST CP-VIOLATING" REGION:

$$(|<m>|)_{MAX} < \sqrt{(\Delta m^2_{atm})_{MIN}}$$

$$(|<m>|)_{MIN} > \sqrt{(\Delta m^2_{atm})_{MAX}}\,(\cos 2\theta_\odot)_{MAX}$$

$$|<m>| = \xi\left[((|<m>|_{EXP})_{MIN} \pm \Delta\right]$$

OBTAINED FOR THE MAXIMAL VALUE OF THE CORRESPONDING $M_{NUCLEAR}$

$\xi \geq 1.$

NECESSARY CONDITION FOR ESTABLISHING CP-VIOLATION:

$$\xi < \frac{\sqrt{(\Delta m^2_{atm})_{MIN}}}{\sqrt{(\Delta m^2_{atm})_{MAX}}\,(\cos 2\theta_\odot)_{MAX} + 2\Delta} \cong \frac{1}{(\cos 2\theta_\odot)_{MAX}}$$

CP - VIOLATION CAN BE ESTABLISHED PROVIDED:

- $|\langle m \rangle|$ IS MEASURED WITH AN ERROR $\lesssim (15-20)\%$;
- $\left.\begin{array}{ll} \Delta m^2_{atm} & (IH) \\ m^2_{\bar{\nu}_e} & (QD) \end{array}\right\}$ IS MEASURED WITH AN ERROR $\lesssim 10\%$
- $\tan^2\theta_\odot \gtrsim 0.55$
- $\left.\begin{array}{ll} \alpha_{32} & (IH) \\ \alpha_{21} & (QD) \end{array}\right\}$ LIE IN THE INTERVALS $\sim (\pi/2 - 3\pi/4)$ or $(5\pi/4 - 3\pi/2)$
- $\xi < 2$

(PASCOLI, PETCOV, RODEJOHANN HEP-PH/0209059)

CONCLUSIONS

- WE ARE AT THE BEGINNING OF THE ERA OF HIGH PRECISION MEASUREMENTS OF THE ν-MIXING PARAMETERS

- THE STRATEGIES TO BE FOLLOWED DEPEND CRUCIALLY ON THE RESULTS THE KAMLAND EXPERIMENT WILL OBTAIN

- IF LMA SOLUTION CONFIRMED,

  - $\Delta m^2_\odot$, $\theta_\odot$
  - OR IF $\Delta m^2_\odot \gtrsim 2 \cdot 10^{-4}\,eV^2$,

    POST KAMLAND AT $L \sim 20$ KM: $\Delta m^2_\odot$, θ_{13}, NH VERSUS IH (VERY CHALLEGING)

  - OPENS THE POSSIBILITY TO SEARCH FOR CP-VIOLATION IN ν-OSCILLATIONS (δ)

  - $\Delta m_{atm} = \Delta m^2_{31}$ - MINOS

  - θ_{13} : SK (HK, UNO)

  SUPERBEAMS : $|\Delta m^2_{atm}|$, θ_{23}, θ_{13}, δ

  ν-FACTORIES : Δm^2_{atm}, θ_{23}, θ_{13}, δ

$(\beta\beta)_{0\nu}$ - DECAY EXPERIMENTS:

- MAJORANA NATURE OF ν_j
- TYPE OF SPECTRUM (NH, IH, QD)
- ABSOLUTE ν - MASS SCALE

^3H β - DECAY, COSMOLOGY...