The $(\beta\beta)_{0\nu}$-Decay Effective Neutrino Mass at the milli-eV Frontier

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Compelling Evidences for $\nu-$Oscillations

$-\nu_{\text{atm}}$: SK UP-DOWN ASYMMETRY

θ_Z-, $L/E-$ **dependences of $\mu-$like events**

Dominant $\nu_\mu \longrightarrow \nu_\tau$ K2K, MINOS; CNGS (OPERA)

$-\nu_\odot$: **Homestake, Kamiokande, SAGE, GALLEX/GNO**

Super-Kamiokande, SNO, BOREXINO; KamLAND

Dominant $\nu_e \longrightarrow \nu_{\mu,\tau}$ **BOREXINO; KamLAND..., LowNu**

$-$ LSND

Dominant $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$; **MiniBOONE 11/04/07: negative result**

$$\nu_{l\text{L}} = \sum_{j=1} U_{lj}\,\nu_{j\text{L}} \qquad l = e, \mu, \tau.$$

B. Pontecorvo, 1957; 1958; 1967;

Z. Maki, M. Nakagawa, S. Sakata, 1962;

Compelling Evidences for $\nu-$Oscillations: 3-ν mixing

$$\nu_{l\mathrm{L}} = \sum_{j=1} U_{lj}\, \nu_{j\mathrm{L}} \qquad l = e, \mu, \tau.$$

B. Pontecorvo, 1957; 1958; 1967;
Z. Maki, M. Nakagawa, S. Sakata, 1962;

PMNS Matrix: Standard Parametrization

$$U = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,
- δ - Dirac CP-violation phase, $\delta = [0, 2\pi]$,
- α_{21}, α_{31} - the two Majorana CP-violation phases.
- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 7.6 \times 10^{-5}$ eV$^2 > 0$, $\sin^2\theta_{12} \cong 0.305$, $\cos 2\theta_{12} \gtrsim 0.26$ (3σ),
- $|\Delta m^2_{\text{atm}}| \equiv |\Delta m^2_{31}| \cong 2.4$ $(2.5) \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} \cong 1$,
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} < 0.040$ (0.056) 2σ (3σ).

A.Bandyopadhyay, S.Choubey, S.Goswami, S.T.P., D.P.Roy, arXiv:0804.4857;

T. Schwetz et al., arXiv:0808.2016

Neutrino Oscillation Parameters

parameter	bf	1σ acc.	2σ range	3σ range
Δm^2_{21} [10^{-5} eV^2]	7.6	3%	7.3 – 8.1	7.1 – 8.3
$\|\Delta m^2_{31}\|$ [10^{-3} eV^2]	2.4	6%	2.1 – 2.7	2.0 – 2.8
$\sin^2\theta_{12}$	0.32	9%	0.28 – 0.37	0.26 – 0.40
$\sin^2\theta_{23}$	0.50	16%	0.38 – 0.63	0.34 – 0.67
$\sin^2\theta_{13}$	–	–	$\leq$ 0.033	$\leq$ 0.050

Best fit values (bf), relative accuracies at 1σ, and 2σ and 3σ allowed ranges of three-flavor neutrino oscillation parameters from a combined analysis of global data.

T. Schwetz, arXiv:0710.5027[hep-ph]

• $\text{sgn}(\Delta m^2_{\text{atm}}) = \text{sgn}(\Delta m^2_{31})$ not determined

$$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{31} > 0, \quad \text{normal mass ordering}$$

$$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{32} < 0, \quad \text{inverted mass ordering}$$

Convention: $m_1 < m_2 < m_3$ - NMO, $m_3 < m_1 < m_2$ - IMO

$$m_1 \ll m_2 < m_3, \qquad \text{NH},$$

$$m_3 \ll m_1 < m_2, \qquad \text{IH},$$

$$m_1 \cong m_2 \cong m_3, \; m^2_{1,2,3} >> \Delta m^2_{\text{atm}}, \; \text{QD}; \; m_j \gtrsim 0.10 \text{ eV}.$$

• Dirac phase δ: $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$, $l \neq l'$; $A^{(l,l')}_{\text{CP}} \propto J_{\text{CP}} \propto \sin\theta_{13} \sin\delta$

• Majorana phases α_{21}, α_{31}:

– $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$ not sensitive;

S.M. Bilenky, J. Hosek, S.T.P.,1980;
P. Langacker, S.T.P., G. Steigman, S. Toshev, 1987

– $|<m>|$ in $(\beta\beta)_{0\nu}$–decay depends on α_{21}, α_{31};

– $\Gamma(\mu \to e + \gamma)$ etc. in SUSY theories depend on $\alpha_{21,31}$;

– BAU, leptogenesis scenario: $\alpha_{21,31}$!

Future Progress

• Determination of the nature - Dirac or Majorana, of ν_j .

• Determination of sgn(Δm^2_{atm}), type of $\nu-$ mass spectrum

$$m_1 \ll m_2 \ll m_3, \qquad \text{NH},$$

$$m_3 \ll m_1 < m_2, \qquad \text{IH},$$

$$m_1 \cong m_2 \cong m_3,\ m^2_{1,2,3} >> \Delta m^2_{\text{atm}},\ \text{QD};\ m_j \gtrsim 0.10 \text{ eV}.$$

• Determining, or obtaining significant constraints on, the absolute scale of ν_j-masses, or min(m_j).

• Status of the CP-symmetry in the lepton sector: violated due to δ (Dirac), and/or due to α_{21}, α_{31} (Majorana)?

• Measurement of, or improving by at least a factor of (5 - 10) the existing upper limit on, $\sin^2\theta_{13}$.

• High precision determination of $\Delta m^2_{\odot}$, $\theta_{\odot}$, Δm^2_{atm}, θ_{atm}.

• Searching for possible manifestations, other than ν_l-oscillations, of the non-conservation of L_l, $l = e, \mu, \tau$, such as $\mu \to e + \gamma$, $\tau \to \mu + \gamma$, etc. decays.

• Understanding at fundamental level the mechanism giving rise to the $\nu-$ masses and mixing and to the L_l-non-conservation. Includes understanding

– the origin of the observed patterns of ν-mixing and ν-masses ;

– the physical origin of CPV phases in U_{PMNS} ;

– Are the observed patterns of ν-mixing and of $\Delta m^2_{21,31}$ related to the existence of a new symmetry?

– Is there any relations between $q-$mixing and $\nu-$ mixing? Is $\theta_{12}+\theta_c=\pi/4$?

– Is $\theta_{23}=\pi/4$, or $\theta_{23}>\pi/4$ or else $\theta_{23}<\pi/4$?

– Is there any correlation between the values of CPV phases and of mixing angles in U_{PMNS}?

• Progress in the theory of ν-mixing might lead to a better understanding of the origin of the BAU.

– Can the Majorana and/or Dirac CPVP in U_{PMNS} be the leptogenesis CPV parameters at the origin of BAU?

If $\nu_j -$ Majorana particles, U_{PMNS} contains (3-ν mixing)

δ-Dirac, α_{21}, α_{31} - Majorana **physical CPV phases**

ν-oscillations $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$, $l, l' = e, \mu, \tau$,

- **are not sensitive to the nature of ν_j,**

S.M. Bilenky et al.,1980;
P. Langacker et al., 1987

- **provide information on $\Delta m^2_{jk} = m^2_j - m^2_k$, but not on the absolute values of ν_j masses.**

The Majorana nature of ν_j can manifest itself in the existence of $\Delta L = \pm 2$ processes:

$$K^+ \rightarrow \pi^- + \mu^+ + \mu^+$$
$$\mu^- + \ (\text{A}, \text{Z}) \rightarrow \mu^+ + \ (\text{A}, \text{Z} - 2)$$

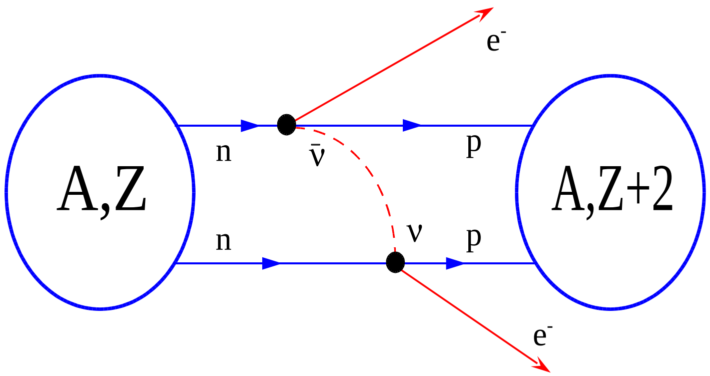
The process most sensitive to the possible Majorana nature of ν_j - $(\beta\beta)_{0\nu}$-decay

$$(\text{A}, \text{Z}) \rightarrow (\text{A}, \text{Z} + 2) + e^- + e^-$$

of even-even nuclei, ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd.

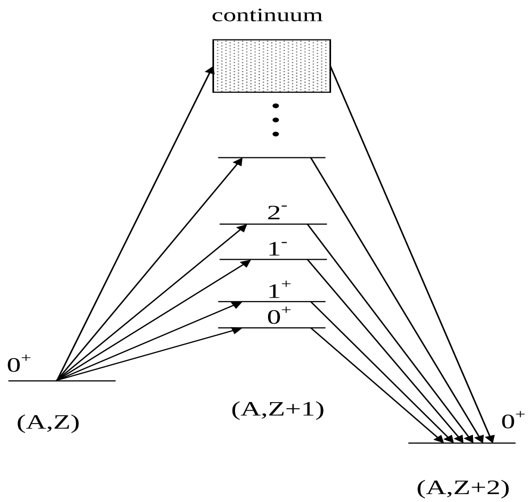
$2n$ from (A,Z) exchange a virtual Majorana ν_j (via the CC weak interaction) and transform into $2p$ of (A,Z+2) and two free e^-.

Nuclear $0\nu\beta\beta$-decay



strong in-medium modification of the basic process

$dd \rightarrow uue^{-}e^{-}(\overline{\nu}_e\overline{\nu}_e)$



virtual excitation
of states of all multipolarities
in (A,Z+1) nucleus

V. Rodin, talk at Gran Sasso, 2006

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

- Majorana nature of ν_j
- Type of $\nu-$mass spectrum (NH, IH, QD)
- Absolute neutrino mass scale

^{3}H β-decay , cosmology: m_ν (QD, IH)

- CPV due to Majorana CPV phases

ν_j- Dirac or Majorana particles, **fundamental problem**

ν_j-Dirac: **conserved lepton charge exists,** $L = L_e + L_\mu + L_\tau$, $\nu_j \neq \bar{\nu}_j$

ν_j-Majorana: **no lepton charge is exactly conserved,** $\nu_j \equiv \bar{\nu}_j$

The observed patterns of $\nu-$mixing and of $\Delta m^2_{\rm atm}$ and $\Delta m^2_\odot$ can be related to Majorana ν_j and an approximate symmetry:

$$L' = L_e - L_\mu - L_\tau$$

S.T.P., 1982

See-saw mechanism: ν_j- Majorana

Establishing that ν_j are Majorana particles would be as important as the discovery of $\nu-$ oscillations.

$A(\beta\beta)_{0\nu} \sim <m>$ M(A,Z), M(A,Z) - NME,

$$|<m>| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 \; e^{i\alpha_{21}} + m_3 |U_{e3}|^2 \; e^{i\alpha'_{31}} \right|$$

$$= \left| m_1 \; c_{12}^2 \; c_{13}^2 + m_2 \; s_{12}^2 \; c_{13}^2 \; e^{i\alpha_{21}} + m_3 \; s_{13}^2 \; e^{i\alpha'_{31}} \right|, \quad \theta_{12} \equiv \theta_{\odot}, \; \theta_{13}\text{- CHOOZ}$$

α_{21}, α_{31} - the two Majorana CPVP of the PMNS matrix; $\alpha'_{31} \equiv \alpha_{31} - 2\delta$

CP-invariance: $\alpha_{21} = 0, \pm\pi$, $\alpha_{31} = 0, \pm\pi$;

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

relative CP-parities of ν_1 and ν_2, and of ν_1 and ν_3 .

L. Wolfenstein, 1981;

S.M. Bilenky, N. Nedelcheva, S.T.P., 1984;

B. Kayser, 1984.

$|<m>|$: m_j, $\theta_\odot \equiv \theta_{12}$, θ_{13}, $\alpha_{21,31}$

$m_{1,2,3}$ - in terms of $\min(m_j)$, $\Delta m^2_{\rm atm}$, $\Delta m^2_\odot$

S.T.P., A.Yu. Smirnov, 1994

Convention: $m_1 < m_2 < m_3$ - NMO, $m_3 < m_1 < m_2$ - IMO

$$\Delta m^2_\odot \equiv \Delta m^2_{21}, \quad m_2 = \sqrt{m_1^2 + \Delta m^2_\odot},$$

while either

$$\Delta m^2_{\rm atm} \equiv \Delta m^2_{31} > 0, \quad m_3 = \sqrt{m_1^2 + \Delta m^2_{\rm atm}}, \quad \text{normal mass ordering}, \quad \text{or}$$

$$\Delta m^2_{\rm atm} \equiv \Delta m^2_{32} < 0, \quad m_1 = \sqrt{m_3^2 + |\Delta m^2_{\rm atm}| - \Delta m^2_\odot}, \quad \text{inverted mass ordering}$$

The neutrino mass spectrum –

Normal hierarchical (NH) if $m_1 << m_2 << m_3$,

Inverted hierarchical (IH) if $m_3 << m_1 \cong m_2$,

Quasi-degenerate (QD) if $m_1 \cong m_2 \cong m_3 = m$, $m_j^2 >> |\Delta m^2_{\rm atm}|$; $m_j \gtrsim 0.1$ eV

Given $|\Delta m^2_{\rm atm}|$, $\Delta m^2_\odot$, $\theta_\odot$, θ_{13},

$$|<m>| = |<m>| \, ({\rm m_{min}}, \alpha_{21}, \alpha_{31}; {\rm S}), \; {\rm S} = {\rm NO(NH), IO(IH)}.$$

$A(\beta\beta)_{0\nu} \sim <m>$ M(A,Z), M(A,Z) - NME,

$$|<m>| \cong \left|\sqrt{\Delta m^2_\odot}\sin^2\theta_{12}e^{i\alpha} + \sqrt{\Delta m^2_{31}}\sin^2\theta_{13}e^{i\beta}\right|, \quad m_1 \ll m_2 \ll m_3 \text{ (NH)},$$

$$|<m>| \cong \sqrt{m_3^2 + \Delta m^2_{13}}\left|\cos^2\theta_{12} + e^{i\alpha}\ \sin^2\theta_{12}\right|, \quad m_3 < (\ll) m_1 < m_2 \text{ (IH)},$$

$$|<m>| \cong m\left|\cos^2\theta_{12} + e^{i\alpha}\ \sin^2\theta_{12}\right|, \quad m_{1,2,3} \cong m \gtrsim 0.10 \text{ eV (QD)},$$

$\theta_{12} \equiv \theta_\odot$, θ_{13}-CHOOZ; $\alpha \equiv \alpha_{21}$, $\beta + 2\delta \equiv \alpha_{31}$.

CP-invariance: $\alpha = 0, \pm\pi$, $\beta_M = 0, \pm\pi$;

$$|<m>| \lesssim 5 \times 10^{-3} \text{ eV, NH};$$

$$\sqrt{\Delta m^2_{13}}\cos 2\theta_{12} \cong 0.013 \text{ eV} \lesssim |<m>| \lesssim \sqrt{\Delta m^2_{13}} \cong 0.055 \text{ eV}, \quad \text{IH};$$

$$m\cos 2\theta_{12} \lesssim |<m>| \lesssim m,\ m \gtrsim 0.10 \text{ eV}, \quad \text{QD}.$$

Best sensitivity: Heidelberg-Moscow ^{76}Ge experiment.

Claim for a positive signal at $> 3\sigma$:

H. Klapdor-Kleingrothaus et al., PL B586 (2004),

$|{<}m{>}|\ = (0.1 - 0.9)$ eV (99.73% C.L.).

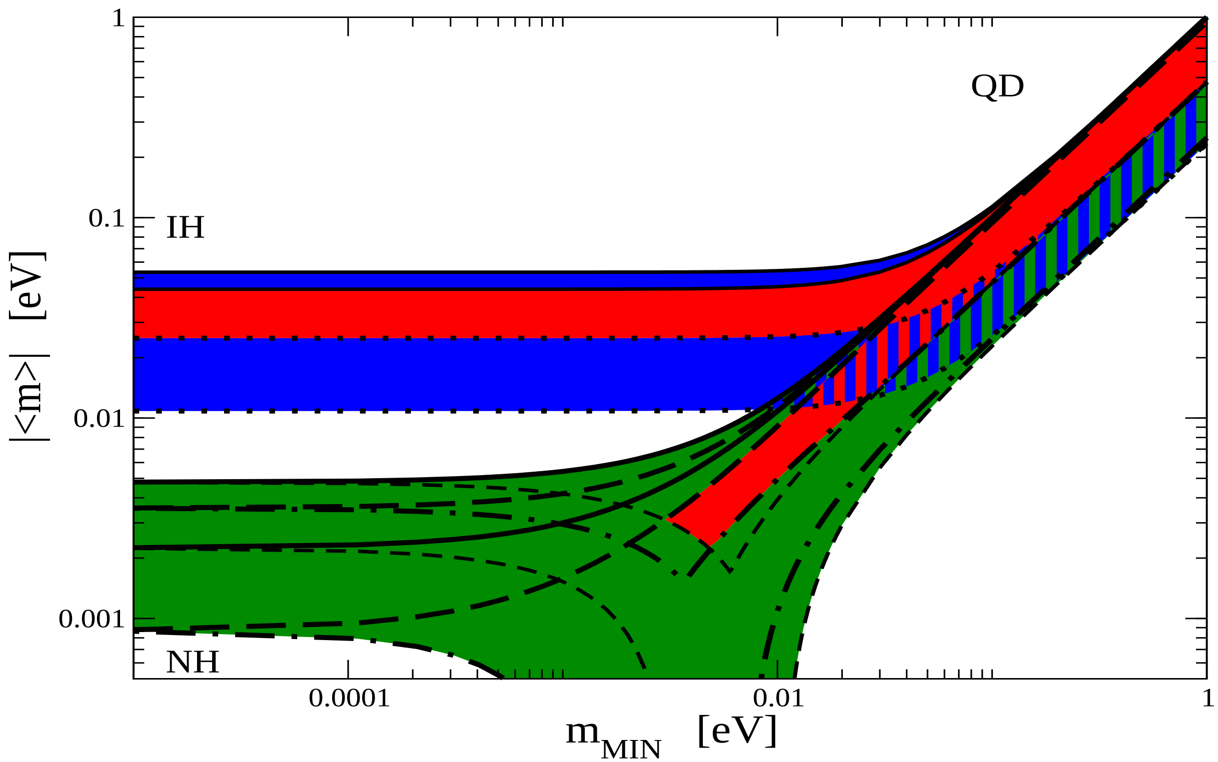
IGEX ^{76}Ge: $|{<}m{>}|\ < (0.33 - 1.35)$ eV (90% C.L.).

Taking data - NEMO3 (^{100}Mo), CUORICINO (^{130}Te):

$|{<}m{>}|\ <$(0.7–1.2) eV, $|{<}m{>}|\ <$(0.18–0.90) eV (90% C.L.).

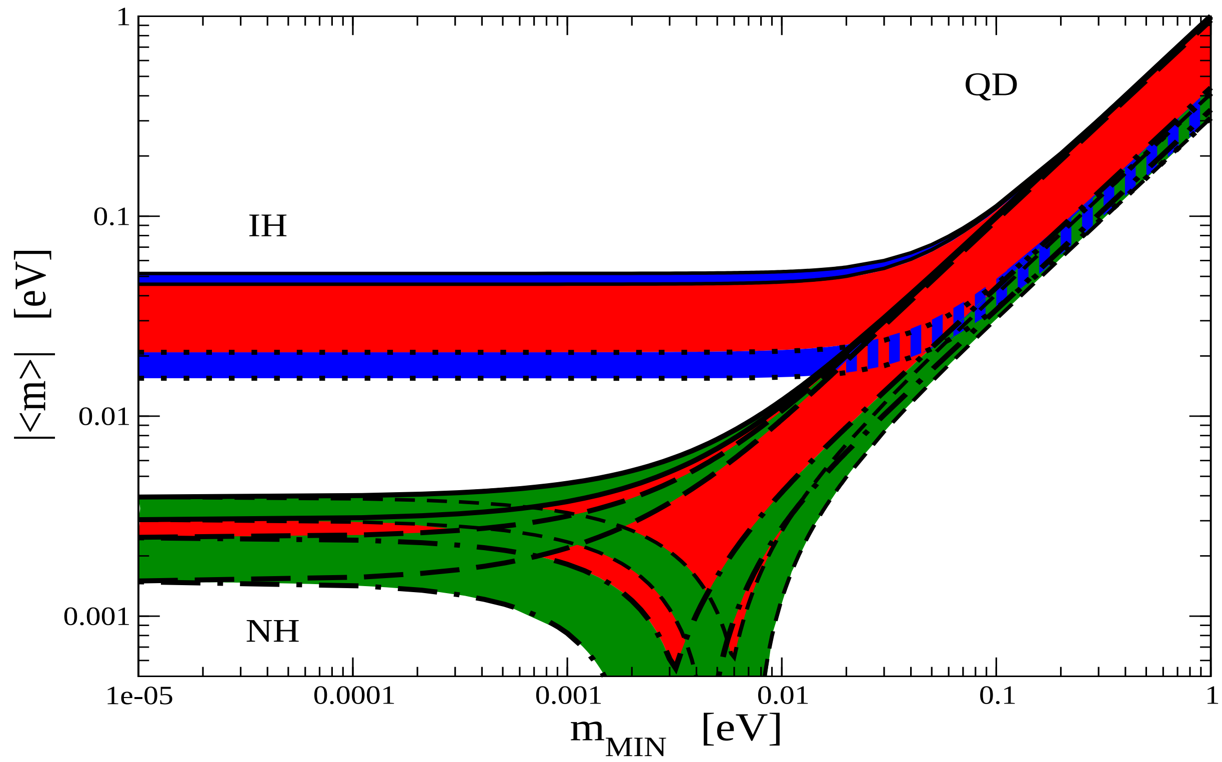
Large number of projects: $|{<}m{>}|\ \sim (0.01 - 0.05)$ eV

CUORE - ^{130}Te;
GERDA - ^{76}Ge;
SuperNEMO - ^{82}Se,...;
COBRA - ^{116}Cd;
EXO - ^{136}Xe;
MAJORANA - ^{76}Ge;
MOON - ^{100}Mo;
CANDLES - ^{48}Ca;
XMASS - ^{136}Xe.



S. Pascoli, S.T.P., 2006

The current 2σ ranges of values of the parameters used.



$\sin^2\theta_{13} = 0.015 \pm 0.006$; $1\sigma(\Delta m^2_\odot) = 2\%$, $1\sigma(\sin^2\theta_\odot) = 4\%$, $1\sigma(|\Delta m^2_{atm}|) = 2\%$;

$2\sigma(|<m>|\ )$ used.

Majorana CPV Phases and $|<m>|$

CPV can be established provided

- $|<m>|$ measured with $\Delta \lesssim 15\%$;

- $\Delta m^2_{\rm atm}$ (IH) or m_0 (QD) measured with $\delta \lesssim 10\%$;

- $\xi \lesssim 1.5$;

- α_{21} (QD): in the interval $\sim [\frac{\pi}{4} - \frac{3\pi}{4}]$, or $\sim [\frac{5\pi}{4} - \frac{3\pi}{2}]$;

- $\tan^2\theta_\odot \gtrsim 0.40$.

S. Pascoli, S.T.P., W. Rodejohann, 2002

S. Pascoli, S.T.P., L. Wolfenstein, 2002

S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226

No "No-go for detecting CP-Violation via $(\beta\beta)_{0\nu}$-decay"

V. Barger *et al.*, 2002

Possible Future Developments

- Suppose, ν-oscillation data: $\Delta m^2_{\rm atm} < 0$.

- Suppose, $(\beta\beta)_{0\nu}$-decay experiments: $|<m>| < 0.01$ eV.

Massive neutrinos ν_j (most likely) are Dirac particles, or there exist additional contributions to $A((\beta\beta)_{0\nu})$, which compensate the light Majorana neutrino exchange contribution.

- If, however, ν-oscillation data: $\Delta m^2_{\rm atm} > 0$; $(\beta\beta)_{0\nu}$-decay experiments: $|<m>| < 0.01$ eV.

This is perfectly compatible with massive neutrinos being Majorana particles and neutrino mass spectrum with normal ordering.

The quest for $|<m>|$ will continue.

The next frontier (most likely) will be $|<m>| \sim 10^{-3}$ eV.

Under what conditions $|<m>| > 10^{-3}$ eV?

$\nu-$Mass Spectrum with Normal Ordering

$$m_1 < (\ll) m_2 < m_3.$$

If $m_1 \ll m_2 < m_3$ (NH spectrum), $m_2 \simeq \sqrt{\Delta m^2_{\odot}},\ m_3 \simeq \sqrt{\Delta m^2_{\rm atm}}$.

One has

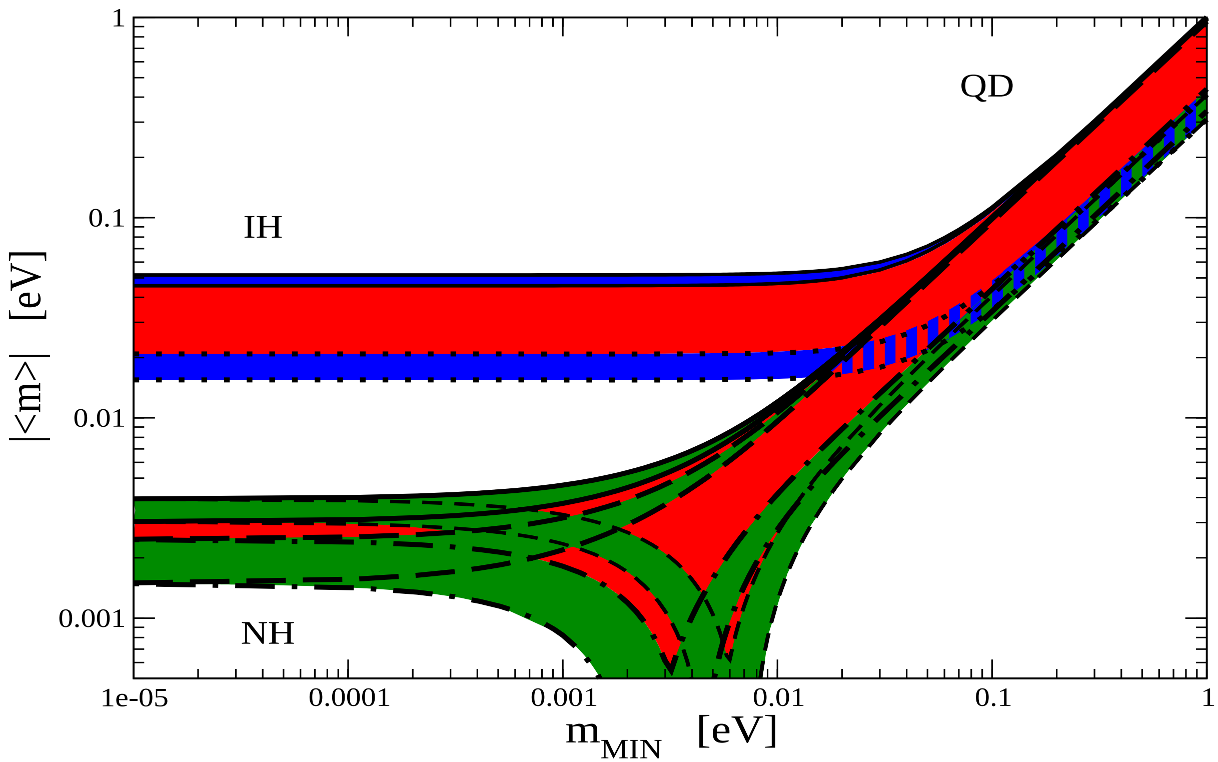
$$|{<}m{>}| = \left|(m_1 \cos^2\theta_{\odot} + \sqrt{m_1^2 + \Delta m^2_{\odot}} \sin^2\theta_{\odot})(1 - |U_{\rm e3}|^2) e^{i\alpha_{21}} + \sqrt{m_1^2 + \Delta m^2_{\rm atm}} |U_{\rm e3}|^2 e^{i\alpha_{31}}\right|$$

$$\simeq \left|\sqrt{\Delta m^2_{\odot}}(1 - |U_{\rm e3}|^2) \sin^2\theta_{\odot} + \sqrt{\Delta m^2_{\rm atm}} |U_{\rm e3}|^2 e^{i(\alpha_{31}-\alpha_{21})}\right|$$

If $m_1 = 0$, $|{<}m{>}|$ depends on $\alpha_{32} = \alpha_{31} - \alpha_{21}$.

At 3σ: $|{<}m{>}| \lesssim 6 \times 10^{-3}$ eV; at 2σ: $|{<}m{>}| \gtrsim 0.6$ meV.

($\sqrt{\Delta m^2_{\rm atm}}|U_{\rm e3}|^2 \lesssim 1.5$ meV, $\sqrt{\Delta m^2_{\odot}} \sin^2\theta_{\odot} \cong (2.1 - 3.2)$ meV.)



$\sin^2\theta_{13} = 0.015 \pm 0.006$; $1\sigma(\Delta m^2_\odot) = 2\%$, $1\sigma(\sin^2\theta_\odot) = 4\%$, $1\sigma(|\Delta m^2_{\rm atm}|) = 2\%$;

$2\sigma(|{<}\,m\,{>}|\ )$ used.

Normal Hierarchical Spectrum

$m_1 \simeq 0,\ m_2 \simeq \sqrt{\Delta m^2_\odot},\ m_3 \simeq \sqrt{\Delta m^2_{\rm atm}},\ \ m_1 + m_2 + m_3 = 0.058$ eV

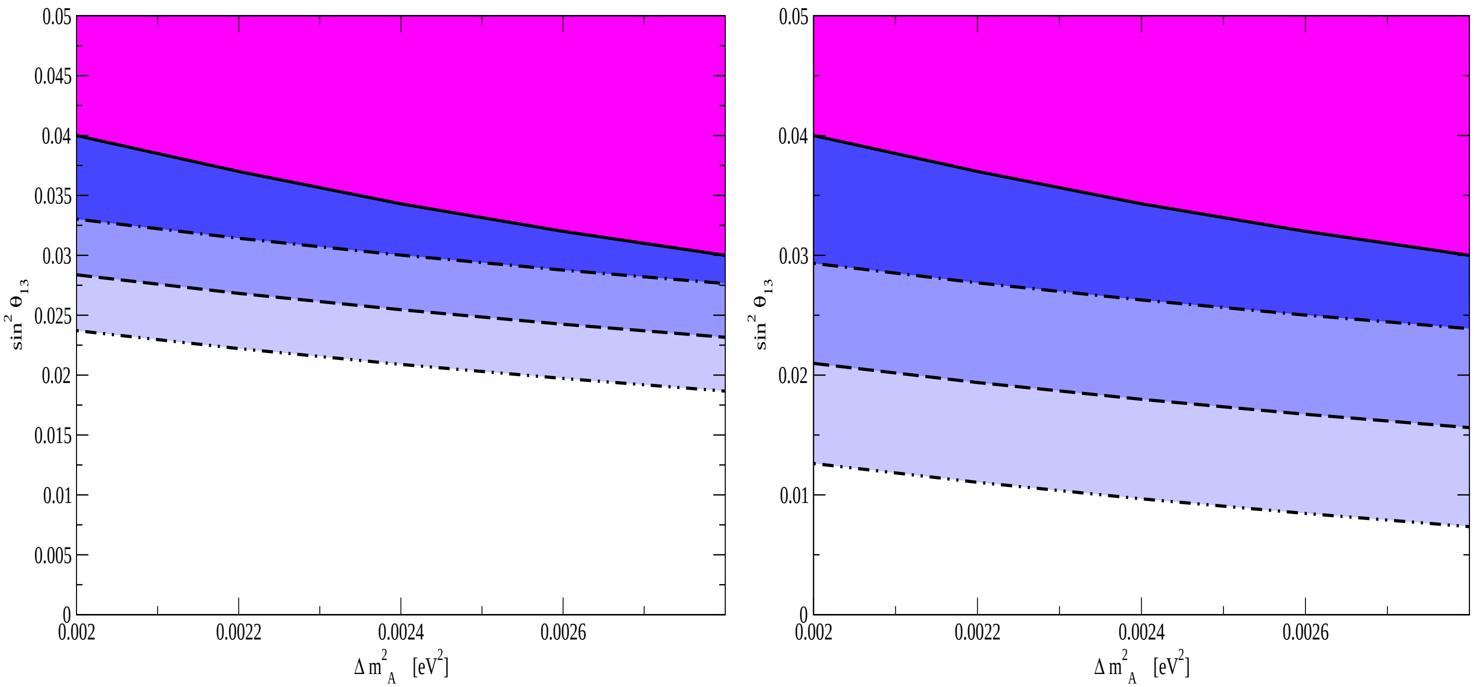
$$|{<}m{>}| \ \simeq \left| \sqrt{\Delta m^2_\odot}(1 - |U_{\rm e3}|^2) \sin^2\theta_\odot + \sqrt{\Delta m^2_{\rm atm}} |U_{\rm e3}|^2 e^{i(\alpha_{31}-\alpha_{21})} \right|$$

In the "extreme" case $\alpha_{32} = \pi$,

$$|{<}m{>}| \ = 0 : \quad \sin^2\theta_{13} = \frac{\sqrt{\Delta m^2_\odot}}{\sqrt{\Delta m^2_{\rm atm}}} \sin^2\theta_{12}.$$

Using the best fit values: $\sin^2\theta_{13} \simeq 0.05$.

If $\sin^2\theta_{13} \lesssim 0.01\ (0.03)$, we have $|{<}m{>}| \ \gtrsim 2.2\ (1.2) \times 10^{-3}$ eV for any α_{32}.



The blue regions show the values of $\sin^2\theta_{13}$ versus Δm^2_{31} for which $|<m>| <$ 1 meV at 1 (2) [3] σ (region bounded from below by the dash-dotted (dashed) [dash-double-dotted] line for $\sin^2\theta_\odot = 0.32$. The error on $\sin^2\theta_{13}$ is taken to be 0.004 (0.008) in the left (right) plot ($\delta(\Delta m^2_\odot) = 2\%$, $\delta(\sin^2\theta_\odot) = 4\%$, $\delta(|\Delta m^2_{\rm atm}|) = 2\%$).

S. Pascoli, S.T. P, 2008.

The case of small $\sin^2\theta_{13}$ ($\sin^2\theta_{13} \lesssim 3\times 10^{-3}$)

$$|<m>| \simeq \left| m_1 \cos^2\theta_\odot + \sqrt{m_1^2 + \Delta m^2_\odot}\,\sin^2\theta_\odot e^{i\alpha_{21}} \right| (1 - |U_{e3}|^2)$$

In the "extreme" case $\alpha_{21} = \pi$,

$$|<m>| = 0: \quad m_1 = m_2 \tan^2\theta_{12}$$

If $m_1 \gtrsim 6.6\times 10^{-3}$ eV, we have $|<m>| \gtrsim 10^{-3}$ eV for any α_{21}.

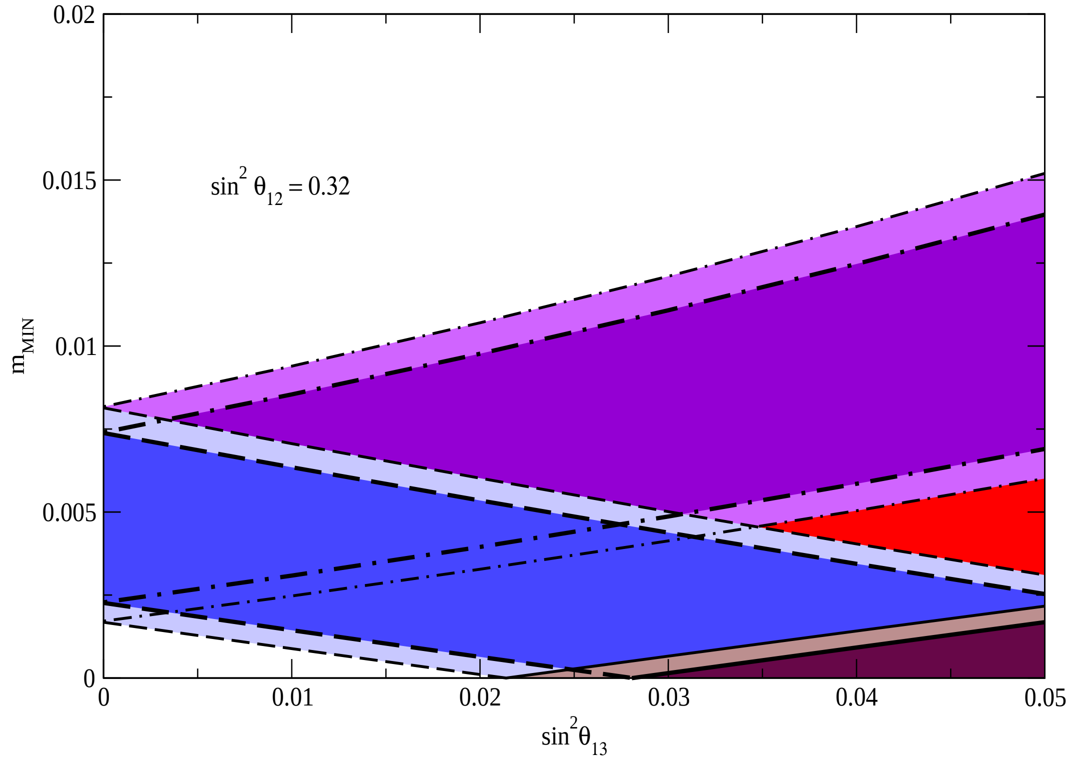
Thus, one has $|<m>| \gtrsim 10^{-3}$ eV, provided $m_1 + m_2 + m_3 \gtrsim 0.070$ eV.

The General Case

$|\langle m \rangle| \geq 10^{-3}$ eV requires

$m_1 \gtrsim 1.5 \times 10^{-2}$ eV $(m_1 + m_2 + m_3 \gtrsim 0.074$ eV$)$

or $m_1 \lesssim 2 \times 10^{-3}$ eV



The colored regions denote the ranges of $m_{\text{min}} = m_1$ for which $|{<}m{>}| \ < 10^{-3}$ eV and are delimited by thick (thin) lines at 1 (2) σ. The CP-conserving patterns are indicated by i) solid lines for the case $++-$, ii) dashed lines for the $+-+$ one, and iii) dashed-dotted lines for $+--$. The red triangular region requires CP-violation.

Conclusions

Determining the nature - Dirac or Majorana, of massive neutrinos is of fundamental importance for understanding the origin of neutrino masses.

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

- **Can establish the Majorana nature of ν_j**

- **Can provide unique information on the ν mass spectrum**

- **Can provide unique information on the absolute scale of ν masses**

- **Can provide information on the Majorana CPV phases**

$\Delta m^2_{\rm atm} > 0$ **and** $|{<}\,m\,{>}| \ < 0.01$ **eV: perfectly compatible with massive ν's being Majorana particles and ν-mass spectrum with normal ordering.**

Thus if $|{<}\,m\,{>}| \ < 0.01$ **eV, the quest for** $|{<}\,m\,{>}|$ **will continue.**

The next frontier (most likely) will be $|{<}\,m\,{>}| \ \sim 10^{-3}$ **eV.**

$|{<}\,m\,{>}| \ \geq 10^{-3}$ **eV requires** $m_1 \gtrsim 1.5 \times 10^{-2}$ **eV (**$m_1 + m_2 + m_3 \gtrsim 0.074$ **eV)**

or $m_1 \lesssim 2 \times 10^{-3}$ **eV (**$m_1 + m_2 + m_3 \simeq (0.058 - 0.061)$ **eV).**

SUPPORTING SLIDES

Absolute Neutrino Mass Measurements

The Troitzk and Mainz ^{3}H β-decay experiments

$$m_{\nu_e} < 2.3 \text{ eV} \qquad (95\% \text{ C.L.})$$

There are prospects to reach sensitivity

$$\text{KATRIN}: \qquad m_{\nu_e} \sim 0.2 \text{ eV}$$

Cosmological and astrophysical data: the WMAP result combined with data from large scale structure surveys (2dFGRS, SDSS)

$$\sum_j m_j \equiv \Sigma < (0.4 - 1.7) \text{ eV}$$

The WMAP and future PLANCK experiments can be sensitive to

$$\sum_j m_j \cong 0.4 \text{ eV}$$

Data on weak lensing of galaxies by large scale structure, combined with data from the WMAP and PLANCK experiments may allow to determine

$$\sum_j m_j : \qquad \delta \cong 0.04 \text{ eV}.$$