Prospects for neutrino mass scale
and hierarchy from non-oscillation experiments

NuFact 08
Valencia - 04 July 2008

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• Neutrino masses

• Absolute mass scale

• Type of mass hierarchy

• Synergy between \((\beta\beta)_{0\nu}\)-decay and other experiments

• Conclusions
\[ \Delta m_{\odot}^2 \ll \Delta m_A^2 \] implies at least 3 neutrinos.

**Normal ordering**

\[
\begin{align*}
\Delta m_{\odot}^2 & \uparrow \\
\Delta m_A^2 & \\
\Delta m_{\odot}^2 & \downarrow
\end{align*}
\]

\[
\begin{align*}
m_1 &= m_{\text{MIN}} \\
m_2 &= \sqrt{m_{\text{MIN}}^2 + \Delta m_{\odot}^2} \\
m_3 &= \sqrt{m_{\text{MIN}}^2 + \Delta m_A^2}
\end{align*}
\]

**Inverted ordering**

\[
\begin{align*}
\Delta m_{\odot}^2 & \uparrow \\
\Delta m_A^2 & \\
\Delta m_{\odot}^2 & \downarrow
\end{align*}
\]

\[
\begin{align*}
m_1 &= \sqrt{m_{\text{MIN}}^2 + \Delta m_A^2 - \Delta m_{\odot}^2} \\
m_2 &= \sqrt{m_{\text{MIN}}^2 + \Delta m_A^2} \\
m_3 &= m_{\text{MIN}}
\end{align*}
\]

Measuring neutrino masses requires to know \( m_{\text{MIN}} \) and \( \text{sign}(\Delta m_{31}^2) \).

We neglect in the following the LSND signal \( \Rightarrow \) sterile \( \nu \) or new physics.
We can identify 3 types of spectra:

- **NH:** \( m_1 \ll m_2 \ll m_3 \)
- **IH:** \( m_3 \ll m_1 \approx m_2 \)
- **QD:** \( m_1 \sim m_2 \sim m_3 \)

and two interpolating ones PNH and PIH.
Neutrino oscillations are sensitive only to $\Delta m^2$.

- Direct mass searches in tritium beta decay experiments.
- Cosmological observations.
- Measurement of time-of-flight of SN neutrinos.
- Some information from $(\beta\beta)_{0\nu}$-decay.
Direct mass measurements

Direct mass searches in tritium beta decay experiments.

The differential decay rate is:

\[
\frac{d\Gamma}{dE_e} = \sum_i |U_{ei}|^2 \frac{d\Gamma_i}{dE_e}(m_i)
\]

with

\[
\frac{d\Gamma_i}{dE_e} = C|M|^2 p_e (E_e + m_e)(E_e - E_0) \sqrt{(E_e - E_0)^2 - m_i^2} F(E_e)
\]
2 – Neutrino masses

- **QD** ($m_1 \simeq m_2 \simeq m_3$):

\[
\frac{d\Gamma}{dE_e} = \sum_i |U_{ei}|^2 \frac{d\Gamma_i}{dE_e}(m_0) = \frac{d\Gamma_i}{dE_e}(m_0)
\]

- **NH** ($m_1 \ll m_2 \ll m_3$):

\[
\frac{d\Gamma}{dE_e} = |U_{e1}|^2 \frac{d\Gamma_i}{dE_e}(0) + |U_{e2}|^2 \frac{d\Gamma_i}{dE_e}(\sim 0) + |U_{e3}|^2 \frac{d\Gamma_i}{dE_e}(\sqrt{\Delta m^2_{A}})
\]
\[
= \frac{d\Gamma_i}{dE_e}(m = 0)
\]

- **IH** ($m_3 \ll m_1 \simeq m_2$):

\[
\frac{d\Gamma}{dE_e} = (|U_{e1}|^2 + |U_{e2}|^2) \frac{d\Gamma_i}{dE_e}(\sqrt{\Delta m^2_{A}}) + |U_{e3}|^2 \frac{d\Gamma_i}{dE_e}(0))
\]
\[
= \frac{d\Gamma_i}{dE_e}(m = \sqrt{\Delta m^2_{A}})
\]

[Bilenky, Mateev, Petcov, PLB639]
3H-decay experiments: Troiztk and Mainz.

They provide the most stringent present limit (95% C.L.):

\[ m_0 < 2.3 \text{ eV} \]

[Kraus et al., EPJC 40; Lobashev et al., NPBPS 91]

Cryogenic experiments detecting the \( \beta \)-spectrum of \( ^{87}\text{Re} \) (Genova and Milan, MARE, MANU-2):

\[ m_0 < 19 \text{ eV} \] at 90% CL

[Galeazzi, Gatti et al., 1999, 2001; Gatti, NPBPS 91]

\[ m_0 < 15 \text{ eV} \] at 90% CL

[Sisti et al., NPBPS143]
• KATRIN is the next generation of $^3$H-decay experiments.

• KATRIN can reach a sensitivity to $m_0 \sim 0.2$ eV (90% CL), covering all the QD spectrum!

• a mass signal of $m_\nu = 0.35(0.30)$ eV can be measured with 5 (3) $\sigma$ evidence.
Exploiting the effects of massive neutrinos on the CMB and structure formation it is possible to constrain the sum of neutrino masses.

\[ \Sigma m_\nu < 1.5 \ (0.61) \text{ eV (95\%CL)} \]

[Komatsu et al., WMAP, arXiv:0803.0547]

A detailed discussion in S. Pastor’s talk.
SN neutrinos: time of flight

The time-of-flight delay of a flux of massive neutrino with mean energy $E$ is:

$$\Delta T \simeq \frac{m^2}{E^2} D \frac{\Delta E}{E}$$

A bound on $m_\nu$ can be set by requiring that $\Delta T < \Delta T_{\text{obs}}$:

$$m_\nu < 14 \text{eV} \left(\frac{E}{10 \text{MeV}}\right) \sqrt{\frac{\Delta E}{E} \frac{\Delta T_{\text{obs}}}{10 \text{sec}} \frac{50 \text{kpc}}{D}}$$

From the observation of SN1987A, a limit of $m_\nu < 5-30 \text{ eV}$:

$$m_\nu < 5.7 \text{ eV} \ (95\% \ \text{probability})$$

[Loredo and Lamb, PRD 65]
2 – Neutrino masses

**Type of hierarchy**

- $(\beta\beta)_{0\nu}$-decay exp.  
  [e.g. S.P., Petcov, Rodejohann, Schwetz]

- Neutrino oscillations by exploiting matter effects (requires sizable $\sin^2 \theta_{13}$):
  a) LBL neutrino oscillation experiments (degeneracies). (see Saoulidou’s and Mena’s talk)  
  [e.g. Agarwalla, Aoki, Barger, Burguet-Castell, Choubey, de Gouvea, Donini, Fernandez Martinez, Fogli, Freund, Hagiwara, Hernandez, Huber, Kajita, Kayser, Lindner, Lindroos, Lisi, Marfatia, Maltoni, Meloni, Mena, Minakata, Nunokawa, Okamura, Orme, Ota, Palomares-Ruiz, Parke, S. P., Petcov, Raychaudhuri, Rigolin, Sato, Yasuda, Whisnant, Winter, Jenkins]
  b) atmospheric neutrinos (see M. Maltoni’s talk)  
  [e.g. Bernabeu, Gandhi, Ghosal, Goswami, Huber, Indumathi, Maltoni, Mehta, Murthy, Palomares-Ruiz, Petcov, Schwetz]

- Vacuum neutrino oscillations: require very high precision measurement of $\Delta m^2_A$.  
  [e.g. de Gouvea, Jenkins, Kayser, Nunokawa, Parke, Petcov, Piai, Zukanovich Funchal]
neutrinoless double beta decay: \((A, Z) \rightarrow (A, Z + 2) + 2e^-,\) is the most sensitive of processes \((\Delta L = 2)\) which can probe the nature of neutrinos (Dirac vs Majorana).

\((\beta\beta)_{0\nu}\)-decay has a special role in the study of neutrino properties, as it probes the violation of global lepton number, and it might provide information on the neutrino mass spectrum, absolute neutrino mass scale and CP-V.
The half-life time, $T^{1/2}_{0\nu}$, of the $(\beta\beta)^{0\nu}$-decay can be factorized, for light Majorana neutrinos, as:

$$\left[T^{1/2}_{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 |< m >|^2$$

- $|< m >|$ is the effective Majorana mass parameter:

$$|< m >| \equiv |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha_{21}} + m_3|U_{e3}|^2 e^{i\alpha_{31}}|,$$

- $|M_F - g_A^2 M_{GT}|$ are the nuclear matrix elements (NME). They need to be evaluated theoretically.

The extracted value of $|< m >|$ from a measurement of $T^{1/2}_{0\nu}$ requires the knowledge of NME.
The present bound on $|<m>|$ depends on the nuclei used:

$|<m>| < (0.35 - 1.05) \text{ eV}$ (Heidelberg-Moscow, $^{76}$Ge),

$|<m>| < (0.20 - 0.68) \text{ eV}$ (Cuoricino, $^{130}$Te),

$|<m>| < (0.8 - 1.3) \text{ eV}$ (NEMO3, $^{100}$Mo).

Evidence of $(\beta\beta)_{0\nu}$-decay was reported [Klapdor-Kleingrothaus and Krivosheina, PLB 586 and MPLA 21]: $|<m>|_{BF} = (0.32 \pm 0.03) \text{ eV}$.

The next generation of $(\beta\beta)_{0\nu}$-decay exp (GERDA, SNO+, SuperNEMO, EXO, Majorana, CUORE, Cobra ...) aim to $|<m>| \sim 10-30 \text{ meV}$.
The predictions for $|\langle m \rangle|$ depend strongly on the type of spectrum.

- **NH:**
  $$|\langle m \rangle| \simeq \sqrt{\Delta m^2} \cos^2 \theta_{13} \sin^2 \theta_{\odot} + \sqrt{\Delta m^2_A} \sin^2 \theta_{13} e^{i\alpha_{32}}$$

- **IH:**
  $$\sqrt{\Delta m^2_A} \cos 2\theta_{\odot} \leq |\langle m \rangle| \simeq \sqrt{1 - \sin^2(2\theta_{\odot}) \sin^2 \frac{\alpha_{21}}{2}} \Delta m^2_A \leq \sqrt{\Delta m^2_A}$$

  $|\langle m \rangle|$ has a significant lower bound

  $$0.01 \text{ eV} \lesssim |\langle m \rangle| \lesssim 0.06 \text{ eV}$$

- **QD:**
  $$|\langle m \rangle| \simeq m_{\bar{\nu}_e} \left| \left( \cos^2 \theta_{\odot} + \sin^2 \theta_{\odot} e^{i\alpha_{21}} \right) \cos^2 \theta_{13} + \sin^2 \theta_{13} e^{i\alpha_{31}} \right|$$

  $$|\langle m \rangle| \gtrsim 0.03 \text{ eV}$$
All the allowed range for $|\langle m \rangle|$ for QD and IH is in the range of sensitivity of present and upcoming $^{0}\beta\beta$-decay experiments.

[e.g. S.P., Petcov, PLB544; S.P., Petcov, Rodejohann, PLB558; S.P., Petcov and Schwetz, NPB734; S. P., Petcov, in pub in PRD]
If $|<m>| > 0.2$ eV, this would imply QD spectrum ($m_0 > 0.2$ eV).

$(\beta/\beta)_{0\nu}$-decay can also constrain a range of $m_0$:

$|<m>| \leq m_0 \leq \frac{|<m>|}{\cos 2\theta_{\odot}}$

The measurement of $m_0$ is entangled with the value of the Majorana CP-violating phases.
If $0.01 \text{ eV} \lesssim |\langle m \rangle| \lesssim 0.05 \text{ eV}$, the spectrum is of the IH type: inverted hierarchy and $m_{\text{MIN}}$ negligible.

There is a narrow range of values of $m_{\text{MIN}}$ for which the hierarchy can be normal. To disentangle the two cases additional information is required.
If $|\langle m \rangle| < 0.01$ eV, the only possibility is normal hierarchy, for Majorana neutrinos.
In addition, if a (far) future experiment is sensitive to $|\langle m \rangle| \sim 1$ meV and no positive signal is found, Majorana neutrinos will be constrained to be with partial normal hierarchical spectrum and $m_1 \sim$ few meV.

[S. P., Petcov, in pub PRD]
A careful analysis yields:

\[
\begin{array}{cccc}
10^{-4} & 10^{-3} & 10^{-2} & 10^{-1} \\
\end{array}
\]

\[
\begin{array}{cccc}
\sigma_{\beta\beta} \ [\text{eV}] & 10^{-3} & 10^{-2} & 10^{-1} \\
\end{array}
\]

\[
\begin{array}{cccc}
\text{observed } |<m>| \ [\text{eV}] & 10^{-4} & 10^{-3} & 10^{-2} & 10^{-1} \\
\end{array}
\]

Perfectly known NME

Factor 2 uncertainty from NME

Factor 3 uncertainty from NME

No information on the mass ordering

Inverted ordering excluded at 2\(\sigma\)

To the right a signal is observed at 2\(\sigma\)

Either IH or QD spectrum

QD with no information on ordering

To the right the NH spectrum is excluded

\[
\sin^2 \theta_{13} = 0.03 \pm 0.006, \quad \sin^2 \theta_{12} = 0.31 \pm 3\%, \quad \Delta m^2_{21} = 8 \times 10^{-5} \pm 2\%, \quad |\Delta m^2_{31}| = 2.2 \times 10^{-3} \pm 3\%
\]

[S.P., Petcov and Schwetz, NPB734]

The nuclear matrix uncertainties have a mild impact.
● $(\beta\beta)_{0\nu}$-decay and LBL exp are complementary in the quest for $\nu$-masses. They exploit completely different physics effects.

1) If $\sin^2 2\theta_{13} \ll 0.001 - 0.0001$, future generation LBL experiments will not be able to resolve the type of hierarchy. $(\beta\beta)_{0\nu}$-decay is a viable alternative.

2) If $\nu$’s are Dirac particles, $(\beta\beta)_{0\nu}$-decay will not find any signal. Neutrino oscillations in LBL exp. do not depend on neutrino nature and can determine the type of hierarchy.
$(\beta\beta)_{0\nu}$-decay and LBL have a strong synergy: important information can be obtained from combining their results.

1) Probing Dirac particles and lepton number conservation:

If LBL establishes that is IH and $(\beta\beta)_{0\nu}$-decay searches find no signal with $|<m>| < 10$ meV, this implies that neutrinos are Dirac particles.
2) Probing new physics

If LBL establishes that is IH and $(\beta\beta)_{0\nu}$-decay searches finds $|<m>| = \text{few meV}$, then there needs to be additional new-physics contributions to $(\beta\beta)_{0\nu}$-decay which partially cancel the one of light neutrino masses.
3) Measuring small neutrino masses

If LBL experiments provide a determination of the hierarchy, \((\beta\beta)_{0\nu}\)-decay experiments can provide information on small neutrino masses.

For example, for normal hierarchy (from LBL), a measurement of \( |<m>| \) would allow to constrain \( m_1 \) in a rather narrow range, even for \( m_1 \) which are not at reach in near future direct neutrino mass measurements.
4) **Solving one degeneracy in LBL experiments.**

The physics reach of future LBL experiments is affected by degeneracies:

\[
\Delta m^2_{31}, \theta_{13}, \delta, \theta_{23}, \Delta m^2_{31'}, \theta'_{13}, \delta', \theta'_{23} \Rightarrow P, \overline{P}
\]

\[|<m>| < 10 \text{ meV with positive signal} \Rightarrow \text{NH, this solves the } \Delta m^2_{31} - \delta \text{ LBL degeneracy and improves on the sensitivity to CP-violation.}\]
Establishing the nature of neutrinos, their masses and CPV is of fundamental importance for understanding the origin of neutrino masses and flavour.

- $^3$H-decay experiments and cosmological observations can provide information on the mass scale for QD spectrum.

- $(\beta\beta)_{0\nu}$-decay plays a special role as it can test lepton number violation, provide information on the neutrino mass spectrum and, possibly, on CPV.

- LBL experiments can determine the type of hierarchy if $\theta_{13}$ is sufficiently light.

- $^3$H-decay, $(\beta\beta)_{0\nu}$-decay and LBL experiments have important synergies and complementarities.