LIMITS FROM NEUTRINOLESS DOUBLE-β DECAY

Revised September 2003 by P. Vogel (Caltech) and A. Piepke (University of Alabama).

Neutrinoless double-beta ($0\nu\beta\beta$) decay, if observed, would signal violation of the total lepton number conservation. The process can be mediated by an exchange of a light Majorana neutrino, or by an exchange of other particles. However, the existence of $0\nu\beta\beta$-decay requires Majorana neutrino mass, no matter what the actual mechanism is. As long as only a limit on the lifetime is available, limits on the effective Majorana neutrino mass, and on the lepton-number violating right-handed current can be obtained, independently on the actual mechanism. These limits are listed in the next three tables. In the following we *assume* that the exchange of light Majorana neutrinos ($m_{\nu_i} \leq \mathcal{O}(10\ \text{MeV})$) contributes dominantly to the decay rate.

Besides a dependence on the phase space ($G^{0\nu}$) and the nuclear matrix element ($M^{0\nu}$), the observable $0\nu\beta\beta$-decay rate is proportional to the square of the effective Majorana mass ($\langle m_{\beta\beta}\rangle$), $(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot |\langle m_{\beta\beta}\rangle|^2$, with $\langle m_{\beta\beta}\rangle = \sum_i U^2_{ei} m_{\nu_i}$. The sum contains, in general, complex CP phases in U^2_{ei}, i.e., cancelations may occur. For three neutrino flavors there are three physical phases for Majorana neutrinos and one for Dirac neutrinos. The two additional Majorana phases affect only total lepton number violating processes. Given the general 3×3 mixing matrix for Majorana neutrinos, one can construct other analogous lepton number violating quantities, $\sum_i U_{\ell i} U_{\ell' i} m_{\nu_i}$. However, these are currently much less constrained than $\langle m_{\beta\beta}\rangle$.

Nuclear structure calculations are needed to deduce $\langle m_{\beta\beta}\rangle$ from the decay rate. While $G^{0\nu}$ can be calculated reliably, the computation of $M^{0\nu}$ is subject to considerable uncertainty. If the spread among different ways of evaluating the nuclear matrix elements is taken as a measure of error, then there is a factor of $\sim$3 uncertainty in the derived $\langle m_{\beta\beta}\rangle$ values.

The particle physics quantities to be determined are thus nuclear model-dependent, so the half-life measurements are listed first. Where possible, we reference the nuclear matrix

CITATION: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

elements used in the subsequent analysis. Since rates for the more conventional $2\nu\beta\beta$ decay serve to calibrate the nuclear theory, results for this process are also given.

Neutrino oscillation experiments yield strong evidence that at least some neutrinos are massive. However, these findings shed no light on the mass hierarchy, the absolute neutrino mass values or the properties of neutrinos under CP conjugation (Dirac or Majorana). The atmospheric neutrino anomaly implies $\Delta m^2_{atm} \sim (2-3) \times 10^{-3}$ eV^2 and a large mixing angle $\sin^2\theta_{atm} \approx \sin^2\theta_{23} \approx 0.5$. Oscillations of solar ν_e and reactor $\bar{\nu}_e$ neutrinos lead to the unique 'LMA solution' with $\Delta m^2_{sol} \sim 7 \times 10^{-5}$ eV^2 and $\sin^2\theta_{sol} \approx \sin^2\theta_{12} \approx 0.3$. The investigation of reactor $\bar{\nu}_e$ at 1 km baseline indicates that electron type neutrinos couple only weakly to the third mass eigenstate with $\sin^2\theta_{13} < 0.03$. The so called 'LSND evidence' for oscillations at short baseline requires $\Delta m^2 \sim 0.2 - 2$ eV^2 and small mixing.

Based on these results (and neglecting the not yet confirmed LSND signal): $|\langle m_{\beta\beta}\rangle|^2 \approx |\cos^2\theta_{sol}\ m_1 + e^{i\alpha_1}\ \sin^2\theta_{sol}\ m_2 + e^{i\alpha_2}\ \sin^2\theta_{13}\ m_3|^2$, with α_1, α_2 denoting CP phases. The apparent smallness of $\sin^2\theta_{13}$ thus effectively shields $\langle m_{\beta\beta}\rangle$ from one of the CP phases. Given the present knowledge of the neutrino oscillation parameters, both of the Δm^2 values and of the mixing angles, one can derive the relation between the effective Majorana mass and the mass of the lightest neutrino, as illustrated in Fig. 1. The contribution of possible sterile neutrinos has been neglected.

If the neutrinoless double-beta decay is observed, it will be possible to fix a *range* of absolute values of the masses m_{ν_i}. However, if direct neutrino mass measurements, e.g. using beta decay (which is sensitive to $m_{\nu_e}^{2(\mathrm{eff})} = \sum_i |U_{ei}|^2 m^2_{\nu_i}$), also yield positive results, we may learn something about the otherwise inaccessible CP phases. To do so we have to assume that the Majorana mass is responsible for the decay and that the calculations of $M^{0\nu}$ will be improved. Unlike the direct neutrino mass measurements, however, a limit on $\langle m_{\beta\beta}\rangle$ does not allow one to constrain the individual mass values m_{ν_i} even when the mass differences Δm^2 are known.

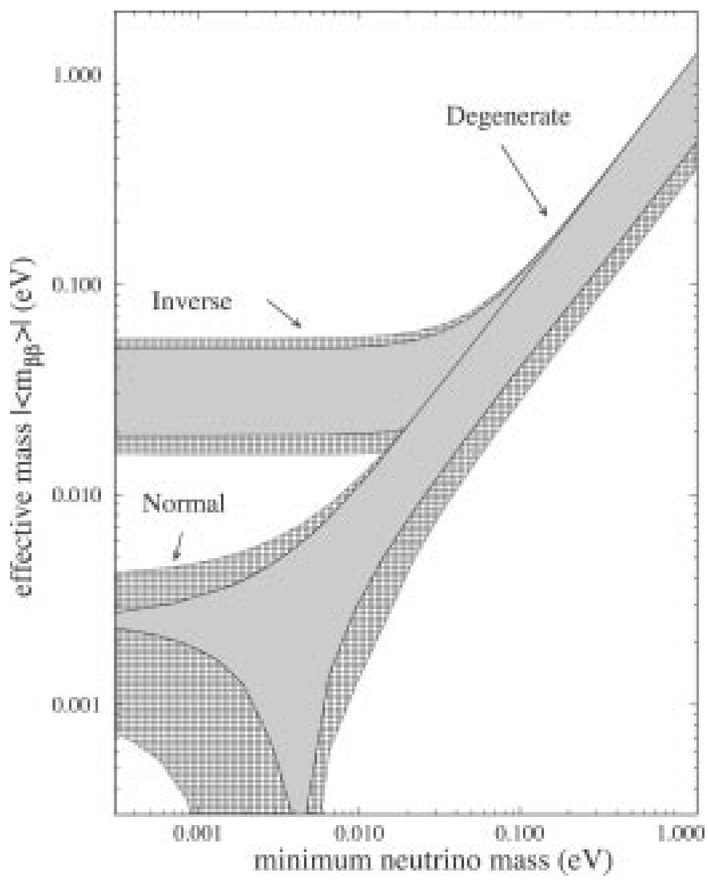

Figure 1: Dependence of the effective Majorana mass $\langle m_{\beta\beta}\rangle$ derived from the rate of neutrinoless double-beta decay $(1/T^{0\nu}_{1/2} \sim \left|\langle m_{\beta\beta}\rangle\right|^2)$ on the absolute mass of the lightest neutrino. The arrows indicate the three possible neutrino mass patterns or "hierarchies." The curves are based on the 'LMA solution,' $\Delta m^2_{sol} = 7 \times 10^{-5}$ eV^2, $\sin^2\theta_{sol} = 0.3$, and $\Delta m^2_{atm} = 2.4 \times 10^{-3}$ eV^2, $\theta_{13} = 0$. The cross-hatched region is covered if one σ errors on these oscillation parameters are included.

Depending on the pattern of neutrino mass, $0\nu\beta\beta$-decay may be driven by the small Δm^2_{sol}, "normal hierarchy" in Fig. 1 ($\langle m_{\beta\beta}\rangle \sim \sin^2\theta_{sol}\sqrt{\Delta m^2_{sol}} \sim 5$ meV), or by the larger Δm^2_{atm}, "inverse hierarchy" in Fig. 1 ($\langle m_{\beta\beta}\rangle \sim \sqrt{\Delta m^2_{atm}} \sim 50$ meV). In the so called "degenerate" scenario an overall mass offset exists and $\langle m_{\beta\beta} \rangle$ is relatively large.

Neutrino oscillation data imply the existence of a *lower limit* for the Majorana neutrino mass for some of the mass patterns. Several new double-beta searches have been proposed to probe the interesting $\langle m_{\beta\beta} \rangle$ mass range.

If lepton-number violating right-handed current weak interactions exist, the $0\nu\beta\beta$ decay rate also depends on the quantities $\langle \eta \rangle = \eta \sum_i U_{ei} V_{ei}$ and $\langle \lambda \rangle = \lambda \sum_i U_{ei} V_{ei}$, where V_{lj} is a matrix analogous to U_{lj} but describing the mixing with the hypothetical right-handed neutrinos and the coupling constants η and λ characterize the strength of the corresponding right-right and right-left weak interactions. The $\langle \eta \rangle$ and $\langle \lambda \rangle$ vanish for massless or unmixed neutrinos due to the unitarity of the generalized mixing matrix containing both the U and V matrices. The limits on $\langle \eta \rangle$ are of order 10^{-8}, while the limits on $\langle \lambda \rangle$ are of order 10^{-6}. The reader is cautioned that a number of earlier experiments did not distinguish between η and λ. In addition, see the section on Majoron searches for additional limits set by these experiments.