NEUTRINOLESS DOUBLE-β DECAY

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Neutrinoless double-beta ($0\nu\beta\beta$) decay 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 or other possible mechanisms mediating $0\nu\beta\beta$ decay can be obtained, independently on the actual mechanism. These limits are listed in the next three tables, together with a claimed $0\nu\beta\beta$-decay signal reported by part of the Heidelberg-Moscow collaboration. There, a 4σ excess of counts at the decay energy is used for a determination of the Majorana neutrino mass. This signal has not yet been independently confirmed. In the following we *assume* that the exchange of light Majorana neutrinos ($m_i \leq \mathcal{O}(10\ \text{MeV})$) 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 $\langle m_{\beta\beta}\rangle^2 = |\sum_i U^2_{ei} m_i|^2$. The sum contains, in general, complex CP phases in U^2_{ei}, *i.e.*, cancellations 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 processes to which lepton-number changing amplitudes contribute. Given the general 3×3 mixing matrix for Majorana neutrinos, one can construct other analogous lepton number violating quantities, $\langle m_{\ell\ell'}\rangle = \sum_i U_{\ell i} U_{\ell' i} m_i$. 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 uncertainty. Indiscriminate averaging over all published matrix element values would result, for any given nuclide, in a factor of ∼3 uncertainty in the derived $\langle m_{\beta\beta}\rangle$ values. More recent evaluations, insisting that the known $2\nu\beta\beta$ rate is correctly reproduced, result in a considerable reduction in the spread of the $M^{0\nu}$ values. *E.g.* in [1], the spread appears to be as low as ±30%. 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 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.

Oscillation experiments utilizing atmospheric-, accelerator-, solar-, and reactor-produced neutrinos and anti-neutrinos yield strong evidence that at least some neutrinos are massive. However, these findings shed no light on the 3,1 mass hierarchy, the absolute neutrino mass values, or the properties of neutrinos under CPT-conjugation (Dirac or Majorana).

If the, thus far unconfirmed, LSND evidence is set aside all oscillation experiments can be consistently described using three interacting neutrino species with two mass splittings and three mixing angles. Full three flavor analyses such as *e.g.* [2] yield: $\Delta m^2_{atm} \sim (2.4^{+0.5}_{-0.6}) \times 10^{-3}$ eV^2 and $\sin^2\theta_{atm} = 0.44^{+0.18}_{-0.10}$ for the parameters observed in atmospheric and accelerator experiments. Oscillations of solar ν_e and reactor $\bar{\nu}_e$ lead to $\Delta m^2_{\odot} = (7.92 \pm 0.71) \times 10^{-5}$ eV^2 and $\sin^2\theta_{\odot} = 0.314^{+0.057}_{-0.047}$ (all errors at 95% CL). The investigation of reactor $\bar{\nu}_e$ at ∼1 km baseline, combined with solar neutrino and long baseline reactor experiments, 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. If confirmed by the ongoing MiniBooNE experiment, this phenomenon would require the addition of at least one more non-interacting neutrino species.

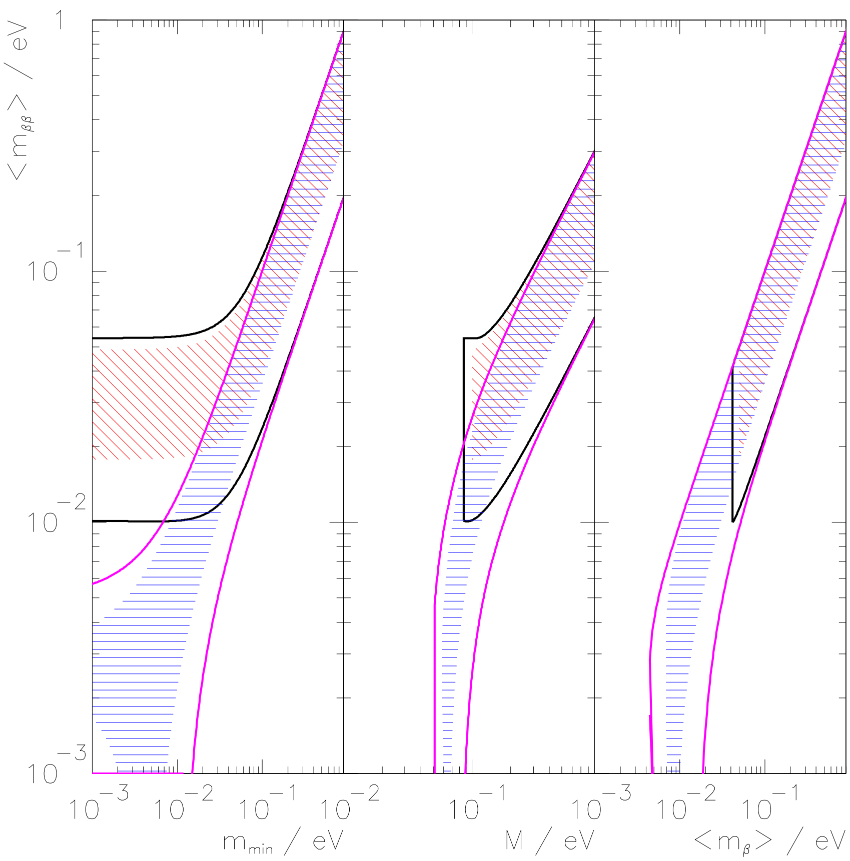

Figure 1: The left panel shows the dependence of $\langle m_{\beta\beta}\rangle$ on the absolute mass of the lightest neutrino m_{min}. The middle panel shows $\langle m_{\beta\beta}\rangle$ as a function of the summed neutrino mass M, while the right panel depicts $\langle m_{\beta\beta}\rangle$ as a function of the mass $\langle m_{\beta}\rangle$. In all panels the width of the hatched areas is due to the unknown Majorana phases and thus irreducible. The allowed areas given by the solid lines are obtained by taking into account the errors of the oscillation parameters. The two sets of solid lines correspond to the normal and inverted hierarchies. These sets merge into each other for $\langle m_{\beta\beta}\rangle \geq 0.1$ eV, which corresponds to the degenerate mass pattern. See full-color version on color pages at end of book.

Based on the 3-neutrino analysis: $\langle m_{\beta\beta}\rangle^2 \approx |\cos^2\theta_{\odot}\ m_1 + e^{i\Delta\alpha_{21}} sin^2\theta_{\odot}\ m_2 + e^{i\Delta\alpha_{31}}\sin^2\theta_{13}\ m_3|^2$, with $\Delta\alpha_{21}, \Delta\alpha_{31}$ denoting the physically relevant Majorana CP-phase differences (possible Dirac phase δ is absorbed in these $\Delta\alpha$). Given the present knowledge of the neutrino oscillation parameters one can derive the relation between the effective Majorana mass and the mass of the lightest neutrino, as illustrated in the left panel of Fig. 1. The three mass hierarchies allowed by the oscillation data: normal ($m_1 < m_2 < m_3$), inverted ($m_3 < m_1 < m_2$), and degenerate ($m_1 \approx m_2 \approx m_3$), result in different projections. The width of the innermost hatched bands reflects the uncertainty introduced by the unknown Majorana phases. If the experimental errors of the oscillation parameters are taken into account, then the allowed areas are widened as shown by the outer bands of Fig. 1. Because of the overlap of the different mass scenarios, a measurement of $\langle m_{\beta\beta} \rangle$ in the degenerate or inversely hierarchical ranges would not determine the hierarchy. The middle panel of Fig. 1 depicts the relation of $\langle m_{\beta\beta} \rangle$ with the summed neutrino mass $M = m_1 + m_2 + m_3$, constrained by observational cosmology. The oscillation data thus allow to test whether observed values of $\langle m_{\beta\beta} \rangle$ and M are consistent within the 3 neutrino framework. The right hand panel of Fig. 1, finally, shows $\langle m_{\beta\beta} \rangle$ as a function of the average mass $\langle m_\beta \rangle = [\Sigma |U_{ei}|^2 m_i^2]^{1/2}$ determined through the analysis of low energy beta decays. The rather large intrinsic width of the $\beta\beta$-decay constraint essentially does not allow one to positively identify the inverted hierarchy, and thus the sign of Δ^2_{atm}, even in combination with these other observables.

It should be noted that systematic uncertainties of the nuclear matrix elements are not folded into the mass limits reported by $\beta\beta$-decay experiments. Taking this additional uncertainty into account would further widen the projections. The uncertainties in oscillation parameterers affect the width of the allowed bands in an asymmetric manner, as shown in Fig. 1. For example, for the degenerate mass pattern ($\langle m_{\beta\beta} \rangle \geq 0.1$ eV) the upper edge is simply $\langle m_{\beta\beta} \rangle \sim m$, where m is the common mass of the degenerate multiplet, independent of the oscillation parameters, while the lower edge is $m \cos(2\theta_\odot)$. Similar arguments explain the other features of Fig. 1.

If the neutrinoless double beta decay is observed, it will be possible to fix a *range* of absolute values of the masses m_i. 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_i even when the mass differences Δm^2 are known.

Neutrino oscillation data imply, for the first time, 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, its strength can be characterized by the phenomenological coupling constants η and λ. The $0\nu\beta\beta$ decay rate then depends on $\langle \eta \rangle = \eta \sum_i U_{ei} V_{ei}$ and $\langle \lambda \rangle = \lambda \sum_i U_{ei} V_{ei}$ that vanish for massless or unmixed neutrinos ($V_{\ell j}$ is a matrix analogous to $U_{\ell j}$ but describing the mixing with the hypothetical right-handed neutrinos). This mechanism of the $0\nu\beta\beta$ decay could be, in principle, distinguished from the light Majorana neutrino exchange by the observation of the single electron spectra. The limits on $\langle \eta \rangle$ and $\langle \lambda \rangle$ are listed in a separate table. 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.

References

1. V.A. Rodin *et al.*, Phys. Rev. **C68**, 044302 (2003).
2. G.L. Fogli *et al.*, `hep-ph/0506083`.