NEUTRINOLESS DOUBLE-β DECAY

Revised August 2013 by P. Vogel (Caltech) and A. Piepke (University of Alabama).

Neutrinoless double-beta ($0\nu\beta\beta$) decay would signal violation of 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, on the lepton-number violating right-handed current or other possible mechanisms mediating $0\nu\beta\beta$-decay can be obtained, independently of 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 is tension between that claim and several recent experiments which did not find evidence for $0\nu\beta\beta$ decay. In the following we assume that the exchange of light Majorana neutrinos ($m_{\nu_i} \leq 10$ 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 $\langle m_{\beta\beta}\rangle^2 = |\sum_i U^2_{ei} m_{\nu_i}|^2$. 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. There is only one phase if neutrinos are Dirac particles. The two additional Majorana phase differences 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, $\langle m_{\ell\ell'}\rangle = \sum_i U_{\ell i} U_{\ell' i} m_{\nu_i} (l \text{ or } l' \neq e)$. 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, the computation of $M^{0\nu}$ is subject to uncertainty. Comparing different nuclear model evaluations indicates a factor $\sim$2 to 3 spread in the calculated nuclear matrix elements. 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 some nuclear models (e.g. QRPA-based calculations), 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 mass hierarchy (*i.e.*, on the sign of Δm^2_{31}), the absolute neutrino mass values or the properties of neutrinos under CPT-conjugation (Dirac or Majorana).

All confirmed 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.* [1] yield: $|\Delta m^2_{31}| = 2.55^{+0.06}_{-0.09}$ $(2.43^{+0.07}_{-0.06}) \times 10^{-3}$ eV^2 and $\sin^2\theta_{23} = 0.613^{+0.022}_{-0.040}$ $(0.600^{+0.026}_{-0.031})$ for the parameters observed in atmospheric and accelerator experiments, where the values correspond to the normal (inverted) hierarchies. Observations of solar ν_e and reactor $\bar{\nu}_e$ lead to $\Delta m^2_{21} = 7.62^{+0.19}_{-0.19} \times 10^{-5}$ eV^2 and $\sin^2\theta_{12} = 0.320^{+0.016}_{-0.017}$. The investigation of reactor $\bar{\nu}_e$ at $\sim$1.5 km baseline shows that electron type neutrinos couple only weakly to the third mass eigenstate with $\sin^2\theta_{13} = 0.0246^{+0.0029}_{-0.0028}$ $(0.0250^{+0.0026}_{-0.0027})$. (All errors correspond to 1σ.)

Based on the 3-neutrino analysis: $\langle m_{\beta\beta}\rangle^2 = |\cos^2\theta_{13}\cos^2\theta_{12}m_1 + e^{i\Delta\alpha_{21}}\cos^2\theta_{13}\sin^2\theta_{12}m_2 + e^{i\Delta\alpha_{31}}\sin^2\theta_{13}m_3|^2$, 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 and Dirac 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 $m_{tot} = m_1 + m_2 + m_3$, constrained by observational cosmology. The oscillation data thus allow to test whether observed values of $\langle m_{\beta\beta} \rangle$ and m_{tot} are consistent within the 3 neutrino framework and the light neutrino-exchange dominance assumption. The right hand panel of Fig. 1, finally, shows $\langle m_{\beta\beta} \rangle$ as a function of the kinematical mass $\langle m_\beta \rangle = [\Sigma |U_{ei}|^2 m_{\nu_i}^2]^{1/2}$ determined through the analysis of the electron energy distribution in low energy beta decays. The rather large intrinsic width of the $\beta\beta$-decay constraint essentially does not allow to positively identify the inverted hierarchy, and thus the sign of Δm_{31}^2, even in combination with these other observables. Naturally, if the value of $\langle m_{\beta\beta} \rangle \leq 0.01$ eV, but non-zero is ever established then normal hierarchy becomes the only possible scenario.

It should be noted that systematic uncertainties of the nuclear matrix elements are not folded into the mass projections shown in Fig. 1. Taking this additional uncertainty into account would further widen the allowed areas. The uncertainties in oscillation parameters 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 $m \cos(2\theta_{12})$. 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_{ν_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_{ν_i} even when the mass differences Δm^2 are known.

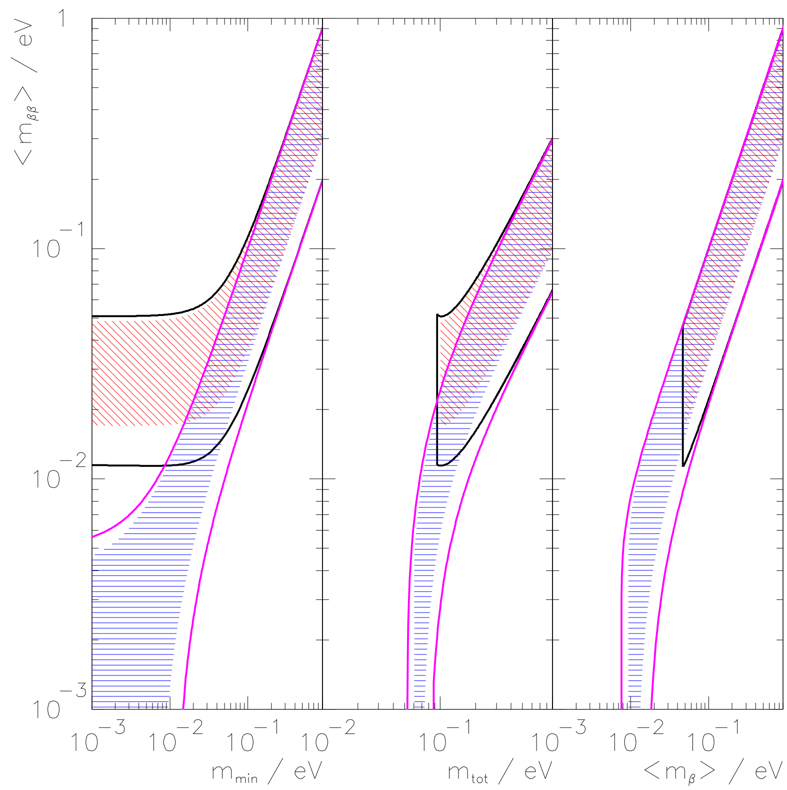

Figure 1: The left panel shows the dependence of $\langle m_{\beta\beta}\rangle$ on the absolute mass of the lightest neutrino m_{min}. The middle panel shows $\langle m_{\beta\beta}\rangle$ as a function of the summed neutrino mass m_{tot}, while the right panel depicts $\langle m_{\beta\beta}\rangle$ 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 (at the 3σ level [1]) . 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.

Neutrino oscillation data imply, for the first time, the existence of a lower limit ~ 0.013 eV for the Majorana neutrino mass for the inverted hierarchy mass pattern while $\langle m_{\beta\beta}\rangle$ could, by fine tuning, vanish in the case of the normal mass hierarchy. Several new double beta searches have been proposed to probe the interesting $\langle m_{\beta\beta}\rangle$ mass range, with the prospect of full coverage of the inverted mass hierarchy region within the next decade.

If lepton-number-violating right-handed current weak interactions exist, their strength can be characterized by the phenomenological coupling constants η and λ (η describes the coupling between the right-handed lepton current and left-handed quark current while λ describes the coupling when both currents are right-handed). 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. D.V. Forero, M. Tortola, and J.W.F. Valle, Phys. Rev. **D86**, 073012 (2012).