62. Neutrinoless Double-β Decay

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Observation of 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 a nonvanishing 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, by assuming that one of these "new physics" possibilities dominates. These limits are listed in the Double-β Decay Listings of the experimental measurements.

All suggested mechanism of the $0\nu\beta\beta$ decay (see-saw type I-III) explain, at the same time, the very small masses of the weakly interacting neutrinos by involving new energy scales Λ. The exchange of light Majorana neutrinos is the simplest of them, involving very high scale and Λ^{-2} suppression. In the following we assume that it contributes dominantly to the decay rate. By doing that it is easy to compare the sensitivities of different experiments. 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 then to the square of the effective Majorana mass $\langle m_{ee}\rangle$, $(T^{0\nu}_{1/2})^{-1} = G^{0\nu}\cdot|M^{0\nu}|^2\cdot\langle m_{ee}\rangle^2$, with $\langle m_{ee}\rangle^2 = |\sum_i U^2_{ei} m_{\nu_i}|^2$. Here U_{ei} are elements of the first row of the PMNS matrix (see the Neutrino Masses, Mixing, and Oscillation review). 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 relevant 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, $\langle m_{\ell\ell'}\rangle = \sum_i U_{\ell i} U_{\ell' i} m_{\nu_i} (\ell \text{ or } \ell' \neq e)$. However, these are currently much less constrained than $\langle m_{ee}\rangle$.

Nuclear structure calculations are needed to deduce $\langle m_{ee}\rangle$ from the decay rate. While $G^{0\nu}$ can be calculated accurately, the computation of $M^{0\nu}$ is subject to uncertainty. Comparing different nuclear model evaluations indicates a factor ∼2-3 spread in the calculated nuclear matrix elements. Nuclear structure calculation consistently overestimate Gamow-Teller (axial current) matrix elements. This inability of the nuclear models to reproduce Gamow-Teller decay rates is often parametrized in form of a modified coupling constant g_A. Many nuclear theorists interpret this shortcoming as evidence that important physics is missing in the modeling of weak nuclear transitions. It is not clear how these observed uncertainties impact $0\nu\beta\beta$-matrix elements. Nevertheless, this constitutes an additional element of uncertainty. Recent work, [1] shows how the discrepancy between experimental and theoretical axial current matrix elements in β decay might be resolved. However, application of this approach to the $0\nu\beta\beta$ decay remains to be accomplished. 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 conventional $2\nu\beta\beta$ decay serve to constrain the nuclear theory models, and the $2\nu\beta\beta$ decay represents an irreducible background in the $0\nu\beta\beta$ decay search, results for this process are also given.

Oscillation experiments utilizing atmospheric, accelerator, solar, and reactor produced neutrinos and anti-neutrinos show that at least two out of three neutrinos are massive. However, these findings so far shed no light on the mass ordering (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. (For values of the mixing angles and mass square differences see the corresponding tables.)

Based on the 3-neutrino analysis: $\langle m_{ee}\rangle^2 = |\cos^2\theta_{13}\cos^2\theta_{12}m_1 + e^{i\Delta\alpha_{21}}\cos^2\theta_{13}\sin^2\theta_{12}m_2 + e^{i\Delta\alpha_{31}}\sin^2\theta_{13}m_3|^2$, with $\Delta\alpha_{21}, \Delta\alpha_{31}$ denoting the physically relevant Majorana CP-phase differences (the possible Dirac phase δ is absorbed in these $\Delta\alpha$). Given the present knowledge of the neutrino oscillation parameters one can derive a relation between the effective Majorana mass and the mass of the lightest neutrino, as illustrated in Figure 14.9 in the Neutrino Oscillation review. The three mass orderings 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 colored bands reflects the uncertainty introduced by the unknown Majorana and Dirac phases as well as the experimental errors of the oscillation parameters. The latter causes only minor broadening of the bands. Because of the overlap of the different mass scenarios, a measurement of $\langle m_{ee}\rangle$ would not reveal the mass ordering, provided the value of $\langle m_{ee}\rangle$ is in the overlapping range.

Analogous plots depict the relation of $\langle m_{ee}\rangle$ with the summed neutrino mass $m_{tot} = m_1 + m_2 + m_3$, constrained by observational cosmology, and $\langle m_{ee}\rangle$ as a function of the mass value $\langle m_\beta\rangle = [\Sigma|U_{ei}|^2 m_{\nu_i}^2]^{1/2}$ determined through the analysis of the electron energy distribution in low energy beta decays. (See Fig. 1 of [2].) The oscillation data thus allow one to test whether observed values of $\langle m_{ee}\rangle$ and m_{tot} or $\langle m_\beta\rangle$ are consistent within the 3 neutrino framework. However, the rather large intrinsic width of the $\beta\beta$-decay constraints essentially does not allow one to positively identify the inverted mass ordering, and thus the sign of Δm^2_{31}, even in combination with these other observables. Naturally, if a value of $0 < \langle m_{ee}\rangle \leq 0.01$ eV is ever established in the light Majorana exchange scenario, then the normal mass ordering becomes the only possibility.

It should be noted that systematic uncertainties of the nuclear matrix elements and possible quenching of the axial current matrix elements are sometimes not folded into the mass limits reported by $\beta\beta$-decay experiments. Taking this additional uncertainty into account would further widen the projections. The plots are based on a 3-neutrino analysis. If it turns out that additional, i.e. sterile light neutrinos exist, the allowed regions would be modified substantially.

If 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 $\langle m_{ee}\rangle$ does not allow one to constrain the individual mass values m_{ν_i} even when the mass differences Δm^2 are known.

Neutrino oscillation data imply the existence of a lower limit ~ 0.014 eV for the Majorana neutrino mass for the inverted mass ordering pattern, while $\langle m_{ee}\rangle$ could, by fine tuning, vanish in the case of the normal mass ordering. Several new double-beta searches have been proposed to probe the interesting $\langle m_{ee}\rangle$ mass range, with the prospect of full coverage of the inverted mass ordering region within the next decade.

The $0\nu\beta\beta$ decay mechanism discussed so far is not the only way in which the decay can occur. Numerous other possible scenarios have been proposed, however, all of them requiring not only new physics but also existence of new, so far unobserved, particles. It will be a challenging task to decide which mechanism was responsible once $0\nu\beta\beta$ decay is observed. LHC experiments may reveal corresponding signatures for new physics of lepton number violation. If lepton-number violating right-handed weak current interactions exist, its 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). The observation of the single electron spectra could, in principle, allow us to distinguish this mechanism of $0\nu\beta\beta$ from the light Majorana neutrino exchange driven mode. 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] P. Gysbers *et al.*, Nature Phys. **15**, 5, 428 (2019), [arXiv:1903.00047].

[2] M. J. Dolinski, A. W. P. Poon and W. Rodejohann, Annu. Rev. Nucl. Part. Sci. **69**, 219 (2019), [arXiv:1902.04097].