LIMITS FROM NEUTRINOLESS DOUBLE-β DECAY

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Neutrinoless double-beta decay, if observed, would signal violation of the total lepton number conservation. The process can be mediated by an exchange of light Majorana neutrino, or by an exchange of other particles. As long as only a limit on its lifetime is available, limits on the effective Majorana neutrino mass, and on the lepton-number violating right-handed current admixture can be obtained, independently on the actual mechanism. These are considered in the following three tables.

At present there is a strong evidence that neutrinos oscillate, i.e. that at least some neutrinos are massive (although one cannot decide whether the mass is Majorana or Dirac). In particular, the atmospheric neutrino anomaly implies $\Delta m^2 \sim 3 \times 10^{-3}$ eV^2 and hence sets the scale of possible neutrino masses at $\sim 5 \times 10^{-2}$ eV. It is likely that the search for neutrinoless double-beta decay will reach sensitivity to this scale in a foreseeable future.

If the exchange of a massive Majorana neutrino is the mechanism responsible for neutrinoless double-beta decay, the decay rate is proportional to the square of the "effective Majorana mass" $\langle m_\nu \rangle^2 = | \sum_i U_{ei}^2 m_{\nu_i} |^2$, where the sum is over all masses $m_{\nu_i} \lesssim 10$ MeV. This sum contains, in general, complex numbers, *i.e.* cancelations may occur due to the CP phases in U_{ei}^2. These phases are peculiar to massive Majorana neutrinos, and affect only total lepton number violating processes. If and when neutrinoless double-beta decay is observed, it will make it therefore possible (assuming still that the Majorana mass is responsible for the decay) to fix a *range* of absolute values of the masses m_{ν_i}. However, if at the same time the direct neutrino mass measurements, *e.g.* in beta decay, yield a positive result, one can learn something about the otherwise inaccessible CP phases. Unlike the direct neutrino mass measurements, however, a limit on $\langle m_\nu \rangle$ does not allow one to constrain the individual mass values m_{ν_i} (even when the mass differences Δm^2 are known).

The derived quantities are dependent on the nuclear model, so the half-life measurements are given first. Where possible, we list the references for the nuclear matrix elements used in the subsequent analysis. Since rates for the more conventional $2\nu\beta\beta$ decay serve to calibrate the theory, results for this process are also given. As an indication of the spread among different ways of evaluating the matrix elements, we show in Fig. 1 some representative examples for the most popular nuclei. The rates, $1/T_{1/2}$, are plotted so that the most favorable cases appear tallest.

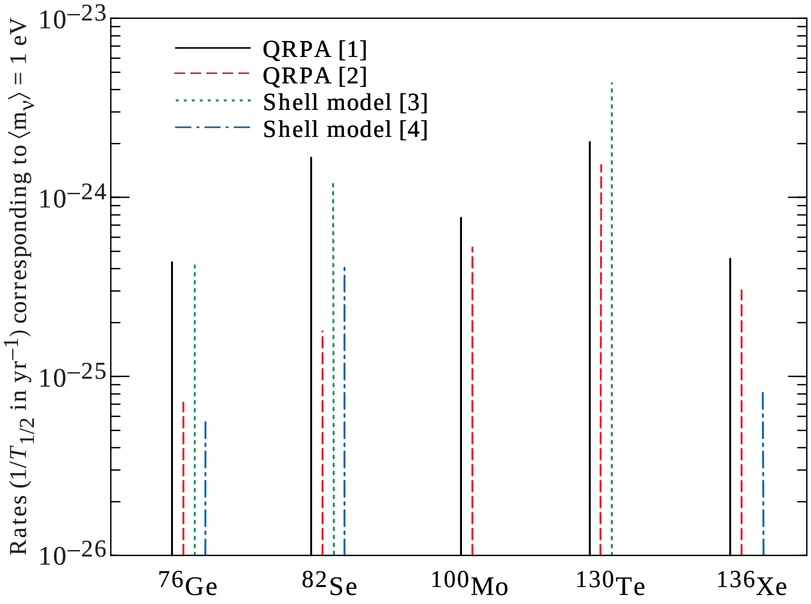

Figure 1: Decay rates (in yr^{-1}) calculated for $\langle m_\nu \rangle = 1$ eV by various representative methods and different authors for the most popular double-beta decay candidate nuclei. The QRPA results from Ref. 2 are recalculated for $g_A = 1.25$ and $\alpha' = -390$ MeV fm^3.

To define the limits on lepton-number violating right-handed current admixtures, we display the relevant part of a phenomenological current-current weak interaction Hamiltonian:

$$\begin{aligned} H_W =& (G_F/\sqrt{2}) \\ & \times (J_L \cdot j_L^\dagger + \kappa J_R \cdot j_L^\dagger + \eta J_L \cdot j_R^\dagger + \lambda J_R \cdot j_R^\dagger) + \text{h.c.} \end{aligned} \quad (1)$$

where $j_L^\mu = \bar{e}_L\gamma^\mu\nu_{eL}$, $j_R^\mu = \bar{e}_R\gamma^\mu\nu_{eR}$, and J_L^μ and J_R^μ are left-handed and right-handed hadronic weak currents. Experiments are not sensitive to κ, but quote limits on quantities proportional to η and λ.In analogy to $\langle m_\nu \rangle$ (see Eq. 17 in "Neutrino mass" minireview at the beginning of the 2000 Neutrino Particle Listings), the quantities extracted from experiments are $\langle\eta\rangle = \eta\sum U_{ej}V_{ej}$ and $\langle\lambda\rangle = \lambda\sum U_{ej}V_{ej}$, where $V_{\ell j}$ is a matrix analogous to $U_{\ell j}$ (see Eq. 2 in the "Neutrino mass" from the 2000 edition), but describing the mixing among right-handed neutrinos. The quantities $\langle\eta\rangle$ and $\langle\lambda\rangle$ therefore vanish for massless or unmixed neutrinos. Also, as in the case of $\langle m_\nu \rangle$, cancelations are possible in $\langle\eta\rangle$ and $\langle\lambda\rangle$. 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 warned that a number of earlier experiments did not distinguish between η and λ. Because of evolving reporting conventions and matrix element calculations, we have not tabulated the admixture parameters for experiments published earlier than 1989.

See the section on Majoron searches for additional limits set by these experiments.

Very recently, a reanalysis of a subset of data collected by the Heidelberg-Moscow collaboration was interpreted as evidence for the neutrinoless $\beta\beta$ decay of ^{76}Ge [5]. The statistical significance of the claim is 2.2–3.1 σ depending on the analysis method. Provided that the finding withstands further scrutiny, or better yet, is independently confirmed, the deduced half-life of $1.9^{+16.8}_{-0.7} \times 10^{25}$y implies that $\langle m_\nu \rangle = 0.39^{+0.17}_{-0.28}$ eV for the nuclear matrix elements used in Ref. 5 and $\langle m_\nu \rangle \approx 0.4$–$1.3$ eV for the range of nuclear matrix elements discussed above. This extraordinary claim would imply, in turn, that $\langle m_\nu \rangle \gg \sqrt{\Delta m^2}$, where the quantities Δm^2 are based on the atmospheric and solar neutrino oscillation results.

References

1. A. Staudt, K. Muto, and H.V. Klapdor-Kleingrothaus, Europhys. Lett. **13**, 31 (1990).
2. J. Engel, P. Vogel, and M.R. Zirnbauer, Phys. Rev. **C37**, 731 (1988).

3. W.C. Haxton and G.J. Stephenson Jr., Prog. in Part. Nucl. Phys. **12**, 409 (1984).
4. E. Caurier *et al.*, Phys. Rev. Lett. **77**, 1954 (1996).
5. H.V. Klapdor-Kleingrothaus *et al.*, Mod. Phys. Lett. **16**, 2409 (2001).