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# Theoretical bounds for majoron emission from nuclear double-beta decay processes

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**Abstract.** Theoretical upper limits for the neutrino–majoron coupling constant, $g$, are extracted from a systematic calculation of neutrinoless double-beta decay rates for transitions in $^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{128}$Te, $^{130}$Te and $^{136}$Xe. The nuclear wavefunctions which we have used to compute the theoretical bounds on $g$ have been tested in calculations involving two-neutrino and neutrinoless double-beta decay rates. The resulting value is of the order of $g \approx 10^{-4}$, in good agreement with recently reported data by the Heidelberg–Moscow–LNGS collaboration.

Violation of lepton-number symmetry in the context of weak interactions [1–6] makes neutrino–majoron coupling possible. The majoron, i.e. the massless Goldstone boson associated with the spontaneous symmetry breaking of the baryon minus lepton number conservation (B−L), has been described recently in terms of a weak-isospin-singlet representation [7]. Previous attempts, such as triplet [2] and doublet [3,4] majoron models, have been excluded by recent LEP data [8]. The LEP data are consistent with $N_g = 2.99 \pm 0.01$ lepton flavours. One possibility of accounting for the breaking of the B–L symmetry is to consider it as a global symmetry breaking of the $U(1)_{\mathrm{B-L}}$ (global) added to the $SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}}$ groups. This alternative does not bring any new lepton flavours and is not ruled out *a priori* by LEP data.

As shown in [7], the singlet–majoron model could contribute to neutrinoless double-beta decay. In the model of [7] the ratio between decay rates with, and without, majoron emission, for neutrinoless double-beta decay, has been computed as a function of the scale, $v$, of the symmetry breaking. This scale factor is furthermore related to the neutrino–majoron coupling constant, $g$, and to the electron–neutrino mass, $m$, through the relation $g = m/v$, which is valid if only one neutrino flavour is considered. This definition can be extended to account for three neutrino flavours by replacing $g$ and $m$ by their corresponding averaged values, $\langle g \rangle$ and $\langle m \rangle$, as introduced below. As argued in [7], to get a significant contribution to neutrinoless double-beta decay, the scale factor $v$ has to be in the range 10–100 keV or smaller. *This estimate is based on the approximations used to evaluate the neutrino mass*, as well as the proposed form of the coupling between majorons and neutrinos.

The significance of majoron emission for double-beta decay processes is evident since, with this expected value for the scale of the global $U(1)_{\mathrm{B-L}}$ symmetry breaking, the neutrinos can be massive ($m \approx gv$) and can be coupled to majorons ($J$) and to the scalar boson ($\rho$) which is the majoron partner [7]. Therefore, for some values of the coupling constant ($g$) the contribution of majoron–neutrino couplings to the neutrinoless double-beta

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decay can compete with the contribution coming from a majorana mass term and left–right and right–right interactions (if one goes beyond the standard $SU(2)_L \times U(1)_Y$ model).

Concerning the nuclear-structure component of the problem, it can be shown [9] that the same nuclear matrix elements are needed to compute neutrinoless double-beta decay rates with, and without, majoron emission. The ratio between the decay rates, $\Gamma_{\beta\beta}^{(0\nu)}/\Gamma_{\beta\beta}^{(0\nu M)}$, can be written independently of the nuclear matrix elements involved ($M_{GT}$ and $M_F$ in the commonly adopted approximation [9]). The point is that, in accordance with the data from [23], neutrinoless double-beta decay transitions, if observed, can be dominated by the emission of scalar majorons ($\rho + iJ$). This mechanism yields, approximately, $t_{1/2}^{(0\nu M)} \approx 10^{-2} t_{1/2}^{(0\nu)}$ [23].

The Lagrangian introduced in [7] allows for the computation of decay rates starting from the calculation of the relevant nuclear matrix elements and phase-space factors [9]. The Lagrangian in [7] is independent of the specifics of the majoron model and it can be expressed in the form:

$$L_g = \frac{1}{2} \sum_{jk} g_{jk} \bar{N}_j \ (\rho + iJ) N_k. \tag{1}$$

In writing (1) we have already expressed the coupling of the scalar field $(\rho + iJ)$ from [7] with different majorana neutrinos $N_j$ and $N_k$ by $g_{jk}$ . In this fashion the coupling constant $g$ from [7] has been replaced by $g_{jk}$. Decay rates for double-beta decay, starting with this Lagrangian, have the form given by [9]. In deriving the corresponding expression we have kept leading-order terms in powers of $1/(q + k)^2$, $k$ being the majoron momentum and $q$ being the neutrino momentum.

The estimation by Berezhiani *et al* [7] of the neutrino–majoron coupling constant $g$ is based on nuclear-structure calculations of double-beta decay rates and on the corresponding extracted values for the averaged neutrino mass. These calculations have been performed with schematic nucleon–nucleon forces [10] and using closure and parametrized forms for neutrino potentials [11]. Although these nuclear-structure results suffice for a first estimate of $g$, it is necessary to confirm the findings of [7] starting from more realistic nuclear-structure calculations.

In this work we aim to set limits to the neutrino–majoron coupling strength from microscopic calculations of neutrinoless nuclear double-beta decay processes. In the following we describe the main elements entering the present calculations.

The nuclear matrix elements have been calculated using the formalism of [12] deriving the transition operators from the quark level and using a realistic nucleon–nucleon $G$-matrix. The corresponding two-body interaction has been renormalized to take into account the finite size of the model space where the calculations are performed. The closure approximation was abandoned and the transition operators were treated dynamically without resorting to the commonly adopted static limit [9]. At this point our nuclear-structure model and the description of the beta-decay form factors and transition densities differ from the ones of [7] and [23].

The correctness of the procedure concerning the nuclear-structure part of the calculation has already been tested in the two-neutrino double-beta decay case [13]. The predicted half-life ratio $t_{1/2}^{(2\nu)}(^{130}\mathrm{Te})/t_{1/2}^{(2\nu)}(^{128}\mathrm{Te}) = 4.8 \times 10^{-4}$ agrees nicely with data [14]. Also the predicted value for the half-life of the decay from $^{76}$Ge agrees with the data obtained by Avignone *et al* [15].

These are very sensitive tests for the wavefunctions, since a strong suppression of the nuclear matrix elements is needed to reproduce the data, but, at the same time, a nuclear mass dependence of the matrix elements is required in order to account for the ratio between decay rates of neighbouring nuclei. For further details of the nuclear-structure assumptions which we have adopted the reader is referred to [12, 16].

The half-life expression, written for ground-state-to-ground-state transitions, reads

$$[t_{1/2}^{(0\nu M)}(0^+ \to 0^+)]^{-1} = |\langle g\rangle|^2 (M_m^{(s)})^2 G_B. \tag{2}$$

It contains the phase-space integral $G_B$ [9] and the nuclear-structure information resides in the matrix element $M_m^{(s)}$ [12]. The quantity $\langle g\rangle$ of (2) is the effective majoron–neutrino coupling constant averaged over light-neutrino generations [9]. The previous approximation schemes of [7] and [23] are based on the use of closure and neutrino potentials and the substitution $M_m^{(s)} \to M_{GT} - M_F$ is made.

Table 1 shows the calculated values of the nuclear matrix element $M_m^{(s)}$ for transitions where the lower limit of the half-life of the majoron emission can be estimated experimentally. Using the experimental lower limit of the half-life in (2) one can give an estimate of the effective neutrino–majoron coupling strength. The resulting upper limits of $|\langle g\rangle|$ are given in the last column of table 1.

**Table 1.** Values for the effective neutrino–majoron coupling constant, $\langle g\rangle$, extracted from experimental half-lives, $t_{1/2}^{(0\nu M)}$, are listed. Theoretical nuclear matrix elements and phase-space factors are denoted by $M_m^{(s)}$ and $G_B$, respectively (see equation (2)).

| Nucleus | $G_B$ | $\lvert M_m^{(s)}\rvert$ | $(t_{1/2}^{(0\nu M)})\,\exp[y]$ | $\lvert\langle g\rangle\rvert$ |
|---|---|---|---|---|
| $^{48}$Ca | $1.97 \times 10^{-15}$ | 0.68 | $> 7.2 \times 10^{20}$ [a] | $< 8.5 \times 10^{-4}$ |
| $^{76}$Ge | $6.02 \times 10^{-17}$ | 1.40 | $> 1.7 \times 10^{22}$ [b] | $< 5.0 \times 10^{-4}$ |
| $^{82}$Se | $4.94 \times 10^{-16}$ | 1.37 | $> 4.4 \times 10^{20}$ [c] | $< 1.1 \times 10^{-3}$ |
| $^{128}$Te | $4.91 \times 10^{-18}$ | 1.43 | $> 7.7 \times 10^{24}$ [d] | $< 7.8 \times 10^{-5}$ |
| $^{130}$Te | $6.48 \times 10^{-15}$ | 1.42 | $> 1.5 \times 10^{21}$ [e] | $< 5.0 \times 10^{-4}$ |
| $^{136}$Xe | $6.74 \times 10^{-16}$ | 1.40 | $> 7.2 \times 10^{21}$ [f] | $< 2.3 \times 10^{-4}$ |

[a] [17], [b] [18], [c] [19], [d] [20], [e] [21], [f] [22].

The values in table 1 do in fact confirm the result of [7]. The most stringent limit, $|\langle g\rangle| < 7.8 \times 10^{-5}$, is provided by the decay $^{128}\mathrm{Te} \to {}^{128}\mathrm{Xe}$. For the cases which we have reported here the theoretical bound on the electron–neutrino mass has been found to be of the order of $\langle m_\nu\rangle < 2$–$3$ eV [12, 16].

The above results support the conclusions of [7] concerning the competition between neutrinoless double-beta decay channels with and without majoron emission. Therefore, as stated in [7], majoron emission may not only constitute an important component of the background but, additionally, it can shift the end point of the electron sum energy spectrum.

This statement seems to be confirmed, for the first time, by the results produced by the Heidelberg–Moscow–Gran Sasso collaboration [23], which has set the bounds for $\langle g\rangle$ (of the order of $10^{-4}$) starting from the counting of events in the $^{76}$Ge transition for sum-electron energies in the range 600 to 2000 keV. In this energy domain, majoron emission would yield a half-life of the order of $t_{1/2}^{(0\nu M)} \approx 1.66 \times 10^{22}$ yr [23].

In conclusion we have shown that the results of [7] are indeed supported by realistic nuclear-structure calculations of neutrinoless double-beta decay processes. The scale factor of the lepton symmetry breaking, $\nu$, extracted from our present results is of the order of 20 keV. This value is in the range of values allowing a detectable majoron signal [7, 23]. Consequently the present value for the upper limit of the effective neutrino–majoron coupling strength is of the order of $10^{-4}$.

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