Limits on Neutrino Masses from Neutrinoless Double-β Decay

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Neutrinoless double-β decay is of fundamental importance for the determining neutrino mass. By combining a calculation of nuclear matrix elements within the framework of the microscopic interacting boson model with an improved calculation of phase space factors, we set limits on the average light neutrino mass and on the average inverse heavy neutrino mass (flavor-violating parameter).

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The process $0\nu\beta\beta$ in which a nucleus X is transformed into a nucleus Y with the emission of two electrons and no neutrinos, ${}^{Z}_{A}X_N \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^-$, is of fundamental importance for determining the Majorana, or Dirac, nature of the neutrino and confirming a nonzero value of its mass as established by neutrino oscillation experiments [1–3], which constitutes physics beyond the standard model. The half-life for this process can be written as

$$[\tau_{1/2}^{(0\nu)}]^{-1} = G_{0\nu}|M_{0\nu}|^2|f(m_i, U_{ei})|^2, \tag{1}$$

where $G_{0\nu}$ is a phase space factor (PSF), $M_{0\nu}$ is the nuclear matrix element (NME), and f contains physics beyond the standard model through the masses m_i and elements U_{ei} of the mixing matrix of the neutrino (or other hypothetical particle beyond the standard model). We have recently (i) introduced a new method [4], the microscopic interacting boson model (IBM-2), to calculate the NME in a consistent way for all nuclei of interest and (ii) improved the calculation of the phase space factors (PSF) by solving the Dirac equation for the outgoing electrons in the presence of a charge distribution and including electron screening [5]. In this Letter, we present results of a calculation that combines the NMEs and the PSFs to half-lives. By comparing with current experimental limits we then set limits on neutrino masses and their couplings.

Starting from the weak Lagrangian, $\mathcal{L}$, one can derive the transition operator inducing the decay, which, under certain circumstances, can be factorized as $T(p) = H(p)f(m_i, U_{ei})$, where $p = |\vec{q}|$ is the momentum transferred to the leptons [6–8]. The transition operator $H(p)$ has the form

$$H(p) = \tau_n^\dagger \tau_{n'}^\dagger[-h^F(p) + h^{GT}(p)\vec{\sigma}_n \cdot \vec{\sigma}_{n'} + h^T(p)S^p_{nn'}]. \tag{2}$$

The factors $h^{F,GT,T}(p)$ are given by $h^{F,GT,T}(p) = v(p)\tilde{h}^{F,GT,T}(p)$, where $v(p)$ is called the neutrino "potential" and $\tilde{h}(p)$ are the form factors, listed in Ref. [8]. This form assumes the closure approximation which is expected to be good a approximation for $0\nu\beta\beta$ decay [9,10], since the neutrino momentum is of the order of 100 MeV/c while the energy scale of the nuclear excitations is 1 MeV, and all multipoles in the intermediate odd-odd nucleus contribute to the decay. (Conversely, the approximation is not expected to be good for $2\nu\beta\beta$ decay, where the neutrino momentum is of order 2 MeV/c, and only 1^+ and 0^+ states in the intermediate odd-odd nucleus contribute to the decay). The finite nucleon size is taken into account by taking the coupling constants momentum dependent and short range correlations (SRC) into account by convoluting $v(p)$ with the correlation function $J(p)$ taken as a Jastrow function. The functions $f(m_i, U_{ei})$ and $H(p)$ depend on the model of $0\nu\beta\beta$ decay. Here, we explicitly consider two cases: (i) the emission and reabsorption of a light ($m_{\text{light}} \ll 1$ keV) neutrino and (ii) the emission and reabsorption of a heavy ($m_{\text{heavy}} \gg 1$ GeV) neutrino. For scenario (i), the function f can be written as

$$f = \frac{\langle m_\nu \rangle}{m_e}, \qquad \langle m_\nu \rangle = \sum_{k=\text{light}} (U_{ek})^2 m_k, \tag{3}$$

where U is the neutrino mixing matrix. The average neutrino mass is given in terms of mixing angles and phases [11] and is constrained by atmospheric, solar, and neutrino oscillation experiments. The potential $v(p)$ for this case is $v(p) = 2\pi^{-1}[p(p + \tilde{A})]^{-1}$ where $\tilde{A}$ is the so-called closure energy. For scenario (ii), the transition operator can be written as $T_h(p) = H_h(p)f_h(m_i, U_{ei})$, where the index h refers to heavy. The function f_h can be written as

$$f_h = m_p\left\langle\frac{1}{m_h}\right\rangle, \qquad \left\langle\frac{1}{m_h}\right\rangle = \sum_{k=\text{heavy}} (U_{ek_h})^2 \frac{1}{m_{k_h}}. \tag{4}$$

The neutrino potential is $v_h(p) = 2\pi^{-1}(m_e m_p)^{-1}$. The function f_h is often written as η and called the flavor-violating parameter. The average inverse heavy neutrino mass has, in the past, been considered as an unconstrained parameter. However, recently, it has been suggested [12] that some constraints can be put on this quantity from large hadron collider (LHC) physics and lepton flavor violating processes. The effect of heavy neutrinos on neutrinoless double-β decay has been illustrated within the context of a

TABLE I. Neutrinoless double-β decay matrix elements $M^{(0\nu)}$ in IBM-2 with Argonne CCM SRC and $g_A = 1.269$, in QRPA with Argonne CCM SRC and $g_A = 1.254$, and ISM with UCOM SRC and $g_A = 1.25$.

A	IBM-2	QRPA[a]	ISM[b]
48	2.28		0.85
76	5.98	5.81	2.81
82	4.84	5.19	2.64
96	2.89	1.90	
100	4.31	4.75	
110	4.15		
116	3.16	3.54	
124	3.89		2.62
128	4.97	4.93	2.88
130	4.47	4.37	2.65
136	3.67	2.78	2.19
148	2.36		
150	2.74		
154	2.91		
160	4.17		
198	2.25		

[a]Ref. [15].
[b]Ref. [16].

specific model as a function of the mass of the lightest heavy neutrino in the range 1–500 GeV.

We have calculated the nuclear matrix elements within the framework of the microscopic interacting boson model, IBM-2 [13], in all nuclei of interest. Details of the calculation are given in Ref. [4] and in a forthcoming long publication [14]. Matrix elements $M^{(0\nu)}$ for light neutrino exchange are shown in Table I and Fig. 1, where they are compared with those calculated with other methods, most notably QRPA [15] and ISM [16] with the same (or similar) approximations for the SRC. We note, both in Table I and Fig. 1, a close correspondence between the IBM-2 and QRPA calculations, while the ISM results are approximately a factor of 2 smaller than IBM-2/QRPA. (The origin of the difference is not completely clear. The three models make different approximations and at different levels. A recent combined analysis of $0\nu\beta\beta$ and $2\nu\beta\beta$ decay [14] seems to indicate that the main difference is the size of the model space in which the calculations are done. This is substantiated by the observation that the behavior with mass number of all three calculations is similar and that they can be reconciled by a simple renormalization). Matrix elements $M_h^{(0\nu)}$ for heavy neutrino exchange are shown in Table II. By combining the matrix elements with the phase space factors of Ref. [5], we obtain the expected half-lives shown in Table III, left, and Fig. 2 for light neutrino exchange and Table IV, left, for heavy neutrino exchange. It should be noted that the combination must be done consistently. If the phase space factors of Ref. [5] are used, the nuclear matrix elements $M^{(0\nu)}$ of Tables I and II must be multiplied by g_A^2, that is $M_{0\nu} = g_A^2 M^{(0\nu)}$ in Eq. (1).

Using the experimental upper limits from a compilation of Barabash [18], the IBM-2 matrix elements of Tables I and II and the phase space factors of [5], we estimate current limits on the neutrino mass given in Tables III, right, and Table IV, right, which are the main results of this Letter. In Table IV, we give limits both on the flavor-violating parameter η and on the average heavy neutrino mass, defined as $\langle m_{\nu_h}\rangle/m_p = (M_W^4/M_{WR}^4)\eta^{-1}$, where $M_W = 80.41 \pm 0.10$ GeV and M_{WR} is assumed to be $M_{WR} = 3.5$ TeV. While the former is model independent, the latter depends on the model of left-right mixing [12].

These results are obtained using the free value of the axial vector coupling constant as obtained from neutron decay, $g_A = 1.269$. It is known from single β decay and $2\nu\beta\beta$ decay that g_A is renormalized in nuclei. There are

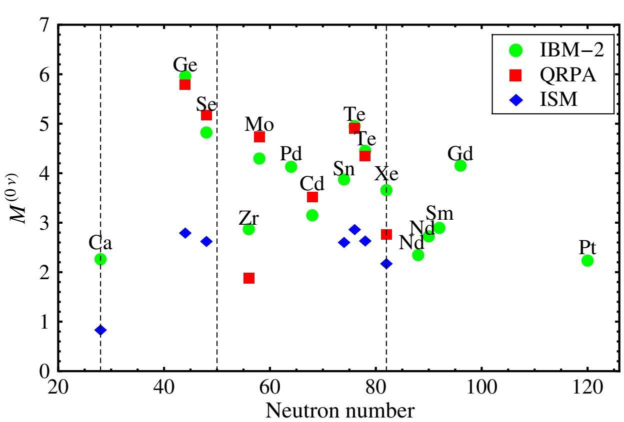

FIG. 1 (color online). Nuclear matrix elements $M^{(0\nu)}$ for $0\nu\beta\beta$ decay in IBM-2 compared with QRPA [15] and ISM [16].

TABLE II. Neutrinoless double-β decay matrix elements $M_h^{(0\nu)}$ in IBM-2 with Argonne CCM SRC and $g_A = 1.269$, and in QRPA with Argonne CCM SRC, $g_A = 1.25$ and intermediate size for the model space.

A	IBM-2	QRPA[a]
48	46.3	
76	107	233
82	84.4	226
96	99.0	
100	165	250
110	155	
116	110	
124	79.6	
128	101	
130	92.0	234
136	72.8	
148	103	
150	116	
154	113	
160	155	
198	104	

[a]Ref. [17].

TABLE III. Left: Calculated half-lives in IBM-2 for neutrinoless double-β decay for $\langle m_\nu \rangle = 1$ eV and $g_A = 1.269$. Right: Upper limit on neutrino mass from current experimental limit from a compilation of Barabash [18]. The value reported by Klapdor-Kleingrothaus *et al.* [19], the limit from IGEX [20], and the recent limits from KamLAND-Zen [21] and EXO [22] are also included.

Decay	$\tau_{1/2}^{0\nu}(10^{24}$ yr)	$\tau_{1/2,\mathrm{exp}}^{0\nu}$(yr)	$\langle m_\nu \rangle$(eV)
^{48}Ca → ^{48}Ti	0.782	$>5.8 \times 10^{22}$	<3.7
^{76}Ge → ^{76}Se	1.19	$>1.9 \times 10^{25}$	<0.25
		1.2×10^{25} [a]	0.32
		$>1.6 \times 10^{25}$ [b]	<0.27
^{82}Se → ^{82}Kr	0.423	$>3.6 \times 10^{23}$	<1.1
^{96}Zr → ^{96}Mo	0.588	$>9.2 \times 10^{21}$	<8.0
^{100}Mo → ^{100}Ru	0.340	$>1.1 \times 10^{24}$	<0.56
^{110}Pd → ^{110}Cd	1.22		
^{116}Cd → ^{116}Sn	0.602	$>1.7 \times 10^{23}$	<1.9
^{124}Sn → ^{124}Te	0.737		
^{128}Te → ^{128}Xe	6.94	$>1.5 \times 10^{24}$	<2.2
^{130}Te → ^{130}Xe	0.355	$>2.8 \times 10^{24}$	<0.36
^{136}Xe → ^{136}Ba	0.512	$>5.7 \times 10^{24}$ [c]	<0.30
		$>1.6 \times 10^{25}$ [d]	<0.18
^{148}Nd → ^{148}Sm	1.79		
^{150}Nd → ^{150}Sm	0.213	$>1.8 \times 10^{22}$	<3.4
^{154}Sm → ^{154}Gd	3.94		
^{160}Gd → ^{160}Dy	0.606		
^{198}Pt → ^{198}Hg	2.64		

[a] Ref. [19].
[b] Ref. [20].
[c] Ref. [21].
[d] Ref. [22].

two reasons for the renormalization: (i) the limited model space within which the calculation of the NME is done and (ii) the omission of non-nucleonic degrees of freedom ($\Delta, N^*, \ldots$). Since the coupling constant g_A appears to the fourth power in the lifetime, the renormalization effect is non-negligible, and it will amount to a multiplication of

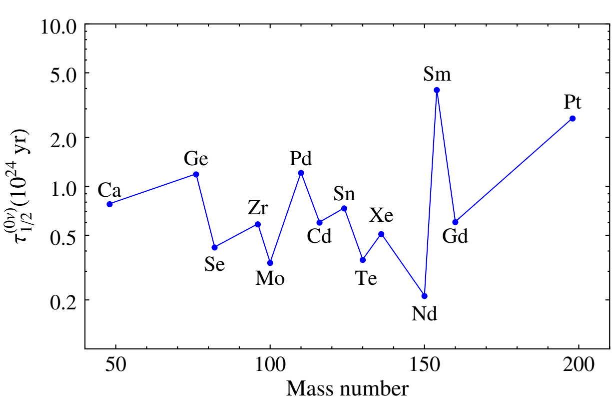

FIG. 2 (color online). Expected half-lives for $\langle m_\nu \rangle = 1$ eV, $g_A = 1.269$. The points for ^{128}Te and ^{148}Nd decays are not included in this figure. The figure is in semilogarithmic scale.

TABLE IV. Left: Calculated half-lives for neutrinoless double β decay with exchange of heavy neutrinos for $\eta = 2.75 \times 10^{-7}$ and $g_A = 1.269$. Right: Upper limits of $|\eta|$ and lower limits of heavy neutrino mass (see text for details) from current experimental limit from a compilation of Barabash [18]. The value reported by Klapdor-Kleingrothaus *et al.* [19], the limit from IGEX [20], and the recent limits from KamLAND-Zen [21] and EXO [22] are also included.

Decay	$\tau_{1/2}^{0\nu_h}(10^{24}$ yr)	$\tau_{1/2,\mathrm{exp}}^{0\nu_h}$(yr)	$\lvert\eta\rvert(10^{-7})$	$\langle m_{\nu_h} \rangle$(GeV)
^{48}Ca → ^{48}Ti	0.096	$>5.8 \times 10^{22}$	<3.54	>0.73
^{76}Ge → ^{76}Se	0.190	$>1.9 \times 10^{25}$	<0.275	>9.4
		1.2×10^{25} [a]	0.346	7.5
		$>1.6 \times 10^{25}$ [b]	<0.300	>8.6
^{82}Se → ^{82}Kr	0.070	$>3.6 \times 10^{23}$	<1.22	>2.1
^{96}Zr → ^{96}Mo	0.025	$>9.2 \times 10^{21}$	<4.56	>0.6
^{100}Mo → ^{100}Ru	0.012	$>1.1 \times 10^{24}$	<0.285	>9.1
^{110}Pd → ^{110}Cd	0.044			
^{116}Cd → ^{116}Sn	0.025	$>1.7 \times 10^{23}$	<1.06	>2.5
^{124}Sn → ^{124}Te	0.089			
^{128}Te → ^{128}Xe	0.846	$>1.5 \times 10^{24}$	<2.07	>1.2
^{130}Te → ^{130}Xe	0.042	$>2.8 \times 10^{24}$	<3.38	>7.6
^{136}Xe → ^{136}Ba	0.066	$>5.7 \times 10^{24}$ [c]	<0.296	>8.7
		$>1.6 \times 10^{25}$ [d]	<0.177	>14.6
^{148}Nd → ^{148}Sm	0.048			
^{150}Nd → ^{150}Sm	0.006	$>1.8 \times 10^{22}$	<1.58	>1.6
^{154}Sm → ^{154}Gd	0.132			
^{160}Gd → ^{160}Dy	0.022			
^{198}Pt → ^{198}Hg	0.063			

[a] Ref. [19].
[b] Ref. [20].
[c] Ref. [21].
[d] Ref. [22].

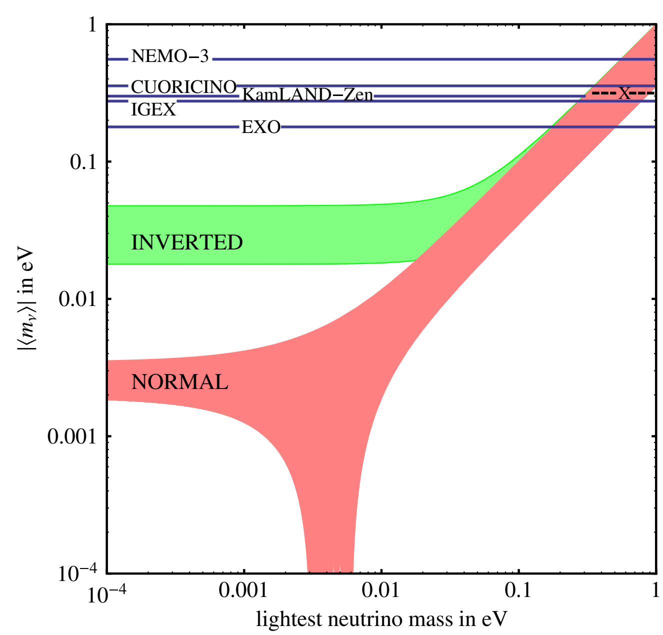

FIG. 3 (color online). Current limits to $\langle m_\nu \rangle$ from CUORICINO [23], IGEX [20], NEMO-3 [24], KamLAND-Zen [21], and EXO [22] and IBM-2 nuclear matrix elements. The value of Ref. [19] is shown by *X*. It is consistent only with nearly degenerate neutrino masses. The figure is in logarithmic scale.

the limits in Table III and IV by a factor of 2–4. Details of the renormalization procedure, as well as of the calculation of the renormalized matrix elements NME, will be given in a forthcoming longer publication [14]. The question of whether or not $0\nu\beta\beta$ matrix elements should be renormalized as much as $2\nu\beta\beta$ matrix elements is the subject of much debate. In $2\nu\beta\beta$ only 1^+ and 0^+ states in the intermediate odd-odd nucleus contribute to the decay, while in $0\nu\beta\beta$ all multipoles play a role. In this Letter, we do not dwell on this question but rather present results with the unrenormalized value $g_A = 1.269$, summarized in Fig. 3. From this figure, one can see that in the immediate future only the degenerate region can be tested by experiments and that the exploration of the inverted region must await much larger (> 1 ton) experiments, especially if g_A in $0\nu\beta\beta$ is renormalized as much as in $2\nu\beta\beta$ decay. From the same figure, one can also see that even the one-ton experiments will not be able to reach into the normal hierarchy.

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