Title
Limits on Majoron-Emitting Double-Beta Decays of 136Xe in KamLAND-Zen

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We present limits on Majoron-emitting neutrinoless double-beta decay modes based on an exposure of 112.3 days with 125 kg of $^{136}$Xe in KamLAND-Zen.

We analyze the spectrum obtained from a 38.6 kg-year exposure of $^{136}$Xe in KamLAND-Zen (KamLAND-Zen Collaboration) (Dated: May 30, 2012)

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The search for neutrinoless double-beta ($0\nu\beta\beta$) decay is the best probe of the Majorana nature of the neutrino known at present. The observation of this process would immediately imply total lepton number violation and the equivalence of the neutrino and the antineutrino, irrespective of the mechanism by which the decay is mediated [1]. Although most current experimental efforts focus on the detection of $0\nu\beta\beta$ decay mediated by light Majorana neutrino exchange, many other mechanisms have been proposed. Some exotic models [2, 3] predict decays proceeding through the emission of massless Nambu-Goldstone (NG) bosons, referred to as Majorons. Precise measurements of the invisible decay width of the Z boson in LEP showed that traditional Majoron models require severe fine-tuning [4]. However, a number of additional models have been proposed which avoid such fine tuning, including modes in which the Majoron can carry leptonic charge, and need not be a NG boson [5], or in which $0\nu\beta\beta$ decay proceeds through the emission of two Majorons [6]. These models predict different shapes for the spectrum of the summed energy of the two emitted $\beta$'s. In this report we analyze the spectrum obtained from a 38.6 kg-year exposure of $^{136}$Xe with KamLAND-Zen [7] to derive new limits on several of these decay modes.

The main distinguishing features of the models are listed in the third, fourth, and fifth columns: whether the Majoron is a NG boson or not, its leptonic charge ($L$), and the model’s spectral index ($\nu$), respectively. The spectral index is de-
TABLE I: Different Majoron emission models [6, 8–10], and the KamLAND-Zen limits for the corresponding Majoron-emitting $0\nu\beta\beta$ decay half-lives ($T_{1/2}$) and effective Majoron-neutrino coupling constants ($\langle g_{\nu}\rangle$) for $^{136}$Xe at 90% C.L. The model notation in the first column follows references [6, 11]. The third, fourth, fifth, and sixth columns indicate whether the Majoron is a NG boson or not, its leptonic charge ($L$), and the model’s spectral index ($n$), and the form of the nuclear matrix element, respectively.

<table>
<thead>
<tr>
<th>Model</th>
<th>Decay Mode</th>
<th>NG boson</th>
<th>$L$</th>
<th>$n$</th>
<th>Matrix Element</th>
<th>Results from this measurement $T_{1/2}$ (yr)</th>
<th>$\langle g_{\nu}\rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IB $0\nu\beta\beta\chi_0^0$</td>
<td>no</td>
<td>0</td>
<td>1</td>
<td>$M_F - M_{GT}$ [12, 13]</td>
<td>$&gt; 2.6 \times 10^{24}$</td>
<td>$(0.8 - 1.6) \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>IC $0\nu\beta\beta\chi_0^0$</td>
<td>yes</td>
<td>0</td>
<td>1</td>
<td>$M_F - M_{GT}$ [12, 13]</td>
<td>$&gt; 2.6 \times 10^{24}$</td>
<td>$(0.8 - 1.6) \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>ID $0\nu\beta\beta\chi_0^0$</td>
<td>no</td>
<td>0</td>
<td>3</td>
<td>$M_{F_{\nu,2}} - M_{GT_{\nu,2}}$ [8]</td>
<td>$&gt; 4.5 \times 10^{23}$</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>IE $0\nu\beta\beta\chi_0^0$</td>
<td>yes</td>
<td>0</td>
<td>3</td>
<td>$M_{F_{\nu,2}} - M_{GT_{\nu,2}}$ [8]</td>
<td>$&gt; 4.5 \times 10^{23}$</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>IIB $0\nu\beta\beta\chi_0^0$</td>
<td>no</td>
<td>$-2$</td>
<td>1</td>
<td>$M_F - M_{GT}$ [12, 13]</td>
<td>$&gt; 2.6 \times 10^{24}$</td>
<td>$(0.8 - 1.6) \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>IIC $0\nu\beta\beta\chi_0^0$</td>
<td>yes</td>
<td>$-2$</td>
<td>3</td>
<td>$M_{CR}$ [8]</td>
<td>$&gt; 4.5 \times 10^{23}$</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>IID $0\nu\beta\beta\chi_0^0$</td>
<td>no</td>
<td>$-1$</td>
<td>3</td>
<td>$M_{F_{\nu,2}} - M_{GT_{\nu,2}}$ [8]</td>
<td>$&gt; 4.5 \times 10^{23}$</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>IIE $0\nu\beta\beta\chi_0^0$</td>
<td>yes</td>
<td>$-1$</td>
<td>7</td>
<td>$M_{F_{\nu,2}} - M_{GT_{\nu,2}}$ [8]</td>
<td>$&gt; 1.1 \times 10^{22}$</td>
<td>1.2</td>
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<tr>
<td>IIF $0\nu\beta\beta\chi_0^0$</td>
<td>gauge boson</td>
<td>$-2$</td>
<td>3</td>
<td>$M_{CR}$ [8]</td>
<td>$&gt; 4.5 \times 10^{23}$</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>“bulk” $0\nu\beta\beta\chi_0^0$</td>
<td>bulk field</td>
<td>0</td>
<td>2</td>
<td>–</td>
<td>$&gt; 1.0 \times 10^{24}$</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1: KamLAND-Zen visible energy spectra for different $^{136}$Xe decay modes, characterized by the spectral index $n$. The resolution-limited line ($\sigma = (6.6 \pm 0.3%)/\sqrt{E(\text{MeV})}$) at the Q-value indicates the $0\nu\beta\beta$ decay peak without Majoron emission.

The energy spectrum of selected candidate events between 0.5 and 4.8 MeV is shown in Fig. 2. The $\beta\beta$ decay rates are estimated from a likelihood fit to the binned energy spectrum. In the fit, background contributions from external sources, from the $^{222}$Rn-$^{218}$Pb and $^{228}$Th-$^{208}$Pb chains, and from $^{11}$C and $^{10}$C (muon spallation products), as well as the parameters of the detector energy response model are allowed to vary but are constrained by their independent measurement [7]. On the other hand, backgrounds without independent measurements, namely $^{85}$Kr, $^{40}$K, non-equilibrium $^{210}$Bi, and the $^{238}$U-$^{222}$Rn and $^{232}$Th-$^{228}$Th decay chains, are left unconstrained. As in Ref. [7] the background in the $0\nu\beta\beta$ region of interest, simultaneously with a possible contribution from one of the $0\nu\beta\beta$ modes to obtain an upper limit on its rate.

The experimental investigation reported here is based on data collected with KamLAND-Zen between October 12, 2011, and February 9, 2012, and includes the data used in Ref. [7] plus an additional 34.7 days, for a total live-time of 112.3 days. The target liquid scintillator (LS) contains (2.44 ± 0.01)% by weight of enriched xenon gas, obtained by augmenting the measurement by gas chromatography (2.52 ± 0.07)% [7], with a comparison of the total xenon weight and LS volume introduced into the detector during LS filling, (2.44 ± 0.01)%. The detector status and data quality were stable over the data-set. The fiducial volume for the reconstructed event vertex is defined as a spherical shape of 1.2 m radius at the detector center, containing (125 ± 7) kg of $^{136}$Xe. Other event selection criteria are applied as described in [7]. The total systematic uncertainty on the $\beta\beta$ decay half-life measurement is 5.2%, slightly improved from the 5.9% of [7] owing to the supplemental xenon concentration measurement.

Fig. 1 shows predicted energy spectra of $^{136}$Xe decay for different values of the spectral index $n$, corresponding to $2\nu\beta\beta$ ($n = 5$), $0\nu\beta\beta\chi_0^0$ ($n = 1, 2,$ and 3), and $0\nu\beta\beta\chi_0^0\chi_0^0$ ($n = 3$ and 7). The spectra have been convolved with the KamLAND-Zen detector response function, including the energy resolution and energy scale non-linearities. In this analysis, the dominant contribution from $2\nu\beta\beta$ decay is fit simultaneously with a possible contribution from one of the $0\nu\beta\beta$ modes to obtain an upper limit on its rate.
The 90% C.L. upper limit for the different Majoron-emitting decay modes are taken from [12, 13] and [21], respectively, while those for other decays are taken from [8]. From the half-life limit of the ordinary Majoron-emitting decay mode we obtain an upper limit of \(\langle g_{ee}\rangle < (0.8 - 1.6) \times 10^{-5}\) at 90% C.L. This is the most stringent limit on \(\langle g_{ee}\rangle\) to date among all \(\beta\beta\) decay nuclei [4, 11, 14–20]. The previous best limit from a laboratory experiment was from NEMO-3 for \(^{100}\)Mo: \(\langle g_{ee}\rangle < (3.5 - 8.5) \times 10^{-5}\) [18]. Our new limit corresponds to more than a factor of 2.2 improvement over this previous result. The limits on the effective Majoron-neutrino coupling constant for \(^{136}\)Xe for all investigated Majoron-emitting \(0\nu\beta\beta\) decays are summarized in Table I.

Other limits on \(\langle g_{ee}\rangle\) are available from geochemistry and astrophysics. Half-life limits on \(^{126}\)Te from geochemistry experiments can be interpreted as an effective coupling limit of \(\langle g_{ee}\rangle < 3 \times 10^{-5}\) [22], although the half-life determinations have been criticized [23] and may require a downward correction by almost a factor of 3. The observation of neutrinos from SN1987A and of their time distribution indicates that Majoron emission does not play a dominant role in core collapse processes, allowing one to exclude the range \(4 \times 10^{-7} < \langle g_{ee}\rangle < 2 \times 10^{-5}\) [24–26] for the ordinary Majoron-emitting decay mode. While previous limits combined with the supernova data still allowed a gap region of \(2 \times 10^{-5} < \langle g_{ee}\rangle < 9 \times 10^{-5}\) [18], our new result completely excludes this region. The SN1987A limit therefore significantly extends the KamLAND-Zen limit down to \(\langle g_{ee}\rangle < 4 \times 10^{-7}\). Multiplying by the square-root of the ratio of phase space factors, one finds that this limit excludes the possibility that ordinary Majoron-emitting decay modes play a dominant role to light Majorana neutrino exchange for \(m_{\beta\beta} > 20\,\text{meV}\). This range almost covers the entire \(m_{\beta\beta}\) parameter space in the case of the inverted neutrino mass hierarchy [27].

In summary, we have reported new limits from KamLAND-Zen on Majoron-emitting \(0\nu\beta\beta\) decay half-lives for \(^{136}\)Xe. In particular, for ordinary Majoron-emitting \(0\nu\beta\beta\) decay (spectral index \(n = 1\)), we obtained an improved limit on the effective Majoron-neutrino coupling constant \(\langle g_{ee}\rangle\) by more than a factor of 2.2 over earlier searches. Combined with limits on \(\langle g_{ee}\rangle\) from SN1987A, the KamLAND-Zen result strongly disfavors a dominant contribution from ordinary Majoron-emitting decay modes for neutrino masses in the inverted hierarchy scheme.

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