REVIEW OF DOUBLE BETA DECAY EXPERIMENTS

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Abstract. The brief review of current experiments on search and studying of double beta decay processes is done. Best present limits on $\langle m_\nu \rangle$ and $\langle g_{ee} \rangle$ are presented. Prospects of search for neutrinoless double beta decay in new experiments with sensitivity to $\langle m_\nu \rangle$ at the level of $\sim 0.01-0.1$ eV are discussed.

1 Introduction

Interest in $0\nu\beta\beta$ decay has seen a significant renewal in recent 10 years after evidence for neutrino oscillations was obtained from the results of atmospheric, solar, reactor, and accelerator neutrino experiments. These results are impressive proof that neutrinos have a nonzero mass. The detection and study of $0\nu\beta\beta$ decay may clarify the following problems of neutrino physics: (i) lepton number non-conservation, (ii) neutrino nature: whether the neutrino is a Dirac or a Majorana particle, (iii) absolute neutrino mass scale (a measurement or a limit on $m_1$), (iv) the type of neutrino mass hierarchy (normal, inverted, or quasidegenerate), (v) CP violation in the lepton sector (measurement of the Majorana CP-violating phases).

2 Present status

2.1 Two neutrino double beta decay

The $2\nu\beta\beta$ decay ($(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}$) is a second-order process, which is not forbidden by any conservation law. The detection of this process provides the experimental determination of the nuclear matrix elements (NME) involved in the $\beta\beta$-decay processes. This leads to the development of theoretical schemes for NME calculations both in connection with the $2\nu\beta\beta$ decays as well as the $0\nu\beta\beta$ decays. Table 1 displays the present-day averaged and recommended values of $T_{1/2}(2\nu)$ from [1].

2.2 Neutrinoless double beta decay

The $0\nu\beta\beta$ decay ($(A, Z) \rightarrow (A, Z + 2) + 2e^-$) violates the law of lepton-number conservation ($\Delta L = 2$) and requires that the Majorana neutrino has a nonzero rest mass or that an admixture of right-handed currents be present in weak interaction. Also, this process is possible in some supersymmetric models, where $0\nu\beta\beta$ decay is initiated by the exchange of supersymmetric particles. This decay also arises in models featuring an extended Higgs sector within

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Table 1: Average and recommended $T_{1/2}(2\nu)$ values (from [1]).

| Isotope       | $T_{1/2}(2\nu)$, yr |
|---------------|----------------------|
| $^{48}$Ca     | $4.4^{+0.6}_{-0.5} \cdot 10^{19}$ |
| $^{76}$Ge     | $1.6^{+0.13}_{-0.10} \cdot 10^{21}$ |
| $^{82}$Se     | $(0.92 \pm 0.07) \cdot 10^{20}$ |
| $^{96}$Zr     | $(2.3 \pm 0.2) \cdot 10^{19}$ |
| $^{100}$Mo    | $(7.4 \pm 0.4) \cdot 10^{18}$ |
| $^{100}$Mo-$^{105}$Ru($0^+$) | $6.2^{+0.7}_{-0.5} \cdot 10^{20}$ |
| $^{116}$Cd    | $(2.85 \pm 0.15) \cdot 10^{19}$ |
| $^{128}$Te    | $(2.0 \pm 0.3) \cdot 10^{24}$ |
| $^{130}$Te    | $(6.9 \pm 1.3) \cdot 10^{20}$ |
| $^{136}$Xe    | $(2.20 \pm 0.06) \cdot 10^{21}$ |
| $^{150}$Nd    | $(8.2 \pm 0.9) \cdot 10^{18}$ |
| $^{150}$Nd-$^{150}$Sm($0^+$) | $1.33^{+0.45}_{-0.26} \cdot 10^{20}$ |
| $^{238}$U     | $(2.0 \pm 0.6) \cdot 10^{21}$ |

The $0\nu\beta\beta$ decay with Majoron emission

2.3 Neutrinoless double beta decay with Majoron emission

The $0\nu\chi^0\beta\beta$ decay ($(A, Z) \rightarrow (A, Z + 2) + 2e^- + \chi^0$) requires the existence of a Majoron. It is a massless Goldstone boson that arises due to a global breakdown of (B-L) symmetry, where B and L are, respectively, the baryon and the lepton number. The Majoron, if it exists, could play a significant role in the history of the early Universe and in the evolution of stars. The best obtained limits on
0νχ0ββ decay are presented in Table 3. Present conservative limit can be set as ⟨gee⟩ < 10⁻⁵.

Table 3: Best present results on 0νχ0ββ decay (ordinary Majoron) at 90% C.L. The NME from [3,4,5,6,7,8], phase-space factors from [14] and g₄ = 1.27 were used.

| Isotope | T₁/₂, y | ⟨gee⟩, ×10⁻⁵ | Experiment |
|---------|---------|---------------|------------|
| ⁷⁰Ge    | > 6.4 · 10²² | < 6.3 – 15.8   | Heidelberg-Moscow [15] |
| ⁸²Se    | > 1.5 · 10²² | < 5.0 – 11.6   | NEMO-3 [16] |
| ¹⁰⁰Mo   | > 4.4 · 10²² | < 1.6 – 4.1    | NEMO-3 [11] |
| ¹³⁶Xe   | > 2.6 · 10²⁴ | < 0.4 – 1.0    | KamLAND-Zen [17] |

3 Current large-scale experiments

3.1 EXO-200

EXO–200 (Enriched Xenon Observatory) is operating at the Waste Isolation Pilot Plant (WIPP, 1585 m w.e.) since May 2011. The experiment consists of 175 kg of Xe enriched to 80.6% in ¹³⁶Xe housed in a liquid time projection chamber (TPC). Both ionization and scintillation are used to measure the energy with a resolution of 3.9% (FWHM) at 2,615 MeV. The detector is capable of effectively rejecting rays through topological cuts. Results obtained after ∼ 3000 h of measurements are the following [20, 21]:

\[ T_{1/2} (2ν, ^{136}Xe) = [2.165 \pm 0.016(stat) \pm 0.050(syst)] \cdot 10^{21} \text{yr} \quad (4) \]
\[ T_{1/2} (0ν, ^{136}Xe) > 1.6 \cdot 10^{25} \text{yr} \quad (5) \]

With the present background, the predicted EXO–200 sensitivity after 5 years of data taking will be \( T_{1/2} \sim 4 \cdot 10^{25} \text{ yr} \) (⟨m_ν⟩ \sim 0.10–0.24 eV).

3.2 KamLAND-Zen

The detector KamLAND–Zen is a modification of the existing KamLAND detector carried out in the summer of 2011. The ββ source/detector is 13 tons of Xe-loaded liquid scintillator (Xe–LS) contained in a 3.08 m diameter spherical

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¹I would like to stress that I use here phase-space factor values (G) from [14]. These values are ∼ 2 times higher then in [18], for example. This difference can be explain as follows: in [18] "canonical" formulas from [19] to calculate G were used. But in [14] it was mentioned that factor 2 was lost in [19].

²Recently more weaker limit was published using ∼ 3 times higher statistics, \( T_{1/2} (0ν, ^{136}Xe) > 1.1 \cdot 10^{25} \text{yr} \) [22].
Inner Balloon (IB). The IB is suspended at the center of the KamLAND detector. The outer LS acts as an active shield for external $\gamma$-rays and as a detector for internal radiation from the Xe–LS or IB. The Xe–LS contains $(2.52 \pm 0.07)\%$ by weight of enriched xenon gas (full weight of xenon is $\sim 330$ kg). The isotopic abundances in the enriched xenon is $(90.93 \pm 0.05)\%$ of $^{136}$Xe. Main obtained results are the following [17,13]:

$$T_{1/2} (2\nu, ^{136}\text{Xe}) = [2.30 \pm 0.02(stat) \pm 0.12(syst)] \cdot 10^{21}\text{yr} \ (6)$$

$$T_{1/2} (0\nu, ^{136}\text{Xe}) > 1.9 \cdot 10^{25}\text{yr} \ (7)$$

$$T_{1/2} (0\nu\chi^0, ^{136}\text{Xe}) > 2.6 \cdot 10^{24}\text{yr} \ (8)$$

Now the Collaboration undertakes efforts to understand and decrease the background. In principle, it could be lowered by factor $\sim 100$ (in this case sensitivity will be improved by factor $\sim 10$).

Table 4: Seven most developed and promising projects. Sensitivity at 90% C.L. for three (1-st step of GERDA and MAJORANA, first step of SuperNEMO, SNO+, CUORE-0 and KamLAND-Zen) five (EXO, SuperNEMO and CUORE) and ten (full-scale GERDA and MAJORANA) years of measurements is presented. M - mass of isotopes.

| Experiment | Isotope | M, kg | Sensitivity | Sensitivity | Status |
|------------|---------|-------|-------------|-------------|--------|
| CUORE [23,24] | $^{130}\text{Te}$ | 11 | $5 \times 10^{24}$ | 230–570 | in progress |
| | | 200 | $10^{26}$ | 50–130 | in progress |
| GERDA [25] | $^{76}\text{Ge}$ | 40 | $2 \times 10^{26}$ | 80–190 | in progress |
| | | 1000 | $6 \times 10^{27}$ | 15–35 | R&D |
| MAJORANA [26] | $^{76}\text{Ge}$ | 30 | $1.5 \times 10^{26}$ | 90–200 | in progress |
| | | 1000 | $6 \times 10^{27}$ | 15–35 | R&D |
| EXO [27] | $^{136}\text{Xe}$ | 200 | $4 \times 10^{25}$ | 100–240 | in progress |
| | | 5000 | $2 \times 10^{27}$ | 14–33 | R&D |
| SuperNEMO [28] | $^{82}\text{Se}$ | 7 | $6.5 \times 10^{24}$ | 240–560 | in progress |
| | | 100–200 | $(1–2) \times 10^{26}$ | 44–140 | R&D |
| KamLAND-Zen [29] | $^{136}\text{Xe}$ | 320 | $2 \times 10^{26}$ | 44–105 | in progress |
| | | 1000 | $6 \times 10^{26}$ | 25–60 | R&D |
| SNO+ [30] | $^{130}\text{Te}$ | 800 | $10^{26}$ | 50–130 | in progress |
| | | 8000 | $10^{27}$ | 16–40 | R&D |

3.3 GERDA-I

GERDA is a low-background experiment which searches for the neutrinoless double beta decay of $^{76}\text{Ge}$, using an array of high-purity germanium (HPGe) detectors isotopically enriched in $^{76}\text{Ge}$ [25]. The detectors are operated naked
in ultra radio-pure liquid argon, which acts as the cooling medium and as a passive shielding against the external radiation. The experiment is located in the underground Laboratori Nazionali del Gran Sasso of the INFN (Italy, 3500 m w.e.). The Phase I of GERDA use eight enriched coaxial detectors refurbished from Heidelberg-Moscow and IGEX experiments (corresponding to approximately 18 kg of \(^{76}\text{Ge}\)). The energy resolution is \(\approx 4.5\) KeV at \(2.039\) MeV. GERDA-I measurements have been started in November 2011 and stopped in May of 2013. Results of the measurement are \([10,31]\):

\[
T_{1/2} (2\nu, ^{76}\text{Ge}) = [1.84 \pm 0.14(stat) \pm 0.10(syst)] \cdot 10^{21}\text{yr} \quad (9)
\]

\[
T_{1/2} (0\nu, ^{76}\text{Ge}) > 2.1 \cdot 10^{25}\text{yr} \quad (10)
\]

In 2014 new \(~20\) kg of HPGe crystals will be added and experiment will be transformed to Phase II (GERDA-II).

4 Future large-scale experiments

Seven of the most developed and promising experiments which can be realized within the next few years are presented in Table 4. The estimation of the sensitivity to \(\langle m_\nu \rangle\) is made using NMEs from \([3,4,5,6,7,8]\) and phase-space factor values from \([9]\).

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