Neutrinoless Double Beta Decay Experiments

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Neutrinoless double beta decay is the only process known so far able to test the neutrino intrinsic nature: its experimental observation would imply that the lepton number is violated by two units and prove that neutrinos have a Majorana mass components, being their own anti-particle. While several experiments searching for such a rare decay have been performed in the past, a new generation of experiments using different isotopes and techniques have recently released their results or are taking data and will provide new limits, should no signal be observed, in the next few years to come. The present contribution reviews the latest public results on double beta decay searches and gives an overview on the expected sensitivities of the experiments in construction which will be able to set stronger limits in the near future.

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1 Introduction

Double beta decay is the simultaneous beta decay of two neutrons in a nucleus. The reaction can be calculated in the standard model of particle physics as a second order process: \((A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e\). The two neutrino double beta decay \((2\nu\beta\beta)\) has been observed in eleven nuclei, where single beta decay is energetically forbidden, and very high half-lives, between \(7 \times 10^{18}\) yr and \(2 \times 10^{24}\) yr have been measured [1, 2]. Several models extending the standard model predict that a neutrinoless double beta decay \((0\nu\beta\beta)\) should also exists: \((A,Z) \rightarrow (A,Z+2) + 2e^-\). It’s observation would imply that lepton number is violated by two unit and that neutrinos have a Majorana mass component. The standard mechanism for \(0\nu\beta\beta\) assumes that the process is mediated by light and massive Majorana neutrinos and that other mechanisms potentially leading to neutrinoless double beta decay are negligible [3].

With a light Majorana neutrino exchange, it would be possible to derive an effective neutrino mass using nuclear matrix element and phase space factor predictions. For recent reviews on the subject, see Ref. [4, 5].

Several experiments searching for neutrinoless double beta decay have been performed in the past, going back for at least half a century, with increasing sensitivities. Two main approaches have been followed. Indirect methods are based on the measurements of anomalous concentrations of the daughter nuclei in selected samples after very long exposures (i.e. radiochemical methods). Direct methods, on the other hand, try to measure in real time the properties of the two electrons emitted in \(\beta\beta\) decay. The detectors can be homogeneous, when the \(\beta\beta\) source is the detector medium and in-homogeneous when external \(\beta\beta\) sources are inserted in the detector.

In the following sections, the status of the art on \(0\nu\beta\beta\) searches will be presented with special emphasis on large scale running experiments.

2 Double Beta Decay in \(^{136}\)Xe

\(^{136}\)Xe is a very interesting double beta decay emitter candidate. It has a high \(Q_{\beta\beta} = 2457\) keV, in a region which can have lower contaminations from radioactive background events. It can can be dissolved in liquid scintillators or used as gas allowing to realize a homogeneous detector providing both scintillation and ionization signals. Two large experiments have searched for \(0\nu\beta\beta\) in Xe: EXO-200 has used xenon in an homogeneous medium (both as \(0\nu\beta\beta\) source and as detector), while in KamLAND-Zen it has been dissolved as a passive \(\beta\beta\) source in a liquid scintillator detector.
2.1 EXO

The Enriched Xenon Observatory \cite{EXO200} is an experiment in operation at the Waste Isolation Pilot Plant (WIPP), at a depth of about 1600 m water equivalent near Carlsbad in New Mexico (USA). The experiment is built around a large liquid Xenon Time Projection Chamber filled with about 200 kg of liquid Xenon enriched to about 80.6\% in the $^{136}$Xe isotope. In contrast to standard TPCs, the experiment uses liquid xenon which can be concentrated in a smaller volume with the same mass concentration. To overcome the limitation of worse energy resolutions compared to gaseous TPCs, the experiment exploits the readout of both scintillation and ionization signals produced by interacting particles in xenon. Moreover, by combining both signals (scintillation light and ionization charges), the experiment is able to reject background events characterized by different charge to light collection ratio. Finally, by using the difference in the arrival time between the scintillation and ionization signals a z-coordinate of the event is reconstructed. The experiment started data taking in May 2011.

In June 2012, the collaboration reported the first results on $0\nu\beta\beta$ decay, analyzing and exposure of 32.5 kg yr. The $2\nu\beta\beta$ and $0\nu\beta\beta$ signals were extracted simultaneously with a fit to the single-site (SS) and multiple-site (MS) spectra, in an energy range between 0.7 MeV and 3.5 MeV (see left plots of Figure 1). The fit takes into consideration the main radioactive background sources and a lower limit to the $0\nu\beta\beta$ life-time has been derived \cite{EXO2012}:

$$T_{0\nu}^{1/2} > 1.6 \times 10^{25} \text{ yr} \ @ 90\% \ C.L.$$ .

The measurement has been recently updated with a higher exposure (100 kg yr) and with an improved detection sensitivity \cite{EXO2013}. The claimed half-life sensitivity, $1.9 \cdot 10^{25}$ yr, is an improvement by a factor of 2.7 compared to previous EXO-200 results. They find no statistically significant evidence for $0\nu\beta\beta$ decay but set a worse half-life limit of $1.1 \cdot 10^{25}$ yr at 90\% CL.

Very recently the EXO collaboration has published an update on $2\nu\beta\beta$ life-time measurement \cite{EXO2014} using 127.6 days of live-time. The measurement,

$$T_{2\nu}^{1/2} = 2.165 \pm 0.016(\text{stat.}) \pm 0.059(\text{syst.}) \times 10^{21} \text{ yr} ,$$

is the most precisely measured half-life $2\nu\beta\beta$ decay to date.

A future evolution of EXO \cite{EXO2015} is moving in the direction of a tonne scale experiment, with an active mass of few tonnes of $^{136}$Xe and improved energy resolution and background suppression.

2.2 KamLAND-Zen

The KamLAND-Zen experiment is based on a modification of the existing KamLAND \cite{KamLAND} detector carried out in the summer of 2011. KamLAND is located at a
Figure 1: Left: EXO-200. Energy spectra in the $^{136}$Xe $Q_{\beta\beta}$ region for Multiple Site (top) and Single Site (bottom) events. The 1 (2) $\sigma$ region around $Q_{\beta\beta}$ is shown by solid (dashed) vertical lines. Taken from Ref. [7]. Right: KamLAND-Zen. Energy spectra of selected candidate events together with the best-fit backgrounds and $2\nu\beta\beta$ decays. Figure taken from Ref. [13].

depth of about 2700 m water equivalent at the Kamioka underground neutrino observatory near Toyama in Japan. The experiment has been equipped with 13 tons of Xe-loaded liquid scintillator (Xe-LS) contained inside a 3.08 m diameter spherical inner balloon. The isotopic abundance of the enriched xenon has been measured to be about 90.9% $^{136}$Xe and 8.9% $^{134}$Xe. The experiment started data taking in October 2011 and after an exposure of 30.8 kg yr of $^{136}$Xe (77.6 days) it reported a measurement of the $2\nu\beta\beta$ half-life[12]:

$$T_{1/2}^{2\nu} = 2.38 \pm 0.02(\text{stat}) \pm 0.40(\text{syst}).$$

Careful studies have been performed by the collaboration to identify the various background sources contributing to the energy spectra (see right plot of Figure 1). The spectrum shows a clear peak in the ROI that is compatible with a $^{110m}$Ag contamination of the inner balloon. An attempt to purify the Xe-LS has been performed, but unfortunately the filtration did not produce the desired effect: the background counting rate due to $^{110m}$Ag decreased only slightly, from 0.19 ± 0.02 cts/(tonne-day) to 0.14 ± 0.03 cts/(tonne-day).

The $0\nu\beta\beta$ limit reported so far by the experiment is[13]:

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ yr} \ @ \ 90\% \ \text{C.L.}$$

A careful and long lasting (1.5 yr) purification activity has allowed to reduce
radioactive impurities and to start a new data taking phase at the end of 2013. A preliminary analysis of both running phases [14] improves the current $0\nu\beta\beta$ limit to

$$T_{1/2}^{0\nu} > 2.6 \times 10^{25} \text{ yr @ 90\% C.L.}$$

Several detector improvements are foreseen in the years to come and an increase in the Xe mass (up to 1 ton) is expected [14].

3 Double Beta Decay in $^{76}$Ge

Germanium became a warhorse of $0\nu\beta\beta$ decay searches once it was realized that $^{76}$Ge emitter could be embedded in solid state detectors using a calorimetric approach with High Purity Germanium (HPGe) diodes. Thanks to their excellent energy resolution (germanium diodes are still the best gamma spectroscopy detectors to date) in the order of 0.1-0.2% FWHM at 2 MeV and to the industrial manufacturing technology, sizable mass detectors can be built. Unfortunately, due to the quite low natural abundance of $^{76}$Ge (7.8%), isotopically enriched material has to be procured, before constructing HPGe didoes. Milestone experiments have been performed by the Heidelberg-Moscow [15] (HdM) and IGEX [16] collaborations: they used 11 kg and 8 kg of isotopically enriched (up to 86%) $^{76}$Ge germanium diodes operated in low activity vacuum cryostats located in underground laboratories, Laboratori Nazionali del Gran Sasso (LNGS), in Italy for HdM, and Laboratorio Subterraneo de Canfranc (LSC), in Spain for IGEX.

The Germanium $Q_{\beta\beta}$ is not very high, ($Q_{\beta\beta} = 2039.061 \pm 0.007$ keV [17]) and lies in a region where contamination from background sources are possible: apart from the $^{238}$U and $^{232}$Th decay chains that can contribute to the $0\nu\beta\beta$ region-of-interest (ROI), sizable contamination can arise from long-lived cosmogenically produced isotopes ($^{68}$Ge and $^{60}$Co in copper and germanium activation) and from few anthropogenic radioisotopes. Therefore the experiments have to fight background reduction with careful screening of all the materials close to the detectors and develop pulse shape discrimination techniques to further reduce the background contamination.

Part of the HdM collaboration claimed evidence for a peak at $Q_{\beta\beta}$ which corresponds to a half-life central value of $T_{1/2}^{0\nu} = 1.19 \cdot 10^{25}$ yr [18]. The result was later refined with pulse shape analysis (PSA) techniques giving a half life $T_{1/2}^{0\nu} = 2.23^{+0.44}_{-0.31} \cdot 10^{25}$ yr [19]. For a discussion on the two results, see [4].

Two larger scale experiment, GERDA[20] in Europe and MAJORANA[21] in USA, are exploiting the germanium diodes technology and beside scrutinizing the previous claims [18]-[19] they will try to push the experimental sensitivity to the limits.
3.1 GERDA

The GERmanium Detector Array (GERDA) experiment operates germanium diodes made of isotopically modified material, enriched to about 86% in $^{76}$Ge, without encapsulation in a liquid argon cryogenic bath. The experiment aims to pursue very low backgrounds thanks to ultra-pure shielding against environmental radiation. The germanium detectors are suspended in strings into the cryostat where 64 m$^3$ of LAr are used both as a coolant and shield. The stainless steel cryostat vessel is covered, from the inside, with copper lining to reduce gamma radiation from the cryostat walls. The vessel is surrounded by a large tank filled with high purity water (590 m$^3$) which further shields the inner volumes from the experimental hall radiation (absorbing $\gamma$s and moderating neutrons). Moreover it provides a sensitive medium for the muon system which operates as a Cerenkov muon veto.

The first phase of the experiment has started on November 9, 2011 using eight reprocessed coaxial germanium detectors from the HdM and IGEX experiments together with three natural germanium diodes. In July 2012, two of the coaxial detectors with natural isotopic abundance have been replaced by five new enriched Broad Energy Germanium (BEGe) detectors. The latters are a sub-sample of the thirty new BEGe detectors recently constructed by Canberra for the Phase II of the experiment.

The first 5.04 kg yr data, collected before the insertion of the new BEGe detector, have been used to measure the half-life of the $2\nu\beta\beta$ decay of $^{76}$Ge [22]. The extracted half-life is

$$T_{1/2}^{2\nu} = \left(1.84^{+0.09}_{-0.08 \text{ fit}} +0.11_{-0.06 \text{ syst}}\right) \times 10^{21}\text{yr}.$$

After having studied the background decomposition of the collected energy spectra [23], keeping the $0\nu\beta\beta$ ROI blinded, Pulse Shape Discrimination techniques have been developed for coax and BEGe detectors [24].

The $0\nu\beta\beta$ analysis [25] covers the full data taking, from November 9, 2011 to May 21, 2013, for a total exposure of 21.60 kg·yr. Data were grouped into three subsets with similar characteristics: (1) the golden data set contains the major part of the data from coaxial detectors, (2) two short run periods with higher background levels when the BEGe detector were inserted (silver data set) and (3) the BEGe detectors data set. Figure. 2 shows the energy spectrum around the region of interest with and without PSD selection. No excess of events was observed over a flat background distribution. Seven events were seen in the range $Q_{\beta\beta} \pm 5$ keV before PSD cuts, while 5.1 were expected. Only 3 events survived (classified as Single-Site Events [25]) after PSD cuts and no event remained in $Q_{\beta\beta} \pm \sigma_E$. To derive the number of signal counts $N_{0\nu}$, a profile likelihood fit of the spectrum was performed. The fit function was given by the sum of a constant term for the background and of a Gaussian for the signal events. The profile likelihood ratio was limited to the region $1/T_{1/2}^{0\nu} > 0$. The best fit was obtained for $N_{0\nu} = 0$, that is no excess of signal events above background. The
Figure 2: Top: Energy spectrum for the sum of all $^{enr}$Ge detectors in the range 2020-2060 keV, without PSD (empty histogram) and with PSD (black histogram). The red dashed curve is the expectation based on the central value of [18], the blue curve is instead based on the 90% upper limit derived by GERDA, $T_{1/2}^{0\nu} = 2.1 \times 10^{25}$ yr. Bottom: Energy spectrum in the range 1880-2240 keV, the vertical dashed lines indicate the interval 1930-2190 keV used for the background estimation. Taken from Ref. [25].

The lower limit on the half-life is:

$$T_{1/2}^{0\nu} > 2.1 \times 10^{25}\text{yr} \at 90\% \text{ C.L.},$$

including systematic uncertainties. This limit corresponds to $N^{0\nu} < 3.47$ events. A Bayesian calculation using a flat prior distribution for $1/T_{1/2}^{0\nu}$ from 0 to $10^{-24}$/yr gives $T_{1/2}^{0\nu} > 1.9 \times 10^{25}\text{yr} \at 90\% \text{ C.I.}$

The data do not show any peak at $Q_{\beta\beta}$ and the result does not support the claim described in Ref. [19]. The GERDA result is consistent with the negative result from IGEX and HdM. A combined profile likelihood fit including all these three negative results gives a 90% probability limit: $T_{1/2}^{0\nu} > 3.0 \times 10^{25}\text{yr} \at 90\% \text{ C.L.}$

A new phase II of the GERDA experiment is planned to start at the end of 2014, after a shutdown phase prepared to upgrade the experiment infrastructure and install thirty new BEGe diodes. The detectors, which have been characterized at the HADES underground laboratory [26] in Belgium, will increase the experiment active mass by about 20 kg (of which 3.6 kg, corresponding to 5 BEGe diodes, were inserted during phase I and their data included in the published results [25]). Thanks to liquid argon instrumentation and enhanced pulse shape discrimination power of the new BEGe...
detectors, a background reduction from the current BI of about $2 \cdot 10^{-2}$ cts/(keV kg yr) to $0.1 \cdot 10^{-2}$ cts/(keV kg yr) is expected. With the new configuration, the experiment is supposed to collect an exposure of about 100 kg yr and and improve the $0\nu\beta\beta$ sensitivity to $T_{1/2}^{0\nu} > 1.35 \cdot 10^{26}$ yr.

### 3.2 MAJORANA

While GERDA is preparing the phase II data taking in Europe, the MAJORANA collaboration in USA is planning to build a large mass germanium experiment using the status of the art technology in diode production with a accurate selection and custom production of radio-pure materials. The proposal is to mount HPGe diodes inside ultra clean electro-formed copper vacuum cryostats and place the whole apparatus in a very deep underground laboratory. Presently, the MAJORANA collaboration is building a prototype, the MAJORANA demonstrator (MJD), to prove the feasibility of the experiment and measure the background conditions. The MJD will be constructed and operated in the Sanford Underground Research Facility (SURF) at a depth of 1500 m in South Dakota, USA. The MJD will use about 40 kg of germanium diodes (with about 30 kg of enriched germanium diodes) and, with performances comparable to those of GERDA, is expected to start data taking in 2014.

Depending on the results of GERDA Phase II and the MAJORANA demonstrator, a next generation germanium experiment using of the order of 1 ton of enriched germanium diodes is under discussion. The effort could be built in stages, starting to merge the GERDA Phase II and MAJORANA diodes in a common effort environment while constructing new diodes from enriched material to enlarge the detector active mass.

### 4 Double Beta Decay in $^{130}$Te

Tellurium is another good candidate suitable for $\beta\beta$ decay searches: due to its high natural abundance (33.8%) isotopic enrichment is not needed and it can be used in the form of TeO$_2$ to build bolometric detectors. Bolometers are calorimeters operated at milli-kelvin temperatures that can measure the energy released in the crystal by interacting particles through their temperature rise. Finally the $Q_{\beta\beta}$ of the decay is relatively high ($Q_{\beta\beta} = 2527$ keV) meaning small background contamination in the ROI.

#### 4.1 Cuore

The Cryogenic Underground Detector for Rare Events (CUORE) is an experiment under construction exploiting a large mass of bolometers: its design consists of about
1000 natural TeO₂ crystals grouped in 19 separated towers. Each crystal is a cube with a side of 5 cm and a mass of 750 g. The small temperature rise originating from nuclear decays in the crystals are read using Neutron Transmutation Doped (NTD) Ge termistors. The array will be operated at about 10 mK in a custom He³/He⁴ dilution refrigerator. The experiment will be located at LNGS in the same experimental hall of the GERDA experiment. The technology has been successfully validated with the Cuoricino [29] experiment. The first installed CUORE tower, CUORE0 has been configured as a stand-alone experiment and is currently taking data to study the background rates and sensitivities expected for CUORE. Recent results from CUORE0 [30] show a good energy resolution of 5.2 keV FWHM at the ²²⁸Tl line (2615 keV) and a background counting rate of 0.063±0.006 cts/(keV·kg·yr) [30]. The full CUORE experiment will start data taking in 2015 with an expected sensitivity on 0νββ of 2.1 × 10²⁶ yr.

5 Conclusions

Neutrinoless double beta decay is an exciting physics topic and double beta decay searches keep on playing a unique role in neutrino physics: probing the lepton number conservation, they can shed light on the Dirac/Majorana nature of neutrinos and indirectly measure the absolute neutrino mass scale with high sensitivity. Several large mass, high sensitivity, experiments will be running in the next few years and they will provide important results on 0νββ. In case of a positive signal, an observation with several isotopes is needed for convincing evidence. The results would imply that neutrino follow an inverted hierarchy mass scheme and allow to directly measure the neutrino mass scale. Even a missing observation of 0νββ on all the isotopes under investigation would play an important role and the results would have to be combined with those coming from future neutrino oscillation experiments (reactors and long baseline).

Concerning the direct hierarchy mass scheme, at present none of the experiments seems to have any reasonable chance of going below the inverted hierarchy scheme. Therefore, new strategies and revolutionary techniques would have to be developed to push further the experimental sensitivities.

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