Status of double beta decay experiments using isotopes other than $^{136}\text{Xe}$

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Abstract

Neutrinoless double beta decay is a lepton-number violating process predicted by many extensions of the standard model. It is actively searched for in several candidate isotopes within many experimental projects. The status of the experimental initiatives which are looking for the neutrinoless double beta decay in isotopes other than $^{136}\text{Xe}$ is reviewed, with special emphasis given to the projects that passed the R&D phase.

The results recently released by the experiment GERDA are also summarized and discussed. The GERDA data give no positive indication of neutrinoless double beta decay of $^{76}\text{Ge}$ and disfavor in a model-independent way the long-standing observation claim on the same isotope. The lower limit reported by GERDA for the half-life of neutrinoless double beta decay of $^{76}\text{Ge}$ is $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90 % C.L.), or $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr, when combined with the results of other $^{76}\text{Ge}$ predecessor experiments.

Keywords: Neutrinoless double beta decay, Majorana neutrino mass

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1. Neutrinoless double beta decay

Many extensions of the standard model of particle physics predict the existence of the neutrinoless double beta ($0\nu\beta\beta$) decay:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^-.$$
Such a transition violates by two units the lepton number conservation and it is thus forbidden by the standard model. The $0\nu\beta\beta$ decay is actively searched for in different candidate isotopes by many experimental programs throughout the world: its observation would bring far-reaching consequences and demonstrate that neutrinos are Majorana particles [1, 2, 3, 4, 5]. In the assumption that the decay is mainly driven by the exchange of light Majorana neutrinos, it is possible to establish an absolute scale for the neutrino mass, provided that the nuclear matrix elements are known. The experimental signature of $0\nu\beta\beta$ is a mono-energetic peak at the $Q$-value of the decay ($Q_{\beta\beta}$).

A claim of observation of the $0\nu\beta\beta$ decay of $^{76}\text{Ge}$ was made more than ten years ago [6], based on the re-analysis of the data of the Heidelberg-Moscow experiment [7]. The net $0\nu\beta\beta$ signal reported in Ref. [8] is $(28.75 \pm 6.86)$ events. The same Ref. [8] reports the most probable value of the half-life of the decay, $T_{1/2}^{0\nu}=1.19 \cdot 10^{25}$ yr: this indirectly provides the proportionality factor which links the number of counts to the inverse of the half-life, and which depends on experimental parameters, like efficiency and exposure. Being the number of events proportional to $1/T_{1/2}^{0\nu}$, the one-sigma range for $T_{1/2}^{0\nu}$ can be calculated as $T_{1/2}^{0\nu}=(1.19^{+0.37}_{-0.23}) \cdot 10^{25}$ yr. Later, the same group reanalyzed the data and strengthened the claim [9], by using a novel event selection method based on the pulse shape information[1]. However, major inconsistencies in the calculation of the half-life $T_{1/2}^{0\nu}$ from the number of events presented in Ref. [9], which should involve an efficiency factor of the pulse shape selection, were pointed out recently [10].

This paper summarizes the status of the experiments worldwide which are looking (or will look in the future) for the $0\nu\beta\beta$ decay in isotopes other than $^{136}\text{Xe}$ — that are described in a separate paper [11]. A special focus is given to the projects that passed the R&D phase and are now in a more advanced development stage (design, construction, commissioning, or data taking) and to the experiment GERDA, which recently reported results on $0\nu\beta\beta$ decay of $^{76}\text{Ge}$.

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1The number of events ascribed to the $0\nu\beta\beta$ decay is $11.32 \pm 1.75$ events, which is converted to $T_{1/2}^{0\nu}=(2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr in Ref. [9].
2. Overview of the present projects

Table 1: Compilation of the present active initiatives searching for $0\nu\beta\beta$ in isotopes other than $^{136}$Xe. For each of them, it is reported the candidate isotope, the location and the development status.

| Project                  | Isotope | Location | Status                      |
|--------------------------|---------|----------|-----------------------------|
| GERDA [12, 13]           | $^{76}$Ge | LNGS     | Phase I completed           |
|                          |         |          | Upgrade to Phase II         |
| Cuore-0/Cuore [14, 15]   | $^{130}$Te | LNGS | Data taking                |
|                          |         |          | Commissioning               |
| Majorana Demonstrator [16] | $^{76}$Ge | SURF | Commissioning               |
| SuperNEMO Demonstrator [17] | $^{82}$Se | LSM | R&D, Construction           |
| SNO+ [18]                | $^{130}$Te | SNOLAB  | R&D, Construction           |
| CANDLES [19]             | $^{48}$Ca | Kamioka | R&D, Construction           |
| Cobra [20]               | $^{116}$Cd | LNGS | R&D                         |
| Lucifer [21]             | $^{82}$Se | LNGS | R&D                         |
| DCBA [22]                | many [Japan] |          | R&D                         |
| AMoRE [23]               | $^{100}$Mo [Korea] | | R&D                         |
| MOON [24]                | $^{100}$Mo [Japan] | | R&D                         |

One of the main goals of all neutrinoless double beta decay experiments in the last decade was to confirm or refute the observation claim. Due to the large uncertainties in the calculations of nuclear matrix elements for the $0\nu\beta\beta$ candidate isotopes (e.g. Ref. [25] for a compilation of recent calculations in $^{76}$Ge and $^{136}$Xe), experiments employing $^{76}$Ge are best suited to scrutinize the observation claim, by the direct comparison of $T^{0\nu}_{1/2}$. On the other hand, the observation of the $0\nu\beta\beta$ in a different isotope would be mandatory to confirm and certify a discovery.

Many candidate $0\nu\beta\beta$ isotopes are being considered in experimental programs or R&D, notably $^{76}$Ge, $^{130}$Te, $^{136}$Xe, $^{82}$Se, $^{150}$Nd, $^{100}$Mo, $^{48}$Ca and $^{116}$Cd. These nuclei are characterized by their own $Q_{\beta\beta}$-values and nuclear matrix elements (NME), which make them more or less favorable in terms of decay rate for a given neutrino effective mass and of expected background. However, it has been shown [10, 26, 27] that the phase space and the NME effects nearly compensate, so that the specific decay rates are the same within a factor of two for all candidate isotopes above. In particular, an effective
neutrino mass of a few tens of meV would yield a decay rate of approximately 1 decay/(ton·yr) in all isotopes.

Given the lack of a “golden” candidate isotope for $0\nu\beta\beta$ searches, the choice is mostly driven by practical or experimental grounds, such as: easiness of isotope enrichment, energy resolution, half-life of the neutrino-accompanied double beta decay ($2\nu\beta\beta$), scalability and modularity of the design, and of course cost. A somewhat special role is played by $^{76}\text{Ge}$, because of the historical reasons and because of the observation claim made with it.

Exposures in the scale of tens of kg·yr have been achieved so far in $^{76}\text{Ge}$, $^{136}\text{Xe}$, $^{130}\text{Te}$ and $^{100}\text{Mo}$. The experiments under development and construction are hence aiming to the scale of the hundreds of kg·yr, which allows for the initial assay of the “inverted hierarchy” region $^{[28]}$.

Table 1 reports an inventory of the present active $0\nu\beta\beta$ projects using isotopes other than $^{136}\text{Xe}$. They are in different phases of development, ranging from data taking to initial R&D. The projects that are in the construction phase or data taking are briefly reviewed in the following.

### 2.1. Cuore-0 and Cuore

The Cuore experiment $^{[14]}$ at the INFN Gran Sasso Laboratory (LNGS), Italy, is going to search for the $0\nu\beta\beta$ of $^{130}\text{Te}$ ($Q_{\beta\beta}=2528$ keV) by using the bolometric technique $^{[29]}$ which was already demonstrated by MiniBETA $^{[30]}$ and Cuoricino $^{[31]}$. The Cuoricino precursor experiment collected an exposure of 19.7 kg·yr and gave a lower limit on the half-life of $^{130}\text{Te}$, $T_{1/2}^{0\nu}>2.8\times10^{24}$ yr $^{[32]}$.

The Cuore experiment will deploy 988 crystals of TeO$_2$ (741 kg in total, 206 kg of $^{130}\text{Te}$), arranged in a large array made of 19 towers, each containing 52 crystals in 13 planes. The crystals will be operated in a cryostat, at a temperature of a few mK. The target background at $Q_{\beta\beta}$ is 0.01 cts/(keV · kg of TeO$_2$ · yr).

The first step of the Cuore assembly is Cuore-0: it is a full Cuore tower, which has been cooled down and operated in the old Cuoricino cryostat since March 2013. Cuore-0 served to define and test the Cuore assembly procedures, but it is also a real data-taking experiment, having 51 crystals out of 52 properly working. It demonstrated that a complete Cuore tower can be assembled in less than four weeks. Calibrations performed with a $^{232}\text{Th}$ source show that the spectroscopic performances and the energy resolution (5.7 keV FWHM at $Q_{\beta\beta}$) are well within expectations $^{[15]}$. The Cuore-0 background measured
from the initial 7.1 kg yr exposure is 0.07 cts/(keV kg yr), limited by the radioactivity of the old Cuoricino cryostat \[15\]. Given the background and the energy resolution, Cuore-0 is expected to surpass with one year of live time the $^{130}\text{Te}$ 0$\nu\beta\beta$ half-life sensitivity achieved by Cuoricino.

Meanwhile, the construction of the full Cuore experiment is regularly ongoing, concerning both the assembly of the detector towers (which is foreseen to be completed in July, 2014) and the commissioning of the cryogenic plant. The first cool down of the set up is expected by end of 2014. The sensitivity of the full-scale experiment after 5 yr of data taking and with a background of 0.01 cts/(keV kg yr) is about $10^{26}$ yr (90% C.L.) \[33\].

2.2. Majorana Demonstrator

The MAJORANA demonstrator (MJD) project plans to construct and operate large modular arrays of high-purity germanium (HPGe) detectors for the search of the 0$\nu\beta\beta$ decay of $^{76}\text{Ge}$ \[16\]. The set up is located underground at the 4850-feet level of the SURF Laboratory, United States. The main goal of the project is to demonstrate that an appropriate low-background level can be achieved to justify the design and the construction of a $^{76}\text{Ge}$ ton-scale experiment.

The target background in a 4-keV wide region of interest (ROI) at the $Q_{\beta\beta}$ of the $^{76}\text{Ge}$ decay ($Q_{\beta\beta}=2039$ keV) is 3 counts/(ROI ton yr), after all analysis cuts. This scales to 1 count/(ROI ton yr) in a one-ton experiment. The MJD set up is designed to be very compact: the array of HPGe detectors is hosted in two independent ultra-clean vacuum cryostats, made out of electroformed copper. The cryostats are surrounded by a low-background passive shielding made of copper and lead, with an active muon veto. In the first phase, 40 kg of HPGe p-type point-contact detectors will be deployed (20 kg in each cryostat), 30 kg of which are made out of germanium isotopically enriched in $^{76}\text{Ge}$ ($^{\text{enr}}\text{Ge}$).

The first step of the commissioning was performed in 2013 with a prototype vacuum cryostat, having the same design as the final cryostats but made out of non-electroformed copper. Two strings of natural detectors were deployed and operated. The subsequent steps of the MJD commissioning will be the operation of the first cryostat (seven strings of $^{\text{enr}}\text{Ge}$ detectors with a few natural detectors), in Summer 2014, and of the second cryostat (three strings of $^{\text{enr}}\text{Ge}$ detectors and four strings of natural detectors), in about Summer 2015.
2.3. SuperNEMO Demonstrator

The SuperNEMO project [17] is the successor of the completed NEMO3 experiment [34], which was in operation at the Modane underground Laboratory (LSM), France, between 2003 and 2011. The main design feature of the experiment is the tracking capability, allowing to detect separately the two electrons emitted in the $0\nu\beta\beta$ decay. The source is in the form of very thin foils and does not coincide with the detector. This gives the maximum flexibility in the choice of the candidate $0\nu\beta\beta$ isotopes: actually seven of them were studied in NEMO3, the most important one being $^{100}$Mo.

The NEMO3 detector was composed by 6180 drift chambers (Geiger cells) for the tracking part, and 1940 plastic scintillators (read out by photomultipliers) for the calorimetry part. A key experimental figure of merit is the energy resolution (8% FWHM at $Q_{\beta\beta}$), which determines the background due to the $2\nu\beta\beta$ decay. The background level achieved in NEMO3 at the $Q_{\beta\beta}=3034$ keV of $^{100}$Mo was $1.2 \cdot 10^{-3}$ cts/(keV-kg-yr), mainly ascribed to $2\nu\beta\beta$ decay and to $^{222}$Rn-induced events: all other background sources are efficiently suppressed by the topological reconstruction. No events were found in the high-energy range [3.2-10.0] MeV in a total exposure of 47 kg-yr (collected with many isotopes). Recently new results have been released by NEMO3 on the $0\nu\beta\beta$ decay of $^{100}$Mo: 18 events were observed in the range [2.8-3.2] MeV, to be compared with $16.4 \pm 1.3$ expected from background, after a 34.7 kg-yr exposure. This turns out in a lower limit on the half-life $T_{1/2}^{0\nu} > 1.1 \cdot 10^{24}$ yr (90% C.L.) [35].

The SuperNEMO project [17] will use the same design and technology which were successfully employed in NEMO3. The goal is to deploy up to 100 kg of target isotope within 20 identical modules at LSM. $^{82}$Se is the primary choice as the target isotope but $^{150}$Nd and $^{48}$Ca are also considered, depending on the development of viable enrichment procedures. The SuperNEMO Collaboration will firstly operate one module (7 kg of $^{82}$Se) as a demonstrator: it is presently under construction at LSM. Each module will contain 2000 drift chambers for the tracking part and 712 plastic scintillators for the calorimetry; it will be shielded by iron (300 tons) and water. In order to meet the background specifications, the energy resolution was improved by a factor of two in SuperNEMO, namely to 4% (FWHM) at $Q_{\beta\beta}$. Furthermore, very stringent limits must be achieved for the $^{208}$Tl, $^{214}$Bi and $^{222}$Rn radioactivity of the source foils. In this case, it is anticipated that the SuperNEMO demonstrator can run background-free for 7 kg of $^{82}$Se and two years of data.
taking.

2.4. SNO+

The facilities and infrastructures of the former SNO heavy-water neutrino experiment [36] at SNOLAB, Canada, are being refurbished and upgraded to support a new project, named SNO+. In particular, heavy water is replaced by liquid scintillator as the main target, thus providing a much superior light yield. Given the low background and the tracking capability, SNO+ has several physical reaches (e.g. supernova and solar neutrinos), but priority has been granted to the \(0\nu\beta\beta\) decay searches. The candidate \(0\nu\beta\beta\) isotope is \(^{130}\text{Te}\), which will be deployed in the detector in the form of 0.3% loading of the liquid scintillator [18, 37]. The total mass of \(^{130}\text{Te}\) in the fiducial volume (3.5 m) would hence be 800 kg. The main experimental issue is to achieve a sufficient energy resolution (i.e. a sufficient light yield from the loaded scintillator) such to suppress the background from the two-neutrino decay. For an energy resolution \(\sigma=4\%\) at \(Q_{\beta\beta}=2528\) keV, a potential sensitivity is expected to 200 meV neutrino effective mass in two years of data taking. The milestones anticipated by the SNO+ Collaboration are to fill the SNO detector with purified liquid scintillator in the mid of 2014, and then to load the scintillator with Te-based compounds in early 2015.

2.5. CANDLES

CANDLES is a project which aims to look for the \(0\nu\beta\beta\) decay of \(^{48}\text{Ca}\) by using CaF\(_2\) detectors [19, 38]. The decay has a very high \(Q_{\beta\beta}\)-value (4272 keV), which makes the experiment practically insensitive to the environmental \(\gamma\) background. Given the very low natural abundance of \(^{48}\text{Ca}\) (0.187%), isotopic enrichment is mandatory for a competitive experiment: R\&D is ongoing to identify and optimize a viable enrichment strategy. The basic design of the project is to operate CaF\(_2\) detectors immersed in a 4\(\pi\) active shield made out of liquid scintillator. The CANDLES III experiment is presently taking data since Spring 2013 at the Kamioka underground laboratory, Japan. It is operating 96 CaF\(_2\) detectors (305 kg of total mass, but with natural \(^{48}\text{Ca}\) abundance) immersed in liquid scintillator [39]. Due to the usage of non-enriched Ca, CANDLES III cannot be competitive in terms of sensitivity to \(0\nu\beta\beta\) decay, but the experimental performance (e.g. energy resolution) and the achievable background are being studied and optimized. The CANDLES III set up is scheduled to take data for 2014 and 2015, before the transition to the next upgrades.
(CANDLES IV and CANDLES V), in which detectors enriched in $^{48}\text{Ca}$ will be deployed, provided that the current R&D on the enrichment is successfully completed. However, the funding for the next phases of CANDLES has not been secured yet.

3. The Gerda experiment

The GERDA experiment at the Gran Sasso National Laboratory (LNGS) of INFN, Italy, is searching for the $0\nu\beta\beta$ decay of $^{76}\text{Ge}$ [12]. The recent physics results from the Phase I data [13] are summarized and reviewed here.

3.1. The experimental set up

The operational design of the GERDA experiment follows the concept proposed in Ref. [40]: high-purity germanium (HPGe) detectors made out of material isotopically enriched in $^{76}\text{Ge}$ ($^{\text{enr}}\text{Ge}$) are operated naked in liquid argon. The liquid argon is contained in a stainless steel cryostat of 4 m radius: it provides at the same time a very radio-pure passive shielding against the external radiation and the cooling which is necessary to operate HPGe detectors. The cryostat is enclosed in a 3 m-thick water volume, which gives additional shielding against external $\gamma$-rays and neutrons. The water is equipped with 66 photo-multipliers and is operated as a Cherenkov veto, to identify events in the detectors that are originated by muon-induced showers. The $^{\text{enr}}\text{Ge}$ detectors are deployed within vertical strings containing two or three elements each. Neighbor strings are kept very close to maximize the background rejection by anti-coincidence in the detector array: genuine $0\nu\beta\beta$ decays mostly release the total amount of energy ($Q_{\beta\beta}=2039$ keV) in one detector only. Particular care was devoted to reduce the amount of material close to the detectors (holders, cables, electronics, etc.), and to maximize the radio-purity of all components.

In the first Phase of GERDA, which lasted from November 2011 to May 2013, the existing coaxial $^{\text{enr}}\text{Ge}$ detectors previously operated by the HdM [7] and Igex [11, 42] experiments were re-used. The data from six out of the eight detectors could be considered for the physics analysis (14.6 kg); the other two detectors exhibited high leakage current or other instabilities. In June 2012, five newly produced $^{\text{enr}}\text{Ge}$ detectors of BEGe type (manufactured by Canberra) were deployed [12]. They are the outcome of the first production batch of GERDA custom-made $^{\text{enr}}\text{Ge}$ detectors, after their initial test-bench
The data of four out of the five BEGe detectors (3.0 kg) could be used for physics analysis. The total exposure accumulated within the GERDA Phase I is 21.6 kg·yr, with a duty factor of about 88% [13]. A temporary increase of the background of the coaxial detectors in the energy range of interest for the 0νββ searches was observed after the deployment of the BEGe detectors; the background came back to the previous level in approximately 20 days [45]. The data of the coaxial detectors taken during this period was labeled as “silver data set” (1.3 kg·yr exposure), while all the rest was labeled as “golden data set” (17.9 kg·yr). The BEGe data available for physics analysis amount to 2.4 kg·yr.

The energy reconstruction is performed off-line by using a semi-gaussian filter [46]. The exposure-averaged energy resolution at Qββ is (4.8 ± 0.2) keV and (3.2 ± 0.2) keV full width at half-maximum (FWHM), for the coaxial and BEGe detectors, respectively [45]. The energy scale was determined and monitored by one-hour irradiations with three 228Th radioactive sources, that were performed every one or two weeks. The shift of the position of the 2615 keV γ-line from the 208Tl decay between two consecutive calibrations is about 0.5 keV rms, which is much smaller than the characteristic energy resolution of the detectors. In addition, the stability of the electronics was monitored in real-time by regularly injecting charge pulses of fixed amplitude into the input of the amplifiers.

3.2. Data analysis and results

Two main paradigms drove the analysis strategy of GERDA Phase I:

- blind analysis. All events in a 40 keV range around Qββ were initially not made available for the analysis (neither the energy nor the pulse shape). Background model and pulse shape discrimination techniques were developed and validated on the open data. All procedures and cuts were frozen before the unblinding.

- all valid physics data are considered for the analysis. The available data are separated in three data sets, which differ for background and energy resolution, and a combined analysis is performed. This approach allows to maximize the amount of data which is accounted for the analysis, and avoids the lower-quality data (e.g. the “silver” data set) to spoil the sensitivity of the higher-quality ones, because data are never summed up.
A complete and quantitative background model was developed and validated before the unblinding, using a fraction (85%) of the final data set [45]. The predictions provided by the model were checked “a posteriori” against the final data set (without any additional fit) and were found to be consistent with the events uncovered from the blinded region. The main outcomes from the background model affecting the 0νββ analysis were that: (1) the expected background at Qββ has a flat energy spectrum in a relatively large range; (2) no intense γ-lines are expected in the vicinity of Qββ. As a consequence, the experimental GERDA spectrum was fitted by using a flat background model between 1930 and 2190 keV (apart from two known γ-lines at 2104 keV and 2119 keV).

The sum energy spectrum of GERDA is displayed in Fig. 1 with and without the pulse shape discrimination (PSD) described in Ref. [47]. Notice that the spectra of the three data sets are shown here together, but they were considered separately for the analysis. The typical background level achieved in
the coaxial detectors before PSD was about $2 \cdot 10^{-2}$ cts/(keV-kg-yr). The effect of the PSD was to reduce the continuous background by approximately a factor of two for the coaxial detectors and by a factor > 5 for the BEGe detectors, for a $0\nu\beta\beta$ signal acceptance of 90% and 92%, respectively. Since the sensitivity of the experiment scales as signal/$\sqrt{\text{background}}$, the optimal configuration for the GERDA PSD cuts was achieved by keeping a high acceptance and a moderate background rejection [48]. More strict PSD cuts – which further reduce the residual background at the price of a lower signal acceptance – do not provide any improvement in sensitivity.

Having fixed all cuts and procedures in advance, the data unblinding revealed seven events in the energy range $Q_{\beta\beta} \pm 5$ keV, as summarized in Table 2, three events survived the PSD analysis, at energies 2036.9 keV (“silver”), 2041.3 keV (“golden”) and 2035.5 keV (“golden”), respectively. No events were found within $\pm 1\sigma$ from the $Q_{\beta\beta}$ value, being $\sigma$ the expected (root mean square) width of the Gaussian peak due to energy resolution. The number of events at $Q_{\beta\beta}$ is consistent with the expectations from a constant background, as derived from the energy range 1930–2190 keV (see Table 2).

There is no indication of unidentified $\gamma$-lines in the region of interest $Q_{\beta\beta} \pm 20$ keV. In particular, the possible presence of weak $\gamma$-like structures at 2016 keV and 2052 keV from the $^{214}$Bi decay can be assessed quantitatively by the comparison with the more intense $^{214}$Bi line at 2204 keV [49]. The lines at 2016 keV and 2052 keV were observed in the HdM spectrum [6]: they were a major discussion topic in the early times after the publication of the observation claim [8, 50, 51, 52]. The intensity of the 2204 keV line (5.08% branching ratio) in GERDA is $(0.8 \pm 0.3)$ cts/kg-yr [52], before PSD, corresponding to 17.3 ± 6.5 counts. This is an order of magnitude lower than the level observed in HdM, $(8.1 \pm 0.5)$ cts/kg-yr [53]. The number of counts expected in the GERDA data for the structures at 2016 keV and 2052 keV is < 1, as summarized in Table 3.

Calibration data taken with $^{228}$Th and $^{56}$Co sources proved that all $\gamma$-ray peaks and all double-escape events (that are kinematically mimicking the $0\nu\beta\beta$ decay) are reconstructed at the correct position [48]. This confirms that there are no significant effect of ballistic deficit in GERDA, and that the $0\nu\beta\beta$ signal is expected at $Q_{\beta\beta}$.

\footnote{The structure at 2016 keV would emerge as a combination of a line at 2016.7 keV and two unresolved lines at 210.8 and 201.6 keV, respectively.}
Table 2: Summary of the events detected by GERDA in the energy range $Q_{\beta\beta}$±5 keV, before and after the PSD cuts. The events are subdivided in the three reference data sets (“golden coaxial”, “silver coaxial” and BEGe). The expected number of background events is also shown, as derived from the interpolation range of Fig. 1.

| Data set | Without PSD | With PSD |
|----------|-------------|----------|
|          | observed | expected | observed | expected |
| golden   | 5        | 3.3      | 2        | 2.0      |
| silver   | 1        | 0.8      | 1        | 0.4      |
| BEGe     | 1        | 1.0      | 0        | 0.1      |

Table 3: Evaluation of the intensity of the weak $^{214}$Bi lines at $Q_{\beta\beta}$ in GERDA from the $^{214}$Bi line observed at 2204 keV. The full energy peak efficiency is assumed to be approximately the same at 2016, 2053 and 2204 keV, so intensities are scaled according to the branching ratios only.

| Line (keV) | Branching ratio | Intensity (counts) |
|------------|-----------------|--------------------|
| 2204.2     | 5.08%           | 17.3 ± 6.5         |
| 2010.8 + 2016.7 + 2021.6 | 0.067%       | (0.23)             |
| 2052.9     | 0.069%          | (0.23)             |

The limit for the number of events in the $0\nu\beta\beta$ peak at $Q_{\beta\beta}$ was derived by a combined maximum likelihood fit of the energy spectra. The three data sets were analyzed individually, each with its own average background (free parameter) and energy resolution. The inverse half-life of the $0\nu\beta\beta$ decay $1/T_{1/2}^{0\nu}$ (which is proportional to the number of counts) is kept as a common free parameter. The analysis was performed with a frequentist (baseline) and a Bayesian approach, using the same likelihood function [13, 48]. The best fit is obtained for $1/T_{1/2}^{0\nu}=0$, namely, no counts ascribed to the $0\nu\beta\beta$ decay. The frequentist analysis gives a limit $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr, at 90% C.L., to be compared with a median expected sensitivity of $2.4 \cdot 10^{25}$ yr. When the data from the predecessor experiments HDM [7] and IGEX [41] are included into a combined fit, the limit is strengthened to $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr, at 90% C.L. The likelihood profiles obtained in this analysis are shown in Ref. [48]. For the Bayesian approach, a flat prior probability distribution was taken for $1/T_{1/2}^{0\nu}$ between 0 and $10^{-24}$ yr$^{-1}$. The marginalized posterior distribution $p(1/T_{1/2}^{0\nu})$ is shown in Fig. 2 for the GERDA data and for the combination with IGEX and HDM. The most probable value is $1/T_{1/2}^{0\nu}=0$ in both cases. The 90% probability quantile of the GERDA posterior distribution

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Figure 2: Posterior pdf \( p(1/T_{1/2}^{0\nu}) \) for the inverse half-life derived from the Bayesian analysis. The red (thin) and black (thick) solid lines are the posterior distributions obtained for the GERDA data alone and for the combination of GERDA with IGEX and HdM, respectively. The dashed peak shows the observation claim according to Ref. [8]. The shaded area in green covers the 90% credibility interval for the combined analysis \( (1/T_{1/2}^{0\nu} < 0.34 \cdot 10^{-25} \text{ yr}^{-1}) \).

is \( T_{1/2}^{0\nu} > 1.9 \cdot 10^{25} \text{ yr} \) (90% credible interval), for a median sensitivity of \( 2.0 \cdot 10^{25} \text{ yr} \). The limit coming from the combined analysis with HdM and IGEX is \( T_{1/2}^{0\nu} > 2.9 \cdot 10^{25} \text{ yr} \) (90% credible interval).

The negative result obtained by GERDA (also in combination with the predecessor experiments) can be compared quantitatively against the observation claim of Ref. [8]. The result given in Ref. [9] is not considered here because of the inconsistencies pointed out in Ref. [10]. The hypothesis \( H_1 \), which is a \( 0\nu\beta\beta \) decay with \( T_{1/2}^{0\nu} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25} \text{ yr} \), is compared to the null hypothesis \( H_0 \), which is background only. The hypothesis \( H_1 \) predicts \( (5.9 \pm 1.4) \) events from the \( 0\nu\beta\beta \) decay in \( Q_{\beta\beta} \pm 2\sigma \) sitting on a constant background of \( (2.0 \pm 0.3) \) events, after all PSD cuts. There are actually 3 counts observed by GERDA in \( Q_{\beta\beta} \pm 2\sigma \), and none of them is in \( Q_{\beta\beta} \pm 1\sigma \). A set of \( 10^4 \) Monte Carlo repetitions of the GERDA experiments was gener-
ated with the assumption of the hypothesis $H_1$, to evaluate in which fraction of the cases the profile likelihood analysis yields $1/T_{1/2}^{0\nu}=0$ as the best fit [48]. It was found that $P(1/T_{1/2}^{0\nu}=0 | H_1)=0.01$, i.e. the probability to produce the actual outcome of GERDA with the $0\nu\beta\beta$ signal reported in Ref. [8] is 1%. From the Bayesian analysis it was also possible to derive the Bayes factor, i.e. the odd ratio between the two hypotheses under testing. It is $P(H_1)/P(H_0)=0.024$ with the GERDA data alone, which is further reduced to $P(H_1)/P(H_0)=0.0002$ when the IGEX and HDM data are included in the fit. The long-standing claim for a $0\nu\beta\beta$ signal in $^{76}$Ge is hence strongly disfavored.

3.3. Transition to Phase II

The transition to the Phase II of GERDA is presently ongoing. The goal of the Phase II is to increase by an order of magnitude the sensitivity on the $T_{1/2}^{0\nu}$ of $^{76}$Ge, namely to the scale of a few $10^{26}$ yr [54]. This will be achieved by the increase of the total detector mass and by the further suppression of the background at $Q_{\beta\beta}$, down to $10^{-3}$ cts/(keV·kg·yr). About 30 custom-made enrGe BEGe detectors are available for GERDA Phase II, totaling about 20 kg mass. They have been produced by Canberra Olen and they have been accurately characterized at the HADES underground facility, Belgium [44]. The first batch of the production (5 enrGe BEGe detectors) was deployed in GERDA Phase I and hence tested in the real-life environment. No anomalies with internal or surface contamination were observed in the newly produced detectors; in particular, the surface contamination from $^{210}$Po turned out to be much smaller than for the coaxial detectors.

There are two main handles to achieve a background reduction by one order of magnitude with respect to Phase I: (1) further reduce the amount and the radioactivity of the materials in close vicinity of the detectors; (2) better reject the residual background by the powerful PSD of the BEGe detectors [55] and by the instrumentation of the liquid argon volume surrounding the detector array as an active veto.

A new front-end read-out and cabling are being developed with better radio-purity: this allows to place the front-end very close to the detectors ($<2$ cm) and hence to improve the energy resolution. Furthermore, new high voltage and signal cables are made available, with improved radio-purity and $^{222}$Rn emanation. The scintillation light of liquid argon in the 500 liter volume surrounding the HPGe detector array will be detected by photo-multipliers and SiPM detectors, thus turning the volume into an active veto system, which
is very effective for the identification of background coming from external $\gamma$ sources.
The commissioning of the Phase II set up is expected to start before Summer 2014.

4. Conclusions

Studies of the most popular candidate isotopes for the $0\nu\beta\beta$ decay indicate that there is not a theoretical “golden isotope”, which is clearly favored in terms of specific decay rate for a given Majorana neutrino mass. In spite of the differences in the nuclear matrix elements and in the phase space factors, all isotopes yield approximately the same decay rate. Therefore, other technical and practical parameters enter into the play – as energy resolution, background, scalability and cost – which can easily compensate for a less favorable nuclear matrix elements or a lower $Q_{\beta\beta}$-value.

There are presently many experimental and R&D programs ongoing, taking different candidate isotopes into consideration, that aim to reach an exposure in the scale of hundreds of kg·yr within the next 5-10 years. In particular: (1) GERDA has completed the data taking for Phase I (21.6 kg·yr) and is currently upgrading the set up for the Phase II; (2) Cuore-0 recently started the data taking, as the first step of the ton-scale Cuore project; (3) other experiments are being built, commissioned or designed. New results about the $0\nu\beta\beta$ decay of $^{100}$Mo have been recently released by NEMO3.

The data collected in GERDA Phase I were subject to a blind analysis. No positive signal was found at the $Q_{\beta\beta}$-value of $^{76}$Ge, with a background of approximately $10^{-2}$ cts/(keV·kg·yr), after the pulse shape discrimination. A lower limit on the $0\nu\beta\beta$ decay is set to $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr at 90% C.L. (GERDA alone), or $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr (in combination with the predecessor experiments HDM and IGEX). The observation claim of Ref. [8] is hence strongly disfavored by the GERDA data. The comparison is model-independent, since it is referred to the half-life $T_{1/2}^{0\nu}$ of $^{76}$Ge and does not involve theoretical calculations of nuclear matrix elements. The next phase of GERDA, which will start within the next few months, aims to collect an exposure of 100 kg·yr in 3 years, with a further reduced background, to push the sensitivity on $T_{1/2}^{0\nu}$ to the $10^{26}$ yr range.
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