IL NUOVO CIMENTO Vol. 35 C, N. 5 Settembre-Ottobre 2012
DOI 10.1393/ncc/i2012-11314-6

Communications: SIF Congress 2011

Study of double-beta decay with germanium detectors

G. Benato(*)
Universität Zürich (UZH) - Zürich, Switzerland

ricevuto il 31 Dicembre 2011; revisionato il 7 Marzo 2012; approvato il 15 Marzo 2012

Summary. — The neutrinoless double-beta decay is widely considered to be the easiest way to discriminate between the Dirac and the Majorana nature of neutrinos. The study of such process is being carried out with different isotopes and methods for more than two decades, but no result is yet univocally accepted by the Physics community. One of the most developed technologies makes use of germanium crystals, in which the radioactive source and the detector coincide. A brief review will be given about the characteristics of germanium experiments, the expected signal, the past and the present experiments. A more accurate study will be dedicated to the GERDA experiment, which is presently at the beginning of its data taking.

PACS 14.60.St – Non-standard-model neutrinos, right-handed neutrinos, etc.
PACS 95.55.Vj – Neutrino, muon, pion and other elementary particle detectors; cosmic ray detectors.

1. – Introduction

The search for neutrinoless double-beta decay ($0\nu2\beta$) is commonly regarded as the most affordable method to study the nature of neutrinos. The existence of such process would mean that neutrinos are Majorana particles, *i.e.* they are their own antiparticle. Moreover, this would involve the violation of the total lepton number and would be a very clear indication for the presence of Physics beyond the Standard Model.

An accurate explanation of the theory regarding the $0\nu2\beta$ decay is given in [1], while an up-to-date review both of the theoretical and of the experimental aspects of the process is provided in [2]. In this article a description of the different experimental techniques with their limits and capabilities is given, with particular attention to the experiments that are presently taking data or being developed.

A few dozens of isotopes are able to undergo double-beta decay [1,3]. This is possible if the final nucleus has a lower binding energy than its parent and if the single beta decay is energetically forbidden. The two-neutrino double-beta ($2\nu2\beta$) decay was firstly

(*) E-mail: gbenato@physik.uzh.ch

theorized by Maria Goeppert-Mayer in 1935 [4], while the $0\nu2\beta$ process was introduced by Wendel H. Furry in 1939 [5].

The main limit for double-beta decay experiments is given by the very high half-lives of the considered processes. Namely, the current estimations and/or limits for the $2\nu2\beta$ decays are at least of order 10^{18} y, while for the $0\nu2\beta$ case the half-lives are greater that 10^{23} y [6,7]. As a consequence the materials used in the experiments have to be as radio-pure as possible. Moreover a great quantity of the considered isotope and a long period of data taking (*i.e.* a few years) are needed.

The present paper is focused on the search for $0\nu2\beta$ decay in germanium-based experiments. The characteristics, pros and cons of this method are described. Moreover the expected signal and background are depicted. In the final part a summary of the past and present experiments is given, with particular attention to the currently running GERDA experiment.

2. – Germanium-based experiments

One of the isotopes that can undergo a double-beta decay is ^{76}Ge, which decays into ^{76}Se. ^{76}Ge is present with a 7.83% natural abundance [8], but it is possible to produce germanium crystals with a ^{76}Ge concentration up to 87% [9], thus incrementing of a factor ten the active mass in the crystal. The Q-value of both the $2\nu2\beta$ and $0\nu2\beta$ decay in ^{76}Ge is $Q = M_{^{76}\text{Ge}} - M_{^{76}\text{Se}} - 2m_e = 2039\,\text{keV}$, where $M_{^{76}\text{Ge}}$ and $M_{^{76}\text{Se}}$ are the masses of ^{76}Ge and ^{76}Se nuclei, respectively, and m_e is the electron mass. This Q-value is higher than the energy of most gammas that can induce a background in the measured spectrum, but is still lower than the energy of some other gammas, mainly generated by the radium and the thorium chains. A more accurate description of the gamma background will be given in the next section.

The measurements performed with Ge crystals are mainly calorimetric. The detectors have an approximately cylindrical shape with about 8 cm diameter and height. In the bottom part a cylindrical well, called borehole, is generally present. The outer and the upper surfaces are doped with lithium, while the bottom surface and the borehole (if present) are doped with boron. A depletion voltage of about 3000 V is applied to the surfaces, thus increasing the electrons and holes mobility inside the crystal. The energy released by a particle/gamma interacting with Ge is measured by collecting the charges at the boron-doped surface. A very accurate description of Ge detectors and their properties can be found in [10]. It is worth noting that the calorimetric nature of the measurement does not allow to reconstruct the path covered by the particles/photons inside the detector([1]). An accurate study of the pulse-shape allows to distinguish among different types of events, like multiple-scattering gammas or superficial alphas, but this is not an easy task.

Two types of Ge detectors are currently used in neutrino physics. The "traditional" High Purity Germanium diode (HPGe) is a cylinder with a radius of about 4 cm, a height of about 8 cm and a borehole of about 0.5 cm radius and 4 cm height on the bottom part. The Broad Energy Germanium diode (BEGe) has been developed only in the last decade and has a purely cylindrical shape, with both radius and height of about 4 cm. This simpler form reflects on a higher resolution and the possibility to perform a more accurate Pulse Shape Discrimination (PSD).

([1]) Some "segmented" detectors are now available, but they have not yet be successfully used in the study of $0\nu2\beta$ decay.

The great advantage given by Ge detectors with respect to other techniques used in the $0\nu2\beta$ Physics is the energy resolution. A typical HPGe diode has a 0.2% FWHM resolution at the Q-value [10], while a BEGe detector can reach a 0.1% FWHM resolution at the same energy [11].

Another advantage of using Ge detectors is given by the very high purity of the crystals, which can be of order 1 ppb [12]. In particular, the thorium and radium impurities are chemically extracted during the crystal growth, while the formation of other radioactive isotopes (*e.g.*, the ^{68}Ga, which decays via β-process with 2921 keV Q-value) is avoided by minimizing the time during which the Germanium is on the Earth's surface. Since such β-decays could mimic a double-beta signal, much attention has to be given to the production procedure of the germanium crystals. The present-day technology allows to reach such a purity that the dominant background is induced by contaminants located outside the crystal. The standard procedure to reduce the rate of events induced in Ge by external radiation is to place the experiment in an underground laboratory and to build a so-called *graded shielding*. The diode is put inside a structure with layers of different materials with higher levels of radio-purity from the outer to the inner one. Usually in the new experiments an active veto against cosmic muons is present, while some other technologies to veto the gamma radiation are being developed [12].

On the other side, germanium-based experiments are strongly limited by the realization cost. The enrichment of Ge is successfully made by only one manufacturer [9], while only a couple of companies are able to produce Ge crystals with a sufficient purity level. This reflects on very high prices and could forbid the realization of experiments with more than 100 kg Ge mass.

3. – Double beta decay signal in germanium detectors

The study of double beta decays in Ge detectors is made through the inspection of the measured energy spectrum. Neglecting the nucleus recoil, the $2\nu2\beta$ decay final state has four emitted particles: what we can see are two electrons emitted at the same time, therefore inducing a unique signal in the diode, while the two antineutrinos escape and appear as missing energy. Consistently the measured spectrum is a broad continuum arising from zero and ending in correspondence to the Q-value. The formula describing the $2\nu2\beta$ energy distribution, calculated on the basis of nuclear structure models and simple kinematics, is given by [13]

$$F(E) = E\big(E^4 + 10E^3 + 40E^2 + 60E + 30\big)(Q - E)^5, \tag{1}$$

where E is the energy sum of the two electrons and Q the Q-value of the reaction.

On the contrary, the $0\nu2\beta$ decay consists of only two electrons being emitted at the same time. For the momentum conservation and neglecting again the nucleus recoil, they will be emitted in opposite directions, each carrying an energy equal to half of the Q-value. A short calculation shows that a 1 MeV electron gets stopped in about 1 mm of germanium [14]. The Ge diode is not able to distinguish two 1 MeV electrons being emitted at the same place and in the same time, since the spatial resolution of Ge crystals is very poor [10]. As a result, the recorded energy spectrum will present a peak at the Q-value of the reaction.

A third possible decay is that involving the Majoron (χ^0) emission ($\chi^02\beta$), which is a light neutral boson invoked by some extensions of the Standard Model [2]. In this case the final state has, always neglecting the nucleus recoil, three particles, the two electrons and the Majoron. As for the $2\nu 2\beta$ decay, only the electrons can be seen by the detector and the measured spectrum will also be a continuum distribution. This can be distinguished from the $2\nu 2\beta$ spectrum because its maximum height will be shifted towards higher energies, since in this case the total available energy is distributed among three particles. Namely in this case the energy distribution would be [13]

$$F(E) = E\big(E^4 + 10E^3 + 40E^2 + 60E + 30\big)(Q - E). \tag{2}$$

Experimental measurements or limits for ^{76}Ge exist for all the three decays.

- For the $2\nu 2\beta$ decay the current literature value is $T_{1/2}^{2\nu 2\beta} = [1.5\pm0.1]\cdot 10^{21}$ y, averaged over the most sensitive experiments performed up to now [6, 7] (see sect. **4**).
- For the $0\nu 2\beta$ decay both a measurement and a limit are present, calculated on the basis of the data of the Heidelberg-Moscow experiment (HdM) [15]. Both the limit and the measured value for the half-life are of order 10^{25} y. A more accurate description of these measurement will be given in subsect. **4**˙2.
- For the $\chi^0 2\beta$ decay, only a limit of $T_{1/2}^{\chi^0 2\beta} > 6.4 \cdot 10^{22}$ y (90% CL) is available [16].

Clearly the difference of at least one order of magnitudes between the half-lives of the $2\nu 2\beta$ and the $\chi^0 2\beta$ decay strongly limits the possibility to see the Majoron emission. Namely the two distributions would superimpose and the $\chi^0 2\beta$ spectrum would be overwhelmed by the $2\nu 2\beta$ one even in the absence of any external background. Up to now the highest amount of data was collected by the HdM experiment, with about $8\cdot 10^4$ events attributed to $2\nu 2\beta$ decay [6], which led to the limit reported above. A much higher statistics or a lower background is therefore needed to test the Majoron existence.

On the other side the probability for two electrons generated by a $2\nu 2\beta$ event to induce a signal in proximity of the Q-value is very low. Namely only $(3.4 \cdot 10^{-3})$% of the $2\nu 2\beta$ events fall above 1900 keV and only $(2 \cdot 10^{-6})$% fall above 2000 keV (calculated from eq. (1)). Since the typical resolution of a Ge diode is about 4–5 keV (or better) at 2000 keV, the $2\nu 2\beta$ decay does not influence the $0\nu 2\beta$ spectrum.

From these considerations it follows that the main background for $0\nu 2\beta$ Ge experiments is represented by the radioactivity of the materials surrounding the Ge crystals. This background is represented by gamma-rays emitted by several isotopes typically present in the experiment shielding. A brief list of the most common background sources is the following:

- ^{232}Th and its daughters are present in most of the metallic parts of the experiments and are unavoidable because of the very high ^{232}Th half-life $(1.4 \cdot 10^{10}$ y). In particular, a 2614.5 keV gamma is emitted by ^{208}Tl, one of the last members of the chain. This high-energy gamma induces a continuum also in the region around 2039 keV.
- ^{238}U and its daughters are also present in the metallic parts and, as in the previous case, are not removable. The members of this chain emit also high-energy gamma-rays. Some examples are the 2204.2 and 2447.9 keV gammas emitted by ^{214}Bi.
- ^{40}K is present in almost every part of the experiments and emits only one gamma with 1460.8 keV energy. It is therefore a background for the $2\nu 2\beta$ decay, but not for the $0\nu 2\beta$ one.

TABLE I. – *Summary of the available measurements* $2\nu2\beta$ *and* $0\nu2\beta$ *decay in* ^{76}Ge. N *is the number of events used in the calculation.* S/B *is the signal-to-background ratio. The first error reported for the HdM experiment is the statistical error, while the second is systematic* [17]. *The limits at* 68% *CL are reported with a* *, *those at* 90% *with* **. *An accurate analysis of the here presented results can be found in* [6] *and* [7]. *For the HdM experiment no commonly accepted result is available (see text).*

Experiment	Year	N	S/B	$T_{1/2}^{2\nu2\beta}$ (years)	$T_{1/2}^{0\nu2\beta}$ (years)
CNPSIC [18]	1989			$> 1.0 \times 10^{20**}$	$> 1.6 \cdot 10^{23**}$
ITEP/YePI [19]	1990	$\sim 4 \times 10^3$	$\sim 1/8$	$(0.9 \pm 0.1) \times 10^{21}$	$> 1.3 \cdot 10^{24*}$
PNL-USC [20]	1990	758	$\sim 1/6$	$(1.1^{+0.6}_{-0.3}) \times 10^{21}$	
PNL-USCbis [21]	1991	132	~ 4	$(9.2^{+0.7}_{-0.4}) \times 10^{20}$	
PNL-USCbis [22]	1994	132	~ 4	$(1.2^{+0.2}_{-0.1}) \times 10^{21}$	
IGEX [23]	1996	$\sim 3 \times 10^3$	~ 1.5	$(1.1 \pm 0.2) \times 10^{21}$	$> 4.2 \cdot 10^{24**}$
IGEX [24, 25]	1999	$\sim 3 \times 10^3$	~ 1.5	$(1.45 \pm 0.15) \times 10^{21}$	$> 0.8 \cdot 10^{25*}$
HdM [17]	2003	$\sim 8 \times 10^4$	~ 1.5	$(1.74 \pm 0.01^{+0.18}_{-0.16}) \times 10^{21}$	?

– ^{60}Co is mostly present in copper parts and emits two gammas at 1173.2 and 1332.5 keV with about 100% intensity and also a gamma at 2158.6 keV with a $1.2 \cdot 10^{-3}$% intensity. The first two lines constitute a background for the $2\nu2\beta$ spectrum, while the second could be a source of background for the $0\nu2\beta$ case.

– ^{58}Co is also present in copper parts and emits one gamma at 820.8 keV. Anyway thanks to its half-life of about 71 days, ^{58}Co is not a major trouble in double beta decay experiments.

– ^{222}Ra and its daughters are present everywhere, especially underground, and emit some alphas with energies above 5 MeV. A possible background is therefore given by degenerated alphas which release only a fraction of their original energy in the active region of the germanium diodes. Also too avoid this, the Ge crystals are usually kept in nitrogen atmosphere, while in the GERDA experiment the diodes are deployed naked in Liquid Argon (LAr).

4. – History of double beta decay experiments

Up to now the measurement of the double beta decay in ^{76}Ge has been done in five experiments. All but one made use of enriched germanium detectors. Since ^{76}Ge does not emit any gamma, the only way to find the half-life of the process is to look at the continuum after having subtracted all the known backgrounds.

A summary of the available measurements is reported in table I.

4·1. *Evolution of the* $2\nu2\beta$ *study.* – The first $2\nu2\beta$ decay experiment with ^{76}Ge was done by the Caltech-Neuchatel-Paul Scherrer Institut Collaboration in 1989: the data refers to an exposure of 3.93 kg · y, leading to the upper limit of $T_{1/2}^{2\nu2\beta} > 1.0 \times 10^{20}$ y (90% CL) [18].

In 1990 a Collaboration between the Moscow Institute for Theoretical and Experimental Physics and the Yerevan Physical Institut (ITEP/YePI) employed for the first time two enriched germanium detectors, with 85% of ^{76}Ge. The two enriched detectors were put inside a cryostat together with a germanium detector with natural isotopic abundance. The half-life measurement was obtained by subtracting the spectrum of the natural germanium detector to the summed spectrum of the two enriched detectors [19].

At the same time an American Collaboration between the Pacific Northwest Laboratory and the University of South Carolina (PNL-USC) made an analogous experiment using two natural germanium detectors [20].

In 1991 the ITEP/YePI and the PNL-USC Collaborations joined together to deploy one 0.25 kg enriched detector in the PNL-USC ultralow-background cryostat in Homestake Mine, (USA). A total exposure of $0.059\,\text{kg}\cdot\text{y}$ led to a half-life $T^{2\nu2\beta}_{1/2} = (9.2^{+0.7}_{-0.4})\times 10^{20}$ y [21]. In 1994 the result was corrected to $T^{2\nu2\beta}_{1/2} = (1.2^{+0.2}_{-0.1})\times 10^{21}$ y [22].

In 1996 the IGEX experiment used about 8 kg of enriched germanium and found a half-life $T^{2\nu2\beta}_{1/2} = (1.1 \pm 0.2) \times 10^{21}$ y [23]. In 1999 this value was revisited to $T^{2\nu2\beta}_{1/2} = (1.45 \pm 0.15) \times 10^{21}$ y [24, 25].

A new measurement was published in 2003 by part of the HdM Collaboration after having collected $41.57\,\text{kg}\cdot\text{y}$ of data. The background was simulated and subtracted from the experimental spectrum. The extracted half-life is $T^{2\nu2\beta}_{1/2} = (1.74 \pm 0.01(\text{stat})^{+0.18}_{-0.16}(\text{syst}))\times 10^{21}$ y [17]. On the same time, the Russian part of the collaboration published a similar value (using the same data): $(T^{2\nu2\beta}_{1/2} = 1.78 \pm 0.01(\text{stat})^{+0.08}_{-0.10}(\text{syst})) \times 10^{21}$ y [26].

The weighted average for the measurements with signal-to-background ratio greater than one is $T^{2\nu2\beta}_{1/2} = (1.5 \pm 0.1) \times 10^{21}$ y [6].

4·2. *Evolution of the $0\nu2\beta$ study.* – The case of the neutrinoless double beta decay is more intriguing: up to now only the HdM experiment reported an evidence for it. It is important to note that the publications were signed only by part of the collaboration and much criticism was made upon the claim. The first paper was published in 2001 and reported a half-life of $T^{0\nu2\beta}_{1/2} = [0.8\text{–}18.3] \cdot 10^{25}$ y (95% CL) with a best value of $1.5 \cdot 10^{25}$ y [27], calculated with a 54.98 kg exposure and a Background Index (BI) of (0.17 ± 0.01) events/keV $\cdot$ kg $\cdot$ y before applying the PSD. This claim was criticized on the basis of the following reasons [28, 29].

– A previous paper [16] reported a limit of $T^{0\nu2\beta}_{1/2} > 1.9 \cdot 10^{25}$ (90% CL) with a $47.7\,\text{kg}\cdot\text{y}$ exposure and the same experimental set-up, so the analysis seems to be strongly model dependent.

– The entire spectrum is not presented, but only a 80 keV window around 2039 keV is shown. In this window several peaks are present: some of them are attributed to ^{214}Bi (part of the radium series) and one to the $0\nu2\beta$ decay, while some of them remain unrecognized, even if they are more prominent than that at 2039 keV.

– By studying the entire spectrum given in [16] and comparing the relative intensities of the gamma lines, the peaks attributed to ^{214}Bi seem not to be recognizable with the HdM exposure and BI. Therefore also the $0\nu2\beta$ peak seem to be spurious.

– The analysis seems to strongly depend on the choice of the energy window. The analysis was repeated by others (see [29]), leading to a maximum 1.5 σ evidence. In the HdM procedure the assumption of a flat background is made, but in that case the background would be better estimated on a wide region, not only a few keV around the Q-value.

- The effectiveness of the method in charge of the peak recognition is not demonstrated, *i.e.* it is not shown that this method works with the known peaks and does not find any peak if no peak exists in a certain energy region.
- The PSD should select the single site events ($0\nu2\beta$ case) and reject the multi-site events originated by gammas interacting with atoms in different parts of a Ge diode. But both the background and the $0\nu2\beta$ peak seem to be equally suppressed.

Later some other papers were published with improved values for the $0\nu2\beta$ half-life. The latest result is $T_{1/2}^{0\nu2\beta} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ y [30]. This value was deduced from an *a posteriori* re-analysis and can strongly depend on the known expected result.

It is also worth noting that analyzing the same data, another part of the collaboration published a limit of $T_{1/2}^{0\nu2\beta} \geq 1.55 \cdot 10^{25}$ y (90% CL) [26].

An important task for the present new-generation Ge experiments is therefore to test the claim of Klapdor and either confirm or reject its estimation with much higher accuracy.

5. – The GERDA experiment

Among the present experiments involved in the study of double beta decay, the GERmanium Detector Array (GERDA [12]) is one of the most promising ones and the only Ge experiment currently taking data. It is located in the Hall A at the Gran Sasso National Laboratory (LNGS). The experiment is carried on by an international collaboration formed by 17 Universities and Institutions from 7 different countries.

GERDA aims to reach a factor 100 lower Background Index (BI) in the $0\nu2\beta$-decay Region Of Interest (ROI) than previous experiments. This is pursued by directly immersing naked germanium detectors in Liquid Argon (LAr). Doing so the radioactive contaminants present in the material surrounding the detectors are strongly reduced. Cryogenic liquids like LAr have double advantage: on one side argon can be continuously purified, on the other side a big volume of LAr acts as a shield for gamma-rays coming from outside.

GERDA timetable is organized in two phases:

- in Phase I the germanium detectors from HdM and IGEX experiments are used. In total 17.7 kg of enriched germanium crystals are available, corresponding to 15.2 kg of ^{76}Ge, if an isotopic abundance of 86% is assumed. In November 2011 the Phase I has officially started with a BI $= 0.045^{+0.015}_{-0.011}$ counts/(keV $\cdot$ kg $\cdot$ y) in the $Q_{\beta\beta} \pm 200$ keV region [31].
- In Phase II new enriched Broad Energy Germanium detectors (BEGe) will be employed for an additional 20 kg germanium mass. The aim is to reach a 100 kg $\cdot$ y exposure in three years of measurements. BEGe detectors are currently being produced and tested. The planned BI for Phase II is 10^{-3} counts/(keV $\cdot$ kg $\cdot$ y), that would allow to measure the Majorana neutrino mass down to $m_M \leq 0.09$–0.29 eV (90% CL), depending on the matrix element used [12]. In order to reach the 10^{-3} counts/(keV $\cdot$ kg $\cdot$ y) BI, new effort must be made in the background suppression. This can be done, for example, by a pulse shape analysis improvement and by exploiting the LAr scintillation light as an anti-coincidence veto.

The main task for GERDA is background suppression. In particular, GERDA background is given by the radioactivity of the employed material and by cosmic radiation. For the latter, GERDA is located in the LNGS tunnel, under 3400 m of water equivalent. The remaining cosmic muons flux is read by scintillators located above and below the experimental set-up so that muon-generated events can be rejected. The germanium crystals are immersed in 70 m^3 of LAr, contained in a stainless-steel cryostat of 4.2 m in diameter. In this way photons and particles have to cover a long distance through LAr before reaching germanium, so that the flux is strongly reduced. The cryostat itself is immersed in 590 m^3 of ultrapure water, that shields photons and neutrons from outside. Moreover, particles passing through the water induce Cerenkov light, which is read by PMTs uniformly distributed in the water tank.

A class 10000 clean room is located on the top of the water tank. The clean room is necessary in order to minimize the LAr contamination risk and it is used for the handling of germanium detectors. A lock system is mounted inside the clean room and is the only connection between the cryostat inner and the rest of the world. It is flushed with gaseous nitrogen to minimize radon exposure during mounting and testing of enriched detectors. The detectors are hanged by a stainless-steel strip that is controlled by the lock. The germanium detector calibration is done by inserting ^{228}Th sources in LAr in proximity of the Ge detectors, while the energy resolution is estimated using ^{60}Co sources.

5˙1. *Capabilities of GERDA Phase I*. – Given a total mass of 17.7 kg of germanium and a BI $= 0.045^{+0.015}_{-0.011}$ counts/(keV · kg · y), one would ask how much time is needed to test the claim of Klapdor with enough accuracy. The limit on the $0\nu2\beta$ decay half-life corresponding to the 90% CL is given by [12]

$$T_{1/2}^{0\nu2\beta} > 4.3 \cdot 10^{24} \cdot \varepsilon \cdot a \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}\ [\mathrm{y}], \tag{3}$$

where ε is the detection efficiency, a the ^{76}Ge isotopic abundance in the crystals, M the total Ge mass and ΔE the energy resolution (FWHM).

Assuming an energy resolution of 4 keV at 2039 keV, a detection efficiency of 95% [32] and an isotopic abundance of 86% of ^{76}Ge, the following exposure is needed for GERDA to test the Klapdor claim ($T_{1/2}^{0\nu2\beta,\mathrm{HdM}} = 2.23^{+0.44}_{-0.31} \cdot 10^{25}$ y) with the 90% CL:

$$t_{\min} = \frac{BI \cdot \Delta E}{M} \cdot \left(\frac{T_{1/2}^{0\nu2\beta,\mathrm{HdM}}}{4.3 \cdot 10^{24} \cdot \varepsilon \cdot a} \right)^2 = 0.41\,\mathrm{y}. \tag{4}$$

If the GERDA takes data for one year in the same conditions, the achievable limit is $T_{1/2}^{0\nu2\beta} > 3.5 \cdot 10^{25}$ y. In Phase II with the current BI, three years of data taking and 37.7 kg of germanium would allow to increase the limit up to $T_{1/2}^{0\nu2\beta} > 8.8 \cdot 10^{25}$ y. If also the expected BI for Phase II is reached, the best limit achievable by GERDA is $T_{1/2}^{0\nu2\beta} > 5.9 \cdot 10^{26}$ y.

On the other side one can calculate the number of expected $0\nu2\beta$ events with exposure t if the claim of Klapdor is true. This is given by

$$N_{\mathrm{exp}}^{0\nu2\beta}(t) = N_0 - N(t) \simeq N_0 \lambda t, \tag{5}$$

where N_0 is the initial number of ^{76}Ge nuclei and $\lambda = \ln 2/T_{1/2}^{0\nu 2\beta}$. Given the current ^{76}Ge mass of 15.2 kg, there follows $N_0 = 1.2 \cdot 10^{26}$. Using the last value published by Klapdor, the decay constant is $\lambda = 3.1^{+0.6}_{-0.4} \cdot 10^{-26}\,\text{y}^{-1}$. Considering also the detection efficiency we have $N_{\text{exp}}^{0\nu 2\beta}(t) \simeq \varepsilon N_0 \lambda t$. On the basis of this, the expected number of events for GERDA Phase I with the current BI and one year exposure is $3.6^{+0.7}_{-0.5}$ over a background of 3.0 counts. Repeating the exercise for the Phase II with the nominal BI, in three years of data taking GERDA would collect 23^{+5}_{-3} events over a background of 0.4 counts, well above the five sigma threshold.

6. – Conclusion

The study of double beta decay with germanium detectors has been a crucial argument in the last twenty years. A precise estimation has been reached for the half-life of the two-neutrino mode, while no commonly accepted measurement has been done for the neutrinoless process. A claim of observation has been published by part of the Heidelberg-Moscow Collaboration, but lot of criticism has been raised against the analysis procedure. It is therefore a main task for the present and future experiments to test the claim with enough accuracy.

Among the new generation Ge experiments, GERDA is the only one that is currently taking data. It is expected to either confirm or reject Klapdor's claim in about half a year of exposure, within the current experimental configuration. A further improvement of the experiment with a corresponding BI decrease would allow to test the existence of the neutrinoless double beta decay up to a half-life of $5.9 \cdot 10^{26}$ y.

REFERENCES

[1] Giunti C. and Kim C. W., *Fundamentals of Neutrino Physics and Astrophysics* (Oxford University Press) 2007, pp. 494–498.

[2] Gómez-Cadenas J. J., Martín-Albo J., Mezzetto M., Monrabal F. and Sorel M., arXiv:1109:5515v1, preprint (2011).

[3] Tretyak V. and Zdesenko Y., *At. Data Nucl. Data Tables*, **80** (2002) 83.

[4] Goeppert-Mayer M., *Phys. Rev.*, **48** (1935) 512.

[5] Furry W. H., *Phys. Rev.*, **56** (1939) 1184.

[6] Barabash A. S., *Czech. J. Phys.*, **56** (2006) 437.

[7] Barabash A. S., *Phys. At. Nucl.*, **73** (2010) 162.

[8] Coursey J. S., Schwab D. J., Tsai J. J. and Dragoset R. A, `http://www.nist.gov/pml/data/comp.cfm`, webpage (2010).

[9] Shubin A. N. *et al.*, *Atom. Energy*, **101** (2006) 588.

[10] Gilmore G., *Practical Gamma-ray Spectrometry* (Wiley) 2008, pp. 45–52.

[11] Agostini M. *et al.*, *JINST*, **6** (2011) P04005.

[12] Abt I. *et al.* (GERDA Collaboration), *GERDA The GERmanium Detector Array for the search of neutrinoless ββ decay of* ^{76}Ge *at LNGS*, Proposal to the LNGS P38/04, September 2004, `http://www.mpi-hd.mpg.de/gerda/reportsLNGS/proposal_21sept.pdf`.

[13] Tretyak V. and Zdesenko Y., *At. Data Nucl. Data Tables*, **61** (1995) 43.

[14] `http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html`.

[15] Günther M. *et al.* (Heidelberg-Moscow Collaboration), *Phys. Rev. D*, **55** (1997) 54.

[16] Klapdor-Kleingrothaus H. V. *et al.*, *Eur. Phys. J. A*, **12** (2001) 147.

[17] Dörr C. and Klapdor-Kleingrothaus H. V., *Nucl. Instrum. Methods A*, **513** (2003) 596.

[18] Fisher P. *et al.*, *Phys. Lett. B*, **218** (1989) 257.
[19] Vasenko A. A. *et al.*, *Mod. Phys. Lett. A*, **5** (1990) 1299.
[20] Miley N. S. *et al.*, *Phys. Rev. Lett.*, **65** (1990) 3092.
[21] Avignone F. T. *et al.*, *Phys. Lett. B*, **256** (1991) 559.
[22] Avignone F. T., *Prog. Part. Nucl. Phys.*, **32** (1994) 223.
[23] Aalseth C. E. *et al.* (IGEX Collaboration), *Nucl. Phys. B (Proc. Suppl.)*, **48** (1996) 223.
[24] Morales A., *Nucl. Phys. B (Proc. Suppl.)*, **77** (1999) 335.
[25] Aalseth C. E. *et al.* (IGEX Collaboration), *Nucl. Phys. B (Proc. Suppl.)*, **70** (1999) 236.
[26] Bakalyarov A. M. *et al.*, *Phys. Part. Nucl. Lett.*, **2** (2005) 77.
[27] Klapdor-Kleingrothaus H. V., Dietz A., Harney H. L. and Krivosheina I. V., *Mod. Phys. Lett. A*, **16** (2001) 2409.
[28] Elliott S. R. *et al.*, *Mod. Phys. Lett. A*, **17** (2002) 1475.
[29] Feruglio F., Strumia A. and Vissani F., *Nucl. Phys. B*, **637** (2002) 345.
[30] Klapdor-Kleingrothaus H. V. and Krivosheina I. V., *Mod. Phys. Lett. A*, **21** (2006) 1547.
[31] The GERDA Collaboration, *GERDA Progress report to the LNGS scientific committee*, LNGS-EXP 33/05 add. 13/11, October 2011, `http://www.mpi-hd.mpg.de/gerda/reportsLNGS/gerda-lngs-sc-oct11-shwup.pdf`.
[32] Klapdor-Kleingrothaus H. V. *et al.*, *Phys. Lett. B*, **586** (2004) 198.