IL NUOVO CIMENTO Vol. 35 C, N. 6 Novembre-Dicembre 2012
DOI 10.1393/ncc/i2012-11352-0

Colloquia: LaThuile12

Searching for double-beta decays with the GERDA experiment

S. Hemmer(*) for the GERDA Collaboration

Dipartimento di Fisica e Astronomia, Università di Padova and INFN, Sezione di Padova Via Marzolo 8, 35131 Padova, Italy

ricevuto il 7 Settembre 2012

Summary. — The search for neutrinoless double-beta decay ($0\nu\beta\beta$) is presently the only feasible way to approach the fundamental question regarding the Majorana or Dirac nature of the neutrino. The observation of $0\nu\beta\beta$ would be the proof that the neutrino is a Majorana particle, *i.e.* that it is its own antiparticle. The measurement of the half-life of $0\nu\beta\beta$ would give direct access to a determination of the effective Majorana mass of the neutrino. The Germanium Detector Array (GERDA) experiment at the LNGS underground laboratories uses high-purity germanium detectors to search for $0\nu\beta\beta$ of ^{76}Ge. The experiment started Phase I in November 2011, using 15 kg of enriched germanium crystals with the goal of a background index of 10^{-2} counts/(keV·kg·y). A second, later phase will double the mass of the enriched detectors and aim at a background at the level of 10^{-3} counts/(keV·kg·y). This contribution presents the status of the GERDA Phase I data taking. A short outlook is given on the ongoing preparations for Phase II.

PACS 14.60.Pq – Neutrinos mass and mixing.
PACS 14.60.St – Nonstandard model neutrinos, right-handed neutrinos, etc.
PACS 29.40.Wk – Solid-state detectors.

1. – Neutrinoless double-beta decay

Oscillation measurements have established that the neutrinos are massive particles. The two squared mass differences have been measured, one in absolute value, one also in sign. There are, however, still many open questions: Is the neutrino a Majorana particle, that is its own antiparticle? Is the neutrino mass hierarchy normal or inverted? What is the absolute neutrino mass scale?

The only practical way to experimentally test the nature of the neutrino is the search for neutrinoless double-beta decay ($0\nu\beta\beta$). The observation of this process would be the proof that the neutrino has at least a Majorana component with a non-zero mass [1].

(*) E-mail: sabine.hemmer@pd.infn.it

Neutrino-accompanied double-beta decay ($2\nu\beta\beta$) has been observed for several nuclei [2] that cannot decay via single beta decay. In this standard-model allowed decay, the nucleus undergoes double-beta decay under emission of two electrons and two antineutrinos $\overline{\nu}_e$. Due to the presence of the $\overline{\nu}_e$, the combined energy spectrum of the two electrons is continuous. If neutrinos are Majorana particles, the $\overline{\nu}_e$ emitted in one beta decay can be absorbed in the other, leading to $0\nu\beta\beta$. This process is not allowed by the Standard Model and the lepton number is violated by two units. Since all energy released in the decay is carried by the outgoing electrons, the experimental signature is a sharp peak at the Q-value of the decay, $Q_{\beta\beta}$, in their combined energy spectrum. From the half-life $T_{1/2}$ of $0\nu\beta\beta$ the effective Majorana mass, $\langle m_{\beta\beta}\rangle$, can be deduced:

$$T_{1/2}^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta}\rangle^2,$$

$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} {U_{e_i}}^2\, m_i\right|,$$

where the U_{e_i} are the electron-neutrino elements from the mixing matrix, m_i are the neutrino mass eigenvalues, $G^{0\nu}(Q_{\beta\beta}, Z)$ is the phase-space factor of the decay of a nucleus with atomic number Z and Q-value $Q_{\beta\beta}$, and $|M^{0\nu}|^2$ is the nuclear matrix element. Assuming the neutrino exchange to be the dominant mechanism of the process it provides also information on the absolute mass scale.

2. – Search for $0\nu\beta\beta$ in ^{76}Ge

If it exists, $0\nu\beta\beta$ is an extremely rare process. If the number of signal events, N_S, is larger than the standard fluctuation expected for the number of background events, N_b, the sensitivity S on $T_{1/2}$ of an experiment scales as

$$S \sim \epsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}\,,$$

where ϵ is the detection efficiency, a the abundance of the $2\nu\beta\beta$ isotope, M the detector mass, t the measurement time, $b = N_b/(M \cdot t \cdot \Delta E)$ the background index, and ΔE the energy region of interest, ROI, which scales with the resolution of the detector. From this, the requirements on the experiment can be deduced: large ϵ, good energy resolution, small b, long t, and large $a \cdot M$.

These demands make germanium detectors an attractive option for the search for $0\nu\beta\beta$. Since ^{76}Ge is an isotope that undergoes double-beta decay, the detector is also the source. Germanium can be produced very radio-pure, guaranteeing a small intrinsic b and the typical energy resolution is of the order of (0.1–0.2)%.

There are also some disadvantages, though. The Q-value of ^{76}Ge is only 2039 keV, and thus the external b is rather large. In addition, a of ^{76}Ge in natural germanium is only 7.8%, so that costly enrichment is needed.

Table I shows the exposure, b, and the derived lower limits on $T_{1/2}$ for two former experiments that deployed germanium detectors to search for $0\nu\beta\beta$, the Heidelberg-Mowscow (HdM) experiment [3], and the IGEX experiment [4].

The corresponding upper limits on $\langle m_{\beta\beta}\rangle$ are of the order of 0.1 to 1 eV. The large uncertainties on $\langle m_{\beta\beta}\rangle$ are due to the uncertainties in the calculation of $|M^{0\nu}|^2$ [5].

TABLE I. – *Previous* ^{76}Ge *experiments.*

	HdM	IGEX
Exposure [kg·y]	71.1	8.9
b [counts/(keV·kg·y)]	0.11	0.17
$T_{1/2}$ limit (90% CL) [y]	$1.9 \cdot 10^{25}$	$1.6 \cdot 10^{25}$
Reference	[3]	[4]

There has been the claim of a signal by a part of the HdM collaboration [6] with $T_{1/2} = (0.69–4.18) \cdot 10^{25}$ y (3σ range), corresponding to $\langle m_{\beta\beta} \rangle = (0.24–0.58)$ eV.

3. – The GERDA experiment

3·1. *The experiment.* – GERDA is an experiment [7] designed for the search for $0\nu\beta\beta$ of ^{76}Ge. GERDA will be operated in two phases. In the first phase, germanium detectors from the IGEX and HdM experiments are reused. There are about 15 kg of germanium detectors which have been enriched in ^{76}Ge to a level of about 86% and an additional 15 kg of natural germanium detectors. The design goal for the background index is of the order of 10^{-2} counts/(keV·kg·y). An exposure of 15 kg·y will allow to reach $\langle m_{\beta\beta} \rangle \leq (0.23–0.39)$ eV [5] and thus to check the signal claim. In the second phase, an additional 20 kg of new enriched germanium detectors will be added and the background will be further reduced down to 10^{-3} counts/keV·kg·y. With an exposure of 100 kg·y, it will be possible to measure half-lives of the order of $1.5 \cdot 10^{26}$ y, corresponding to measuring $\langle m_{\beta\beta} \rangle$ down to (0.09–0.15) eV [5].

The sensitivity of the GERDA experiment is limited by the background. A large contribution to the background comes from cosmic radiation. To avoid it, the experiment was built in the INFN Gran Sasso underground laboratories. The overlaying rock provides in average 3400 m of water equivalent shielding, suppressing the cosmic-ray muon flux by a factor 10^6 (1 muon/(m^2·h)).

The environmental background component is reduced by graded shielding: The germanium detectors are submerged in a stainless-steel cryostat with a diameter of 4.2 m, filled with 64 m^3 of liquid Argon (LAr). Material close to the detectors is minimized: the bare germanium detectors are directly submerged in the LAr, using minimal support and cabling. Figure 1a shows a string with three Phase I detectors in their low-mass holders. The cryostat is surrounded by a water tank with a diameter of 10 m and a height of 9 m, containing 580 m^3 of ultra-pure water. The water serves as shielding for photons and spallation neutrons from outside the water tank. The water tank is equipped with photomultiplier tubes to detect the Čerenkov light of remaining cosmic muons. All materials used to build the experiment were screened to guarantee their radio-purity. On top of the water tank, a class 10 000 clean room is located and the detector strings are inserted into the cryoliquid through a lock system. The exposure for the detectors above ground is avoided as far as possible to reduce cosmogenic activation to a minimum. A sketch of the GERDA experiment is depicted in fig. 1b.

Several techniques have been developed to reject remaining background events. In general, background events have a different topology than $0\nu\beta\beta$ events. Most $0\nu\beta\beta$

(a) (b) (c)

Fig. 1. – (a) A detector string. (b) A sketch of the GERDA experiment. (c) The mini-shrouds.

events will deposit their energy locally within a sphere with a radius of $\leq 1\,\mathrm{mm}$ due to the limited range of electrons in germanium. These are so-called single-site events. The main background contribution comes from Compton-scattered photons. Their energy deposits are usually separated by centimeters, producing so-called multi-site events. It is therefore very unlikely that more than one detector in the array has an energy deposit in the case of a signal event. So, an anticoincidence cut between different detectors allows for further reduction of the background.

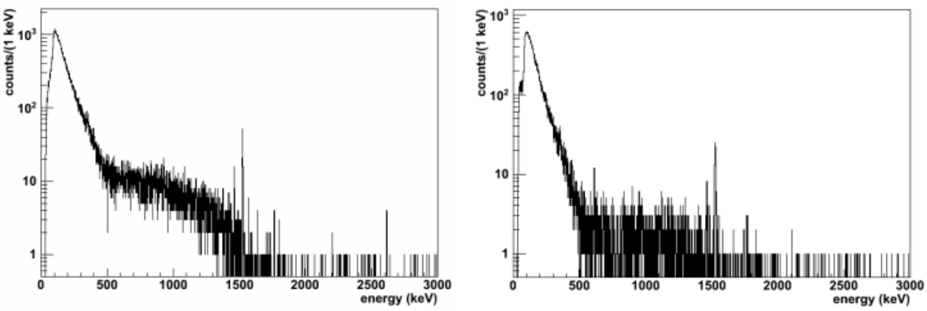
Background events can additionally be reduced using pulse shape analysis (PSA) [8,9]. In this case, the pulses generated by the detectors in response to the energy depositions are analyzed. This allows to distinguish between different event topologies and thus to discard background events.

3˙2. *Phase I data taking.* – In November 2011, the first phase of the GERDA experiment started. All eight enriched germanium detectors (five from the HdM experiment and three from the IGEX experiment) with a total mass of 14.6 kg and three natural germanium detectors with a total mass of 7.6 kg were deployed in GERDA. Due to instabilities and high leakage currents, two of the enriched detectors are not used for analysis.

The energy spectra for the enriched and natural detectors with a lifetime of 95 days are shown in fig. 2a and fig. 2b, respectively. The exposures are 3.80 kg·y and 1.97 kg·y. The contribution from $2\nu\beta\beta$ dominates the spectrum between 400 and 1400 keV for the enriched detectors.

In the energy region below 500 keV, the spectrum is dominated by the decays of ^{39}Ar. Since ^{39}Ar is a pure beta emitter with a Q-value of 565 keV, these decays do not add any background in the ROI around 2039 keV.

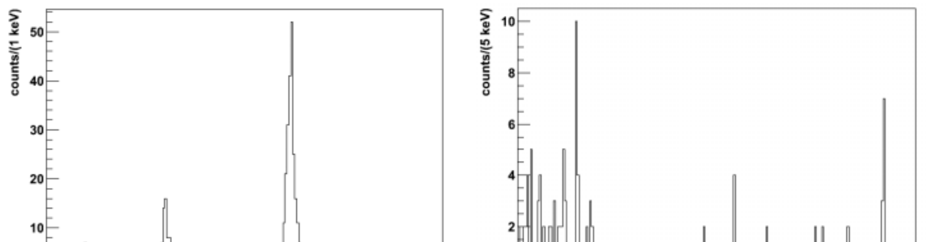
Another background that is easily distinguishable in the spectra is a line at 1525 keV. The spectrum around this energy is depicted in fig. 3a. The line can be attributed to decays of ^{42}Ar to ^{42}K (Q-value = 600 keV) and the subsequent decays to ^{42}Ca [10]. In 82% of the cases, ^{42}K decays directly to the ^{42}Ca ground state. In the other 18% of the cases, ^{42}K decays to an excited level of ^{42}Ca which de-excites under emission of a 1524.7 keV photon, explaining the line in the GERDA energy spectrum. The Q-value



(a) (b)

Fig. 2. – (a) The energy spectrum of the enriched germanium detectors. (b) The energy spectrum of the natural germanium detectors. The lifetime is 95 d, corresponding to an exposure of 3.80 kg·y and 1.97 kg·y, respectively.

of the decay of ^{42}K is 3525.4 keV, well above the ROI. The electron which is released in the decay can deposit energy in one of the germanium detectors. Since it loses energy in the LAr as well as in the deadlayer of the detector, the energy deposited in the active volume of the detector can be close to the Q-value of $0\nu\beta\beta$. Thus, the decays of ^{42}K add background in the ROI. During the commissioning of GERDA it was found that the line strength at 1525 keV was significantly higher than expected from previous limits [11]. It could be considerably reduced by putting the detectors in a field-free configuration, that is by avoiding electrical fields in their proximity. This minimizes the attraction of positively charged ^{42}K ions to the detector vicinity. The field-free configuration was achieved by closing the electrical field lines originating from the voltage-biased surfaces of the detectors on a thin copper layer closely surrounding each detector string. These so-



(a) (b)

Fig. 3. – (a) The energy spectrum of the enriched germanium detectors around 1525 keV in the field-free configuration. The peak at 1460 keV can be accounted to ^{40}K background decays. (Its two decay modes have Q-values of 1311 keV and 1504 keV, respectively, and therefore cannot contribute to the background in the ROI.) (b) The energy spectrum of the enriched detectors around the ROI. The lifetime is 95 d, corresponding to an exposure of 3.80 kg·y.

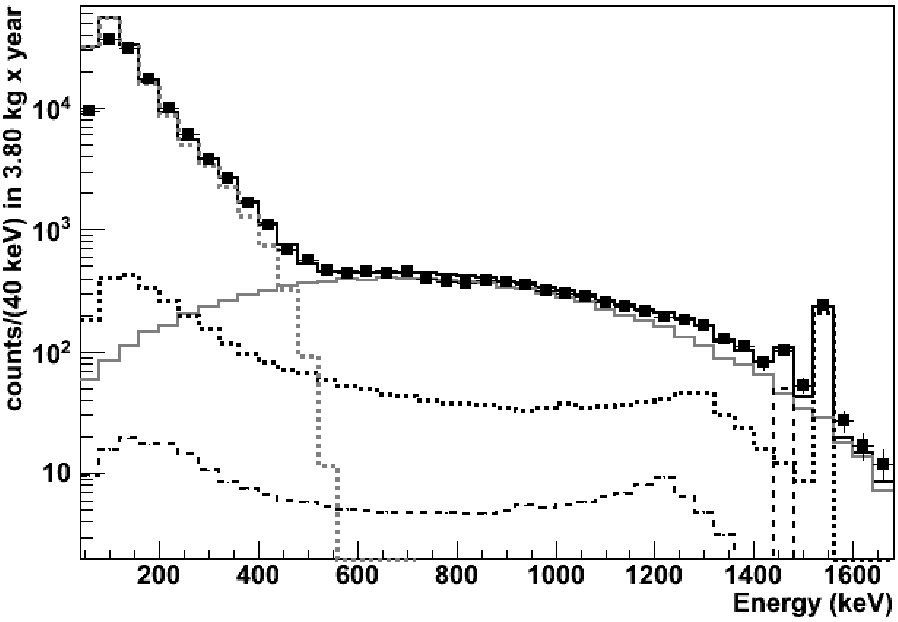


Fig. 4. – Comparison of the energy spectrum of the enriched detectors with MC. The single contributions are from ^{42}K (black dotted line), ^{40}K (black dashed line), ^{39}Ar (grey dotted line) and $2\nu\beta\beta$ of ^{76}Ge (grey continuous line). The black squares are the data for an exposure of 3.80 kg·y (lifetime = 95 d). They are well reproduced by the sum of all MC contributions shown with the black continuous line.

called mini-shrouds can be seen in fig. 1c. Nevertheless, also in the field-free configuration the count rate at 1525 keV remains approximately two times the expectation. The subject is still under investigation.

To quantify the background in the ROI, the events are counted that have an energy deposit in only one detector and no signal from the muon veto and that fall in the 200 keV energy window centered at 2039 keV, the Q-value of $0\nu\beta\beta$. No information about the events in the region between 2019 keV and 2059 keV is available since this region is subject to blinding. From the number of events in the ROI and excluding the blinded window, the background index is determined. It is $0.017^{+0.009}_{-0.005}$ counts/(keV·kg·y) for the enriched detectors, using the first GERDA runs with an exposure of 3.80 kg·y. For the natural germanium detectors it is $0.049^{+0.015}_{-0.013}$ counts/(keV·kg·y) with an exposure of 1.97 kg·y. The energy spectrum around the ROI for the enriched detectors is depicted in fig. 3b.

The background is most likely a combination of several contributions: photons and degraded α's from decays of isotopes present in the ^{232}Th- and ^{238}U-chains, ^{42}K beta decays, and decays of cosmogenic isotopes like ^{60}Co and ^{68}Ge. The achieved background index for the enriched detectors is slightly higher than the design goal of 10^{-2} counts/keV·kg·y. It is, however, a factor ten smaller than that of the previous experiments mentioned in sect. **2**. Also note that no pulse shape analysis has been applied yet.

Figure 4 shows a comparison of the data energy spectrum of the enriched detectors with Monte Carlo simulations (MC) of the various contributions in the energy region up to 1700 keV. The contributions that are considered are the following:

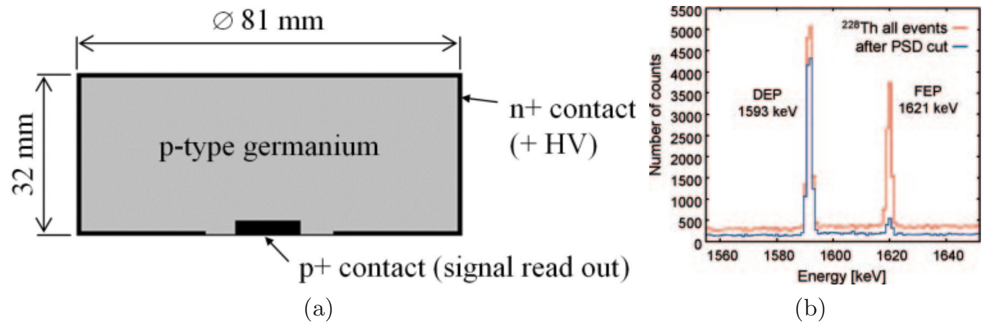


Fig. 5. – (a) Sketch of a BEGe detector. (b) The energy spectrum of a ^{228}Th source before (red) and after (black) PSA. Both graphics were taken from ref. [14].

– ^{42}K: The decays were simulated homogeneously distributed in the LAr surrounding the detectors. The peak at 1525 keV was used to normalize the MC.

– ^{40}K: The decays were simulated in the detector holders and normalized using the peak at 1460 keV.

– ^{39}Ar: The decays were simulated homogenously distributed in the LAr surrounding the detectors. The specific activity used to normalize the MC was taken from ref. [12].

– ^{76}Ge: To normalize the MC of $2\nu\beta\beta$ to the data, the result for $T_{1/2}$ from HdM [13] was used.

All contributions were simply added up without performing a fit. They describe the data very well.

3˙3. *Phase II preparations*. – For the second phase of the GERDA experiment about 20 kg of additional enriched germanium detectors will be deployed. To achieve the goal of a background index of 10^{-3} counts/(keV·kg·y), it is crucial to fully exploit the potential of PSA. Therefore, so-called broad-energy germanium (BEGe) detectors will be used. These p-type germanium detectors have an n^+-contact covering the whole outer surface and a small p^+-contact on the bottom. A sketch of such a detector can be seen in fig. 5a.

Thanks to their geometry, BEGe detectors allow for an excellent PSA performance which can be exploited to reduce the background [14]. In fig. 5b an example of an energy spectrum of a ^{228}Th source measured with a BEGe detector is shown. The double-escape peak (DEP) events at 1593 keV are mainly single-site events and have thus a topology which is very similar to the $0\nu\beta\beta$ signal events. The peak at 1621 keV originates predominantly from Compton-scattered photons and thus contains mainly multi-site events. With PSA, this background peak can be reduced to about 10% of its original height, while 90% of the signal-like events in the DEP remain [14]. This powerful tool will be a decisive factor for reaching the Phase II background goal.

Seven of the new enriched BEGe detectors have already been produced and are currently being tested in the HADES underground laboratory in Mol, Belgium.

Another ongoing effort regarding the preparations for the second phase of the GERDA experiment is the possibility to read out scintillation light from LAr. As LAr is a scintillator material, particles crossing this medium can be detected by detecting the scintillation light they produce. This is a very effective method to significantly reduce the external background contribution. The LArGe [15] test facility at the Gran Sasso laboratories was built to investigate this strategy.

4. – Conclusions

The observation of $0\nu\beta\beta$ is at present the only experimentally feasible way to test the Majorana-nature of the neutrino. Previous experiments have set limits on the half-life of this decay on the order of 10^{25} y and a claim of evidence has been made by a subgroup of the HdM experiment.

GERDA is a new-generation $0\nu\beta\beta$ experiment. In a first phase, the claim will be checked. In a second phase, limits on the half-life of the order of $1.5 \cdot 10^{26}$ y will be reached.

The experiment started Phase I data taking in November 2011. A background measurement based on the first data taken with enriched detectors with an exposure of 3.80 kg·y gives a background index of $0.017^{+0.009}_{-0.005}$ counts/(keV·kg·y), very close to the design goal of 10^{-2} counts/(keV·kg·y). The experiment is running smoothly and first results on $2\nu\beta\beta$ are expected very soon.

REFERENCES

[1] Schechter J. and Valle J., *Phys. Rev. D*, **25** (1982) 2951.
[2] Barabash A. S., *Phys. At. Nucl.*, **74** (2011) 603.
[3] Klapdor-Kleingrothaus H. V. *et al.*, *Eur. Phys. J. A*, **12** (2001) 147.
[4] Aalseth C. E. *et al.*, *Phys. Rev. D*, **65** (2002) 092007.
[5] Smolnikov A. and Grabmayr P., *Phys. Rev. C*, **81** (2010) 028502.
[6] Klapdor-Kleingrothaus H. V. *et al.*, *Phys. Lett. B*, **586** (2004) 198.
[7] Abt I. *et al.*, arXiv:hep-ex/0404039 (2004).
[8] Majorovits B. and Klapdor-Kleingrothaus H. V., *Eur. Phys. J. A*, **6** (1999) 463.
[9] González D. *et al.*, *Nucl. Instrum. Methods A*, **515** (2003) 634.
[10] Firestone R. B. *et al.*, *Table of Isotopes*, 8th edition (Wiley) 1996.
[11] Ashitkov V. D. *et al.*, arXiv:nucl-ex/0309001 (2003).
[12] Benetti P. *et al.*, *Nucl. Instrum. Methods A*, **574** (2007) 83.
[13] Dörr C. and Klapdor-Kleingrothaus H. V., *Nucl. Instrum. Methods A*, **513** (2003) 596.
[14] Budjáš D. *et al.*, *JINST*, **4** (2009) P10007.
[15] Heisel M., *LArGe - A liquid argon scintillation veto for GERDA*, PhD thesis, Ruperto-Carola Universität Heidelberg (2011).