IL NUOVO CIMENTO **38 C** (2015) 26
DOI 10.1393/ncc/i2015-15026-1

COLLOQUIA: IFAE 2014

Current experiments in germanium $0\nu\beta\beta$ search — GERDA and MAJORANA

K. VON STURM(*)

Dipartimento di Fisica "Galileo Galilei", Università degli Studi di Padova and INFN, Sezione di Padova - Via Francesco Marzolo 8, 35131 Padova, Italy

received 7 January 2015

Summary. — There are unanswered questions regarding neutrino physics that are of great interest for the scientific community. For example the absolute masses, the mass hierarchy and the nature of neutrinos are unknown up to now. The discovery of neutrinoless double beta decay ($0\nu\beta\beta$) would prove the existence of a Majorana mass, which would be linked to the half-life of the decay, and would in addition provide an elegant solution for the small mass of the neutrinos via the seesaw mechanism. Because of an existing discovery claim of $0\nu\beta\beta$ of ^{76}Ge and the excellent energy resolution achievable, germanium is of special interest in the search for $0\nu\beta\beta$. In this article the state of the art of germanium $0\nu\beta\beta$ search, namely the GERDA experiment and MAJORANA demonstrator, is presented. In particular, recent results of the GERDA collaboration, which strongly disfavour the above mentioned claim, are discussed.

PACS `13.15.+g` – Neutrino interactions.
PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `23.40.-s` – β decay; double β decay; electron and muon capture.
PACS `29.40.-n` – Radiation detectors.

1. – Introduction

Almost 60 years after the discovery of the electron neutrino in the Savannah-River experiment, neutrinos are still of major scientific interest as some of their fundamental properties are yet unmeasured. The neutrino masses, and even their scale and hierarchy, remain unknown, although they were proven to be non-zero by the observation of neutrino oscillations [1]. Furthermore, the appealing possibility persists for neutrinos to be Majorana particles; a field ν describing a neutrino and its charge conjugate would be equivalent $\nu = \nu^C$ [2-4]. Double beta decay ($\beta\beta$) is a second order weak decay

(*) E-mail: `vonsturm@pd.infn.it`

transforming two neutrons bound in a nucleus simultaneously into two protons via virtual levels. In addition to the known decay mode (1) with two neutrinos in the final state, a second mode (2) without the neutrinos is theoretically possible:

$$2\nu\beta\beta: \quad A(Z,N) \rightarrow A(Z+2,N-2) + 2e^- + 2\bar{\nu}_e, \tag{1}$$

$$0\nu\beta\beta: \quad A(Z,N) \rightarrow A(Z+2,N-2) + 2e^-, \tag{2}$$

$2\nu\beta\beta$ has been measured in a handful of isotopes with live-times of $(10^{18} - 10^{24})$ yr [5,6]. Neutrinoless double beta decay ($0\nu\beta\beta$) is a by two units lepton number violating decay; thus forbidden in the Standard Model, requiring new physics. The only practical way to prove that neutrinos are of Majorana nature is to search for $0\nu\beta\beta$. The detection of this decay would not only prove the existence of a Majorana mass but also provide an elegant solution for the small neutrino masses [7]. Furthermore, it could give a handle on the neutrino mass scale [8], provided that the nuclear matrix elements are known [9] and no unknown neutrinos exist. The searched for signature is a mono-energetic line at the endpoint of the $2\nu\beta\beta$ spectrum ($Q_{\beta\beta} = (2039.061 \pm 0.007)$ keV for ^{76}Ge [10]).

Since 2004, an observation claim (KK claim) of $0\nu\beta\beta$ of ^{76}Ge by a subgroup of the Heidelberg-Moscow experiment (HdM) is pending, reporting a half-life of $T^{0\nu}_{1/2} = \left(1.19^{+0.37}_{-0.23}\right) \cdot 10^{25}$ yr based on (28.75 ± 6.86) events in 71.7 kg yr of data [11-13]. A reanalysis based on pulse shapes was published by the same group in 2006 [14]; however, major inconsistencies in the calculation of $T^{0\nu}_{1/2}$ were pointed out in reference [15], suggesting incorrect central value and errors.

In principle every even-even isotope with $\beta^{-/+}$ decay energetically forbidden and the existence of a lower energy state can decay via $2\nu\beta\beta$ being a candidate for the search of $0\nu\beta\beta$. However, because of its unique energy resolution and the pending claim, ^{76}Ge is particularly interesting in the search for $0\nu\beta\beta$. This paper reports on active experiments in ^{76}Ge $0\nu\beta\beta$ search, namely the Majorana demonstrator and the Gerda experiment. The latter reported new results in 2013 [16] which are discussed in section **3**.

There are two possible scenarios for the neutrino mass hierarchy: The normal and the inverted one. Inverted means that the neutrino mass Eigenstate commonly referred to as m_3 would be the lightest one. To access all the inverted neutrino mass hierarchy half-life values of $2 \cdot 10^{28}$ yr have to be covered. Such a sensitivity can only be reached on a reasonable time scale with a tonne-scale experiment. The normal hierarchy is not accessible with present experimental techniques supposing that the lightest neutrino mass is $m_{\text{light}} < 10$ meV.

2. – The MAJORANA demonstrator

The Majorana demonstrator (MJD) is a research and development project for a future tonne-scale experiment [17]. It is located at the Sanford Underground Research Facility (SURF) at Lead, South Dakota, with an overburden of 4300 m.w.e. MJD will deploy up to 40 kg of Ge crystals of p-type point contact (PPC) type stacked in modules. The modules are put in two copper vacuum cryostats surrounded by a compact shield consisting of copper, lead and polyethylene (from inside to outside). The copper used for the vacuum cryostats, the detector holders as well as the inner part of the copper shield is underground electroformed and reaches an exceptional radiopurity at a sub μBq/kg level [18]. All other materials are screened and selected to be as radiopure as possible. A radon enclosure is installed to lower the contamination by out-gassing radon from surrounding materials. In addition to the passive shield an active muon veto is installed. The goal of MJD is to demonstrate the achievability of a background index (BI) of $\approx 3\,\mathrm{cts/(ROI\,t\,yr)}$, where ROI is a 4 keV Region Of Interest around $Q_{\beta\beta}$, and to reach a sensitivity of $T^{0\nu}_{1/2} > 10^{26}$ yr. Focused on the optimization of processes and costs, the modular detector array is meant to be scalable to a one tonne experiment. In addition, MJD wants to go to the very low energy range with a sub-keV threshold to search for Dark Matter and Axions [19]. At the moment, MJD is in its first experimental stage operating two strings of broad energy germanium (BEGe) detectors made of natural Ge ($^{\mathrm{nat}}$Ge) to integrate and test all components. The electroforming laboratory is operational since 2011 and all infrastructure, namely the shield floor, the liquid nitrogen system, an assembly table with an air baring system and a glove box and a clean space, is installed and functional. In a second experimental phase, MJD will operate seven strings of PPC detectors of enriched Ge ($^{\mathrm{enr}}$Ge) for commissioning in a first cryostat. The third phase completes the setup with a second cryostat containing half $^{\mathrm{nat}}$Ge and half $^{\mathrm{enr}}$Ge. This final stage will contain in total about 30 kg of 86% $^{\mathrm{enr}}$Ge and about 10 kg of $^{\mathrm{nat}}$Ge with an abundance of $\approx 8\%$ ^{76}Ge. The second and third stages are planned in short succession at the end of 2014 and in summer 2015.

3. – The GERDA experiment

The Gerda experiment is located at Laboratori Nazionali del Gran Sasso (LNGS) of Istituto Nazionale di Fisica Nucleare (INFN) in Italy with an overburden of about 3600 m.w.e. In contrast to Majorana, Gerda is operating Ge detectors bare in liquid Argon (LAr) [20]. A copper lined stainless steel cryostat, 4 m in diameter and containing 63 m^3 of LAr, is surrounded by a 3 m-thick Muon Cerenkov Water Veto which also serves as passive γ and neutron shield. It is instrumented with 66 photomultipliers to identify muon induced events. Through a lock-system from a glove box in the clean room above the neck of the cryostat, the detectors are submerged into the cryostat. The roof of the clean room is covered by an additional muon veto made of plastic scintillator panels which is meant to cover the weak spot of the water veto: The neck of the cryostat. Special care was devoted to the selection of radiopure materials for construction and to a sparse design of all components near the detectors (holders, electronics, cables, etc.) to reduce thereby introduced background.

Phase I data taking was completed in May 2013. In total, 21.6 kg yr of data from $^{\mathrm{enr}}$Ge were recorded with a duty factor of 88%. The major part was taken with refurbished detectors from the IGEX and HdM experiments but also 2.4 kg yr were collected with recently produced detectors of BEGe type that were inserted in June 2012. The signal read-out in Gerda is done with charge-sensitive amplifiers and the single traces are digitized with a 100 MHz FADC. Weekly ^{228}Th calibrations, a calibration with ^{56}Co and constant monitoring with a test pulser assure the stability of the detectors and a correct energy reconstruction, which is done off-line using a semi-Gaussian filter. First selection cuts discard events in coincidence with muons and coincident events in different detectors as $0\nu\beta\beta$ is most probable to release all its energy in a small region inside one detector. Also, events within 1 ms in one detector were discarded as they are likely to belong to the Bi-Po decay chain.

The first 5.04 kg yr were used to re-evaluate the half-life of $2\nu\beta\beta$ of Ge. In addition to $2\nu\beta\beta$, the model of the spectrum contains ^{42}K which is a daughter of ^{42}Ar, ^{40}K and ^{214}Bi which is present in the detector holders. The spectral fit was done in the region from 600 to 1800 keV using a binned maximum likelihood approach. The best estimate of the $2\nu\beta\beta$ half-life is $T^{2\nu}_{1/2} = 1.84^{+0.14}_{-0.10}$ yr [21]. This value is longer than previously measured, which is probably due to a better signal to background ratio.

Table I. – *Gerda Phase I result: background index (BI) and observed/expected counts in $Q_{\beta\beta} \pm 5\,keV$ without and with pulse shape discrimination (PSD)* [16].

Data set	BI^a wo./with PSD	obs./expect. cts wo. PSD	obs./expect. cts with PSD
Golden	$18 \pm 2\,/\,11 \pm 2$	5 / 3.3	2 / 2.0
Silver	$63^{+16}_{-14}\,/\,30^{+11}_{-9}$	1 / 0.8	1 / 0.4
BEGe	$42^{+10}_{-8}\,/\,5^{+4}_{-3}$	1 / 1.0	0 / 0.1

^{a} In 10^{-3} cts/(keV kg yr)

For the analysis of $0\nu\beta\beta$, the existing data was split in three different sets: 1) data from BEGe detectors being 2.4 kg yr, 2) "silver coaxial" data containing 20 days (1.3 kg yr) after the insertion of the BEGe detectors in the cryostat, which show an elevated background index, and 3) the rest data from coaxial detectors named "golden coaxial" being the major part with 17.9 kg yr. All three data sets were analysed separately with independent background indices and resolutions. The average energy resolution at $Q_{\beta\beta}$ is (4.8 ± 0.2) keV for the coaxial detectors and (3.2 ± 0.2) keV for the BEGes. A 40 keV window around $Q_{\beta\beta}$ was blinded before freezing the analysis to avoid bias. Before unblinding, the background model [22] and the pulse shape analysis [23] were validated. After unblinding, the model predictions in the ROI were found consistent with the measurement. The background is expected to be flat, except for two peaks at 2104 and 2119 keV, in a large region around $Q_{\beta\beta}$ and no intense gamma lines are expected in its vicinity. For both BEGe detectors and coaxial detectors, pulse shape analysis techniques were developed. For the BEGe detectors, a cut on the A/E parameter was done which is the amplitude of the current pulse divided by the energy. A/E was corrected for an exponential time drift. The acception of signal-like events of the A/E cut is $(92 \pm 2)\%$ and the rejection of background events is 80%. To analyse the pulse shape of the semi-coaxial detectors a TMVA neural network was set up working on 50 values of the pulse rise times. It has an acceptance of $\left(90^{+5}_{-9}\right)\%$ and a rejection of 45%. As the sensitivity of Gerda scales with signal/$\sqrt{\text{background}}$ a high signal acceptance and a rather moderate rejection were kept. The neural network method was cross-checked with two independent methods [23].

The results after unblinding for BI and the counts in the ROI are displayed in table I. No indication for unidentified lines at $Q_{\beta\beta} \pm 20$ keV was found. A comparison to more intense γ lines of ^{214}Bi gives an expectation of < 1 cts in the Gerda data for possible lines at 2016 and 2052 keV. The observed counts are fully compatible with the expectation and the best fit obtained is $1/T^{0\nu}_{1/2} = 0$, meaning no counts associated to $0\nu\beta\beta$. The Frequentist (Bayesian) analysis gives a lower limit of $T^{0\nu}_{1/2} > 2.1(1.9) \cdot 10^{25}$ yr at 90%CL with an expected sensitivity of $T^{0\nu}_{1/2} > 2.4(2.0) \cdot 10^{25}$ yr [16]. Including previous results from the HdM [12] and IGEX [24] experiments this limit is strengthened to $T^{0\nu}_{1/2} > 3.0(2.9) \cdot 10^{25}$ yr at 90%CL [11, 16].

4. – Conclusion

The search for $0\nu\beta\beta$ is ongoing and efforts are made towards tonne-scale experiments which are necessary to cover all the inverted neutrino mass hierarchy. Active experiments in $0\nu\beta\beta$ search of ^{76}Ge are MJD and Gerda. The Gerda Phase I result, reported in 2013, strongly disfavours the KK claim [11, 16]. MJD will soon start the commissioning phase whereas Gerda is already preparing for a second data taking phase. Gerda

Phase II will collect 100 kg yr of data within 3 yr. With an augmented active detector mass, a reduced background and a new veto, that makes use of the scintillation light of LAr, the aim is to push the sensitivity for $T_{1/2}^{0\nu}$ in the 10^{26} yr range [11].

* * *

The author would like to thank the GERDA COLLABORATION for valuable comments and suggestions on the talk for the IFAE 2014 conference and on this proceeding, and S.R. Elliot from the MAJORANA COLLABORATION for the kind supply with material.

REFERENCES

[1] BALANTEKIN A. B. and HAXTON W. C., *Prog. Particle Nucl. Phys.*, **71** (2013) 150 doi: 10.1016/j.ppnp.2013.03.007.
[2] VERGADOS J. D., EJIRI H. and ŠIMKOVIC F., *Rep. Prog. Phys.*, **75** (2012) 106301 doi: 10.1088/0034-4885/75/10/106301.
[3] GÓMEZ-CADENAS J. J. *et al.*, *Riv. Nuovo Cimento*, **35** No. 2 (2012) 29 doi: 10.1393/ncr/i2012-10074-9.
[4] BILENKY S. M. and GIUNTI C., *Mod. Phys. Lett. A*, **27** (2012) 1230015 doi: 10.1142/S0217732312300157.
[5] BARABASH A. S., *Phys. Rev. C*, **81** (2010) 035501 doi: 10.1103/PhysRevC.81.035501.
[6] TRETYAK V. I. and ZDESENKO Y. G., *At. Data Nucl. Data Tables*, **80** (2002) 83 doi: 10.1006/adnd.2001.0873.
[7] MOHAPATRA R. N. and SENJANOVIĆ G., *Phys. Rev. Lett.*, **44** (1980) 912 doi: 10.1103/PhysRevLett.44.912.
[8] SCHECHTER J. and VALLE J. W. F., *Phys. Rev. D*, **25** (1982) 2951 doi: 10.1103/PhysRevD.25.2951.
[9] BAREA J., KOTILA J. and IACHELLO F., *Phys. Rev. C*, **87** (2013) 014315 doi: 10.1103/PhysRevC.87.014315.
[10] MOUNT B. J., REDSHAW M. and MYERS E. G., *Phys. Rev. C*, **81** (2010) 032501 doi: 10.1103/
PhysRevC.81.032501.
[11] PANDOLA L., *Physics of the Dark Universe*, **4** (2014) 17 doi: 10.1016/j.dark.2014.05.005.
[12] KLAPDOR-KLEINGROTHAUS H. V. *et al.*, *Eur. Phys. J. A*, **12** (2001) 147 doi: 10.1007/s100500170022.
[13] KLAPDOR-KLEINGROTHAUS H. V. *et al.*, *Phys. Lett. B*, **586** (2004) 198 doi: 10.1016/j.physletb.2004.02.025.
[14] KLAPDOR-KLEINGROTHAUS H. V. and KRIVOSHEINA I. V., *Mod. Phys. Lett. A*, **21** (2006) 1547 doi: 10.1142/S0217732306020937.
[15] SCHWINGENHEUER B., *Ann. Phys. (Leipzig)*, **525** (2013) 269 doi: 10.1002/andp.201200222.
[16] AGOSTINI M. *et al.*, *Phys. Rev. Lett.*, **111** (2013) 122503 doi: 10.1103/PhysRevLett.111.122503.
[17] WILKERSON J. F. *et al.*, *J. Phys.: Conf. Ser.*, **375** (2012) 042010 doi: 10.1088/1742-6596/375/1/042010.
[18] HOPPE E. W. *et al.*, *Nucl. Instrum. Methods A*, **764** (2014) 116 doi: 10.1016/j.nima.2014.06.082.
[19] GIOVANETTI G. K. *et al.*, *J. Phys.: Conf. Ser.*, **375** (2012) 012014 doi: 10.1088/1742-6596/375/1/012014.
[20] ACKERMANN K.-H. *et al.*, *Eur. Phys. J. C*, **73** (2013) 2330 doi: 10.1140/epjc/s10052-013-2330-0.
[21] THE GERDA COLLABORATION, *J. Phys. G: Nucl. Part. Phys.*, **40** (2013) 035110 doi: 10.1088/0954-3899/40/3/035110.
[22] AGOSTINI M. *et al.*, *Eur. Phys. J. C*, **74** (2014) 2764 doi: 10.1140/epjc/s10052-014-2764-z.
[23] AGOSTINI M. *et al.*, *Eur. Phys. J. C*, **73** (2013) 2583 doi: 10.1140/epjc/s10052-013-2583-7.
[24] AALSETH C. E. *et al.*, *Phys. Rev. D*, **65** (2002) 092007 doi: 10.1103/PhysRevD.65.092007.