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Status of the GERDA experiment

Riccardo Brugnera[∗†]
Dipartimento di Fisica e Astronomia dell'Università di Padova, Padova, Italy
INFN Padova, Padova, Italy
E-mail: riccardo.brugnera@pd.infn.it

M. Agostini[n], **M. Allardt**[c], **E. Andreotti**[q,e], **A.M. Bakalyarov**[l], **M. Balata**[a], **I. Barabanov**[j], **M. Barnabé Heider**[f,n‡], **N. Barros**[c], **L. Baudis**[r], **C. Bauer**[f], **N. Becerici-Schmidt**[m], **E. Bellotti**[g,h], **S. Belogurov**[k,j], **S.T. Belyaev**[l], **G. Benato**[r], **A. Bettini**[o,p], **L. Bezrukov**[j], **T. Bode**[n], **V. Brudanin**[d], **D. Budjáš**[n], **A. Caldwell**[m], **C. Cattadori**[h], **A. Chernogorov**[k], **F. Cossavella**[m], **E.V. Demidova**[k], **A. Domula**[c], **V. Egorov**[d], **R. Falkenstein**[q], **A. Ferella**[r§] **K. Freund**[q], **N. Frodyma**[b], **A. Gangapshev**[j,f], **A. Garfagnini**[o,p], **C. Gotti**[h¶], **P. Grabmayr**[q], **V. Gurentsov**[j], **K. Gusev**[l,d,n], **K.K. Guthikonda**[r], **W. Hampel**[f], **A. Hegai**[q], **M. Heisel**[f], **S. Hemmer**[o,p], **G. Heusser**[f], **W. Hofmann**[f], **M. Hult**[e], **L.V. Inzhechik**[j‖], **L. Ioannucci**[a], **J. Janicskó Csáthy**[n], **J. Jochum**[q], **M. Junker**[a], **T. Kihm**[f], **I.V. Kirpichnikov**[k], **A. Kirsch**[f], **A. Klimenko**[f,d∗∗] **K.T. Knöpfle**[f], **O. Kochetov**[d], **V.N. Kornoukhov**[k,j], **V.V. Kuzminov**[j], **M. Laubenstein**[a], **A. Lazzaro**[n], **V.I. Lebedev**[l], **B. Lehnert**[c], **H.Y. Liao**[m], **M. Lindner**[f], **I. Lippi**[p], **X. Liu**[m††] **A. Lubashevskiy**[f], **B. Lubsandorzhiev**[j], **G. Lutter**[e], **C. Macolino**[a], **A.A. Machado**[f], **B. Majorovits**[m], **W. Maneschg**[f], **M. Misiaszek**[b], **I. Nemchenok**[d], **S. Nisi**[a], **C. O'Shaughnessy**[m‡‡] **L. Pandola**[a], **K. Pelczar**[b], **G. Pessina**[g,h], **A. Pullia**[i], **S. Riboldi**[i], **N. Rumyantseva**[d], **C. Sada**[o,p], **M. Salathe**[f], **C. Schmitt**[q], **J. Schreiner**[f], **O. Schulz**[m], **B. Schwingenheuer**[f], **S. Schönert**[n], **E. Shevchik**[d], **M. Shirchenko**[l,d], **H. Simgen**[f], **A. Smolnikov**[f], **L. Stanco**[p], **H. Strecker**[f], **M. Tarka**[r], **C.A. Ur**[p], **A.A. Vasenko**[k], **O. Volynets**[m], **K. von Sturm**[q,o,p], **V. Wagner**[f], **M. Walter**[r], **A. Wegmann**[f], **T. Wester**[c], **M. Wojcik**[b], **E. Yanovich**[j], **P. Zavarise**[a], **I. Zhitnikov**[d], **S.V. Zhukov**[l], **D. Zinatulina**[d], **K. Zuber**[c], **G. Zuzel**[b].

[a]) INFN Laboratori Nazionali del Gran Sasso, LNGS, Assergi, Italy

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[b]) Institute of Physics, Jagiellonian University, Cracow, Poland
[c]) Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[d]) Joint Institute for Nuclear Research, Dubna, Russia
[e]) Institute for Reference Materials and Measurements, Geel, Belgium
[f]) Max-Planck-Institut für Kernphysik, Heidelberg, Germany
[g]) Dipartimento di Fisica, Università Milano Bicocca, Milano, Italy
[h]) INFN Milano Bicocca, Milano, Italy
[i]) Dipartimento di Fisica, Università degli Studi di Milano e INFN Milano, Milano, Italy
[j]) Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
[k]) Institute for Theoretical and Experimental Physics, Moscow, Russia
[l]) National Research Centre “Kurchatov Institute”, Moscow, Russia
[m]) Max-Planck-Institut für Physik, München, Germany
[n]) Physik Department and Excellence Cluster Universe, Technische Universität München, Germany
[o]) Dipartimento di Fisica e Astronomia dell‘Università di Padova, Padova, Italy
[p]) INFN Padova, Padova, Italy
[q]) Physikalisches Institut, Eberhard Karls Universität Tübingen, Tübingen, Germany
[r]) Physik Institut der Universität Zürich, Zürich, Switzerland

The study of neutrinoless double beta ($0\nu\beta\beta$) decay is the only one presently known approach to the fundamental question if the neutrino is a Majorana particle, i.e. its own anti-particle. The observation of $0\nu\beta\beta$ decay would prove that lepton number is not conserved, establish that neutrino has a Majorana component and, assuming that light neutrino is the dominating process, provide a method for the determination of its effective mass. GERDA is a new $0\nu\beta\beta$ decay experiment which is currently taking data at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN in Italy. It implements a new shielding concept by operating bare diodes made from Ge with enriched ^{76}Ge in high purity liquid argon supplemented by a water shield. The aim of GERDA is to verify or refute the recent claim of discovery, and, in a second phase, to achieve a two orders of magnitude lower background index than past experiments, to increase the sensitive mass and to collect an exposure of 100 kg·yr. The paper will discuss design, physics reach, and status of data taking of GERDA.

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*Speaker.
†On behalf of the GERDA Collaboration
‡*Present Address:* CEGEP St-Hyacinthe,Québec, Canada
§*Present Address:* INFN LNGS, Assergi, Italy
¶*also at:* Università di Firenze, Italy
‖*also at:* Moscow Inst. of Physics and Technology,Russia
***also at:* Int. Univ. for Nature, Society and Man “Dubna”, Russia
††*Present Address:* Shanghai Jiaotong University, Shanghai, China
‡‡*Present Address:* University North Carolina, Chapel Hill, USA

1. Introduction

Since their discovery neutrinos have been an object of extensive experimental study and the knowledge about their properties has advanced our understanding of weak interactions significantly. Still unanswered, however, is the very fundamental question whether the neutrino is a Majorana particle like most extensions of the Standard Model (SM) predict. The study of $0\nu\beta\beta$ decay is the only one presently known approach to answer this question. If the decay occurs without the emission of neutrinos then their Majorana nature is proven. In the following, firstly (section 2) we give a brief summary of the theory and the present experimental status; then in section 3 we describe the GERDA experiment: its goals and the detector; in section 4 the present status of data taking and the $2\nu\beta\beta$ ^{76}Ge half-life measurement. At the end the future programs are briefly described.

2. Theory and present experimental results

$0\nu\beta\beta$ decay is a very slow lepton-number violating nuclear transition that can happen if neutrinos have mass and are their own antiparticles. An initial nucleus (Z,A) decays to $(Z+2,A)$, emitting two electrons. A related transition, called two-neutrino double beta ($2\nu\beta\beta$) decay results in the emission of two electron antineutrinos in addition to the electrons, also a very rare process but it does not violate any conservation rule and in fact it has been observed in a number of experiments. If the $0\nu\beta\beta$ decay is mediated by the exchange of a light Majorana neutrinos, the half-life is

$$[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)]^{-1} = G^{0\nu}(Q_{\beta\beta},Z)|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2 \tag{2.1}$$

where $G^{0\nu}$ is the exactly calculable phase space integral, $M^{0\nu}$ is the nuclear matrix element, $\langle m_{\beta\beta}\rangle$ is the effective Majorana mass of the electron neutrino:

$$\langle m_{\beta\beta}\rangle \equiv |\sum_k m_k U_{ek}^2| \tag{2.2}$$

Here the m_ks are the masses of the three light neutrinos and U is the matrix that transforms states with well-defined mass into states with well-defined flavour. So, the observation of $0\nu\beta\beta$ decay would not only establish the Majorana nature of the neutrino but also provide a measurement of its effective mass $\langle m_{\beta\beta}\rangle$ and through the Eq. 2.2 the absolute mass scale for the neutrino can be investigated. In Eq. 2.1 the nuclear matrix element $M^{0\nu}$ is not well known, presently most calculations give the same result for a given matrix element to within a factor of 2 or 3.

At present there is only one claim for a positive $0\nu\beta\beta$ decay result by Klapdor-Kleingrothaus *et al*. [1] as part of the Heidelberg-Moscow Collaboration (HDM) : $T_{1/2}^{0\nu}(^{76}\text{Ge}) = 1.19^{+0.37}_{-0.23} \times 10^{25}$ yr at 1σ. The other most sensitive limits with the candidate nucleus ^{76}Ge are from the IGEX experiment [2]: $T_{1/2}^{0\nu} \geq 1.6 \times 10^{25}$ yr (90% C.L.), and the HDM experiment [3]: $T_{1/2}^{0\nu} \geq 1.9 \times 10^{25}$ yr (90% C.L.). Both experiments have ceased their data taking years ago. Currently the most sensitive experiments are KamLAND-Zen [4] and EXO-200 [5] looking for $0\nu\beta\beta$ decay of ^{136}Xe and GERDA itself [6] using ^{76}Ge. Nuclear matrix elements calculations are necessary in order to relate the different isotopes. For that reason, the experiments using ^{136}Xe cannot refute the claim in a model-independent manner. GERDA, instead, is able to make a direct test using the same isotope and also the same detectors of HDM and IGEX after refurbishment.

3. The GERDA design

The GERDA experiment [6] located in Hall A of the Laboratori Nazionali del Gran Sasso (LNGS) has the aim to search for $0\nu\beta\beta$ decay using enriched ^{76}Ge detectors. Its experimental signature is a peak at the Q-value of the decay ($Q_{\beta\beta} = 2039.061 \pm 0.007$ keV [7]). The experiment will proceed in several phases. In Phase I, existing enriched ^{76}Ge of HDM and IGEX experiments for a total mass of $\sim$ 18 kg will be used. The goal for the background index (BI) is 10^{-2} cts/(keV·kg·yr). In these conditions and after an exposure of 20 kg·yr the sensitivity for a 90% C.L. exclusion limit will be $T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ yr, sufficient to check the Klapdor-Kleingrothaus's claim. In its Phase II with additional 20 kg of enriched Ge detectors and a background of 10^{-3} cts/(keV·kg·yr) and a 100 kg·yr exposure GERDA will reach the sensitivity of $T^{0\nu}_{1/2} > 1.5 \times 10^{26}$ yr at 90% C.L. corresponding to about 130 meV (with the matrix elements cited in [8]). Depending on the results obtained in Phase I and Phase II, it is also foreseen a Phase III with the aim of reaching the 10 meV scale, this requires $\mathscr{O}(1\text{t})$ of enriched Ge and represents another huge step, which can only be afforded in the context of a world-wide collaboration.

GERDA, shown as an artist view in Fig. 1, uses naked Ge crystals immersed in liquid Ar (LAr). The shielding of external environmental backgrounds is realized using an onion-like structure consisting of, from outside to inside: hyper-pure water in a 10 m diameter tank shown open in Fig. 1, a stainless steel cryostat with internal lining of copper and ultra-pure LAr. The Ge diodes are assembled into arrays suspended in the centre of the LAr volume.

The method followed by GERDA to reach the BI of 10^{-2} cts/(keV·kg·yr) in Phase I is the following.

- The quantitative evaluation of all background sources in every component of the apparatus by analytical methods or Monte Carlo simulations. These calculations provide the allowed specific activity for each component, depending on its location relative to the detectors.

- Shielding: γ's from the external environment (like ^{208}Tl) with H_2O (3 m thickness) and LAr (2 m thickness) shields; from ^{228}Th in the stainless steel cryostat with a Cu shield and LAr; μ-induced prompt signals with two vetoes, a plastic scintillator roof and the water used as Cherenkov medium.

- Mechanical design implementing a minimum mass suspension and contact system for the Ge detectors. Notice also that in GERDA the detectors are surrounded by low Z materials, a fact that minimizes the muon induced neutron background and makes the experiment feasible at the depth of Gran Sasso. Development of front-end electronics with low background budget.

Another powerful method to reject background events is the pulse shape discrimination (PSD) analysis. The two electrons of the signal deposit their energy within a few millimeters, whilst gammas, which constitute the principal background, do that often, typically with a few Compton scatterings separated by a few centimeters. Consequently, signal events are "single site" (SS); background events are "multiple site" (MS). SS can be distinguished from MS with PSD analysis and anti-coincidence between diodes. The new Broad Energy Germanium (BEGe) detectors studied and built for the Phase II (see 4 and 5) have shown advanced capability of PSD (see Ref. [9]).

Figure 1: Artist view of the GERDA experiment. The following components are labeled in the picture: (1) the Ge array strings (not to scale), (2) the LAr cryostat, (3) the internal copper shield, (4) the instrumented Water Tank and (5) the Clean Room with the Lock insertion system (6). From [6].

4. The Status of Phase I

The data taking of Phase I started on November 9, 2011. Till February 7, 2013 , after 372.8 live days, an exposure of 16.71 kg·yr was collected. The Phase I data taking will last up to the collection of ∼20 kg·yr, which is foreseen to happen in the middle of May 2013. In order to avoid bias in the analysis, the ±20 keV energy region around $Q_{\beta\beta}$ was blinded. It will be opened only after all selection and analysis cuts will be finalized. All eight enriched semi-coaxial detectors coming from the previous experiments HDM and IGEX were deployed in GERDA together with three natural Ge semi-coaxial detectors. Soon after the deployment two enriched detectors started to drive high leakage current and cannot be used for analysis. In the middle of July 2012 five enriched BEGe diodes (the detectors foreseen for Phase II) were deployed removing 2 natural diodes. Apart from that, the data taking is running smoothly with stable operation. The performances of each detector in terms of energy resolution and stability of the energy scale are monitored by performing calibration runs every one or two weeks using ^{228}Th sources. Values of energy resolution between 4.2 and 5.3 keV (FWHM) at 2614.5 keV have been obtained: they can be transformed into a mass weighted mean of 4.5 keV (FWHM) at $Q_{\beta\beta}$ = 2039 keV. The energy resolution of the 2614.5 keV line for all semi-coaxial detectors is shown in the upper part of Fig. 2 for the first months of data taking. No significant variation or trend are visible. The lower part of Fig. 2 shows the shifts in position of the same γ line, all data stay inside a range of ± 1.3 keV. Scaling linearly with energy to $Q_{\beta\beta}$ the stability is within ± 1 keV.

The upper plot of Fig. 3 shows the spectra obtained using all the enriched semi-coaxial detectors (red curve) and all the enriched BEGe diodes (green curve). The enriched BEGe spectrum

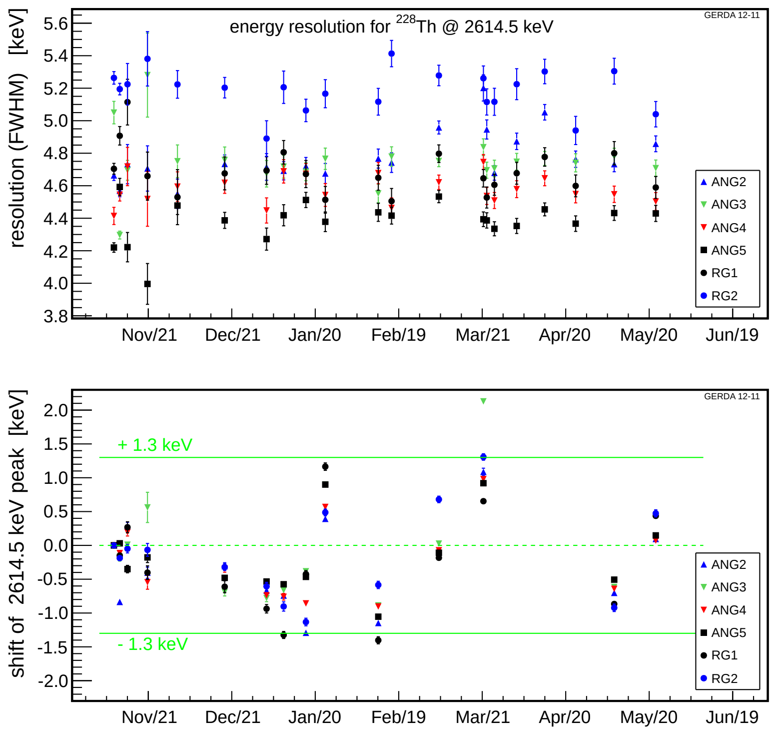

Figure 2: Upper plot: the energy resolution of the semi-coaxial Ge detectors is shown for several energy calibration with a ^{228}Th source. Lower plot: variations of the 2614.5 keV γ line peak position between successive calibrations. The green lines indicate $\pm$ 1 keV variation at $Q_{\beta\beta}$ when scaled linearly in energy. From [6].

is scaled to the exposure of the semi-coaxial diodes. The low energy part up to 565 keV is dominated by the β-decay of cosmogenic ^{39}Ar, between 600 and 1500 keV the histograms show an enhanced continuous spectrum from $2\nu\beta\beta$ decays. In all spectra, γ lines from decays of ^{40}K and ^{42}K are identified. In the spectrum of semi-coaxial detectors γ lines from ^{214}Bi, ^{208}Tl and a peak-like structure around 5.3 MeV corresponding to the decay of ^{210}Po on the detector p^{+} surfaces are visible. The region around $Q_{\beta\beta}$ is shown in Fig. 3 (middle plot for semi-coaxial detectors, lower plot for BEGe detectors). The BI for the enriched semi-coaxial detectors is 0.022$\pm$0.003 cts/(keV·kg·yr) calculated from the data using a region of $\pm$ 100 keV around $Q_{\beta\beta}$ and excluding the 40 keV blinded window. This BI is already, without any PSD analysis, about a factor 10 lower than the BI's achieved by the previous ^{76}Ge experiments (HDM, IGEX).

4.1 Measurement of $T^{2\nu}_{1/2}$ of the two neutrino-double beta decay

The $2\nu\beta\beta$ decay of atomic nuclei, with the simultaneous emission of two electrons and two anti-neutrinos, conserves lepton number and is allowed within the SM, regardless of the nature of the neutrino. It is characterized by an extremely low decay rate because it is a second-order process. So far it is the rarest decay ever observed in laboratory experiments. The measurement of the $2\nu\beta\beta$ half-life ($T^{2\nu}_{1/2}$) is of some interest. Indeed it has been suggested [10, 11] that, within the

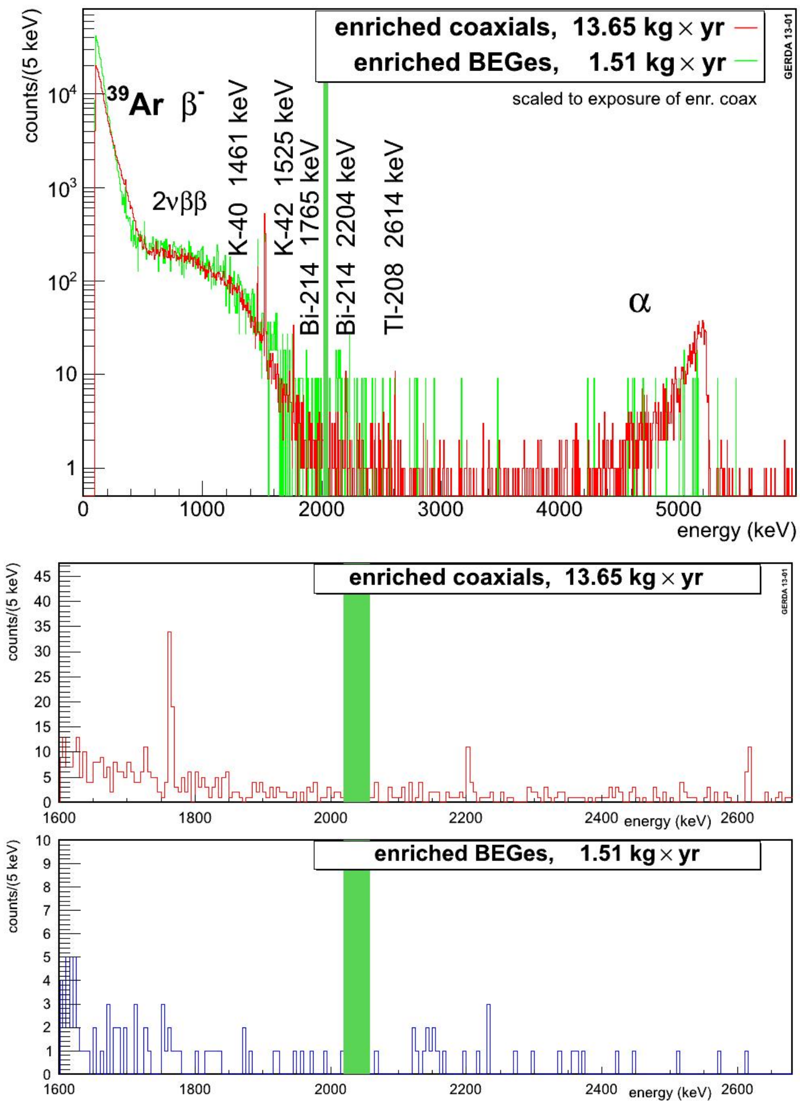

Figure 3: Upper plot: Spectra obtained using all the enriched semi-coaxial detectors (red curve) and all the enriched BEGe detectors (green curve). The enriched BEGe spectrum is scaled to the exposure of the semi-coaxial diodes. Middle and lower plots: zoom of the spectrum around the $Q_{\beta\beta}$ for the enriched semi-coaxial (middle plot) and BEGe (lower plot) detectors diodes. The green bands in all the three plots indicate the blinding region of 40 keV around $Q_{\beta\beta}$.

same model framework, the evaluation of the nuclear matrix element for the $2\nu\beta\beta$ decay ($M_{2\nu}$) from $T_{1/2}^{2\nu}$ measurements could set some constraints on $M_{0\nu}$. Moreover, $M_{2\nu}$ can be compared with the predictions based on charge exchange experiments [12, 13]. An agreement between those two evaluations will increase the knowledge of the reaction mechanisms and the nuclear structure aspects involved in $2\nu\beta\beta$.

The data set considered for the $2\nu\beta\beta$ analysis [14] was taken between November 9, 2011 and March 21, 2012 corresponding to an exposure of 5.04 kg·yr. The $2\nu\beta\beta$ analysis was performed

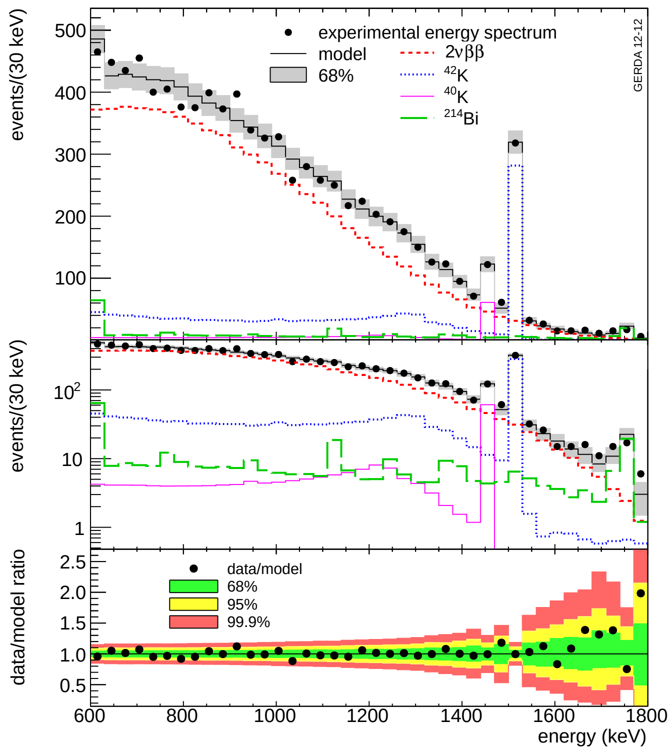

Figure 4: The upper panel shows the experimental data (black markers) and the best fit model (black histogram) for the sum of the semi-coaxial detectors in linear scale, the middle one in logarithmic scale. Individual components are shown with coloured histograms. The shaded band covers the 68% probability range for the model expectation. The lower panel gives the ratio between experimental data and the prediction of the best fit model. The smallest intervals containing the 68%, 95% and 99.9% probability for the expectation are shown in green, yellow and red regions, respectively. From [14].

in the energy range between 600 and 1800 keV. Below 600 keV the GERDA energy spectrum is largely dominated by ^{39}Ar decays. From Monte Carlo simulations, the probability of $2\nu\beta\beta$ decay fully contained in the active volume of the detectors and producing a total energy release between 600 and 1800 keV is about 63.5%. The probability of releasing energy in the region above 1800 keV is less than 0.02%: therefore the energy region above 1800 keV gives no information on the $2\nu\beta\beta$ process. The total number of events in the selected energy window is 8796. The experimental spectra of the diodes were analyzed following a binned maximum likelihood approach described in [15]. The analysis region was divided into 40 bins of 30 keV. A global model was fitted to the observed energy spectra. It includes the ^{76}Ge $2\nu\beta\beta$ decay and three main background components: ^{42}K, ^{214}Bi and ^{40}K. The presence of such background sources was established by the observation of their characteristic γ lines in the energy spectra: 1525 keV from ^{42}K keV, 1460 keV from ^{40}K, and 609 keV and 1764 keV due to ^{214}Bi. The $2\nu\beta\beta$ decay half-life is common in the fit to the six semi-coaxial detector spectra. The intensities of the background components are independent for each detector. The shapes of the energy spectra for the signal and the three backgrounds contamination are obtained from Monte Carlo simulations, separately calculated for each detector. The simulations are performed using the MAGE code [16] based on GEANT4 [17]. The spectrum of the two electrons emitted in the ^{76}Ge $2\nu\beta\beta$ decay follows the distribution of [18] as implemented in the DECAY0 [19] code. The ^{42}K activity is uniformly distributed in the LAr volume. The actual position of the ^{40}K and ^{214}Bi emitters is not known very well: in the Monte Carlo simulation a "close source" assumption was made. The spectral fit was performed using the Bayesian Analysis Toolkit (BAT) [20]. Well chosen prior probability density functions (PDF) were given for $T^{2\nu}_{1/2}$, for the active volume fractions and ^{76}Ge isotopic abundances of the germanium diode. Fig. 4 shows the data together with the best fit model (black histogram) with its 68% uncertainties. The best fit model returns 8797.0 events in comparison to 8796 data events, with the following components: ^{76}Ge $2\nu\beta\beta$ (79%), ^{42}K (14.1%), ^{218}Bi (3.8%) and ^{40}K (2.1%). The signal-to-background ratio in the region 600-1800 keV is around 4 to 1, much better than that for any past experiment observing the ^{76}Ge $2\nu\beta\beta$ decay. The best half-life estimate, having marginalized over all nuisance parameters, gives:

$$T^{2\nu}_{1/2} = \left(1.84^{+0.09}_{-0.08}\,\mathrm{fit}\;\;^{+0.11}_{-0.06}\,\mathrm{syst}\right) \times 10^{21}\mathrm{yr} \tag{4.1}$$

The first error comes from the statistics and the marginalization of the nuisance parameters, while the second relates to the additional systematic uncertainties. Active masses and ^{76}Ge isotopic abundances (left free as nuisance parameters) drive the uncertainties coming from the fit procedure, while the dominant systematic uncertainties is due to the background model. From the present GERDA result and using the improved electron wave functions reported in [21] it is possible to calculate the nuclear matrix element for the ^{76}Ge $2\nu\beta\beta$ decay: $M_{2\nu} = 0.133^{+0.004}_{-0.005}$ MeV^{-1}. The value is consistent with ^{76}Ge $M_{2\nu}$ extracted from the charge exchange reactions (d,^{2}He) and (^{3}He,t) [12, 13].

5. The Status of Phase II

As already explained in section 3, the life of the GERDA experiment has been organized in two phases. Phase I will be completed in the middle of May 2013 with the aim to prove or disprove the discovery claim. Phase II has the goal to improve the sensitivity by an order of magnitude, that is to reach $T^{0\nu}_{1/2} > 1.5 \times 10^{26}$ yr. For pure Majorana exchange, this higher sensitivity will constrain the effective electron neutrino mass to less than 100 meV, this value depending on the choice of the nuclear matrix elements. This improvement of a factor ten of the sensitivity will be obtained with the following strategy:

- a reduction of a factor ten of the BI, that is in Phase II the goal is to reach a BI of 1.0×10^{-3} cts/(keV·kg·yr);
- adding 30 new enriched BEGe detectors (20.1 kg);
- collecting an exposure of 100 kg·yr.

30 new enriched BEGe detectors have been already produced by Canberra Olen and fully tested by the GERDA collaboration. In order to reach the aforementioned very low BI various actions

will be performed. Detector holders, FE electronics cards, cables and all the foreseen material near the detectors will be accurately selected in order to satisfy the limits imposed by the BI. Active suppression methods such as PSD analysis and the readout of the scintillation light of the liquid argon will be used to further reject the background. The work for the modification of the GERDA detector will start in the fall 2013 and it is foreseen to be completed early in 2014, after that a commissioning phase will start.

6. Conclusions

GERDA searches for $0\nu\beta\beta$ decay of ^{76}Ge implementing a new shielding concept. Bare enriched Ge diodes are operated in high purity LAr supplemented by a water shield. The experiment has started its Phase I data taking in November 2011 and will continue up to the collection of ~ 20 kg·yr, which is foreseen to happen in the middle of May 2013. The goal of Phase I is to prove or disprove the Klapdor-Kleingrothaus claim. After the completion of Phase I, there will be a major upgrade (Phase II) with the aim to improve the sensitivity by about a factor of 10 ($T_{1/2} > 1.5 \cdot 10^{26}$ yr). The present data taking of Phase I is running smoothly and the achieved BI around the $Q_{\beta\beta}$ is about a factor 10 lower than that of the previous Ge $0\nu\beta\beta$ decay experiments. With the first 5.04 kg·yr GERDA has measured the half-life of the $2\nu\beta\beta$ decay of ^{76}Ge: $T^{2\nu}_{1/2} = \left(1.84^{+0.09}_{-0.08}\,\mathrm{fit}\ ^{+0.11}_{-0.06}\,\mathrm{syst}\right) \times 10^{21}$yr. The total uncertainty is comparable to what was obtained by other ^{76}Ge experiments, in spite of the much smaller exposure. This is due to the GERDA superior signal-to-background ratio.

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