Background modeling for the GERDA experiment

N. Becerici-Schmidt on behalf of the GERDA collaboration

Max-Planck-Institut für Physik, München, Germany

Abstract. The neutrinoless double beta (0νββ) decay experiment GERDA at the LNGS of INFN has started physics data taking in November 2011. This paper presents an analysis aimed at understanding and modeling the observed background energy spectrum, which plays an essential role in searches for a rare signal like 0νββ decay. A very promising preliminary model has been obtained, with the systematic uncertainties still under study. Important information can be deduced from the model such as the expected background and its decomposition in the signal region. According to the model the main background contributions around Q_{ββ} come from ^{214}Bi, ^{228}Th, ^{42}K, ^{60}Co and α emitting isotopes in the ^{226}Ra decay chain, with a fraction depending on the assumed source positions.

Keywords: neutrinoless double beta decay, Majorana neutrino, \(^{76}\text{Ge}\), enriched germanium detectors, liquid argon, surface contamination

PACS: 14.60.Pq Neutrino mass and mixing, 23.40.-s β decay; double β decay; electron and muon capture, 23.60.+e α decay, 29.85.Fj Data analysis

INTRODUCTION

Neutrinoless double beta (0νββ) decay, \((A, Z) \rightarrow (A, Z + 2) + 2e^-\), is a hypothetical process with an extremely low expected rate. For some even-even nuclei β decay is energetically forbidden. They can however simultaneously emit two electrons and two antineutrinos via neutrino accompanied double beta (2νββ) decay. These nuclei can make a 0νββ transition if lepton number is violated and if neutrino has a Majorana component, thus leading to physics beyond the standard model of particle physics [1]. The expected signal of 0νββ decay is a peak at the Q_{ββ} value of the decay. The lower limits with 90\% C.L. on the 0νββ half life of ^{76}\text{Ge} are given by HdM and IGEX experiments as \(1.9 \times 10^{25}\) yr [2] and \(1.6 \times 10^{25}\) yr [3], respectively. There is also a controversial claim of observation with a half life of \(1.19 \times 10^{25}\) yr [4] from a subgroup of the HdM experiment.

The GERmanium Detector Array (GERDA) experiment at the National Gran Sasso Laboratory (LNGS) of INFN is searching for 0νββ decay of the \(^{76}\text{Ge}\) isotope [5]. The physics data taking for Phase I has started in November 2011, with the goal of testing the claim. The achieved background index (BI) around Q_{ββ} is an order of magnitude lower than the one of the precursor experiment HdM. The first physics result of Phase I is a measurement of the half life of 2νββ decay as \(1.84^{+0.14}_{-0.10} \times 10^{21}\) yr [6]. Due to the superior signal-to-background ratio, a precision comparable to latest results which were obtained with a much more exposure has been achieved.

GERDA follows a blind analysis strategy in Phase I; events in a 40 keV window around Q_{ββ} are not available for analysis. The unblinding is planned for Summer 2013, when a sufficient exposure is acquired and the selection cuts are finalized. In this paper, an analysis for modeling of the observed background spectrum in Phase I is described and preliminary results are shown.

EXPERIMENTAL SETUP AND DATA TAKING

The GERDA experiment implements a novel technique by operating an array of high-purity germanium (HPGe) detectors directly submerged in liquid argon (LAr). The Phase I physics data taking has started in November 2011 with semi-coaxial p-type HPGe detectors, eight of them enriched in \(^{76}\text{Ge}\) and three of them with natural abundance. BEGe type detectors produced for Phase II are also being tested in Phase I setup. The details of the GERDA experiment and Phase I data taking has been presented in [5].

The analysis is performed on the data from coaxial detectors acquired until March 2013, with a total exposure of 13.65 kg·yr for the sum enriched coaxial detectors \((\text{enr}\text{Ge}-\text{coax})\) and 2.77 kg·yr for one natural coaxial detector \((\text{nat}\text{Ge}-\text{coax})\) considered here. The surface of the detectors have a conductive lithium layer (n\(^+\) contact) and a boron implanted layer (p\(^+\) contact) which are separated by a groove. They form dead layers \((dl)\) on the surface measured to be nearly 2 mm for the n\(^+\) and expected to be less than a \(\mu\)m for the p\(^+\) surface (see Figure 1.)
FIGURE 1. Left: Schematic drawing of a coaxial type HPGe detector. Middle: A Phase I detector after reprocessing. Right: The detector is mounted upside down in its holder.

ANALYSIS OF THE BACKGROUND SPECTRUM

The main background sources in GERDA Phase I, identified by their characteristic γ lines or by other features in the observed energy spectrum, are $^{60}$Co, $^{40}$K, $^{39}$Ar and $^{42}$K ($^{42}$Ar) due to LAr, $2νββ$ decay of $^{76}$Ge, $^{226}$Ra ($^{232}$U-series), $^{228}$Ac and $^{228}$Th ($^{232}$Th-series). At any rate, presence of these sources in the setup was known mainly due to the screening of materials for radio purity tests or due to the LAr surrounding the bare detectors.

This section describes the analysis for modeling the observed background energy spectrum. Firstly, the energy region above 3.5 MeV ($Q_{β}$ of $^{42}$K) is analyzed. Practically no significant contribution from sources other than α decays is expected in this region. After obtaining an α model that describes the spectrum at high energies, a larger energy window is analyzed that includes the $Q_{ββ}$ region.

Analysis of the α-induced background

A very prominent peak structure around 5.3 MeV with a tail towards lower energies has been observed in the energy spectrum of the $^{enriched}$Ge-coax (depicted in Figure 2) due to $^{210}$Po α decays. Also a significant number of events observed above 5.3 MeV reveals that there are other sources than $^{210}$Po contributing to the spectrum. Other peak structures observed with lower intensities, i.e., around 4.7 MeV, 5.4 MeV and 5.9 MeV, indicate a contribution from the successive α decays in $^{226}$Ra decay chain.

α particles with energies between 4 MeV and 9 MeV have several tens of μm range in Ge and in LAr. Therefore, they can only deposit energy in the active volume if they decay on or close to the $p^+$ surface ($dl < 1$ μm) of the detectors and can induce events at $Q_{ββ}$ after their energies degrade in LAr and $dl$.

In the following, analyses of the event rate distributions and of the energy spectrum of events above 3.5 MeV are described. While the source of the events which are dominant in different regions can be inferred from the time analysis, a model of the energy spectrum can allow to estimate their contributions around $Q_{ββ}$.

FIGURE 2. Energy spectrum of the $^{enriched}$Ge-coax in high energy region measured in GERDA Phase I.
Bayesian inference

The probability of the model and its parameters, the posterior probability is given from Bayes theorem as

\[ P(\hat{\lambda} | \mathbf{n}) = \frac{P(\mathbf{n} | \hat{\lambda}) P_0(\hat{\lambda})}{\int P(\mathbf{n} | \hat{\lambda}) P_0(\hat{\lambda}) d\hat{\lambda}} \]  

(1)

where \( P(\mathbf{n} | \hat{\lambda}) \) denotes the likelihood and \( P_0(\hat{\lambda}) \) the prior probability of the parameters. When analyzing the binned distributions of data arising from a Poisson process, the likelihood is written as the product of the probability of data given the model and parameters in each bin

\[ P(\mathbf{n} | \hat{\lambda}) = \prod_i P(n_i | \lambda_i) = \prod_i \frac{e^{-\lambda_i} \lambda_i^{n_i}}{n_i!} \]

(2)

where \( n_i \) is the observed number of events and \( \lambda_i \) is the expected number of events in the \( i \)-bin bin.

The analysis of both event rate and energy distributions is carried out by fitting the binned distributions due to the method described. One of the merits of Bayesian analysis is the possibility to add initial knowledge to the analysis in order to get a better answer. This is done by giving prior probabilities on the parameters whenever available. The computation is done using the Bayesian Analysis Toolkit BAT [7].

Event rate analysis

The event rate distributions are obtained for two different energy regions; 3.5 – 5.3 MeV where \(^{210}\)Po is dominant and 5.3–7.5 MeV where events only due to \(^{226}\)Ra decay chain are expected. The distribution for the first region follows an exponential decrease as expected from an initial \(^{210}\)Po \((T_{1/2} = 138.4\) d) contamination. Two models are used to fit the distribution; an exponential rate (assuming only \(^{210}\)Po) and exponential plus a constant rate (allowing other contributions) by giving a Gaussian prior on the half life parameter with a mean value of 138.4 days and a standard deviation of 0.2 days. Note that a constant component can be due to \(^{226}\)Ra \((T_{1/2} = 1600\) yr) and/or \(^{222}\)Ra. The distribution for the second region looks flat as expected from \(^{226}\)Ra and fitted only with a constant.

The expected number of events, \( \lambda_i \), is corrected for the live time fraction. While performing a fit with an exponential function it is written as

\[ \lambda_i = \varepsilon_i \int_{(i-1)\Delta t}^{i\Delta t} N_0 \cdot e^{-\ln2t/T_{1/2}} dt \]

(3)

where \( \varepsilon_i \) is the value in the \( i \)-bin bin of the live time fraction distribution, \( \Delta t \) is the bin width, \( N_0 \), the initial event rate and \( T_{1/2} \), the half life are the parameters of the model. The distribution for the 3.5 – 5.3 MeV region was described better with the second model with a small constant term of \((0.57\pm0.16)\) cts/day to an initial rate of \((7.9\pm0.4)\) cts/day decreasing exponentially with a half life of \((138.4\pm0.2)\) days. A fit with a non informative prior on the half life parameter was also performed, resulting in a half life of \((130.4\pm22.4)\) days, which is in very good agreement with the half life of \(^{210}\)Po. The distribution for the 5.3 – 7.5 MeV region is described very well with a constant rate of \((0.09\pm0.02)\) cts/day, supporting the assumption of an initial \(^{226}\)Ra source.

Figure 3 shows the results of the performed fits, i.e. data (what has been measured) together with the expectation (what is expected to be measured given the live time fraction) due to the best fit model (what was supposed to be measured for a 100% live time fraction). Comparison of data and expectation due to model is done by giving 68%, 95% and 99.9% probability intervals for the expectation.

Spectral analysis

Analysis of the energy spectrum is done under the assumption that events above 3.5 MeV come from \(^{210}\)Po \( \alpha \) decays and from the successive \( \alpha \) decays in the \(^{226}\)Ra decay chain. While former is only assumed on the p+ surface, the latter starting from \(^{222}\)Rn assumed also in LAr. This is expected since \(^{222}\)Rn emanates into LAr from materials with \(^{220}\)Rn contamination in the close vicinity of the detectors. The expected energy spectrum of all the components are obtained
FIGURE 3. Results of fitting the event rate distribution for the 3.5–5.3 MeV region with an exponential plus constant (left) and for the 5.3–7.5 MeV region with a constant. The best fit model with 68% uncertainty band and the live time fraction distribution are shown in the upper panels. The observed and the expected number of events in the lower ones. Also shown are the smallest intervals containing the 68%, 95% and 99.9% probability for the expectation in green, yellow and red regions, respectively [8].

through MC simulations in MAGE [9] by using a detailed description of the GERDA Phase I setup. Spectra for different $d_l$ thicknesses (100 nm – 1 $\mu$m) are simulated to derive the effective $d_l$ thickness.

The simulated spectra are fitted to the observed spectrum with a 50 keV binning in 3.5–7.5 MeV region by giving flat priors on the parameters. The analysis is also done for the natGe-coax which shows a similar spectral features but a lower $^{210}$Po rate and enhanced structures from $^{226}$Ra decay chain. The model describes both spectra very well (see Figure 4). The results are stable wrt. the choice of bin width. According to the model the expected background contribution in $Q_{\beta\beta} \pm 5$ keV is $(2.1 \pm 0.5) \times 10^{-3}$ cts/(keV·kg·yr) ($\sim$10%) for the enrGe-coax mostly (7%) coming from LAr decays resulting in a linear spectrum with a small slope unlike surface decays. The contribution of $\alpha$ induced events depends on the analyzed data set, since the surface contaminations are detector dependent and initial $^{210}$Po rate is decreasing in time.

FIGURE 4. The upper panels show the best fit model (black histogram) and observed spectrum (black markers) for enrGe-coax (left) and natGe-coax(right). Individual components of the model are shown as well. The lower panel shows the ratio of data and model and the smallest intervals containing 68%, 95% and 99.9% probability for the model expectation.
A global model for the background spectrum

The $\alpha$ induced event model alone successfully describes the observed energy spectrum down to 3.5 MeV. Below 3.5 MeV many other background components contribute to the spectrum, some of them also relevant around $Q_{\beta\beta}$. The analysis window is therefore expanded down to 570 keV to obtain a full background decomposition at $Q_{\beta\beta}$. The part where the beta spectrum of $^{39}$Ar ($Q_\beta=565$ keV) is the dominating component without any relevance at $Q_{\beta\beta}$ is not included in the analysis. All the components – namely, $2\nu\beta\beta$ decay of $^{76}$Ge, $^{42}$K, $^{40}$K, $^{214}$Bi, $^{228}$Th, $^{60}$Co and the $\alpha$ model – that are expected to contribute in this energy window are considered in a global fit. Some parameters are given an informative prior probability, e.g. a Gaussian prior probability distribution for the expected $^{214}$Bi decays on the $p^+$ surface is given according to the $\alpha$ model. The best fit model together with the observed spectrum is shown in Figure 5, which is rather a qualitative demonstration of the success of the model. Many cross-checks and systematic uncertainties are still under study. Therefore, the details of the analysis and its results are intentionally neither shown nor discussed. Nevertheless, one important conclusion can be made: The main contributions around $Q_{\beta\beta}$ come from $^{214}$Bi, $^{228}$Th, $^{42}$K, $^{60}$Co and $\alpha$ emitting isotopes in the $^{226}$Ra decay chain, with a fraction depending on the assumed source position and distribution.

FIGURE 5. Data (filled histogram) from the enriched coaxial detectors and the best fit model (black histogram). The red band masks the region of interest.

CONCLUSIONS

A model for the observed background energy spectrum in GERDA Phase I is obtained. The model allows to have a decomposition of the background at $Q_{\beta\beta}$. Other important informations that can be deduced from the background model are, the expected number of background events and the spectral shape of background around $Q_{\beta\beta}$. These are essential inputs for a reliable result in the upcoming $0\nu\beta\beta$ analysis. After all the necessary cross checks are performed and systematic uncertainties are evaluated, the results will be presented in a paper from the GERDA collaboration.

REFERENCES

1. Vergados J.D. et al. 2012 Rep. Prog. Phys. 75 106301
2. Zuber K. 2012 Pramana: J. Phys. 79 Issue 4, 781.
3. Bilenki S.M. and Giunti C. 2012 Mod. Phys. Lett. A 27 1230015
4. Schwingerheuer B. 2012 “Status and prospects of searches for neutrinoless double beta decay”, submitted to Annalen der Physik, preprint arXiv:1210.7432
5. Avignone F.T., Elliott S.R. and Engel J. 2008 Rev. Mod. Phys. 80 481
6. Gomez-Cadenas J.J. et al. 2012 Riv. Nuovo Cimento 35 29
7. Klapdor-Kleingrothaus H.V . et al. (Heidelberg-Moscow Collaboration) 2001 Eur. Phys. J. A 12 147
8. Aalseth C.E. et al. (Igex Collaboration) 2001 Phys. Rev. D 65 092007
9. Klapdor-Kleingrothaus H.V . et al. (Heidelberg-Moscow Collaboration) 2004 Phys. Lett. B 586 198
10. K.H. Ackermann et al. (GERDA Collaboration) 2013 “The GERDA experiment for the search of 0\nu\beta\beta decay in $^{76}$Ge”, Eur. Phys. J. C 73 2330
11. Agostini M. et al. (GERDA Collaboration) 2013 J. Phys. G: Nucl. Part. Phys. 40 035110
12. Caldwell A, Kollar D and Kröninger K 2009 Comput. Phys. Comm. 180 2197
13. Aggarwal R and Caldwell A 2012 Eur. Phys. J. Plus 127 24
14. Boswell M et al.2011 IEEE Trans. Nucl. Sci. 58 1212