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Identification of photons in double beta-decay experiments using segmented germanium detectors—Studies with a GERDA phase II prototype detector

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Abstract

The sensitivity of experiments searching for neutrinoless double beta-decay of germanium was so far limited by the background induced by external γ-radiation. Segmented germanium detectors can be used to identify photons and thus reduce this background component.

The GERmanium Detector Array, GERDA, will use highly segmented germanium detectors in its second phase. The identification of photonic events is investigated using a prototype detector. A focus is placed on the comparison with Monte Carlo data.

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1. Introduction

Neutrinoless double beta-decay ($0\nu\beta\beta$) is expected to occur, if the neutrino is a massive Majorana particle. The observation of the $0\nu\beta\beta$-process would not only reveal the nature of the neutrino as a Majorana particle but could also provide information about the absolute neutrino mass scale (see, e.g. [1]).

The germanium isotope ^{76}Ge is a prominent candidate for the observation of the $0\nu\beta\beta$-process. Experiments searching for neutrinoless double beta-decay of ^{76}Ge use high purity germanium detectors as source and detector simultaneously. Their sensitivity is limited by unidentified background events which in previous experiments were mostly induced by external γ-radiation. The Heidelberg–Moscow and IGEX experiments set 90% C.L. lower limits on the half-life of the process of $T_{1/2} > 1.9 \times 10^{25}$ years [2] and $T_{1/2} > 1.6 \times 10^{25}$ years [3], respectively. An evidence for the observation of the $0\nu\beta\beta$-process was claimed by parts of the Heidelberg–Moscow collaboration with $T_{1/2} = 1.2 \times 10^{25}$ years [4].

The GERmanium Detector Array, GERDA [5], is a new germanium double beta-decay experiment being installed in Hall A of the INFN Gran Sasso National Laboratory (LNGS), Italy. Its main design feature is to operate germanium detectors directly in liquid argon which serves as cooling medium and as a shield against external γ-radiation. A detailed description of the experiment can be found in Refs. [5,6].

The detectors for the second phase of the experiment (Phase II) will be enriched in ^{76}Ge to a level of about 86% and will have a mass of approximately 2 kg each. For the first time, highly segmented germanium detectors will be used in a double beta-decay experiment. The segmentation scheme is chosen to reduce the background level in the energy region around $Q_{\beta\beta} = 2039$ keV. The current detector design foresees a six-fold segmentation in the azimuthal angle ϕ and a three-fold segmentation in the height z. All segments and the core are read out separately to allow a better identification of photons. The estimated gain in background

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reduction for the GERDA experiment is discussed in Ref. [6].

In this paper the results of a study with a GERDA Phase II prototype detector are presented. The identification of events with photons in the final state is investigated, i.e. photons emitted either in the primary reaction or as bremsstrahlung are tagged by analyzing the event topology. Section 2 summarizes the photon identification using coincidences between segments. The underlying physics processes and their signatures are described as are the event selection and the analysis strategy. Section 3 describes the experimental setup of the prototype detector and the data sets collected. The Monte Carlo simulation is introduced in Section 4. The results of the study are given in Section 5. A focus is placed on the comparison of the experimental results with Monte Carlo data which is described in the same section. Section 6 concludes and discusses the significance for the GERDA experiment.

2. Identification of photon events using segment coincidences

The volume over which energy in a single event is deposited inside a detector depends on the incident particles and energy. Segmented detectors can be used to identify some of the events with photons in the final state by requiring coincidences between the segments of a detector. This technique is well established in nuclear experiments such as AGATA [7] and GRETA [8], and provides a basis for γ-ray tracking [9].

The potential of segmented detectors for double beta-decay experiments has also been investigated by the MAJORANA collaboration [10] using a clover detector [11], a group of four closely packed detectors with two longitudinal segments each, and Monte Carlo simulations [12].

2.1. Signatures and physics processes

The signatures of events encountered in double beta-decay experiments can be classified according to the particles in the final state. A detailed classification for these events is given in Ref. [6]. For the identification of photon events only two such classes are considered here:

- *Class L*: Local energy deposit. Three different types of events are part of this class: (a) Events with only electrons in the final state. Electrons in the MeV-energy region have a range of the order of a millimeter in germanium [6,13]. Energy is therefore deposited locally. Double beta-decay events which have two electrons in the final state are of this type (these events correspond to Class I events in Ref. [6]). (b) Events with photons in the final state in which a photon Compton-scatters only once inside the fiducial volume of the detector. Energy is thus deposited locally. (c) 'Double escape' events: If a photon produces an electron-positron pair and both photons from the subsequent annihilation escape, energy is deposited locally.
- *Class M*: Multiple energy deposits. Photons emitted in radioactive decays have energies in the MeV-energy region and interact dominantly through Compton scattering in germanium. The range of these photons is of the order of centimeters. The different interactions are separated by distances large compared to the scale of Class L events. This class is composed of Classes II–IV in Ref. [6].

It should be noted that with the technique presented in this paper the three event types in Class L cannot be separated but only be distinguished from Class M events.

2.2. Event selection and identification of photon events

Due to the well separated multiple energy deposits Class M events are expected to deposit energy predominantly in more than one segment. Class L events will predominantly deposit energy in only one segment.[1] Events in which more than one segment measures deposited energy can thus be identified as Class M events.

3. Experimental setup and data sets

3.1. Experimental setup

The GERDA Phase II prototype detector under study is a high purity n-type germanium crystal with a true coaxial geometry. It is 70 mm high and has an outer diameter of 75 mm. The inner diameter is 10 mm. The detector is six-fold segmented in the azimuthal angle ϕ and three-fold segmented in the height z. It is placed inside a two-walled aluminum cryostat with a combined thickness of 6 mm. The operation voltage of the detector is (+)3000 V.

A schematic diagram of the detector and the experimental setup is given in Fig. 1. The core and each segment are read out using charge sensitive PSC 823 pre-amplifiers. The pre-amplified signals are digitized using a data acquisition system based on 5 14-bit ADC PIXIE-4 modules at a sampling rate of 75 MHz. In this configuration the energy resolution of the core is approximately 2.6 keV (FWHM at 1333 keV), the energy resolution of the segments varies between 2.4 and 4.7 keV with an average segment energy resolution of 3.3 keV. The threshold of the core and the segments was set to 20 keV. Cross-talk between the core and the segment pre-amplifiers and a constraint in the DAQ system, which resulted in the inability to handle late arriving signals, caused a fraction of less than 10% of individual segment signals to not be recorded. A detailed description of the setup and the prototype detector properties was published [14].

[1] The case that charge carriers created in a single interaction cause a signal in two segments (charge sharing) is not accounted for. This effect is expected to be negligible for detectors of the size and segmentation scheme chosen. Experimental studies are planned for the near future.