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Search for the β decay of ^{96}Zr

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ABSTRACT

^{96}Zr and ^{48}Ca are unique among double-β decay candidate nuclides in that they may also undergo single-β decay. In the case of ^{96}Zr, the single-β decay mode is dominated by the fourth-forbidden β decay with a 119 keV *Q* value. A search was conducted for the β decay of ^{96}Zr by observing the decay of the daughter ^{96}Nb nucleus. Two coaxial high-purity germanium detectors were used in coincidence to detect the γ-ray cascade produced by the daughter nucleus as it de-excited to the ground state. The experiment was carried out at the Kimballton Underground Research Facility and produced 685.7 days of data with a 17.91 g enriched sample. No counts were seen above background, producing a limit of $T_{1/2} > 2.4 \times 10^{19}$ year. This is the first experimental search that is able to discern between the β decay and the double-β decay to an excited state of ^{96}Zr.

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1. Introduction

Two-neutrino double-β (2νββ) decay is a second order nuclear decay that has been observed in 11 nuclides. Among these 11, ^{96}Zr is unique, along with ^{48}Ca, in that the single β decay is energetically allowed, but highly suppressed. The 0^+ ^{96}Zr nucleus must undergo a sixth forbidden β decay to the 6^+ ground state or a fourth forbidden β decay to the first two excited states, 5^+ and 4^+, of ^{96}Nb. Reference [1] theoretically estimated that the decay is dominated by the transition to the 5^+ state with a half-life of 2.4×10^{20} year. This estimate is 10 times larger than the half-life of the 2νββ decay to the ground state of ^{96}Mo measured by the NEMO-3 collaboration: $T_{1/2} = [2.35 \pm 0.14$ (syst) ± 0.16(stat)] $\times 10^{19}$ year [2].

A current interest is measuring 2νββ decay to excited nuclear states. Measurement of this decay mode may provide additional information on the nuclear structure of the decay and aid in calculations of the nuclear matrix element. Furthermore, decays to an excited state could be used as a consistency test for 0νββ in ton-scale experiments using one isotope [3]. The most likely excited state 2νββ decay is to the first excited 0_1^+ state. For ^{96}Zr, this has an expected half-life comparable to that of the β decay mode [4]. The β decay daughter, ^{96}Nb, decays with a half-life of 23.35 h and emits a cascade of γ rays, as is shown in Fig. 1.

2. Experimental method

The apparatus was initially constructed to search for 2νββ decays to excited final states. The results of the search for the 2νββ decay of ^{96}Zr to excited states are given in Ref. [5], and a complete description of the detector system is given in Ref. [6]. Two γ rays from the γ-ray cascade are detected in coincidence by two high-purity germanium (HPGe) detectors in order to minimize the experimental background. Previous limits on the β and ββ decay to excited states used a single HPGe detector and were focused on the detection of the single 778.2 keV γ ray [7,8]. These works produced high quality limits, but as this γ ray could be produced from either the β decay or the ββ decay to the first excited 0_1^+ state, the technique is inherently limited as it cannot distinguish between the two decay modes.

2.1. Detector apparatus

Two coaxial HPGe detectors sandwich a disk-shaped sample. Both germanium crystals are 88 mm in diameter and 50 mm in length. The HPGe detectors are surrounded by a NaI annulus, which is used as an active veto and Compton suppression shield. Additionally, two plastic scintillator end caps are positioned on each side of the annulus to provide additional veto power. The entire apparatus is surrounded by two layers of passive shielding: 0.75 in. oxygen-free high conductivity copper and 6 in. of lead. The experimental apparatus is housed in the Kimballton Underground Research Facility (KURF), which provides 1450 m of water

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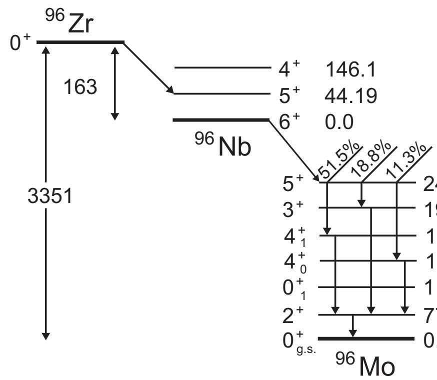

Fig. 1. The single-β decay of ^{96}Zr and its daughter, ^{96}Nb. The figure is not to scale and all energy values are given in keV.

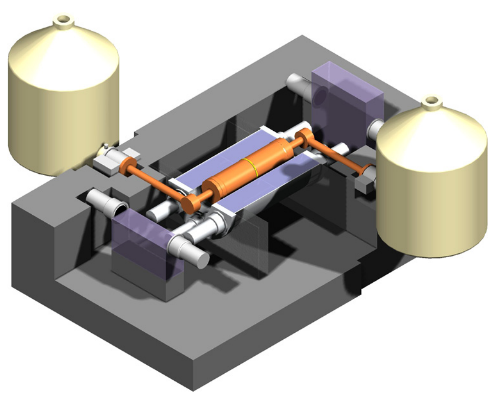

Fig. 2. Diagram of the detector system. The copper plates are not shown and are located between the NaI annulus and lead shielding.

equivalent overburden [9]. A diagram of this apparatus is shown in Fig. 2.

Five signals are recorded for each generation of the master trigger: the pulse height of each HPGe detector, the timing between the HPGe detectors, and two copies of the veto timing. Every event originating in a HPGe detector is recorded and the coincidence criteria are enforced in software. The HPGe detector readout is calibrated to energy approximately every four days using at least four naturally occurring background peaks. Each run is examined for gain shifts, and runs exhibiting such behavior are excluded from the analysis. The long term stability of the HPGe detectors was monitored by investigating the detector's count rate, energy resolution, and efficiency.

2.2. *Enriched ^{96}Zr sample*

Enriched $^{96}ZrO_2$ samples were leased from Oak Ridge National Laboratory, as the small natural abundance of ^{96}Zr, 2.8%, can limit the experimental sensitivity. A 7.2835 g sample enriched to 91.4% ^{96}Zr and a 26.9685 g sample enriched to 64.2% ^{96}Zr were placed in an acrylic container of diameter of 69.95 mm and a thickness of 10.22 mm. The two samples together total 17.914 g of ^{96}Zr. 685.7 days (1.877 year) of data were produced with this enriched sample in place.

3. Analysis procedure

The transitions in ^{96}Nb are below the detection threshold of the current experiment. ^{96}Nb decays with a 23.35 h half-life to ^{96}Mo, with a branching ratio of 96.7% to the 5^+ state. The 5^+ state then de-excites, producing a γ-ray cascade ideal for detection by the two-coaxial HPGe apparatus. Detection of the de-excitation γ rays from the 5^+ state would provide a direct measurement of ^{96}Zr's β decay. The three most probable decay modes are given in Table 1. These decay modes represent 81.6% of all possible decays, with no single remaining decay having a branching ratio $>4.5\%$. All of these decays contain three coincident γ rays, which differentiates the analysis from that of ββ decay to excited states, where the signal region involves only two coincident γ rays.

Table 1
The three most probably decay sequences for the 5^+ state of ^{96}Mo. The branching ratio f_b and the energy of the three de-excitation γ rays is given for each sequence.

Decay sequence	f_b (%)	γ_1 (keV)	γ_2 (keV)	γ_3 (keV)
$5_0^+ \to 4_1^+ \to 2_0^+ \to 0_0^+$	51.5	568.9	1091.3	778.2
$5_0^+ \to 3_0^+ \to 2_0^+ \to 0_0^+$	18.8	460.0	1200.0	778.2
$5_0^+ \to 4_0^+ \to 2_0^+ \to 0_0^+$	11.3	810.8	849.9	778.2

3.1. *Event selection*

The region of interest (ROI) for β decay was chosen very carefully in order to maximize the signal-to-noise ratio while minimizing systematic uncertainties involved in calculating the detector efficiency. The result is a search for events where two of the three γ rays are detected in coincidence, with the third escaping the HPGe detectors. This is referred to as a two γ-ray event. No cuts are made on the NaI annulus, as the third γ ray may interact in the annulus. The background was found to be sufficiently low without using the NaI veto due to the coincidence between the two HPGe detectors.

A second search procedure was conducted for events where two γ rays have complete energy deposition in one HPGe detector and the third γ ray is detected in coincidence. This is referred to as a three γ-ray event. In a three γ-ray events, the NaI is used in anticoincidence, as full energy deposition occurs in the HPGe detectors and leaves no signal in the NaI annulus. Although the three-γ ray event ROI has a smaller efficiency than two γ-ray events, by a factor of 5–6, the summing of the two γ rays will result in higher energy event with a corresponding lower background.

Candidate events must match the energy of the ROI, within $\pm 2\sigma$ of the detector resolution, and the expected background was extrapolated from the data. This is the same analysis procedure detailed in Ref. [5] for the $2\nu\beta\beta$ decay to excited states. The resulting histograms are shown in Fig. 3 for the decay mode with the highest branching ratio, $5_0^+ \to 4_1^+ \to 2_0^+ \to 0_0^+$. The top two histograms illustrate the search for two γ-ray events, while the bottom three histograms show the search for three γ-ray events.

The results of this analysis are detailed in Table 2. The analysis is performed for the three decay modes detailed in Table 1. Each decay mode produces three γ rays, resulting in three different two γ-ray events. There are three additional possible three γ-ray events, giving a total of six possible coincident regions of interest per decay mode. Of these, three were found to be unfit for analysis and are not included. The 568.9–778.2 keV coincidence was contaminated by the 569.8–1063.7 keV γ-ray coincidence resulting from neutron scattering on lead. The 460.0–778.2 keV coincidence was contaminated by the 463.0–911.2 keV γ-ray coincidence from ^{228}Th. Finally, the $1200.0+778.2=1978.2$ keV region of interest was excluded because it appears close to the ADC cutoff energy, where nonlinearities in the calibration could possibly occur.

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