Study of double beta decay of ^{94}Zr to the first excited state of ^{94}Mo

N. Dokania[1],* V. Nanal[1], G. Gupta[1], S. Pal[2], R. G. Pillay[1], P. K. Rath[3], V.I. Tretyak[4,5], A. Garai[6,7], H. Krishnamoorthy[6,7], C. Ghosh[1], P. K. Raina[8], and K. G. Bhushan[9]

[1]*DNAP, Tata Institute of Fundamental Research, Mumbai, India*
[2]*Pelletron Linac Facility, Tata Institute of Fundamental Research, Mumbai, India*
[3]*Department of Physics, University of Lucknow, Lucknow , India*
[4]*Institute for Nuclear Research, MSP 03680 Kyiv, Ukraine*
[5]*INFN, sezione di Roma, I-00185 Rome, Italy*
[6]*India based Neutrino Observatory, Tata Institute of Fundamental Research, Mumbai, India*
[7]*Homi Bhabha National Institute, Anushaktinagar, Mumbai, India*
[8]*Department of Physics, Indian Institute of Technology, Ropar, India and*
[9]*Technical Physics Division, Bhabha Atomic Research Centre, Mumbai, India*

Introduction

Double beta decay (DBD) is a process of fundamental interest in particle physics. DBD to the excited states have been probed at low background facilities using HPGe detectors with half-life limits in a range of $T_{1/2} \sim 10^{18} - 10^{25}$ y [1]. The transitions to excited states can provide supplementary information on DBD and is relevant to the theoretical calculations of Nuclear Transition Matrix Element (NTME) for the process. In the present work, DBD of ^{94}Zr to ^{94}Mo ($0^+ \rightarrow 2_1^+, E_{exc} =$ 871.1 keV) is studied with the Tifr Low background Experimental Setup (TiLES). No evidence of this decay was observed using 232 g.y exposure of ^{nat}Zr. The lower half-life limit obtained is $T_{1/2} > 2.0 \times 10^{20}$ y (68% C.L.), improved by one order of magnitude than the earlier reported value [2].

Experimental Details

The TiLES consists of a low background, high efficiency HPGe detector (70% relative efficiency) [3]. The detector is shielded with 5 cm low activity OFHC Cu, 10 cm low activity Pb (^{210}Pb < 0.3 Bq/kg), a Radon exclusion box and an active muon veto system using three plastic scintillators (50 cm × 50 cm × 1 cm each). A 14-bit, 100 MHz CAEN N6724 digitizer is used for the data acquisition. A C++ based algorithm performs the anti-coincidence between the Ge detector and the plastic scintillator signals within a coincidence window of $\pm 2.5 \mu s$. The data is analyzed using the ROOT analysis framework and LAMPS software. The live time of the counting setup is estimated to be 99.5% using a 10 Hz pulser. The stability of energy scale is better than 1% over a period of 12 weeks. The ^{nat}Zr (99.9% purity) from Princeton Scientific Corp. was used. The elemental composition and impurity analysis of the sample was done using SIMS and ICPMS methods and the results are given in Table I. The thickness and hence mass of the Zr sample to be

TABLE I: Impurity levels in the Zr sample obtained from the SIMS and ICPMS measurement.

From SIMS		From ICPMS	
Element	Conc. (ppm)	Element	Conc. (ppb)
Hf	135	^{238}U	200
Fe	55	^{232}Th	25
Al	40	^{235}U	< 5
Ni	15		
Cr	12		
Sn	12		
Others	<10		

*Electronic address: nehadokania1@gmail.com

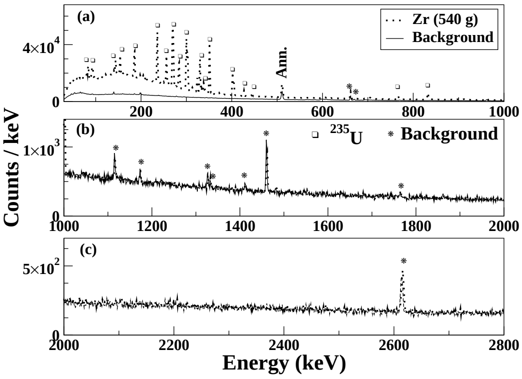

FIG. 1: Gamma ray spectra of the 540 g Zr sample and room background for a counting time of 74 d.

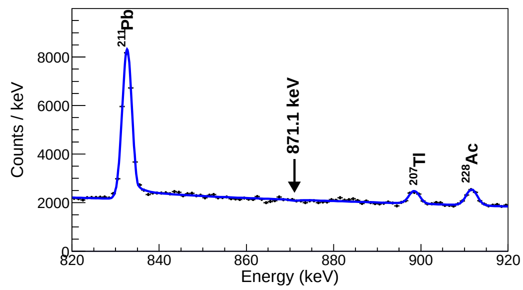

FIG. 2: Gamma ray spectrum of the Zr sample (E_γ = 820-920 keV) for the 232 g.y exposure. Fit is shown by line and the data by circles [4].

mounted was optimized using Geant4 based Monte Carlo (MC) simulations. The Zr block 60 × 75 × 18 mm^3 was mounted at 7 mm from the face of the detector on a 2 mm thick Perspex plate in stages of 180, 360 and 540 g.

Data Analysis and Results

Fig. 1 shows the gamma ray spectra of the 540 g Zr sample together with the room background counted for a period of 74 days. The gamma rays seen with the Zr sample are mostly produced from the decay chain of ^{235}U. The data set amounting to a total exposure of 232 g.y of $^{\mathrm{nat}}$Zr is considered for the analysis. The background is modeled with a Chebyshev polynomial in energy range of (E_γ = 820-920 keV) using RooFit. The peak at 832.0 keV is fitted with a Crystal Ball function while the 897.8 and 911.2 keV peaks have been fitted with a Gaussian function (see Fig. 2). When no signal is observed, the half-life limit is

$$T_{1/2} > \frac{ln2.\ N_A.\ i}{A} \sum_{k=1}^{3} \frac{M_k.\ \epsilon_k.\ t_k}{lim\ S} \qquad (1)$$

where N_A is Avogadro's number, i is the isotopic abundance of ^{94}Zr (16.58%) and A is the molecular mass of Zr (91.224). The ϵ_k is the detection efficiency for 871.1 keV computed from MC simulations, M_k is the mass of the Zr sample and t_k is the counting period for the corresponding data set k. The initial kinematics of the gamma ray was generated using the event generator DECAY0. The signal at 871.1 keV with a fixed sigma of 1 keV gives number of events as -97 ± 84. The limit S is calculated using the Feldman-Cousins method at 68% and 90% C.L. [5]. The half-life limit obtained is $T_{1/2}$ ($0^+ \rightarrow 2_1^+$) $> 2.0 \times 10^{20}$ y at 68% C.L. ($6.1{\times}10^{19}$ y at 90% C.L.). The systematic uncertainty in the half-life limit is 8.8%. The current limit is improvement by an order of magnitude than the previous reported value of $T_{1/2} > 1.3 \times 10^{19}$ y at 68% C.L. [2]. Theoretical predictions based on QRPA and PHFB nuclear models yield $T_{1/2} \sim 10^{32-36}$ y.

Summary

The DBD of ^{94}Zr ($0^+ \rightarrow 2_1^+$) is studied using a $\sim$ 230 cm^3 HPGe detector and the half-life limit obtained is $T_{1/2} > 6.1 \times 10^{19}$ y at 90% C.L. ($T_{1/2} > 2.0 \times 10^{20}$ y at 68% C.L.). The 68% C.L. limit is improvement by an order of magnitude over the existing one while the 90% C.L. limit is reported for first time.

References

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