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Limit on the radiative 0νECEC decay of ^{36}Ar

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Abstract

First limits on the neutrinoless double electron capture process of ^{36}Ar have been derived from measurements with a 1.6 kg bare high-purity germanium detector submerged in 70 liters of liquid argon. The obtained limit for the radiative decay with the emission of a single photon is $T_{1/2}(0^+ \rightarrow \text{g.s. with single } \gamma) \geq 1.9 \cdot 10^{18}$ years (68% C.L.). It is comparable to recent results obtained in dedicated experiments investigating different isotopes. The measurements were performed during detector tests in the framework of the Gerda experiment.

1 Introduction

The Gerda experiment [1] will search for the neutrinoless double beta decay of ^{76}Ge. Bare high-purity germanium detectors enriched in ^{76}Ge will be submerged in liquid argon serving simultaneously as a shield against external radioactivity and cooling medium. Since natural argon contains the isotope ^{36}Ar with an abundance of 0.336%, which is expected to be unstable undergoing double electron capture (ECEC) [2], one can search as well for the radiative neutrinoless double electron capture (0νECEC) of this isotope in the same setup. The energy levels of the A=36 isobar triplet are shown in Fig. 1 [3]. No measurements of the half life limit exist. Theoretical calculations have been carried out for the two neutrino decay mode with half live 10^{29} years. In the process of neutrinoless double electron capture (0νECEC), two orbital electrons are absorbed by the nucleus: $2e^- + A(Z) \Rightarrow A(Z-2) + Q$. The momentum-energy conservation requires the released energy Q to be emitted with some additional particle(s). For the two neutrino double electron capture process the energy is carried away by the two neutrinos. We consider the neutrinoless process in which the released energy is carried out by photons. The experimental signature of this decay consists of the emission of three photons with total energy Q: two X-rays with energies of the corresponding holes in the electron shells of the daughter atom produced by the ECEC capture, and one photon taking the rest of the available energy. The K-K capture decay to a ground state under emission of a single photon is forbidden by the conservation of angular momentum. However electrons capture from the K and L shells is possible. A detailed discussion of the 0νECEC process with emission of photons can be found e.g. in [5, 6]. The photon with energy Eγ = Q − E_K − E_L can be detected by a high resolution germanium detector. In the case of ^{36}Ar, the daughter, ^{36}S, has no excited states in the ECEC process. Therefore, ECEC decay must be a $0^+ \to 0^+$ ground state to ground state transition, and one electron is captured from the K shell and one from the L shell. The here investigated decay consists of the emission of three photons with $E_K = 2.47$ keV, $E_L = 0.23$ keV and $E_\gamma = 430.8$ keV given the $Q_{ECEC} = 433.5$ keV. The experimental signature used in this experiment is the detection of $E_\gamma = 430.8$ keV photons with a high-purity germanium (HPGe) detector submerged in liquid argon.

2 Experimental Details

The measurements were performed in the GERDA underground detector laboratory, the GERDA-LArGe facility, located at LNGS. The laboratory is equipped with a radon-reduced clean bench mounted to a dewar system. It is designed to operate bare germanium detectors submerged in liquid argon. The leakage current, the energy resolution and the detector stability were investigated during the period from August to October 2006. Spectroscopy measurements were done using a Cobalt-60 source. The detector parameters as leakage current and energy resolution was stable during the full period of operation. The moderate shield of the test bench consists of 2.5 cm of lead surrounding the Dewar. It slightly suppresses external radiation. A 300 cm^3 natural high-purity germanium crystal was mounted in a special low mass holder to provide suspension, high voltage and signal contacts. The holder made of copper and PTFE was suspended on 80 cm long Kevlar strings. The strings were attached to a Dewar flange on which a Canberra 2002 warm FET preamplifier was installed. The Dewar contained 70 liters of liquid argon. The detector was positioned in the center of the Dewar. A standard ORTEC data acquisition amplifier and ADC were used to collect the spectra. The background data used for this analysis were acquired in between the regular stability measurements and correspond to 10 live time days. The resolution of the ^{40}K 1460 keV background line was 4.3 keV FWHM.

3 Results and Analysis

Fig. 2 displays the sum spectrum and the region of interest around 430 keV. In the spectrum shape the background index amounts to 440 counts/(keV·day). The simulation codes EGSnrc[9] and TEFF[10] were used to determine the efficiency of detecting photons emitted homogeneously distributed in the liquid argon volume. The energy dependence of the detection efficiency is shown in Fig. 3. Using the obtained values of background count rate and energy resolution, the limit for 0νECEC decay of the ^{36}Ar is calculated. For a detector which is surrounded by a radiative source, the half life limit can be written as follows (similar equations for the sensitivity limits can be found e.g. in [11]):

$$T_{1/2}(0^+ \rightarrow g.s.\ with\ single\ \gamma) \;\geq\; \ln 2 \cdot \varepsilon \cdot a \cdot \frac{M \cdot N_A}{A} \cdot \sqrt{\frac{\Delta T}{b \cdot \Delta E}}, \tag{1}$$

where, ε is the efficiency of the full energy peak detection, a is the isotopic abundance of isotope, M is the total mass of source, N_A is the Avogadro number, A is the atomic number of isotope, ΔT is the measurement live time, b is the background rate per unit energy and ΔE is the energy window around the peak position. Using the values given in Tab. 1, the half life limit of the ^{36}Ar radiative 0νECEC process to the ground state is $1.9 \cdot 10^{18}$ years with 68% confidence level.

4 Conclusions

First limits on the neutrinoless double electron capture process of ^{36}Ar have been derived from measurements with a bare high-purity germanium detector submerged in liquid argon. The obtained limit is comparable to recent results obtained in dedicated experiments which are presented in the Tab. 2. The half life limits for these experiments are in the range of $10^{16} \div 10^{19}$ years. The sensitivity of the experiment presented here is limited by external radiation of the detector test stand which is not designed as a low-background setup. The GERDA-LARGE facility, which will be used to test backgrounds of phase I detectors prior to their operation in GERDA, will provide improved limits. External radiation will be suppressed by a massive passive shield, the mass of argon will increase to approximately one tone and up to nine detectors could in principle be operated simultaneously. The sensitivity will then be limited by the Bremsstrahlung of ^{39}Ar beta decays (Q= 550 keV, $T_{1/2}$=269 y). Monte Carlo simulation gives a count rate which is of the order of 3 counts/(keV·y·kg) in tne HPGe detectors [23]. Additional background will come from $2\nu\beta\beta$ decay of ^{76}Ge. This background is approximately an 1.5 counts/(keV·y·kg) in the region of interest and is comparable to the ^{39}Ar one. For one year of measurements, the expected sensitivity will be in the range of $10^{22} \div 10^{23}$ years. If the X-ray could be detected with a reasonable sensitivity, a X-ray – gamma coincidence could be exploited as an additional signature to reduce the ^{39}Ar Bremsstrahlung background. The ultimate sensitivity will be achieved in GERDA with the operation of 40 kg of phase I and phase II detectors.

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Mass of liquid argon, kg	100
Isotopic abundance, %	0.336
Live time, days	10.0
Background index, counts/keV/day	440
Energy interval, keV	4
Efficiency at 430.8 keV, %	0.26
Reaction Q value, keV	433.5
E_K, keV	2.47
E_L, keV	0.23

Table 1: Experimental parameters and values.

Isotope	Abundance, %	Mode	$T_{1/2}$, y	Ref.
^{36}Ar	0.336	0νECEC	$1.9 \cdot 10^{18}$ (68%)	this work
^{50}Cr	4.345	$(0\nu{+}2\nu)$ECβ^+	$1.3 \cdot 10^{18}$ (95%)	Bikit et al. (2003) [12]
^{64}Zn	48.63	0νECEC	$1.0 \cdot 10^{18}$ (68%)	Danevich et al. (2005) [13]
		0νECβ^+	$1.3 \cdot 10^{20}$ (90%)	Kim et al. (2003) [13]
^{74}Se	0.89	0νECEC	$6.4 \cdot 10^{18}$ (90%)	Barabash et al. (2006) [14]
		$(0\nu{+}2\nu)$ECβ^+	$1.9 \cdot 10^{18}$ (90%)	-”-
^{106}Cd	1.25	2νECEC	$4.8 \cdot 10^{19}$ (90%)	Stekl et al. (2006) [15]
^{108}Cd	0.89	0νECEC	$2.5 \cdot 10^{17}$ (68%)	Danevich et al. (2003) [16]
^{112}Sn	0.97	$(0\nu{+}2\nu)$ECβ^+	$1.5 \cdot 10^{18}$ (68%)	Kim et al. (2003) [17]
^{120}Te	0.09	2νECEC	$9.4 \cdot 10^{15}$ (90%)	Kiel et al. (2003) [18]
^{130}Ba	0.106	0νECβ^+	$2.0 \cdot 10^{17}$ (90%)	Cerulli et al. (2004) [19]
^{136}Ce	0.185	2νECEC	$4.5 \cdot 10^{16}$ (68%)	Belli et al. (2003) [20]
^{138}Ce	0.251	2νECEC	$6.1 \cdot 10^{16}$ (68%)	-”-
^{180}W	0.12	0νECEC	$1.3 \cdot 10^{17}$ (68%)	Danevich et al. (2003) [21]

Table 2: Recent results of half-life measurements for ECEC and ECβ^+ processes with transition to ground state.

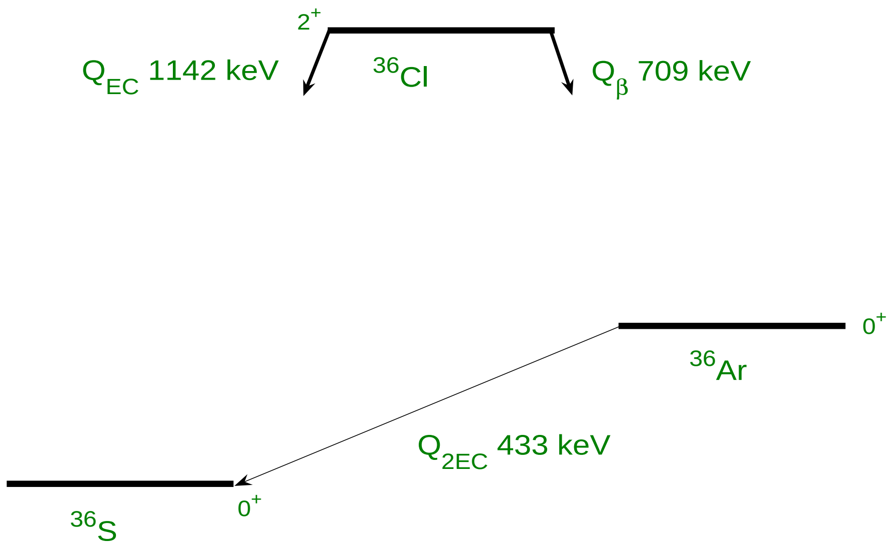

Figure 1: Lowest energy levels of isobar triplet A=36 with double electron capture decay of ^{36}Ar.

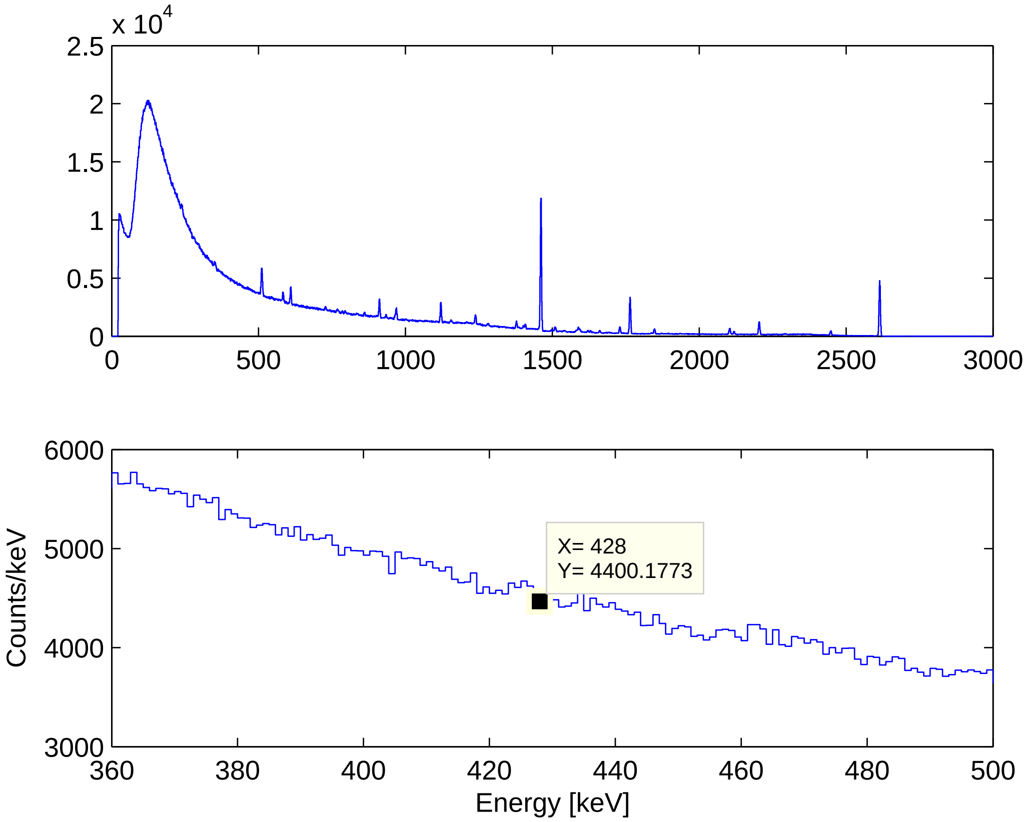

Figure 2: Background spectrum of Germanium detector in liquid Argon measured 10.0 days.

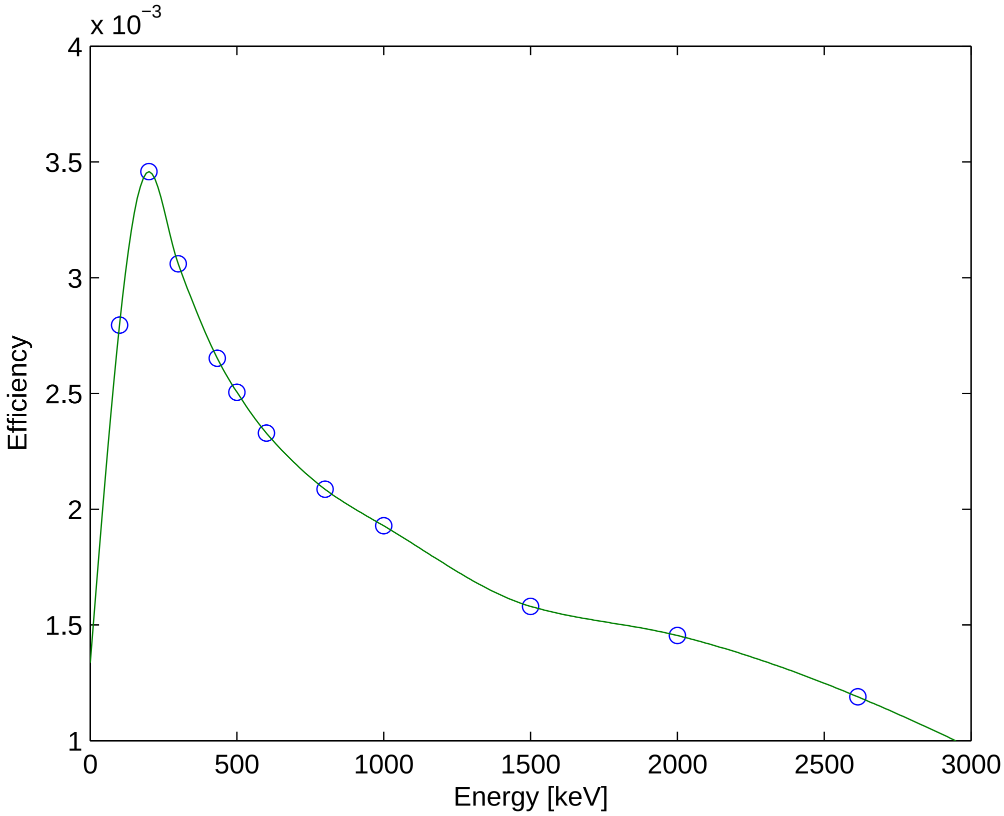

Figure 3: Full energy peak detection efficiency for 300 cm^3 HPGe detector submersed in the 70 liter argon Dewar. Simulation was done with uniformly distributed sources in liquid Argon.