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Search for double beta decay of ^{116}Cd with enriched ^{116}CdWO$_4$ crystal scintillators (Aurora experiment)

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Abstract.
The Aurora experiment to investigate double beta decay of ^{116}Cd with the help of 1.162 kg cadmium tungstate crystal scintillators enriched in ^{116}Cd to 82% is in progress at the Gran Sasso Underground Laboratory. The half-life of ^{116}Cd relatively to the two neutrino double beta decay is measured with the highest up-to-date accuracy $T_{1/2} = (2.62 \pm 0.14) \times 10^{19}$ yr. The sensitivity of the experiment to the neutrinoless double beta decay of ^{116}Cd to the ground state of ^{116}Sn is estimated as $T_{1/2} \geq 1.9 \times 10^{23}$ yr at 90% CL, which corresponds to the effective Majorana neutrino mass limit $\langle m_\nu \rangle \leq (1.2 - 1.8)$ eV. New limits are obtained for the double beta decay of ^{116}Cd to the excited levels of ^{116}Sn, and for the neutrinoless double beta decay with emission of majorons.

1. Introduction

Observations of neutrino oscillations give a clear evidence of effects beyond the Standard Model of particles (see, e.g., review [1]) and provide a strong motivation to investigate neutrinoless double beta ($0\nu2\beta$) decay of atomic nuclei. The $0\nu2\beta$ decay violates the lepton-number conservation and is only possible if neutrino is a massive Majorana particle. Therefore, search for $0\nu2\beta$ decay is considered as a promising way to clarify the nature of the neutrino, check the lepton number conservation, determine the absolute scale of the neutrino mass and the neutrino mass hierarchy, test the existence of effects beyond the Standard Model, in particular, existence of

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hypothetical Nambu-Goldstone bosons (majorons) and right-handed currents in weak interaction [2, 3, 4, 5, 6, 7].

The isotope ^{116}Cd is one of the most promising 2β nuclei thanks to the favorable theoretical estimations of the decay probability ([2, 3]), large energy release $Q_{2\beta} = 2813.50(13)$ keV [8], relatively high isotopic abundance $\delta = 7.49\%$ [9] and a possibility of isotopic enrichment in a large amount.

Experimental investigations of ^{116}Cd 2β decay were realized by tracking detectors with enriched cadmium foil as source [10, 11, 12], and by calorimetric approach using $CdWO_4$ crystal scintillators [13, 14, 15] and CdZnTe room temperature semiconductors [16]. The 2β decay to excited levels of ^{116}Sn were also searched for with low background HPGe γ detectors [17, 18]. Large volume radiopure cadmium tungstate crystal scintillators were produced from cadmium enriched in ^{116}Cd to 82% ($^{116}CdWO_4$) to investigate double beta decay of ^{116}Cd [19]. The crystals show excellent scintillation properties and low level of radioactive contamination [20, 21]. Preliminary results of the Aurora experiment were reported in the conference proceedings [22, 23]. Here we present recent results of the experiment.

2. Experiment

Two $^{116}CdWO_4$ crystal scintillators with a total mass 1.162 kg (1.584×10^{24} of ^{116}Cd nuclei) are installed in the low background DAMA/R&D set-up operated at the Gran Sasso Underground Laboratory of I.N.F.N. (Italy). The low background set-up with the $^{116}CdWO_4$ detectors has been modified several times to improve the energy resolution and to decrease background. In the last configuration of the set-up the $^{116}CdWO_4$ crystal scintillators are fixed in polytetrafluoroethylene containers filled with ultrapure liquid scintillator. The liquid scintillator improves the light collection from the $^{116}CdWO_4$ crystal scintillators and serves as an anti-coincidence veto counter. The scintillators are viewed through high purity quartz light-guides ($\oslash 7 \times 40$ cm) by low background high quantum efficiency photomultiplier tubes (PMT, Hamamatsu R6233MOD). The detectors are installed inside a low radioactive copper box flushed with high pure nitrogen gas with an external shield made of radiopure materials: copper (15 cm), lead (15 cm), cadmium (1.5 mm) and paraffin (4 to 10 cm). The whole set-up is enclosed in a plexiglas box also flushed with high purity nitrogen gas to remove radon. An event-by-event data acquisition system based on a 1 GS/s 8 bit transient digitizer (Acqiris DC270) records time and pulse profile of events. The energy scale and the energy resolution of the detector are checked periodically with ^{22}Na, ^{60}Co, ^{137}Cs, and ^{228}Th γ sources. The energy resolution of the $^{116}CdWO_4$ detector for 2615 keV γ quanta of ^{208}Tl is FWHM $\approx 5\%$.

3. Results and discussion

The energy spectrum of β and γ events accumulated over 12015 h by the $^{116}CdWO_4$ detectors is presented in Fig. 1. The β and γ events were selected with the help of two pulse-shape discrimination methods: the optimal filter method to select α particles, and the front edge analysis to select Bi–Po events (fast sub-chains ^{212}Bi–^{212}Po and ^{214}Bi–^{214}Po from ^{232}Th and ^{238}U chains, respectively) from internal contamination of the crystals by U and Th. Besides, both the pulse-shape discrimination techniques are also sensitive to pile-ups of $^{116}CdWO_4$ and liquid scintillator signals. The experimental spectrum was fitted in the energy interval $(660 - 3300)$ keV by the model constructed from the two neutrino double beta ($2\nu2\beta$) spectrum of ^{116}Cd, the distributions of the $^{116}CdWO_4$ crystal scintillators internal contamination by potassium, thorium and uranium (taking into account possible disequilibrium of the ^{232}Th and ^{238}U chains), and the contribution from external γ quanta (from radioactive contamination of the PMTs, quartz light-guides and copper of the passive shield). Response of the $^{116}CdWO_4$ detector to the 2β processes in ^{116}Cd as well as to the radioactive contamination of the set-up were simulated with EGS4 package [24]. The initial kinematics of the particles emitted in the decay of the nuclei was given by an event generator DECAY0 [25]. The fit gives the following half-life of ^{116}Cd relatively to the $2\nu2\beta$ decay to the ground state of ^{116}Sn:

$$T_{1/2}^{2\nu2\beta} = [2.62 \pm 0.02(stat.) \pm 0.14(syst.)] \times 10^{19} \text{ yr.}$$

The main sources of the systematic error are the uncertainties of the radioactive contamination of the crystal scintillators and of the details of the set-up, and variation of the effect's area depending on the interval of the fit. The signal to background ratio is 2.6:1 in the energy interval (1.1 − 2.8) MeV. The comparison of the ^{116}Cd $2\nu2\beta$ half-life obtained in the Aurora experiment with other experiments is given in Fig. 2. The result is in agreement with the previous experiments [10, 11, 12, 13, 14, 15], however the half-life of ^{116}Cd is determined in the present study with the highest accuracy.

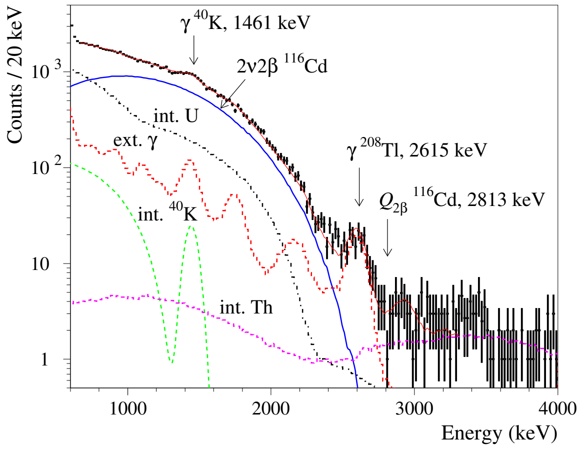

Figure 1. The energy spectrum of β and γ events accumulated over 12015 h together with the main components of the background model: $2\nu2\beta$ decay of ^{116}Cd ("$2\nu2\beta$ ^{116}Cd"), the distributions of the internal contamination of the ^{116}CdWO$_4$ crystals by potassium ("int. ^{40}K"), thorium ("int. Th") and uranium ("int. U"), and the contribution from external γ quanta ("ext. γ").

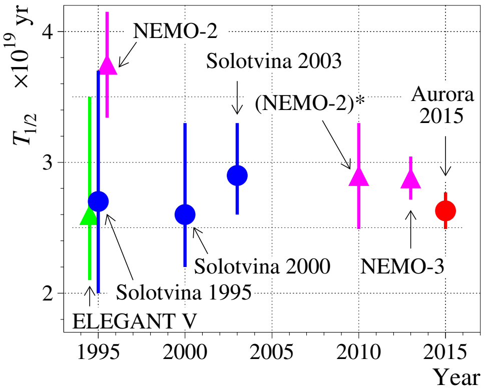

Figure 2. Comparison of the ^{116}Cd $2\nu2\beta$ half-life obtained in the Aurora experiment with other experiments: ELEGANT V [10], Solotvina [13, 14, 15], NEMO-2 [11] and NEMO-3 [12]. A reevaluated NEMO-2 value [26] is labelled as (NEMO-2)*.

There are no other peculiarities in the experimental data which could be interpreted as 2β processes in ^{116}Cd. To estimate limit on $0\nu2\beta$ decay of ^{116}Cd to the ground state of ^{116}Sn we have used data of two runs with the lowest background in the region of interest: the current one and the accumulated over 8696 h in the set-up described in [22]. The sum energy spectrum is presented in Fig. 3. The background counting rate of the detector in the energy interval $(2.7-2.9)$ MeV (which contains 80% of the $0\nu2\beta$ distribution) is ≈ 0.1 counts/(yr×kg×keV). A fit of the spectrum in the energy interval $(2560-3200)$ keV by the background model constructed from the distributions of the $0\nu2\beta$ decay of ^{116}Cd (effect searched for), the $2\nu2\beta$ decay of ^{116}Cd with the half-life 2.62×10^{19} yr, the internal contamination of the crystals by ^{110m}Ag and ^{228}Th, and the contribution from external γ quanta gives an area of the expected peak $S = -3.7 \pm 10.2$, which gives no evidence of the effect. In accordance with [27] 13.3 counts are excluded at 90% confidence level. Taking into account the 99% efficiency of the pulse-shape discrimination to select β (γ) events and 99% efficiency of the front edge analysis (98% in total), we got the following new limit on the $0\nu2\beta$ decay of ^{116}Cd to the ground state of ^{116}Sn:

$$T_{1/2}^{0\nu2\beta} \geq 1.9 \times 10^{23} \text{ yr.}$$

The half-life limit corresponds to the effective neutrino mass limit $\langle m_\nu \rangle \leq (1.2 - 1.8)$ eV, obtained by using the recent nuclear matrix elements reported in [28, 29, 30, 31], the phase space factor from [32] and the value of the axial vector coupling constant $g_A = 1.27$.

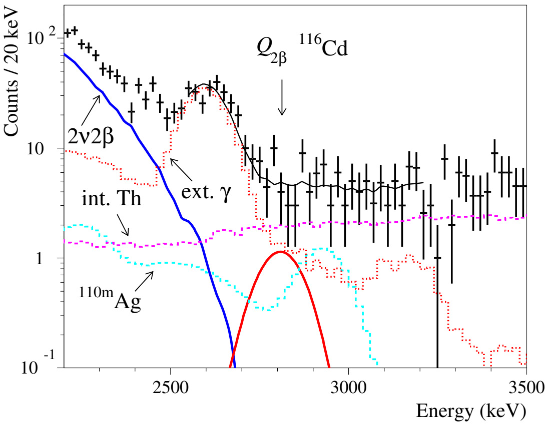

Figure 3. The energy spectrum of β and γ events accumulated over 20711 h with the ^{116}CdWO$_4$ detectors in the region of interest together with the background model: the $2\nu2\beta$ decay of ^{116}Cd ("$2\nu2\beta$"), the internal contamination of the ^{116}CdWO$_4$ crystals by cosmogenic ^{110m}Ag ("^{110m}Ag") and ^{228}Th ("int. Th"), and the contribution from external γ quanta ("ext. γ").

Limits on 2β decay processes in ^{116}Cd to the excited levels of ^{116}Sn, and for the $0\nu2\beta$ decay with emission of one (χ), two (2χ) and bulk (χ^{bulk}) majorons were derived from the fits of the data in the energy intervals with a high effect to background ratio. The results are presented in Table 1. Using the bound on the $0\nu2\beta$ decay with one majoron emission and the same calculations of the nuclear matrix elements we have estimated a limit on the effective majoron neutrino coupling constant $g_{\nu\chi} \leq (5.3 - 8.5) \times 10^{-5}$.

4. Conclusions

The Aurora experiment is in progress to investigate 2β processes in ^{116}Cd by using enriched ^{116}CdWO$_4$ scintillation detectors. The $2\nu2\beta$ half-life of ^{116}Cd is measured with the highest up-to-date accuracy: $T_{1/2} = (2.62 \pm 0.14) \times 10^{19}$ yr. The new improved $0\nu2\beta$ half-life limit was set as $T_{1/2} \geq 1.9 \times 10^{23}$ yr at 90% CL, which corresponds to the effective Majorana neutrino mass $\langle m_\nu \rangle \leq (1.2 - 1.8)$ eV. New limits on the 2β decay to excited levels of ^{116}Sn and the $0\nu2\beta$ decay with emission of one, two and bulk majorons were set at the level of $T_{1/2} \geq (10^{20} - 10^{22})$ yr. Using the limit $T_{1/2} \geq 1.1 \times 10^{22}$ yr on the $0\nu2\beta$ decay with one majoron emission we have obtained one of the strongest limits on the effective majoron neutrino coupling constant $g_{\nu\chi} \leq (5.3 - 8.5) \times 10^{-5}$. It is worth noting that we have observed a segregation of thorium, radium and potassium in the crystal growing process, which provides a possibility to improve substantially the radiopurity of the ^{116}CdWO$_4$ crystal scintillators by re-crystallization, which is in progress now.

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Table 1. The half-life limits and half-life value on the 2β decay processes in ^{116}Cd. The most stringent limits obtained in the previous experiments are given for comparison. The limits are given at the 90% CL except the results [17], which are given at the 68% CL.

Decay mode	Transition, level of ^{116}Cd (keV)	$T_{1/2}$ (yr)	Previous result
0ν	g.s.	$\geq 1.9 \times 10^{23}$	$\geq 1.7 \times 10^{23}$ [15]
0ν	$2^+(1294)$	$\geq 6.2 \times 10^{22}$	$\geq 2.9 \times 10^{22}$ [15]
0ν	$0^+(1757)$	$\geq 6.3 \times 10^{22}$	$\geq 1.4 \times 10^{22}$ [15]
0ν	$0^+(2027)$	$\geq 4.5 \times 10^{22}$	$\geq 6.0 \times 10^{21}$ [15]
0ν	$2^+(2112)$	$\geq 3.6 \times 10^{22}$	$\geq 1.7 \times 10^{20}$ [17]
0ν	$2^+(2225)$	$\geq 4.1 \times 10^{22}$	$\geq 1.0 \times 10^{20}$ [17]
$0\nu\chi$	g.s.	$\geq 1.1 \times 10^{22}$	$\geq 8.0 \times 10^{21}$ [15]
$0\nu2\chi$	g.s.	$\geq 9.0 \times 10^{20}$	$\geq 8.0 \times 10^{20}$ [15]
$0\nu\chi^{bulk}$	g.s.	$\geq 2.1 \times 10^{21}$	$\geq 1.7 \times 10^{21}$ [15]
2ν	g.s.	$= (2.62 \pm 0.14) \times 10^{19}$	see Fig. 2
2ν	$2^+(1294)$	$\geq 9.0 \times 10^{20}$	$\geq 2.3 \times 10^{21}$ [18]
2ν	$2^+(1757)$	$\geq 1.0 \times 10^{21}$	$\geq 2.0 \times 10^{21}$ [18]
2ν	$2^+(2027)$	$\geq 1.1 \times 10^{21}$	$\geq 2.0 \times 10^{21}$ [18]
2ν	$2^+(2112)$	$\geq 2.3 \times 10^{21}$	$\geq 1.7 \times 10^{20}$ [17]
2ν	$2^+(2225)$	$\geq 2.5 \times 10^{21}$	$\geq 1.0 \times 10^{20}$ [17]

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