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New results of the experiment to search for double beta decay of ^{106}Cd using ^{106}CdWO$_4$ scintillator

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A low-background experiment to study double-beta decay processes in ^{106}Cd using a ^{106}CdWO$_4$ crystal scintillator (mass 215 g) enriched in ^{106}Cd to 66% has been performed at the Laboratori Nazionali del Gran Sasso (LNGS), in Italy. Events in the ^{106}CdWO$_4$ detector are recorded in (anti)coincidence with two large-volume CdWO$_4$ scintillation counters. The setup, designed for high detection efficiency and background suppression, was operated for 1075 days. Energy and timing calibrations, pulse-shape discrimination, and Monte Carlo simulations were used to characterize the detector response and background components. No evidence of double-beta decay was observed. New half-life limits were set for various decay modes and channels, reaching sensitivities in the range $T_{1/2} \sim 10^{20} - 10^{22}$ yr. In particular, the limit on the $2\nu\varepsilon\beta^+$ decay to the ground state of ^{106}Pd was established at $T_{1/2} > 7.7 \times 10^{21}$ yr (90% C.L.), approaching the region of theoretical predictions.

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1. Introduction

Neutrino oscillations imply non-zero neutrino masses beyond the Standard Model (SM) of particle physics; the absolute mass scale, ordering, and the Dirac/Majorana nature of neutrinos remain open questions [1, 2]. The most sensitive probe is neutrinoless double beta decay ($0\nu2\beta$), which violates lepton number by two units and would establish the Majorana nature of neutrinos [2, 3]. The two-neutrino mode ($2\nu2\beta$), allowed in the SM, has been observed in 11 nuclei with half-lives in the range $T_{1/2} = 10^{18}$–10^{24} yr [4, 5]. By contrast, the most sensitive $0\nu2\beta$ searches reach $T_{1/2} > (0.03$–$2.3) \times 10^{26}$ yr, corresponding to $m_\nu < (0.04$–$0.35)$ eV [6–8].
While most programs target $0\nu2\beta^-$, the “double-beta plus” processes (2EC, ECβ^+, $2\beta^+$) probe the same lepton-number-violating mechanisms and, for 0ν2EC, can benefit from resonant enhancement [9, 10]. These channels are experimentally more challenging; to date there are only two indications of 2ν2EC in ^{78}Kr and ^{130}Ba with half-lives $T_{1/2} \sim 10^{21}$–10^{22} yr [11, 12], and one observation in ^{124}Xe with the half-life $T_{1/2} \sim 10^{22}$ yr [13]. Nonetheless, the signatures of ECβ^+ and $2\beta^+$ decays are distinctive: positron-emitting modes produce characteristic 511-keV annihilation γ rays, enabling powerful coincidence tagging.
^{106}Cd is an attractive candidate thanks to its large $Q_{2\beta} = 2775.39(10)$ keV [14], relatively high natural abundance $\delta = 1.245(22)\%$ [15] (among the highest for double-beta-plus candidates), the availability of enrichment, and mature radiopure CdWO$_4$ technology [16, 17]. Here we report an analysis of a 1075-day exposure with an enriched ^{106}CdWO$_4$ scintillator operated in coincidence with two CdWO$_4$ counters [18–20].

2. Experimental setup and data taking

The experimental setup consists of one enriched ^{106}CdWO$_4$ crystal (215 g, 66% in ^{106}Cd) viewed by a low-radioactivity PMT via quartz light-guide and plastic scintillator, surrounded by two large CdWO$_4$ scintillators acting as counters [18–20]. Optical interfaces use silicone grease; reflectivity is improved with PTFE and aluminized films. The assembly is enclosed in the DAMA/R&D setup, which consists of high-purity inner/external copper and passive Pb/Cd/poly shielding; high-purity N$_2$ gas is flushed into the shielding to suppress environmental radon. The apparatus was operative at the LNGS (3.8 km w.e.).
Signals were digitized at 1 GSample/s over 100 μs. To limit the ^{113}Cd/^{113m}Cd rate, triggers require either that the energy deposited in the enriched ^{106}CdWO$_4$ crystal, E^{106}, exceeds 0.5 MeV or $E^{106} > 0.05$ MeV in time coincidence with ≥ 1 CdWO$_4$ counter above 0.05 MeV. A PTFE pipe enabled periodic γ calibrations without opening the setup.

3. Analysis overview

The detector response was calibrated at the start and multiple times during the run using ^{22}Na, ^{60}Co, ^{137}Cs, and ^{228}Th γ sources. Gain drifts were tracked with internal β edges; after ~649 days the PMT of the ^{106}CdWO$_4$ was replaced. Across the full dataset the energy resolution is well described by FWHM $= A\sqrt{E_\gamma}$ (keV), with averaged $A = 4.92$ for the ^{106}CdWO$_4$ and $A = 3.65$, 3.20 for the two CdWO$_4$ counters. The time resolution was determined with ^{22}Na by selecting 511 keV annihilation

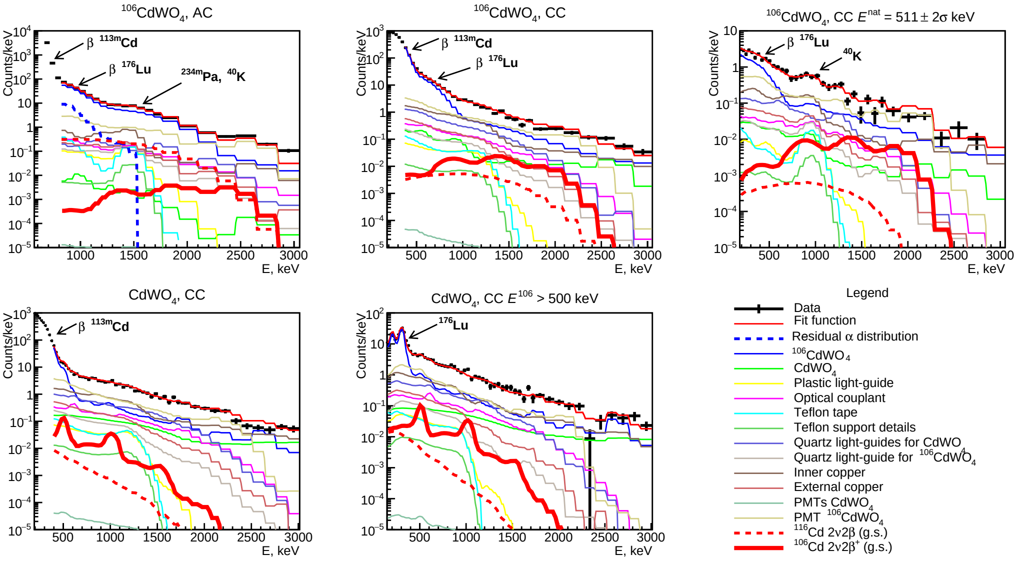

Figure 1: Simultaneous fit to the $\gamma\&\beta$ spectra from the ^{106}CdWO$_4$ detector and the two CdWO$_4$ counters under the selection conditions described in the text. The thin red solid curves show the best-fit model, while individual components attributed to impurities in detector materials and shielding are displayed separately (see legend). An expected $2\nu2\beta^+$ signal spectrum for ^{106}Cd→^{106}Pd (g.s.), normalized to the excluded half-life $T_{1/2} = 1.7 \times 10^{22}$ yr, is overlaid as a thick solid red line in all panels [20].

quanta in the counters. We obtain FWHM ≃ 54 ns and a coincidence selection efficiency of 92(2)% in the window -50 ns $\leq \Delta t < 100$ ns [20].

Pulse-shape discrimination (PSD) separates αevents from $\gamma\&\beta$ scintillation signals via an optimal-filter shape indicator [21, 22]. The SI centroids and widths versus energy are parametrized, yielding reasonable $\alpha/\gamma\&\beta$ separation [20]. Quenching of α's in the γ scale is accounted for using the measured α/γ ratios: $0.12(2) + 0.011(2)\, E_\alpha$ for ^{106}CdWO$_4$ and $0.08(1) + 0.015(2)\, E_\alpha$ for CdWO$_4$ (with E_α in MeV) [19, 23].

Experimental spectra were constructed under two selection conditions: (i) the ^{106}CdWO$_4$ detector in anti-coincidence (AC) with the CdWO$_4$ counters; (ii) the ^{106}CdWO$_4$ detector in coincidence (CC) with the CdWO$_4$ detectors. For positron-emitting channels we additionally require a 511-keV annihilation tag in at least one counter in the energy interval $E^{nat} = 511 \pm 2\sigma_E$. Below 0.5 MeV the response is dominated by ^{113,m}Cd β decays in the enriched crystal, while PSD suppresses the residual α component above ~0.5 MeV. In CC events with $E^{106} > 500$ keV, the counters show the characteristic ^{176}Lu lines at 202 and 307 keV; a ^{40}K feature at 1461 keV is also visible at higher energy. To study the response of experimental setup, we build a Monte Carlo background model with EGSnrc [24] and DECAY0 kinematics [25]. The model includes U/Th/K in all materials with broken secular equilibrium treated via sub-chains, residual α's in ^{106}CdWO$_4$, ^{176}Lu and $^{113(m)}$Cd in the crystals, and ^{116}Cd $2\nu2\beta$ in the enriched scintillator (fixed by its isotopic concentration). Selection effects from PSD and timing are folded into the background modeling. We perform a simultaneous binned likelihood fit above 0.8 MeV for AC and above 0.4 MeV for CC (see Fig. 1) allowing component normalizations to float within prior constraints where available [20].

Table 1: Half-life limits (90% C.L.) for 2β decay modes of ^{106}Cd. Theoretical predictions are reported where available.

Channel (final state)	Theoretical $T_{1/2}$ (yr)	$\lim T_{1/2}$ (yr) at 90% C.L.
$2\nu 2\beta^+$ (g.s.)	$(5.4–880) \times 10^{25}$ [27, 28], $> 2.4 \times 10^{27}$ [29]	1.7×10^{22}
$2\nu 2\beta^+$ (512 keV)	$(1.5–25) \times 10^{27}$ [27]	1.5×10^{22}
$0\nu 2\beta^+$ (g.s.)	$(1.4–32) \times 10^{27}$ [27]	2.2×10^{22}
$0\nu 2\beta^+$ (512 keV)	—	1.5×10^{22}
2νECβ^+ (g.s.)	$(1.4–240) \times 10^{21}$ [27, 28, 30, 31], $> 2.7 \times 10^{22}$ [29]	7.7×10^{21}
2νECβ^+ (512 keV)	$(5.3–24) \times 10^{25}$ [30], $> 1.1 \times 10^{25}$ [29]	9.9×10^{21}
2νECβ^+ (1128 keV)	3.7×10^{30} [30]	1.2×10^{22}
2νECβ^+ (1134 keV)	$(1.3–13) \times 10^{26}$ [30], $> 1.1 \times 10^{27}$ [29]	1.3×10^{22}
0νECβ^+ (g.s.)	$(1.0–17) \times 10^{26}$ [10, 27]	1.5×10^{22}
0νECβ^+ (512 keV)	—	2.1×10^{22}
0νECβ^+ (1128 keV)	—	1.9×10^{22}
0νECβ^+ (1134 keV)	$(1.0–21) \times 10^{29}$ [10]	2.1×10^{22}
2ν2EC (g.s.)	$(2.0–230) \times 10^{20}$ [27, 28, 30, 31]	—
2ν2EC (512 keV)	$(1.5–9.4) \times 10^{27}$ [30], $> 4.0 \times 10^{26}$ [29]	2.2×10^{20}
2ν2EC (1128 keV)	9.9×10^{28} [30]	9.3×10^{20}
2ν2EC (1134 keV)	$(1.1–11) \times 10^{23}$ [30]	1.4×10^{21}
2ν2EC (1562 keV)	$> 5.4 \times 10^{28}$ [29]	7.9×10^{20}
2ν2EC (1706 keV)	$> 1.9 \times 10^{25}$ [29]	4.6×10^{21}
2ν2EC (2001 keV)	$> 8.9 \times 10^{24}$ [29]	1.4×10^{21}
2ν2EC (2278 keV)	$> 2.1 \times 10^{27}$ [29]	1.8×10^{21}
0ν2EC (g.s.)	—	1.2×10^{21}
0ν2EC (512 keV)	—	1.9×10^{21}
0ν2EC (1128 keV)	—	1.7×10^{21}
0ν2EC (1134 keV)	—	2.2×10^{21}
0ν2EC (1562 keV)	—	2.0×10^{21}
0ν2EC (1706 keV)	—	1.7×10^{21}
0ν2EC (2001 keV)	—	3.3×10^{21}
0ν2EC (2278 keV)	—	1.2×10^{21}
Res. 0ν2EC (2718 keV)	$> 5.2 \times 10^{24}$ [32, 33], $> 7.9 \times 10^{23}$ [10]	2.0×10^{21}
Res. 0ν2EC (2741 keV)	$> 5.2 \times 10^{24}$ [33]	1.2×10^{21}
Res. 0ν2EC (2748 keV)	$2 \times 10^{29}–2 \times 10^{34}$ [9]	1.9×10^{21}

4. Results: 2β decay half-life limits

No signal-like excess compatible with ^{106}Cd 2β channels is observed over 1075 days. Thus, limits on the half-life were extracted using the following formula:

$$\lim T_{1/2} = \frac{N(^{106}\mathrm{Cd}) \ln 2 \; t}{\lim N_{\mathrm{dec}}}, \tag{1}$$

where $N(^{106}\mathrm{Cd}) = 2.42\times10^{23}$ is the number of ^{106}Cd nuclei, t is the measurement time, and $\lim N_{\mathrm{dec}}$ is the number of decays of the process searched for which can be excluded at 90% C.L. estimated using the recommendations [26]. The results are reported in Table 1. These bounds improve or confirm previous constraints [18, 19], and the 2νECβ^+ (g.s.) limit reaches the range of theoretical expectations [27–33]. Resonant 0ν2EC transitions are constrained near 10^{21} yr, competitive with past searches [9, 10].

5. Conclusions

Operating an enriched ^{106}CdWO$_4$ scintillator in coincidence with two CdWO$_4$ for 1075 days, we find no evidence of double beta processes in ^{106}Cd and set limits up to $\sim 10^{22}$ yr (90% C.L.). The $2\nu\mathrm{EC}\beta^+$ (g.s.) bound is 7.7×10^{21} yr; resonant $0\nu2\mathrm{EC}$ to 2718, 2741, 2748 keV levels are limited at $(1.2–2.0) \times 10^{21}$ yr. Analysis of the complete data set of the experiment is in progress.

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