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Precise measurement of $2\nu2\beta$ decay of ^{100}Mo with Li$_2$MoO$_4$ low temperature detectors: preliminary results

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Abstract. The half-life of ^{100}Mo relatively to the $2\nu2\beta$ decay to the ground state of ^{100}Ru was measured as $T_{1/2} = (6.99 \pm 0.15) \times 10^{18}$ yr with the help of enriched in ^{100}Mo lithium molybdate scintillating bolometers in the EDELWEISS-III low background set-up at the Modane underground laboratory. This is the most accurate value of the $2\nu2\beta$ half-life of ^{100}Mo.

INTRODUCTION

Two-neutrino double-beta ($2\nu2\beta$) decay is detected in 11 nuclei with the half-lives in the range $T_{1/2} \sim 10^{18} - 10^{24}$ yr [1, 2, 3]. The $2\nu2\beta$ decay of ^{100}Mo was first observed by the ELEGANT V counting experiment [4]. After several measurements with the help of different detection techniques [5, 6, 7, 8, 9, 10], the most accurate study of the $2\nu2\beta$ decay have been performed in a calorimetric experiment using zinc molybdate ($ZnMoO_4$) low temperature bolometers (with uncertainty at the level of $\sim$ 11%) [11], and by the NEMO-3 collaboration by detecting the two electrons with a combination of tracking and calorimeter information ($\sim$ 6%) [12]. In the present experiment the $2\nu2\beta$ decay of ^{100}Mo was measured by enriched in ^{100}Mo lithium-molybdate ($Li_2{}^{100}MoO_4$) crystal scintillators as low temperature scintillating bolometers. The preliminary results of the measurements have been reported in [13, 14].

EXPERIMENT

Four $Li_2{}^{100}MoO_4$ crystal scintillators produced from molybdenum enriched in the isotope ^{100}Mo to (96.9 ± 0.2)% with sizes $\oslash 44 \times (40-46)$ mm and the total mass 808.87 g were utilized in the experiment. Each crystal was equipped with a neutron transmutation doped (NTD) germanium temperature sensor glued on their surface, and with a heavily-doped silicone heater to control the detector thermal response. Germanium discs $\oslash 44 \times 0.17$ mm, also equipped with NTD sensors, were used as photo-detectors. Simultaneous detection of the heat and scintillation signals allows discrimination between β/γ and α events to reduce α background. The R&D of Li_2MoO_4 based scintillating bolometers is described in [13, 14, 15]. The detector modules were operated in the low-background cryostat of the EDELWEISS-III dark-matter experiment [16] at the Modane underground laboratory (France). The energy scale and energy resolution of the detectors were calibrated with ^{40}K, ^{133}Ba, and ^{232}Th gamma sources. E.g., the energy resolution (full width at half of maximum) of the detectors was measured as $\sim$ 6 keV for γ quanta with energy 2614.5 keV of ^{208}Tl.

RESULTS AND DISCUSSION

The energy spectrum accumulated with $Li_2{}^{100}MoO_4$ detectors over the exposure 42.235 kg×d (3.797×10^{23} nuclei of ^{100}Mo×yr) is shown in Fig. 1. α events have been eliminated from the data by using a light-assisted particle identification with at least 9σ α/β selection efficiency [13, 14]. In addition, a pulse-shape discrimination cut was then applied to the signals. A total exposure-weighted average β events selection efficiency is (96.46±0.60)%.

Several weak peaks in the spectrum can be ascribed to radioactive contamination by K, Ra and Th of the set-up, while the counting rate above ~1 MeV is mainly caused by the $2\nu2\beta$ decay of ^{100}Mo. The observed ^{40}K peak swelling is consistent with part of the population being due to EC decays of potassium inside the detector plus the atomic shell relaxation following this decay. A model of the experimental spectrum was built from the following components: $2\nu2\beta$ decay of ^{100}Mo to the ground state of ^{100}Ru; $2\nu2\beta$ decay of ^{100}Mo to the first 0^+ 1130.3 keV excited level of ^{100}Ru with the half-life $T_{1/2} = [7.5 \pm 0.6(\text{stat.}) \pm 0.6(\text{syst.})] \times 10^{20}$ yr [17]; γ quanta of ^{40}K from the detector parts; γ quanta of ^{214}Pb and ^{214}Bi (contamination of the set-up by radium); β particles and bremsstrahlung γ quanta from ^{210}Bi (daughter of ^{210}Pb) in the materials close to the detectors; γ quanta of ^{228}Ac, ^{212}Pb, ^{212}Bi and ^{208}Tl (contamination of the set-up by thorium; activity of ^{228}Ac was taken as a free parameter, ^{212}Pb, ^{212}Bi and ^{208}Tl were assumed in equilibrium with ^{228}Th); internal contamination of the scintillators by ^{40}K, ^{87}Rb, ^{90}Sr and ^{90}Y (in

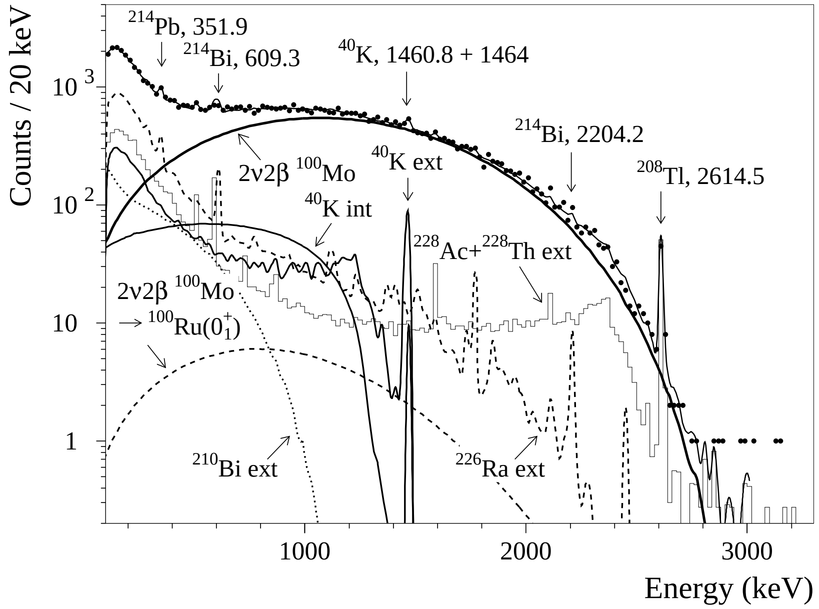

FIGURE 1. The energy spectrum of β/γ events accumulated with Li$_2{}^{100}$MoO$_4$ scintillating bolometers (exposure is 42.235 kg×d) and its fit by the components of background in the energy interval $100-3000$ keV. Energies of γ peaks are in keV.

TABLE I. Estimated systematic uncertainties of the ^{100}Mo half-life (%).

Number of ^{100}Mo nuclei	± 0.4
Live time	± 0.22
Pulse-shape discrimination cut to accept β events	± 0.60
Interval of fit	$^{+0.80}_{-0.86}$
Localization of radioactive sources in the set-up	± 0.85
Monte Carlo simulated models statistic	± 0.30
Energy scale instability	± 0.46
$2\nu2\beta$ spectral shape	± 1.0
Mechanism of decay (HSD instead of SSD)	$+0.14$
Total systematic error	$^{+1.80}_{-1.83}$

equilibrium). Bulk U/Th radioactivity of the crystals is omitted, taking into account that the activity of ^{100}Mo in the crystals is three orders of magnitude higher than the limits on activities of U/Th daughters [13, 14]. The models were Monte Carlo simulated using GEANT4 package [18, 19, 20] with initial kinematics given by the DECAY0 event generator [21]. The $2\nu2\beta$ distribution was simulated using an assumption about the single-state dominance (SSD) hypothesis, taking into account that the data of the NEMO-3 experiment favors the SSD mechanism in ^{100}Mo [12]. The model well describes the experimental data in a wide energy interval (see Fig. 1).

The best fit achieved in the energy interval 940 keV – 2860 keV provides the half-life $T_{1/2} = [6.988 \pm 0.074(\text{stat.})] \times 10^{18}$ yr. The statistical error already does include correlations to the background models. The systematic error includes uncertainties of the number of ^{100}Mo nuclei, live time of the experiment, pulse-shape discrimination cut to accept β events, interval of fit, localization of radioactive sources in the set-up, statistical fluctuations of the simulated background models, energy scale instability, theoretically calculated $2\nu2\beta$ spectral shape, mechanism of decay (high-state dominance instead of SSD). A summary of the systematic uncertainties is given in Table I.

Summing all the systematic uncertainties and the statistical error in quadrature, the half-life of ^{100}Mo relative to the $2\nu2\beta$ decay to the ground state of ^{100}Ru is:

$$T_{1/2} = (6.99 \pm 0.15) \times 10^{18} \text{ yr.}$$

The half-life value, being the most accurate one, is in an agreement with all the previous counting experiments [4, 5, 6, 7, 8, 10, 11, 12].

An effective nuclear matrix element for $2\nu 2\beta$ decay of ^{100}Mo to the ground state of ^{100}Ru can be calculated as $|M_{2\nu}^{eff}| = 0.186 \pm 0.002$ by using the phase-space factor 4134×10^{-21} yr^{-1} from [22]. The effective nuclear matrix element can be written as product $M_{2\nu}^{eff} = g_A^2 \times M_{2\nu}$, where g_A is the axial vector coupling constant, $M_{2\nu}$ is nuclear matrix element.

CONCLUSION

The half-life of the $2\nu 2\beta$ decay of ^{100}Mo to the ground state of ^{100}Ru was measured with the highest up-to-date accuracy as $T_{1/2} = (6.99 \pm 0.15) \times 10^{18}$ yr with enriched $Li_2{}^{100}MoO_4$ scintillating bolometers at the Modane underground laboratory (France). The systematic error is mainly due to the uncertainty in the background model. The half-life and the spectral shape accuracy are expected to be further improved in the CUPID-Mo experiment running now in its first phase with 20 enriched $Li_2{}^{100}MoO_4$ scintillating bolometers (with mass ≈ 0.2 kg each). Precise measurement of the $2\nu 2\beta$ decay spectral shape can be realized by measurement also of four Li_2MoO_4 detectors (already produced from molybdenum depleted in the isotope ^{100}Mo to 0.007%) in the same conditions.

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