UC Berkeley

UC Berkeley Previously Published Works

Title

Precise measurement of $2\nu 2\beta$ decay of ^{100}Mo with Li_2MoO_4 low temperature detectors: Preliminary results

Permalink

<https://escholarship.org/uc/item/4g9143hk>

Journal

AIP Conference Proceedings, 2165(1)

ISSN

0094-243X

ISBN

9780735419100

Authors

Armengaud, E
Augier, C
Barabash, AS
et al.

Publication Date

2019-10-25

DOI

10.1063/1.5130966

Peer reviewed

Precise measurement of $2\nu 2\beta$ decay of ^{100}Mo with Li_2MoO_4 low temperature detectors: preliminary results

E. Armengaud,¹ C. Augier,² A.S. Barabash,³ F. Bellini,^{4,5} A. Beno,⁶
M. Beretta,⁵ L. Bergé,⁷ N. Besson,¹ J. Billard,² Yu.A. Borovlev,⁸
Ch. Bourgeois,⁹ V. Brudanin,¹⁰ P. Camus,⁶ L. Cardani,⁵ N. Casali,⁵ A. Cazes,²
M. Chapellier,⁷ F. Charlieux,² M. de Combarieu,¹¹ F.A. Danevich,^{12, a)}
I. Dafinei,⁵ M. De Jesus,² L. Dumoulin,⁷ K. Eitel,¹³ F. Ferri,¹ B.F. Fujikawa,¹⁴
J. Gascon,² L. Gironi,^{15, 16} A. Giuliani,^{7, 17} V.D. Grigorieva,⁸ M. Gros,¹
E. Guerard,⁹ H.Z. Huang,¹⁸ R. Huang^{LBNL},¹⁴ J. Johnston,¹⁹ A. Juillard,²
H. Khalife,⁷ M. Kleifges,²⁰ V.V. Kobychiev,¹² Yu.G. Kolomensky,¹⁴
S.I. Konovalov,³ A. Leder,¹⁹ J. Kotila,²¹ P. Loaiza,⁹ R. Maissonobe,²
E.P. Makarov,⁸ P. de Marcillac,⁷ S. Marnieros,⁷ X-F. Navick,¹ C. Nones,¹
V. Novati,⁷ E. Olivieri,⁷ L. Pagnanini,^{22, 23} P. Pari,²⁴ L. Pattavina,²²
M. Pavan,^{15, 16} B. Paul,¹ H. Peng,¹⁸ G. Pessina,^{15, 16} S. Pirro,²³ D.V. Poda,^{7, 12}
O. Polischuk,¹² E. Previtali,^{15, 16} E. Queguiner,² T. Redon,⁷ S. Rozov,¹⁰
C. Rusconi,²⁵ V. Sanglard,² K. Schäffner,^{26, 27} Y. Shen,¹⁸ B. Schmidt,¹⁴
V.N. Shlegel,⁸ B. Siebenborn,¹³ S. Sorbino,⁵ C. Tomei,⁵ V.I. Tretyak,¹²
V.I. Umatov,³ L. Vagneron,² M. Velázquez,^{28, 29} M. Vignati,⁵ M. Weber,²⁰
L. Winslow,¹⁹ M. Xue,³⁰ E. Yakushev,¹⁰ and A.S. Zolotarova¹

¹⁾IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

²⁾Univ Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, F-69622, Villeurbanne, France

³⁾National Research Centre Kurchatov Institute, Institute of Theoretical and Experimental Physics, 117218 Moscow, Russia

⁴⁾Dipartimento di Fisica, Sapienza Università di Roma, P.le Aldo Moro 2, I-00185, Rome, Italy

⁵⁾INFN, Sezione di Roma, P.le Aldo Moro 2, I-00185, Rome, Italy

⁶⁾CNRS-Néel, 38042 Grenoble Cedex 9, France

⁷⁾CSNSM, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, 91405 Orsay, France

⁸⁾Nikolaev Institute of Inorganic Chemistry, 630090 Novosibirsk, Russia

⁹⁾LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, 91898 Orsay, France

¹⁰⁾Laboratory of Nuclear Problems, JINR, 141980 Dubna, Moscow region, Russia

¹¹⁾IRAMIS, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

¹²⁾Institute for Nuclear Research, 03028 Kyiv, Ukraine

¹³⁾Karlsruhe Institute of Technology, Institut für Kernphysik, 76021 Karlsruhe, Germany

¹⁴⁾Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

¹⁵⁾Dipartimento di Fisica, Università di Milano Bicocca, I-20126 Milano, Italy

¹⁶⁾INFN, Sezione di Milano Bicocca, I-20126 Milano, Italy

¹⁷⁾DISAT, Università dell'Insubria, 22100 Como, Italy

¹⁸⁾Department of Physics, Fudan University, Shanghai 200433, PR China

¹⁹⁾Massachusetts Institute of Technology, Cambridge, MA 02139, USA

²⁰⁾Karlsruhe Institute of Technology, Institut für Prozessdatenverarbeitung und Elektronik, 76021 Karlsruhe, Germany

²¹⁾Finnish Institute for Educational Research, University of Jyväskylä, P.O. Box 35, Jyväskylä FI-40014, Finland

²²⁾Gran Sasso Science Institute, I-67100 L'Aquila, Italy

²³⁾INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi (AQ), Italy

²⁴⁾IRAMIS, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

²⁵⁾Department of Physics and Astronomy, University of South Carolina, SC 29208, Columbia, USA

²⁶⁾INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi (AQ), Italy

²⁷⁾Gran Sasso Science Institute, I-67100 L'Aquila, Italy

²⁸⁾ICMCB, CNRS, Université de Bordeaux, 33608 Pessac Cedex, France

²⁹⁾Université Grenoble Alpes, CNRS, Grenoble INP, SIMAP, 38402 Saint Martin d'Hères, France

³⁰⁾Department of Modern Physics, University of Science & Technology of China, Hefei 230027, PR China

^{a)}Corresponding author: danevich@kinr.kiev.ua

Abstract. The half-life of ^{100}Mo relatively to the $2\nu 2\beta$ 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 $2\nu 2\beta$ half-life of ^{100}Mo .

INTRODUCTION

Two-neutrino double-beta ($2\nu 2\beta$) 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 $2\nu 2\beta$ 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 $2\nu 2\beta$ 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 $2\nu 2\beta$ decay of ^{100}Mo was measured by enriched in ^{100}Mo lithium-molybdate ($\text{Li}_2^{100}\text{MoO}_4$) crystal scintillators as low temperature scintillating bolometers. The preliminary results of the measurements have been reported in [13, 14].

EXPERIMENT

Four $\text{Li}_2^{100}\text{MoO}_4$ crystal scintillators produced from molybdenum enriched in the isotope ^{100}Mo to $(96.9 \pm 0.2)\%$ with sizes $\varnothing 44 \times (40 - 46)$ 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 $\varnothing 44 \times 0.17$ 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 ~ 6 keV for γ quanta with energy 2614.5 keV of ^{208}Tl .

RESULTS AND DISCUSSION

The energy spectrum accumulated with $\text{Li}_2^{100}\text{MoO}_4$ detectors over the exposure $42.235 \text{ kg}\cdot\text{d}$ (3.797×10^{23} nuclei of $^{100}\text{Mo}\cdot\text{yr}$) 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 $(96.46 \pm 0.60)\%$.

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 $2\nu 2\beta$ 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: $2\nu 2\beta$ decay of ^{100}Mo to the ground state of ^{100}Ru ; $2\nu 2\beta$ 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 $\text{Li}_2^{100}\text{MoO}_4$ scintillating bolometers (exposure is $42.235 \text{ kg} \times \text{d}$) 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
$2\nu 2\beta$ 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 $2\nu 2\beta$ 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 $T_{1/2} = [6.988 \pm 0.074(\text{stat.})] \times 10^{18} \text{ yr}$. 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 $2\nu 2\beta$ 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 $2\nu 2\beta$ 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 $4134 \times 10^{-21} \text{ yr}^{-1}$ 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 $T_{1/2} = (6.99 \pm 0.15) \times 10^{18} \text{ yr}$ with enriched $\text{Li}_2^{100}\text{MoO}_4$ 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 $\text{Li}_2^{100}\text{MoO}_4$ scintillating bolometers (with mass $\approx 0.2 \text{ kg}$ 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.

ACKNOWLEDGMENTS

The authors gratefully thank Prof. F. Iachello for communications relative to single state dominance in ^{100}Mo . The investigations were a part of the program of LUMINEU, a project receiving funds from the Agence Nationale de la Recherche (ANR, France). This work has been funded in part by the P2IO LabEx (ANR-10-LABX-0038) in the framework “Investissements d’Avenir” (ANR-11-IDEX-0003-01) managed by the Agence Nationale de la Recherche (France). The group from Institute for Nuclear Research (Kyiv, Ukraine) was supported in part by the IDEATE International Associated Laboratory (LIA). F.A. Danevich gratefully acknowledges support from the Jean d’Alembert fellowship program (project CYGNUS) of the Paris-Saclay Excellence Initiative, grant number ANR-10-IDEX-0003-02. A.S. Zolotarova was supported by the “IDI 2015” project funded by the IDEX Paris-Saclay, ANR-11-IDEX-0003-02. A.S. Barabash, S.I. Konovalov, I.M. Makarov, V.N. Shlegel and V.I. Umatov were supported by Russian Science Foundation (grant No. 18-12-00003). J. Kotila thanks Academy of Finland (Grant No. 314733) for support. O.G. Polishuk was supported in part by the project “Investigations of rare nuclear processes” of the program of the National Academy of Sciences of Ukraine “Laboratory of young scientists”.

REFERENCES

1. V.I. Tretyak, Yu.G. Zdesenko, *At. Data Nucl. Data Tables* **80**, 83 (2002).
2. R. Saakyan, *Annu. Rev. Nucl. Part. Sci.* **63**, 503 (2013).
3. A.S. Barabash, *arXiv:1907.06887*
4. H. Ejiri et al., *Phys. Lett. B* **258**, 17 (1991).
5. D. Dassié et al., *Phys. Rev. D* **51**, 2090 (1995).
6. M. Alston-Garnjost et al., *Phys. Rev. C* **55**, 474 (1997).
7. A. De Silva, M.K. Moe, M.A. Nelson, M.A. Vient, *Phys. Rev. C* **56**, 2451 (1997).
8. V.D. Ashitkov et al., *JETP Lett.* **74**, 529 (2001).
9. H. Hidaka, C.V. Ly, K. Suzuki, *Phys. Rev. C* **70**, 025501 (2004).
10. R. Arnold et al., *Phys. Rev. Lett.* **95**, 182302 (2005).
11. L. Cardani et al., *J. Phys. G* **41**, 075204 (2014).
12. R. Arnold et al., *Eur. Phys. J. C* **79**, 440 (2019).
13. D.V. Poda et al., *AIP Conf. Proc.* **1894**, 020017 (2017).
14. E. Armengaud et al., *Eur. Phys. J. C* **77**, 785 (2017).
15. T.B. Bekker et al., *Astropart. Phys.* **72**, 38 (2016).
16. E. Armengaud et al., *JINST* **12**, P08010 (2017).
17. R. Arnold et al., *Nucl. Phys. A* **925**, 25 (2014).
18. S. Agostinelli et al., *Nucl. Instrum. Meth. A* **506**, 250 (2003).
19. J. Allison et al., *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).
20. J. Allison et al., *Nucl. Instrum. Meth. A* **835**, 186 (2016).
21. O.A. Ponkratenko et al., *Phys. At. Nucl.* **63**, 1282 (2000).
22. J. Kotila, F. Iachello, *Phys. Rev. C* **85**, 034316 (2012).