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DOUBLE BETA DECAY OF ^{100}Mo

V.D.Ashitkov[1], *A.S.Barabash*[1], *S.G.Belogurov*[1], *G.Carugno*[2],
S.I.Konovalov[1], *F.Massera*[4], *G.Puglierin*[2],
R.R.Saakyan[1,3], *V.N.Stekhanov*[1], *V.I.Umatov*[1]

[1]Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russia
[2]Dipartimento di Fisica e INFN, Universita di Padova, via Marzolo 8, I-35131 Padova, Italy
[3]Laboratori Nazionali del Gran Sasso dell'INFN, I-67010 Assergi (L'Aquila), Italy
[4]INFN, Sezione di Bologna, 40126, via Berti Pichat, 6/2 (Bologna), Italy

Using a liquid argon ionization chamber, the $2\nu\beta\beta$ decay of ^{100}Mo was detected with its half-life of $(7.5 \pm 1.1(\text{stat.}) \pm 1.5(\text{syst.})) \cdot 10^{18}$ y. The limits on half-lives for the 0ν and $0\nu\chi^0$ decays of ^{100}Mo were estimated as $9.3(5.0) \cdot 10^{21}$ and $4.3(2.7) \cdot 10^{20}$ y respectively at 68 % (90%) C.L. Available world data for the $2\nu\beta\beta$ decay of ^{100}Mo lead to the average «world» value of the half-life, $T_{1/2} = (8.0 \pm 0.7) \cdot 10^{18}$ y, which corresponds to the nuclear matrix element, $M_{\text{GT}} = 0.118 \pm 0.005$.

При исследовании $2\nu\beta\beta$-распада ^{100}Mo с помощью ионизационной камеры на жидком аргоне получен предел на период полураспада $(7{,}5 \pm 1{,}1(\text{стат.}) \pm 1{,}5(\text{сист.})) \cdot 10^{18}$ лет. Пределы для 0ν- и $0\nu\chi^0$-моды распада ^{100}Mo оценены соответственно на уровне $9{,}3(5{,}0) \cdot 10^{21}$ и $4{,}3(2{,}7) \cdot 10^{20}$ лет для 68 % (90 %) C.L. Достигнутые мировые значения периода полураспада ^{100}Mo для $2\nu\beta\beta$-моды дают среднее значение этой величины $T_{1/2} = (8{,}0 \pm 0{,}7) \cdot 10^{18}$ лет, что соответствует ядерному матричному элементу $M_{\text{GT}} = 0{,}118 \pm 0{,}005$.

INTRODUCTION

Intensive research for the neutrinoless double beta decay is due to its connection with fundamental aspects of particle physics (see, for example, reviews [1–3]). The main interest in this process is certainly concerned with neutrino mass, because if the $0\nu\beta\beta$ decay were detected, then, according to the theory, the mass of at least one neutrino must be nonzero and this mass is of the Majorana type.

At the moment only lower limits on half-lives ($T_{1/2}$) have been obtained experimentally. These limits are used to deduce upper limits on the Majorana neutrino mass, the right-handed current admixture parameter, the Majoron–Majorana neutrino coupling constant, etc. However, uncertainties in nuclear matrix elements (NME) calculations do not allow reliable limits to be placed on these fundamental values. In this context the detection of $2\nu\beta\beta$ decay becomes of particular importance because information on experimental values of NME(2ν) for different nuclei enables a more accurate calculation of both NME(2ν) and NME(0ν). Besides that, more precise study of the 2ν decay mode is interesting from the point of view of a search for a possible time variation of the weak interaction coupling constant [4, 5].

The nuclide ^{100}Mo is one of the most attractive for investigations of $\beta\beta$ decay. It has a large $\beta\beta$ transition energy, 3,034 keV. In addition the transition $^{100}\text{Mo}(0^+_{\text{g.s.}})-^{100}\text{Ru}(0^+_{\text{g.s.}})$

is characterized by the highest value of NME for both the 2ν decay mode (extracted from experiments, see Ref. 6, for example) and the 0ν decay mode (as predicted by recent calculations [2, 7]). The study of the $2\nu\beta\beta$ decay of ^{100}Mo may be useful for checking the low-lying-state dominance hypothesis [8–10]. As was pointed out in [4, 5], ^{100}Mo is a good candidate for the geochemical $2\nu\beta\beta$ decay experiments. Follow-up comparison of the geochemical results with the results of the direct (counter) experiments will allow a conclusion on the variability of the weak interaction constant to be deduced (it is presented in detail in [4, 5]). In this connection the problem of measuring the half-life of the $2\nu\beta\beta$ decay of ^{100}Mo with a high accuracy assumes great importance. Up to date there are a few positive results for the $2\nu\beta\beta$ decay of ^{100}Mo [11–15]. The experimental values of the half-life are inside the interval from $[6.75^{+0.37(\mathrm{stat})}_{-0.42(\mathrm{stat})} \pm 0.68(\mathrm{syst.})] \cdot 10^{18}$ [15] to $11.5^{+3.0}_{-2.0} \cdot 10^{18}$ y [11].

This work presents the results of a new independent detection of the $2\nu\beta\beta$ decay of ^{100}Mo using a liquid ionization chamber. Besides that, the average «world» value of ^{100}Mo half-life and the corresponding NME for the $2\nu\beta\beta$ transition are given.

1. EXPERIMENTAL PROCEDURE

The experiment is being carried out in the Gran Sasso Underground Laboratory (3,500 m w.e. deep). The experimental setup consists of a liquid argon ionization chamber placed in passive shielding (15 cm of lead)[1], a gas system, electronics and a data acquisition system. The active detection portion of the chamber is composed of alternating circular planes of anodes and cathodes with screen grids placed between them. The cathodes are made of molybdenum foil approximately 50 mg/cm^2 thick. The chamber contains 14 cathodes, 15 anodes and 28 screening grids. The chamber has been assembled with eight cathodes containing enriched molybdenum (98.4 % ^{100}Mo) and six cathodes with natural molybdenum (9.6 % ^{100}Mo). Radioactive impurities of the Mo samples are less than 0.015 Bq/kg for ^{214}Bi, 0.0015 Bq/kg for ^{208}Tl and 0.04 Bq/kg for ^{234m}Pa.

Each anode is connected to a charge-sensitive preamplifier, followed by an amplifier and a flash ADC with the 50 ns sampling time. The energy resolution (FWHM) is 6 % at an energy of 3 MeV. The trigger for data collection requires that at least one anode signal exceeds the threshold (0.8 MeV). Each trigger causes digitized signals from all the anodes to be written to a data tape. Data processing is performed off-line. Two-electron events (events with two neighboring anode signals with a time difference of less than 0.6 μs) are selected. The detection efficiency is calculated by Monte Carlo simulation. A more detailed description of the experimental setup can be found in [16–18].

2. RESULTS

The results presented here were obtained with 137.8 g (313 hours of data taking) and 306 g (2,063 hours of data taking) of enriched Mo. Figure 1 shows the energy spectra of two-electron events for enriched (651.4 kg·h) and natural (441.1 kg·h) molybdenum. The threshold for the

[1]During the last 708 h run the chamber operated with an additional partially installed antineutron passive shielding (30 cm of water and 1 cm of boron acid).

first electron is equal to 0.8 MeV, for the second one is 0.5 MeV. Events from natural Mo cathodes are used for background estimation.

0ν *decay.* To reduce the background the energy threshold for each electron of a pair has been selected to be 1 MeV. The energy range 2.8–3.1 MeV has been studied with an additional selection of signal shape. As a result, four events in the enriched molybdenum and four events in the natural Mo (i.e., 5.9 events if recalculated for 651.4 kg·h) have been detected. Using the detection efficiency (6.9 %), one can obtain the limit on the $0\nu\beta\beta$ decay of ^{100}Mo, $T_{1/2} > 9.3(5.0)\cdot 10^{21}$ y at 68 % (90 %) C.L.

$0\nu\chi^0$ *decay.* The energy interval of 2.3–3.0 MeV has been investigated. 1,165 events for the enriched Mo foils and 1,157 events for the natural foils (recalculated for 651.4 kg·h) have been obtained. For the efficiency of 5.7 % we have got the limit, $T_{1/2} > 4.3(2.7)\cdot 10^{20}$ y at 68 % (90 %) C.L.

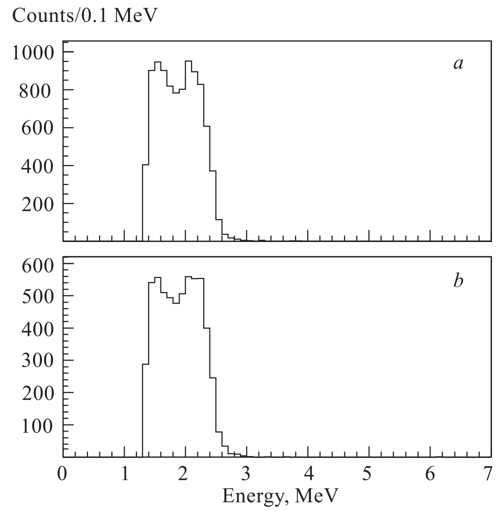

Fig. 1. Energy spectra of two-electron events for enriched (651.4 kg·h) (*a*) and natural (441.1 kg·h) molybdenum (*b*)

2ν *decay.* Events have been analysed in the energy interval of $1.4-2.3$ MeV, where the signal-to-background ratio is maximal. Background subtraction has led to the final value of the effect, 802 ± 122 events. Using the calculated detection efficiency of the $2\nu\beta\beta$ decay of ^{100}Mo (2.2 %), one gets the half-life

$$T_{1/2} = (7.5 \pm 1.1(\text{stat.}) \pm 1.5(\text{syst.}))\cdot 10^{18}\ \text{y}.$$

The systematic error is mainly due to the possible contributions of radioactive impurities in the foils. We consider this result as preliminary one. The experiment will be continued and we hope to decrease both statistical and systematical errors.

3. DISCUSSION

Table 1 presents all the available positive experimental results on the half-life of ^{100}Mo. Only the preliminary result of M.Moe et al. [12] is not given because we use their more precise final result [15]. The last line shows the average of the half-lives of all the five experiments. The average estimate has been performed according to the usual technique of calculation of the average value with different variances (see, for example, [19]), summing up the statistical and systematic errors in quadrature.

Using the phase factor $G = 8.9\cdot 10^{-18}$ y^{-1} (for $g_{\text{A}} = 1.25$) [6] and our average «world» half-life, one can get NME (2ν) for the transition of ^{100}Mo($0^+_{\text{g.s.}}$) –^{100}Ru($0^+_{\text{g.s.}}$), $M_{\text{GT}} = (0.23 \pm 0.01)$ MeV^{-1} or $M_{\text{GT}} = (0.118 \pm 0.005)$ (scaled by the electron rest mass).

The passive antineutron shielding, which is going to be completely installed for the next set of measurements, will decrease the background in the energy range of the $0\nu\beta\beta$ decay of

Table 1. **Experimental half-lives for the $2\nu\beta\beta$ decay of ^{100}Mo**

Year, reference	$T_{1/2}^{2\nu} \cdot 10^{18}$ y
1991, [11]	$11.5^{+3.0}_{-2.0}$
1995, [13]	$9.5 \cdot 0.4(\text{stat}) \pm 0.9(\text{syst.})$
1997, [14]	$7.6^{+2.2}_{-1.4}$
1997, [15]	$6.75^{+0.37(\text{stat})}_{-0.42(\text{stat})} \pm 0.68(\text{syst.})$
2000, present work	$7.5 \pm 1.1(\text{stat}) \pm 1.5(\text{syst.})$
Average	8.0 ± 0.7

^{100}Mo and increase sensitivity to the 0ν and $0\nu\chi^0$ processes up to the levels exceeding the best current results [20]. In addition, our preliminary result on the $2\nu\beta\beta$ decay of ^{100}Mo can be improved as we hope to minimize statistical and systematical errors.

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