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Abstract

Double-beta decay from the ground state of ^{100}Mo to the 0^+ excited state at 1130.29 keV in ^{100}Ru has been observed. A sample of 956g of Mo metal powder isotopically enriched to 98.468% of ^{100}Mo was counted in a Marinelli geometry with a well shielded, ultralow-background germanium detector. The cascade gamma-rays at 539.53 and 590.76 keV were observed. The resulting decay half-life is $1.1^{+0.3}_{-0.2} \cdot 10^{21}$ y at 68% CL.

1. Introduction

Neutrinoless double-beta ($\beta\beta$) decay experiments hold the promise of the discovery of elementary particle physics beyond the standard model. Such experiments, however, depend on calculated nuclear matrix elements for their interpretation of this exotic process. The phase space factor can be calculated accurately, while the Majorana neutrino masses depend sensitively on the details of the neutrino mass matrix of the particular gauge-model employed. The nuclear matrix element, $M^{0\nu}$, must be calculated using a specific model. Review articles discussing such calculations appear in the literature¹⁻³, and the recent experimental status has also been reviewed⁴⁻⁶.

The ordinary allowed second-order weak decay, $2\nu \beta\beta$ -decay, obeys the equation

$$[T_{1/2}^{2\nu}]^{-1} = G^{2\nu}(E, Z) \cdot |M^{2\nu}|^2 \quad (1)$$

where the quantity $G^{2\nu}(E, Z)$ is a kinematical factor depending on electron and neutrino wave functions, and $M^{2\nu}$ is the nuclear matrix element. While $M^{0\nu}$ and $M^{2\nu}$ are not identical, the measurement of $M^{2\nu}$ can provide a valuable test of the nuclear model used to calculate $M^{0\nu}$. The matrix elements $M^{0\nu}$ and $M^{2\nu}$ have been calculated with the nuclear shell model⁷ and with a variety of schematic models, most notably the Quasiparticle Random Phase Approximation (QRPA)⁸⁻¹⁰.

Direct measurements of $T_{1/2}$ and hence $|M^{2\nu}|$, have recently been reported for ^{82}Se ¹¹, ^{76}Ge ¹²⁻¹⁴, and ^{100}Mo ¹⁵⁻¹⁷. All of these measurements involved the $\beta\beta$ -decay from the 0^+ ground state of the parent to the 0^+ ground state of the daughter nuclide. The three measurements of the $\beta\beta$ -decay of ^{100}Mo from its 0^+ ground state to the 0^+ ground state in ^{100}Ru resulted in the following half-lives: $(1.16^{+0.34}_{-0.08}) \cdot 10^{19} \text{ y}$ ¹⁵, $(1.16^{+0.34}_{-0.22}) \cdot 10^{19} \text{ y}$ ¹⁶, and $(3.3^{+2.0}_{-1.0}) \cdot 10^{18} \text{ y}$ ¹⁷.

The phase space factor $G^{2\nu}$ depends on the decay energy and lepton wave functions². In earlier work¹⁸, it was shown that the three isotopes ^{96}Zr , ^{100}Mo , and ^{150}Nd have Q -values high enough to probably allow direct observation of the gamma-rays following $\beta\beta$ -decay to the first excited 0^+ states of the daughter nuclei. The measurement described in this communication involved the $\beta\beta$ -decay transition from the 0^+ ground state of ^{100}Mo to the first excited 0^+ state in ^{100}Ru at 1130.29 keV.

Assuming $|M^{2\nu}|$ is the same for both the ground state and excited state transition, the ratio of decay rates is the ratio of phase space integrals which is equal to 55 for our case². Using the half-life for the ground state transition of references 15 and 16, the predicted half-life is $T_{1/2}(0^+ \rightarrow 0^+_1) = 6.4^{+1.9}_{-0.6} \cdot 10^{20} \text{ y}$.

2. Experimental

The counting facility used in this experiment is located in the Soudan II mine at a depth of 2090 mwe. The system consists of a 132 cm³ intrinsic germanium detector,

Fig. 1. Geometry of shield, Marinelli beaker, and Ge detector.

having an energy resolution of 2.4 keV FWHM at 1332 keV, assembled in a cryostat of low-background copper components housed in a large bulk shield of ordinary lead

which has an inner liner of 5-cm-thick, ~ 150 -year-old lead recovered from a German ship that sank in the North Sea. The old lead liner is used to shield the detector from the radiations of ^{210}Pb and its progeny present in the contemporary lead. The bulk shield is atmospherically sealed and pressurized with the nitrogen boil-off gas from the detector dewar to eliminate radon and its progeny from the shield.

The sample consists of 956g of powdered molybdenum metal enriched to $98.468 \pm 0.009\%$ ^{100}Mo contained in a lucite Marinelli beaker. The sample counting geometry is shown in Fig.1. Since the sample nearly surrounds the detector, this configuration is only suitable for detecting single gamma-ray events. The photopeaks of interest are the 590.76- and 539.53-keV lines corresponding to the de-excitation gamma-ray cascade through the $0_1^+ - 2_1^+ - 0^+$ levels.

3. Results.

The energy spectrum obtained in 9032 hours of counting is shown in the region of interest at 1 keV per channel in Fig.2. Radioactive impurities identified in the sample

Fig. 2. Energy spectrum in the region of interest.

include primordial potassium, thorium, uranium, and radium as well as traces of ^{134}Cs and ^{137}Cs . The 511-keV line from positron annihilation, the 583.19-keV line from ^{208}Tl (^{228}Th), the 563.24, 569.32, and 604.71-keV lines from ^{134}Cs , and the 609.32-keV line from ^{214}Bi (^{226}Ra) are shown in the figure and provide an internal check on the resolution and energy calibration of the system.

The energy regions of the spectrum corresponding to the expected peaks from the $\beta\beta$ -decay de-excitation gamma-rays were fit to gaussian functions on a monotonic continuum and analysed by maximum likelihood technique. The best fit to the continuum in the 500-630 keV region was constructed as a parabola after all peaks ($> 3\sigma$) were rejected. The results are 64.0 ± 19.5 net counts at 539.53 keV and 65.6 ± 17.6

net counts at 590.76 keV where the uncertainties represent one standard deviation (1σ). Monte Carlo calculations were used to obtain efficiency factors of 0.0187 and 0.0177, respectively, for these gamma-rays.

The half-life can be calculated according to the formula

$$T_{1/2} = (\ln 2)Nt/dN \quad (2)$$

where N = number of ^{100}Mo atoms, $5.669 \cdot 10^{24}$; t = the time of counting, 1.031 years; and dN = the number of ^{100}Mo decays. Therefore, at the 68% confidence level, the half-life based on the 539.53-keV photopeak is $T_{1/2} = 1.2^{+0.5}_{-0.3} \cdot 10^{21}$ y, and based on the 590.76-keV photopeak is $T_{1/2} = 1.1^{+0.4}_{-0.2} \cdot 10^{21}$ y. A simultaneous analysis using both photopeaks (539.53- and 590.76-keV) leads to the more precise value of the ($0^+ \rightarrow 0_1^+$) 2ν $\beta\beta$ -decay half-life

$$T_{1/2} = 1.1^{+0.3}_{-0.2} \cdot 10^{21} \text{ y} \quad (3)$$

Table 1. Half-lives and limits for $\beta\beta$ -decay of ^{100}Mo to selected excited levels in ^{100}Ru

$2\beta(0\nu + 2\nu)$ - transition	J^π ; energy of final state, keV	transition energy keV	$T_{1/2}(\text{y}) \cdot 10^{-21}$		
			this work CL 90%	ref. 19 CL 68%	ref. 20 CL 90%
$0^+ - 2_1^+$	$2^+(539.53)$	2493	> 2.3	> 0.14	> 0.5
$0^+ - 0_1^+$	$0^+(1130.29)$	1903	$1.1^{+0.3}_{-0.2} \text{ *)}$	> 0.042	> 1.2
$0^+ - 2_2^+$	$2^+(1362.1)$	1671	> 2.5	> 0.058	> 0.6
$0^+ - 0_2^+$	$0^+(1740.7)$	1292	> 1.5	> 0.035	--

*) CL 68%

Double-beta decay of ^{100}Mo is energetically possible to a host of excited states in ^{100}Ru , and half-lives or limits can also be obtained from the data for each of those possible transitions. The measured half-lives or limits for decay to the first four $J = 0, 2$ levels in ^{100}Ru are given in Table 1. The systematic error, primarily uncertainty in the efficiency, is $\sim 10\%$. Results from this work are compared to literature values for the same transitions^{19,20}.

The measured double-beta decay rate of ^{100}Mo to the first excited 0^+ level in ^{100}Ru can now be used in conjunction with the previously measured ground state double-beta decay rate to calculate the relevant nuclear matrix elements. Similar experiments are being contemplated for measuring the double-beta decay of ^{96}Zr , ^{116}Cd , and ^{150}Nd to the excited states of their daughters.

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