Double beta processes in ^{92}Mo

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The double beta processes in ^{92}Mo are investigated both theoretically and experimentally. An extension of the quasiparticle random-phase approximation (QRPA) approach has been used for the two-neutrino double beta calculations. A HPGe detector and an external source of high-purity natural molybdenum are used to determine new stringent limits on the $(0\nu+2\nu)\beta^+$ EC decay to the ground state and on $(0\nu+2\nu)$ ECEC transitions to excited states. © *1995 American Institute of Physics.*

Double beta decay investigations have mostly concentrated on the $\beta^-\beta^-$ emission (see reviews [1,2]), but very recently more and more attention is also paid to the $\beta^+\beta^+$, β^+EC and ECEC (here EC denotes electron capture) processes in nuclei.[3–8] Detection of the two-neutrino mode of the above processes enables one to determine the magnitude of the nuclear matrix elements involved, which is very important in view of the theoretical calculations for both the 2ν and the 0ν modes of double beta decay. If the $0\nu\beta^-\beta^-$ decay is detected, the experimental limits on the $0\nu\beta^+$ EC half-lives can be used to obtain information about the relative importance of the Majorana neutrino mass and right-handed-current admixtures in electroweak interactions.[4]

This paper presents results from a theoretical investigation of $2\nu\beta^+$EC and 2νECEC processes in ^{92}Mo ($Q_{\mathrm{ECEC}}=1648$ keV; natural abundance is 14.84%) and from an experimental search for the $(0\nu+2\nu)\beta^+$EC transition to the ground state and $(0\nu+2\nu)$ECEC transitions to excited states in ^{92}Zr.

The double Gamow–Teller matrix element can be calculated using an expression from Refs. 3, 9, and 10. The $2\nu\beta\beta$-decay half-life can then be calculated by assuming that the phase space and the nuclear matrix element separate.[11]

The 1^+ states of the odd–odd nucleus are calculated using the pnQRPA approach of Ref. 12, whereas the excited final states $J_f^+=0_1^+,2_1^+,2_2^+$ are described within the charge-conserving QRPA framework. In the following, this extended form of the QRPA method is called the multiple commutator model (MCM).[13] In the MCM the 2_1^+ state is described by the lowest, usually collective, QRPA phonon, whereas the 0_1^+ and 2_2^+ excited states are

TABLE I. Theoretical upper limits for the matrix elements ($M_{GT}^{(2\nu)}$), the corresponding lower limits of the half-lives ($T_{1/2}^{(2\nu)}$) for the 2νECEC and $2\nu\beta^+$EC decays $^{92}Mo \rightarrow ^{92}Zr$, and experimental half-life limits for double beta transitions in ^{92}Mo at a confidence level CL=90%.

	Theory		Experiment		
			this work	previous works	
Transition	$M_{GT}^{2(\nu)}$	$T_{1/2}^{(2\nu)}(y)$	$T_{1/2}^{(0\nu+2\nu)}(y)$	$T_{1/2}^{(0\nu)}(y)$	$T_{1/2}^{(2\nu)}(y)$
ECEC($0^+ \rightarrow 0^+_{g.s.}$)	0.30	$3.0 \cdot 10^{22}$	-	-	-
ECEC($0^+ \rightarrow 2^+_1$)	0.004	-	$2.1 \cdot 10^{20}$	$3 \cdot 10^{18}$ Ref. 18	$3 \cdot 10^{18}$ Ref. 18
ECEC($0^+ \rightarrow 0^+_1$)	0.015	$2.4 \cdot 10^{29}$	$2.7 \cdot 10^{20}$	$4 \cdot 10^{18}$ Ref. 18	$4 \cdot 10^{18}$ Ref. 18
β^+EC($0^+ \rightarrow 0^+_{g.s.}$)	0.30	$2.4 \cdot 10^{25}$	$4.5 \cdot 10^{19}$	$2.7 \cdot 10^{18}$ Ref. 19	$2.3 \cdot 10^{18}$ Ref. 19

assumed to belong to a triplet of two quadrupole phonons ($2^+_1 \otimes 2^+_1$). In the present calculation a harmonic approximation for the two-phonon triplet states is used, i.e., their energies are assumed to be degenerate. Finally, the formalism adopted for the calculation of the reduced matrix elements is discussed in detail in Refs. 3, 9, 10, and 13.

The present MCM calculation uses a valence space consisting of two major oscillator shells, namely the $f-p$ and $s-d-g$ shells, complemented with the intruder orbital $0h_{11/2}$ from above. The single-particle energies were taken from the Woods–Saxon potential with the parametrization of Ref. 14. The two-body matrix elements, needed in the calculations, were obtained from the Bonn potential by the G-matrix procedure. The semiempirical pairing gaps, appropriate for the $A=92$ isobaric chain, were used to fix the overall strength of the pairing channel for protons and neutrons. The particle–hole strength of the QRPA and the pnQRPA channels[12,13] were fixed by the experimental excitation energy of the 2^+_1 state in ^{92}Zr and by the semiempirical location of the Gamow–Teller giant resonance in ^{92}Nb. The strength g_{pp} of the particle–particle channel of the proton–neutron G-matrix interaction[12] was assumed to be bigger than 0.9, which covers the physical region of this parameter.

In the present case the beta-decay observables cannot be used to fix an appropriate value of g_{pp} within the MCM framework. This is due to the lack of experimental data on beta decays of 1^+ states in this isobaric chain. Hence, only the above-mentioned range of g_{pp} can be used in the calculations leading to the upper limits for the various nuclear matrix elements $M_{GT}^{(2\nu)}$ listed in Table I. By using the formalism given in Ref. 11 one can calculate the phase-space factors for the 0^+ final states and thus find the corresponding theoretical lower limits for the $2\nu\beta^+$EC and 2νECEC half-lives $T_{1/2}^{(2\nu)}$. These are compared with their corresponding experimental lower limits in Table I.

The experimental work was performed at the Fréjus Underground Laboratory (depth of 4800 m w.e.) using a low-background 400 cm^3 HPGe detector. The detector was placed inside a passive shielding of 15–20 cm of OFHC copper and 15 cm of ordinary lead. The sample (2484 g of high-purity natural molybdenum) surrounded the HPGe detector. The energy resolution was 2.0 keV for the 1332 keV line of ^{60}Co.

The energy spectrum obtained for 275 hours was compared with background spectrum collected for 1169 hours (Fig. 1). The search for the processes under study was

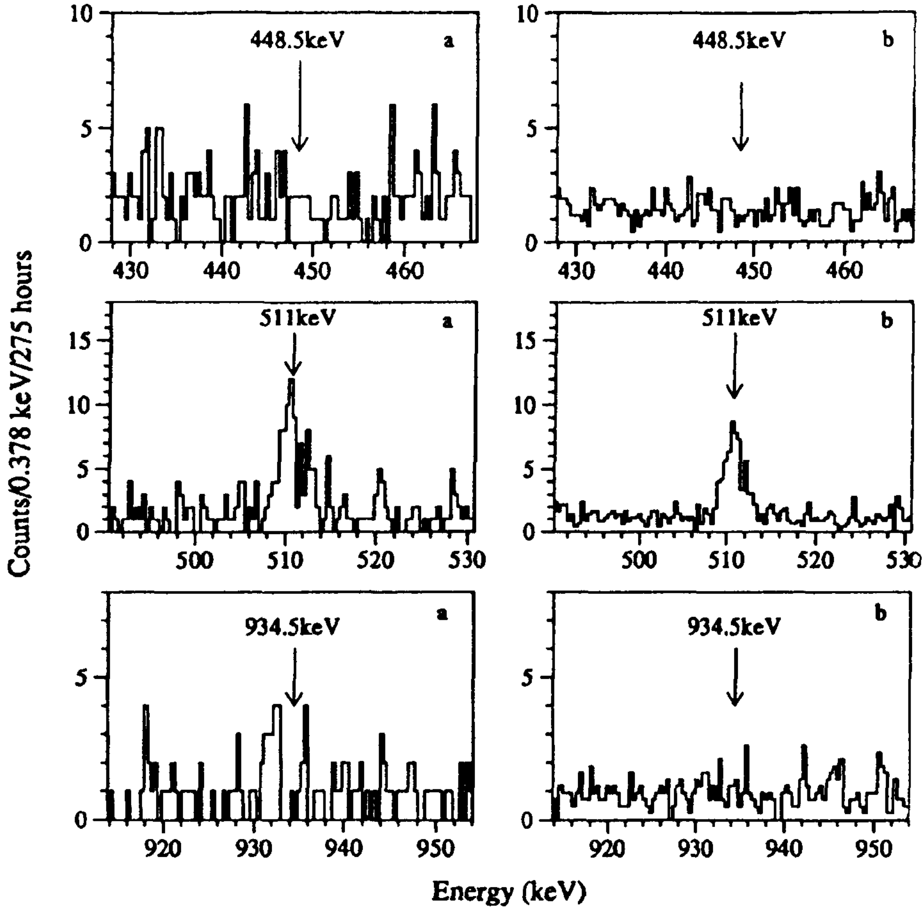

FIG. 1. Partial γ-ray spectra in the energy ranges corresponding to different decay modes of ^{92}Mo: a—with natural Mo sample (for 275 h), b—without Mo sample (normalized to 275 h). The arrows indicate the expected γ-line positions: 511.0 keV—annihilation peak, 448.5 keV $(0_{1^+}\rightarrow 2_1^+)$, 934.5 keV $(2_1^+\rightarrow 0_{g.s.}^+)$.

performed by looking for the 448.5, 511, and 934.5 keV γ rays accompanying these processes.[15] No excess of events was found. The limits on the $(0\nu+2\nu)\beta^+EC(0^+\rightarrow 0_{g.s.}^+)$, $(0\nu+2\nu)ECEC(0^+\rightarrow 2_1^+)$, and $(0\nu+2\nu)ECEC(0^+\rightarrow 0_1^+)$ transitions are presented in Table I. The efficiencies were calculated by simulation using the GEANT3.21 code.[16] The procedure recommended by the Particle Data Group[17] was used to calculate the limits. Table I also presents the best results of previous works for ^{92}Mo. One can see that the new limits exceed the previous ones by one or two orders of magnitude.

As one can see from Table I the present experimental sensitivity is far from the expected values for $2\nu\beta EC(0^+\rightarrow 0_{g.s.}^+)$ decay and for 2νECEC transitions to excited states in ^{92}Zr. The sensitivity can reach $\sim 10^{22}$ years if the molybdenum sample, enriched by ^{92}Mo, is placed closer to the HPGe detector and the measurement time is extended to 1 year. However, this is not enough to detect these processes too. The 2νECEC$(0^+\rightarrow 0^+_{\text{g.s.}})$ transition seems to be more favorable for detection, but only with new experimental devices. For instance, there are some prospects for searching for this process using segmented HPGe (or Si) detectors or proportional counters which would work in a coincidence regime (to detect two x rays simultaneously) and have a low background counting rate at ~25 keV. The existing HPGe detectors, with very low background at this energy,[20–22] give such hope.

Finally, the theoretical matrix elements can be compared with the ones of Ref. 23, where the values $M^{(2\nu)}_{\text{GT}}(0^+\rightarrow 0^+_{\text{g.s.}})=0.254$ and $M^{(2\nu)}_{\text{GT}}(0^+\rightarrow 0^+_{\text{I}})=0.096$ were obtained by using the shell-model approach within a very limited single-particle basis. The resulting value of the ground-state matrix element is close to the upper bound 0.30 obtained in the present calculation, whereas the 0^+_{I} matrix element of Ref. 23 is some 6 times larger than the present results. In any case, using either one of the 0^+_{I} matrix elements, one ends up with a $0^+\rightarrow 0^+_{\text{I}}$ half-life remaining beyond detection in the near future.

To conclude, in this article we have presented theoretical results, calculated in the QRPA framework, for the nuclear matrix elements and half-lives of the $2\nu\beta^+$EC$(0^+\rightarrow 0^+_{\text{g.s.}})$, 2νECEC$(0^+\rightarrow 2^+_{\text{I}})$, and 2νECEC$(0^+\rightarrow 0^+_{\text{I}})$ decays of ^{92}Mo. At the same time, new, more stringent, experimental limits have been obtained for $(0\nu+2\nu)$ECEC transitions to excited states in ^{92}Zr and for the $(0\nu+2\nu)\beta^+$EC$(0^+\rightarrow 0^+_{\text{g.s.}})$ decay of ^{92}Mo.

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