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DOUBLE BETA PROCESSES IN ^{92}Mo

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The double beta processes in ^{92}Mo have been 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. Using a HPGe detector and an external source of high-purity natural molybdenum, new stringent limits on the $(0\nu+2\nu)\beta^+$ EC decay to the ground state and $(0\nu+2\nu)$ ECEC transitions to excited states have been derived.

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 the electron capture) processes in nuclei [3–8]. Detection of the two-neutrino mode of the above processes admits to define the magnitude of the involved nuclear matrix elements 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 was detected, the experimental limits on the $0\nu\beta^+$ EC half-lives could 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 on theoretical investigation of $2\nu\beta^+$EC and 2νECEC processes in ^{92}Mo ($Q_{\text{ECEC}} = 1648$ keV; natural abundance is 14.84%) and 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 expression of [3, 9, 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 [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 assumed to belong to the 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 [3, 9, 10, 13] in detail.

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 [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, approppriate 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.

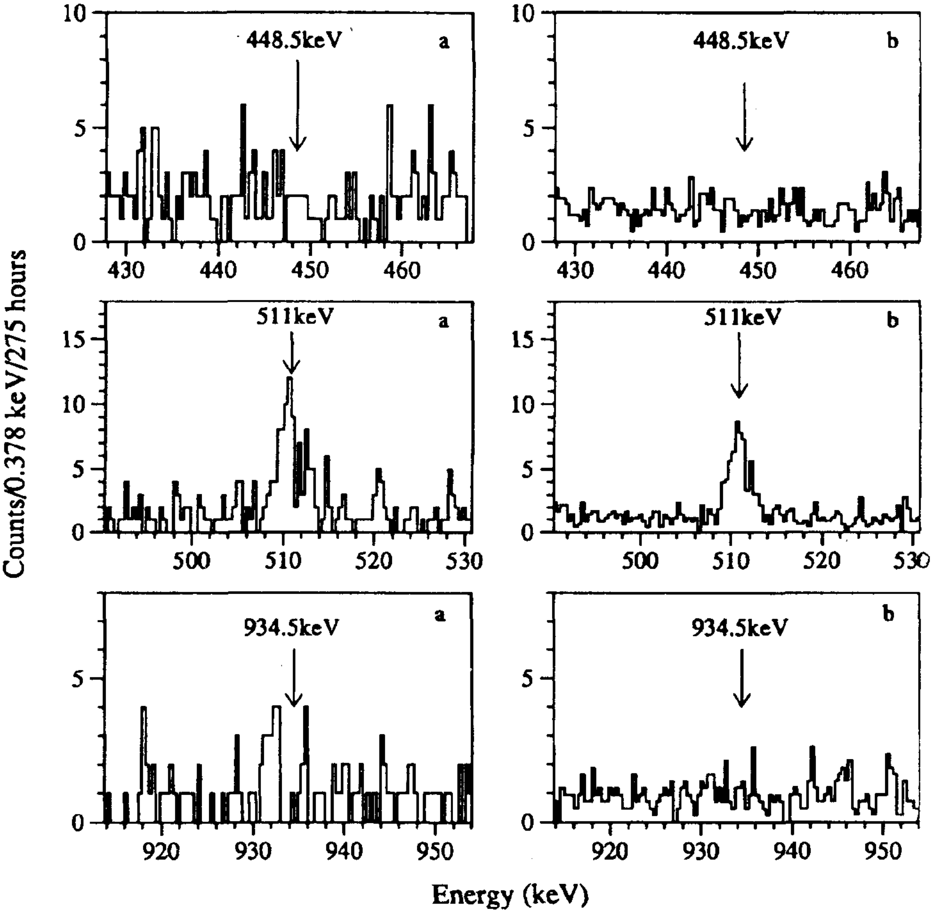
In the present case the beta-decay observables can not be used to fix an approppriate value of g_{pp} within the MCM framework. This is due to lack of experimental data on beta decays of 1^+ states in this isobaric chain. Followingly, only the above-mentioned range of $g_{\rm pp}$ can be used for calculations leading to the upper limits for the various nuclear matrix elements $M_{\rm GT}^{(2\nu)}$ listed in Table. By using the formalism given in [11] one can calculate the phase-space factors for the 0^+ final states and, followingly, 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.

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

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

The experimental work has been performed in the Fréjus Underground Laboratory (depth of 4800 m w.e.) using a low-background 400 cm^3 HPGe detector. The detector is 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 is 2.0 keV for the 1332 keV line of ^{60}Co.

The energy spectrum obtained for 275 hours has been compared with background spectrum collected for 1169 hours (figure). The search for processes under study has been performed by looking for 448.5, 511, and 934.5 keV γ-rays accompanying these processes [15]. No excess of events has been found. Limits on $(0\nu+2\nu)\beta^+$EC($0^+ \to 0^+_{\rm g.s.}$), $(0\nu+2\nu)$ECEC($0^+ \to 2^+_1$) and $(0\nu+2\nu)$ECEC($0^+ \to 0^+_1$)



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 ($0_1^+ \to 2_1^+$), 934.5 keV ($2_1^+ \to 0_{g.s.}^+$)

transitions are presented in Table. Efficiencies have been calculated by simulation using the GEANT3.21 code [16]. To calculate the limits the procedure recommended by the Particle Data Group has been used [17]. Table 1 presents also 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 the Table 1 the present experimental sensitivity is far from the expected values for $2\nu\beta EC(0^+ \to 0^+_{g.s.})$ decay and 2νECEC transitions to excited states in ^{92}Zr. The sensitivity can reach up to $\sim 10^{22}$ years if the molybdenum sample, enriched by ^{92}Mo, will be placed closer to the HPGe detector and the measurement time is extended up to 1 year. However, this is not enough to detect these processes too. The $2\nu ECEC(0^+ \to 0^+_{g.s.})$ transition seems to be more favourable for detection, but only with new experimental devices. For instance, there are some perspectives to search for this process using segmented HPGe (or Si) detectors or proportional counters which would work in 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]. In [23] the values $M^{(2\nu)}_{\rm GT}(0^+ \rightarrow 0^+_{\rm g.s.}) = 0.254$ and $M^{(2\nu)}_{\rm GT}(0^+ \rightarrow 0^+_1) = 0.096$ 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^+_1 matrix element of [23] is some 6 times larger than the present result. In any case, using either one of the 0^+_1 matrix elements, one ends up with a $0^+ \rightarrow 0^+_1$ half-life remaining beyond detection in the near future.

To conclude, in this article we present theoretical results, calculated by using the QRPA framework, for the nuclear matrix elements and half-lives of the $2\nu\beta^+$EC$(0^+ \rightarrow 0^+_{g.s.})$, 2νECEC$(0^+ \rightarrow 2^+_1)$ and 2νECEC$(0^+ \rightarrow 0^+_1)$ 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$(0^+ \rightarrow 0^+_{g.s.})$ decay of ^{92}Mo.

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