New limits on the β^+EC and ECEC processes in ^{74}Se and ^{120}Te

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Abstract. Limits on double-beta processes in ^{74}Se and ^{120}Te have been obtained using a 400 cm^3 HPGe detector and an external source consisting of natural Se or TeO_2 powder. In particular, limit with a 90% C.L. on the ^{74}Se half-life of 5.5×10^{18} y for ECEC(0ν) transitions to the 2_2^+ excited state in ^{74}Ge (1204.2 keV) has been obtained. This transition is discussed in association with a possible enhancement of the decay rate, in this case by several orders of magnitude, because the ECEC(0ν) process is nearly degenerate with an excited state in the daughter nuclide. For other β^+EC and ECEC transitions (to the ground and excited states) obtained limits are on the level $\sim 10^{18} - 10^{19}$ y.

1. Introduction

Most double beta decay investigations have concentrated on the $\beta^-\beta^-$ decay (see recent reviews [1, 2]). Much less attention has been given to the investigation of $\beta^+\beta^+$, β^+EC and ECEC processes (see review [3]). The $\beta^+\beta^+$ and β^+EC processes are less favorable due to smaller kinetic energy available for the emitted particles and Coulomb barrier for the positrons. However, an attractive feature of these processes from the experimental point of view is the possibility of detecting either the coincidence signals from four (two) annihilation γ-rays and two (one) positrons, or the annihilation γ-rays. It is difficult to investigate the ECEC process because one only detects the low energy X-rays. It is interesting to search for transitions to the excited states of daughter nuclei, which are easier to detect given the cascade of higher energy gammas [4]. One can foresee that with improvement in the experimental techniques and increasing the mass of the detectors, the search for $\beta^+\beta^+$, β^+EC and ECEC processes will be considerably extended.

In this paper the results of an experimental investigation of the β^+EC and ECEC processes in ^{74}Se and ^{120}Te (transitions to the ground and excited states of daughter nuclei) are presented.

2. Experimental details

The experiment has been performed in the Modane Underground Laboratory (depth of 4800 m w.e.). The natural selenium and TeO_2 powder samples were measured using a 400 cm^3 low-background HPGe detector with energy resolution of 2.0 keV for the 1332-keV line of ^{60}Co.

The passive shielding consisted of 4 cm of Roman-era lead and 3-10 cm of OFHC copper inside 15 cm of ordinary lead. To remove ^{222}Rn gas, one of the main sources of the background, a special effort was made to minimize the free space near the detector. In addition, the passive shielding was enclosed in an aluminum box flushed with high-purity nitrogen.

The sample of natural selenium powder was placed in a circular plastic box and put on the endcap of the HPGe detector. The mass of the powder was 563 g, 4.69 g of which was ^{74}Se (as the natural abundance is 0.89%). The duration of measurement was 436.56 hours.

The sample of natural TeO_2 powder was placed in a delrin Marinelli box surrounding the HPGe detector. The mass of the powder was 1004.2 g, 0.72 g of which was ^{120}Te. The duration of the measurement was 475.4 hours.

Table 1. The limits on double-beta processes in ^{74}Se. The second column presents γ-ray energies in keV and their efficiencies used to estimate half-lives. Limits on half-lives $T_{1/2}$ are given at a confidence level of 90%. $^{*)}$ For transition with irradiation of e^+e^- pair. $^{**)}$ This transition is suppressed (forbidden).

Transitions	γ-ray(efficiency)	$T_{1/2}, 10^{19}$ y
$L^1L^2, Q' = 1206.9$ keV, ECEC(0ν) to the 2_2^+(1204.2-keV) level of ^{74}Ge	595.8 keV (1.88%) 608.4 keV (1.84%) 1204.2 keV (0.757%)	0.55
$L^1L^2, Q' = 1206.9$ keV, ECEC(0ν) to the 2_1^+(595.8-keV) level of ^{74}Ge	595.8 keV (2.76%) 611.1 keV (2.70%)	1.30
$L^1L^2, Q' = 1206.9$ keV, ECEC(0ν) to the ground state of ^{74}Ge	1206.9 keV (2.13%)	0.41
$K^1L^2, Q' = 1197.2$ keV, ECEC(0ν) to the 2_1^+(595.8-keV) level of ^{74}Ge	595.8 keV (2.75%) 601.4 keV (2.71%)	1.12
$K^1L^2, Q' = 1197.2$ keV, ECEC(0ν) to the ground state of ^{74}Ge	1197.2 keV (2.13%)	0.64
$K^1K^2, Q' = 1185.9$ keV, ECEC(0ν) to the 2_1^+(595.8-keV) level of ^{74}Ge	595.8 keV (2.75%) 590.1 keV (2.76%)	1.57
$K^1K^2, Q' = 1185.9$ keV, ECEC(0ν) to the ground state of ^{74}Ge	511 keV (6.74%) 1185.9 keV (2.15%)	$0.19^{*)}$ $0.62^{**)}$
β^+EC($0\nu + 2\nu$) transition to the ground state of ^{74}Ge	511 keV (6.74%)	0.19
ECEC(2ν) to the (2_2^+)(1204.2-keV) level of ^{74}Ge	595.8 keV (1.88%) 608.4 keV (1.84%) 1204.2keV (0.757%)	0.55
ECEC(2ν) to the 2_1^+(595.8-keV) level of ^{74}Ge	595.8 keV (3.13%)	0.77

3. Results

3.1. Results with ^{74}Se [5]

A search for different β^+EC and ECEC processes in ^{74}Se was carried out using the germanium detector to look for γ-ray lines corresponding to these processes. Hereinafter, Q' is the effective Q-value defined as $Q' = \Delta\text{M} - \epsilon_1 - \epsilon_2$ where ΔM is the difference of parent and daughter atomic masses, ϵ_i is an electron binding energy in a daughter nuclide. The photon detection efficiency for each investigated process has been computed with the CERN Monte Carlo code GEANT 3.21.

The obtained results are presented in Table 1. It is necessary to stress that ^{74}Se has never been investigated before and all results presented here are obtained for the first time.

Table 2. The limits on β^+EC and ECEC processes in ^{120}Te.

Transition	Energy of γ-rays (efficiency)	$T_{1/2}$, 10^{18} y (C.L. 90%)	
		This work	other works
β^+EC($0\nu + 2\nu$); g.s.	511.0 (7.38 %)	0.19	0.121 (0ν) [8]
ECEC(0ν) L^1L^2; g.s.	1691.2 (2.05 %)	0.29	0.00268 (0ν) [8]
ECEC(0ν) K^1L^2; g.s.	1666.4 (2.08 %)	0.39	0.00268 (0ν) [8]
ECEC(0ν) K^1K^2; g.s.	1641.7 (2.08 %)	0.60	0.00268 (0ν) [8]
	511.0 (7.38 %)	0.19	-
ECEC(2ν); g.s.	-	-	0.0094 (2ν) [7]
ECEC($0\nu + 2\nu$); 2^+	1171.26 (2.60 %)	0.75	0.0084 (2ν) [7]

3.2. Results with ^{120}Te [6]

The search for different β^+EC and ECEC processes in ^{120}Te looked for γ-ray lines corresponding to these processes. For ^{120}Sn ϵ is equal to 29.2 keV for the K shell and 4.46 keV, 4.15 keV and 3.93 keV for the L shell (2s, $2p_{1/2}$ and $2p_{3/2}$ levels) . In the case of the L shell the resolution of the detector prohibits separation of the lines so we center the study on the 4.15 keV line.

In the case of ECEC(0ν) transition to the ground state of ^{120}Sn there is a large uncertainty in the energy of the bremsstrahlung γ-quantum because of poor accuracy for ΔM ($\pm$10.3 keV). Thus the position of the peak was varied in the region of the uncertainty and the most conservative value of the limit for the half-life was selected.

The photon detection efficiency for each investigated process has been computed with the CERN Monte Carlo code GEANT 3.21.

The final results are presented in Table 2. In the last column the best previous results are presented for comparison. One can see that the present work is 1.5 to 200 times better than previous measurements [7, 8].

4. Conclusion

For the first time, limits on double-beta processes in ^{74}Se have been obtained. In addition, in this paper we have presented new, more stringent, experimental limits for the different β^+EC and ECEC processes in ^{120}Te.

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References

[1] Avignone F T, Elliott S R and Engel J 2007 *Preprint* nucl-ex/0708.1033
[2] Barabash A S 2006 *JINST* **1** P07002 (*Preprint* hep-ex/0602037)
[3] Barabash A S 2004 *Phys. At. Nucl.* **67** 438
[4] Barabash A S 1994 *JETP Lett.* **59** 644
[5] Barabash A S et al 2007 *Nucl. Phys.* A **785** 371
[6] Barabash A S et al 2007 *J. Phys.* G **34** 1721
[7] Kiel H, Munstermann D and Zuber K 2003 *Nucl. Phys.* A **723** 499
[8] Bloxham T et al 2007 *Phys. Rev.* C **76** 025501