Eur. Phys. J. A **11**, 143–145 (2001)

THE EUROPEAN PHYSICAL JOURNAL A

New limits on the $\beta\beta$ decay of ^{130}Te to excited states of ^{130}Xe

A.S. Barabash[1,a], F. Hubert[2], Ph. Hubert[2], and V.I. Umatov[1]

[1] Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russia,
[2] Centre d'Etudes Nucléaires, IN2P3-CNRS and Université de Bordeaux, F-33175 Gradignan Cedex, France

Received: 16 March 2001
Communicated by J. Äystö

Abstract. Experimental limits on half-lives of the $(0\nu + 2\nu)\beta\beta$ decay of ^{130}Te to excited states of ^{130}Xe are obtained using low-background HPGe detectors. At the 90% CL, these limits are equal to $1.6 \cdot 10^{21}$ y, $2.7 \cdot 10^{21}$ y and $2.3 \cdot 10^{21}$ y for transitions to the 2_1^+, 2_2^+ and 0_1^+ levels, respectively.

PACS. 23.40.-s β decay; double β decay; electron and muon capture

1 Introduction

The main interest in $\beta\beta$ decay is connected with the neutrinoless mode ($0\nu\beta\beta$) as a probe for physics beyond the Standard Model of electroweak interactions. Its existence connects with fundamental aspects of particle physics, *i.e.* the lepton number nonconservation, the existence and nature of neutrino mass, the existence of right-handed currents in the electroweak interaction, the existence of a massless Goldstone boson, the Majoron, the supersymmetry, etc. (see, for instance, [1–4]).

In connection with the $0\nu\beta\beta$ decay, the detection of $\beta\beta$ decay with the emission of two neutrinos ($2\nu\beta\beta$), which is an allowed process of second order in the Standard Model, enables the experimental determination of nuclear matrix elements involved in the $\beta\beta$ decay processes. This, in turn, leads to the development of theoretical schemes for nuclear matrix element calculations both in connection with the $2\nu\beta\beta$ decays as well as the $0\nu\beta\beta$ decays.

The $\beta\beta$ decay can proceed through transitions to the ground state as well as to various excited states of the daughter nuclide. Studies of the latter transitions allow one to obtain supplementary information about $\beta\beta$ decay. Because of smaller transition energies, the probabilities for $\beta\beta$ decay transitions to excited states are substantially suppressed in comparison with transitions to the ground state. But as it was shown [5], by using low-background facilities utilizing HPGe detectors, the $2\nu\beta\beta$ decay to the 0_1^+ level in the daughter nucleus may be detected for such nuclei as ^{100}Mo, ^{96}Zr and ^{150}Nd. In this case the energies involved in the $\beta\beta$ transitions are large enough (1903, 2202 and 2627 keV, respectively), and the expected half-lives are of the order of 10^{20}–10^{21} y. The required sensitivity was only reached for ^{100}Mo and the transition was detected in the three experiments [6–8] with half-life lying within $(6–9)\cdot 10^{20}$ y. Recently, the additional isotopes ^{82}Se, ^{130}Te, ^{116}Cd and ^{76}Ge have become of interest to studies of the $2\nu\beta\beta$ decay to the 0_1^+ level too (see review [9]).

Theoretical estimates of the $2\nu\beta\beta$ decay to a 2^+ excited state have shown that for a few nuclei (^{82}Se, ^{96}Zr, ^{100}Mo, and ^{130}Te) the half-lives can be $\sim 10^{22}$–10^{23} y [4]. This would mean that the detection of such decays becomes possible using the present and new installations in the near future.

It is very important to note that in the framework of QRPA models the behaviour of nuclear matrix elements with g_{pp} parameter is completely different for transitions to the ground and excited (2^+ and 0^+) states [4,10]. This is why the decay to excited states may probe different aspects of the calculational method than the decay to the ground states. So, the search for $\beta\beta$ transitions to the excited states has its own special interest.

In this article, results of an experimental investigation of the $\beta\beta$ decay of ^{130}Te to the excited states in ^{130}Xe are presented. The decay scheme for the triplet ^{130}Te-^{130}I-^{130}Xe is shown in fig. 1. A search for $\beta\beta$ transitions of ^{130}Te to excited states in ^{130}Xe has been carried out using a germanium detector to look for γ-ray lines corresponding to the decay scheme.

2 Experimental

The experimental work has been performed in the Modane Underground Laboratory (depth of 4800 m w.e.). A set of TeO_2 powder samples with tellurium either enriched in ^{130}Te or natural was measured using two low-background HPGe detectors with volumes of 380 and 400 cm^3. Both Ge spectrometers are composed of p-type crystals. For

[a] e-mail: Alexander.Barabash@itep.ru

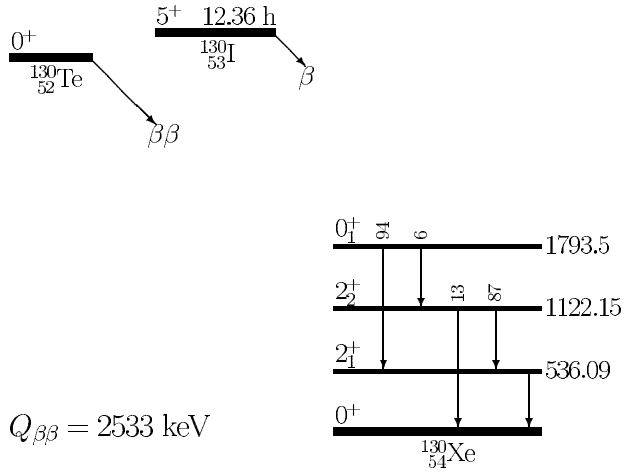

Fig. 1. Decay scheme of ^{130}Te. Energies of the levels are in keV, the relative intensities of γ-rays are in percentages.

Table 1. Information of TeO_2 powder measurements. The sample gives the weight of TeO_2 powder, HPGe is the volume of a Ge detector, η is the ^{130}Te content of a sample, t is the time of counting.

Sample (g)	HPGe (cm^3)	η(%)	t (h)
721.4	400	89.4	567.2
711.0	380	89.4	1192.7
698.0	380	89.4	385.8
587.8	380	89.4	666.0
1004.2	400	34.49	475.4

each HPGe detector the cryostat, the endcap and the main mechanical parts are made of very pure Al-Si alloy. The cryostat has a J-type geometry to shield the crystal from radioactive impurities in the dewar. The passive shielding for each detector is similar and consists of 4 cm of romantime lead and 3–10 cm of OFHC copper inside 15 cm of ordinary lead. To remove the ^{222}Rn gas, one of the main sources of the background, special effort is made to minimize the free space near the detector. In addition, the passive shielding has been enclosed in an aluminum box flushed with high-purity nitrogen.

The electronics consist of currently available spectrometric amplifiers and a 8192 channel ADC. The energy calibration is adjusted to cover the energy range from 50 keV to 3.5 MeV for all the detectors. The energy resolution is 1.8–2.0 keV for the 1332 keV line of ^{60}Co. The electronics were stable during the experiment due to the constant conditions in the laboratory (temperature of 23°C, hygrometric degree of 50%). A daily check on the apparatus assures that the counting rate is statistically constant.

Samples of TeO_2 powder were placed in delrin Marinelli boxes surrounding a HPGe detector. Table 1 presents details of these measurements. The most intensive γ-rays from the decay scheme (fig. 1) were used for analysis, *i.e.* the 536.1 keV γ-quantum for the 2_1^+ level, the 536.1 keV and 586.1 keV γ-quanta for the 2_2^+ level,

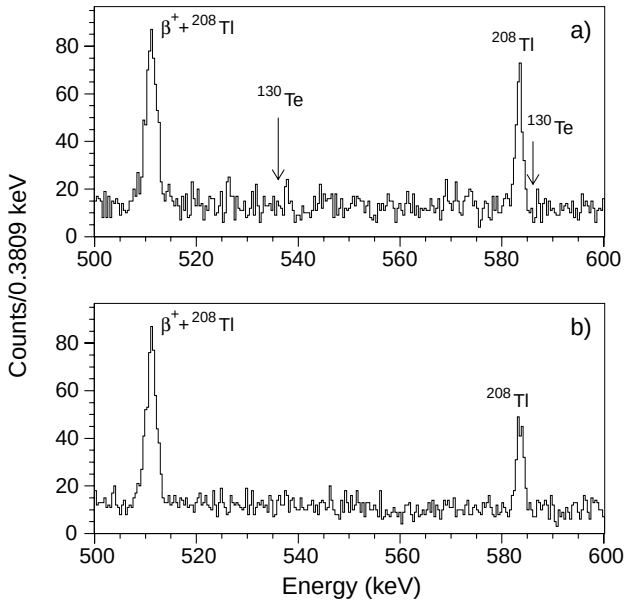

Fig. 2. a) Total γ-ray spectrum in the energy range of (500–600) keV. b) Background spectrum for the same time of measurement.

Table 2. Detection efficiencies (%) for γ-quanta of investigated excited states for every TeO_2 powder measurement. Here are presented the TeO_2 weight of the sample, the parameters of the excited states, and energies of γ-quanta, specified for every excited state. Last row shows quantities A (see text).

Sample	2_1^+	2_2^+		0_1^+	
	536.1	536.1	586.1	536.1	1257.4
721.4 g	4.51	3.32	3.21	3.76	2.10
711.0 g	3.91	2.98	2.84	3.35	1.86
698.0 g	3.88	2.96	2.88	3.34	1.85
587.8 g	3.76	2.86	2.74	3.16	1.74
1004.2 g	3.81	2.89	2.80	3.23	1.90
$A(10^{21}$ y)	22.1	16.7	16.1	18.8	10.5

the 536.1 keV and 1257.4 keV γ-quanta for the 0_1^+ level. The detection efficiencies for photopeaks corresponding to specified γ-quanta are given in table 2. The efficiencies have been computed with the CERN Monte Carlo code GEANT3.21. Special calibration measurements with radioactive sources and powders containing well-known ^{226}Ra activities confirmed that the accuracy of these efficiencies is about 10% for every detector.

3 Analysis and results

To analyze the $2\nu\beta\beta$ decay of ^{130}Te to excited states in ^{130}Xe, a sum of all spectra was made. The contribution of the $\beta\beta$ decay of ^{130}Te to a peak of a specified excited

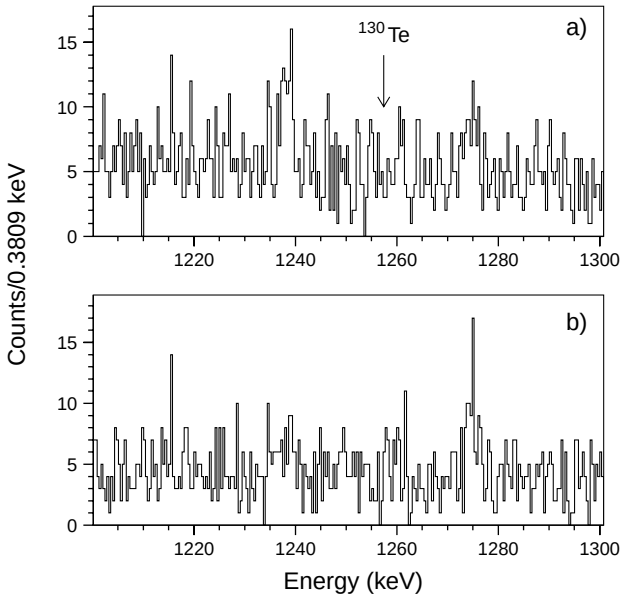

Fig. 3. a) Total γ-ray spectrum in the energy range of (1200–1300) keV. b) Background spectrum for the same time of measurement is shown below.

Table 3. Theoretical and experimental results for $\beta\beta$ decay of ^{130}Te. All limits are given at the CL = 90%.

Transition	$(T^{2\nu}_{1/2})_{\rm calc}$, y [4]	$(T^{0\nu+2\nu}_{1/2})_{\rm exp}$, 10^{21} y	
		this work	other works
$0^+ \to 0^+_{\rm g.s.}$	$2.6 \cdot 10^{20}$–$2.7 \cdot 10^{21}$		0.8 ([a]) [14]
			2.7 ([a]) [15]
$0^+ \to 2^+_1$	$3.0 \cdot 10^{22}$–$2.8 \cdot 10^{24}$	> 1.6	> 2.8 [16]
			> 97 ([b]) [17]
$0^+ \to 2^+_2$	$2.0 \cdot 10^{25}$–$1.0 \cdot 10^{28}$	> 2.7	–
$0^+ \to 0^+_1$	$5.1 \cdot 10^{22}$–$1.39 \cdot 10^{23}$ ([c])	> 2.3	> 25 [b] [17]

([a]) geochemical experiment.
([b]) only 0ν decay mode.
([c]) corrected values (see text).

state is defined by

$$N_{\rm peak} = \frac{\sum_i N_i t_i \varepsilon_i \ln 2}{T_{1/2}} = \frac{A}{T_{1/2}}\,, \qquad (1)$$

where the summation is over all measurements, N_i is the number of ^{130}Te atoms to expose, t_i is the counting time, ε_i is the peak detection efficiency, and $T_{1/2}$ is the half-life of the investigated transition. The quantities A which characterize contributions to peaks under study are given in table 2.

The total spectra for two specified energy ranges are shown in figs. 2a, 3a and the corresponding background spectra (for 3287 hours) in figs. 2b, 3b. As one can see, there are no statistically significant peaks at the pointed places. The lower half-life limits reported in table 3 have been calculated using the likelihood function technique described in the ref. [11,12]. Available data on $\beta\beta$ decay of ^{130}Te from other experimental works and theoretical estimates are presented also in table 3.

Our limits on $\beta\beta$ transitions of ^{130}Te to excited states of a daughter nucleus are valid for the 0ν and 2ν decay modes. As one can see from table 3, our results on transitions to the 2^+_2 (0ν and 2ν modes) and the 0^+_1 (2ν mode) levels of ^{130}Xe have been obtained for the first time. Here it is worth mentioning that theoretical half-lives for $2\nu\beta\beta$ decay to the 0^+_1 level cited in [4] are $\sim$ 200 times less than in table 3. This is related with the error value of the phase-space factor equal to $4.6 \cdot 10^{-20}$ y^{-1}, given in [4]. The corrected value is $2.35 \cdot 10^{-22}$ y^{-1} [13]. Using the new phase-space factor and nuclear matrix elements from [4], half-lives were recalculated and listed in table 3.

The sensitivity of such types of experiments could still be increased up to $\sim 10^{23}$ y by using larger Ge crystals (800–1000 cm^3) with lower background, and by investigating 5–10 kg of ^{130}Te during a few years. In that case there is a chance of detecting the $2\nu\beta\beta$ decay of ^{130}Te to the 0^+_1 level and possibly to the 2^+_1 level of ^{130}Xe. Even limits on these transitions at the level of $> 10^{22}$ y are useful because they allow the exclusion of essential contributions of these decay modes to the total decay rate of ^{130}Te from geochemical measurements.

The authors would like to thank the Modane Underground Laboratory staff for their technical assistance in running the experiment, and are very thankful to Prof. Jouni Suhonen (University of Jyväskylä, Finland) for useful discussion about phase-space factors. We are also very grateful to Michael Hornish (Duke University, USA) for his remarks.

References

1. H.V. Klapdor-Kleingrothaus, Nucl. Phys. B (Proc. Suppl.) **77**, 357 (1999).
2. A. Faessler, F. Šimcovic, J. Phys. G **24**, 2139 (1998).
3. P. Vogel, nucl-th/0005020.
4. J. Suhonen, O. Civitarese, Phys. Rep. **300**, 123 (1998).
5. A. S. Barabash, JETP Lett. **51**, 207 (1990).
6. A. S. Barabash *et al.*, Phys. Lett. B **345**, 408 (1995).
7. A.S. Barabash *et al.*, Phys. At. Nucl. **62**, 2039 (1999).
8. L. De Braeckeleer *et al.*, Phys. At. Nucl. **63**, 1214 (2000).
9. A.S. Barabash, Czech. J. Phys. **50**, 447 (2000).
10. M. Aunola, J. Suhonen, Nucl. Phys. A **602**, 133 (1996).
11. A.S. Barabash *et al.*, J. Phys. G **22**, 487 (1996).
12. A.S. Barabash *et al.*, Nucl. Phys. A **604**, 115 (1996).
13. J. Suhonen, private communication.
14. O.K. Manuel, J. Phys. G **17**, 221 (1991).
15. T. Bernatowicz *et al.*, Phys. Rev. C **47**, 806 (1993).
16. E. Bellotti *et al.*, Europhys. Lett. **3**, 889 (1987).
17. A. Alessandrello *et al.*, Phys. Lett. B **486**, 13 (2000).