ITEP-89-94

Fermilab Library
0 1160 0041648 1

INSTITUTE OF THEORETICAL
AND EXPERIMENTAL PHYSICS

FERMILAB 89-94

APR 24 1995

LIBRARY

A.S. Barabash, R. Gurriarán, F. Hubert, Ph. Hubert
J.L. Reyss, J. Suhonen and V.I. Umatov

Investigation of the $\beta\beta$ decay of ^{96}Zr to excited states in ^{96}Mo

MOSCOW 1994

УДК 539.165 М-16

INVESTIGATION OF THE $\beta\beta$ DECAY OF ^{96}Zr TO EXCITED STATES IN ^{96}Mo: Preprint ITEP 89-94/

A.S.Barabash[a], R.Gurriaran[b], P.Hubert[b], Ph.Hubert[b], J.L.Reyss[c], J.Suhonen[d], V.I.Umatov[a] - M., 1994 - 20p.

The two-neutrino mode of double beta decay ($2\nu\beta\beta$) of ^{96}Zr is investigated both theoretically and experimentally. The calculations, using the quasiparticle random phase approximation approach, show that for ^{96}Zr the detection of $2\nu\beta\beta$ transitions to the first two excited states in the daughter nuclide is possible in the very near future. On the experimental side, new, most stringent limits on half-lives for the double beta decay of ^{96}Zr to excited states in ^{96}Mo have been obtained with a 430 cm^3 "well-type" germanium detector. They range between $5 \cdot 10^{19}$ and $8 \cdot 10^{19}$ years (90% CL).

Fig. - 3, ref. - 32

© Институт теоретической и экспериментальной физики, 1994

[a] *Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russian Federation*

[b] *Centre d'Etudes Nucléaires, IN2P3-CNRS et Université de Bordeaux, F-33175 Gradignan Cedex, France*

[c] *Centre des Faibles Radioactivites, Laboratoire mixte CNRS/CEA, F-91198 Gif sur Yvette, France*

[d] *Department of Physics, University of Jyväskylä, P.O. Box 35, SF-40351 Jyväskylä, Finland*

1 Introduction

At the moment, the neutrinoless double beta decay ($0\nu\beta\beta$) is the best probe for physics beyond the standard model of electroweak interactions. Its existence connects with fundamental aspects of particle physics:

- 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, majoron;
- the structure of Higgs' sector;
- supersymmetry.

To date, only lower limits on half-lives ($T_{1/2}^{0\nu}$) of different nuclei have been obtained experimentally. These limits are used to deduce upper limits on the majorana-neutrino mass, the right-handed-current admixture parameter, the majoron-majorana neutrino coupling constant, etc. (see, for instance, [1]). One particular source of uncertainty in the above analyses is the evaluation of the nuclear matrix elements entering the theoretical expressions for these fundamental observables.

In connection with the $0\nu\beta\beta$ decay, the detection of double 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 double-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. These decays require the same basic many-body nuclear-structure wave functions combined with different transition operators. More exact calculations of nuclear matrix elements allow a more unambiguous extraction of the values of the relevant $0\nu\beta\beta$ observables mentioned above.

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. Right-handed currents, for instance, can be probed with the $0\nu\beta\beta$ decay to the first 2^+ state of the daughter nucleus, and the detection of such a transition would verify the existence of right-handed currents in electroweak interactions.

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 recently [2], 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 corresponding experiments were proposed, and the searches for such transitions in ^{100}Mo, ^{96}Zr and ^{150}Nd were performed in [3-6]. The highest sensitivity ($\sim 3 \cdot 10^{21}$ y) was reached for ^{100}Mo. In this case the weight of the sample was $\sim$1 kg, the enrichment 98.35%, the time of measurement $\sim$1 y, and the volume of the HPGe detector $\sim$100 cm^3. This sensitivity allowed one to detect the $2\nu\beta\beta$ decay of ^{100}Mo to the 0_1^+ state of ^{100}Ru ($T_{1/2} \sim 10^{21}$ y) [4]. In [6] new limits on half-lives ($\sim (1-4) \cdot 10^{19}$) for ^{96}Zr and ^{150}Nd were obtained, and the possibility to reach the sensitivity $\sim 10^{21}$ y was shown.

Up to now, the $2\nu\beta\beta$ decay to a 2^+ excited state has been considered to be strongly suppressed and practically inaccessible to detection [7,8]. However, it has been shown recently [9-11] that the suppression factor might not be so large, and for a few nuclei (^{136}Xe, ^{116}Cd, ^{82}Se, and ^{100}Mo) the half-lives for $(0^+ \rightarrow 2^+_1)$ transitions can be $\sim 10^{23}$ y. This would mean that the detection of such decays becomes possible using the present and new installations in the nearest future.

So the search for $\beta\beta$ transitions to the excited states has its own special interest. Theoretical calculations for transition probabilities to excited states are very important, too. On one hand, the calculations stimulate to perform new experiments, and on the other, the comparison between theoretical and experimental results allows to improve parameters of the theory and to develop different approaches to the theoretical description of $\beta\beta$ decay.

In this article results of theoretical and experimental investigations for the $\beta\beta$ decay of ^{96}Zr to excited states in ^{96}Mo are presented. The half-life for the transition to the ground state of the daughter nucleus has also been calculated. The decay scheme for the triplet ^{96}Zr - ^{96}Nb - ^{96}Mo [12] is shown in Fig. 1. Search for $\beta\beta$ transitions of ^{96}Zr to excited states in ^{96}Mo have been carried out with using a germanium detector to look for γ-ray lines corresponding to the decay scheme. The single β decay of ^{96}Zr is strongly suppressed due to large spin difference between the initial and final nuclei and due to small transition energy. Nevertheless, such decay is possible, and can be detected by looking for γ-rays accompanying the β decay in ^{96}Nb.

2 Theoretical estimates for the half lives

We have calculated the $2\nu\beta\beta$ decay rates of ^{96}Zr to the ground state (g.s.) and various excited states by using the quasiparticle random-phase approximation (QRPA) theory. The formalism adopted for the g.s. transitions is the one of

[13] whereas the calculation of the decay rates to one-phonon states and two-phonon states is discussed in [9,14,15] .

The virtual 1^+ states (1^+_m) of the intermediate odd-odd nucleus in the $2\nu\beta\beta$-decay matrix element [9]

$$M^{(2\nu)}_{\rm GT}(J^+_{\rm f}) = \frac{1}{\sqrt{s}} \sum_{m,m'} \frac{(J^+_{\rm f}\|\hat{\beta}^-\|1^+_{m'})\langle 1^+_{m'}|1^+_m\rangle(1^+_m\|\hat{\beta}^-\|0^+_i)}{[(\frac{1}{2}Q_{\beta\beta}(J^+_{\rm f}) + E(1^+_m) - M_i)/m_{\rm e} + 1]^s} \quad , \tag{1}$$

are calculated using the proton-neutron QRPA (pnQRPA) approach of [16] whereas the excited final states $J^+_{\rm f} = 0^+_1, 2^+_1, 2^+_2$ are described within the charge-conserving QRPA framework [17] . In the displayed reduced matrix elements of (1) the operator $\hat{\beta}^-$ is the usual Gamow–Teller operator [16] and $s = 1 + 2\delta_{J_{\rm f}2}$. Furthermore, $Q_{\beta\beta}(J^+_{\rm f})$ denotes the $2\nu\beta\beta$-decay Q value taking into account the excitation energy of the final state $|J^+_{\rm f}\rangle$ and $E(1^+_m) - M_i$ the energy difference between the mth intermediate 1^+ state and the initial ground state. Two different sets of 1^+ states emerge from the pnQRPA calculation, namely one for the initial nucleus (1^+_m) and the other for the final nucleus $(1^+_{m'})$. The matching of these two sets of states is simulated by the overlap [13] $\langle 1^+_{m'}|1^+_m\rangle$ in (1).

The calculations have been performed in a single-particle basis set consisting of the $N = 3$ and $N = 4$ major oscillator shells supplemented with the $N = 5$ intruder orbital $1h_{9/2}$ for both protons and neutrons. The single-particle energies were obtained from a Coulomb-corrected Woods–Saxon potential [18] and a subsequent BCS calculation was performed for the initial (^{96}Zr) and final (^{96}Mo) nuclei exploiting two-body matrix elements obtained from the Bonn potential [19] using G-matrix techniques. The emerging quasiparticle energies were compared with the low-energy spectra of the neighboring odd nuclei to see how the Woods–Saxon basis works for ^{96}Zr and ^{96}Mo. For ^{96}Mo the Woods–Saxon energies are satisfactory but a slight energy shift was adopted for $2s_{1/2}$ neutron orbital as well as for $1p_{1/2}$ and $0g_{9/2}$ proton orbitals in the case of ^{96}Zr. At the same time the proton and neutron pairing strength [16]

was adjusted to reproduce the semiempirical pairing gaps obtained from the tabulated proton and neutron separation energies [20] of the odd nuclei adjacent to ^{96}Zr and ^{96}Mo.

The proton-proton, neutron-neutron and proton-neutron two-body G matrix elements needed in the QRPA calculation are scaled [14,16] using the experimental excitation energy of the first 2^+ state in ^{96}Mo and the semiempirical location of the Gamow–Teller giant resonance in ^{96}Nb. The particle-particle interaction strength [13,16] , g_{pp}, is left as a free parameter[†] and its most probable value has to be obtained by other means. We have chosen the value $g_{pp} \approx 1.0$ based on previous analyses [13,16,21] and the study of the $A = 98$ transition ^{98}Nb$(1_1^+) \rightarrow$ ^{98}Mo(g.s.), for which the QRPA reproduces the experimental $\log ft$ of 4.5 [22] in the vicinity of $g_{pp} \approx 1.0$.

The above ^{98}Nb(1_1^+) decay is the only known 1_1^+ decay close to the region of interest, and the measured $\log ft$ values of transitions to the various excited final states J_f^+ of ^{98}Mo can be used as a rough check of the calculated nuclear matrix elements for single beta decay transitions to excited states. These decay transitions, in turn, being an essential part of the $2\nu\beta\beta$ decay matrix element, are in a position to supply rough estimates of the magnitude of the nuclear matrix elements concerning $2\nu\beta\beta$ decay transitions to excited final states.

After fixing the value of the strength parameter g_{pp} in the above-described manner one may obtain, in principle, a definite theoretical prediction for the g.s. transition although the magnitude of the g.s. matrix element varies rather strongly in the vicinity of $g_{pp} = 1.0$ [1,13,16,21,23] . A more unambiquous observable for the g.s. transition is the maximum value of the matrix element (in this case 0.53) and the corresponding minimum decay half life ($2.0 \cdot 10^{17}$y). Contrary to the g.s. transition, the matrix elements corresponding to transitions to excited one- and two-phonon states are rather insensitive to the value

[†] The value of g_{pp} could, in principle, be fixed by the beta decay ^{96}Nb$(1_1^+) \rightarrow$ ^{96}Mo(g.s.) (as in the case of ^{100}Mo, see [11]) but no experimental data about this transition exists.

of g_{pp} [9,15] and thus allow for a more unique prediction of the half lives for these transitions. This is the case also in the present calculation.

To improve the accuracy of the half-life computation the energy of the first intermediate 1^+ state, $E(1_1^+)$ in the energy denominator of eq. (1), has usually been normalized to experiment, e.g. in [9,15] . In the present case there is no experimental information about the location of 1^+ states in ^{96}Nb. This introduces an uncertainty into the present calculation since in the pnQRPA formalism it is not possible to predict accurately the 1^+ energies of the odd-odd nucleus relative to the adjacent even-even ground state. In view of this we have allowed the excitation energy of the first 1^+ state in ^{96}Nb to vary between 0.0 and 1.0 MeV. This variation affects particularly strongly the transitions to 2^+ states due to the third power, $s = 3$, in the energy denominator of eq. (1). The variation of the 1^+ energy reflects upon the values of the various matrix elements and the corresponding half lives as seen in Table 2.

3 Experimental setup

We have got the possibility to use a 430 cm^3 "well-type" HPGe detector [24] to study γ radiation resulting from $\beta\beta$ decay to excited states of ^{96}Mo and β decay of ^{96}Zr. Due to larger acceptance in solid angle, the detector with a sample inside the well is a few times more efficient for single γ-rays than conventionally shaped detectors of the same volume where samples are directly laid on the endcap cylinder. However, the well-type crystals are not widely used because they are known to have several shortcomings: - loss of about 10% in resolution, - a limitation to sample volume in the well, - for a cascade of a few γ-rays the efficiency decreases for every γ-line because of the superimposition of γ-ray signals. But for the most probable cases the $\beta\beta$ decay to the excited states is accompanied by not more two γ-rays only, and the probability of simultaneous full absorption of two γ-rays is high enough

for well-type detectors, that one may used for data analysis. The well size is large enough: Ø1.5 cm × 10 cm, with total volume of the well equal to 17.7 cm^3.

The installation was specially designed for low-background measurements in environmental studies. The Ge crystal was mounted in a special low-background cryostat admitting the shielding of the Ge crystal from possible radioactive impurities of the dewar. The endcap, the crystal holder and other metallic parts were made of very high-purity aluminium-(4%) silicon alloy.

The setup was located in the Fréjus Underground Laboratory. The shielding thickness of 4800 m w.e. reduces the cosmic radiation effectively. For shielding from external background, coming from the rock and air, the detector was surrounded by 10 – 15 cm of OFHC copper and then 15 cm of ordinary lead. To remove radon gas from the inner cavities of the shield, a continuous sweeping of the detector by nitrogen gas was adopted, the gas going from liquid nitrogen cryostat through a special hole in the copper shield to the aluminium endcap. In addition, a strong air ventilation keeps a constant low Rn activity of 50 Bq/m^3 in the Fréjus Underground Laboratory.

Within these experimental conditions the background counting rate of the detector is 0.5 count/min in the energy range from 30 keV to 3000 keV. The energy resolution is 2.35 keV on 1332 keV line of ^{60}Co.

Our $\beta\beta$ source consisted of a 18.74 g sample of ZrO_2 powder, contained in a plastic bag. The bag was rolled with close packing and was placed in the well of the detector. The isotopic abundance of ^{96}Zr is 57.3%, whereas the natural abundance is 2.8%. Approximately $5.1 \cdot 10^{22}$ nuclei of ^{96}Zr were exposed to detection. The time of measurement was only 19.4 days.

4 Analysis and results

The total energy spectrum for ZrO_2 sample is shown in fig. 2. All the γ-ray lines have been identified and compared with detector background activities. Different activities in our sample have been evaluated by taking into account efficiencies for γ-lines of isotopes identified. The efficiencies have been calculated according to experimental efficiency curve and experimental values from special calibration measurements. The main detector background comes from natural ^{40}K, radioactive chains of ^{232}Th and ^{238}U, man-made and/or cosmogenic activities of ^{137}Cs and ^{60}Co. The sample has been found to have small radioactive impurities of ^{40}K (1.2 Bq/kg), ^{241}Am (0.05 Bq/kg) and ^{235}U (5.0 mBq/kg).

Fig. 3 shows in more detail parts of the energy spectrum corresponding to γ-lines of the first excited states in ^{96}Mo. Here the summed peak of two γ-rays from the 0_1^+ level are presented too, because its detection efficiency is compatible with single γ-ray lines (see Table 1). No peaks signaling about $\beta\beta$ decay or usual β decay of ^{96}Zr have appeared at energies corresponding to transitions to the excited states in ^{96}Mo.

The corresponding limits for transitions being investigated have been obtained using the likelihood function, which is the product of probabilities for spectrum bins to have their numbers of events. Every bin of the spectrum is considered to affect Poisson distribution with mean value equal to sum of background and contributions of γ-lines. The detector response function for a γ-line is taken to be of gaussian form. which is enough for low-background measurements, but one may use any shape. Background is a straight line fit in the range of peak position $\pm$ 30 standard deviations with rejecting bins under the peak. In our analysis background is supposed to be known with a negligible error. In that case the likelihood function can be written as

$$L(X) = \prod_i \frac{\mu_i^{n_i}}{n_i!} e^{-\mu_i}, \quad \mu_i = X \sum_m \varepsilon_m p_{mi} + b_i \tag{2}$$

where X is the number of transitions under study, ε_m is the detection efficiency of the mth γ-line of transition investigated, p_{mi} is the contribution of the mth γ-line to the ith bin, and b_i is the background for the ith bin. Normalizing $L(X)$ to 1 one has obtained the probability density function used to calculate limits for X at any confidence level [25–27].

Table 1 presents some limits on $\beta\beta$-decay transitions of ^{96}Zr to excited states in ^{96}Mo, calculated by using single γ-lines or sets of γ-lines. As a rule, the use of a set of γ-lines corresponding to one transition investigated gives better limits for the number of transitions, because in that case more information about the spectrum is utilized.

As to the single β-decay of ^{96}Zr, the situation is not very good because the subsequent β-decay of ^{96}Nb gives three or more γ-rays simultaneously, leading to strong decreasing detection efficiencies for γ-ray lines, which is the result of a very large probability for one γ-ray interaction in the Ge crystal (50-70%, depending on energy). The best limit on the half-life of the β-decay of ^{96}Zr from our spectrum is $2.6 \cdot 10^{19}$ y, which is slightly less stringent than the value given in [6] (see Table 2).

5 Discussion

Table 2 represents our theoretical and experimental results, and the best up to date experimental results of other experiments.

The uncertainty in the calculated nuclear matrix elements and, consequently, in expected half-lives is due to the variation of one parameter in the pnQPRA calculation - the excitation energy of the first 1^+ state in ^{96}Nb - between 0 and 1 MeV. It should be noted that the magnitude of the 0_1^+ matrix element is approximately one third of the magnitude of the g.s. matrix element. This result differs from the situation encountered in ^{100}Mo (experimental [4,28] and theoretical [11,29] numbers) and ^{116}Cd [30] where these

matrix elements seem to have roughly the same magnitude. The validity of the present result can be tested, to some extent, by comparing the observed ^{98}Nb(1_1^+) $\rightarrow$ ^{98}Mo(0_1^+) decay rate (logft=5.5) with the calculated one (logft=5.3). On one hand, this comparison is meaningful since most of the contribution to the $2\nu\beta\beta$ matrix element comes from the lowest 1^+ state (that is why also the location of the first 1^+ state in the intermediate nucleus should be known rather well), but on the other hand, due to the special level structure of ^{98}Mo (0_1^+ state falls below the 2_1^+ state), no strong claims can be made on basis of this comparison.

As to the $2\nu\beta\beta$ decay of ^{96}Zr to the ground state of ^{96}Mo, one can compare our expectation for its half-life with calculations of other authors: $T_{1/2}^{2\nu} = 8.5 \cdot 10^{18}$ y [1] and $T_{1/2}^{2\nu} = 1.08 \cdot 10^{19}$ y [23]. It has to be noted that our calculation, as well as the other calculations mentioned above, suffer from the same uncertainty: the rather strong variation of the ground-state matrix element as a function of the particle-particle interaction strength, g_{pp}, in the region of physical interest. By slight variation of this parameter around its most probable value a wide range of decay half lives can be achieved. This property decreases the predictive power of the theory in the case of ground-state transitions.

Fortunately, as mentioned in ch. 2, the predictive power of the theory is better for the decay half-lives of the excited-state transitions. For these transitions the theoretical half-lives vary only very little in the physical region of g_{pp}.

The best experimental limit for the ground-state transition, $T_{1/2}^{2\nu} = 1 \cdot 10^{17}$ y [31], does not contradict the above-mentioned theoretical half-life estimates. At the same time the work [32] tells about the observation of $2\nu\beta\beta$ decay of ^{96}Zr in geochemical experiment with $T_{1/2}^{2\nu} = (3.9 \pm 0.9) \cdot 10^{19}$ years. However, this result needs a more careful check and confirmation as authors cannot explain the excess of ^{98}Mo (along with ^{96}Mo) and do not discuss effects connected

with warm neutron capture which must lead to a large excess of ^{95}Mo, not observed in the experiment. Thus, from our point of view, the question about the observation of this decay is still open.

As one can see, our experimental limits on $\beta\beta$ transitions of ^{96}Zr to the first four excited states in ^{96}Mo exceed the previous ones [6] by a factor of about two. It should be noted that the time of measurement in [6] is 5.4 times more than in our experiment, for a detector volume less than 25% of our one. So the detector with a well gives a higher sensitivity for such transitions where there are one or two γ-rays involved.

Comparison of experimental results with theoretical ones shows that to detect $2\nu\beta\beta$ decay of ^{96}Zr to the 0_1^+ excited state of ^{96}Mo, it is necessary to increase the experimental sensitivity up to $(2-3)\cdot 10^{21}$ years. It may be achieved by increasing the isotope mass up to 100 g and measuring time up to 1 year. Practically the same sensitivity would be obtained if one surrounded a Ge detector of the present volume by $30-40$ kg of natural zirconium with very low content of radioactive impurities.

One should note the perspective, implied by the theoretical results, for search of $2\nu\beta\beta$ decay of ^{96}Zr to the 2_1^+ excited state of ^{96}Mo. For this the well-type Ge detector suits better because of high efficiency for one γ-ray, and necessity to select these transitions from data full of more probable $0^+ \to 0_1^+$ transitions.

6 Conclusion

Improved experimental limits on $2\nu\beta\beta$ decay of ^{96}Zr to excited states in ^{96}Mo have been obtained. The corresponding theoretical half-lives have been calculated with the QPRA model. It is shown that $2\nu\beta\beta$ decay of ^{96}Zr to the 0_1^+ state in ^{96}Mo could be detected with modern low-background HPGe detectors, larger samples and statistical times, leading to sensitivities up to $(2-3)\cdot 10^{21}$

years. Theoretical estimate shows that it is possible to detect the $0^+ \rightarrow 2_1^+$ transition also.

Table 1

Experimental limits ($T_{1/2}^{0\nu+2\nu}$) on the half-lives for $\beta\beta$ decay of ^{96}Zr to excited states in ^{96}Mo, calculated using different sets of γ-lines corresponding to these transitions. E_x is the level energy, ε denotes the γ-line efficiency. Limits are given at the confidence level CL=90%.

Transition	E_x (keV)	γ-lines (keV)	ε (%)	$T_{1/2}^{0\nu+2\nu}$ (10^{19}y)
$0^+ \rightarrow 2_1^+$	778.2	778.2	20.4	7.9
$0^+ \rightarrow 0_1^+$	1147.9	369.7	13.7	4.2
		778.2	5.90	2.3
		1147.9	7.54	1.8
		369.7 + 778.2		6.1
		369.7 + 778.2 + 1147.9		6.8
$0^+ \rightarrow 2_2^+$	1497.8	719.6	5.93	2.7
		778.2	5.37	2.1
		1497.8	6.87	2.7
		719.6 + 778.2		4.4
		719.6 + 778.2 + 1497.8		6.1
$0^+ \rightarrow 2_3^+$	1625.9	778.2	7.56	2.9
		847.7	6.74	2.6
		1625.9	4.55	1.6
		778.2 + 847.7		5.1
		778.2 + 847.7 + 1497.8		5.4

Table 2

The calculated nuclear matrix elements ($M^{2\nu}_{GT}$), corresponding expectations for the half lives ($(T^{2\nu}_{1/2})_{calc}$) and experimental results for $\beta\beta$ decay of ^{96}Zr. Limits on the β decay of ^{96}Zr are presented in the last row. All limits are given at the CL=90% with exception of that marked [b], which has CL=68%.

Transition	$M^{2\nu}_{GT}$	$(T^{2\nu}_{1/2})_{calc}$, (y)	$(T^{0\nu+2\nu}_{1/2})_{exp}$ (10^{19} y)	
			our work	other works
$0^+ \to 0^+_{g.s.}$	$0.12 - 0.31$	$5.8 \cdot 10^{17} - 3.9 \cdot 10^{18}$	–	(3.9 ± 0.9) [a]
				> 0.01 [b]
$0^+ \to 2^+_1$	$0.0046 - 0.038$	$3.3 \cdot 10^{19} - 2.2 \cdot 10^{22}$	> 7.9	> 4.1 [c]
$0^+ \to 0^+_1$	$0.040 - 0.10$	$2.1 \cdot 10^{20} - 1.3 \cdot 10^{21}$	> 6.8	> 3.3 [c]
$0^+ \to 2^+_2$	$0.00064 - 0.0091$	$5.1 \cdot 10^{23} - 1.0 \cdot 10^{26}$	> 6.1	> 2.5 [c]
$0^+ \to 2^+_3$	–	–	> 5.4	> 3.3 [c]
β-decay	–	–	> 2.6	> 3.8 [c]

[a] Geochemical experiment, [32] (see discussion in the text)

[b] 2ν decay mode, taken from ref. [31]

[c] Taken from ref. [6]

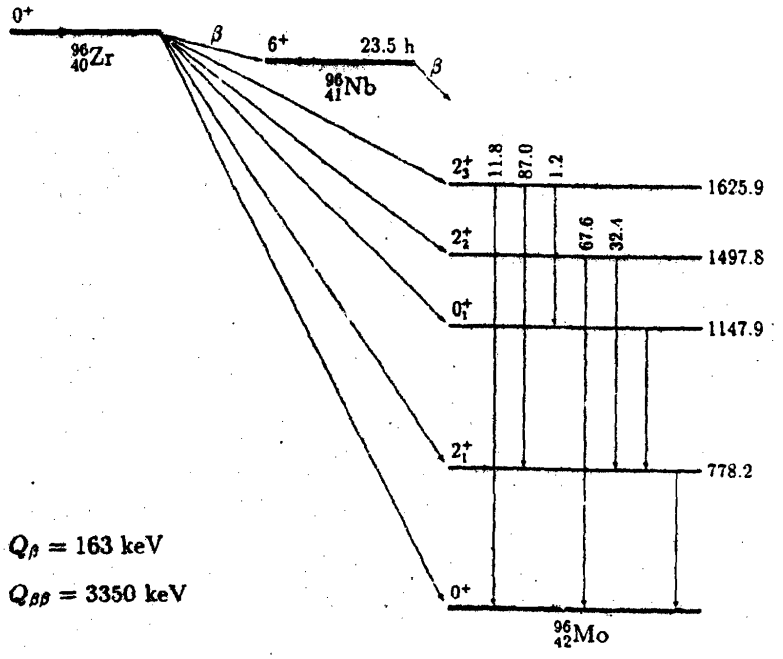

Fig. 1. Level scheme for the triplet of ^{96}Zr – ^{96}Nb – ^{96}Mo. Energies are denoted in keV, the relative γ-ray intensities are given in percents.

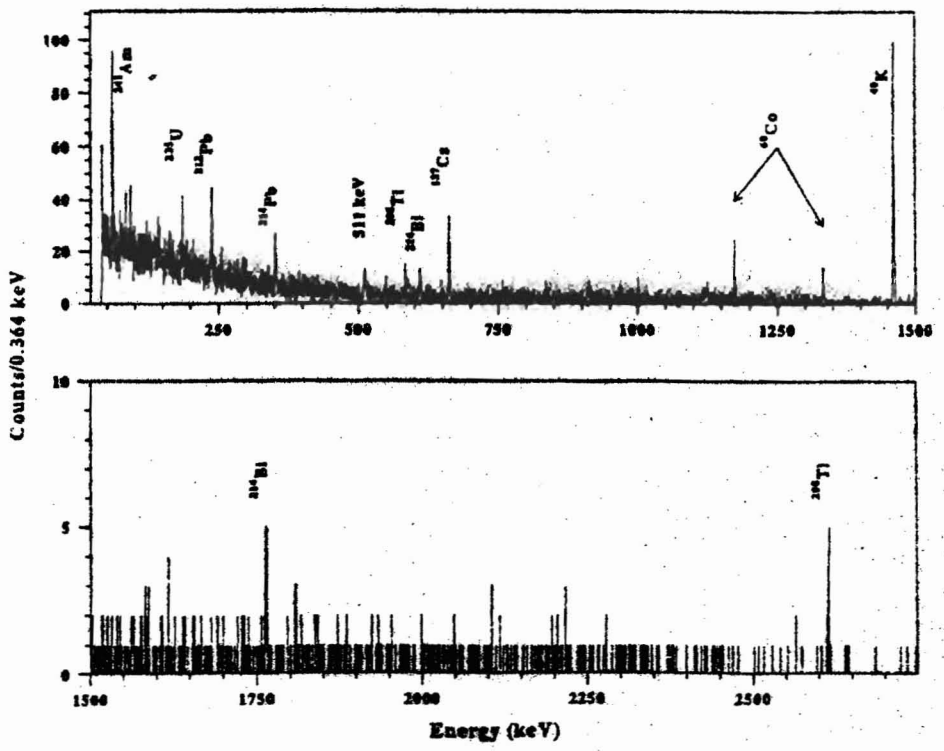

Fig. 2. The total energy spectrum recorded with ZrO_2 powder sample in 19.4 days.

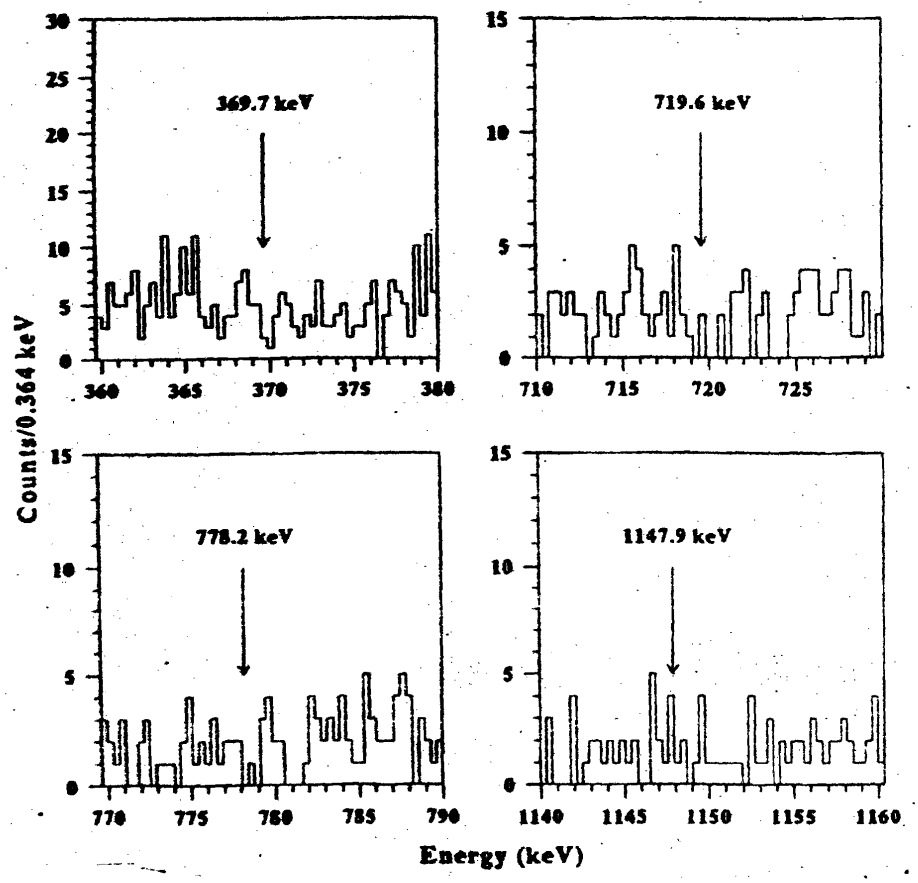

Fig. 3. Partial γ-ray spectra in the energy ranges corresponding to decays of first excited states in ^{96}Mo. The arrows indicate the expected γ-line positions for some transitions: 369.7 keV ($0_1^+ \rightarrow 2_1^+$), 719.6 keV ($2_2^+ \rightarrow 2_1^+$), 778.2 keV ($2_1^+ \rightarrow 0_{g.s.}^+$), 1147.9 keV (the summed peak for 0_1^+ level).

References

[1] M. Moe and P. Vogel, preprint UCI-NEUTRINO 94-5, February 1994, Ann. Rev. Nucl. Part. Sci. (submitted).

[2] A.S. Barabash, JETP Lett. 51 (1990) 207.

[3] A.S. Barabash, A.V. Kopylov and V.I. Cherebovsky, Phys. Lett. B 249 (1990) 186.

[4] A.S. Barabash, F.T. Avignone III, C.K. Guerard, R.L. Brodzinski, H.S. Miley, J.H. Reeves and V.I. Umatov, Proc. 3rd Int. Symp. on weak and electromagnetic interactions in nuclei, Dubna 1992, ed. Ts.D. Vylov (World Scientific, Singapore, 1993) p. 582.

[5] D. Blum, J. Busto, J.E. Campagne, D. Dassié, F. Hubert, Ph. Hubert, M.C. Isaac, C. Izac, S. Jullian, V.N. Kouts, B.N. Kropivyansky, D. Lalanne, T. Lamhamdi, F. Laplanche, F. Leccia, I. Linck, C. Longuemare, P. Mennrath, F. Natchez, F. Scheibling, G. Szklarz, V.I. Tretyak and Yu.G. Zdesenko, Phys. Lett. B 275 (1992) 506.

[6] C. Arpesella, A.S. Barabash, E. Bellotti, C. Brofferio, E. Fiorini, P.P. Sverzellati and V.I. Umatov, Europhys. Lett. 27 (1994) 29.

[7] W.C. Haxton and G J. Stephenson, Jr., Part. Nucl. Phys. 12 (1984) 409. 7

[8] M. Doi, T. Kotani and E. Takasugi, Prog. Theor. Phys. Suppl. 83 (1985) 1.

[9] J. Suhonen and O. Civitarese, Phys. Lett. B 308 (1993) 212.

[10] S. Stoica, Phys. Rev. C 49 (1994) 2240.

[11] J. Suhonen and O. Civitarese, Phys. Rev. C 49 (1994) 3055.

[12] Nuclear Data Sheets 68 (1993) 165.

[13] O. Civitarese, A. Faessler and T. Tomoda, Phys. Lett. B 194 (1987) 11.

[14] J. Suhonen, Nucl. Phys. A 563 (1993) 91.

[15] O. Civitarese and J. Suhonen, Nucl. Phys. A 575 (1994) 251.

[16] J. Suhonen, T. Taigel and A. Faessler, Nucl. Phys. A 486 (1988) 91.

[17] D. J. Rowe, Nuclear collective motion (Methuen, London, 1970).

[18] A. Bohr and B. R. Mottelson, Nuclear structure, vol. 1 (Benjamin, New York, 1969).

[19] K. Holinde, Phys. Reports 68 (1981) 121.

[20] G. Audi and A. H. Wapstra, Nucl. Phys. A 565 (1993) 1.

[21] O. Civitarese, A. Faessler, J. Suhonen and X. R. Wu, Nucl. Phys. A 524 (1991) 404.

[22] C.M. Lederer and V.S. Shirley, Table of isotopes, 7th Ed. (Wiley, New York, Chichester, Brisbane, Toronto, 1978).

[23] A. Staudt, K. Muto and H.V. Klapdor-Kleingrothaus, Europhys. Lett., 13 (1990) 31.

[24] J.L. Reyss, S. Schmidt, F. Legeleux and Ph. Bonté, Journees de Spectrometrie Gamma et X 93, Oct. 93, note CEA 2756 (1993).

[25] O. Helene, Nucl. Instr. and Meth. 212 (1983) 319.

[26] O. Helene, Nucl. Instr. and Meth. A 300 (1991) 132.

[27] V.F. Obraztsov, Nucl. Instr. and Meth. A 316 (1992) 388.

[28] NEMO collaboration, Nucl. Phys. B (Proc. Suppl.) 35 (1994) 369.

[29] A. Griffiths and P. Vogel, Phys. Rev. C 46 (1992) 181.

[30] A. Piepke, M. Beck, J. Bockholt, D. Glatting, G. Heusser, H.V. Klapdor-Kleingrothaus, B. Maier, F. Petry, U. Schmidt-Rohr, H. Strecker, M. Völlinger, A.S. Barabash, V.I. Umatov, A. Müller and J. Suhonen, Nucl. Phys. A 577 (1994) 493.

[31] A.S. Barabash, O.K. Egorov, A.A. Klimenko, E.D. Kolganova, E.A. Pozharova, T.Yu. Skorodko, V.A. Smirnitsky and A.A. Smolnikov, Institute of Experimental and Theoretical Physics, preprint ITEP 131-90 (1990).

[32] A. Kawashima, K. Takahashi and A. Masuda, Phys. Rev. C 47 (1993) 2452.