A possibility for experimentally observing two-neutrino double beta decay

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The half-lives for the decay of ^{100}Mo, ^{96}Zr, and ^{150}Nd by the $2\beta(2\nu)$ channel to the $O^+{}_1$ excited level of the daughter nuclei are estimated ($\sim 10^{20}$–2×10^{21} yr). These decays could be detected at existing low-background installations. Some corresponding experiments are proposed.

The search for 2β decay to excited levels of daughter nuclei is being carried out for the most part as an incidental part of the search for 2β decay to the ground level. In only a few studies have these transitions been the actual goal of the search.[1–5] The energy of the 2β transition in this case is lower than that of the transition to the ground level, so the branching ratio is also much lower. A search for 2β decay to excited levels has thus not inspired any particular optimism among experimentalists.

In the present paper we show that despite all this, it might be possible to detect the $2\beta(2\nu)$ decay of ^{100}Mo, ^{96}Zr, and the ^{150}Nd to the O_1^+ excited level of daughter nuclei at existing low-background installations through the use of Ge detectors.

The detection of $2\beta(2\nu,O^+ - O_1^+)$ transitions would obviously give us the same type of information about $2\beta(2\nu)$ decay as the detection of $2\beta(2\nu)$ transitions to the O^+ ground state of the daughter nuclei. From the standpoint of the size of the phase volume, there is interest in transitions of low-lying O_1^+ levels. An analysis has shown that among all known candidates the most suitable nuclei are ^{100}Mi, ^{96}Zr, and ^{150}Nd, whose $2\beta(O^+ - O_1^+)$ transitions have energies of 1902.6, 2202.1, and 2627 keV, respectively. What decay half-lives would we expect for these $2\nu(O^+ - O_1^+)$ transitions? Since there are no theoretical estimates in the literature (and even if there were, they would not be accurate enough to help), we will estimate these values from the existing experimental data on $2\nu(O^+ - O^+)$ decay.

^{100}Mo–^{100}Ru (O_1^+; 1130.4 keV). In this case the energy of the $2\beta(2\nu;O^+ - O_1^+)$ transition is 1902.6 keV. Klimenko *et al.*[6] have reported observing a positive effect in a search for the $2\beta(2\nu,O^+ - O^+)$ decay of ^{100}Mo (the energy of the 2β transition is 3033 keV). Attributing the entire observed $2\beta(2\nu;O^+ - O^+)$ to the decay of ^{100}Mo, they found[1)] $T_{1/2} = 3.3^{+2}_{-1}\times10^{18}$ yr. Assuming that the nuclear matrix elements of the two transitions are equal, and taking into account the difference between phase volumes, we find a prediction of the decay half-life of ^{100}Mo for the $(2\nu;O^+ - O_1^+)$ mode: $T_{1/2}\approx(4-9)\times10^{20}$ yr. Taking note[1)] into account, we find $T_{1/2}\approx(0.6-1.8)\times10^{21}$ yr.

An excess number of events from ^{100}Mo in the vicinity of the $(2\nu;\ O^+ - O^+)$ mode was also observed in Ref. 7. If the entire excess is attributed to the

$2\beta(2\nu;0^+ - 0^+)$ decay of ^{100}Mo, the value $T_{1/2} = 7\times10^{18}$ yr is found. For the transition $2\beta(2\nu;0^+ - 0_1^+)$ we then find $T_{1/2} \approx 1.2\times10^{21}$ yr.

A corresponding analysis based on the results for ^{76}Ge $\times[T_{1/2}(2\nu;0^+ - 0^+) = 8.6^{+2.6}\times10^{20}$ yr][2] leads to the following estimate for the $2\beta(2\nu;0^+ - 0_1^+)$ decay of ^{100}Mo: $T_{1/2} \approx (1.5-2)\times10^{21}$ yr.

The half-life for the decay of ^{100}Mo by the channel $2\beta(2\nu;0^+ - 0_1^+)$ would thus be expected to be $\sim(0.6-2)\times10^{21}$ yr.

^{96}Zr–^{96}Mo (0_1^+; 1147.9 keV). In this case the energy of the $2\beta(2\nu;0^+ - 0_1^+)$ decay is 2202.1 keV and even larger than that detected in the ^{76}Ge $2\beta(2\nu;0^+ - 0^+)$ decay ($E_{2\beta} = 2041$ keV). Assuming that the nuclear matrix elements of these transitions are equal, and allowing for the difference in phase volumes, we find a prediction for the $2\beta(2\nu;0^+ - 0_1^+)$ decay of ^{96}Zr: $T_{1/2} \approx (3-4)\times10^{20}$ yr.

A corresponding estimate based on results[6,7] for ^{100}Mo yields $T_{1/2} \approx (1-3.6)\times10^{20}$ yr for the $2\beta(2\nu;0^+ - 0_1^+)$ decay of ^{96}Zr.

^{150}Nd–^{150}Sm(0_1^+; 740.4 keV). In this case the energy of the $2\beta(2\nu;0^+ - 0_1^+)$ transition is 2627 keV and higher than the energy of the $2\beta(2\nu;0^+ - 0^+)$ ^{130}Te – ^{130}Xe transition ($E_{2\beta} = 2533$ keV), for which a positive effect has been detected in geochemical experiments[9,10]: $T_{1/2} = (0.5-2.75)\times10^{21}$ yr. We might thus expect $T_{1/2} = (2\nu;0^+ - 0_1^+) \approx (0.3-1.8)\times10^{21}$ yr for ^{150}Nd. For the half-life of the transition to the 0_2^+ (1255.5 keV) state of ^{150}Sm ($E_{2\beta} = 2111.5$ keV) we find the estimate $T_{1/2} \approx (0.4-2)\times10^{22}$ yr. In the case of ^{150}Nd, it would be more correct to make the comparison with specifcially ^{130}Te, because the values of A and Z are approximately the same.

In the 2β decay to the 0_1^+ excited level of a daughter nucleus, the excitation energy is carried off through the emission of two cascade γ rays with definite energies. These transitions could thus be observed either by detecting one γ ray of the cascade or by using a coincidence arrangement, with different detectors detecting both of the cascade γ rays.

We need to particularly stress here that in the case of a search for the $2\beta(2\nu)$ decay to excited states of daughter nuclei we are dealing with (in this formulation of the experiment) the detection of a line with a strictly fixed energy, not the distributed spectrum that we would be dealing with in a search for a transition to the 0^+ ground state of the daughter nucleus. The high energy resolution of Ge detectors would thus provide a high sensitivity to the $2\beta(2\nu)$ decay to excited states—a sensitivity which would be sufficient (as we will show below) for the detection of $2\beta(2\nu;0^+ - 0_1^+)$ transition in ^{100}Mo, ^{96}Zr, and ^{150}Nd.

A detailed analysis of the background level which has been reached at existing low-background installations was carried out in Ref. 11. The lowest background index which has been achieved was that of the apparatus of F. T. Avignone *et al.* That apparatus is an HP Ge detector with a volume of 202 cm^3 surrounded by many layers of passive shielding,[12] installed at a depth of 1438 m. The background in the vicinity of the energy 539.59 keV [which corresponds to the energy of one of the γ rays emitted in the $2\beta(2\nu;0^+ - 0_1^+)$ decay of ^{100}Mo] was ~3.7 events/(keV·yr). If a detector of that sort were surrounded with test sample (e.g., 1 kg of ^{100}Mo, which is available at the Institute of Theoretical and Experimental Physics), and if measurements were carried out for a year, then the sensitivity to the $2\beta(2\nu;0^+ - 0_1^+)$ decay would be $\sim 2\times 10^{22}$ yr (over 2000 h of measurements, $\sim 10^{22}$ yr). Roughly the same sensitivity would be achieved in a search for the $2\beta(2\nu;0^+ - 0_1^+)$ decay[3)] of ^{96}Zr and ^{150}Nd. A similar sensitivity level might be achieved with the apparatus of Caldwell *et al.*[13] in coincidence measurements (this point is discussed in more detail in Ref. 11). Comparing our estimate of the sensitivity with the predictions of $T_{1/2}$ for these isotopes, we reach the unambiguous conclusion that with existing low-background installations it would be possible to detect the two-neutrino double β decay of ^{100}Mo, ^{96}Zr, and ^{150}Nd to the 0_1^+ excited level of the daughter nuclei.

We thus propose a series of experiments to detect $2\beta(2\nu;0^+ - 0_1^+)$ decay of ^{100}Mo, ^{96}Zr, and ^{150}Nd at existing low-background installations. A positive effect might also be found in a study of samples of natural isotopic mixtures, since in this case it would be possible to use samples of a large mass (up to 5–10 kg, or up to 40–50 kg at multiple-crystal installations).

[1)] Some of the effect is due to background events, and the actual decay half-life may be longer by a factor of 1.5–2.

[2)] This is a result found by a collaboration of the Institute of Theoretical and Experimental Physics and the Erevan Physics Institute; it is reported in a review,[8] among other places.

[3)] By now there may be ~ 100 g of ^{150}Nd and ~ 10–20 g of ^{96}Zr. Obtaining 1 kg of these isotopes would not be an insurmountable task.

[1] E. Bellotti *et al.*, Nuovo Cimento **33**, 273 (1982).

[2] E. B. Norman and D. M. Meekhof, Phys. Lett. B **195**, 126 (1987).

[3] E. Bellotti *et al.*, Europhys. Lett. **3**, 889 (1987).

[4] A. S. Barabash *et al.*, Preprint No. 125, Institute of Theoretical and Experimental Physics, TsNII Atominform, Moscow, 1989.

[5] A. S. Barabash *et al.*, Preprint No. 184, Institute of Theoretical and Experimental Physics, TsNII Atomiform, Moscow, 1989.

[6] A. A. Klimenko *et al.*, Preprint No. 11-89, INR, Moscow, 1989.

[7] T. Watanable *et al.*, in *Proceedings of International Symposium WEIN-89*, Montreal, 1989, p. PC04.

[8] A. S. Barabash, Preprint No. 130, Institute of Theoretical and Experimental Physics, TsNII Atomiform, Moscow, 1989.

[9] T. Kirsten *et al.*, in *Proceedings of International Symposium on Nuclear Beta Decay and Neutrinos*, Osaka-1986, Singapore, 1986, p. 81.

[10] O. K. Manuel, in *Proceedings of International Symposium on Nuclear Beta Decay and Neutrinos*, Osaka-1986, Singapore, 1986, p. 71.

[11] A. S. Barabash, Preprint No. 188, Institute of Theoretical and Experimental Physics, TsNII Atomiform, Moscow, 1989.

[12] R. L. Brodzinski *et al.*, Preprint PNL-SA-17191, 1989.

[13] D. O. Caldwell *et al.*, in *Proceedings of the Eighth Moriond Workshop on Fifth Force-Neutrino Physics*, Singapore, 1988, p. 39.

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