How to detect two-neutrino double K capture in a direct (counter) experiment

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The decay half-lives are calculated for several nuclei for decay by the $2K(2\nu)$ channel to the 0_1^+ excited level of the daughter nucleus. It is shown that for the nuclei ^{96}Ru, ^{106}Cd, ^{124}Xe, ^{136}Ce, and ^{156}Dy ($T_{1/2} \simeq 10^{21}-10^{22}$ yr) this type of decay can be detected in existing low-background detectors. Some corresponding experiments are proposed.

The search for and study of processes of double beta decay have attracted considerable attention from experimental physicists. Most of the progress achieved in this field over the past few years has been associated with the detection of two-neutrino β decay for several nuclei (see some reviews[1-3]). This work has provided experimental information on the values of the nuclear matrix elements for $2\beta(2\nu)$ transitions. As a result, it has become possible to test certain theoretical models and to carry out more accurate calculations of nuclear matrix elements for both 2ν decay and 0ν decay. Accurate calculations of nuclear matrix elements for 0ν decay make it possible to find reliable limitations on the mass of the Majorana neutrino, the admixture of right-handed currents in the electroweak interaction, the Majorana–neutrino coupling constant, etc. In the detection of 0ν decay, it has become possible to find accurate values of these quantities. Unfortunately, calculating nuclear matrix elements remains one of the basic problems in the theory of 2β decay. We can expect that the accumulation of experimental information on $2\beta(2\nu)$ processes (highly accurate measurements of the decay half-lives for a wide range of nuclei) and the detection of other types of 2β transitions ($2\beta^+$, $K\beta^+$, and $2K$ processes) will lead to substantial improvements in the quality of calculations of nuclear matrix elements for both 2ν decay and 0ν decay.

There has been much less interest in $2\beta^+(2\nu)$, $K\beta^+(2\nu)$, and $2K(2\nu)$ transitions, since efforts to detect these processes at the existing low-background installations looked hopeless. The $2\beta^+(2\nu)$ and $K\beta^+(2\nu)$processes are highly suppressed in comparison with $2\beta^-(2\nu)$ decay because of the Coulomb barrier for positrons, and because of the much lower kinetic energy which is realized in such transitions. On the other hand, these processes are attractive from the experimental standpoint because it is possible to detect them in a method involving coincidences of the signals from four (or two) annihilation γ rays and two (or one) positrons.

For a $2K(2\nu)$ process, the kinetic energy of the transition can be fairly high (up to ~ 2.8 MeV), and there are no positrons in the final state. This process is difficult to detect, however, since all that is accessible to detection in this case is characteristic radiation (the total energy is $\sim 30-100$ keV for the most promising nuclei). Accordingly, there have been only a few attempts[4-6] to search for this process. The sensitivity of these experiments has been extremely low ($\sim 10^{15}-10^{18}$ yr).

TABLE I.

Nucleus	Isotopic abundance, %	$E^*_{2K}[m_e]$	$T^{2\nu}_{1/2}(2K;0^+-0^+_1)$ yr
^{78}Kr	0.354	2.63	2.4×10^{23}
^{96}Ru	5.46	2.97	$(2.2-4.7)\times 10^{22}$
^{106}Cd	1.22	3.09	$(2.2-3.9)\times 10^{21}$
^{124}Xe	0.096	3.18	3×10^{21}
^{130}Ba	0.101	1.37	1.5×10^{23}
^{136}Ce	0.193	1.44	$8.7\times 10^{20}-2\times 10^{22}$
^{162}Er	0.136	0.60	1.2×10^{24}

In this letter we show that existing low-background detectors can be used to detect $2K(2\nu)$ capture to the 0^+_1 excited state of the daughter nucleus for several isotopes in direct (counter) experiments.

What decay half-lives would we expect for such transitions? To find some estimates we will draw on the results of some recent theoretical calculations of the probability for $2K(2\nu)$ transitions to the 0^+ ground state of daughter nuclei. The probabilities for such transitions have been estimated previously,[7-9] but those previous estimates have been basically qualitative, and they have led to pessimistic predictions of the probabilities for such transitions ("pessimistic" in the sense that the predictions lie beyond existing experimental capabilities). Some accurate calculations of the phase volume have recently been carried out with the help of relativistic wave functions for $2\beta^+(2\nu)$, $K\beta^+(2\nu)$, and $2K(2\nu)$ transitions.[10] Nuclear matrix elements were calculated in Ref. 11 for (0^+-0^+) transitions for four nuclei (^{58}Ni, ^{96}Ru, ^{106}Co, and ^{136}Ce) on the basis of the QRPA model with allowance for a particle–particle interaction in the nucleus. Unfortunately, calculations were carried out for only four nuclei. Accordingly, we adopt the value $M_{GT}(0^+-0^+)=0.3$ for the other nuclei which we are discussing in this letter. This value seems fairly realistic in view of the results calculated in Ref. 11.

Table I shows the results of our estimates of the decay half-lives $T^{2\nu}_{1/2}(0^+-0^+_1)$ for $2K(2\nu)$ transitions to the 0^+_1 excited state of the daughter nuclei. Also shown here are the transition energy E^*_{2K} (in electron masses) and the isotopic abundance of the most promising candidate nuclei. It has been assumed here that the nuclear matrix elements for the (0^+-0^+) and $(0^+-0^+_1)$ transitions are equal.[1)] The difference between the phase volumes has been taken into account [the probability for $2K(2\nu)$ capture is proportional to the transition energy raised to the fifth power]. The values of the phase-volume factors for (0^+-0^+) transitions were taken from Ref. 10.

We see from Table I that the values of $T^{2\nu}_{1/2}$ $(2K;0^+-0^+_1)$ for several nuclei lie in the interval $\sim 10^{21}-10^{22}$ yr. We show below that these processes can be detected in existing low-background detectors.

The basic idea of the experiment can be summarized as follows. The $2K(2\nu)$ capture to the 0^+_1 excited state of the daughter nucleus is to be detected:

$$(A,Z)+2e^- \rightarrow (A,Z-2)^* + 2\nu_e \rightarrow \gamma_1 + \gamma_2. \quad (1)$$

The excitation energy is shed through the emission of two cascade γ rays with a strictly fixed energy. The detection of these γ rays would make it possible to identify this process reliably.

Low-background detectors based on Ge semiconductor detectors with a volume $\sim 200-600$ cm^3 and an extremely low background, $\sim 3-10$ counts/(keV$\times$kg$\times$yr), in the energy range of interest here, 400–700 keV, already exist and are being used successfully.[13,14] If such a detector were surrounded by the isotope of interest (^{96}Ru, ^{106}Cd, ^{124}Xe, ^{136}Ce) with a mass of 1 kg, the sensitivity of the experiment would be $\sim(3-5)\times 10^{22}$ yr per 1 yr of measurements. Roughly the same sensitivity can be achieved by using a Ge detector with active shielding made of NaI(Tl) crystals[15] or by placing the test sample between two large NaI(Tl) crystals and detecting the cascade γ rays in a coincidence arrangement.

Comparing this estimate of the sensitivity of existing low-background installations based on Ge detectors with the predicted decay half-lives for ^{96}Ru, ^{106}Cd, ^{124}Xe, and ^{136}Ce for decay by the $2K(2\nu;0^+-0_1^+)$ channel, we reach the conclusion that this type of decay can be detected today for all these isotopes. We would also like to point out that it would be promising[2)] to search for this process in the case of ^{156}Dy ($E^* = 1.67$ $[m_e]$). With regard to ^{124}Xe, we might suggest a slightly different experimental arrangement: a high-pressure ionization chamber (or proportional counter) filled with ^{124}Xe, surrounded by NaI(Tl) detectors. The characteristic radiation would be detected by the ionization chamber (or proportional counter), and the cascade γ's by the NaI(Tl) detectors. As a result, the useful events (triple coincidences) could be distinguished from background events easily. If 1 kg of the isotope of interest were used, the sensitivity of the experiment would be $\sim 10^{23}$ yr, which is sufficient for detecting $2K(2\nu;0^+-0_1^+)$ capture in ^{124}Xe.

It is technically feasible today to produce 1 kg of the isotopes listed above, although to do so would be quite expensive. The isotopes most accessible are ^{96}Ru, ^{106}Cd, and ^{124}Xe.

In summary, we have shown that it is possible to detect the capture process $2K(2\nu;0^+-0_1^+)$ for several nuclei at existing low-background detectors. We suggest that a series of experiments be carried out to detect this process in ^{96}Ru, ^{106}Cd, ^{124}Xe, ^{136}Ce, and ^{156}Dy at existing low-background detectors and in those being developed.

[1)]This assumption is justified, especially since it recently was confirmed for $2\beta(2\nu)$ decay in an experiment[12] with ^{100}Mo.
[2)]Using $M_{GT}(0^+-0_1^+)=0.3$, we find an expected value $\sim 10^{22}$ yr for the half life for the decay by the $2K(2\nu;0^+-0_1^+)$ channel.

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