New Limit for the Half-Life of $2K(2\nu)$-Capture Decay Mode of $^{78}Kr$.

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Abstract

Features of data accumulated at 1817 hours in the experimental search for $2K(2\nu)$-capture decay mode of $^{78}Kr$ are discussed. The new limit for this decay half-life is found to be $T_{1/2} \geq 2.3 \times 10^{20} \text{ yr.} \ (90\% \ C.L.)$. 
First result for 2K(2ν)-capture decay mode of ⁷⁸Kr was presented in refs. [1]-[2]. The limit derived from the data collected at 254.2 hours was $T_{1/2} \geq 0.9 \times 10^{20}$ yr. (90% C.L.). The theoretical predictions for the half-life of ⁷⁸Kr(2e,2ν)²⁷⁸Se capture are $3.7 \times 10^{21}$ yr. [3], $3.7 \times 10^{22}$ yr. [4] and $6.2 \times 10^{23}$ yr. [5]. Corresponding values of half-life for 2K(2ν)-capture decay mode are $4.7 \times 10^{21}$ yr., $4.7 \times 10^{22}$ yr. and $7.9 \times 10^{23}$ yr. if one takes into account that 2K-electron capture part is 78.6% from a total number of 2e-captures for ⁷⁸Kr [6]. The method used in refs. [1]-[2] allows to reach a level of sensitivity for a half-life up to $10^{22}$ yr. and tests some of theoretical models. Results of the next step of measurement are presented.

Measurements were performed with use of the multiwire wall-less proportional counter (MWPC) with a krypton sample enriched in ⁷⁸Kr. The main features of the counter and measurement conditions have been described in refs. [1]-[3]. The MWPC contains a central main counter (MC) and a surrounding it protection ring counter (RC) in the same body. A common anode wires signal ($P_{AC}$) from RC and $P_{C1}$ and $P_{C2}$ signals from both ends of the MC anode are read out from MWPC. A scheme with signal read out from two sides of the MC anode allows to determine the event relative coordinate $\beta$ along the anode ($\beta = 100 \times P_{C1}/(P_{C1} + P_{C2})$) and to eliminate the events which don’t correspond to a selected working length. A shaping amplifier with 26 $\mu$s integration and differentiation shaping times was used for the amplification of the $P_{C1}$ and $P_{C2}$ pulses to have a good enough energy resolution. A parameter $f = 1000 \times P_{12}/(P_{C1} + P_{C2})$ was used to obtain an information about a pulse rise time and the pulse front features. Signals $P_{12}$ are output pulses of the additional shaping amplifier which amplifies a sum signal ($P_{C1} + P_{C2}$) with the 1.5 $\mu$s shaping times. A value of parameter $f$ depends on the energy space distribution of event in the MC volume.

The K-shell double vacancy of daughter ⁷⁸Se** isotope appears as a result of ⁷⁸Kr 2K(2ν) ⁷⁸Se capture. A total energy released is $2K_{ab} = 25.3$ keV where $K_{ab}$ is a couple energy of K-electrons with the Se nuclear. One can obtain that Se** summary probability to emit one or two characteristic X-rays is 0.837 in assumption that this double vacancy deexcitation is equivalent to sum of two single vacancies deexcitation. The characteristic X-ray ($E_{K\alpha} \cong 11.2$ keV, $E_{K\beta} \cong 12.5$ keV) has a sufficient long path length in a krypton. Two point-like energy releases with a total energy of $2K_{ab}$ (total energy absorption peak) will appear if X-ray will absorb in the MC working volume. One part is the X-ray energy release and the second one is the release of Auger electron cascade energy accompany with the characteristic L-shell X-rays energy. The X-rays may leave the MC volume. One- or two-point event would be detected in this case (escape peak). All single electron background events such as Compton electrons or inner $\beta$-decay electrons will have one-point energy releases. A multi-point event pulse $P_{12}$ would represent a sequence of short pulses with a different time overlap. A number of pulses in the burst corresponds to a number of the local regions where a total ionization distributed. An amplitude and duration of each pulse in a burst depend on a local track length, orientation and distance from the MC anode. The ADCs used to record the $P_{AC}$, $P_{C1}$, $P_{C2}$ and $P_{12}$ signals are triggered with the input pulse amplitude maximum. The $P_{12}$ signal triggering will be done for the first amplitude maximum which corresponds to an energy released in the anode nearest local region. Peaks corresponding to one-point amplitudes $P_{12}$ for a fixed event total energy appear in the event number distribution as a function of parameter $f$ ($f$-distribution). Events with energy released in MC only and the
one in the MC and RC simultaneously named "Type 1" and "Type 2" events, respectively.

A krypton enriched up to 94% in $^{78}$Kr was used to search for the $^{78}$Kr(2K,2$\nu$)$^{78}$Se capture mode. It content an admixture of the natural $\beta$-radioactive $^{85}$Kr ($T_{1/2} = 10.7$ yr, $E_{\beta\text{max}} = 670$ keV) with the volume activity of 0.14 Bk/l.

Measurements were done in the underground laboratory of the Baksan Neutrino Observatory of the Institute for Nuclear Research RAS (Moscow) at a depth of 4900 m w.e.. The MWPC was placed in the low background shield formed by 15 cm of lead, 8 cm of borated polyethylene, and 11 cm of copper.

The own background of the MWPC filled up to 4.8 atm with pure xenon without radioactive contamination was measured preliminary. A background energy spectrum 1 collected at 973.9 h and a conveniently scaled spectrum 2 of a $^{109}$Cd source ($E_\gamma = 88$ keV) are shown on Fig. 1. The spectra consist of ($PC_1 + PC_2$) signals from the type 1 events. There are a peak at $E_\gamma = 88$ keV and the xenon escape peak at $E = E_\gamma - E_{KrK\alpha} = 88 - 28.9 = 58.2$ keV on the curve 2. The peak at 88 kev is not symmetrical because of the radiation scattered in the counter wall. The energy resolution of the 88 keV $\gamma$-line is 13.7%.

The background spectrum has some features. The main peaks correspond to the energy values of 16, 35, 50, 68, 82 and 92 keV. In the energy regions 35 ÷ 68 keV, there are initial peaks accompanied by the escape peaks. The background counting rate in the energy range $20 \div 100$ keV is 91 h$^{-1}$.

Energy spectra 1 and 2 of ($PC_1 + PC_2$) signals from type 1 and type 2 events respectively for the $^{109}$Cd calibration source and the krypton filling are shown on Fig.2a. One can see the 88 keV peak on the spectrum 1. This spectrum was multiplied by coefficient 0.5 for convenient comparison. The energy resolution of this peak is 10.8%. The highest energy peak on the curve 2 is the krypton escape peak with the energy of $E = E_\gamma - E_{KrK\alpha} = 88 - 12.6 = 75.4$ keV. It's appearing in the type 2 events caused by an absorption in the RC of krypton characteristics radiation from the MC. The escape peak on the spectrum 1 is on the left slope of the total absorption peak. The source radiation scattered in the counter body wall lies in this region too. $f$-Distributions correspondent to this spectra are shown on Fig.2b with the same scaling and notation. One can see a peak on the curve 1 with a maximum at $f_1 = 166$ which corresponds to two-point events from the total absorption peak when the KrK$\alpha$-ray ionization collected first on the MC anode. If the photoelectron ionization collected first, the events have a peak with a maximum at $f_2 = 920$. Calculated $f$-values of these maximums should be equal to $f_1 = 1000 \times 12.6/88 = 143$ and $f_2 = 1000 \times (88 - 12.6)/88 = 878$ at a calibration when the amplitude $P12$ equal to ($PC_1 + PC_2$) one for the single-point events. Real values calculated from the experimental data differ slightly from the theoretical ones. This could be explained by nonideality of the experimental set up. A value of $f$-parameter depends on energy also because of it. The energy spectrum 2 on Fig.2a consists of one-point events mainly and it's $f$-distribution 2 has no multi-point peaks. The peaks at $f = 1015$ and $f = 1239$ are one-point peaks for the energy region higher than 16 keV and for the krypton 12.6 keV X-ray peak correspondingly. The $f$-distribution 1 has a one-point peak with the maximum at $f = 1039$.

The type 1 event background energy spectrum of the MWPC with the krypton is shown on Fig.3a (spectrum 1). It collected at 1817 h. A counting rate is 1506 h$^{-1}$ for the energy range $20 \div 100$ keV. Corresponding $\beta$- and $f$-distributions are shown on Fig.3b (curve 1)
and Fig.3c (curve 1). One can see peaks on the ends of the $\beta$-distribution which caused by events from a high energy part of the $^{85}$Kr $\beta$-spectrum mainly collected in an ionization mode at the end effect correction anode bulges. To eliminate this background component, it is sufficient perform the $\beta$-selection of events in the range $36 \leq \beta \leq 58$ (Fig.3b, curve 2). The energy spectrum 2 and $f$-distribution 2 correspond to this selection. One can see from the $f$-distribution 2 that the background events with $f \leq 710$ suppressed mainly. The energy spectrum of events with $36 \leq \beta \leq 58$ and $f \leq 710$ is shown on Fig.3a (spectrum 3). It’s shape repeats main features of the spectrum 1 on the Fig.1 with excluded escape peaks. It means that almost all one-point events from the $^{85}$Kr $\beta$-spectrum excluded by the used selection. The curve 5 on the Fig.3c shows roughly a shape and a place of a $f$-distribution waited for the $^{78}$Kr(2K,2$\nu$)$^{78}$Se multi-point events.

The events with $36 \leq \beta \leq 58$ and $330 \leq f \leq 710$ were used for the final analysis because of there is no any peak-like distortions of the residual energy spectrum 4 (Fig.3a) in the region of interest for the such selection.

A low energy part of this spectrum is shown on the Fig.4 (spectrum 1). A sample of a shape and a place of the $^{78}$Kr(2K,2$\nu$)$^{78}$Se effect is shown as a spectrum 3 (Fig.4). An energy region $25.3 \pm 3.8$ keV include 95% of the events. A background was fitted by using of points before and above this region (spectrum 2). The sum fitted background for the $25.3 \pm 3.8$ keV was found to be 266. The difference is $-4 \pm 23$ or $-19 \pm 111$ yr$^{-1}$. Taking into account the efficiency of the events registration (0.22) and the effective counter length (0.6 of working length), we find that the limit of the half-life of $^{78}$Kr with respect to the 2K(2$\nu$)-capture mode is $T_{1/2} \geq 2.3 \times 10^{20}$ yr (at a 90% C.L.).

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FIG. 1. Energy spectra of (1) background and (2) $^{109}\text{Cd}$ source of ($PC_1 + PC_2$) signals for type 1 events from the MWPC filled up to 4.8 atm with pure xenon.
FIG. 2. (a) - Energy spectra of \((PC1 + PC2)\) signals for type 1 events (1) and type 2 events (2) for \(^{109}\text{Cd}\) source and the MWPC krypton filling. (b) - Corresponding \(f\)-distributions (1) and (2). The curves (1) multiplied by the coefficient 0.5.
FIG. 3.  a) - Background energy spectra. b) and c) - corresponding β- and f-distributions. (1) - 0 ≤ β ≤ 100, 1 ≤ f ≤ 2000; (2) - 36 ≤ β ≤ 58, 1 ≤ f ≤ 2000;(3) - 36 ≤ β ≤ 58, 1 ≤ f ≤ 710; (4) - 36 ≤ β ≤ 58, 330 ≤ f ≤ 710; (5) - sample of a shape of the f-distribution for the 2K-capture $^{78}$Kr events.
FIG. 4. (1) - Background residual energy spectrum. (2) - The best fit. (3) - Sample spectrum of an effect.