# Results of in-depth data analysis of experimental search of 2K(2$\nu$)-capture in Kr-78

Vladimir Kazalov
Baksan Neutrino Observatory
INR RAS

International Session-Conference of the Section of Nuclear Physics of the Physical Sciences Department of the Russian Academy of Sciences, June 06 – June 08 2017, Nalchik

**Yu. Gavriljuk, A. Gangapshev,**

**V. Kazalov, V. Kuzminov, D. Tekueva, S.P. Yakimenko**

*Institute for Nuclear Research of the Russian Academy of Sciences, Moscow  Russia*

**S. Panasenko, S. Ratkevich**

*Karazin Kharkiv National University, Kharkiv, Ukraine*

# Candidates for measurement of $2\nu 2\beta^{+}$-decay

| Transition | $E_{2K}$, MeV | Isotopic abundance, % |
|---|---|---|
| $^{78}Kr \rightarrow ^{78}Se$ | 2.867 | 0.35 |
| $^{96}Ru \rightarrow ^{96}Mo$ | 2.724 | 5.52 |
| $^{106}Cd \rightarrow ^{106}Pd$ | 2.771 | 1.25 |
| $^{124}Xe \rightarrow ^{124}Te$ | 2.866 | 0.10 |
| $^{130}Ba \rightarrow ^{130}Xe$ | 2.610 | 0.11 |
| $^{136}Ce \rightarrow ^{136}Ba$ | 2.401 | 0.20 |

$(Z, A) \rightarrow (Z-2, A) + 2\beta^{+} (+ 2\nu_e)$

$e_a + (Z, A) \rightarrow (Z-2, A) + \beta^{+} (+ 2\nu_e)$

$e_a + e_a + (Z, A) \rightarrow (Z-2, A) + 2\nu_e + 2X$

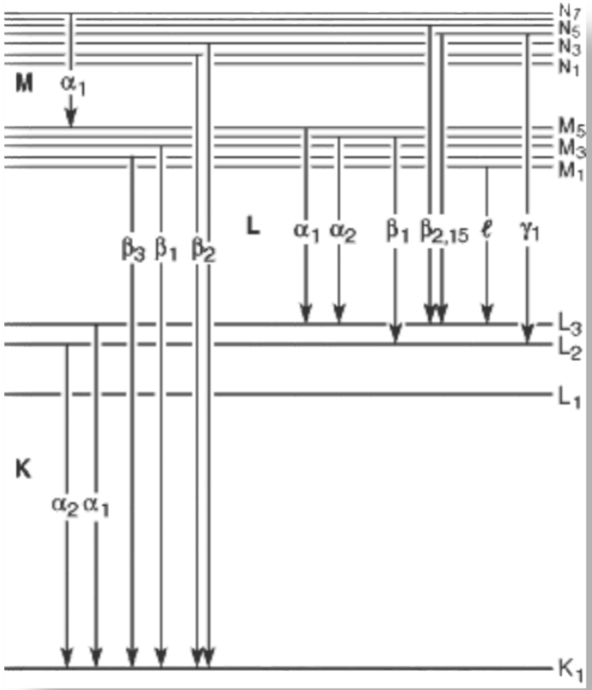
$e_a + e_a + (Z, A) \rightarrow (Z-2, A)^{*} \rightarrow (Z-2, A) + \gamma + 2X$

Se** ------------------------assumption------------------------> Se* + Se*

$\omega_k = 0.596$ *x-ray*

$\omega_e = 0.404$ *e-Auger*

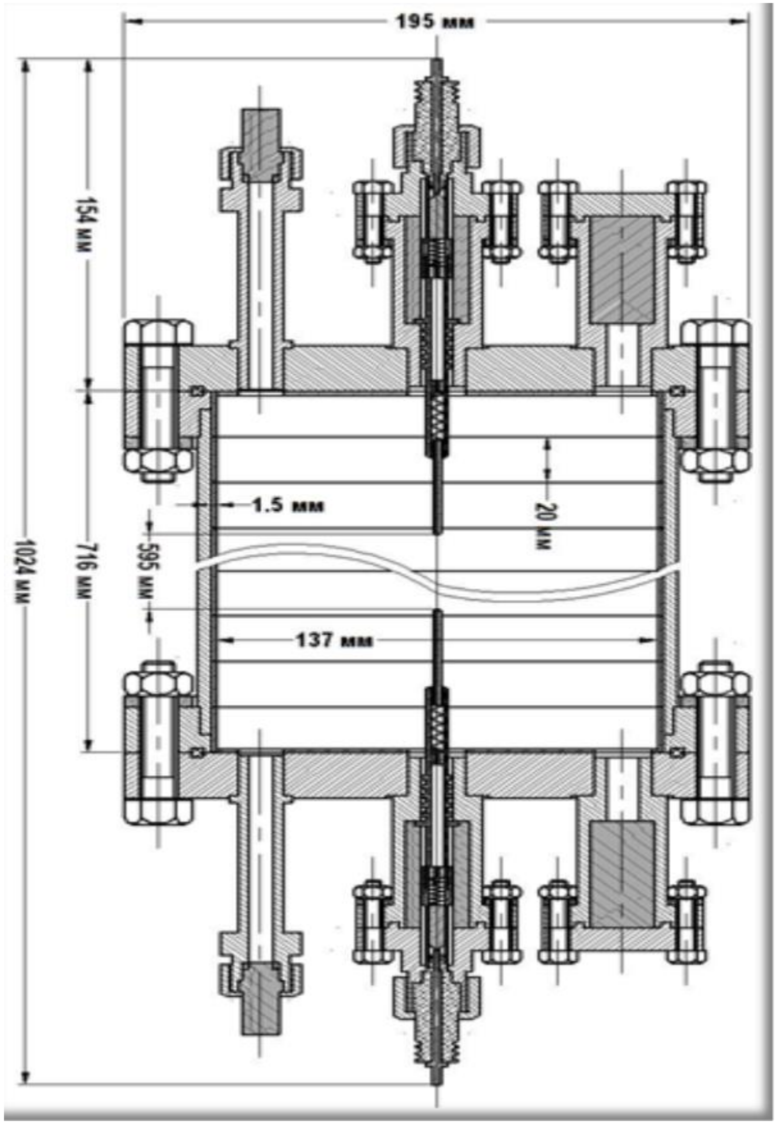
| | | |
|---|---|---|
| $K_{ab} = 12.652$ keV, | | **$2K_{ab} = 25.3$ keV** |
| $K_{\alpha 1} = 11.221$ keV | | 0.574 |
| $K_{\alpha 2} = 11.181$ keV | | 0.298 |
| $K_{\beta 1} = 12.491$ keV | | 0.120 |
| $K_{\beta 2} = 12.651$ keV | | 0.005 |




***Probability of deexcitation***

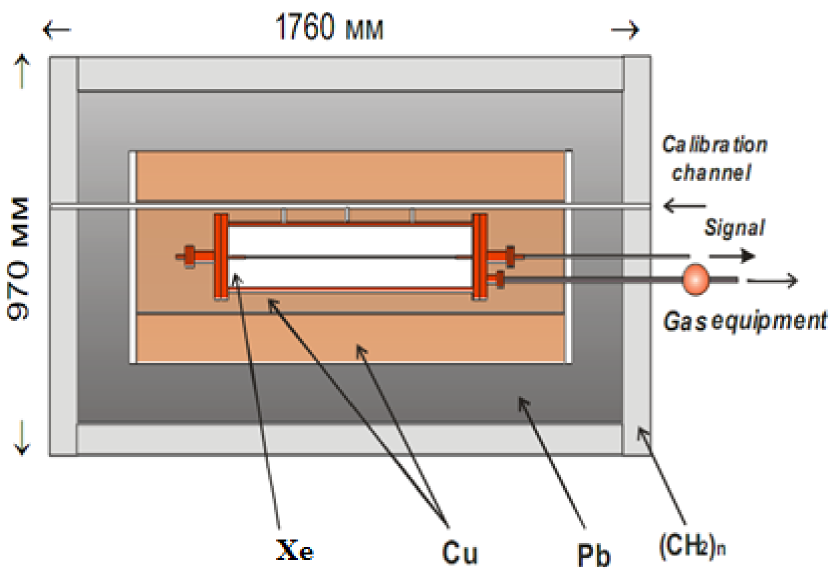
| Se* | Se* | |
|---|---|---|
| $e_a$ | $e_a$ | $0.404^2 = 0.163$ |
| $e_a$ | $\kappa$ | } $= 0.481$ |
| $\kappa$ | $e_a$ | |
| $\kappa$ | $\kappa$ | $0.596^2 = 0.355$ |

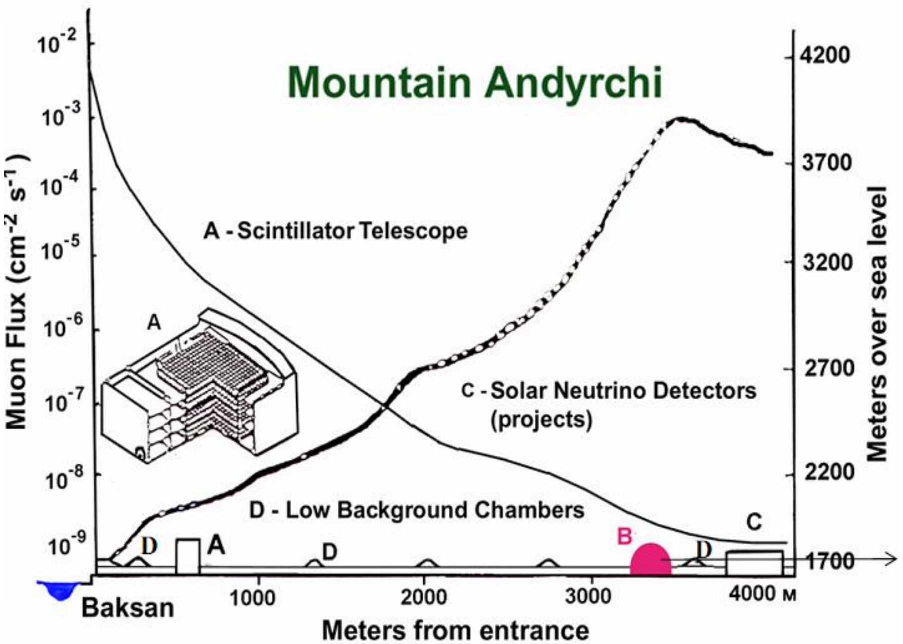
# Schematic view of Proportional Counter




| | |
|---|---|
| **1. Material** | ***Cu*** |
| **2. Total length, mm** | ***1160*** |
| **3. Fiducial length, mm** | ***595*** |
| **4. Outer diameter, mm** | ***150*** |
| **5. Inner diameter, mm** | ***137*** |
| **6. Anode wire diameter, mm** | ***0.010*** |
| **7. Total volume, l** | ***10.37*** |
| **8. Fiducial volume, l** | ***8.77*** |
| **9. Pressure, at** | ***5*** |
| **10. Capacity, pF** | ***31*** |
| **11. Anode resistance, Ohm** | ***613*** |

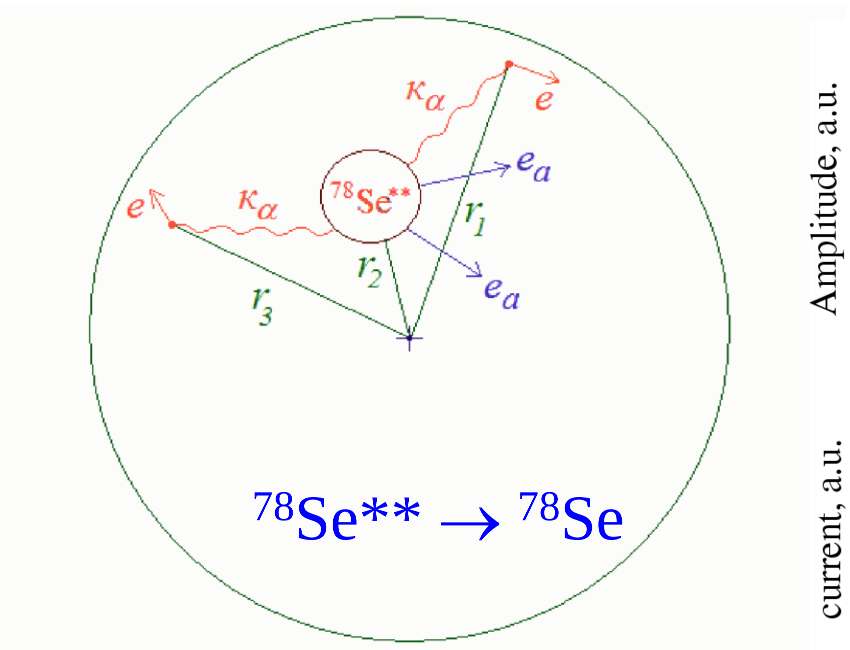
# Low background shield

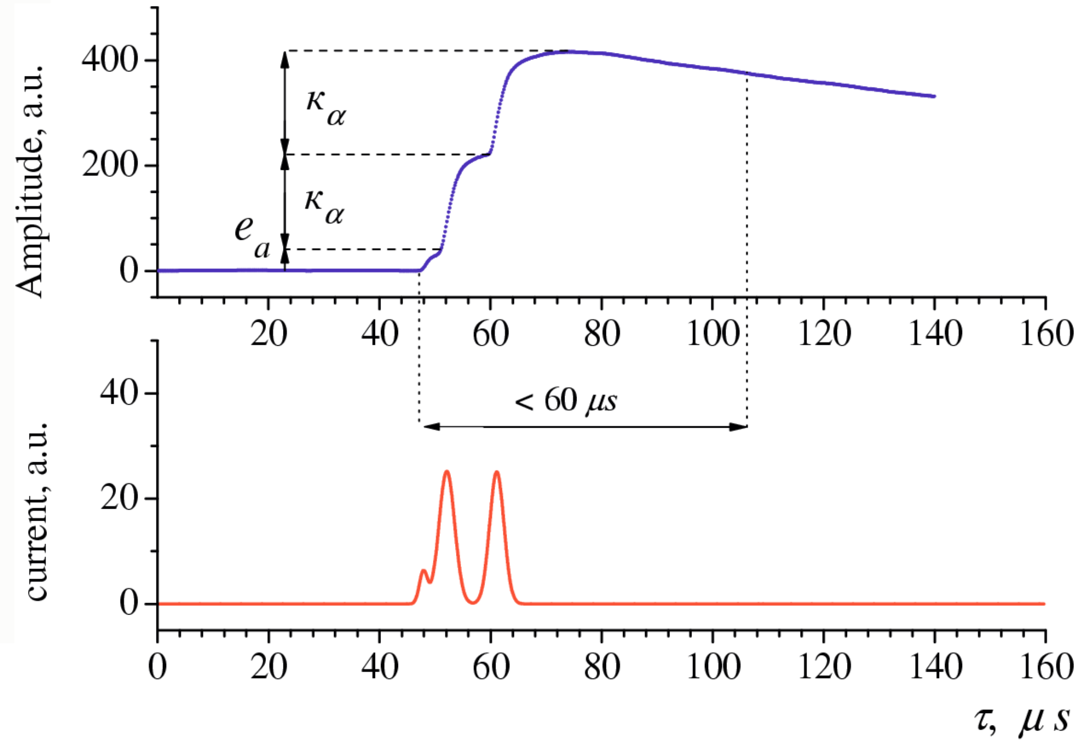



- 18 см – copper (M1)
- 15 cm – lead
- 8cm – borated polyethylene
- depth-4900 m.w.e., $\phi_\mu$=2,23*$10^{-9}$ $cm^{-2}s^{-1}$

# Schematic diagram of the 2K-capture event



PHYSICAL REVIEW C **87**, 035501 (2013)

# Indications of $2\nu 2K$ capture in $^{78}$Kr

Yu. M. Gavrilyuk, A. M. Gangapshev, V. V. Kazalov, and V. V. Kuzminov
*Baksan Neutrino Observatory INR RAS, Russia*

S. I. Panasenko and S. S. Ratkevich*
*V. N. Karazin Kharkiv National University, Kharkiv, Ukraine*

(Received 6 August 2012; published 4 March 2013)

Results from searches of double $K$ capture in $^{78}$Kr in an experiment with the large-volume copper proportional counter, using data samples corresponding of two independent series of measurements with different intrinsic radioactivity background are presented. The total exposure of the low-background measurements is 0.343 kg × y. A combination of methods of selection of useful events with a unique set of characteristics and wavelet analysis of events allowed a reduction of the background by ~2000 times in the energy region of interest. The statistical significance of combined data from two stages of operation equals $2.5\sigma$. Corresponding to such effect, the half-life of $^{78}$Kr relative to $2\nu 2K$ capture equals $T_{1/2} = [9.2^{+5.5}_{-2.6}(\mathrm{stat}) \pm 1.3(\mathrm{syst})] \times 10^{21}$ y. Half-life limits for other $2K$ transitions to the excited states in $^{78}$Se are obtained at the level of $10^{21}$ y in the first time. In particular, limits on $2\nu 2K$ capture to the excited level $0^+_1$ (1499 keV) and resonant neutrinoless double $K$ capture to the level $2^+$ (2838 keV) have been defined on the level of $T_{1/2} \geqslant 5.4 \times 10^{21}$ y at 90% C.L.

DOI: 10.1103/PhysRevC.87.035501 PACS number(s): 23.40.−s, 27.50.+e, 14.60.Pq, 21.10.Tg

# SO and SU processes in Kr-81

chain associated with the double $K$-capture

$$2e_K + (Z, A) \rightarrow (Z-2, A)^{K^{++}} + 2\nu_e,$$
$$\hookrightarrow (Z-2, A) + K_\alpha^h + K_\alpha^s + m \times e_A,$$

chain associated with single $K$-capture

$$e_K + (Z, A) \rightarrow (Z-1, A)^{K^+} + \nu_e$$
$$\hookrightarrow (Z-1, A) + K_\alpha + e_A$$
$$e_K + (Z, A) \rightarrow (Z-1, A)^{K^{++}} + \nu_e + e_K$$
$$\hookrightarrow (Z-1, A) + K_\alpha^h + K_\alpha^s + e_A$$

- double K-shell photoionization of an atom can create a “hollow atom” by absorbing a single photon and releasing both K electrons.
- double K ionization following electron capture (EC) decay of radioactive nuclei. In such a process, there is a small probability that the second electron in the K-shell is excited to an unoccupied level (shake-up; SU) or ejected to the continuum (shake-off; SO).

The total energy release and radiation characteristics of SO processes in the single K-capture decay of Kr-81 are similar to the ones of the 2K-capture in Kr-78. This means that they can create a background masking the decay under investigation.

The total probability of K-shell SO and SU processes to occur is on the order of $10^{-4}$ per a single K-capture.

# Stages of measurements

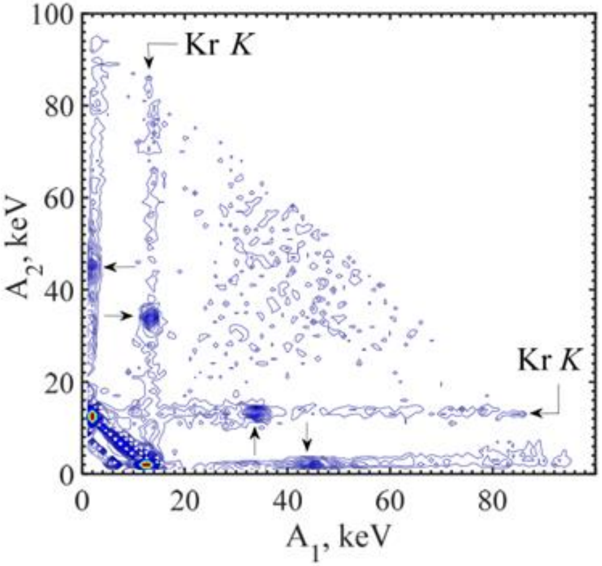
Three stages of measurements were performed with a sample krypton containing Kr-81. Total collection time of experimental data in the first and second stage was 7600 and 8400 h respectively. The LPC operated at the pressure of 4.4 and 4.6 bar in the first and second stage, respectively. In the third stage, the total time of measurement amounted to 12,000 h with a pressure of 5.6 bar. The total number of the recorded EC decay has reached $6.7 \times 10^6$ events.

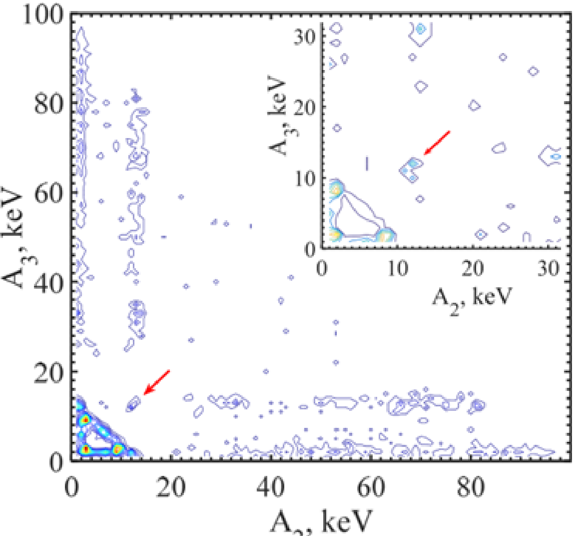
Volume activity of Kr-81 is (0.076±0.004) $min^{-1}\, l^{-1}$

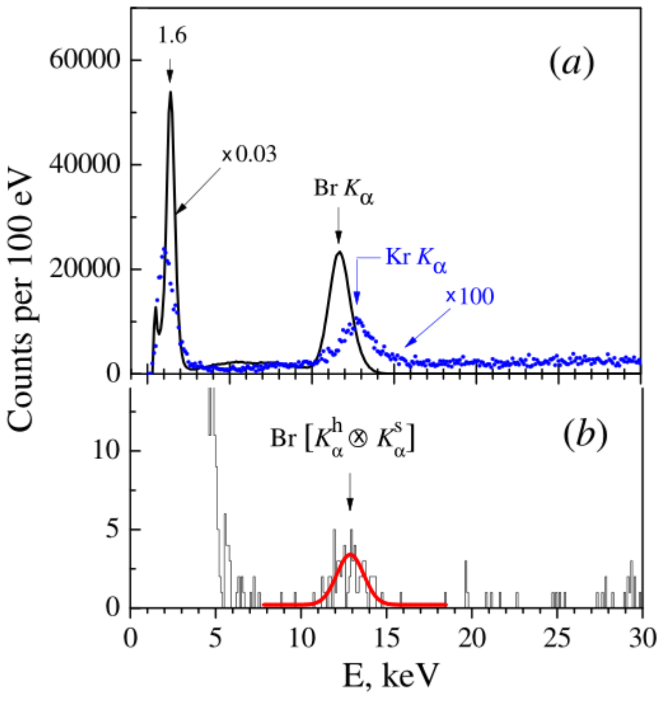
Two stages of measurements were carried out with krypton enriched in Kr-78. The LPC operated at a pressure of 4.4 and 4.6 bar at the first and second stage, respectively. The total collection time amounted to 19,000 h.

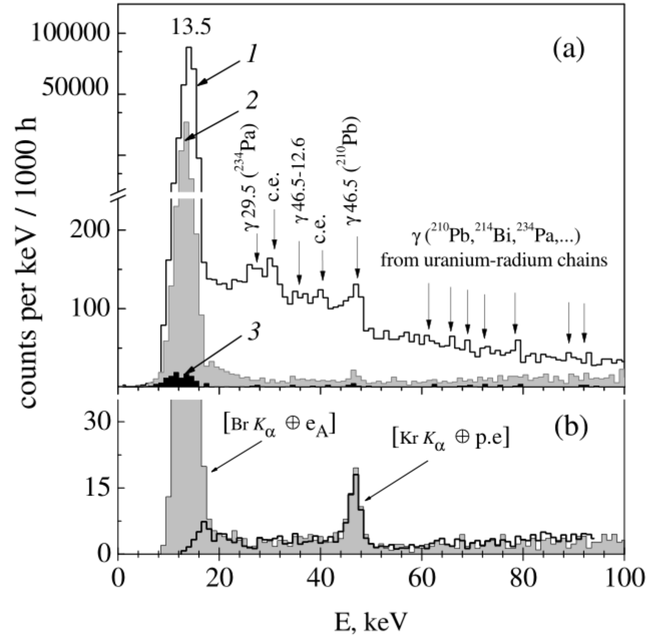
In our analysis of the accumulated data, the double K-shell ionization of the Br-81 daughter was studied by triple coincidence measurements between two practically simultaneous radiations resulting from the filling of the two holes in the K shell: hypersatellite- and satellite-line photons and bromine emitted electrons (sum Auger electrons and K electrons ejected) - $[K^h \otimes K^s \otimes (e_A + e^{SO})]$.

# Two-dimensional amplitude distributions of energy deposits of individual components




**(a)** the spectrum Auger electrons and $K_{\alpha}^{N}$ after the single K-capture decay of Kr-81 and **(b)** a fragment of the coincidence spectrum with $[K^{h} \otimes K^{s}]$

# RESULTS

The total number of Kr-81 K-captures can be estimated from the area under the 13.5 keV TAP curve for all types of events as $N_K = N_K^{exp}/\varepsilon_d = 7.8 \times 10^6$ , where $N_K^{exp} = 6.7 \times 10^6$ - the number of events with the energy of the region 13.5 ± 3.0 keV for a total of 1,175 live days of measurement; $\varepsilon_d = 0.869$ is the absolute efficiency to detect respective radiation.

$$N_{KK} = N_K P_{KK} \omega_{2K} \delta_e \eta = 57 \pm 8,$$ where

## Events selection parameters

Kr-81

$A_2 \sim A_2 \sim 12$ keV, $0.6 < A_1 < 8.5$ keV

$[K_\alpha^h \otimes K_\alpha^S \otimes (eA + e_K^{SO})]$

Kr-78

$A_2 \sim A_2 \sim 12$ keV, $1 < A_1 < 4$ keV

$[K_\alpha^h \otimes K_\alpha^S \otimes eA]$

$N_K = 7.8 \times 10^6$ - the number of K-capture during 81 Kr decays.

$P_{KK} = 6.5 \times 10^{-5}$ - the probability of the double K-shell vacancy production per K-electron capture for Br-81. (Theoretical calculations)

$\delta_e = 0.6$ - the fraction of all ejected K-electrons registered in the coincidence according to the selection criteria.

$\eta = \varepsilon_p \cdot \varepsilon_3 \cdot \alpha_k$ with parameters:

$\varepsilon_p = 0.81 \pm 0.01$ - the probability of two K photons to be absorbed in the operating volume;

$\varepsilon_3 = 0.54 \pm 0.05$ - the efficiency to select three-point events;

$\alpha_k = 0.985 \pm 0.005$ - the fraction of events with two K photons that could be registered as distinct three-point events.

$$N_{coinc}^{dipl} = 42 \pm 6 \Rightarrow P_{KK}^{SO} = [5.7 \pm 0.8(stat) \pm 0.4(syst)] \times 10^{-5}$$

$$N_{coin}^{enr} = 16 \pm 4 \qquad T_{1/2}^{2\nu 2K} = \ln 2 * N_A \times \frac{p_3 * \varepsilon_f * t}{N_{coin}^{enr}} = [1.9^{+1.3}_{-0.7}(stat) \pm 0.3(syst)] \times 10^{22} \text{ yr}$$

$N_a = 1.08 \cdot 10^{24}$ - the number of Kr-78 atoms in the fiducial volume of the counter

$p_3 = 0.47$ - the fraction of 2K-captures accompanied by the emission of two K-photons.

The efficiency is calculated as $\varepsilon_f = \varepsilon_p \cdot \varepsilon_3 \cdot \alpha_k \cdot k_\lambda$ ,

$k_\lambda = 0.85$ - the useful event selection coefficient for a given threshold for λ

$t = 787.7$ days of live measurement

Thank you!