Search for double K capture in ^{78}Kr and imitative processes

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Why study double beta decay?

- Determine neutrino nature (Majorana or Dirac)
- Test of lepton number conservation
- Absolute neutrino mass scale and hierarchy
- Improve nuclear matrix elements

$$(T^{2\nu}_{1/2})^{-1} = G^{2\nu}|M^{2\nu}|^2$$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2|m_{ee}|^2$$

Positive results on ββ decay are detected for 12 isotopes:

$2\nu\beta^-\beta^-$: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

2νECEC: ^{130}Ba(geochemical)

http://www.nndc.bnl.gov/bbdecay

$\beta^+\beta^+$ and β^+EC decays have lower Q value than ECEC, the latter is favorable.

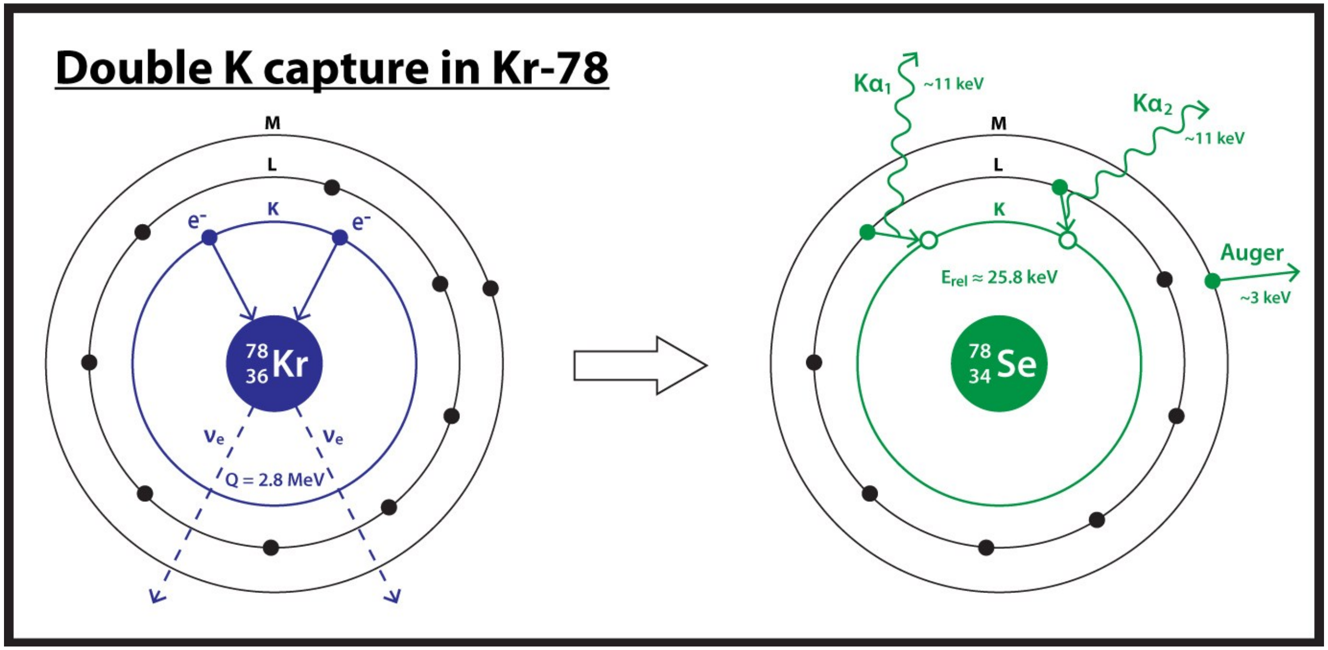
None of them have been detected in direct experiment yet.

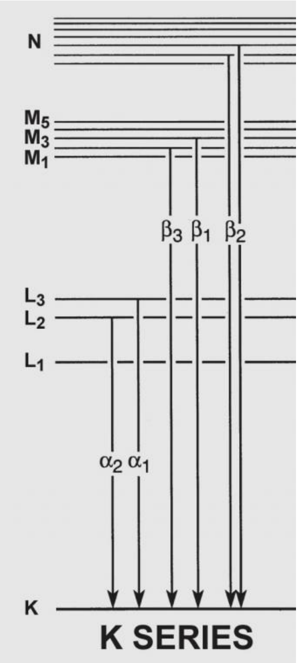
For ^{78}Kr: W(2νECEC) : W(2νβ^+EC) : W(2ν$\beta^+\beta^+$) = 1900 : 580 : 1.

M.B. Voloshin et al., Pis'ma Zh. Eksp. Teor. Fiz. 35, No. 12, 530-532 (1982)

But the ECEC process is hard to study: **no charged particles emitted**.

It can be detected only through **characteristic radiation.**





2K capture in ^{78}Kr is a **78.6%** fraction of all **ECEC** events.

M. Doi and T. Kotani, Prog. Theor. Phys.87, 1207 (1992)

Single K-vacancy characteristic radiation:

$K_{\alpha1}$=**11.221 keV** (58.1%), $K_{\alpha2}$=**11.181 keV** (30.2%)

$K_{\beta1,3}$=**12.491 keV** (11%), $K_{\beta2}$=**12.651 keV** (0.6%)

http://xdb.lbl.gov

Fluorescence yield for Se*: $\boldsymbol{\omega_K}$**=0.596**

Binding energy: $\mathbf{B_K}$ **= 12.65 keV**

Se*	Se*	Se**
e_A	e_A	ω_A^2 = **0.163**
e_A	K_X	$\omega_A{}^*\omega_K$ = **0.241**
K_X	e_A	$\omega_K{}^*\omega_A$ = **0.241**
K_X	K_X	ω_K^2 = **0.355**

First approximation: $\boldsymbol{\omega_K^2}$ = **0.355**

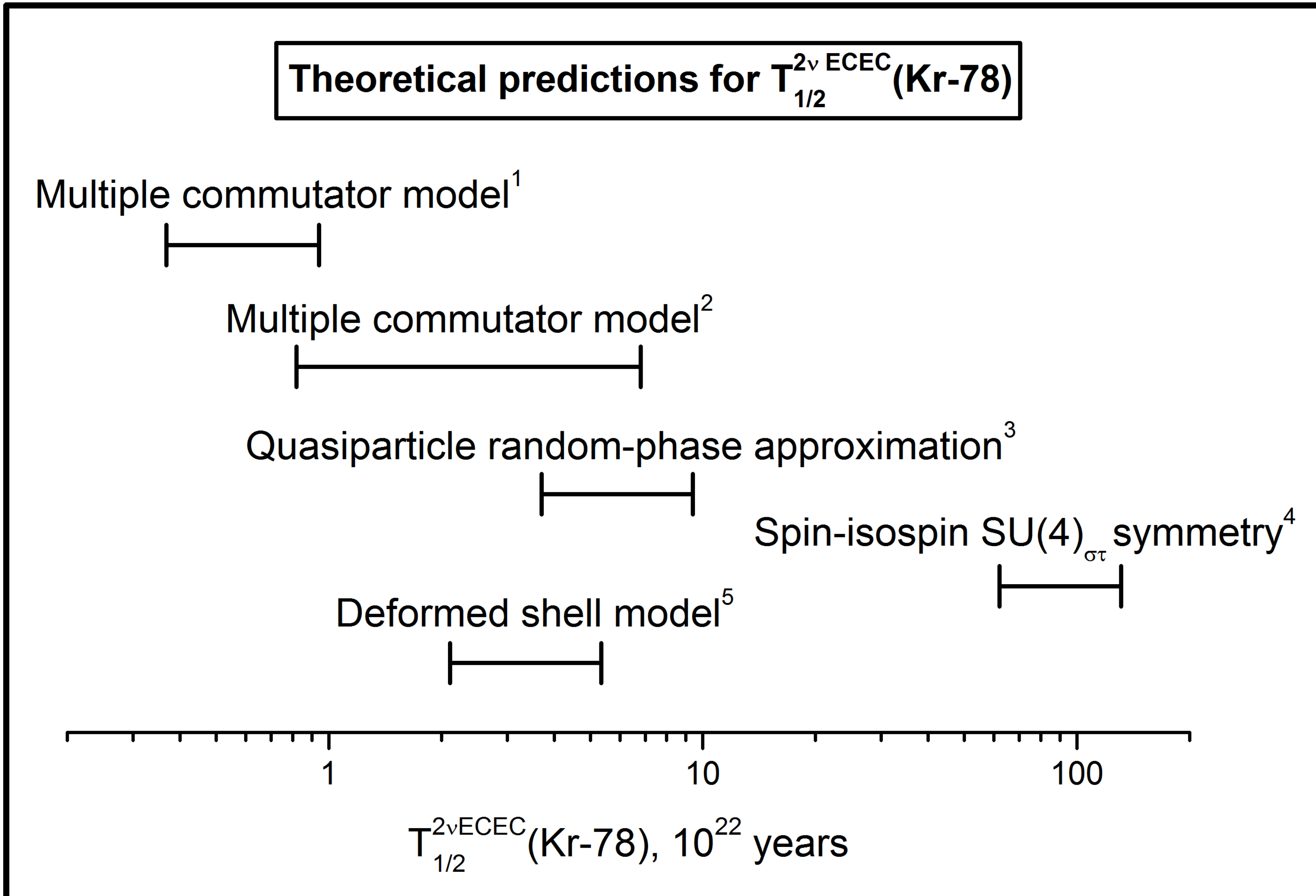
Se** = Se* · Se*, $E_{rel} = 2B_K(Se)$ = **25.3 keV**

Dirac-Fock method: $\boldsymbol{\omega_K^2}$ **= 0.47**

Released energy: E_{rel} = **25.8 keV**

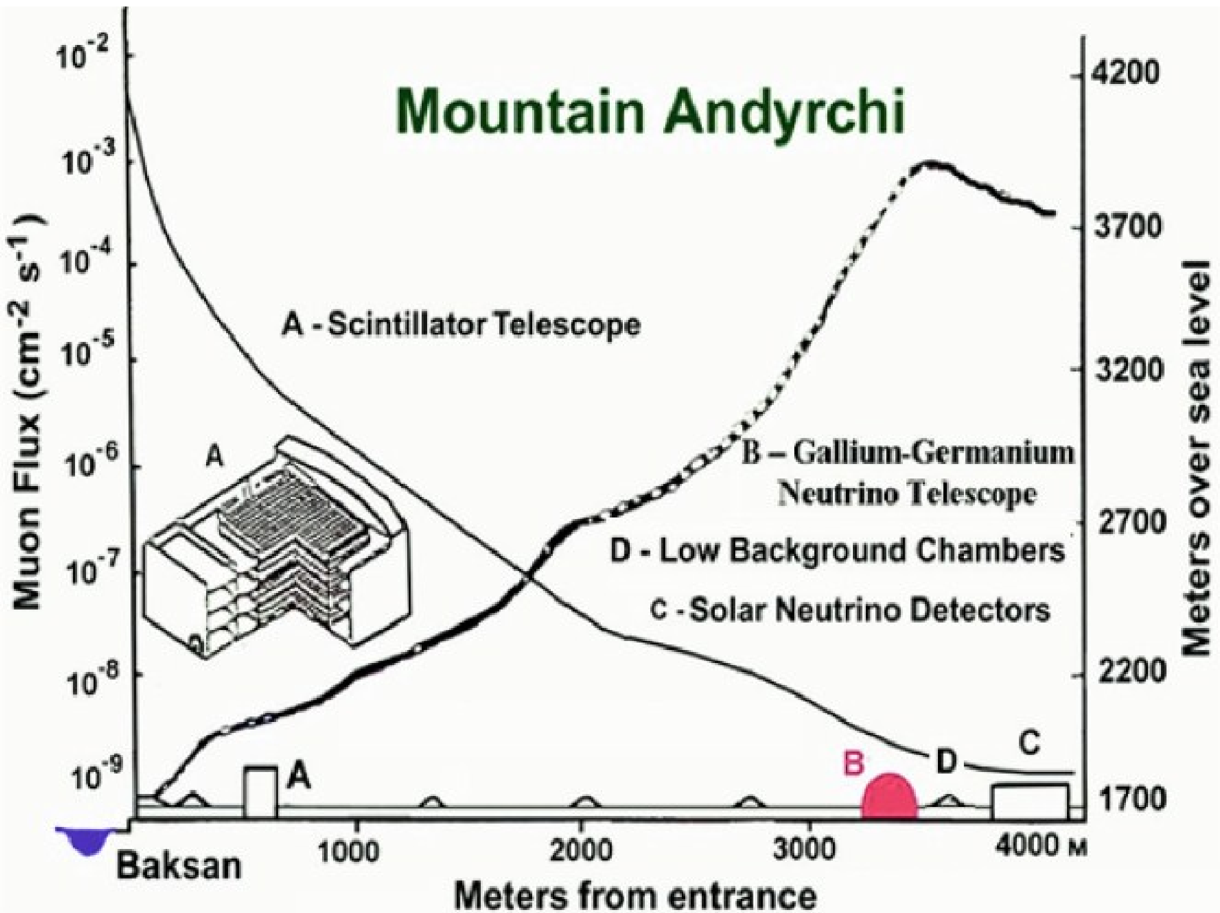
F. F. Karpeshin, M. B. Trzhaskovskaya, and V. V. Kuzminov,
Bull. Russ. Acad. Sci.: Phys.76, 884 (2012).

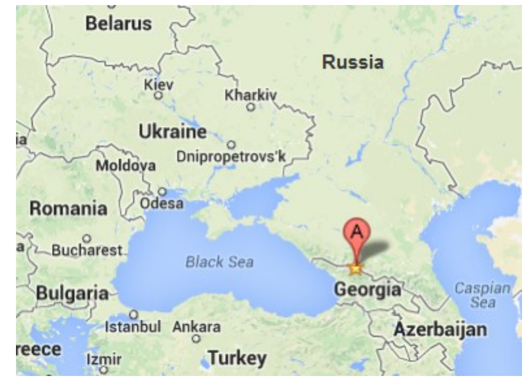
ω_K^2 uncertainty → $T_{1/2}$ syst. error



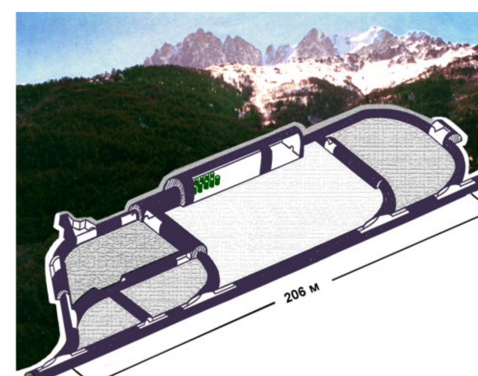
[1] M. Aunola and J. Suchonen, Nucl. Phys. A 602, 133(1996).
[2] J. Toivanen and J. Suhonen,Phys.Rev.C55, 2314 (1997).
[3] M. Hirschet al.,Z. Phys. A347, 151 (1994).
[4] O. Rumyantsev and M. Urin,Phys. Lett. B443, 51 (1998).
[5] S. Mishra, A. Shukla, R. Sahu, and V. K. B. Kota,Phys.Rev.C 78, 024307 (2008).

The experiment has been carried out at the **Baksan Neutrino Observatory INR RAS (Russia)** in one of the chambers of the underground laboratory of the Gallium Germanium Neutrino Telescope during 2005-2012 years.



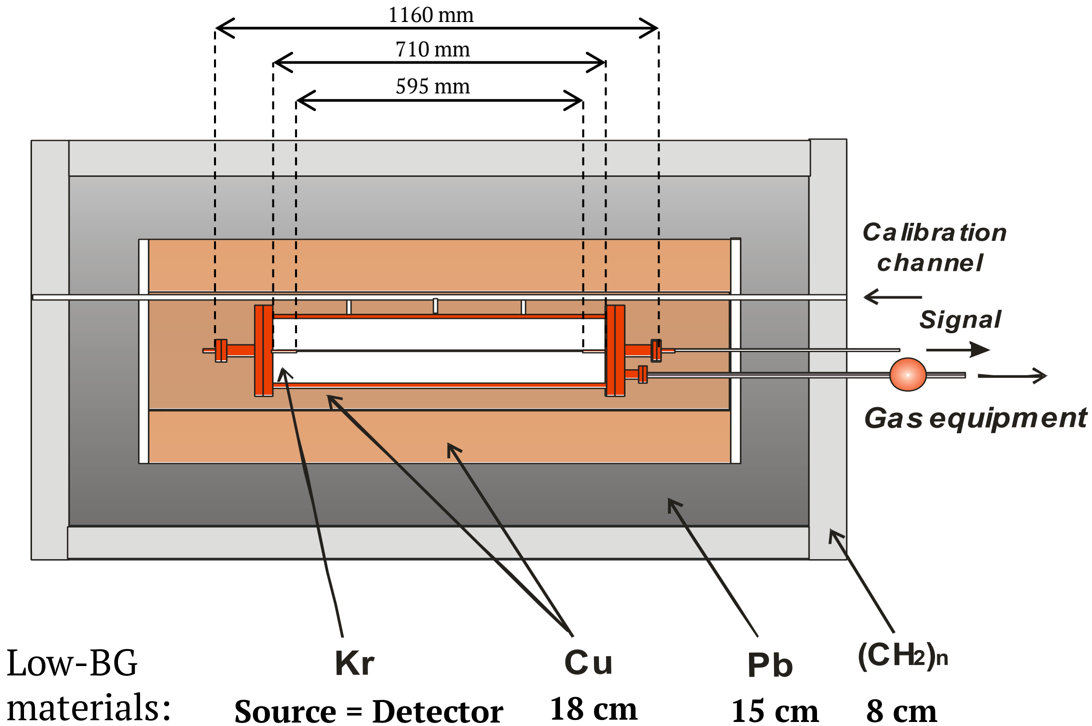


Global Intensity
(3,0±0,15)$\cdot 10^{-9}$ μ cm$^{-2}\cdot$ s^{-1}
~ 4800 m.w.e.



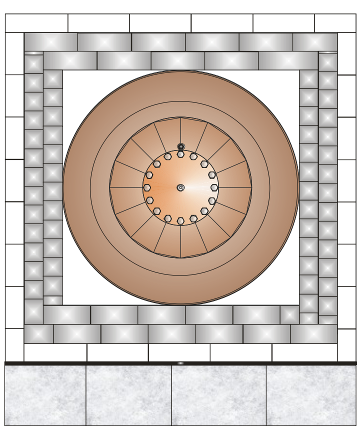

М
штольня
Вспомогательная
В-1
нормально закрытые
В -1
нормально закрытые
К -1
каски

Large low-background copper proportional counter



Main properties:

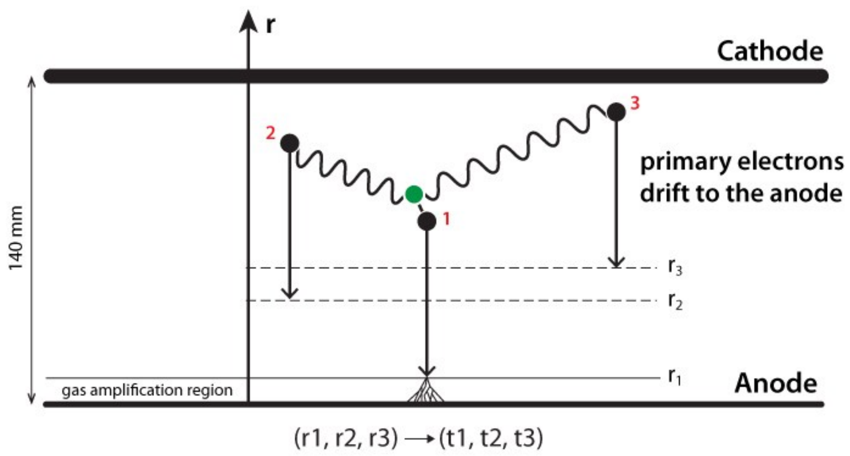
Case material	Cu
Inner diameter, mm	140, 137
Outer diameter, mm	150
Anode diam., mm	0.010
Total volume, L	11.0, 10.3
Operating volume, L	9.16, 8.77
Pressure, bar	4.42, 4.609
Capacity, pF	30.6
Anode resistance , Ohm	613
High voltage, V	2400
Amount of krypton atoms	$1.08 \cdot 10^{24}$



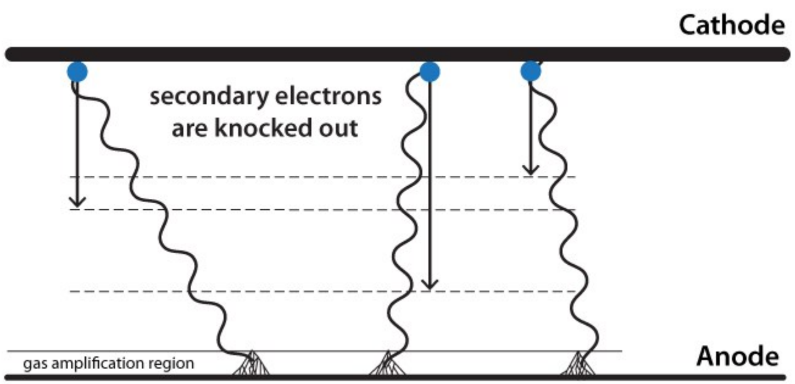
Proportional counter — **Pre-amp (CSA)** — **Amp** — **Dig. Osc.** **LA-n20-12PCI** — **PC**

Samples	Isotope content (vol %)					
	78	**80**	**82**	**83**	**84**	**86**
Enrich. Kr (47.65 L)	99.81	0.17	0.005	0.005	0.005	0.005
Depl. Kr (100 L)	0.002	0.41	41.36	58.23	0.003	-
Nat. Kr	0.354	2.27	11.56	11.55	56.9	17.37

Three-point event



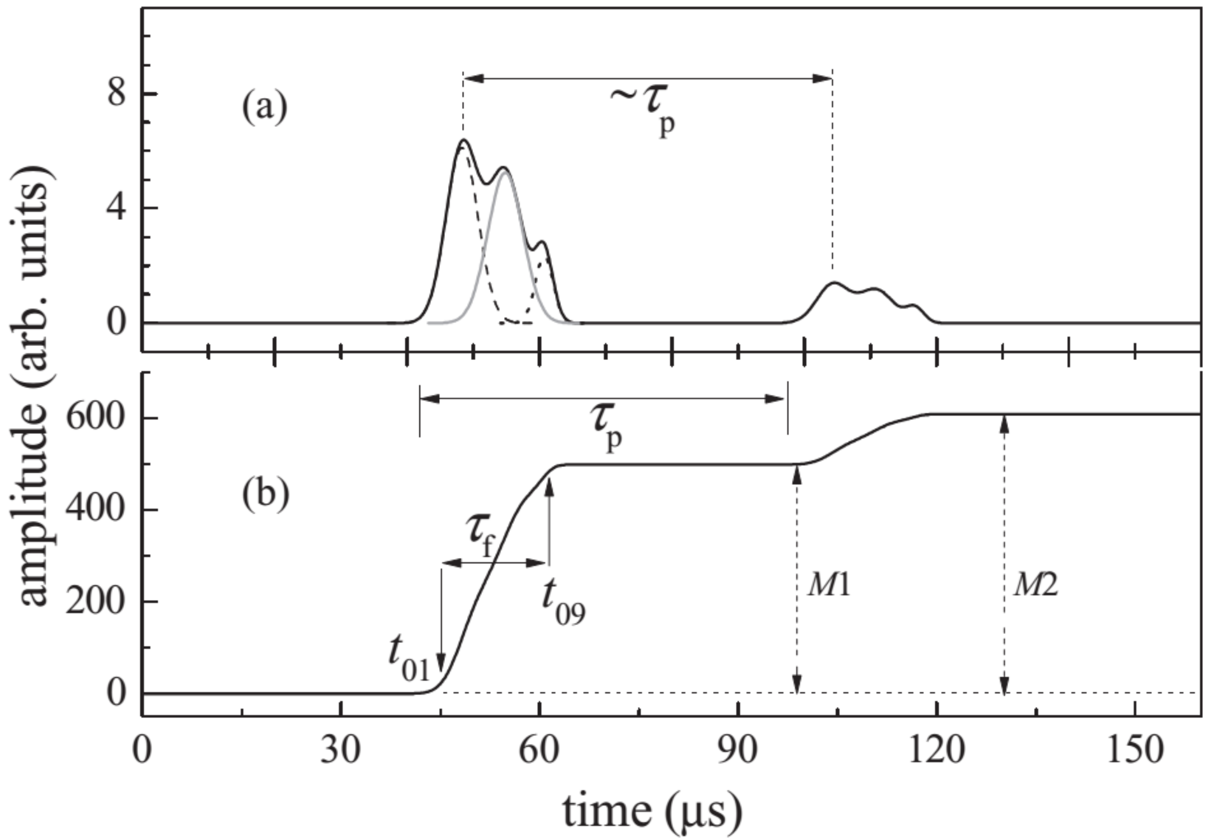
Afterpulse



50% of K_X rays (11 keV) are absorbed at the distance of 16 mm from their origin. Extrapolated range for Auger electrons (3 keV) is 0.5 mm.

Therefore electrons are absorbed almost immediately while X-rays pass far away, creating three clusters of ionization. Information on the primary charge distribution along counter radius is fully represented in the pulse shape. **Three-point events** have a number of unique features and were the subject of study.

Pulse shape analysis



Current pulse

Charge pulse

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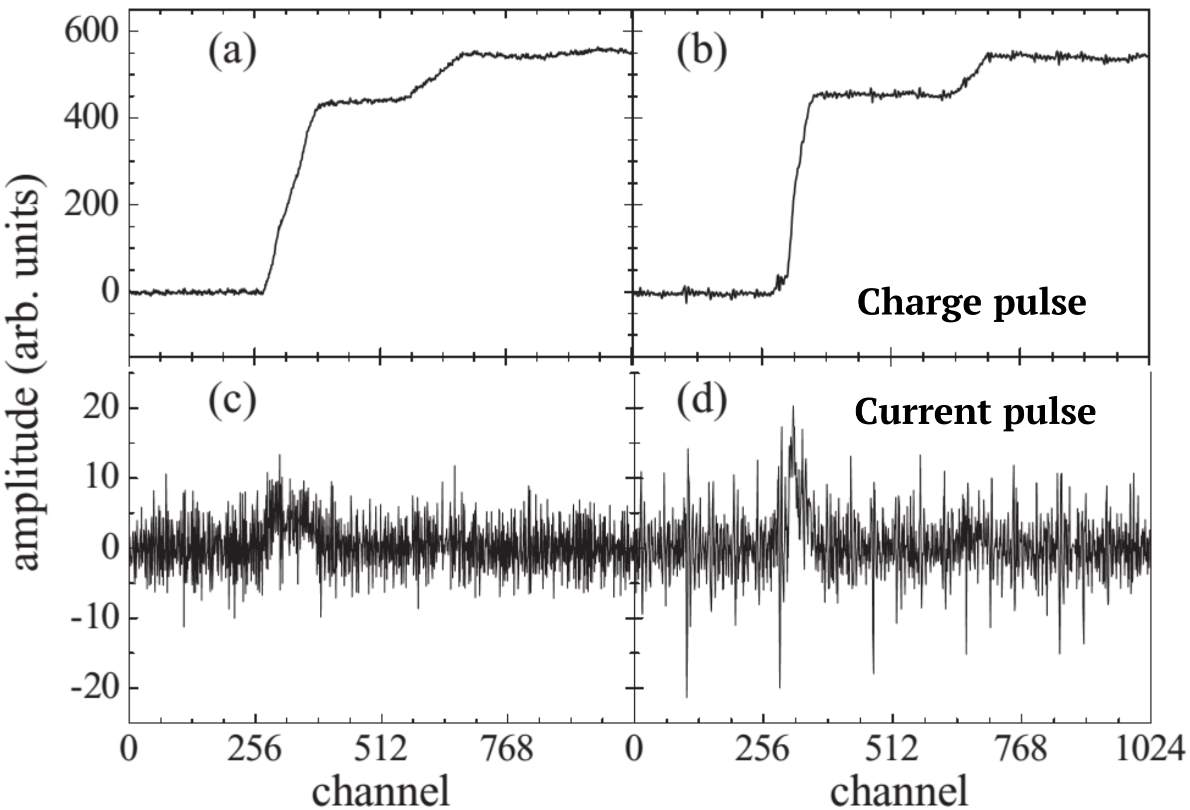
Idealized pulse shape expected from 2K capture in ^{78}Kr leading to three-point event (K,K,e_A).
M1-amplitude is proportional to the energy release in detector.

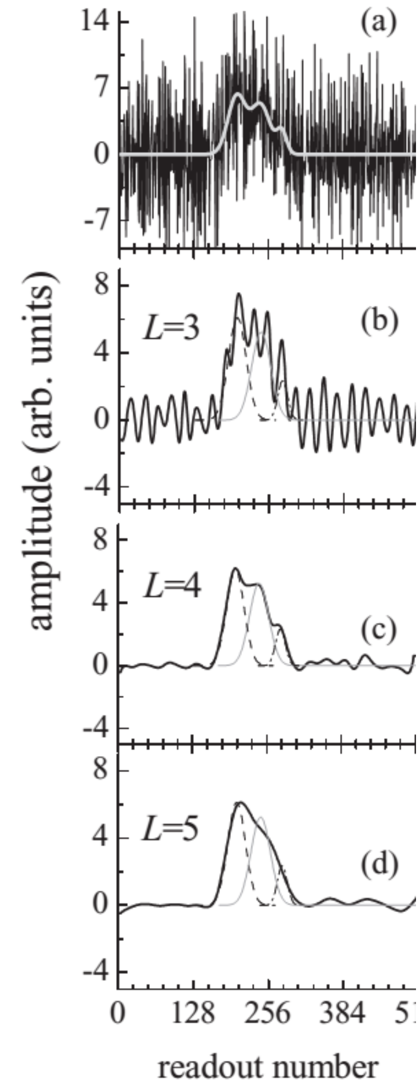
τ_f = $t_{09} - t_{01}$ — **pulse rise time**, t_{01} and t_{09} are moments of 10% and 90% rise of the amplitude

τ_p — time between the primary pulse and the **after-pulse** appearance

$\lambda = (M2 - M1)/M1$ — **relative amplitude** of the afterpulse

Real signals of candidate events





Real signals of candidate events from 2K capture in ^{78}Kr leading to three-point event (K,K,e_A). The signals were denoised with wavelet transformation and were symmetrized by discarding ionic component contribution, leaving only primary electrons' signal.

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Calibration and gas purification

Every ~2 weeks LPC was calibrated with an isotope gamma source of ^{109}Cd: E_γ = 88 keV, Y = 0.036 γ/decay

The samples had no quenching or accelerating gaseous additions and were purified before filling through a Ni/SiO_2 absorber from electronegative admixtures.

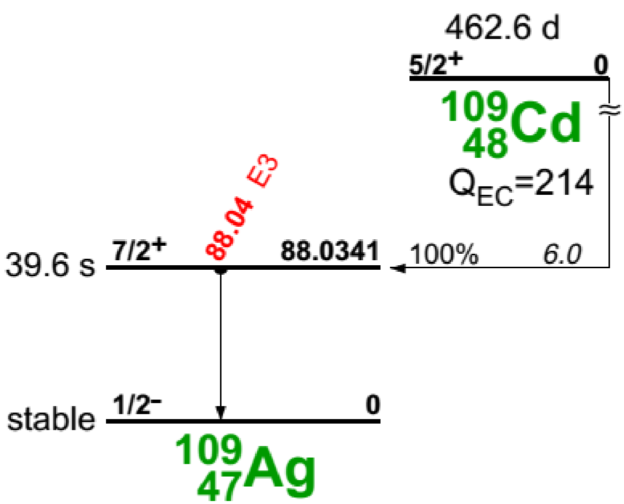
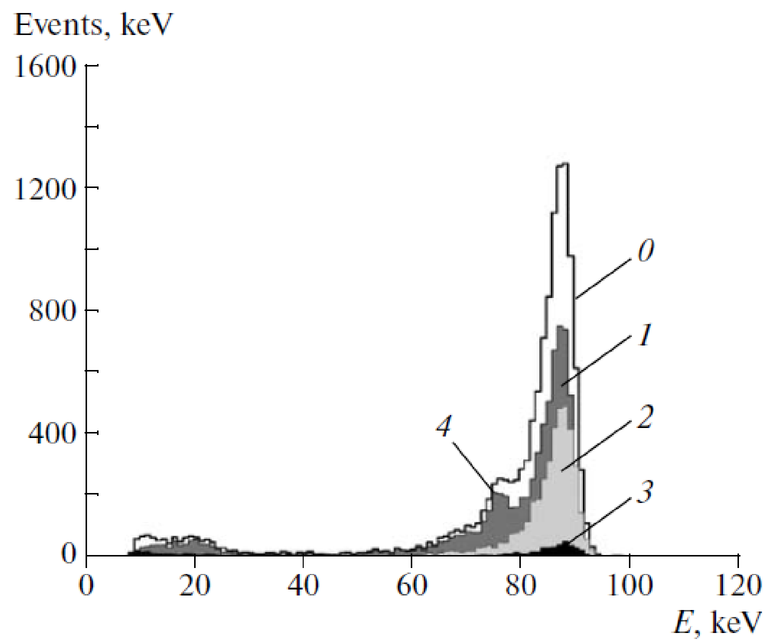


Table of Isotopes EIGHTH EDITION, Richard B. Firestone, Version 1.0, March, 1996



88 keV peak resolution is ~5.7 keV

Two stages of measurements

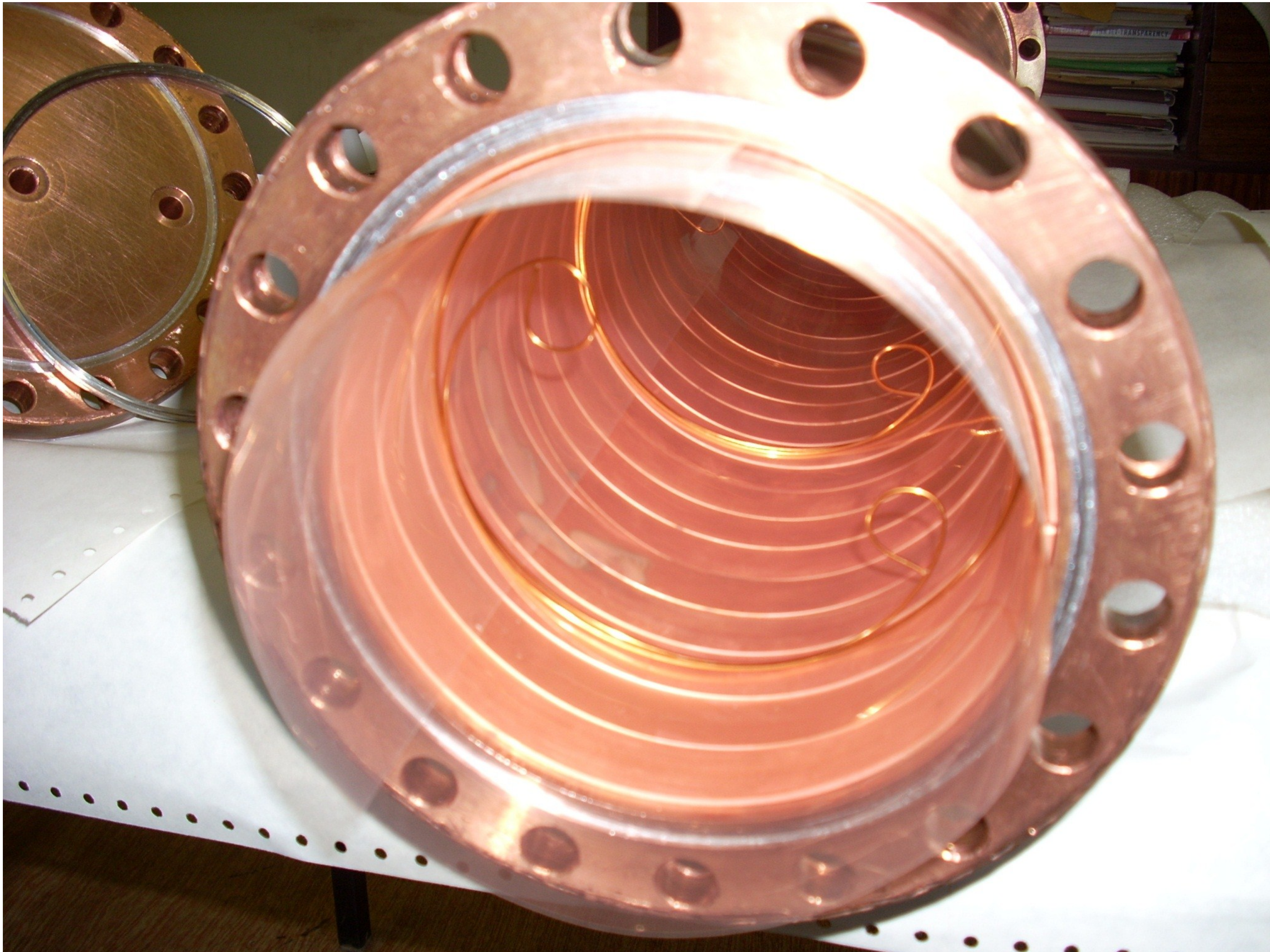
First stage: enriched ^{78}Kr – 8400 h, depleted ^{78}Kr – 5000 h
Second stage: enriched ^{78}Kr – 9457 h, depleted ^{78}Kr – 6243 h

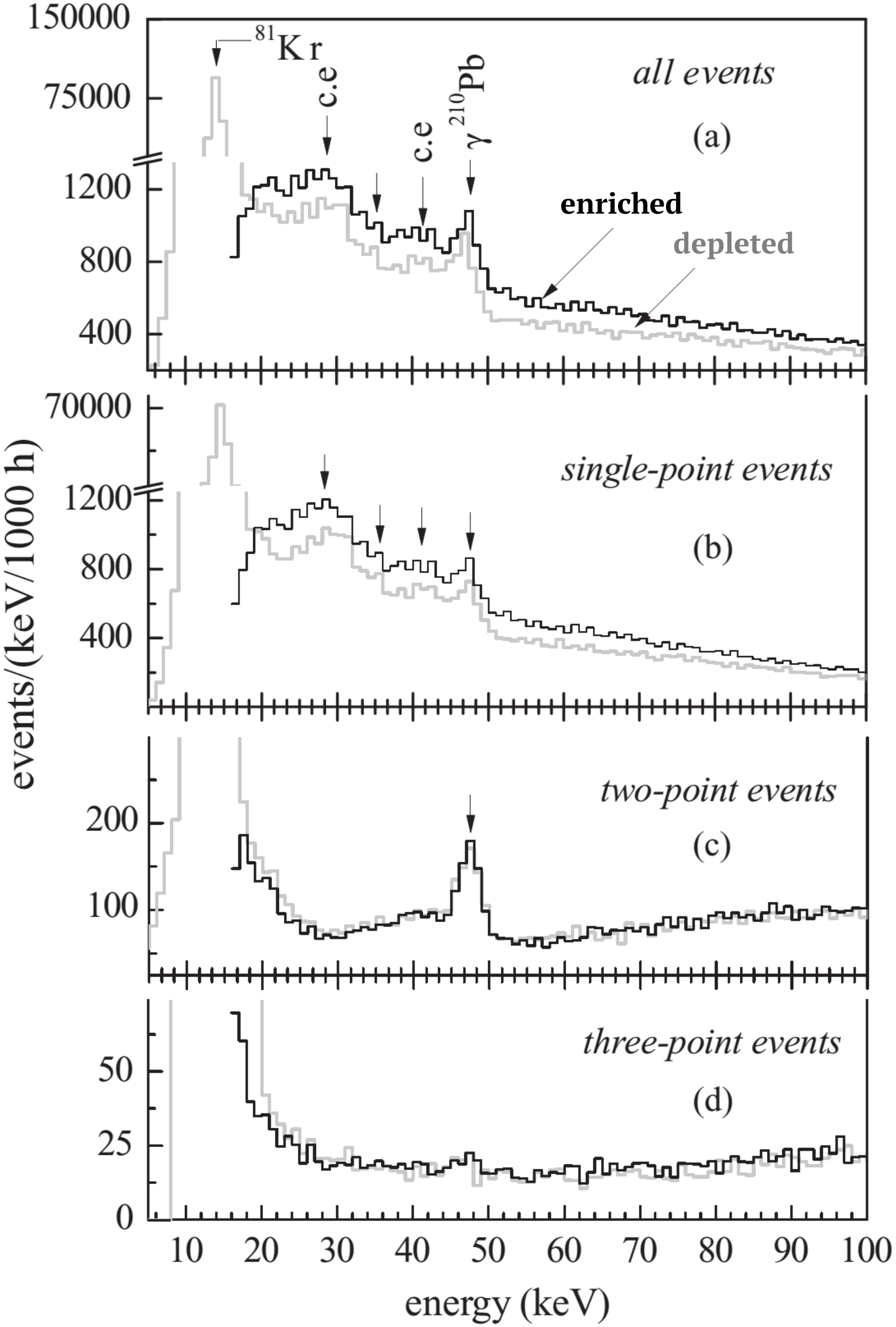
The casing of detector was made of M1k-grade copper. In the second stage, inner surface of counter's casing was shielded with M0k copper, characterized by lower amount of radioactive admixtures. This shielding was made as a tightly adjusted set of rings made of a copper strip (1.5 mm thick and 20 mm wide).

A layer of copper of 1.5 mm thickness completely absorbs electrons escaping from the counter casing with energies up to ~1.6 MeV. Such an update of the setup led to reduction of the background owing to α-particles by ~20 times. The background in the energy range from 10 to 100 keV was reduced by ~7 times. The positive effect of this copper layer led us to add two layers of M0k-copper (3 mm thick) mounted on the inner surface of the flanges.

The total volume between the flanges became 10.3 L, and the operating volume between the ends of the anode wire caps became 8.77 L. The counter was filled with working gases to the pressure of 4.609 bar, and the amount of krypton atoms in the operating volume remained practically the same ($1.08 \cdot 10^{24}$).

Experimental set-up





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First stage spectra

13.5 keV peak resolution is ~2 keV

Background sources:

Sup. from cleaning with ethanol
^{14}C: β^-, $T_{1/2}$ = 5700 y, Q_β = 156.5 keV

Atmosphere
^{81}Kr: EC (K 87.5%), $T_{1/2} = 2.29 \times 10^5$ y
^{81}Br*: E* = 13.5 keV, ω_K=0.614

Atmosphere
^{85}Kr: β^-, $T_{1/2}$ = 10.752 y, Q_β = 687 keV

From ^{238}U decay chain
^{210}Pb: β^-, $T_{1/2}$ = 22.2 y, Q_β = 63.5 keV
84% **^{210}Bi**†: E† =46.5 keV
E_γ =46.5 keV (4.25% per decay)
$E_{c.e.}$=30.1 keV (52% per decay)
$E_{c.e.}$=43.3 keV (13.6% per decay)

Table of Isotopes EIGHTH EDITION, Richard B. Firestone, Version 1.0, March, 1996

Evaluated Nuclear Structure Data File (ENSDF), http://www.nndc.bnl.gov/ensdf

First stage spectra

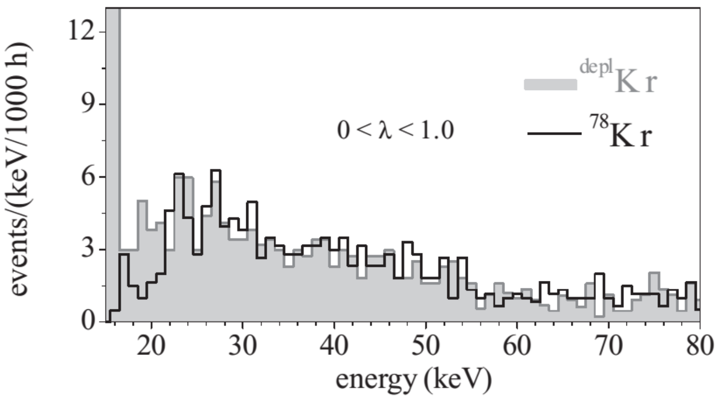
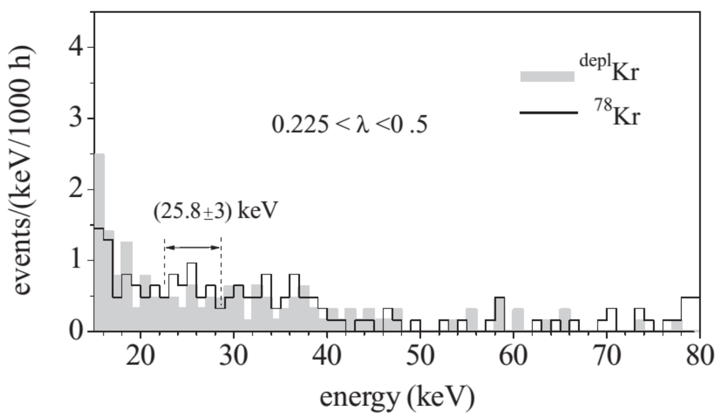


FIG. 6. The three-point spectra selected under the conditions "C1" and "C2".



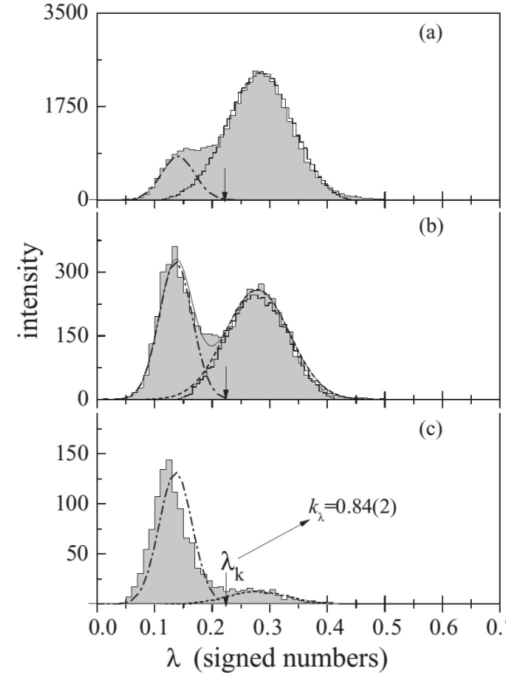


FIG. 8. The distributions of the events in the LPC filled with depleted krypton with energies 11.5−15.5 keV (^{81}Kr, black histogram) and with energies 20−80 keV (shaded region). The dash-dotted and dotted curves are the result of a fitting operation of the shaded region. (a) Single-point events, (b) two-point events, and (c) three-point events.

If three Gaussians' areas correspond to energy depositions E_1, E_2 and E_3 ($E_1 \leqslant E_2 \leqslant E_3$), then the selection criteria are:

C1: 0.9 keV $\leqslant E_1 \leqslant$ 4.5 keV (Auger electrons)

C2: $0.7 \leqslant E_2 / E_3 \leqslant 1.0$ (two K-rays)

λ: $0.225 \leqslant \lambda \leqslant 0.5$, $\lambda = (M2 - M1)/M1$ (proportional range, discards edge effects)

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First stage results

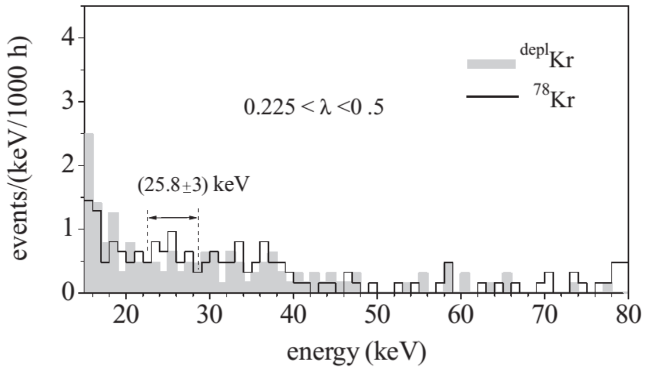

FIG. 9. The three-point spectra selected under the conditions (C1 and C2) and $\lambda \geqslant 0.225$.

Range: (25.8±3) keV
n_{enr} =(38.1±6.3) y^{-1}
n_{depl}=(20.7±6.0) y^{-1}
n_{exp} =$n_1 - n_2$=(17.4±8.7) y^{-1}

The half-life limit has been calculated using formula

$$\lim T_{1/2} = \ln 2 \cdot N \cdot \frac{p_3 \cdot \varepsilon_p \cdot \varepsilon_3 \cdot \alpha_k \cdot k_\lambda}{\lim(n_{\text{exp}})}, \qquad (13)$$

where $N = 1.08 \times 10^{24}$ is the number of ^{78}Kr atoms in the operating volume of the counter, $p_3 = 0.47$ is the fraction of $2K$ captures accompanied by the emission of two K x rays; $\varepsilon_p = 0.81 \pm 0.01$ is the probability of two K photons to be absorbed in the operating volume; $\varepsilon_3 = 0.5 \pm 0.05$ is the efficiency to select three-point events owing to $2K$ capture in ^{78}Kr; $\alpha_k = 0.985 \pm 0.005$ is the fraction of events with two K photons that could be registered as distinct three-point events; $k_\lambda = 0.84 \pm 0.02$ is the useful event selection coefficient for a given threshold for λ [Fig. 8(c)]. The result obtained is

$$T_{1/2}^{2\nu 2K}(\text{g.s.} \rightarrow \text{g.s.}) \geqslant 3.7 \times 10^{21}\ \text{y}(90\%\text{C.L.}).$$

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Second stage spectra

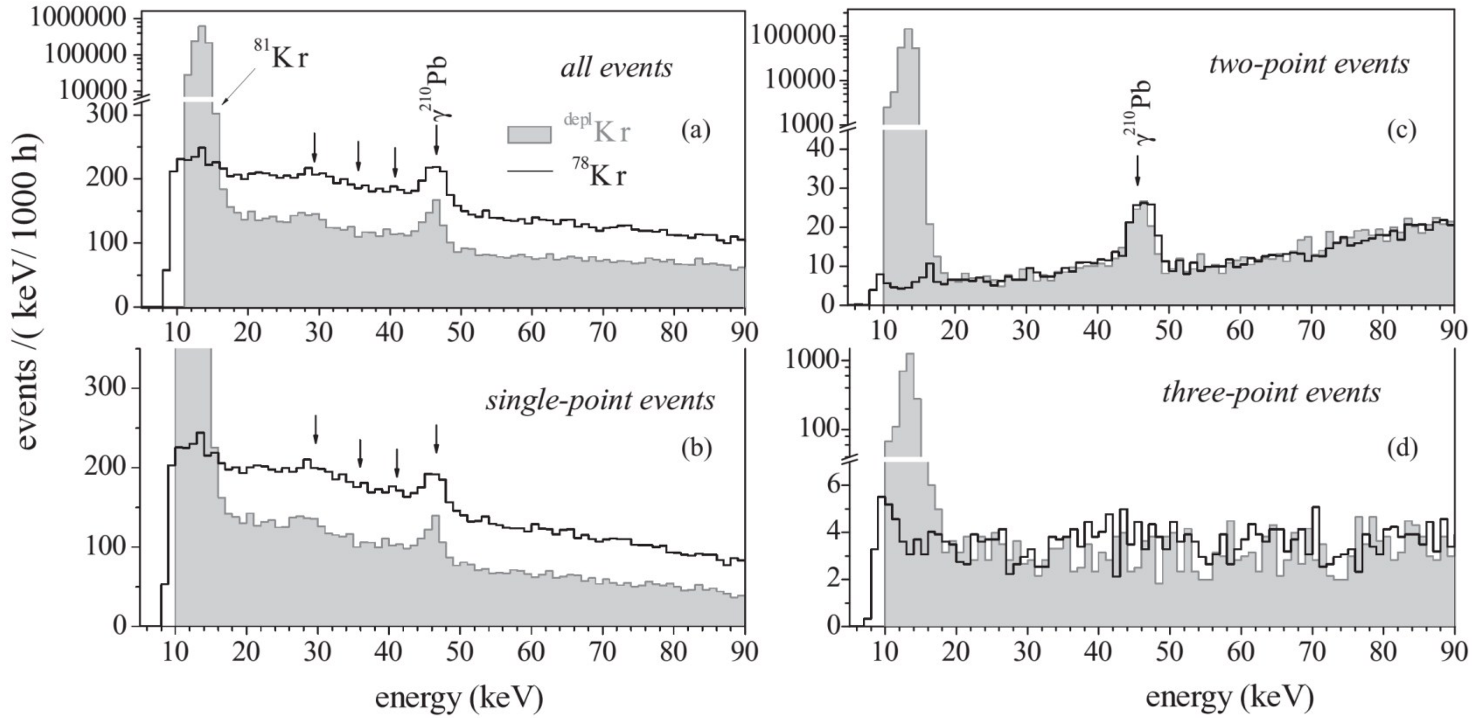

FIG. 10. Pulse height $M1$ spectra (data of the second stage of measurements normalized for 1000 h) of the background of the LPC filled with krypton enriched in ^{78}Kr (black line) and with depleted krypton (gray bar graph). (a) All events, (b) single-point events, (c), two-point events, and (d) three-point events.

Sup. from cleaning with ethanol
^{14}C: β^-, $T_{1/2}$ = 5700 y, Q_β = 156.5 keV

Atmosphere
^{81}Kr: EC (K 87.5%), $T_{1/2}$ = 2.29 ×10^5 y
^{81}Br^{*K}: E^{*K} = 13.5 keV, ω_K=0.614

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From ^{238}U decay chain, through ^{222}Rn
^{210}Pb: β^-, $T_{1/2}$ = 22.2 y, Q_β = 63.5 keV
84% **^{210}Bi†**: $E^\dagger$ =46.5 keV
E_γ =46.5 keV (4.25% per decay)
$E_{c.e.}$=30.1 keV (52% per decay)
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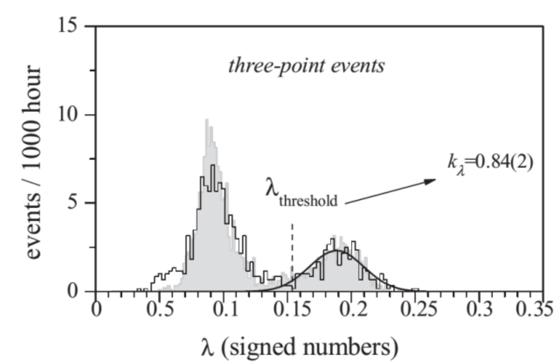

Evaluated Nuclear Structure Data File (ENSDF), http://www.nndc.bnl.gov/ensdf

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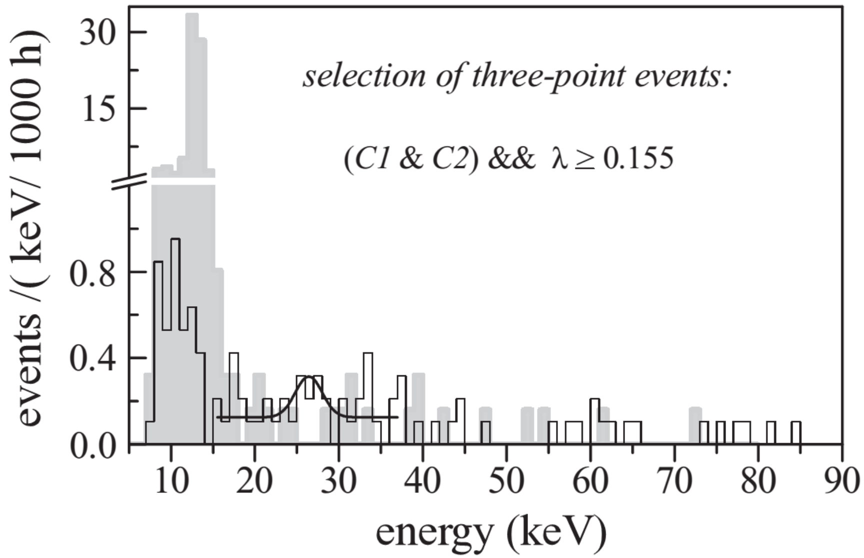
Second stage results



If three Gaussians' areas correspond to energy depositions E_1, E_2 and E_3 ($E_1 \leqslant E_2 \leqslant E_3$), then the selection criteria are:

C1: 0.89 keV $\leqslant E_1 \leqslant$ 4.5 keV (Auger electrons)

C2: $0.7 \leqslant E_2 / E_3 \leqslant 1.0$ (two K-rays)

λ: $0.155 \leqslant \lambda$, $\lambda = (M2 - M1)/M1$

Range: (25.8±3) keV

N_{enr} = 15 (9457 h), n_{enr} =13.9 y^{-1}

N_{depl} = 8 (6243 h), n_{depl}=11.2 y^{-1}

$$N_{\exp} = 6.6^{+6.3}_{-4.3}\ \mathrm{y}^{-1}$$

$$T_{1/2}^{2\nu 2K}(\mathrm{g.s.} \rightarrow \mathrm{g.s.}) = \left[1.8^{+4.4}_{-0.9}(\mathrm{stat}) \pm 0.2(\mathrm{syst})\right] \times 10^{22}\mathrm{y};$$

its conservative value would be

$$T_{1/2}^{2\nu 2K}(\mathrm{g.s.} \rightarrow \mathrm{g.s.}) \geqslant 8.7 \times 10^{21}\mathrm{y}(90\%\mathrm{C.L.}).$$

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G. J. Feldman and R. D. Cousins, Phys.Rev.D57, 3873 (1998)

Combined result

To increase the statistical significance of the observed in both series excess of events, which could be attributed to the effect under study, their results were combined. Average annual count rates have been summed and then normalized to 1 y.

The following count rates of background were obtained $n_1 = 26.0^{+3.8}_{-3.6}$ y^{-1} and $n_2 = 13.2^{+3.6}_{-3.2}$ y^{-1}, giving the count rate of $2\nu 2K$-capture events in ^{78}Kr equal to $n_{\text{exp}} = n_1 - n_2 = 12.8^{+5.2}_{-4.8}$ y^{-1}. Statistical significance of this result is $\sim 2.5\sigma$. At a confidence level of 90% the half-life was found to be

$$\boxed{T_{1/2}^{2\nu 2K}(\text{g.s.} \to \text{g.s.}) = [9.2^{+5.5}_{-2.6}(\text{stat}) \pm 1.3(\text{syst})] \times 10^{21}\text{y},}$$

with a conservative value

$$T_{1/2}^{2\nu 2K}(g.s. \to g.s.) \geqslant 5.5 \times 10^{21}\text{y}.$$

YU. M. GAVRILYUK et al. PHYSICAL REVIEW C87, 035501 (2013)

G. J. Feldman and R. D. Cousins, Phys.Rev.D57, 3873 (1998)

I gained experience in calibration process and gas operation (transfer and purification).

My goal

My goal is to make a revision of results that were obtained in the described experimental search for 2K capture in Kr-78.

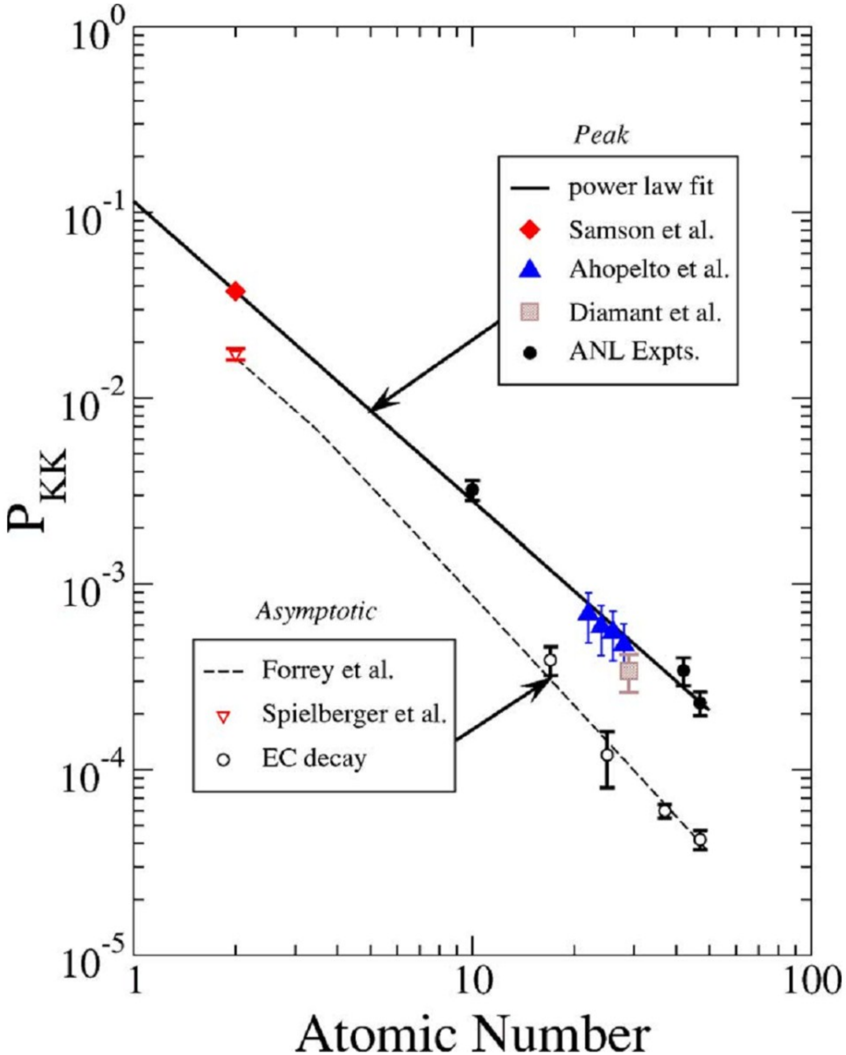
I am trying to identify **background sources** and **effects that could mimic required process**.

Among them may be:

- double photoionization of an atom by single photon
- double ionization caused by electron capture in ^{81}Kr
- subsequent ionization by photoelectron
- photoeffect following Compton scattering
- multiple ionization by beta or alpha particles
- etc.

At the moment I am processing data from irradiation with outer gamma source (^{109}Cd) for the purpose of studying double photoeffect in krypton. On the basis of published papers I have estimated the contribution of **double K-shell photoionization** and **double ionization following electron capture** in ^{81}Kr to the outcome of mentioned experiment.

Double K-shell photoionization



E. P. Kanter et al., PHYSICAL REVIEW A73 022708 (2006)

Photon energy condition:

$$E_\gamma > E_{th} = 2B_K + E_\Delta$$

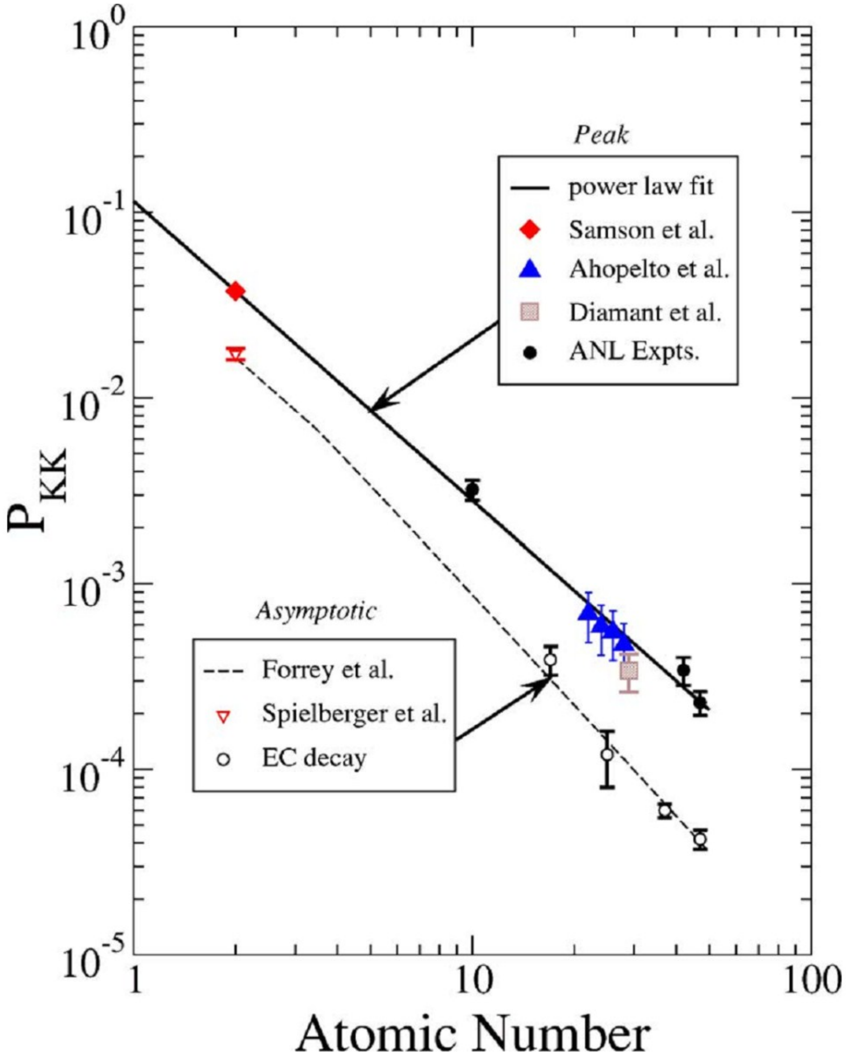
	$2B_K$, keV	E_Δ, keV	E_{th}, keV
Ne	1.740	0.123	1.863
Cu	17.96	0.391	18.351
Mo	40.004	0.65	40.654
Kr	**28.652**	**0.52**	**29.172**

$$P_{KK}(\mathrm{Kr}) = 0.129 \cdot Z^{-1.61} = 3.6 \cdot 10^{-4}$$

29-39 keV: $1.3 \cdot 10^4$ events
If to consider all of them as photoeffect,
We can get ~ 3 events of 2K photoionization in region of 29-39 keV.

R. Diamant et al., Phys. Rev. A, v. 62 (5), 052519(14), (2000).
E. P. Kanter et al., Phys. Rev. Lett., v.83, №3, (1999).
S. H. Southworth et al., AIP Conf. Proc. v. 652, (2003)

Double K-shell ionization following EC



^{81}**Kr**: EC (K 87.5%), $T_{1/2} = 2.29 \times 10^{5}$ y

Due to the change in nuclear charge

$Z \longrightarrow (Z-1)$

SHAKE-OFF process is likely leading to emission of the second K-electron (concept of an energy-independent asymptotic limit of the P_{KK} ratio).

$\mathbf{P_{SO}\,(^{81}Kr) = 0.08 \cdot Z^{-2} = 6{,}2 \cdot 10^{-5}}$

$E = 2B_K(Br) + E_{kin} = 27.4$ keV

We can get ~16 false events at 27.4 keV.

E. P. Kanter et al., PHYSICAL REVIEW A73 022708 (2006)

Conclusions

Combined result of two stages of measurements:

- Total exposure 0.343 kg×y
- Counting rate of 2ν2K capture in ^{78}Kr = $12.8^{+5.2}_{-4.8}\ \mathrm{y}^{-1}$
- $T_{1/2} = [9.2^{+5.5}_{-2.6}(\mathrm{stat}) \pm 1.3(\mathrm{syst})] \times 10^{21}$ y (2.5σ)

  Previous result: $T_{1/2} >= 2.3\times10^{20}$ y (90% C.L.)

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  The value is in agreement with theoretical models
- **Indication** but not evidence

The objective of my Master thesis is to study different background processes for 2K capture in ^{78}Kr.

Summary table

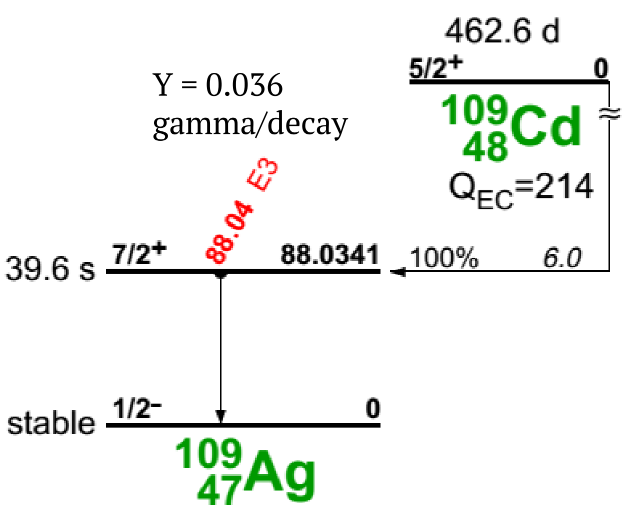
TABLE II. Experimental limits (or values) and theoretical estimates of half-lives for various $\beta\beta$ processes in the transition of ^{78}Kr $\rightarrow$ ^{78}Se. $T_{1/2}$ limits are derived in the present work and Ref. [22] at 90% C.L., while those from Ref. [51] are at 68% C.L. The range given in parentheses for the theoretical estimations of the half-life is given for $g_A/g_V = 1.261$ and 1, respectively.

Transition		Final level of ^{78}Se	$T_{1/2}$ (y)			
			Experiment		Theoretical estimations	
Decay channel	Decay mode		Present work	Other works		
ECEC	2ν	$0^+_{\text{g.s.}}$	–	–	MCM	$(0.37-0.94) \times 10^{22}$ [12]
					MCM	$(0.82-6.80) \times 10^{22}$ [13]
					QRPA	$(3.70-9.40) \times 10^{22}$ [14]
					$SU(4)_{\sigma\tau}$	$(62-156.77) \times 10^{22}$ [15]
					DSM	$(2.11-5.33) \times 10^{22}$ [11]
	2ν	0^+_1, 1499 keV	–	–	MCM	3.7×10^{24} [12]
$2K$	2ν	$0^+_{\text{g.s.}}$	$=9.2^{+5.5}_{-2.6} \times 10^{21}$	$\geqslant 2.3 \times 10^{20}$ [22]	MCM[a]	$(4.7-12) \times 10^{21}$ [12]
	2ν	0^+_1, 1499 keV	$\geqslant 5.4 \times 10^{21}$	–	MCM[a]	4.7×10^{24} [12]
$2K\gamma_b$	0ν	$0^+_{\text{g.s.}}$	$\geqslant 5.5 \times 10^{21}$	–	–	–
$2K$	0ν	2^+, 2838 keV	$\geqslant 5.4 \times 10^{21}$	–	–	–
$K\beta^+$	2ν	$0^+_{\text{g.s.}}$	–	$\geqslant 1.1 \times 10^{20}$ [51]	MCM	6.2×10^{21} [12]
					$SU(4)_{\sigma\tau}$	1.0×10^{24} [15]
$K\beta^+$	0ν	$0^+_{\text{g.s.}}$	–	$\geqslant 5.1 \times 10^{21}$ [51]	–	–
$\beta^+\beta^+$	2ν	$0^+_{\text{g.s.}}$		$\geqslant 2.0 \times 10^{21}$ [51]	–	–
$\beta^+\beta^+$	0ν	$0^+_{\text{g.s.}}$	–	$\geqslant 2.0 \times 10^{21}$ [51]	–	–

[a]The fraction of $2\nu 2K$-capture events in ^{78}Kr with respect to the total number of $2\nu ECEC$-capture events is 78.6% [16].

77	5/2+	−70.169	74.4 m *6*	ε
78	0+	−74.179	≥1.5×10^{21} y **0.355% *3***	2ε
79	1/2−	−74.442	35.04 h *10*	ε
79m	7/2+	−74.312	50 s *3*	IT
80	0+	−77.892	**2.286% *10***	
81	7/2+	−77.694	2.29×10^{5} y *11*	ε
81m	1/2−	−77.503	13.10 s *3*	IT, ε 2.5×10^{-3}%
82	0+	−80.590	**11.593% *31***	
83	9/2+	−79.990	**11.500% *19***	
83m	1/2−	−79.948	1.85 h *3*	IT
84	0+	−82.439	**56.987% *15***	
85	9/2+	−81.480	10.752 y *25*	β−
85m	1/2−	−81.175	4.480 h *8*	β− 78.6%, IT 21.4%
86	0+	−83.266	**17.279% *41***	
87	5/2+	−80.709	76.3 m *5*	β−

NUCLEAR WALLET CARDS, October 2011, Jagdish K. Tuli, National Nuclear Data Center



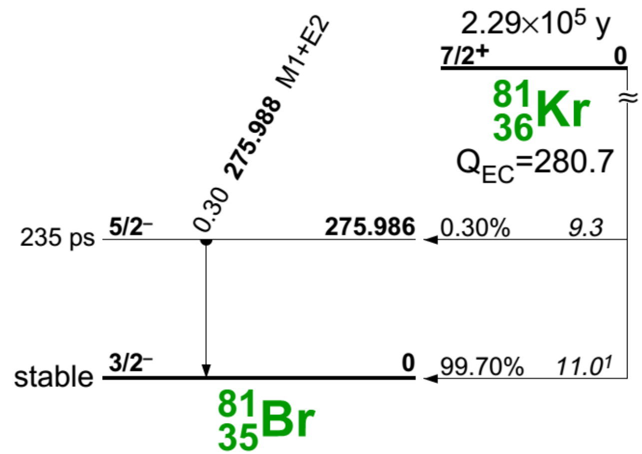
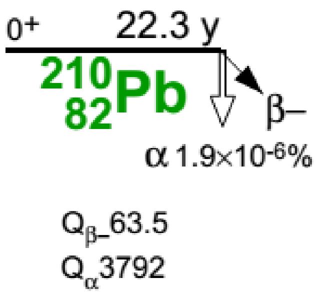
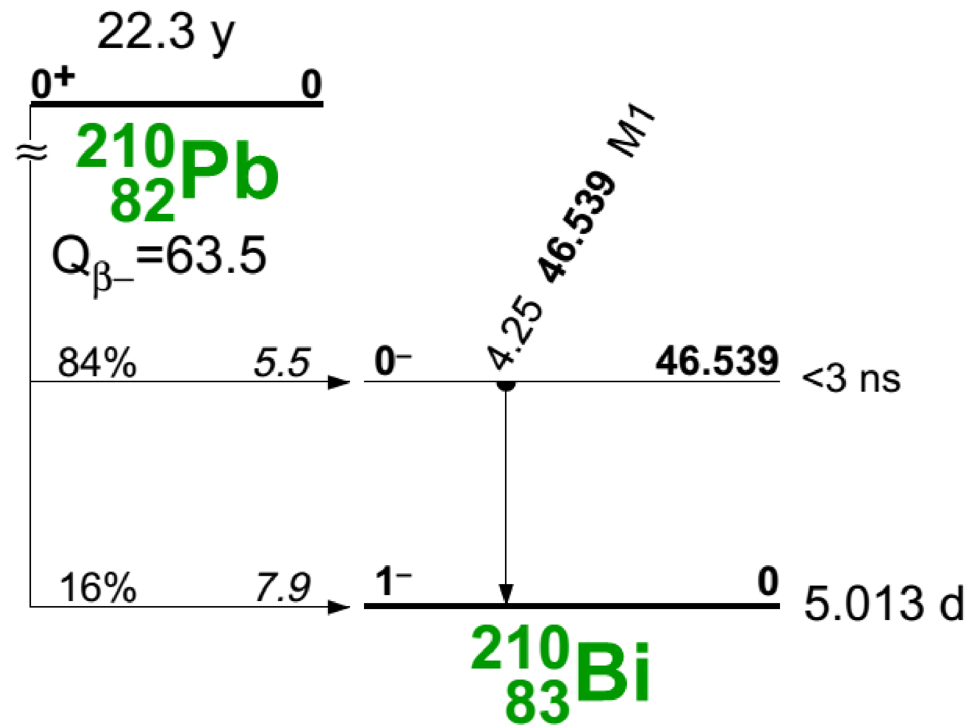


Table of Isotopes EIGHTH EDITION, Richard B. Firestone, Version 1.0, March, 1996





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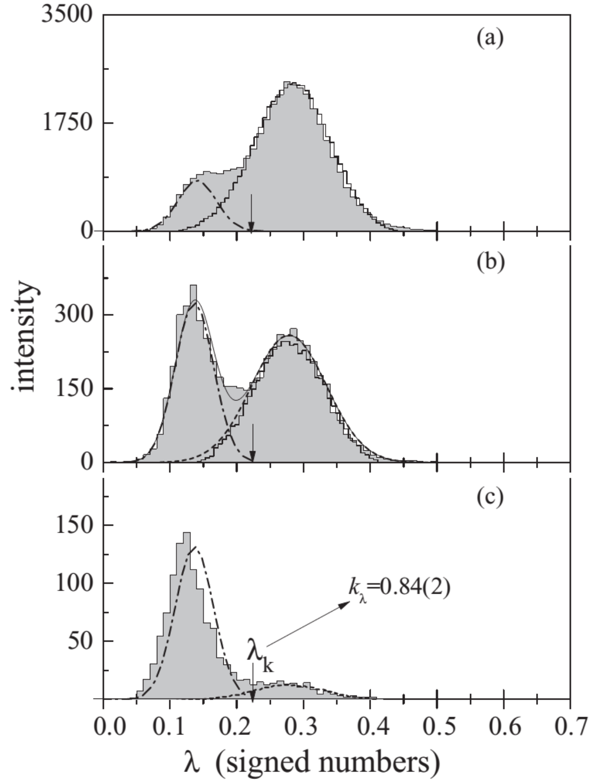


FIG. 8. The distributions of the events in the LPC filled with depleted krypton with energies 11.5−15.5 keV (^{81}Kr, black histogram) and with energies 20−80 keV (shaded region). The dash-dotted and dotted curves are the result of a fitting operation of the shaded region. (a) Single-point events, (b) two-point events, and (c) three-point events.

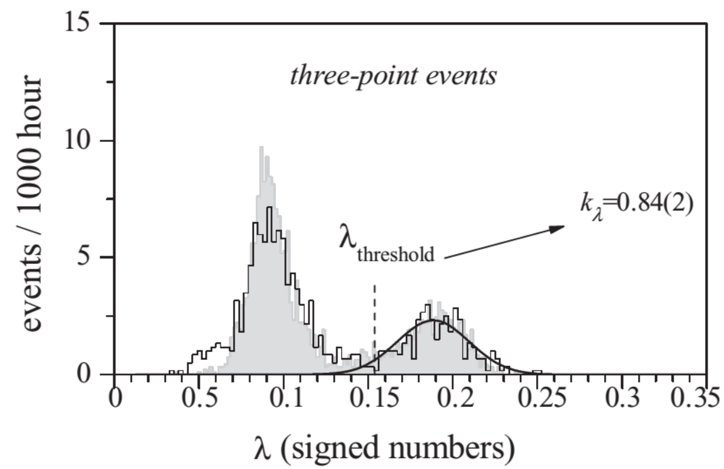
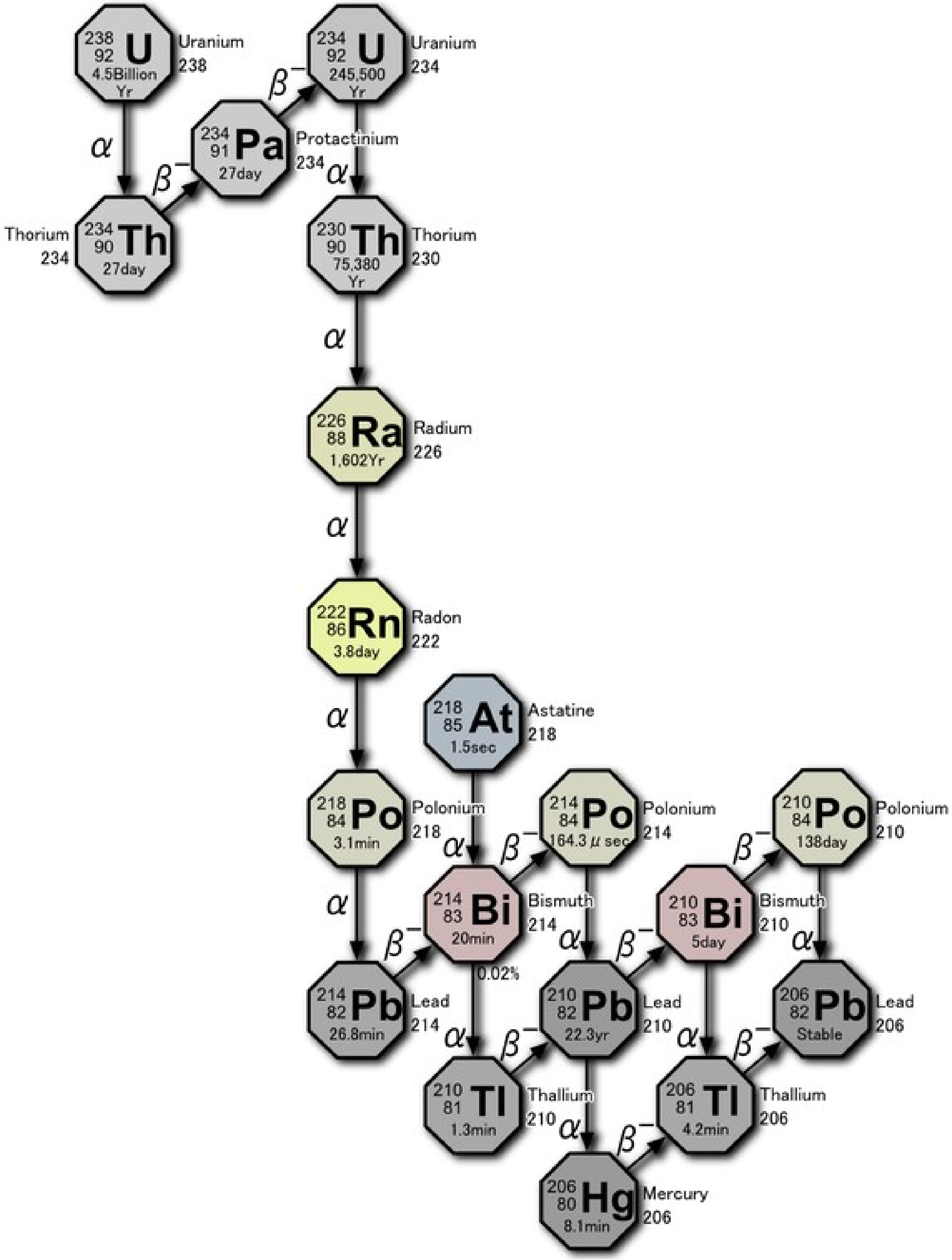


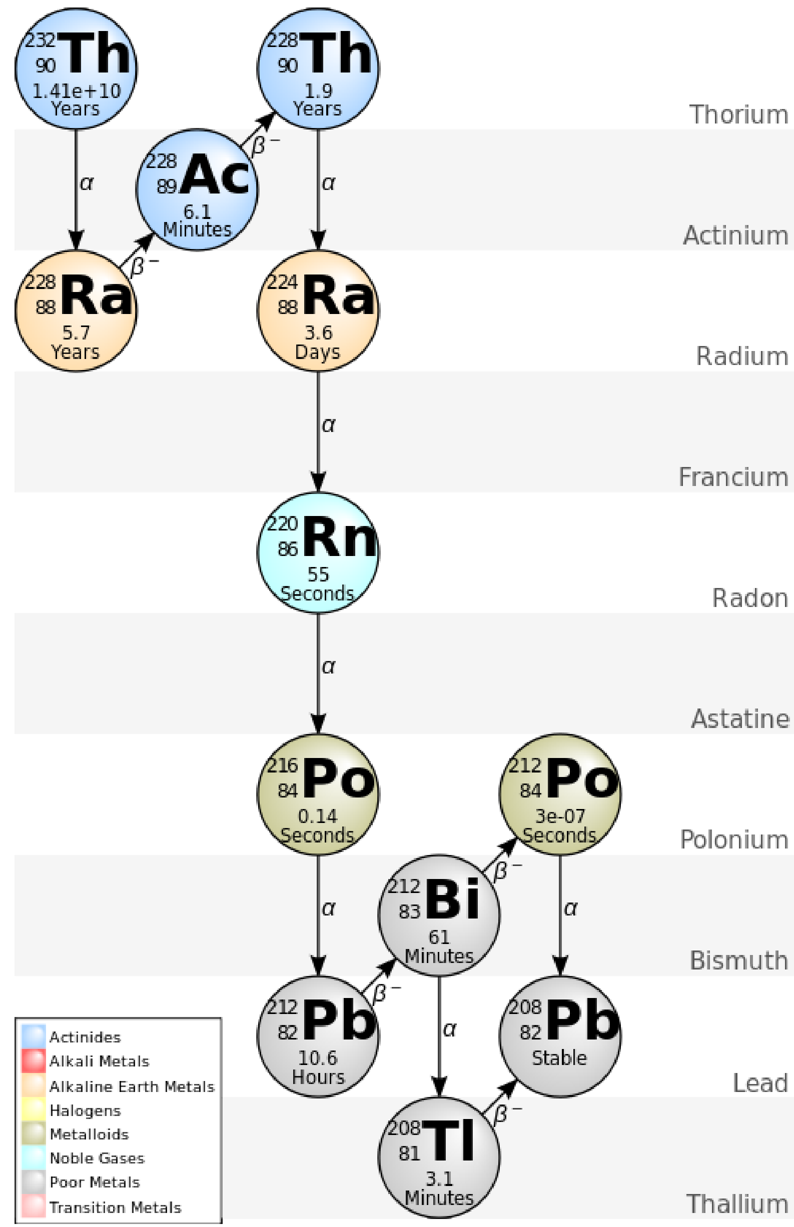
FIG. 11. λ distributions of three-point events in the LPC filled with krypton enriched in ^{78}Kr (black line) and with depleted krypton (gray bar graph).

Cu

Element content, %			
Grade	**Cu**	**O_2**	**P**
M0к	99.97	0.015	0.001
M1к	99.95	0.02	0.002



238 92 U 4.5Billion Yr
Uranium 238
α
β⁻
234 92 U 245,500 Yr
Uranium 234
234 91 Pa 27day
Protactinium 234
β⁻
α
Thorium 234
234 90 Th 27day
230 90 Th 75,380 Yr
Thorium 230
α
226 88 Ra 1,602Yr
Radium 226
α
222 86 Rn 3.8day
Radon 222
α
218 85 At 1.5sec
Astatine 218
218 84 Po 3.1min
Polonium 218
α
β⁻
214 84 Po 164.3 μ sec
Polonium 214
β⁻
210 84 Po 138day
Polonium 210
α
214 83 Bi 20min
Bismuth 214
α
210 83 Bi 5day
Bismuth 210
α
β⁻
β⁻
214 82 Pb 26.8min
Lead 214
0.02%
210 82 Pb 22.3yr
Lead 210
206 82 Pb Stable
Lead 206
α
β⁻
α
β⁻
210 81 Tl 1.3min
Thallium 210
206 81 Tl 4.2min
Thallium 206
α
β⁻
206 80 Hg 8.1min
Mercury 206



232 90 Th 1.41e+10 Years
228 90 Th 1.9 Years
Thorium
228 89 Ac 6.1 Minutes
β⁻
α
α
Actinium
228 88 Ra 5.7 Years
β⁻
224 88 Ra 3.6 Days
Radium
α
Francium
220 86 Rn 55 Seconds
Radon
α
Astatine
216 84 Po 0.14 Seconds
212 84 Po 3e-07 Seconds
Polonium
α
212 83 Bi 61 Minutes
β⁻
α
Bismuth
212 82 Pb 10.6 Hours
β⁻
α
208 82 Pb Stable
Lead
208 81 Tl 3.1 Minutes
β⁻
Thallium
Actinides
Alkali Metals
Alkaline Earth Metals
Halogens
Metalloids
Noble Gases
Poor Metals
Transition Metals

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

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

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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 $\times$ 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 $\sim$2000 times in the energy region of interest. The statistical significance of combined data from two stages of operation equals 2.5σ. Corresponding to such effect, the half-life of ^{78}Kr relative to $2\nu 2K$ capture equals $T_{1/2} = [9.2^{+5.5}_{-2.6}(\text{stat}) \pm 1.3(\text{syst})] \times 10^{21}$ 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.

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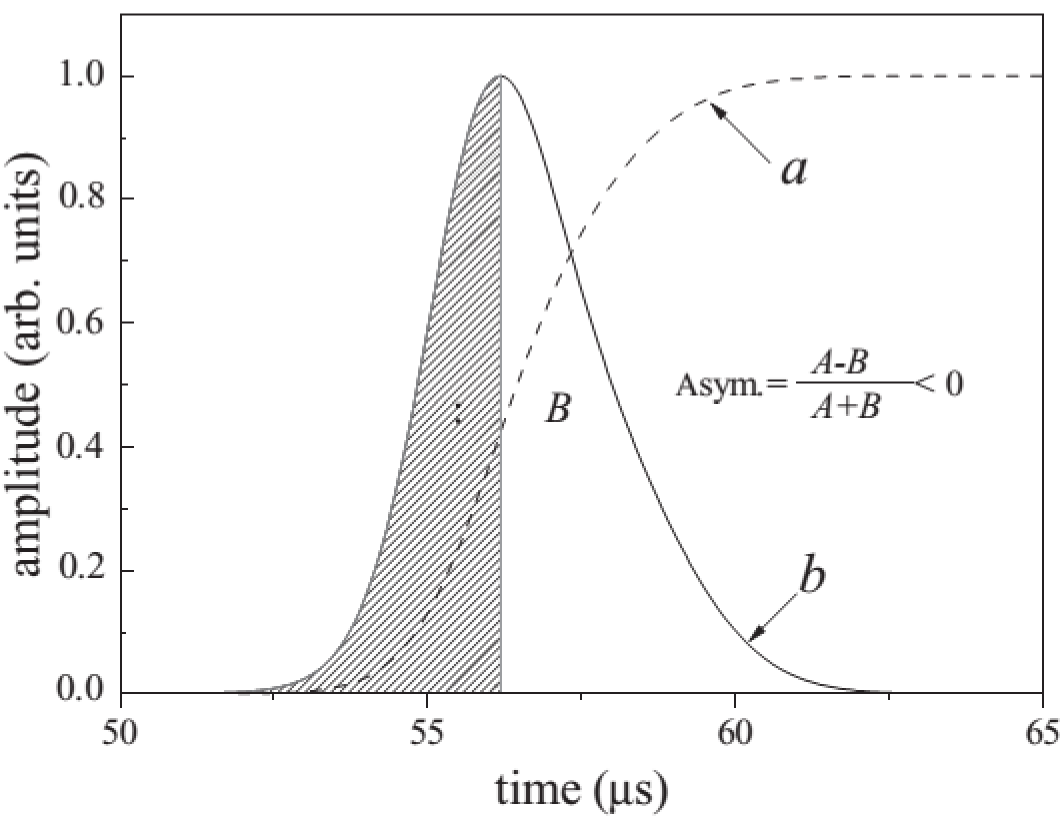
rays, for example, with a layer of NaI(Tl) crystals. The data obtained in our experiment make it possible to estimate of sensitivity S of such an experiment. We assume the efficiency of γ registration to be not worse than $\varepsilon_\gamma = 0.5$. If during 1 y of measurements with described enriched sample there would be no coincidence of useful three-point events with signals, specified in energy, from the γ detector, then, according to Ref. [44], with zero values of a background and signal, the effect by 90% C.L. does not exceed 2.44 y^{-1}. Using Eq. (13) and taking ε_γ into account, one can estimate the sensitivity for the half-life of 1 y of measurement $S = 2.4 \times 10^{22}$ y (at 90% C.L.).



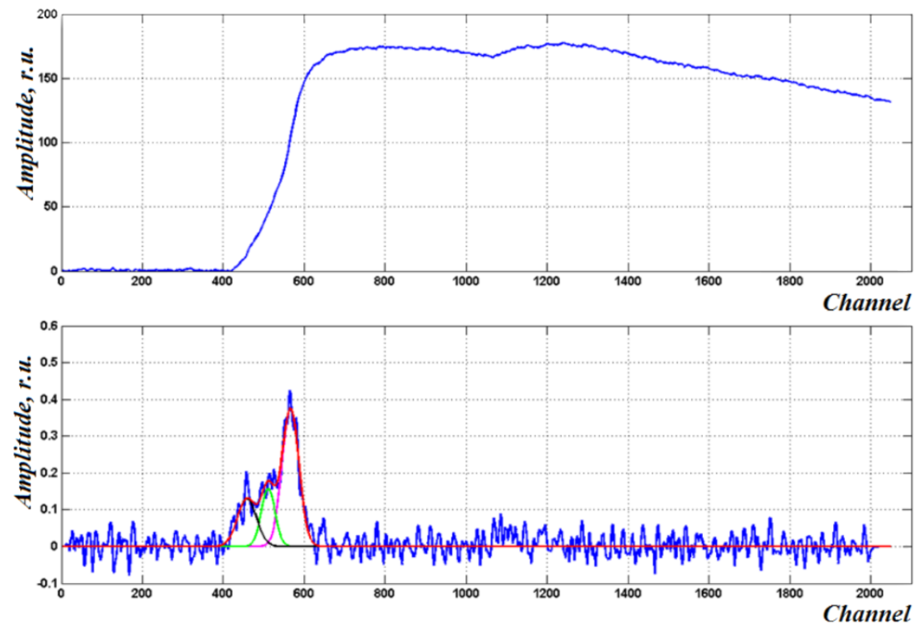
amplitude (arb. units)
0.0
0.2
0.4
0.6
0.8
1.0
time (μs)
50
55
60
65
a
b
B
Asym.= $\frac{A-B}{A+B}$ < 0

Previous result: $T_{1/2} >= 2.3\times10^{20}$y (at a 90% C.L.)

Ju. M. Gavriljuk *et al.*, Phys. Atomic Nuclei **63**, 2201 (2000).

The fraction of 2ν2K-capture events in Kr-78 with respect to the total number of 2νECEC-capture events is 78.6%

$$\lambda = 100 \times M1/(M2 - M1)$$



$$W(2\nu 2K) = 0.786 * W(2\nu ECEC)$$

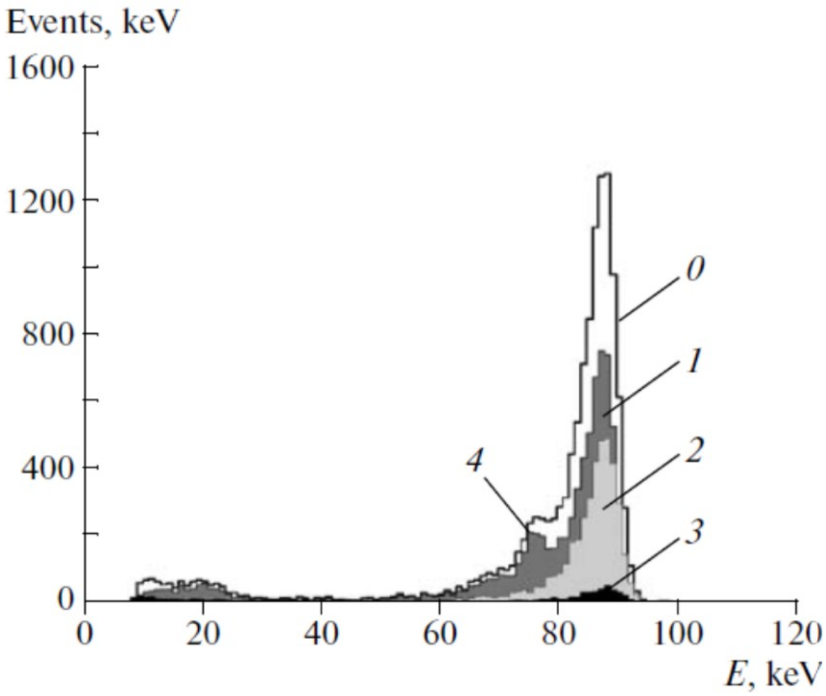
$$Se^{**} \xrightarrow{\text{assumption}} Se^{*} + Se^{*}$$

$\omega_k = 0.596$ *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

Se*	Se*	
e_a	e_a	$0.404^2 = 0.163$
e_a	κ	$\left.\right\} = 0.481$
κ	e_a	
κ	κ	$0.596^2 = 0.355$

Pulse amplitude spectrum from the external ^{109}Cd source located in the middle of the LPC length: (0) all events, (1) single-point events, (2) two-point events, (3) three-point events, and (4) escape peak of characteristic photons.



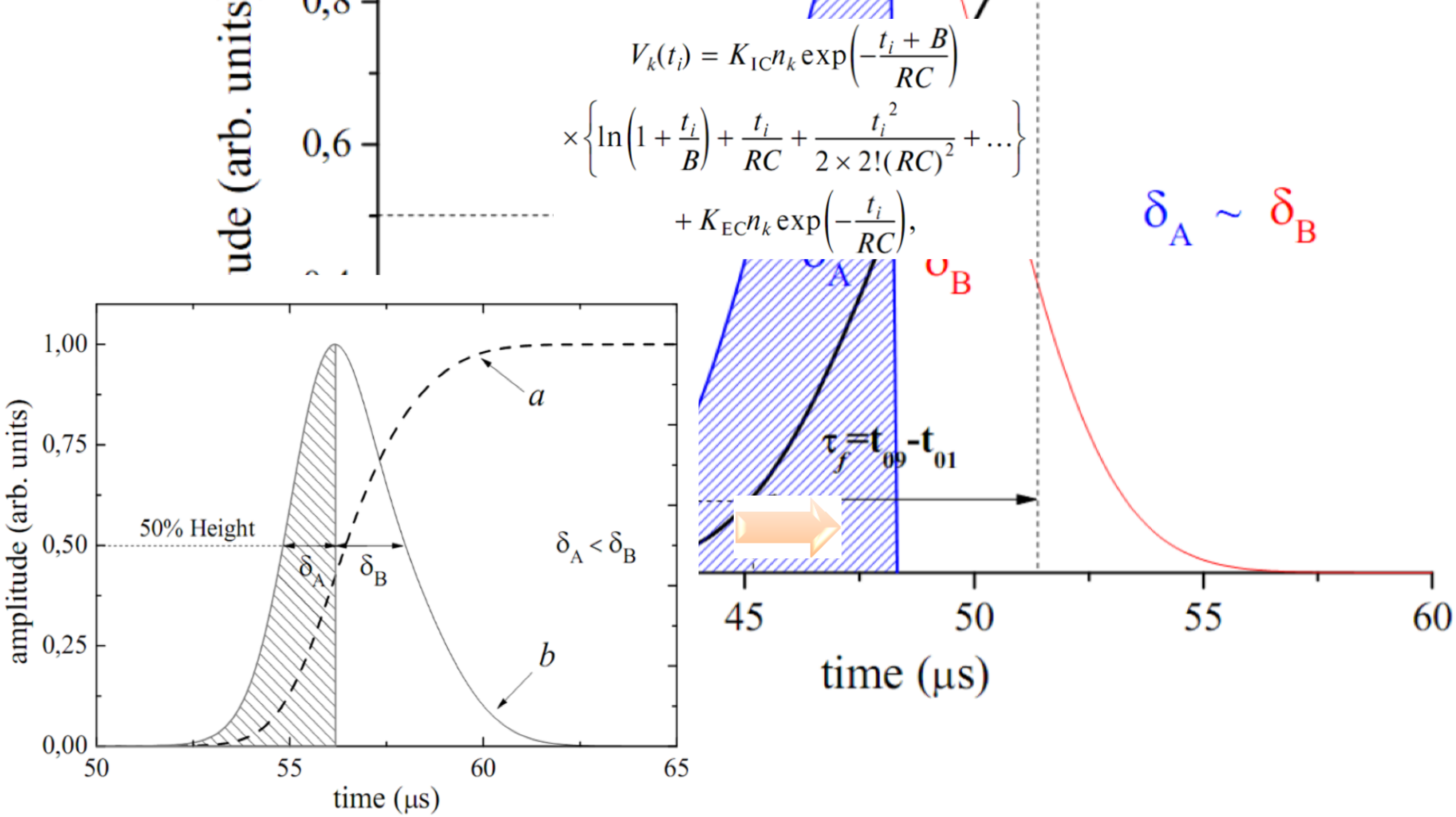
Current pulse normalizing

The current signal produced as a result of gas amplification has an asymmetric form.

The output pulse shape is defined by the superposition of induced charges from single electron avalanches distributed in time and intensity according to: the shape of the current pulse from primary ionization electrons, the shape of a pulse from an individual avalanche, and a finite time of the CSA self-discharge. The last two parameters are responsible for the asymmetry of the output current pulse. The output current pulse can be transformed to a symmetric shape by taking into account the analytical dependence of the amplitude of the output voltage pulse generated by a point (in projection onto the radius at the boundary of the gas amplification region) group of primary ionization electrons as a function of time and discharge constant of the output storage capacitor.

The obtained form of a signal one can describe by a set of Gaussian curves and thus determine the charge that was deposited in separate components of a multipoint event. The calculated area of an individual Gaussian should correspond to the charge (energy) of the corresponding point-like ionization.

$$V_k(t_i) = K_{1C} n_k \exp\left(-\frac{t_i + B}{RC}\right) \times \left\{ \ln\left(1 + \frac{t_i}{B}\right) + \frac{t_i}{RC} + \frac{t_i^{\,2}}{2 \times 2!(RC)^2} + \ldots \right\} + K_{EC} n_k \exp\left(-\frac{t_i}{RC}\right),$$



Neutrinoless double beta decay is a process that violates lepton number conservation. It is predicted to occur in extensions of the Standard Model of particle physics. This Letter reports the results from Phase I of the GERmanium Detector Array (GERDA) experiment at the Gran Sasso Laboratory (Italy) searching for neutrinoless double beta decay of the isotope ^{76}Ge. Data considered in the present analysis have been collected between November 2011 and May 2013 with a total exposure of 21.6 kg·yr. A blind analysis is performed. The background index is about $1 \cdot 10^{-2}$ cts/(keV·kg·yr) after pulse shape discrimination. No signal is observed and a lower limit is derived for the half-life of neutrinoless double beta decay of ^{76}Ge, $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90 % C.L.). The combination with the results from the previous experiments with ^{76}Ge yields $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr (90 % C.L.).

The experimental signature of $0\nu\beta\beta$ decay is a peak at the Q-value of the decay. The two most sensitive experiments with the candidate nucleus ^{76}Ge ($Q_{\beta\beta} = 2039.061 \pm 0.007$ keV [7]) were Heidelberg-Moscow (HDM) [8] and the International GErmanium eXperiment (IGEX) [9, 10]. They found no evidence for the $0\nu\beta\beta$ decay of ^{76}Ge and set lower limits on the half-life $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr and $> 1.6 \cdot 10^{25}$ yr at 90 % C.L., respectively. Part of HDM published a claim to have observed (28.75 ± 6.86) $0\nu\beta\beta$ decays [11] and reported $T^{0\nu}_{1/2} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25}$ yr. Later, pulse shape infor-

[11] H. V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B **586**, 198 (2004).