The background simulation of experiment for searching of 2K-capture in ^{124}Xe

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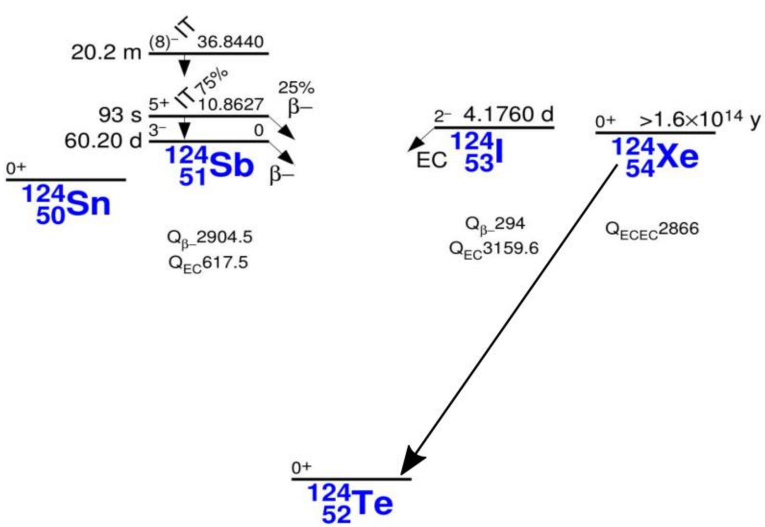
Candidates for measurement of $2\nu 2\beta^+$-decay

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



$(Z, A) \to (Z-2, A) + 2\beta^+ (+ 2\nu_e)$,

$e_b + (Z, A) \to (Z-2, A) + \beta^+ (+ 2\nu_e)$,

$\boxed{e_b + e_b + (Z, A) \to (Z-2, A) + 2\nu_e + 2X}$,

$e_b + e_b + (Z, A) \to (Z-2, A)^* \to (Z-2, A) + \gamma + 2X$.

$$^{124}_{54}Xe \xrightarrow{2e_k} {}^{124}_{52}Te^{**} + 2\nu\,(2{,}865(7)\,MeV)$$

Te*	Te*	
e_a	e_a	$0.142^2 = 0.020$
e_a	K	} 0.246
K	e_a	
K	K	$0.857^2 = 0.734$

K_{ab}= 31.8 keV

E_{2k}= 64.46 keV

ω_k= 0.857 - characteristic quantum

ω_e= 0.142 - Auger electron

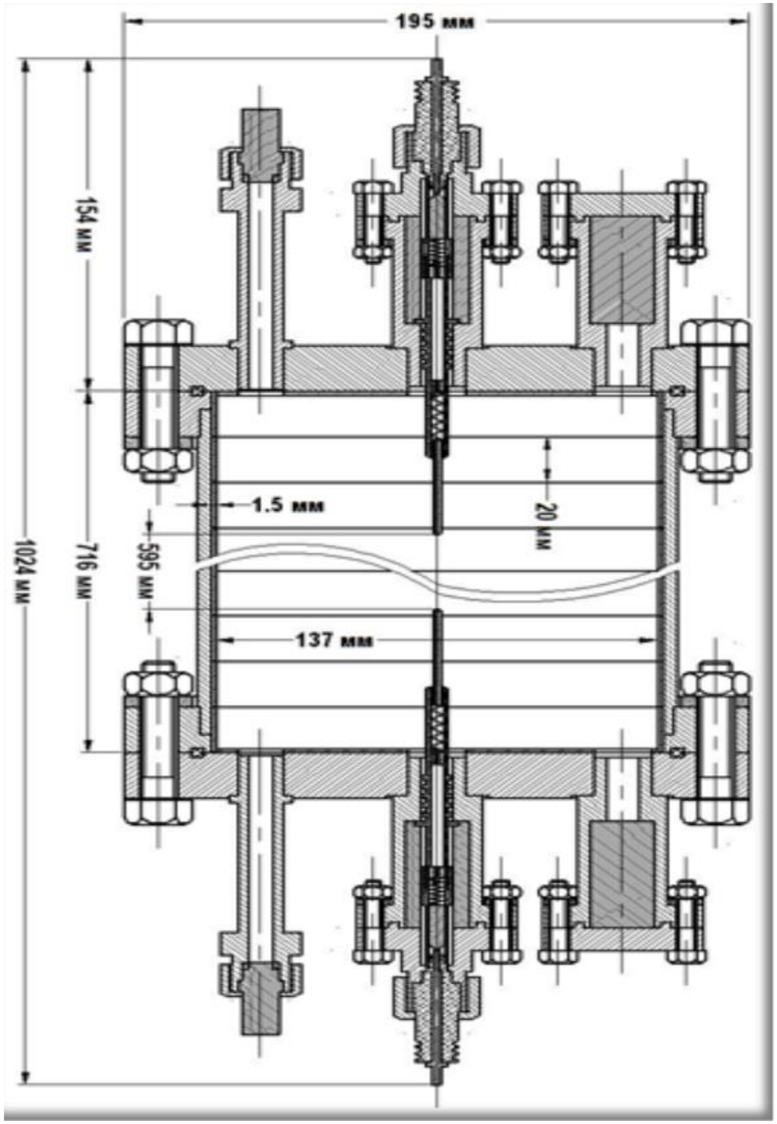
Search area of 2K(2ν)-capture of Xe-124
from 64.46-13= 51.46(52) to 64.46+13=77.46

Te-----------------> Te*+ Te***

K_{ab}=31.81 keV,		
$K_{\alpha 1}$=27.47 keV	**52.2%**	
$K_{\alpha 2}$=27.20 keV	**27.7%**	
$K_{\beta 1}$=30.99 keV	**16.2%**	
$K_{\beta 2}$=31.70 keV	**3.9%**	

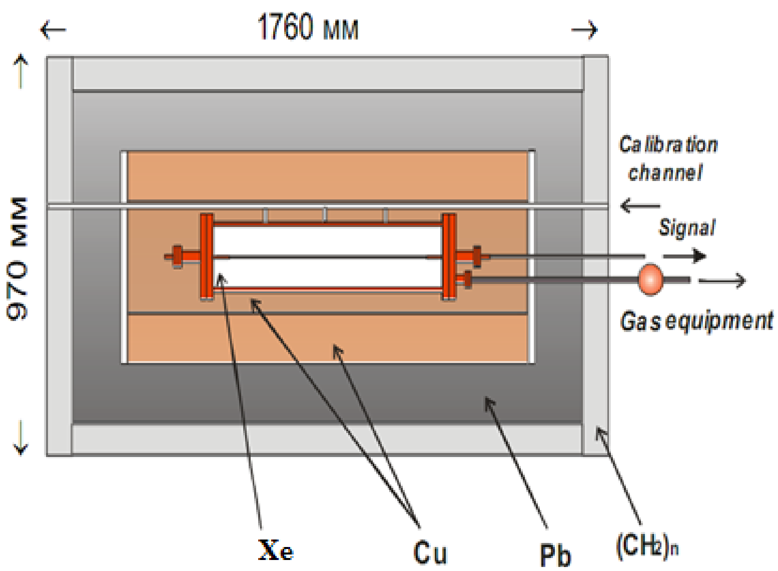
The energies of characteristic photons and an Auger-electron in 2K-capture are determined under the assumption that the filling of the double vacancy of K-shell in one atom is identical to filling two K-shell vacancies, each in a separate atom; the total energy release being 64.46 keV.
The probability of the emission of two characteristic X-ray photons and auger electron equal to 73.4%.

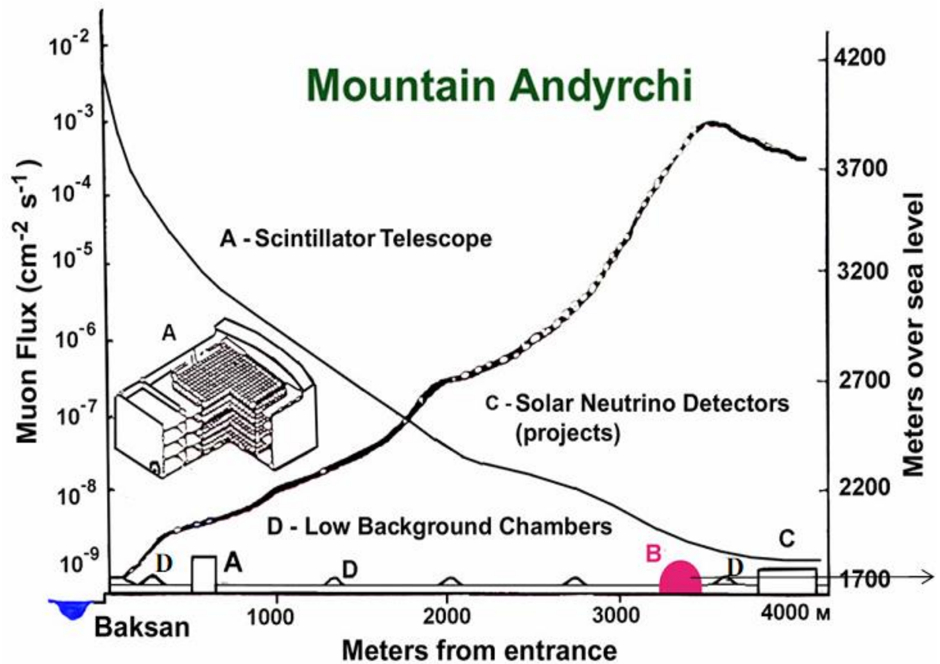
Schematic view of Proportional Counter



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*

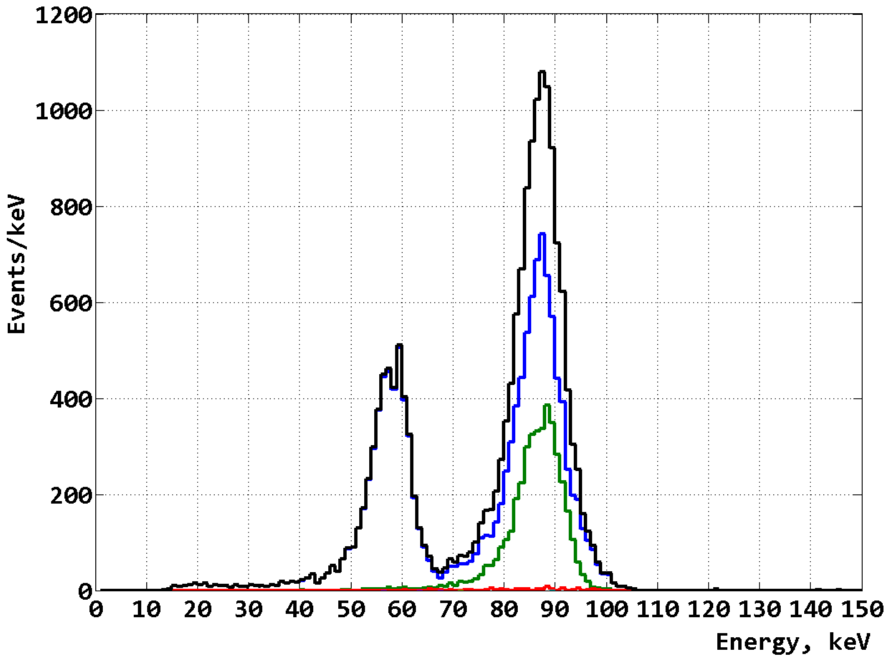
Location of the experimental setup





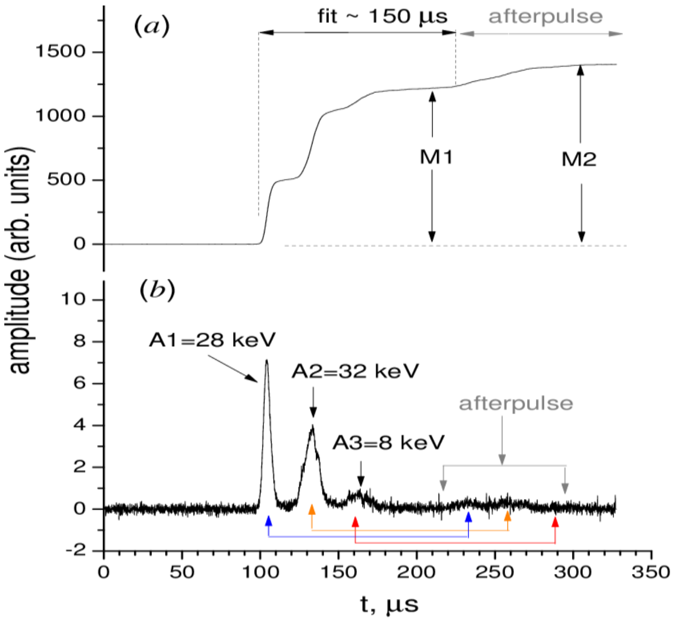
- 18 cm – copper (M1)
- 15 cm – lead
- 8cm – borated polyethylene
- depth-4900 m.w.e., ϕ_μ=2,23*10^{-9} cm^{-2}s^{-1}

The spectrum of the Cd-109 calibration source, 88 keV gamma-line

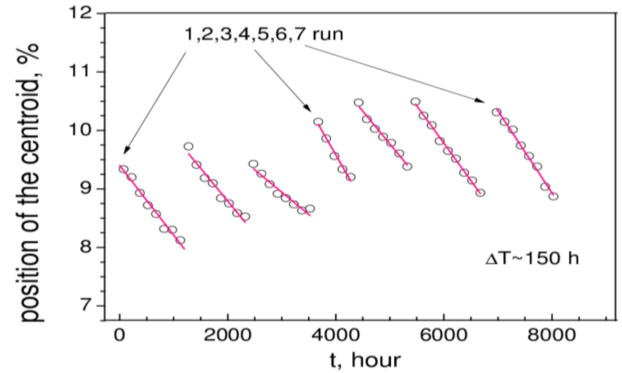


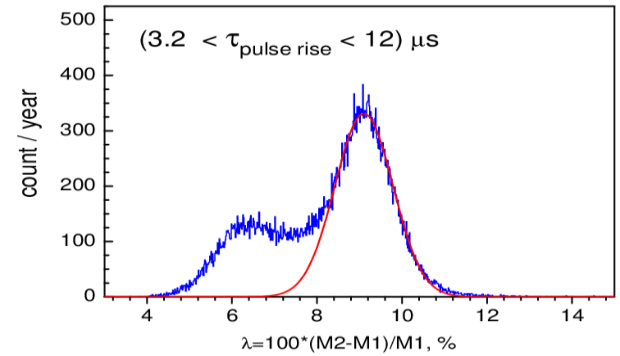
Black – All events
Blue - one point events
Green – two point events
Red – three point events

PSD



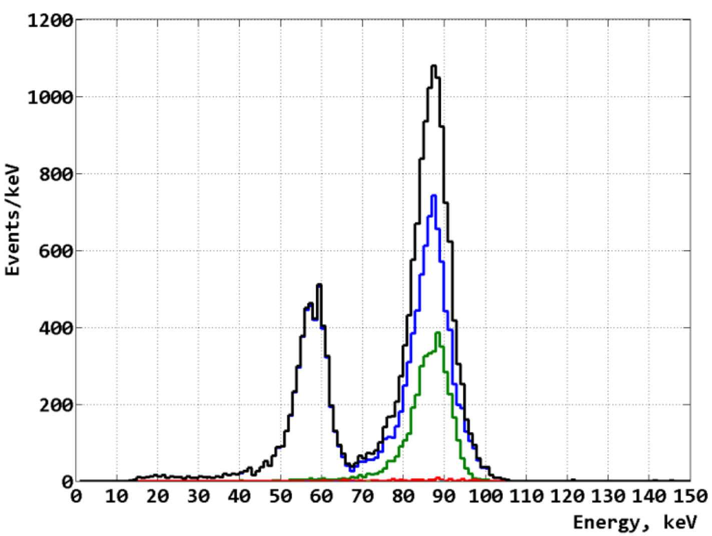
$$\begin{Bmatrix} A_1 \\ A_2 \\ A_3 \end{Bmatrix} \Rightarrow \begin{Bmatrix} m_0 \\ m_1 \\ m_2 \end{Bmatrix}$$





The distribution of events versus parameter β:

Blue spectrum – distribution for background events
Red spectrum – distribution for calibration source Cd109 (88 keV)



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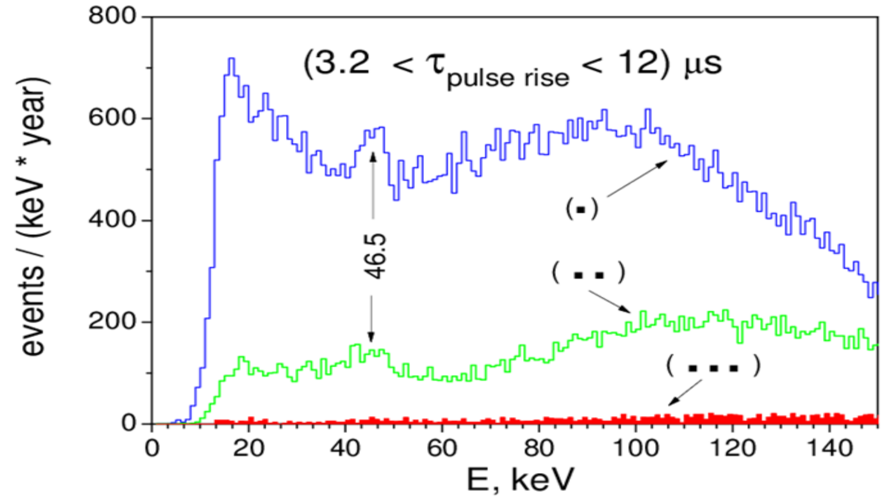
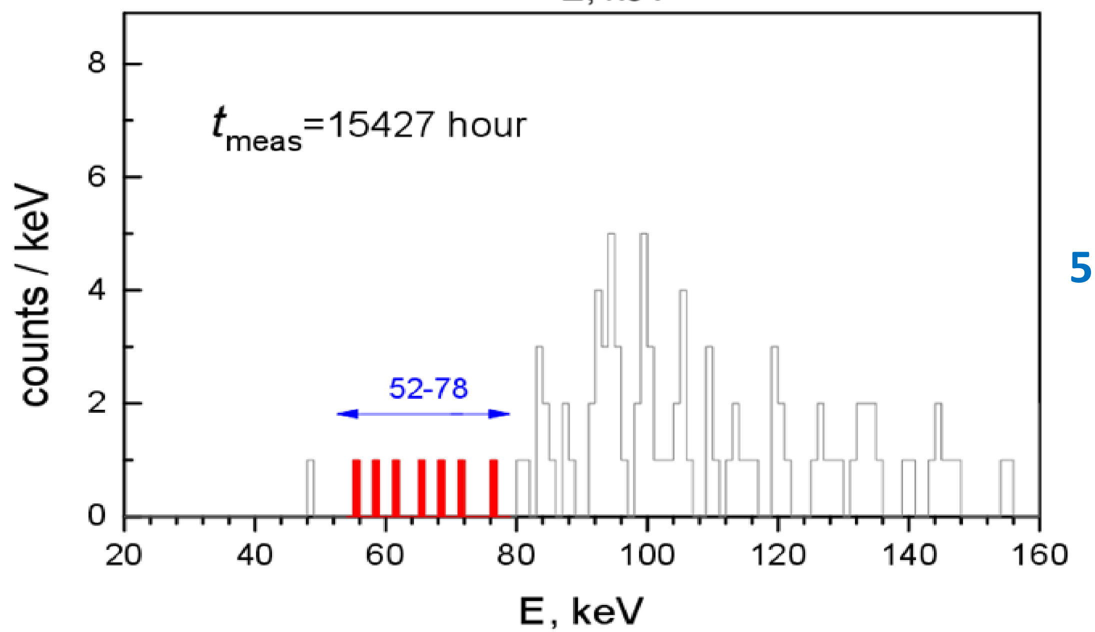
Measurement results for 15427 hours





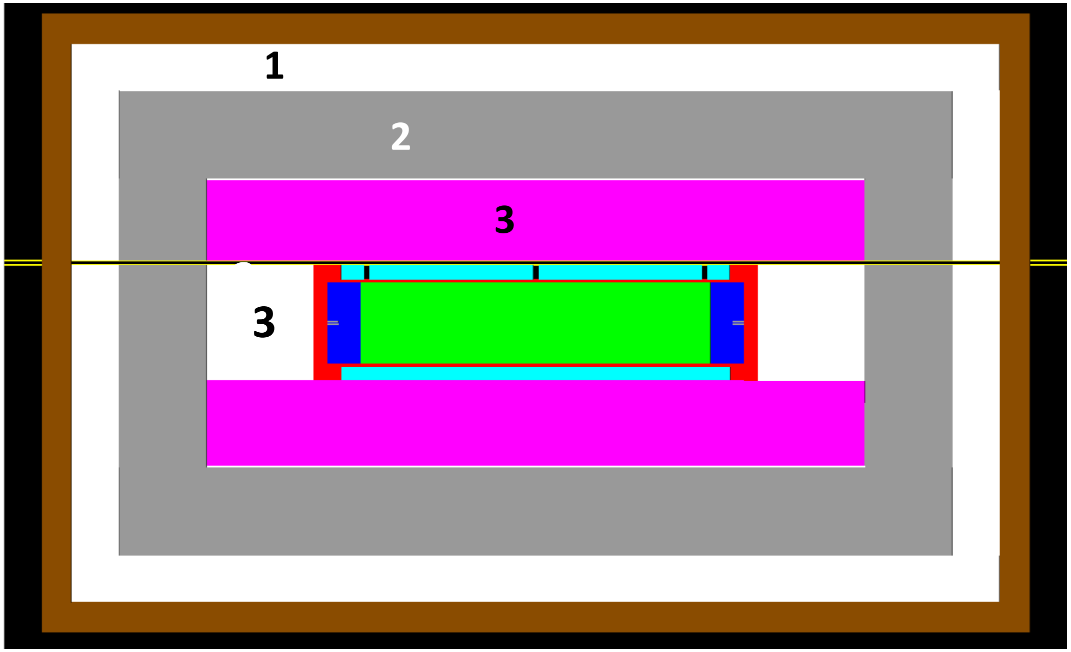
8 <λ< 12

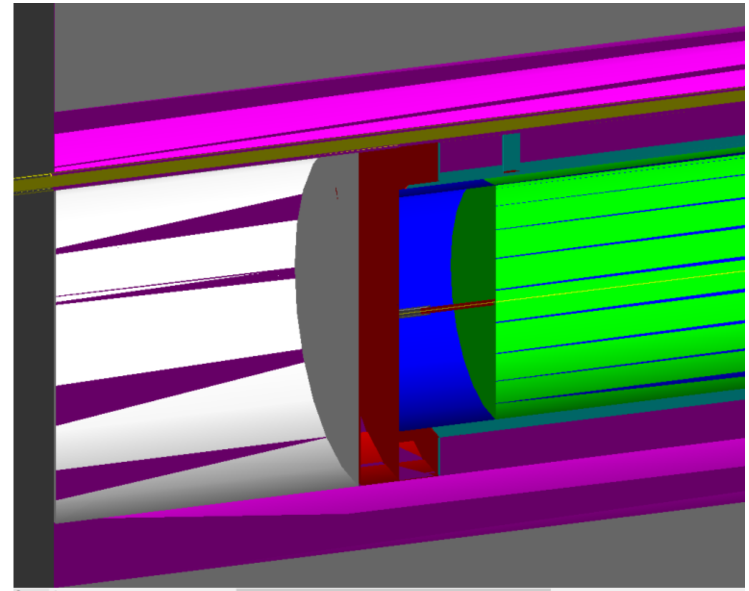
$m_1/m_2 \geq 0.7$

$5keV \leq m_0 \leq 13keV$

Search area of 2K(2ν)-capture of Xe-124 from 64.46-13= 51.46(52) to 64.46+13=77.46

Geant4 model of low-background shield

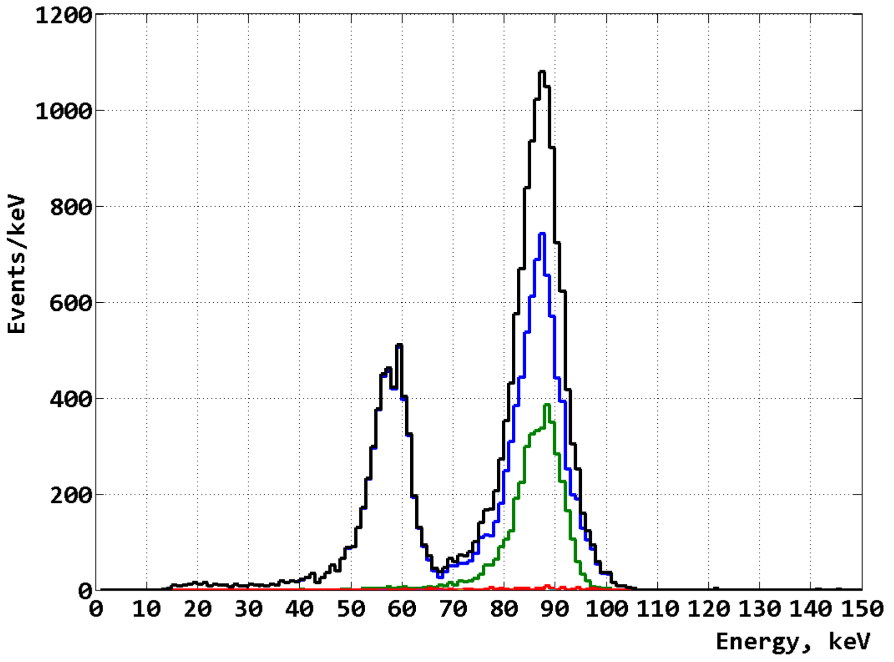


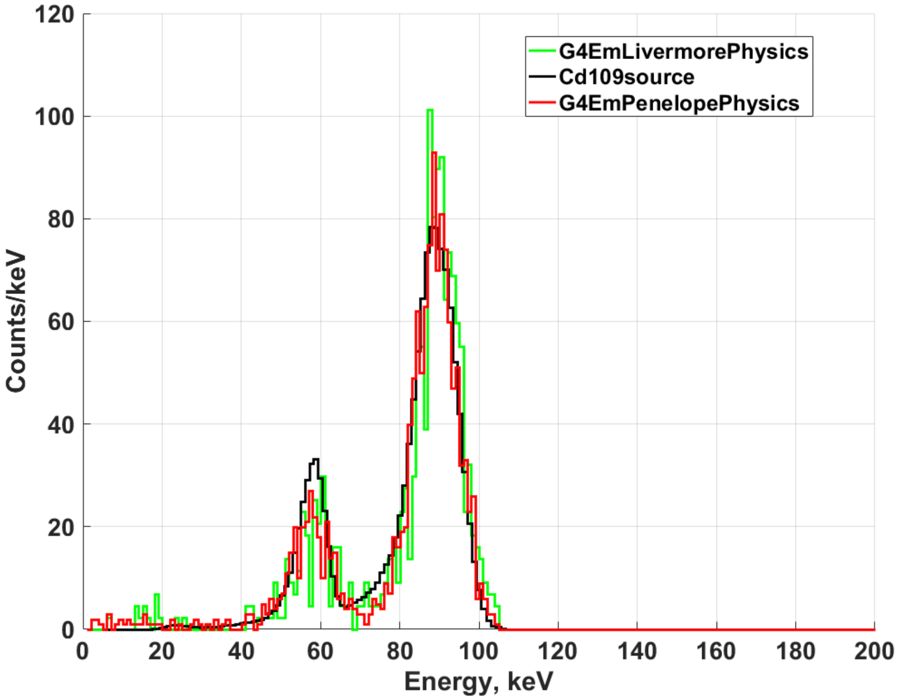


1 - Borated polyethylene
2 - Lead
3 - Copper
Cian – Copper
Red – Prop Counter
Blue – Full gas volume
Green – Fiducial volume

Geant4-10.4.2
G4DecayPhysics
G4RadioactiveDecayPhysics
G4EmPenelopePhysics
G4EmLivermorePhysics (for test)
G4HadronPhysicsQGSP_BIC_HP

Test of Geant4 model





Black – All events
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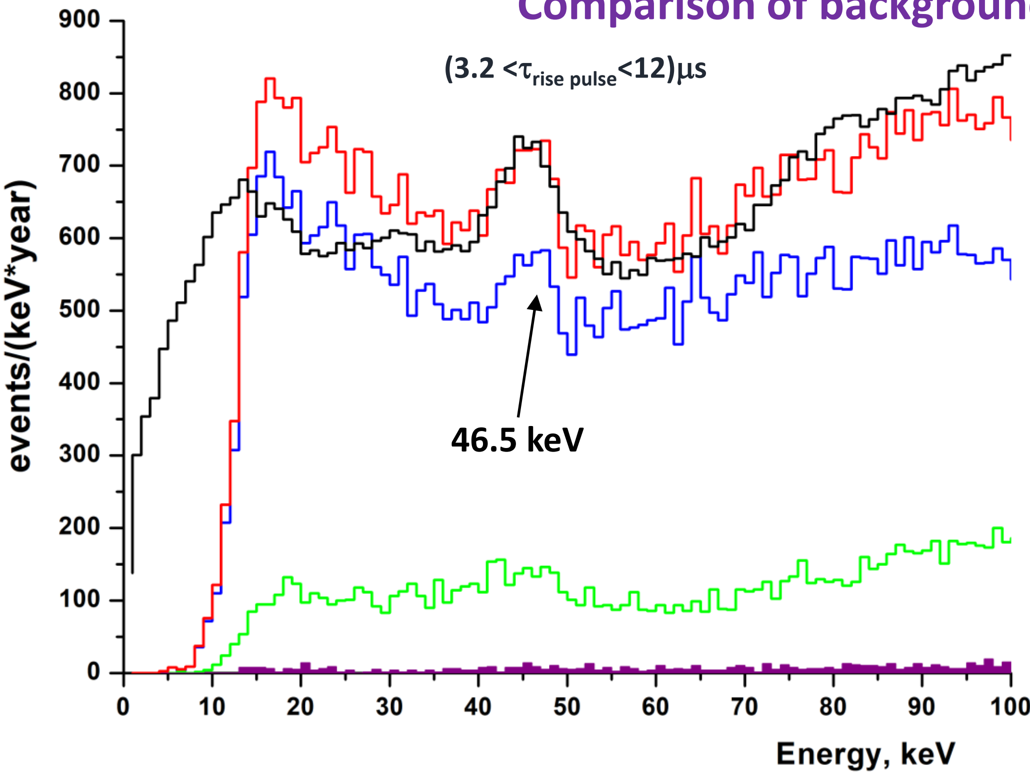
Comparison of background and simulation



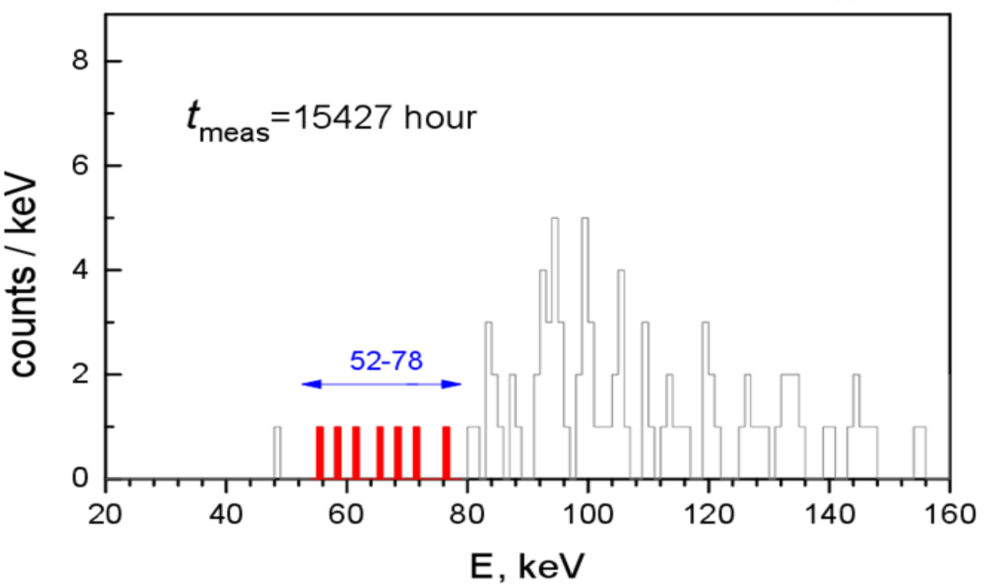
Red – Sum of 1,2 and 3 (.)-events

Black – Geant4 result

Blue – 1(.)-events

Green – 2(.)-events

Purple – 3(.)-events



8 <λ< 12

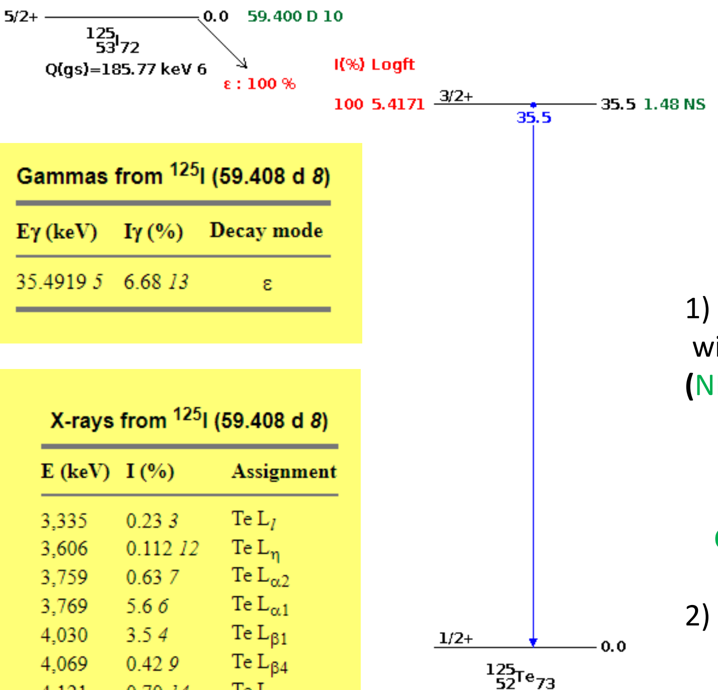
$m_1/m_2 \geq 0.7$

$5\text{keV} \leq m_0 \leq 13\text{keV}$

Search area of 2K(2ν)-capture of Xe-124 from 64.46-13= 51.46(52) to 64.46+13=77.46

The calculation of ^{125}I isotope background events

The ^{125}I is produced from ^{125}Xe and ^{125m}Xe created by thermal neutron capture on ^{124}Xe with a total cross section of 165±11 barn. ^{125}I decays by 100% capture via an excited state of ^{125}Te into the ground state of ^{125}Te.



Gammas from ^{125}I (59.408 d 8)

Eγ (keV)	Iγ (%)	Decay mode
35.4919 *5*	6.68 *13*	ε

X-rays from ^{125}I (59.408 d 8)

E (keV)	I (%)	Assignment
3,335	0.23 *3*	Te L_l
3,606	0.112 *12*	Te L_η
3,759	0.63 *7*	Te $L_{\alpha 2}$
3,769	5.6 *6*	Te $L_{\alpha 1}$
4,030	3.5 *4*	Te $L_{\beta 1}$
4,069	0.42 *9*	Te $L_{\beta 4}$
4,121	0.70 *14*	Te $L_{\beta 3}$
4,173	0.043 *5*	Te $L_{\beta 6}$
4,302	1.01 *11*	Te $L_{\beta 2}$
4,572	0.45 *5*	Te $L_{\gamma 1}$
4,829	0.103 *22*	Te $L_{\gamma 2}$
4,829	0.16 *3*	Te $L_{\gamma 3}$
26,875	0.00324 *12*	Te $K_{\alpha 3}$
27,202	40.6 *12*	Te $K_{\alpha 2}$
27,472	75.7 *23*	Te $K_{\alpha 1}$
30,944	6.83 *20*	Te $K_{\beta 3}$
30,995	13.2 *4*	Te $K_{\beta 1}$
31,237	0.121 *6*	Te $K_{\beta 5}$
31,704	3.81 *11*	Te $K_{\beta 2}$
31,774	0.58 *3*	Te $K_{\beta 4}$

We have several measurements of neutrons in our laboratory.

1) Some features and results of thermal neutron background measurements with the [ZnS(Ag)+6LiF] scintillation detector
(NIM A 841 (2017), 156–161, **http://dx.doi.org/10.1016/j.nima.2016.10.038**)

Neutron flux with energies < 0.5 eV estimated to be
$(2.6\pm0.4)*10^{-5}$ cm^{-2} s^{-1}
Calculating the number of neutrons from the G4 simulation: 0 neutrons/year

2) Fast-Neutron-Flux Measurements in the Underground Facilities at Baksan
(***Physics of Atomic Nuclei, Vol. 63, No. 7, 2000, pp. 1276–1281.***)

Neutron flux with energies above 700 keV estimated to be between
$5.3*10^{-7}$ and $1.8*10^{-7}$ cm^{-2} s^{-1}
Calculating the number of thermal neutrons from the G4 simulation: 2.5 neutrons/year
0.0114 ^{125}I atoms per year in counter

http://www.nndc.bnl.gov
http://nucleardata.nuclear.lu.se/toi

Comparison with other experimental results and theoretical predictions

Experiment	2K capture
XENON 100 [1] (2017)	≥6.5×10^{20}yr.
XMASS-I [2] (2018)	≥2.1×10^{22} yr.
BNO INR RAS [3] (2017)	≥7.7×10^{21} yr.

Calculated half-lives for the 2ν ECEC capture ^{124}Xe

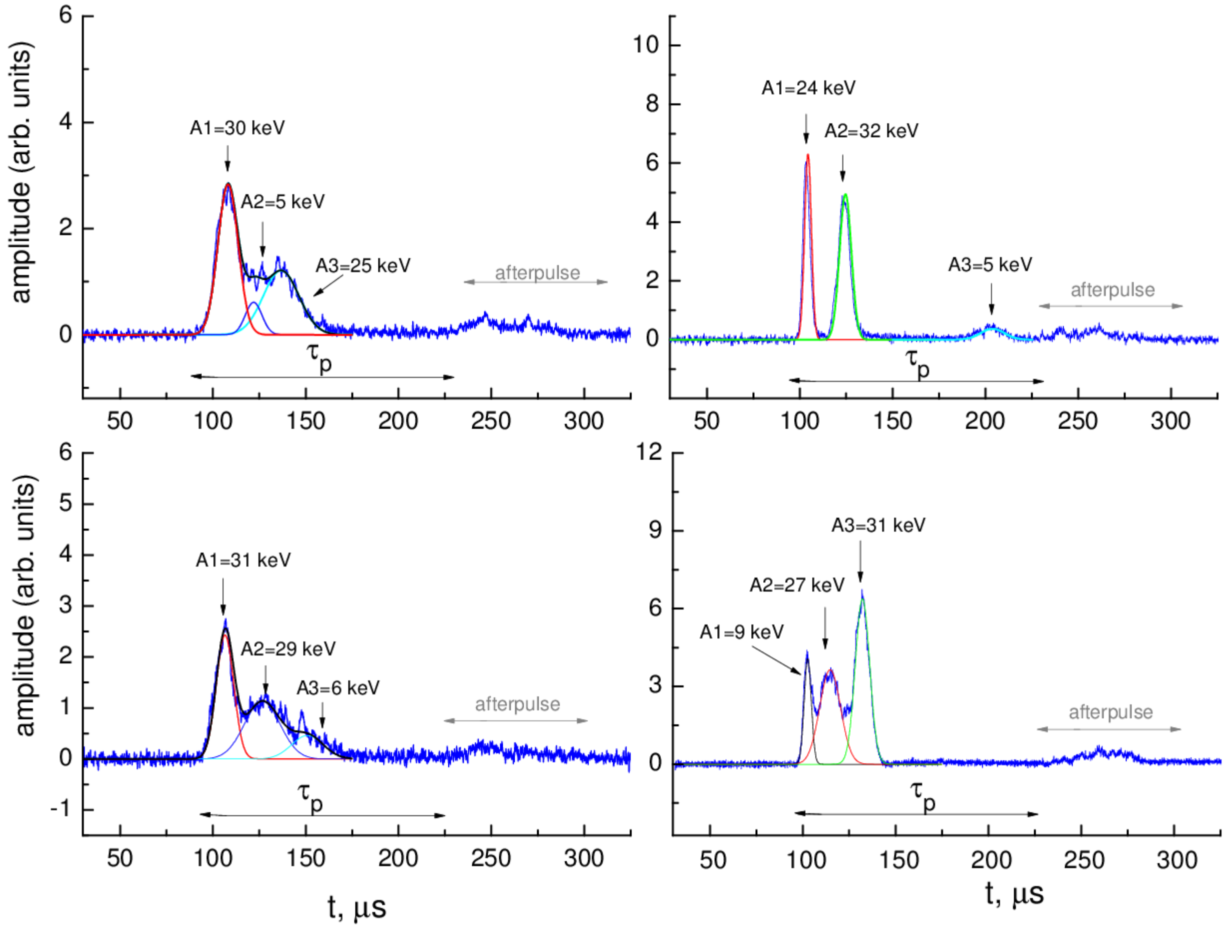
2ν ECEC (10^{21}) yr.	Authors
2.9-7.3	M. Hirsch et al., *Z. Phys. A* 1999
7.0	O.A. Rumyantsev, M.H. Urin *Phys. Lett.B* 1998
7.1-18	S. Singh et al., *Euro. Phys. J. A* 2007
0.4-8.8	J. Suhonen *Journal of Physics G* 2013
61-155	A. Shukla, P.K. Raina *Journal of Physics G* 2007

[1] ***Phys. Rev. C 95, 024605, 2017*** (https://doi.org/10.1103/PhysRevC.95.024605)
[2] ***Progress of Theoretical and Experimental Physics, Volume 2018, Issue 5, 1 May 2018*** (https://doi.org/10.1093/ptep/pty053)
[3] ***Physics of Particles and Nuclei, 2018, Vol. 49, No. 4, pp. 563–568*** (DOI: 10.1134/S106377961804024X)

Thank You!

Backup

Candidates for 2K-capture events



$$T_{1/2} \geq ln2 \times N \times t_{meas}(\eta/n_{exp})$$

$N = 2.85 \cdot 10^{23}$ *- the number of ^{124}Xe atoms*

$\eta=\omega^{2K} \cdot \varepsilon_p \cdot \varepsilon_3 \cdot \alpha_k \cdot k_\lambda$ – the full efficiency of registration

$\omega^{2K} = 0.772$ - fluorescence yield for 2K capture

$\varepsilon_p = 0.809$ - the probability of absorption of three-point event

$\varepsilon_3 = 0.51 \pm 0.05$ - the efficiency of three-point event identification

$\alpha_k = 0.985 \pm 0.005$ - the coefficient of detection of 2K-photons and Auger elections as three-point events

$K_\lambda = 0.89 \pm 0.01$ - the efficiency of λ-selection

$n_{exp} = 7^{+5.5}_{-3.4}$

t_{meas} = 1.76 year

$$\boxed{T_{1/2} \geq 7.7 \cdot 10^{21} \text{ yr. (90\% C.L.)}}$$

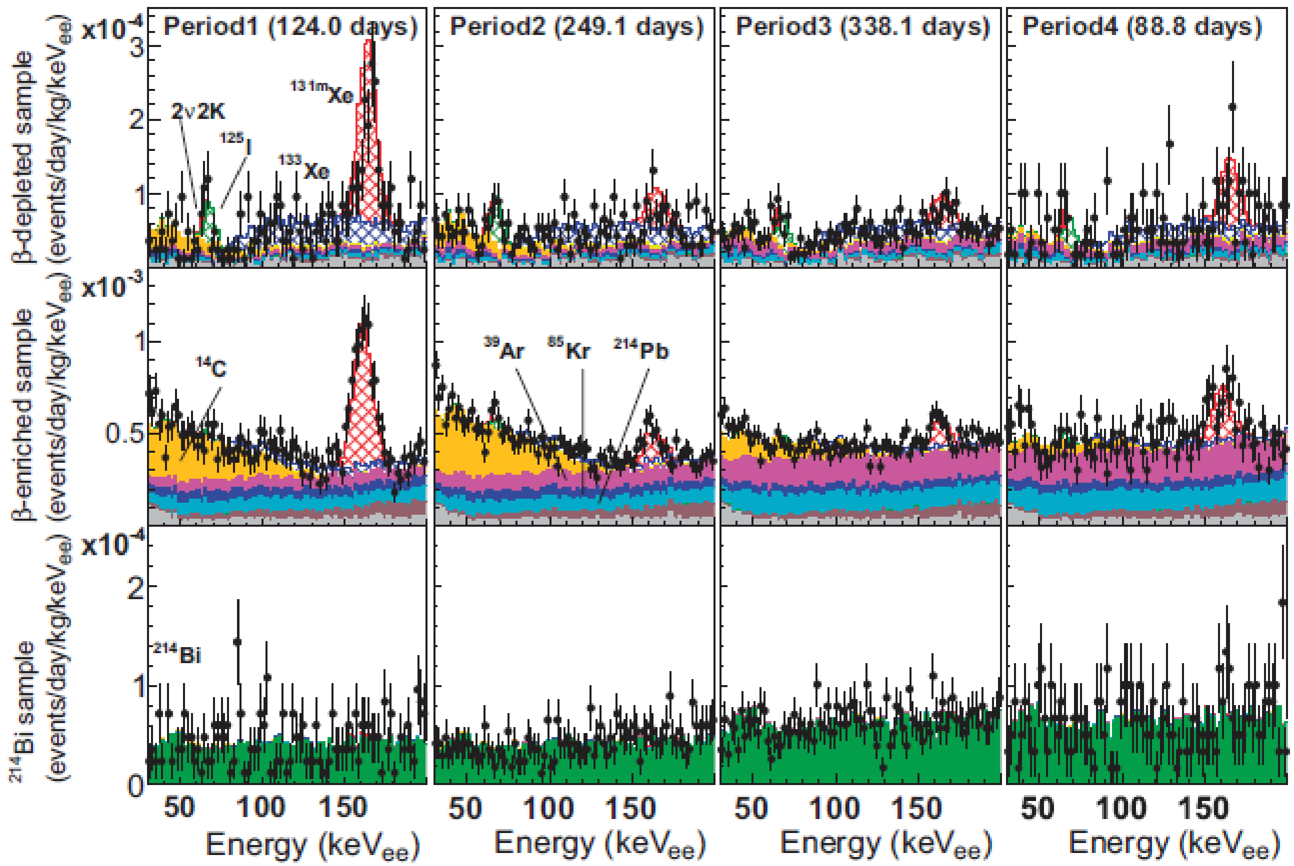


Fig. 4. Energy spectra for the β-depleted samples (top), β-enriched samples (middle), and ^{214}Bi samples (bottom). The observed data spectra (points) are overlaid with the best-fit $2\nu 2K$ signal and background spectra (colored stacked histograms). Colored histograms are the $2\nu 2K$ signal (red filled), ^{125}I (green hatched), ^{131m}Xe (red hatched), ^{133}Xe (blue hatched), ^{14}C (orange filled), ^{39}Ar (magenta filled), ^{85}Kr (blue filled), ^{214}Pb (cyan filled), ^{214}Bi (green filled), ^{136}Xe $2\nu\beta\beta$ (brown filled), and external backgrounds (gray filled).