Evaluation of the sensitivity of the DarkSide-50 experiment to two neutrino double K-capture on ^{36}Ar

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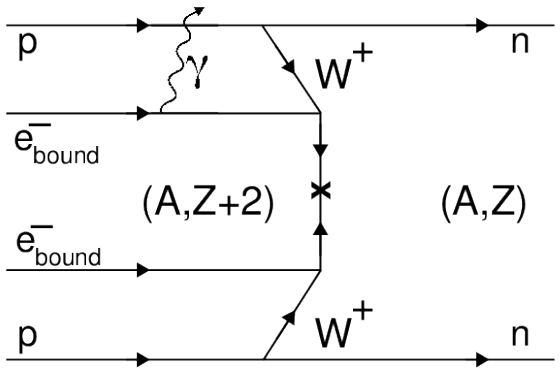
Introduction

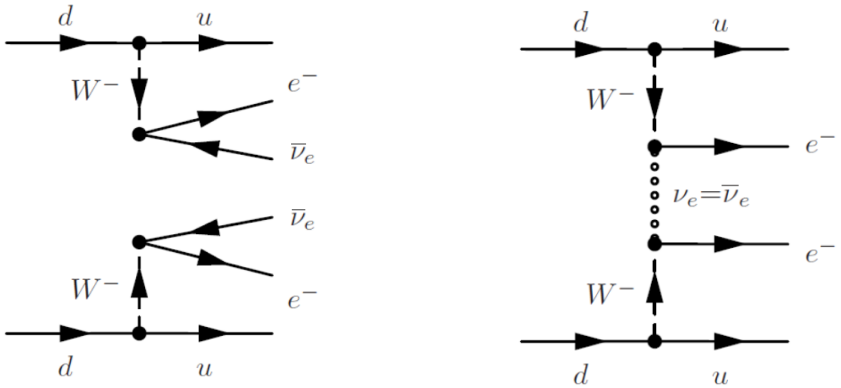
2e-capture

- (2EC2ν) – is found for ^{124}Xe in XENON1T[1] $T_{1/2}^{2EC2\nu} = (1.8 \pm 0.5 \pm 0.1) \times 10^{22}$ yr.;
- limits determined for ^{85}Kr in the Baksan Laboratory[2] $T_{1/2}^{2EC2\nu} > 1.9 \times 10^{22}$yr., CL = 90%;
- (2EC0ν) – not found



2β-decay

- (2β2ν) – experimentally validated for more than 10 nuclei
- (2β0ν) – not found



Registration of 2β0ν- or 2EC0ν-decay will confirm the Majorana nature of neutrino.

2EC2ν is possible for ^{36}Ar.

Purpose and tasks of the work

Purpose

Evaluation of the sensitivity of the DarkSide-50 experiment to two-neutrino double electron capture on the ^{36}Ar

Tasks

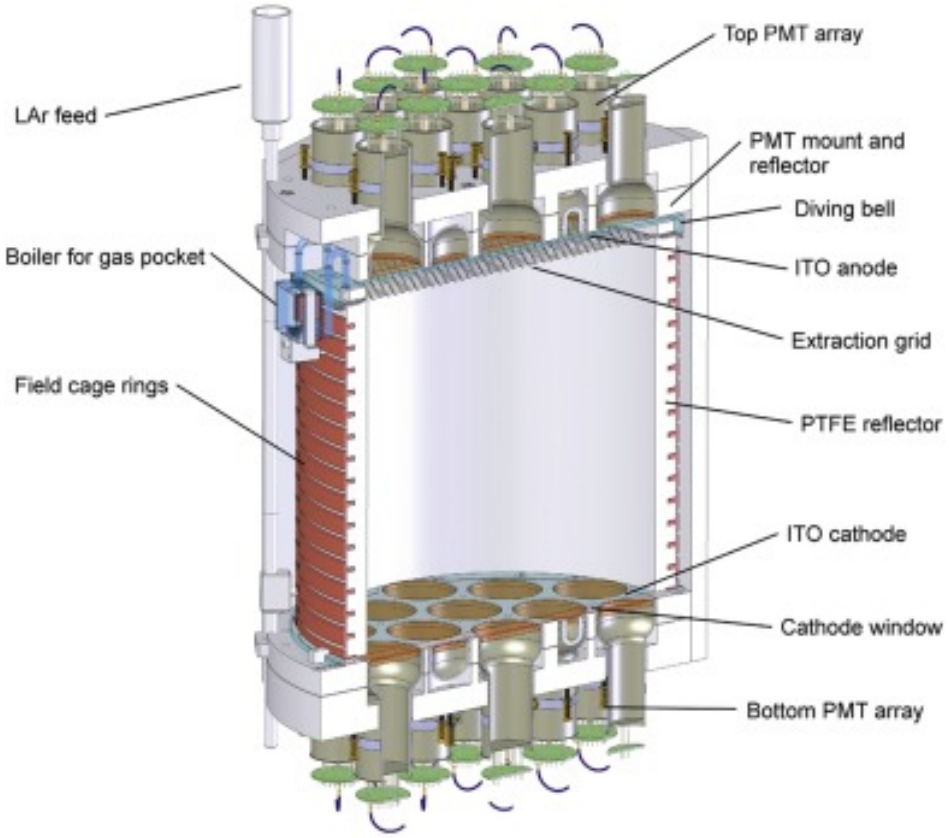
- development of a software code for simulating the energy spectrum of double electron capture (2EC2ν) on ^{36}Ar;
- application of the detector response of the DarkSide-50 detector to the simulated spectrum;
- statistical data analysis using a model spectrum;
- derivation of a lower limit for the half-life of ^{36}Ar.

Novelty

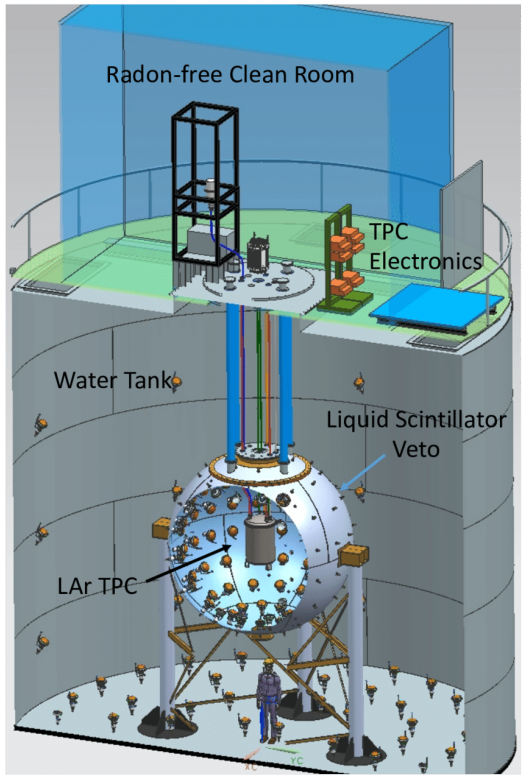
2EC2ν studies have not previously been carried out on argon isotopes.

DarkSide-50 experiment

DarkSide-50 – experiment to search for dark matter particles; two-phase time-projection chamber filled with liquid ultra-pure argon.

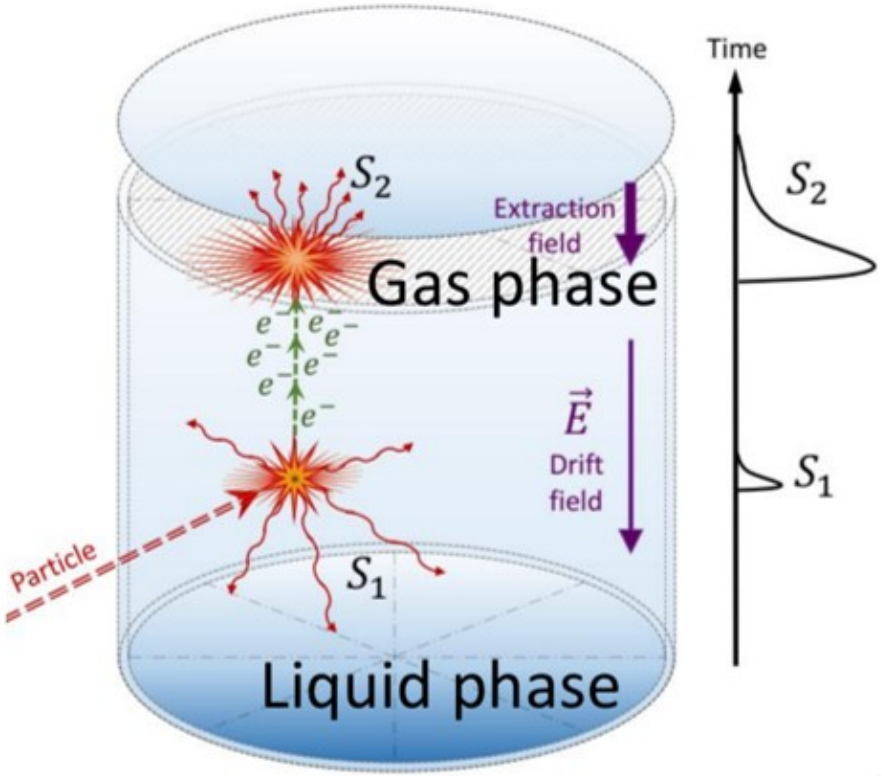


TPC scheme



Detector scheme

The principle of particle detection by the DS-50 detector



- The particle causes a scintillation flash (S1) and ionization of the medium;
- Electroluminescence occurs in a gaseous medium (S2);
- The time interval between S1 and S2 allows to determine the Z coordinate;
- According to S2, you can restore the coordinates (X,Y);
- The ratio of amplitudes S1 and S2 is used to discriminate events from an electron and a recoil nucleus.

Underground argon

- ^{39}Ar was formed in the atmosphere by cosmic rays:

$$n +^{40} Ar \rightarrow^{39} Ar + 2n + \gamma;$$

  The use of argon from underground deposits will reduce the contribution of this component;
- ^{39}Ar is the background source for the experiment and limits the sensitivity at low energies.
- The vast majority of primordial argon consists of isotopes ^{36}Ar and ^{38}Ar;
- ^{36}Ar was formed during nucleosynthesis in massive stars;
- the isotopic abundance of ^{36}Ar in atmosphere greatly exceeds the abundance ^{36}Ar underground:

$$\eta_{AAr} = 0.334\%[3];\ \eta_{UAr} \approx 0.012\%;[4]$$

[3] – according to measurements taken in the atmosphere,
[4] – according to the measurements taken by the underground, the results are provided by Henning Back.

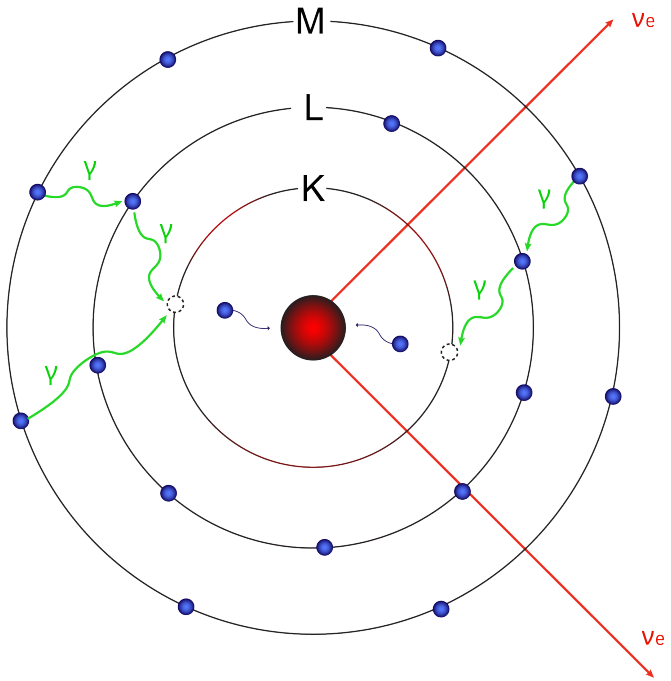
Double electron capture

- Two protons in the nucleus simultaneously capture two electrons from the K-shell, and two neutrinos are emitted (Transitions from the L- and M-shells can also be considered as a second-order effect)
- The problem of detecting double electron capture is reduced to detecting the following processes:
  1. characteristic photon-satellite and Auger-electron ($\sim 35\%$);
  2. two Auger electrons ($\sim 64\%$);
  3. two photons ($\sim 1\%$).
- $E^{(1)}_{2EC2\nu} \approx (2.320 + 2.308)$ keV

  $E^{(2)}_{2EC2\nu} \approx 2 \times 2.308$ keV

  $E^{(3)}_{2EC2\nu} \approx 2 \times 2.447$ keV

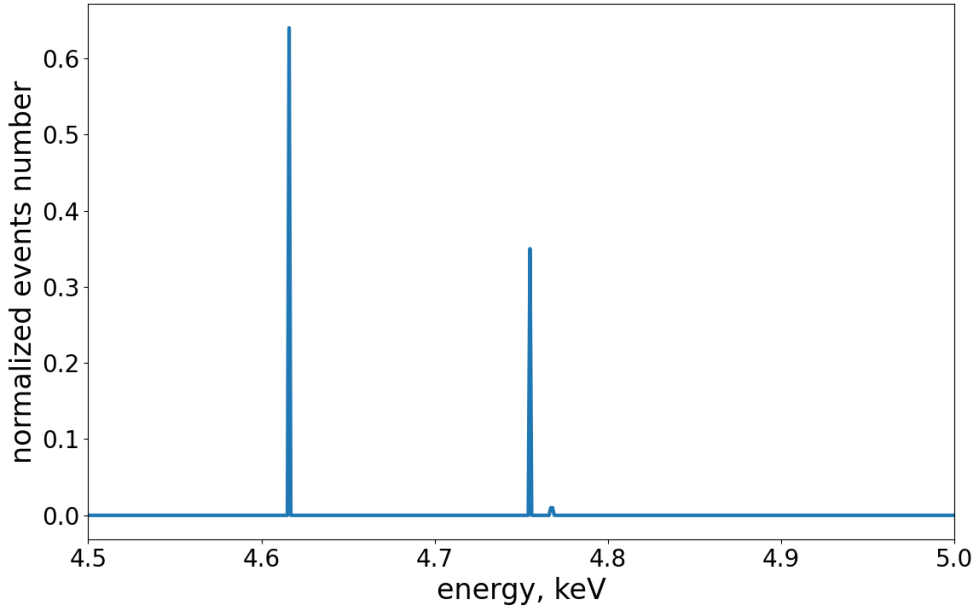
$$^{36}\mathrm{Ar} + 2e^- \longrightarrow {}^{36}\mathrm{S} + 2\nu_e$$



Primary calculations were made by F.F. Karpeshin in the RAINE program at our request.

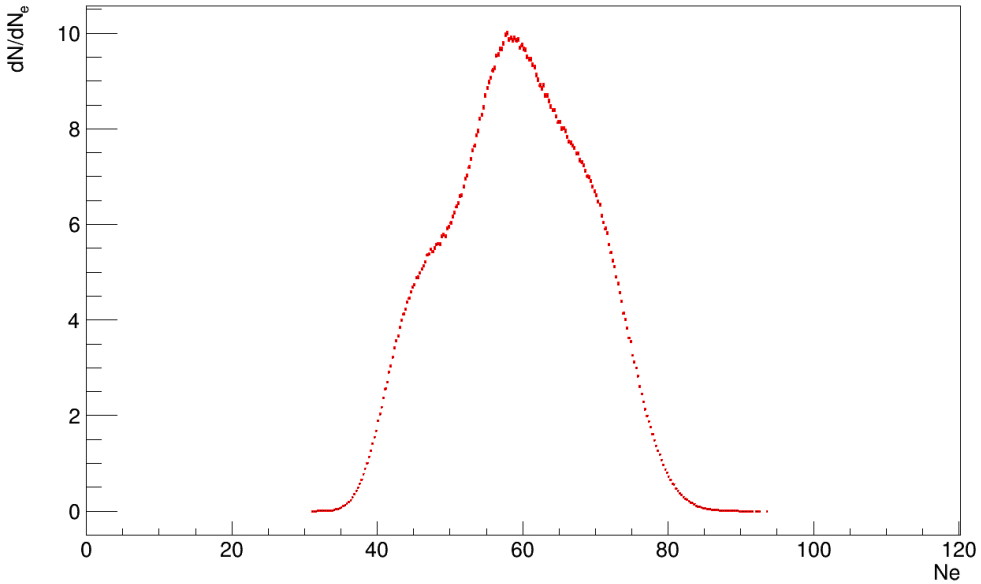
Modeling the spectral component of 2K-capture

Software package DarkSide-50: *lowmass* (based on the latest version of the 630-day 2022 data set)



Top: The radiation spectrum from the 2K-capture

Bottom: Detector response spectrum from the 2K-capture

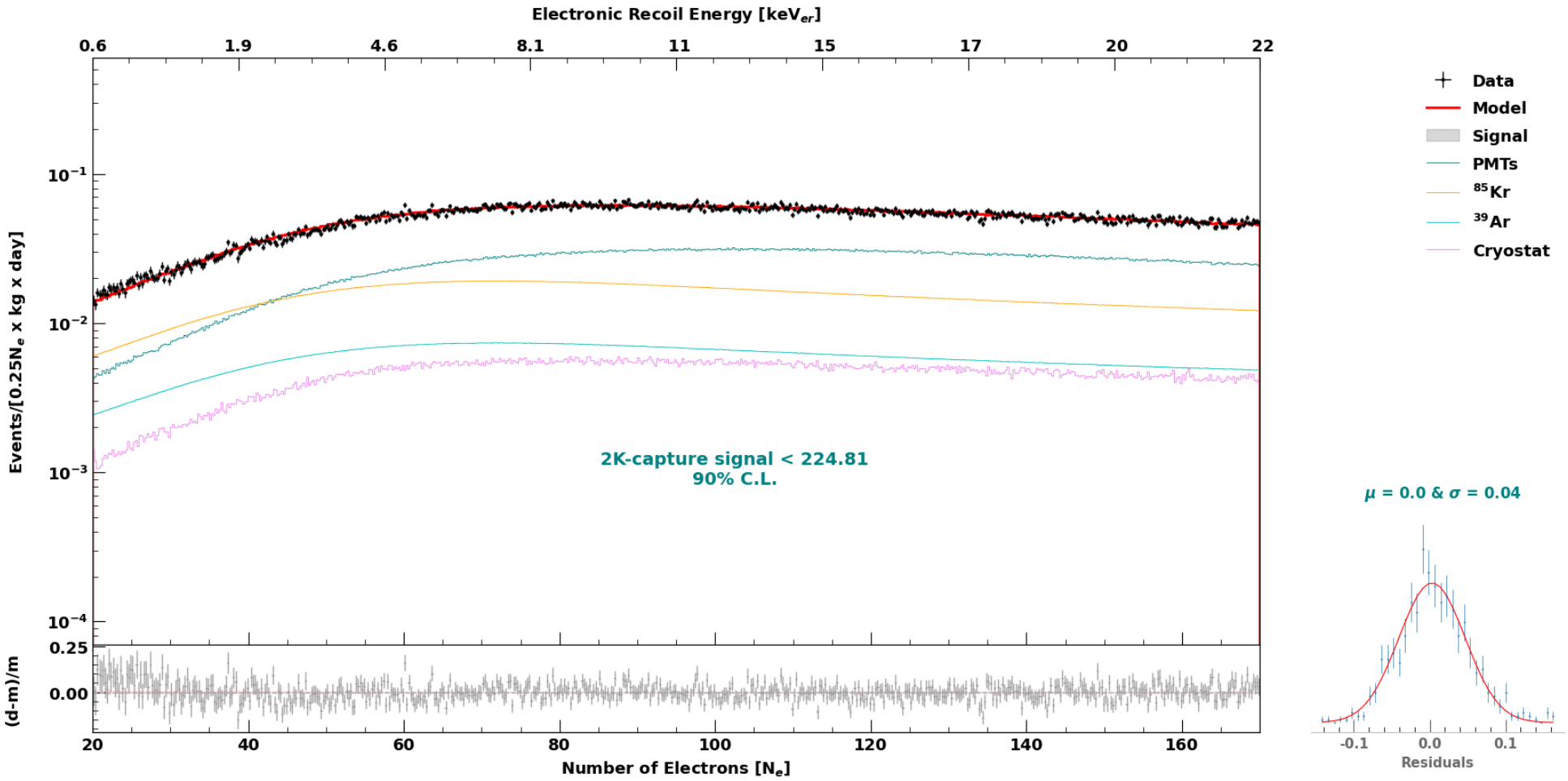


Estimated half-life of ^{36}Ar

- $\eta(^{36}\mathrm{Ar}) \approx (0.012 \div 0.334)\%$ – ^{36}Ar abundance limits in underground argon[4][5]
- $\mathrm{E}_{2\nu 2\mathrm{EC}} \sim 60e^-$ of ionization,
- The background at this energy is $\sim$ 2520 events/$1e^-$.

$$T_{1/2} = \ln(2)\frac{N(^{36}Ar)}{\sqrt{N_{\mathrm{bg}}}} M_{\mathrm{LAr}} \cdot T \sim (10^{20} \div 10^{21}) \text{ years}$$

Data fitting



Fit of the experimental data by the background model
and partial contributions of the background components to this model in range [20,170] N_e.

Lifetime estimation of ^{36}Ar

- Exposure time $T = 630$ days
- target mass $M = 20$ kg
- $M(^{36}\mathrm{Ar}) = 35.9$ g/mol
- ^{36}Ar isotope abundance in UAr: $\eta = (0.012 \div 0.334)\%$
- $N_{2\nu 2\mathrm{EC}} = 225$ events

$$T_{1/2} = \ln(2)\frac{\eta N_A M T}{M(^{36}Ar)N_{2\nu 2\mathrm{EC}}} > (2.2 \times 10^{20} \div 6.0 \times 10^{21}) \text{ years, CL} = 90\%$$

Results

Preliminary result for ^{36}Ar in DarkSide-50

$$T_{1/2} > (2.2 \times 10^{20} \div 6.0 \times 10^{21}) \text{ years, CL} = 90\%$$

Expected result for ^{36}Ar in DarkSide-20k

$M^{\text{DS-20k}} = 400 M^{\text{DS-50}}$; $N_{bg}^{\text{DS-20k}} \sim 0.01 N_{bg}^{\text{DS-50}}$

$$T_{1/2}^{\text{DS-20k}} \sim 200\, T_{1/2}^{\text{DS-50}} \text{ years}$$

Result in XENON1T for ^{124}Xe

$$T_{1/2} = (1.8 \pm 0.5 \pm 0.1) \times 10^{22} \text{ years.}$$

Future plans

- To carry out more thorough calculations of the energies and probabilities of Auger electrons and characteristic photons emissions during the rebuilding of the atomic shell as a result of 2EC2ν by ^{36}Ar;
- to carry out measurements for different samples of argon (DS-50, DS-20k, Lowmass);
- to check the calculation on a target enriched in ^{36}Ar in the future;
- to apply this analysis for DS-20k experiment.

Thank you for attention!

Sourses I

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