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

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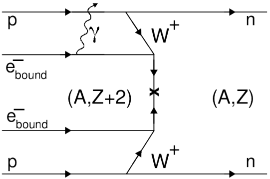
Introduction

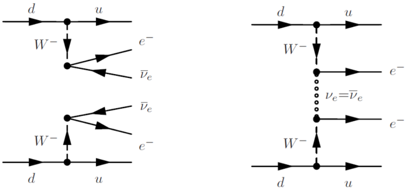
2e-capture

- (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 (argon is the active medium in DarkSide-50 experiment).

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

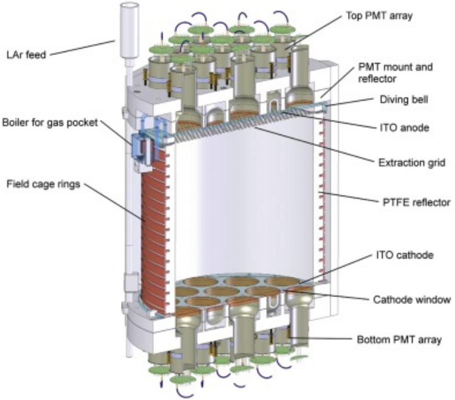
- development of a software code for simulating the energy spectrum of double electron capture (2EC2ν) on ^{36}Ar;
- application of the detector response of the DarkSide-50 detector to the simulated spectrum;
- statistical data analysis using a model spectrum;
- derivation of a lower limit for the half-life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

Novelty

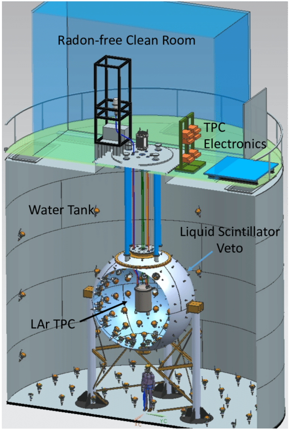
Studies of 2EC2ν have not previously been carried out on argon isotopes.

DarkSide-50 experiment

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

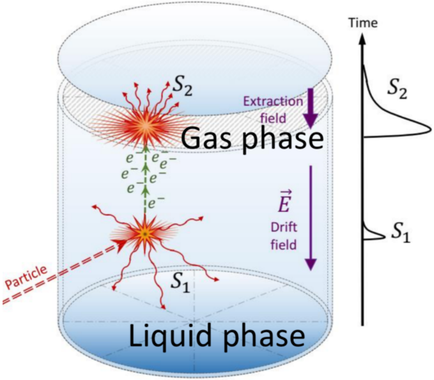


TPC scheme



Detector scheme

The principle of particle detection by the DarkSide-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 — the active medium in DarkSide-50

- ^{40}Ar was form from decay of ^{40}K:

$$e^{-} + {}^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ar} + \nu_e + \gamma$$

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

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

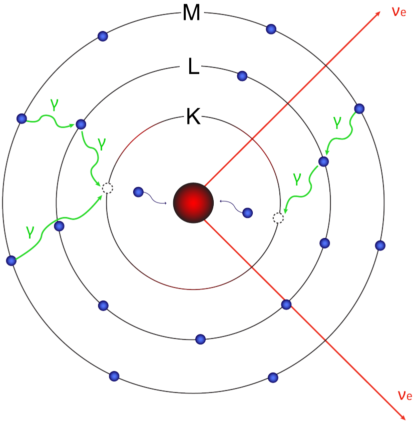
  The use of argon from underground deposits will reduce the contribution of this component;

- ^{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, because potassium is distributed in space about 50,000 times less than argon (on Earth, potassium prevails over argon by 660 times).
- ^{36}Ar was formed during nucleosynthesis in massive stars;
- the isotopic abundance of ^{36}Ar in atmosphere greatly exceeds the abundance ^{36}Ar underground.

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 characteristic fluorescence quanta that appear when two vacancies are filled.
- $E_{2EC2\nu} \approx 4.8$ keV.

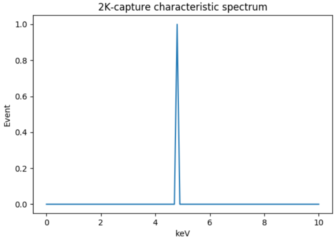
$$^{36}\mathrm{Ar} + 2e^- \longrightarrow {}^{36}\mathrm{S} + 2\nu_e$$



Data analysis

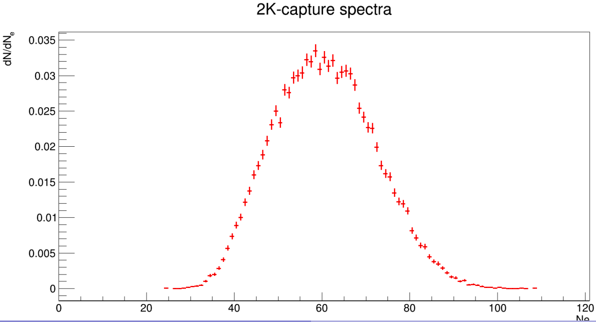
Modeling the spectral component of 2K-capture

The simplified model of response is used here, an exact model is being developed.



- Software package *DarkSide-50:lowmass*

- Top: Characteristic emission spectrum from 2K-capture
- Bottom: Detector response spectrum from 2K-capture



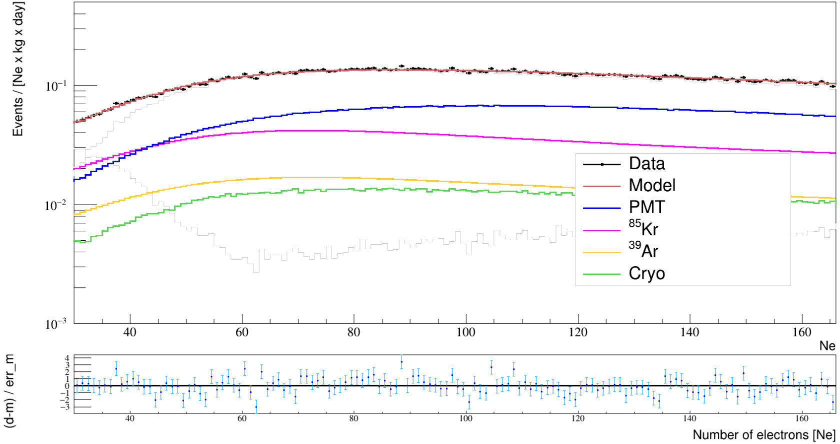
Estimated half-life of ^{36}Ar

- a(^{36}Ar)$\approx (0.0025 \div 0.334)\%$ – ^{36}Ar abundance limits in underground argon[3][4]
- $E_{2\nu 2EC} \approx 4.8$ keV $\sim 60e^{-}$ of ionization,
- The background at this energy is ~ 2100 events/$1e^{-}$ [5].
- Probability of two-photon fluorescence $\epsilon = 50\%$.

$$T_{1/2} = \ln(2) \frac{N(^{36}Ar)}{\sqrt{N_{\text{bg}}}} M_{\text{LAr}} \cdot T \cdot \epsilon \sim (10^{19} \div 10^{21}) \text{ years} \tag{1}$$

Data analysis

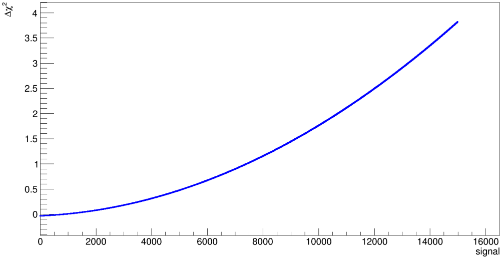
Best background fit



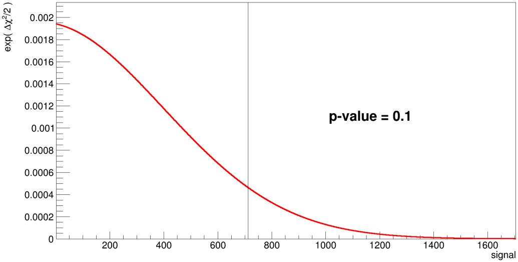
Best fit of the experimental data by the background model (brown line) and partial contributions of the background components to this model in range $[30{,}166]\,N_e$.

Data analysis

- $\Delta y_i = data_i - model_i$
- $\chi^2 = \sum_{i=1}^{n} (\frac{\Delta y_i}{\sigma_i})^2$; i-bin number
- $\Delta\chi^2_{signal} = \chi^2_{signal} - \chi^2_0$;
- $L = e^{-\sum_i \frac{\Delta y_i^2}{2\sigma_i^2}} = e^{-\frac{1}{2}\chi^2}$;

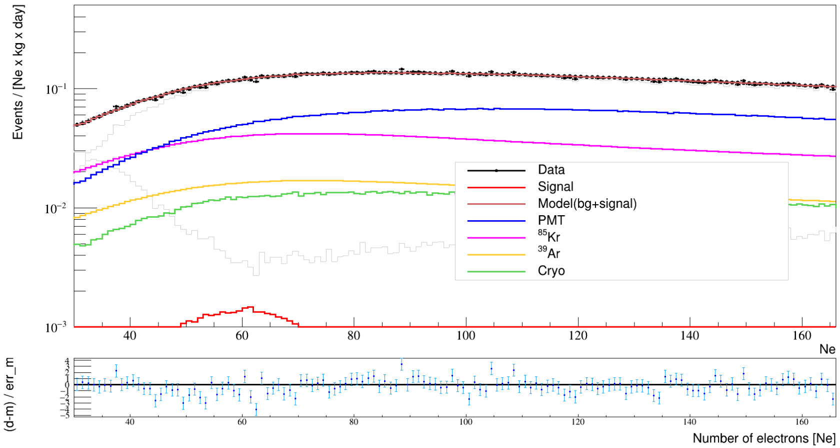


- Top: Change in $\Delta\chi^2$ with increasing signal amplitude
- Bottom: Dependence of the maximum likelihood function on $\Delta\chi^2$



CL=90%;

Data analysis



Fitting experimental data with a background and signal model for CL = 90%.
Fitting was performed in the range [30,166]N_e.

Data analysis

Lifetime estimation of ^{36}Ar for 2K-capture

- $M(^{36}\mathrm{Ar}) = 39.948$ g/mol
- ^{36}Ar isotope abundance in UAr: $\eta = (0.0025 \div 0.334)\%$
- probability of two-photon fluorescence $\epsilon \approx 50\%$

$$T_{1/2} = \ln(2)\frac{\eta N_A M T \epsilon}{M(^{36}Ar) N_{2\nu 2\mathrm{EC}}} > (0.6 \times 10^{19} \div 0.7 \times 10^{21})\ \text{years},\ \mathrm{CL} = 90\%$$

Results

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

$$T_{1/2} > (0.6 \times 10^{19} \div 0.7 \times 10^{21}) \text{ years, CL} = 90\%$$

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

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

Conclusion

- In the future, it is planned to carry out more thorough calculations of the 2EC2ν probabilities on ^{36}Ar and a more accurate calculation of the energy release in this process.
  It is also possible to measure the isotopic abundance of argon in the DS-50 using mass spectroscopy.
- It would be a good option to check the calculation on a target enriched in ^{36}Ar.
- The analysis performed in this work is planned to be carried out during the experiment on the next generation DarkSide detector.

Thank you for attention!

Sourses I

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