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Intensive electron antineutrino source with well defined hard spectrum on the base of nuclear reactor and ^8Li -lithium transfer. The promising experiment for sterile neutrinos search

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ABSTRACT: The concept of combination $\bar{\nu}_e$ -source for future short-baseline experiments is discussed. The source ensures: 1) well defined hard antineutrino flux; 2) the rate of counts more than $\sim 10^3$ per day in the detector volume $\sim m^3$; 3) low level of $(\bar{\nu}_e, p)$ -count-errors — $\lesssim 1\%$. The source is based on (n, γ) -activation of ^7Li near the reactor active zone and transport of the fast β^- -decaying ^8Li isotope toward a remote neutrino detector and back in the closed loop. We propose the low-errors-experiment for reliable search of sterile neutrinos with $\Delta m^2 \sim 1\text{eV}^2$. The results of simulation for (3+1) and (3+2) sterile neutrino models indicate the space regions for search of $\bar{\nu}_e$ -disappearance outside the interval of $\bar{\nu}_e$ -spectrum errors.

KEYWORDS: Oscillation, Dark Matter and Double Beta Decay (experiments), Electroweak interaction

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1 Introduction. Antineutrino spectrum from ^8Li and reactor active zone

In spite of the superiority on neutrino flux the nuclear reactors has a disadvantage: too low hardness of $\bar{\nu}_e$ -spectrum. This character is extremely negative as for considered here reactor antineutrino energy the neutrino cross section is proportional to its energy squared: $\sigma_\nu \sim E_\nu^2$. The spectrum errors are significant ($\sim 5\%$ at the average) and the detected bump in reactor $\bar{\nu}_e$ -spectrum is one more evidence that the distributions often used before were inadequate [1].

The disadvantage of rapidly dropping spectrum can be filled having realized the idea [2] to use a high-purified ^7Li -isotope for construction of lithium blanket (or converter) around the active zone (AZ) of a reactor [3]. A short-lived isotope ^8Li ($T_{1/2} = 0.84\text{s}$) is created under AZ neutrons flux in reaction $^7\text{Li}(n, \gamma)^8\text{Li}$ and at β^- -decay it emits hard antineutrinos of a well determined spectrum with the maximal energy $E_{\bar{\nu}_e}^{\text{max}} = 13\text{MeV}$ and mean one $\langle E_{\bar{\nu}_e} \rangle \simeq 6.5\text{MeV}$. The ^{235}U neutrino spectrum (the main fuel component) is presented in figure 1 in comparison with $\bar{\nu}_e$ -spectrum of ^8Li -isotope [4, 5]. The advantages of hard $\bar{\nu}_e$ -spectrum of ^8Li is clear on the example of sharp rise for cross section of inverse beta decay reaction (with threshold $E_{\text{threshold}} \simeq 1.8\text{MeV}$) $\bar{\nu}_e + p \rightarrow n + e^+$.

Lithium blanket around the AZ acting as a converter of reactor neutrons to antineutrinos is the most simple scheme of lithium antineutrino source with steady spectrum source [3, 7]. As a result the total $\bar{\nu}_e$ -spectrum from AZ and from decays of ^8Li -isotope becomes considerably harder in comparison with the pure reactor neutrino spectrum, which errors strongly rise at the energy above $\sim (5\text{--}6)\text{MeV}$ [7, 8]. Note that reactor antineutrino spectrum is specified also with instability of fuel composition (^{235}U , ^{239}Pu , ^{238}U , ^{241}Pu) which varies in time in operation period.

In this article we will discuss the proposal how to decrease strongly the $(\bar{\nu}_e, p)$ -count-errors arising from the AZ- $\bar{\nu}_e$ -spectrum errors. It will be shown that alongside with low

Figure 1. Spectrum of antineutrinos from β^- -decay of ^8Li [5] and ^{235}U fission fragments [4] (see left axis). Cross section of $(\bar{\nu}_e, p)$ -reaction is on the right axis [6].

count errors the proposed concept of $\bar{\nu}_e$ -source will ensure a high rate of events (more than $\sim 10^3$) in the $\sim m^3$ of the detector per day for 1 GW of reactor power. In order to minimize the number of $(\bar{\nu}_e, p)$ -count-errors it was decided to use ^{235}U as the single fuel isotope similar to investigating reactors: HFIR [9], SM [10] and new reactor PIK [11, 12]. In case of the single burning fuel it will be also significantly simpler to evaluate the $\bar{\nu}_e$ -spectrum from AZ. One more advantage of ^{235}U is the possibility to connect the AZ-neutrino-spectrum-bump with decay products of the single fuel isotope (this advantage is noted also in the work [1]).

The used here ^{235}U -antineutrino spectrum [4] is based on the conversion of experimental cumulative β^- -spectrum obtained from thermal neutron fission products. As a results of conversion the obtained total errors of ^{235}U -fission-products-antineutrino-spectrum ((4.2–4.7)% for $E_{\bar{\nu}_e} = (2.0\text{--}7.25)\text{ MeV}$ and from 5% to 56% for higher energy) include the precision of statistics, the errors of the conversion procedure and registration.

In the work [13] the authors applied the modified conversion procedure with use the latest nuclear information (on known beta branches of the fission products and treatment of the forbidden transitions) and concluded that normalization of antineutrino spectrum need be systematically corrected on $\sim +3\%$. Today the reactor-antineutrino-spectrum is known with precision of several percents that is insufficiently for current analysis of oscillation experiments. Really the significant decrease of the expected count errors caused by not rather accurate description of AZ- $\bar{\nu}_e$ -spectrum (including experimental results and theoretical models) becomes critical for neutrino investigations.

2 Dependence of $\bar{\nu}_e$ -cross section and count events from the total spectrum hardness H

For the next discussion we need to characterize numerically the hardness of the total $\bar{\nu}_e$ -spectrum from AZ and ^8Li -isotopes. The proposed definition of the generalized hardness H for total $\bar{\nu}_e$ -spectrum [14, 15] is:

$$H(\vec{r}) = \bar{n}_\nu \times [F_{\text{Li}}(\vec{r})/F_{\text{AZ}}(\vec{r})], \quad (2.1)$$

Figure 2. Cross section of $(\bar{\nu}_e + p \rightarrow n + e^+)$ -reaction (dash lines) and expected count errors δ_C (solid lines) in the total $\bar{\nu}_e$ -spectrum as function of the hardness H . Values of cross sections at $H = 0$ correspond to $\bar{\nu}_e$ -spectrum from pure ^{235}U . The results are given for thresholds of registration: 3, 4, 5, 6 MeV.

where $F_{\text{Li}}(\vec{r})$ and $F_{\text{AZ}}(\vec{r})$ — densities of lithium $\bar{\nu}_e$ -fluxes from Li-blanket and from AZ, $\bar{n}_\nu \simeq 6.14$ — number of reactor antineutrinos emitted per one fission in the AZ. We admit that the hardness of the total $\bar{\nu}_e$ -spectrum at the point $\vec{r}$ equals one unit of hardness if the ratio of densities $F_{\text{Li}}(\vec{r})/F_{\text{AZ}}(\vec{r})$ is equal to $1/\bar{n}_\nu$.

In fact the total number of $\bar{\nu}_e$ (crossing the neutrino detector) is defined by hardness H as:

$$N_{\bar{\nu}_e} = N_{\text{AZ}} + \langle H(\vec{r}) \rangle \times (N_{\text{AZ}}/\bar{n}_\nu), \quad (2.2)$$

where N_{AZ} — number of $\bar{\nu}_e$ from AZ, $\langle H(\vec{r}) \rangle$ — averaged hardness of the total spectrum in the detector position. The second summand determines the number of lithium antineutrinos. Then for corresponding values of flux densities for the total $\bar{\nu}_e$ -flux in the point $\vec{r}$ we can write:

$$F_{\bar{\nu}_e}(\vec{r}) = F_{\text{AZ}}(\vec{r}) + H(\vec{r}) \times (F_{\text{AZ}}(\vec{r})/\bar{n}_\nu). \quad (2.3)$$

The cross section in the total spectrum is the additive value of $\bar{\nu}_e$ -flux from AZ and from ^8Li [16] and for inverse beta decay reaction $(\bar{\nu}_e, p)$ -reaction we have:

$$\sigma_{\bar{\nu}_e,p}(\vec{r}) = \sigma_{\bar{\nu}_e,p}^{\text{AZ}} + H(\vec{r}) \times \sigma_{\bar{\nu}_e,p}^{\text{Li}}. \quad (2.4)$$

Taking into account the evaluation $\sigma_{\bar{\nu}_e,p}(E)$ of [6], the $\bar{\nu}_e$ -spectrum of ^{235}U (as the main fuel isotope) [4] and ^8Li [5] the cross section (2.4) was calculated as function of the hardness H for thresholds of registration $E_{\text{threshold}} = 3, 4, 5, 6$ MeV (see figure 2). At increase of H -value the strong rise of the cross section is caused by enlarged part of hard lithium neutrinos in the total spectrum. As a result for hard total spectrum the lithium yield to the cross section strongly dominates the reactor part (here we used $\bar{\nu}_e$ -spectrum of ^{235}U [4] as a single fuel isotope) [16] (as in figure 2).

For the perspective experiments the one more important advantage from considered combined $\bar{\nu}_e$ -flux is fall of the expected count errors $\delta_C(H)$ (we study count errors originated

from reactor $\bar{\nu}_e$ -spectrum errors) at increase of the total- $\bar{\nu}_e$ -spectrum-hardness H [16]. The function $\delta_C(H)$ is defined as

$$\delta_C(H) = \frac{\int_{E>E_{\text{threshold}}} \sigma_{\bar{\nu},p}(E) F_U(E, \vec{r}) \delta_U(E) dE}{\int_{E>E_{\text{threshold}}} \sigma_{\bar{\nu},p}(E) [F_U(E, \vec{r}) + F_{\text{Li}}(E, \vec{r})] dE}, \quad (2.5)$$

where: the denominator is the density of registration counts (at 100% efficiency of $(\bar{\nu}_e, p)$ -detecting) in the total $\bar{\nu}_e$ -flux and numerator of the fraction is possible to call as density of count errors; $F_U(E, \vec{r})$ and $F_{\text{Li}}(E, \vec{r})$ dependences of $\bar{\nu}_e$ -flux densities on the energy in the point $\vec{r}$ for ^{235}U and ^8Li correspondingly; $\delta_U(E)$ — energy dependence of $\bar{\nu}_e$ -spectrum errors of ^{235}U [4]. According to definition (2.1) the given hardness H is ensured in the point $\vec{r}$ if in the equation (2.5) we have $F_U(E, \vec{r}) = a\rho_U(E)$ and $F_{\text{Li}}(E, \vec{r}) = a\rho_{\text{Li}}(E) \times [H(\vec{r})/\bar{n}_\nu]$, where: $\rho_U(E)$ and $\rho_{\text{Li}}(E)$ are $\bar{\nu}_e$ -spectra of ^{235}U [4] and ^8Li [5] correspondingly; a — coefficient of flux normalization which is cancelled out in expression (2.5).

The result dependences of averaged count errors on hardness H for the combined spectrum (from AZ with bump in the spectrum plus from ^8Li yield) are presented in figure 2 for specified thresholds. The accurate calculation gives sharp decrease of errors for more hard $\bar{\nu}_e$ -spectrum. It confirms the possibility to decrease the count errors in several times compare the significant count errors in case of $\bar{\nu}_e$ -spectrum of AZ.

3 Antineutrino source with regulated and controlled spectrum on the base of nuclear reactor and lithium transfer

It is possible to supply intensive neutrino fluxes of considerably greater hardness by means a facility with a transport mode of operation: liquid lithium substance is transferred in a closed cycle through a blanket and further toward a remote neutrino detector. (see figure 3). For increasing of hard-lithium-antineutrinos-flux a being pumped reservoir is constructed in the remote part of the closed loop (in the space close to the $\bar{\nu}_e$ -detector). Due to the geometrical factor the total $\bar{\nu}_e$ -spectrum in the detector volume will be strongly harder compare to reactor antineutrino spectrum. In addition such a facility will ensure also an opportunity to investigate $\bar{\nu}_e$ -interaction at different spectrum hardness varying a rate of lithium pumping from zero to maximal rate ensured in this installation [14–17].

The natural lithium consists of two isotopes — ^6Li and ^7Li with concentration 7.5% and 92.5% correspondingly. The beneficial $^7\text{Li}(n, \gamma)^8\text{Li}$ cross section is very small compare to large parasitic absorption on ^6Li : at thermal energy $\sigma_{\text{abs}}(^6\text{Li}) = 937$ b, but this one for $^7\text{Li}(n, \gamma)$ -activation is lower in four orders — $\sigma_{n,\gamma} \simeq 45$ mb. This dictates the necessary grade of ^7Li purification of 0.9999 or 0.9998 as minimum level [3, 18–20].

Instead of metallic lithium we propose to use a heavy water solution of lithium hydroxides — $^7\text{LiOD}$, $^7\text{LiOD} \cdot \text{D}_2\text{O}$ [17–20]. This approach helps to solve two problem: 1) to pump a solution in the scheme with variable spectrum is more simple and safe; 2) the requested mass of high purified ^7Li will strongly decrease and the price of installation will be heavy lower. For presented below results of simulation the 22 m^3 in volume means that

Figure 3. The principal scheme of $\bar{\nu}_e$ -source with variable (regulated) spectrum for short-baseline experiment. The dimensions in the figure correspond to actual sizes used in the simulation. Liquid lithium substance in the blanket (activated by neutrons from Active Zone) is pumped continuously through the delivery channel to the remote reservoir (which is set close to the $\bar{\nu}_e$ -detector) and further back to the blanket. The examples of detector positions are labeled as d . The 3-dimensional view of the reservoir (label R) is given separately. At simulation of the antineutrino disappearance we used the coordinates of points along the line A ($y = 1$). The rate of pumping can be smoothly varied by the installation (not shown) of regime maintenance.

mass of ^7Li in D_2O -solution (LiOD concentration — 9.6%) will decrease in 18 times down to 0.71 t.

The physical sence of the introduced (in part 2) definition for generalized hardness H is the relation between the hard- ^8Li -neutrino-flux and soft flux from AZ for considered space point $\vec{r}$. But from what depends the relative part of ^8Li flux in the hardness H value? These circumstances are the geometrical factor (i.e., the space distribution of ^8Li decaying nuclei and AZ relative to the point $\vec{r}$) and yield of ^8Li isotopes in the activated lithium blanket around AZ. As example the dependence of hardness H from the space coordinates is presented below in the part 4 for considered source with specified parameters.

In order to characterize numerically the yield of ^8Li we define the productivity factor k of the blanket as the number of ^8Li nuclei produced in the blaket volume per one fission in AZ. The value of factor k increases with rize of $^7\text{Li}(n, \gamma)$ -captures relative to parasitic neutron absorption on another isotopes and with decrease of number of neutrons escaping from the blanket. I.e., the productivity factor k specifies the blanket efficiensy for ^8Li production. Note that the definition of hardness is very convenient as in so doing the averaged H value of steady-spectrum- Li -sources (which are considered in [3, 18–20]) is estimated by its factor k . Really if the rate of lithium pumping equals zero then all ^8Li -neutrinos will be escaped from the blanket and for remote detector positions the hardness will be evaluated as $H \simeq k$. From the other side the significant increase of circulation rate for lithium substance (up to $(2\text{--}3)\text{ m}^3\text{s}^{-1}$) enures strong rize of the hardness H in the spase close to the neutrino detector — in ten times and more (see examples in [15, 21]).

The values of k -factors were calculated earlier by neutron transport simulation in different lithium containing blankets. It were obtained the dependencies of k -values: on ^7Li -purification and its mass in the blanket; for different blanket substanses and geometries [3, 18]. The proposed ^7Li purity is 0.9999. So, the blanket filled with (5.7–9.5)% solution of LiOD possess the productivity $k \geq 0.1$.

It is fully realistic to ensure the requested ${}^7\text{Li}$ mass with purification 0.9999 which widely used for light-water power reactors [22, 23] and permanently produced in significant quantity [24, 25]. That is important the production of pure ${}^7\text{Li}$ with enrichment 0.99995 will be also required for work of new concepts of advanced nuclear reactors (as Advanced High Temperature reactor): 25000 kg of 0.99995-enriched ${}^7\text{Li}$ for 1 GW of reactor power (see p. 32 in the document [26]).

It was obtained the equations for fluxes of lithium antineutrinos from the blanket and parts of the closed loop [14, 15, 17]. The flux emitted from the pumped-blanket-volume V_B during the time t is:

$$N_B(t) = \lambda_{n,\gamma} N_0^7 t \{1 - [\varphi(V_B)\varphi(V_0 - V_B)] / \lambda_\beta t_p \varphi(V_0)\}, \quad (3.1)$$

where: $\varphi(y) = 1 - \exp(-\lambda_\beta y / w)$; $\lambda_{n,\gamma}$, λ_β - rate of (n, γ) -reaction and β^- -decay; w — volume being pumped over in a time unit (rate of flow); V_0 — volume of the whole system, $t_p = V_B/w$ — time of pumping over of the blanket volume; N_0^7 — is the starting number of ${}^7\text{Li}$ nuclei at $t = 0$; $\lambda_{n,\gamma} N_0^7$ is the number of ${}^8\text{Li}$ nuclei created in a time unit (assuming that starting number of ${}^8\text{Li}$ nuclei at $t = 0$ is equal to zero).

The flux of lithium antineutrinos from a delivery channel during a time t is the next:

$$N_{cd}(t) = (\lambda_{n,\gamma} N_0^7 t / \lambda_\beta t_p) \times [\varphi(V_B) \times \varphi(w t_d) / \varphi(V_0)], \quad (3.2)$$

where $t_d = L_1/\mathcal{V}$ is the time of lithium delivery from the blanket to the reservoir with linear velocity $\mathcal{V}$. The expression (3.2) allows obtain the flux from any volume parts of the closed cycle specifying the corresponding time intervals of lithium delivery $[t_d^1, t_d^2]$ to the appointed part.

In view of the above accepted for k -factor normalization per one fission in the AZ we have $\lambda_{n,\gamma} N_0^7 / N_{fis} = k$, where N_{fis} — is the number of fissions in AZ in time unit. The proportionality of N_B and N_{cd} to $\lambda_{n,\gamma} N_0^7$ in (3.1) and (3.2) means the direct proportionality of: ${}^8\text{Li}$ -antineutrino flux and hardness H to k -factor according to definition (2.1).

4 Antineutrino fluxes. Compact detectors

For the simulation we specified the next parameters of the source and regime of the operation. Volume of the compact spherical AZ — corresponds to 51 l volume of the high flux research reactor PIK [11, 12]. Thickness of the spherical lithium blanket — 1 m. Volume of the reservoir (rectangular parallelepiped of 0.5 m thickness) was set equal to blanket one. L_1 -distance (between lithium blanket and pumped reservoir) corresponds to the time 1 s of lithium delivery from the blanket to reservoir for appointed rate of pumping $w = 2.25 \text{ m}^3/\text{s}$.

In the model the source volume (see figure 3) was divided on small cells and the number of ${}^8\text{Li}$ nuclei in any cells (see (3.1) and (3.2)) was obtained for the pumping regime. Knowing the reactor and ${}^8\text{Li}$ spectrum, having the data on flux from AZ (that also was segmented) and cell fluxes we calculate the flux, spectrum, hardness at the detector positions. The higher level of hardness (that is important for high rate of counts and low errors) is supported in the close space around the voluminous reservoir. For analysis of

Figure 4. The expected antineutrino fluxes (part (a)) and number of $(\bar{\nu}_e, p)$ -events (part (b)) in the detector depending on the X coordinates along the line A (geometry of figure 3). The results are given for thresholds of registration: 3, 4, 5, and 6 MeV. The total fluxes and total number of events is ensured by $\bar{\nu}_e$ from ${}^8\text{Li}$ and AZ (Active Zone). Close to the reservoir position (given by the two-sided arrow) we can see sharp rise of hardness H (lithium bump) for total $\bar{\nu}_e$ -spectrum (see part (a)).

oscillation we considered the simple geometry where detectors can be shifted along the line A (the geometry of figure 3). This geometry of the detector position is realistic owing to high count rate in the hard neutrino spectrum and possibility to reduce the detector sensitive volume up to $\sim \text{m}^3$ (see below). The applied proton concentration in the detector is typical — $\sim 6.6 \times 10^{22} \text{cm}^{-3}$ (as in KamLAND) [27].

Owing to nuclear reactor (as intensive neutron activator) and remote reservoir (as geometry factor for creation of hard $\bar{\nu}_e$ -spectrum) the proposed source ensures high intensive and well defined neutrino flux in the space close to the reservoir. The result of calculated fluxes and hardness H for points on the line A (see detector position in figure 3) is given in the parts (a) of figure 4. Note that hardness H does not depend on thresholds of registration on definition (2.1).

Thank to the reservoir the total $\bar{\nu}_e$ -flux has lithium bump close the reservoir position. The dependence of cross section as $\sigma_\nu \sim E_\nu^2$ strongly increases the expected number of $(\bar{\nu}_e, p)$ -events in the detector (see parts (b) of the figure 4). As a result of lithium-bump-effect we have strong amplification in the number of expected events and crowding of curves (for

total events) close to detector position compare to part (a) of figure 4. The all results are normalized per cubic meter of the detector, day and gigawatt of the reactor power. The obtained dependencies of expected events (see part (b) in figure 4) allow to state an important conclusion: owing to lithium loop scheme it will be ensured very high rates of events in the wide interval along the line A . Even at the threshold 6 MeV the rates of total events exceed the event rates from AZ at 3 MeV in the wide X -interval from 10 to 28 m. The lower thresholds [(5–4) MeV] for total events registration allow to exceed the AZ-event-rates at 3 MeV in more wide X -interval: (7–32) m and (4– >50) m correspondingly. It is possible to evaluate the statistics which will be accumulated per 1 year (at effective time of operation at power — 240 days; [10]): so, at the $E_{\text{threshold}} = 6$ MeV and detector position $X = 30$ m (the coordinate where the possibilities to detect oscillation to sterile neutrinos for models (3+2)a and (3+2)b are large — see results of the part 5) the expected number of events will be $\sim 2.5 \times 10^5 \text{ m}^{-3} \text{ GW}^{-1}$ at low count errors ($\leq 0.5\%$). The events ensured by the ^8Li antineutrinos are strongly dominates owing to the hardness of $\bar{\nu}_e$ -spectrum of ^8Li . Compare to reactor yield the ^8Li ensure strong rise of registration rate.

After the epochal experiments of F. Reines, C. L. Cowan, and F. A. Nezrik in 1953–1966-th [28] on inverse beta decay registration the next progress was impacted with problems of detector efficiency and precision of obtained data. Rather high rate of events in the total (AZ + Li)-spectrum allows to consider the neutrino detector with compact sensitive volume $\sim \text{m}^3$. Now where are successful engineering of this task and we want to note some features and examples of compact detectors with high levels of efficiency. The similar types can be candidates for investigation with discussed combined neutrino source.

During 1980–1990-th at the Roven nuclear power plant it were constructed two main types of detectors for neutrino experiments (with distance to the core 18, 25, 32.8 and 92.3 m): first type was based on delayed coincidences between signals from positron and neutron capture in gadolinium (doping agent to liquid scintillator); the second one (called as integral detector) registers only neutron captures by ^3He -proportional counters in reaction $n + ^3\text{He} \rightarrow T + p + 765 \text{ keV}$. The detectors of the first type had the volume (238–240) l and efficiency 32% [29]. The integral detectors had ^3He counter matrix deployed in the tank with distilled water (neutrino target) and ensured significantly higher efficiency — (40–54.9)% [30]. On the above we discussed the decrease of count errors if to register the inverse beta decay reaction at increase of energy threshold in hard total neutrino fluxes. Change of registering threshold is possible namely in the detectors based on delayed signal coincidences between positron and neutron-capture. It is important for our purpose that such detectors allow to realize an acquisition and analysis of γ -quantum signals caused by creation of positrons (which carries away the almost full antineutrino energy). The energy of positron is well described as $E_{e^+} \simeq E_{\bar{\nu}_e} - (m_n - m_p)$, where m_n and m_p — mass of neutron and proton correspondingly [6]. Registration of delayed signal coincidences and control of its space coordinates is important also for more strict separation of the background events.

Compact neutrino detectors are developing in many nuclear centers as for purpose of reactor nuclear fuel burnup as for oscillation researches; here in the context of the discussed below short base line experiment we note only some of them: Nucifer [31], DANSS [32, 33], Neutrino-4 [34, 35], Stereo [36], PROSPECT (AD-I version) [37, 38], PANDA [39, 40].

The most difficult metrological problem in interpretation of the neutrino event data is subtraction of the background (from the reactor, radioactive isotopes in the laboratory, the secondary particles produced by cosmic rays) and use of pure materials. The typical passive detector shield are (in order): the inner layer of borated polyethylene (~ 10 cm for effective moderation and capture of reactor neutrons and neutrons produced in next led shield at capture of muons), the led layer (~ 10 cm for muon capture and attenuation of γ - and neutron fluxes from the core) and the outer layer of borated polyethylene or steel (17 cm of steel as in Roven experiment) covering the walls of the laboratory. The passive shield effectively suppress the low energy component of the background: so, in Neutrino-4 experiment (which is realizing on the Earth level, i.e., without deepening under the reactor core) it allowed to decrease the thermal and fast neutron fluxes in 53 and 12 times correspondingly [34, 35]. But the main troubles caused by high energy muons penetrating to the detector, producing γ -quants and neutrons in the target volume and mimicking the inverse beta decay events; this high energy background is not controlled by active shielding and strongly decrease the detector efficiency, which typical values are: (32–55)% [29, 30], 29.4% (in Krasnoyarsk experiment, [41]), 30.3% [31], 42% [37, 38], (9.24–11.6)% [39, 40].

The background condition is characterized by relation of number for neutrino signals to false signals from background: $K = N_s/N_b$. If experiment is realized on the Earth level (as Neutrino-4) this relation is not large: $K = 0.32$. An increase of K value can be achieved by: deepening under the ground (30 meter of water equivalent (mwe) in Rovno experiment [29, 30], where relation $K = 0.9$; at 50 mwe in DANSS the K -value is $\simeq 36$ [32, 33]); strict rejection of the false signals (at only several mwe in PROSPECT experiment the value of $K = 3.1, 2.6$ and 1.8 for distances from 6.9 m, 8.1 m and 9.4 m from the core to detector [37]); fine segmentation of the detector volume as in mobile and very portable PANDA detector (with modest $K \leq 0.1$) which operates out of the reactor building shield and without additional muon veto around the whole detector. Namely the fine segmentation ensured the reliable identification of muons crossing the sensitive volume with deposition of large energy in series of hits and in so way gives the capability to reject these passing tracks [39, 40].

5 Simulation for search of sterile neutrinos on the base of source with regulated spectrum

The several experiments (LSND [42], SAGE [43], MiniBooNe [44, 45], GALLEX [46], reactor experiments [47]) revealed anomalous fluxes and strongly stimulated the discussion on existence of sterile neutrinos. The considered here variants include models with one, two and three type of sterile neutrinos [48–51]. Some investigations indicate that squared-mass difference between sterile and active neutrinos — $\Delta m^2 \sim 1 \text{ eV}^2$. The proposed experiment on sterile neutrino search (see figure 3) is short-baseline experiment and has advantages namely at short distances where the large hardness is ensured. For short base line setup in case of (3+1)-model of three active neutrinos plus one sterile neutrino the probability of existence at distance L is given by two-flavor model as:

$$P = 1 - \sin^2(2\Theta) \times \sin^2[1.27\Delta m_{41}^2(L(\text{m})/E(\text{MeV}))], \quad (5.1)$$

where: Θ — angle of mixing; $\sin^2(2\Theta) = 4|U_{i4}|^2(1 - |U_{i4}|^2)$; U_{i4} — element of mixing matrix for active neutrino flavor $i = e, \mu, \tau$; $\Delta m_{41}^2 (\text{eV}^2)$ — maximum squared-mass difference between sterile and active neutrinos (i.e., $|\Delta m_{41}^2| \gg |\Delta m_{31}^2| \gg |\Delta m_{21}^2|$).

Probability for (3+2)-model with two sterile neutrinos for short base experiment will be:

$$P_e = 1 - 4(1 - |U_{e4}|^2 - |U_{e5}|^2) \times \{ |U_{e4}|^2 \sin^2[1.27 \Delta m_{41}^2 (L/E)] + |U_{e5}|^2 \sin^2[1.27 \Delta m_{51}^2 (L/E)] \} - 4|U_{e4}|^2 |U_{e5}|^2 \sin^2[1.27 \Delta m_{54}^2 (L/E)]. \quad (5.2)$$

The matrix elements for (3+1) and (3+2)-models correspond to best fits of the work [48]: for (3+1) model — $|\Delta m_{41}^2| = 1.78 \text{ eV}^2$, $U_{e4} = 0.151$; for (3+2)a-model — $|\Delta m_{41}^2| = 0.46 \text{ eV}^2$, $U_{e4} = 0.108$, $|\Delta m_{51}^2| = 0.89 \text{ eV}^2$, $U_{e5} = 0.124$; for (3+2)b-model — $|\Delta m_{41}^2| = 0.47 \text{ eV}^2$, $U_{e4} = 0.128$, $|\Delta m_{51}^2| = 0.87 \text{ eV}^2$, $U_{e5} = 0.138$. The update analysis of last experiments gives some differing global-fit-parameters for sterile neutrinos with $\Delta m^2 \sim 1 \text{ eV}^2$ [52] compare to ref. [48].

Figure 5 (see parts (a), (c) and (e)) shows the probability P of $\bar{\nu}_e$ -existence, hardness H of the total spectrum and count errors δ_C for models (3+1), (3+2)a and (3+2)b depending on the X -coordinate along line A at thresholds $E_{\text{threshold}} = 3, 4, 5, 6 \text{ MeV}$. The calculated errors for count events are given here at 100% efficiency of registration. At coordinates of the reservoir the hardness reaches the maximum — see part (a) of figure 5. Owing to large lithium mass in the reservoir the maximum of P value is detected close to its position marked by double arrow. Great spectrum hardness around the reservoir ensures small count errors (below 1%) in the nearby space. The errors are strongly decreased for larger thresholds and can be minimized down to order in value.

For evaluation of possibility to detect oscillation to sterile neutrinos depending on coordinates let us introduce the functional for opportunity of registration. We will compare the maximal P value with the current $P(x)$ along A -line (the geometry of figure 3):

$$\Delta_p(x) = [1 - \delta_C(x_{\text{fix}})] \times P(x_{\text{fix}}) - [1 + \delta_C(x)] \times P(x), \quad (5.3)$$

where: δ_C — count errors; coordinate x_{fix} corresponds to maximal P value close to reservoir ($x_{\text{fix}} \simeq 20 \text{ m}$).

The functional allows to search changes in probability P avoiding the errors caused by reactor $\bar{\nu}_e$ -spectrum: positive functional values indicate X -coordinates where $\Delta_p(x)$ is higher to level-of-total-spectrum-errors. The results for models are obtained at $E_{\text{threshold}} = 3, 4, 5, 6 \text{ MeV}$ (see parts (b), (d), and (f) in figure 5). The analysis for $E_{\text{threshold}} = 3 \text{ MeV}$ (part (b) in figure 5) revealed that the probability to detect oscillation in case of (3+1)-model is close to zero: the $\Delta_p(x)$ curves lay below zero or nearby to it. The significant possibility to detect $\bar{\nu}_e$ -disappearance appears only at threshold increase up to 5–6 MeV — see: $\Delta_p(x=26 \text{ m}) > 4\%$ at 6 MeV (part (b) in figure 5). The effects for the model (3+2)b can exceed zero level by 4% at $x \simeq 6 \text{ m}$ (part (f) in figure 5).

To avoid the large errors we propose an effective solution: to increase the threshold of detecting up to 6 MeV. Really at reservoir position the errors (the reactor spectrum bump is taken into account) decrease in $\sim$ ten times: from 0.4% at $E_{\text{threshold}} = 3 \text{ MeV}$ down to

Figure 5. Probability P of $\bar{\nu}_e$ -existence for three models ((3+1), (3+2)a and (3+2)b on the parts (a), (c) and (e)), count errors δ_C (caused by uncertainties of AZ spectrum) (parts (a), (c) and (e)) and functional $\Delta_P(x)$ for opportunity of $\bar{\nu}_e$ -detecting (parts (b), (d) and (f)) for three models (3+1), (3+2)a and (3+2)b depending on the X -coordinate along line A (geometry of figure 3) at thresholds of registration $E = 3, 4, 5$ and 6 MeV (labeled at curves). Hardness $H(x)$ of the total $\bar{\nu}_e$ -spectrum is presented in the part (a). The all solid lines correspond to the values obtained for $\bar{\nu}_e$ -spectrum with bump taken into account. The curves with points (δ_C and Δ_P for model (3+2)a in parts (c) and (d)) — the data for spectrum without bump. Position of the reservoir is shown by the two-sided arrow on parts: (a), (c) and (e). X -coordinates of the positive functional Δ_P values are the regions where probability of $\bar{\nu}_e$ -detecting is higher to level of total spectrum errors.

	$E_{\text{threshold}} = 3 \text{ MeV}$				$E_{\text{threshold}} = 4 \text{ MeV}$				$E_{\text{threshold}} = 5 \text{ MeV}$				$E_{\text{threshold}} = 6 \text{ MeV}$			
$x, \text{ m}$	10	15	25	30	10	15	25	30	10	15	25	30	10	15	25	30
(3+1)	1	1	2	6	3	3	5	16	9	8	13	59	43	40	54	313
(3+2)a	2	3	5	6	5	7	14	16	16	22	53	50	75	116	268	253
(3+2)b	2	2	4	5	4	6	11	11	12	17	38	35	47	72	167	159

Table 1. Duration of the experiment (in days) for disfavoring of no oscillation hypothesis at C.L.=99% for three models [(3+1), (3+2)a and ((3+2)b] at different thresholds ($E_{\text{threshold}} = 3, 4, 5$ and 6 MeV) and position of the detector $x = 10, 15, 25$ and 30 m .

0.045% at $E_{\text{threshold}} = 6 \text{ MeV}$. For another positions the errors are decreased also in several times. As a result we can obtain the significant increase of opportunity for registration at $E_{\text{threshold}} = 6 \text{ MeV}$: see parts (b), (d) and (f) in figure 5. Note that significant rise of Δ_p takes place also at close distances to AZ: for example for (3+1) model $\Delta_p \simeq 3\%$ at $x \simeq 4\text{--}5 \text{ m}$ and $E_{\text{threshold}} = 6 \text{ MeV}$ (part (b) in figure 5). In the parts (c) and (d) of figure 5 the errors presented as for spectrum with bump as without bump. The analysis showed that presence of bump can increase the count errors up to $\simeq 1\%$ (part (d) of figure 5). Results of simulations for additional geometries of detectors positions are considered in [53].

For evaluation of sensitivity to electron antineutrino disappearance in the experiment and efficiency of the $\Delta_p(x)$ -functional (5.3) the χ^2 -analysis was performed using the data of $\bar{\nu}_e$ -spectrum errors for ^{235}U [4] (with bump taken into account) and assuming 2 degrees of freedom (Δm_{41}^2 and U_{e4}) for (3+1)-model and 4 degrees of freedom (Δm_{41}^2 , U_{e4} and two additional — Δm_{51}^2 and U_{e5}) for (3+2)a and (3+2)b models (see (5.1) and (5.2)). The obtained results (normalized per $m^{-3}\text{GW}^{-1}$ as stated above) disfavor the “no disappearance” (no oscillation) hypothesis at confidence level (C.L.) 99% in time from one day (for short distance from AZ) up to 313 days for $x = 30 \text{ m}$ (see figure 3). Such differences are caused by wide change of fluxes, hardness of the total neutrino spectrum (see figure 4) and increase of registration thresholds $E_{\text{threshold}}$ from 3 to 6 MeV. The results of simulation are given in the table 1 for (3+1), (3+2)a and (3+2)b-models at x -coordinates of the detector: 10, 15, 25 and 30 m. Note here that total oscillation strongly depends on the yield of lithium antineutrinos escaped as from the blanket and reservoir as from the channels (especially from the delivery channel which pass very close to the detector in cases of $x < x_{\text{reservoir}}$). For analyses of prediction given by $\Delta_p(x)$ -functional (see (5.3)) it was considered χ^2 :

$$\chi^2(x) = \sum_i \sum_j (N_{\text{observed}}^{i,j} - N_{\text{expected}}^{i,j})^2 / N_{\text{expected}}^{i,j} \quad (5.4)$$

$$= \sum_i \sum_j \left([1 - \delta_c^{i,j}(x_{\text{fix}})] \times P^{i,j}(x_{\text{fix}}) - [1 + \delta_c^{i,j}(x)] \times P^{i,j}(x) \right)^2 / ([1 + \delta_c^{i,j}(x)] \times P^{i,j}(x)),$$

where: $N_{\text{observed}}^{i,j}$ and $N_{\text{expected}}^{i,j}$ are simulated data for $x_{\text{fix}} \simeq 20 \text{ m}$ and x coordinates correspondingly; i — energy group; j — the number of the current small cell in AZ and lithium containing volume; $\delta_c^{i,j}(x_{\text{fix}})$ and $\delta_c^{i,j}(x)$ — are count errors (caused by AZ neutrino spectrum) at x_{fix} and x coordinates correspondingly; $P^{i,j}(x_{\text{fix}})$ and $P^{i,j}(x)$ — the probabilities of antineutrino existence at the point x_{fix} and x .

$E_{\text{threshold}} = 3 \text{ MeV}$												
	$x = 10 \text{ m}$			$x = 15 \text{ m}$			$x = 25 \text{ m}$			$x = 30 \text{ m}$		
	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t
(3+1)	71.3	99.0	1	97.6	99.0	1	99.0	93.9	2	82.4	99.0	5
(3+2)a	89.3	99.0	1	95.5	99.0	2	98.0	99.0	5	98.9	99.0	6
(3+2)b	97.2	99.0	2	98.8	99.0	2	99.0	97.8	4	99.0	96.8	5
$E_{\text{threshold}} = 4 \text{ MeV}$												
	$x = 10 \text{ m}$			$x = 15 \text{ m}$			$x = 25 \text{ m}$			$x = 30 \text{ m}$		
	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t
(3+1)	85.9	99.0	3	99.0	98.5	4	99.0	87.6	5	89.9	99.0	15
(3+2)a	97.2	99.0	5	98.0	99.0	7	98.96	99.00	14	99.0	97.8	16
(3+2)b	99.0	95.7	4	99.0	97.5	6	99.0	97.2	11	99.0	93.8	11
$E_{\text{threshold}} = 5 \text{ MeV}$												
	$x = 10 \text{ m}$			$x = 15 \text{ m}$			$x = 25 \text{ m}$			$x = 30 \text{ m}$		
	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t
(3+1)	88.0	99.0	8	99.0	97.7	11	99.0	77.2	16	94.8	99.0	62
(3+2)a	99.0	98.5	16	99.0	98.7	22	99.0	94.6	53	99.0	95.9	48
(3+2)b	99.0	91.4	12	99.0	95.3	17	99.0	87.0	38	99.0	91.7	34
$E_{\text{threshold}} = 6 \text{ MeV}$												
	$x = 10 \text{ m}$			$x = 15 \text{ m}$			$x = 25 \text{ m}$			$x = 30 \text{ m}$		
	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t	$\Delta > 0$	$\Delta < 0$	t
(3+1)	98.5	99.0	60	99.0	41.4	41	99.0	35.0	56	99.0	82.9	360
(3+2)a	99.0	72.8	75	99.0	78.0	116	99.0	54.1	268	99.0	53.4	253
(3+2)b	99.0	46.5	47	99.0	53.3	72	99.0	38.4	167	99.0	36.9	159

Table 2. Confidence level (%) for $\Delta_p(x) > 0$ and $\Delta_p(x) < 0$ prediction in time t (in days) of experiment duration. The results are presented for three models [(3+1), (3+2)a and ((3+2)b] at different thresholds ($E_{\text{threshold}} = 3, 4, 5, 6 \text{ MeV}$) and position of the detector $x = 10, 15, 25, 30 \text{ m}$.

If the current difference is positive $[(N_{\text{observed}}^{i,j} - N_{\text{expected}}^{i,j}) > 0]$ we accumulate the $\chi^2(x)$ for positive variant: $\Delta_p(x) > 0$. In the negative case $[(N_{\text{observed}}^{i,j} - N_{\text{expected}}^{i,j}) < 0]$ the separate accumulation of $\chi^2(x)$ gives another sum for $\Delta_p(x) < 0$ variant. This algorithm was realised in simulation of $\chi^2(x)$ values for (3+1), (3+2)a and (3+2)b models at detector efficiency 30%, wide x -interval and thresholds of registration $E_{\text{threshold}} = 3, 4, 5$ and 6 MeV . The results presented in the table 2 for $x = 10, 15, 25$ and 30 m allow compare the C.L. for realization of $\Delta_p(x) > 0$ and $\Delta_p(x) < 0$ scenarios during the time t (in days). So, for (3+1) model at $x = 30 \text{ m}$ and $E_{\text{threshold}} = 3 \text{ MeV}$ the more probable scenario is negative ($\Delta_p(x) < 0$) with C.L. = 99% (compare to positive scenario with C.L. = 82.4%) can be realized in 5 days. In this case the prediction of $\Delta_p(x)$ -functional (see red line at $x = 30 \text{ m}$ in the part (b) of figure 5 and (5.3)) is confirmed by $\chi^2(x)$ value. In case of (3+2)a model

at $E_{\text{threshold}} = 3 \text{ MeV}$ we have disagreement: $\Delta_p(x) > 0$ (see blue line at $x = 10 \text{ m}$ in part (d) of figure 5) compare to opposite $\chi^2(x)$ -indication (C.L. = 89.3% for $\Delta > 0$ and C.L. = 99.0% for $\Delta < 0$). But the functional $\Delta_p(x)$ and $\chi^2(x)$ -analysis begin predict in complete agreement at higher thresholds ($E_{\text{threshold}} = 5$ and 6 MeV): the positive values of $\Delta_p(x)$ for $E_{\text{threshold}} = 5$ and 6 MeV at $x = 10, 15, 25$ and 30 m in figure 5 (see part: (b), (d), (f)) are confirmed at C.L. = 99.0% by results of table 2 for the same thresholds and x -coordinates.

The discussed setup of the experiment for search of sterile neutrinos ensures the possibility to avoid the AZ-neutrino-spectrum-errors for check the (3+1) and (3+2) models at $\Delta m^2 \sim 1 \text{ eV}^2$. The check of models is ensured in the rather wide space interval (as farther away then the reservoir as between AZ and reservoir).

6 Conclusion

The purpose of the work is to confirm the possibility for sterile neutrino search outside the interval of spectrum errors basing on the proposed intensive $\bar{\nu}_e$ -source with hard spectrum. The idea of the source is originated from (n, γ) -activation of pure ^7Li -isotope near the reactor active zone and transfer of lithium to remote detector by the loop scheme. Instead of metallic lithium the more perspective way is use the heavy water solution of ^7Li : in this case the requested mass of purified ^7Li can be decreased in 18 times and will be $\sim 0.71 \text{ t}$.

The total $\bar{\nu}_e$ -spectrum is created by reactor one (fast decreasing and known with significant errors) and well known hard ^8Li -spectrum. Owing to dependence $\sigma_\nu \sim E_\nu^2$ the number of $\bar{\nu}_e$ -interactions strongly increases at rise of the total-spectrum-hardness (thank to ^8Li neutrinos). The definition of the hardness H was introduced and dependence of $(\bar{\nu}_e, p)$ - cross section from H value was obtained. The second very important feature from addition of ^8Li neutrino flux is large decrease of count errors (more than order in value) for harder total spectrum. The function of errors from hardness H was obtained.

It was simulated the variant of the $\bar{\nu}_e$ -source with realistic dimension and regime of operation. The unique advantage of the combination source is also the possibility to vary a lithium flow rate that allows to modify the total-spectrum-hardness (and to measure cross section of neutrino depending on energy) without stop of the experiment.

The realization of the experiment for search of sterile neutrinos with $\Delta m^2 \sim 1 \text{ eV}^2$ is discussed for schemes (3+1) and (3+2) of three active neutrinos plus one and plus two sterile neutrinos. For these cases the total $\bar{\nu}_e$ -fluxes were calculated taking into account ^7Li and reactor spectra with corresponding errors, the dynamics of lithium transfer and dimensions of the installation. It were proposed the scheme of the experiment and calculated the coordinates for search $\bar{\nu}_e$ -disappearance outside the interval of $\bar{\nu}_e$ -spectrum errors. High rate of the detector counts allows to use compact neutrino detectors ($\sim m^3$).

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