THE PROBLEM OF THE REACTOR ANTINEUTRINO SPECTRUM ERRORS AND PROPOSED SOLUTION IN THE SCHEME WITH REGULATED SPECTRUM

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Abstract: The investigation devoted to development and research of performance for novel type of $\bar{\nu}_e$-source which ensures: 1) hard antineutrino flux which significantly larger then reactor $\bar{\nu}_e$-flux; 2) rate of antineutrino detector counts > 10^3 per day.

The proposed scheme is based on ^{7}Li (n,γ)^{8}Li activation near the reactor active zone (AZ) and transport of the fast β^--decaying ^{8}Li ($T_{1/2}$(^{8}Li) = 0.84 s) toward a remote neutrino detector and back in the closed loop to AZ for the next (n,γ)-activation of lithium in the continuous cycle. $\bar{\nu}_e$-spectrum of ^{8}Li is well known and hard: mean energy ~ 6.5 MeV; it's maximum - up to 13 MeV. For the neutrino investigations the source of such combined hard $\bar{\nu}_e$-spectrum (from ^{8}Li and β^--decays of fission products in AZ) has the serious advantages compare to nuclear reactors $\bar{\nu}_e$-spectrum because the neutrino interaction cross section depends on the energy as $\sigma \sim E_\nu^2$. For increasing of hard lithium antineutrinos part in the total spectrum a being pumped reservoir is installed near the $\bar{\nu}_e$-detector. Such an installation will ensure not only harder $\bar{\nu}_e$-spectrum in the detector volume but also an opportunity to register $\bar{\nu}_e$-interaction at different summary spectrum hardness varying smoothly (without stop of the experiment) a rate of ^{8}Li (or it's chemical compound) pumping in the closed loop.

The proposed installation with combined $\bar{\nu}_e$-spectrum can ensure hard antineutrino flux (in the detector position) significantly higher compare to reactor one. The rate of neutrino detector counts in such hard flux can be increased strongly (from times to order and more) compare to counts from reactor $\bar{\nu}_e$-flux part. High count rate allows to use compact detectors with volume about ~ m^3. The calculation confirmed that count errors in such combined $\bar{\nu}_e$-spectrum can be decreased in two times and more compare to errors in reactor $\bar{\nu}_e$-spectrum.

1. INTRODUCTION. ANTINEUTRINO SPECTRUM FROM ^{8}LI AND REACTOR ACTIVE ZONE. GENERALIZED HARDNESS OF THE TOTAL NEUTRINO SPECTRUM (FROM ACTIVE ZONE PLUS FROM ^{8}LI)

The results in registration, accumulation and understanding of neutrino data in many cases are determined by characteristics of the neutrino source, such as neutrino flux and spectrum. First of all the main problems of neutrino detection are associated with extremely small cross sections of these reactions. What is why a high neutrino flux is determining requirement for obtaining of reliable results. Today the maximal intensive neutrino flux is ensured by nuclear reactors - the most widely and traditionally used $\tilde{\nu}_e$-sources.

In spite of the apparent superiority on neutrino flux the nuclear reactors has a disadvantage: too-small hardness of $\tilde{\nu}_e$-spectrum. This character is extremely negative as the probability of registration strongly depends on neutrino energy. For the considered here reactor antineutrino energy the neutrino cross section is proportional to it's energy squared - $\sigma_\nu \sim E_\nu^2$. Antineutrinos $\tilde{\nu}_e$ emitted at β^--decay of fission fragments in a nuclear reactor have rapidly decreasing spectrum and energy $E_{\bar{\nu}} \leq 10$ MeV (i. e., them spectrum is too-small).

The disadvantage of rapidly dropping spectrum can be filled having realized the idea [1] to use a high-purified isotope ^{7}Li for construction of lithium blanket (also called as converter) around the active zone of a reactor [2]. A short-lived isotope ^{8}Li ($T_{½}$ = 0.84 s) is created under flux of reactor neutrons in the reaction ^{7}Li(n,γ)^{8}Li and at β^{-}-decay it emits hard antineutrinos of a well determined spectrum with the maximum energy $E_{\tilde{\nu}}^{\max}$ =13.0 MeV and mean value $\bar{E}_{\tilde{\nu}}$ = 6.5 MeV.

The neutrino spectrum from ^{235}U (as the main fuel component) is presented in the Fig. 1 in comparison with ^{8}Li neutrino spectrum [3,4]. The advantages of hard $\tilde{\nu}$-spectrum of ^{8}Li is clear visible on the example of sharp rise for cross section of inverse beta decay reaction ($\bar{\nu}_e + p \rightarrow n + e^{+}$) (see Fig.1).

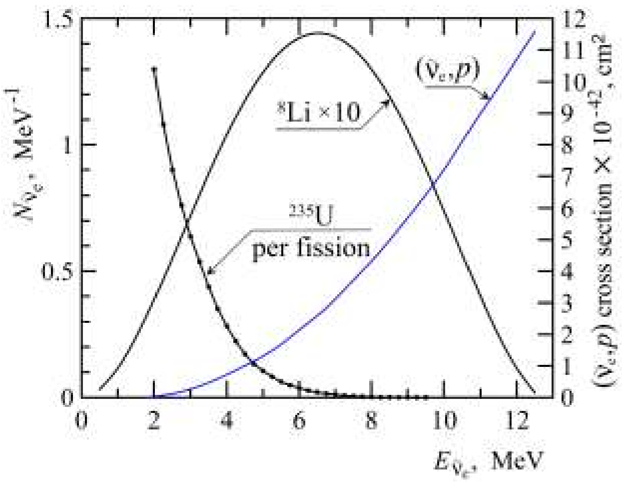

Fig. 1. Spectrum of antineutrinos from β^{-}-decay of ^{8}Li [4] (see left axis) and fission fragments of ^{235}U [3] (left axis). Cross section of ($\tilde{\nu}$ reaction is given on the right axis [5].

So, this blanket will act as a converter of reactor neutrons to antineutrinos. In fact the such construction of the blanket around the active zone (as a neutron source) is the most simple scheme of lithium antineutrino source. We can call this type of the $\tilde{\nu}$ source as steady spectrum source [2, 6–8]. As a result the total $\tilde{\nu}$-spectrum from the active zone of a reactor and from decays of ^{8}Li isotope becomes considerably harder in comparison with the pure reactor neutrino spectrum. Note that reactor antineutrino spectrum is specified also with another problem as instability in time due to dependence of partial spectra from nuclear fuel composition (^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu) which vary in time in operation period. The distribution of the total reactor $\tilde{\nu}$–spectrum is known with significant errors which strongly rise at the energy above ~ (5–6) MeV [9,6].

Let us define the productivity factor of the blanket k (or possible to call k as coefficient of blanket efficiency) as number of ^{8}Li nuclei produced in the lithium blanket per one fission in the active zone. It is clear that the hardness of the total spectrum will more larger as productivity factor k will be more higher. An illustration of the resulting total spectrum in case of rising productivity factor is given in the Fig. 2.

For our purpose (creation of the neutrino source of significantly larger hardness than possible to obtain by above mentioned simple scheme) let us introduce the definition of the generalized hardness for total neutrino spectrum [10,11]. Let $F_{\rm Li}(\vec{r})$ and $F_{\rm AZ}(\vec{r})$ - densities of lithium antineutrinos flux from the blanket and antineutrino flux from the active zone, $\bar{n}_{\nu}$ = 6.14 - number of reactor antineutrinos emitted per one fission in the active zone. We admit that the hardness of the summary $\tilde{\nu}$ - spectrum at the point $\vec{r}$ equals one unit of hardness if the ratio of densities $F_{\rm Li}(\vec{r})/F_{\rm AZ}(\vec{r})$ equals to $1/\bar{n}_{\nu}$. Then the total spectrum generalized hardness is:

$$H(\vec{r}) = n_\nu \frac{_{\text{Li}}(\vec{r})}{F_{\text{AZ}}(\vec{r})} \quad (1)$$

This definition is very convenient as in so doing the averaged (over the blanket volume) value generalized hardness (for the total ~ -spectrum) of steady spectrum sources (these models are also considered in [2,6-8]) is estimated by the value of its productivity factor k of the blanket. Taking into account this definition of the hardness the values of productivity factors k on the Fig. 2 coincide with values of the generalized hardness H for total spectra.

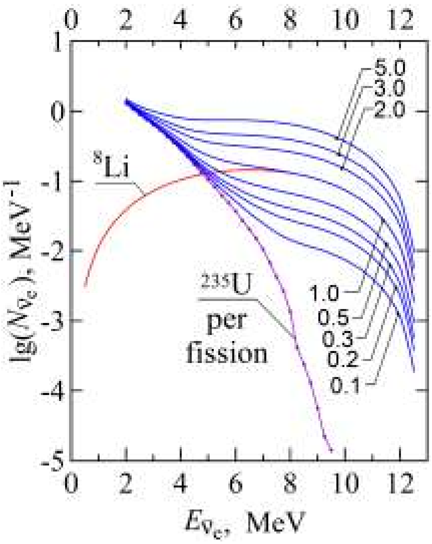

Fig. 2. Neutrino spectrum from: [235]U [3], [8]Li [4] and total spectra (from combination of active zone and [7]Li blanket) for different factors k indicated for curves [2,11,12].

2. ANTINEUTRINO SOURCE WITH VARIABLE AND REGULATED SPECTRUM ON THE BASE OF ^{8}LI ISOTOPE

It is possible to supply powerful neutrino fluxes of considerably greater hardness by means a facility with a transport mode of operation: liquid lithium is pumped over in a closed cycle through a blanket and further toward a remote neutrino detector (Fig. 3). For increasing of a part of hard lithium antineutrinos a being pumped reservoir is constructed near the ~ -detector. Such a facility will ensure not only more hard spectrum in the location of a detector but also an opportunity to investigate ~ -interaction at different spectrum hardness varying a rate of lithium pumping over in the proposed scheme with the closed loop [10-13].

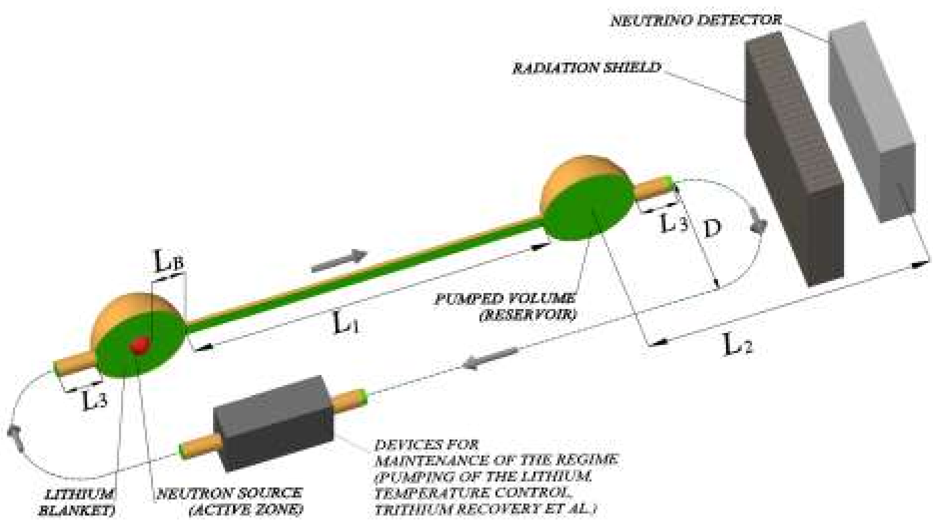

Fig. 3. The principal scheme of the neutrino source with variable (regulated and controlled) spectrum.

Lithium in the blanket (activated by reactor active zone neutrons) is pumped continuously through the delivery channel to the remote volume (reservoir, which is set close to the neutrino detector) and further back to the blanket. The rate of pumping can be smoothly varied by the installation for maintenance of the regime. L_1 - distance between lithium blanket and pumped reservoir. L_2 - distance from the reservoir center and neutrino detector. L_B - the lithium layer in the blanket. L_3 - straight length of the channels before (and after) the channel turning along the direction of lithium pumping. D - the diameter of channel turning.

Due to the geometrical factor the total $\tilde{\nu}$-spectrum in the detector volume (i. e., the resulting $\tilde{\nu}$-spectrum formed by $\tilde{\nu}$-flux from the reactor active zone plus from β^--decay of ^{8}Li) will be more harder compare to reactor antineutrino spectrum. It is clear that the closer to the reservoir will be detector the total spectrum will be harder. From the other side if the detector will be farther from the reactor then the part of the soft reactor $\tilde{\nu}$-spectrum in the total spectrum will be more small. For the fixed distance L_1 between the lithium blanket and the reservoir and fixed L_2 (from the detector to the reservoir) the most harder spectrum is ensured for the position along the direction from the lithium blanket to the pumped reservoir.

3. DEPENDENCE OF ($\tilde{\nu}$ CROSS SECTION AND ERRORS OF THE TOTAL $\tilde{\nu}$-SPECTRUM FROM THE GENERALIZED HARDNESS *H*.

The $\tilde{\nu}$-cross section in the total spectrum is the additive value of the cross sections in the $\tilde{\nu}$-flux from the active zone and from ^{8}Li antineutrinos [2,11,12,14]. In fact the total number of $\bar{\nu}_e$ (entering to the neutrino detector) is:

$$N_{\tilde{\nu}} \ldots H(\vec{r}) \frac{\ldots}{\bar{n}}, \tag{2}$$

where N_{AZ} - number of $\bar{\nu}_e$ from the active zone, $\bar{n}_\nu$ - number of $\bar{\nu}_e$ from the active zone per one fission, $H(\vec{r})$ - averaged generalized hardness of the total spectrum in the detector position. The second summand determines the number of lithium antineutrinos.

More strictly for density of the total $\tilde{\nu}$-flux in the point $\vec{r}$ we can write:

$$F_{\tilde{\nu}} \ldots (\vec{r}) + H(\vec{r}) \frac{\ldots}{\bar{n}}, \tag{3}$$

where $F_{AZ}(\vec{r})$ - density of the $\tilde{\nu}$-flux from the active zone, $H(\vec{r})$ - the exact value of the generalized hardness in the point $\vec{r}$.

As the cross section is the additive value then (similar to (2) and (3)) for the inverse beta decay reaction ($\bar{\nu}_e + p \rightarrow n + e^+$) we can write the cross section for the total $\tilde{\nu}$-spectrum:

$$\sigma_{\bar{\nu}_e p}(\vec{r}) = \sigma_{\bar{\nu}_e p} + H(\vec{r}) \times \sigma_{\bar{\nu}_e p}. \tag{4}$$

The threshold of the reaction is 1.8 MeV but often (depending on the background) the used threshold is 3 MeV. Taking into account the data of [5] the cross section (4) was calculated as function of the hardness H for the $E_{threshold}$ = 3 MeV (see Fig. 4).

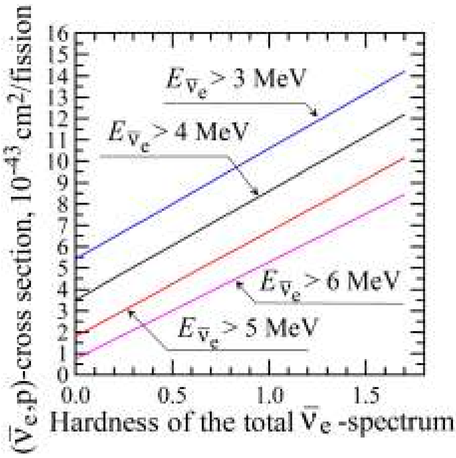

Fig. 4. Cross section of ($\bar{\nu}_e + p \rightarrow n + e^+$)*-reaction in the total* $\bar{\nu}_e$*-spectrum as function of the hardness H. Values of cross sections at H=0 correspond to* $\bar{\nu}_e$*– spectrum from pure* ^{235}*U. The results are given for different thresholds of registration: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

At increase of H-value the double rise (and more) of the cross section is caused by enlarged part of lithium neutrinos in the total spectrum and energy squared dependence $\sigma_\nu \sim E_\nu^2$.

For lithium spectrum the relative yield to the cross section (4) ensured by more high energy neutrinos is significantly larger compare to the the reactor spectrum (here in calculation we used $\bar{\nu}_e$-spectrum of ^{235}U [15] as a single fuel isotope). This fact suggest to us to recalculate the cross section for more higher thresholds. The results (for thresholds - $E_{threshold}$ = 4, 5 and 6 MeV) show that for hard total spectrum the lithium yield to the cross section strongly dominates the reactor part [12,14] (see Fig. 4).

For the perspective experiments we need to evaluate the advantages from the combined $\bar{\nu}_e$-flux (from AZ plus from β^--decay of ^{8}Li) given by well known ^{8}Li spectrum. Last years the problem of $\bar{\nu}_e$-spectrum errors become very serious as the recent measurements of $\bar{\nu}_e$-spectrum in Daya Bay, Reno and Double Chooz experiments reveal significant excess of neutrinos with energy 5-7 Mev in the spectrum [16]. This bump in experimental spectrum caused active discussion of the used models, nuclear databases and understanding of some results in reactor oscillation experiments.

Here we want to confirm the decrease of count errors in case of such combined $\bar{\nu}_e$-flux. For this purpose we calculated the dependence of errors (in the total $\bar{\nu}_e$-spectrum) on the energy of antineutrinos and then these errors were averaged on their total $\bar{\nu}_e$-spectra for every of thresholds: $E_{threshold}$ = 3, 4, 5, 6 MeV [12,14].

The result dependences of averaged errors on hardness H for the combined spectrum (from AZ with bump in the spectrum plus from ^{8}Li) for specified thresholds are presented in Fig. 5. In the first evaluation of the count errors (caused by errors of the $\bar{\nu}_e$-spectrum of AZ we had realized the more simple way: the count errors were averaged for whole energy interval from $E_{threshold}$ up to o the maximal energy in the total spectrum of the considered hardness H. After that the obtaned error (specified for the every considered H) were used to calculation of the relative count errors for the every considered hardness H. In spite of the simplicity of the evaluation this rough calculation had allowed to reveal the promising way: to decrease the errors by means of increase of hardness H from one side and increase of the threshold $E_{threshold}$ of registration from the second side.

But the more accurate calculation with detailed energy bins and evaluation of errors for each of bins depending on the hardness H gives more sharp decrease of errors for more harder $\bar{\nu}_e$-spectrum. These results are strongly important as demonstrates the possibility to decrease the count errors in several times compare the significant errors in case of $\bar{\nu}_e$-spectrum of AZ.

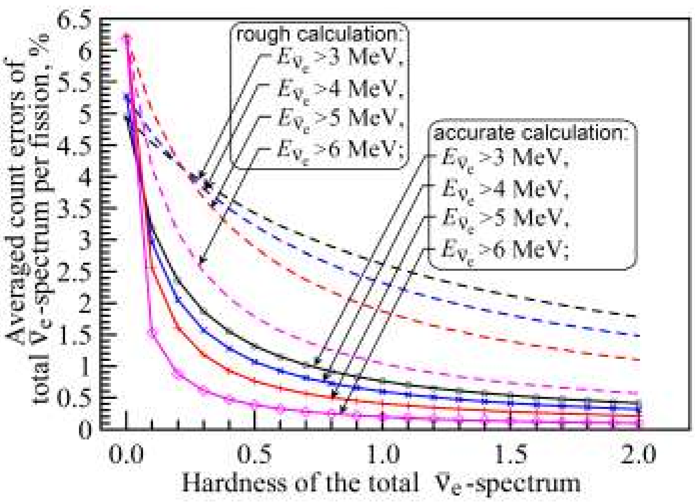

Fig. 5. Dependence of the averaged errors of the total $\bar{\nu}_e$-spectra from value of the hardness H for the indicated $E_{threshold}$ = 3, 4, 5, 6 MeV (the error values for rough and accurate (i.e., detailed) calculations in energy bins) [12,14]. The AZ $\bar{\nu}_e$-spectrum was taken into account with bump as in Daya Bay experiment [16].

The next task of the work is to evaluate the expected $\bar{\nu}_e$ – fluxes at the detector position and number of $(\bar{\nu}_e$,p)– interaction in the scintillator $\bar{\nu}_e$ – detector. The geometry for calculation is presented in the Fig. 6, where the detector position was shown by dotted lines (detector position along the line from lithium blanket center to the center of the pumped reservoir: S=17.9 m, L_2=3.5 m [11,17]); the detector position appointed by solid lines corresponds the common case. In the calculation the applied proton concentration was typical - about $6.6 \cdot 10^{22}$ cm^{-3} (as in KamLAND liquid scintillator [18]). The considered volume of the detector is small [namely owing to the high density of $\bar{\nu}_e$ – flux and large hardness H of the total antineutrino spectrum (see below)] - 1 m^3. The expected number of interaction in the detector volume is normalized per day (24 hours). The specification of registration efficiency was not take into modelling and was considered conditionally as 100%. The all calculations were normalized on the power of the nuclear reactor power 1000 MW. The density of $\bar{\nu}_e$ – flux from a nuclear reactor is determined by its power P and for distance R is:

$$F\,[\mathrm{cm}^{-2}\cdot \mathrm{s}^{-1}] \cong \bar{n}\,P / 4\pi R^2 \bar{E} = 1.5 \cdot 10^{12} P\,[\mathrm{MW}] / R^2[\mathrm{m}], \qquad (5)$$

where $\bar{n} \cong 6.14$ - mean number of β^--decays for both fission fragments of ^{235}U, $\bar{E} \cong 200$ MeV - mean energy released at ^{235}U-fission.

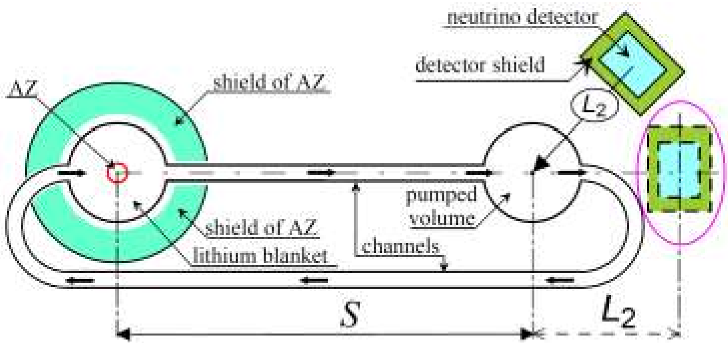

Fig. 6. The installation scheme used for calculation of $\bar{\nu}_e$ – fluxes and counts at the detector position. The detector position used for the calculation is shown by dotted lines [it is the position along the line connected the centers of the blanket (around the reactor active zone -AZ) and pumped reservoir].

The obtained $\bar{\nu}_e$ – flux densities at the detector position are shown in the Fig.7. The reactor neutrino fluxes don't depend on the hardness of the total antineutrino flux and are indicated by four levels corresponding to thresholds $E_{\mathrm{threshold}}$ = 3, 4, 5 and 6 MeV. $\bar{\nu}_e$ – fluxes from ^{8}Li rise strongly depending on the hardness H.

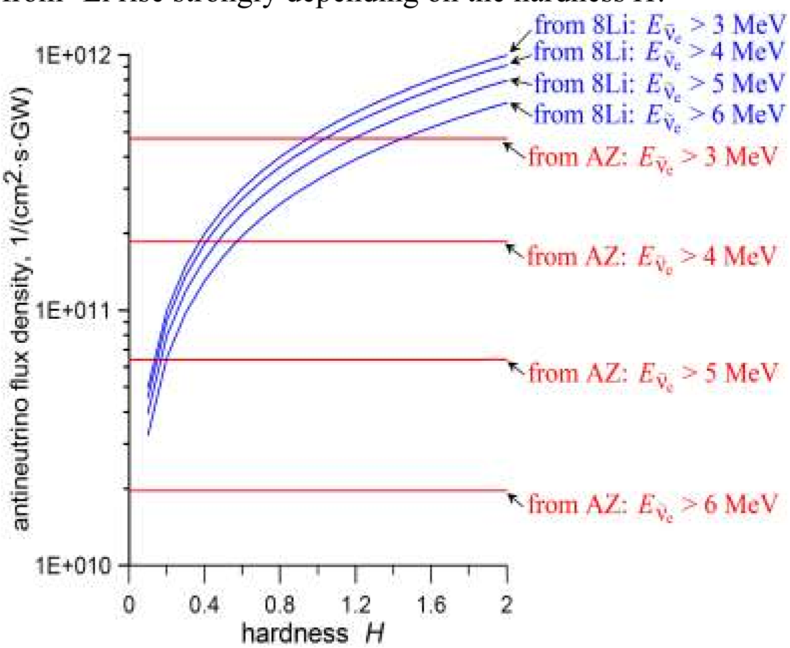

Fig. 7. The $\bar{\nu}_e$ – fluxes densities from $\bar{\nu}_e$ of AZ and from whole mass of ^{8}Li in the installation (of the geometry - Fig.6, S=17.9m,L_2=3.5m) depending on the hardness H for different thresholds ($E_{threshold}$ = 3, 4, 5 and 6 MeV). The all results are normalized on the reactor power 1 GW.

Knowing the antineutrino fluxes we calculated the expected number of interaction in the detector volume 1 m^3: the obtained results are presented in the Fig.8. It is clear that counts ensured by the ^{8}Li antineutrinos are strongly dominates owing to the hardness of $\bar{\nu}_e$-spectrum of ^{8}Li. It is very important to note that the realistic values of the hardness *H* that can be achievable are about H ≈ 1 [11,17]. The achievable rate of counts is exclusively high even for the considered small detector volume about 1 m^3 (Fig.8).

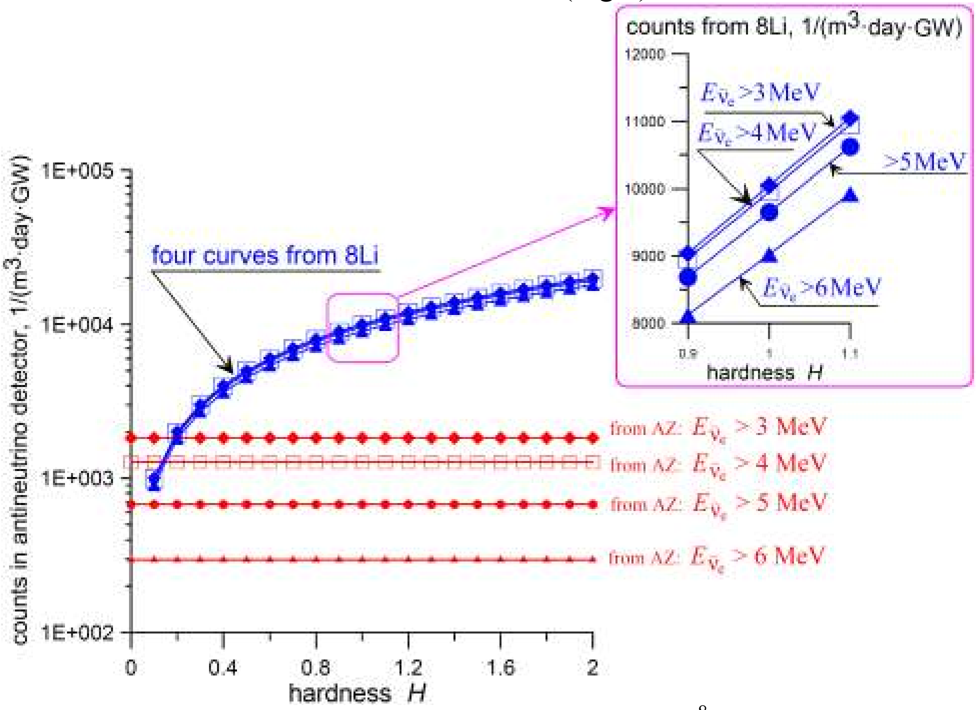

Fig. 8. The expected counts (from AZ $\bar{\nu}_e$-fluxes and from ^{8}Li antineutrinos) in the 1 m^3 detector volume depending on the hardness H for different thresholds $E_{threshold}$ = 3, 4, 5 and 6 MeV. Calculation were realized for the geometry of the Fig.6 (S=17.9 m, L_2=3.5 m) with position of the detector shown by dotted lines. The efficiency of registration was assumed as 100% (by convention). The all results were normalized on the reactor power 1 GW.

4. CONCLUSION

Here we considered the perspective variant of intensive ~ -source on the base of ^{7}Li isotope in the loop scheme with nuclear reactor (as neutron source).

It was proposed the definition of the generalized hardness *H* of the total ~ -spectrum (i.e., the summary ~ -spectrum from nuclear reactor and from ^{8}Li) at the detector position. Due to the well defined and hard ~ -spectrum of ^{8}Li (that is very important as the ~ -cross section is proportional to energy squared - $\sigma_\nu \sim E_\nu^2$) this type of the lithium antineutrino source becomes very perspective to ensure: 1) high ~ -count rate in the detector and 2) significanly lower errors compare to nuclear reactors as traditional high flux ~ - source.

It was obtaned the dependence of the averaged errors of the total $\bar{\nu}_e$-spectra from value of the hardness *H* for the indicated thresholds ($E_{\text{threshold}}$ = 3, 4, 5 and 6 MeV) of neutrino registration. This results reveal the possibility to decrease the errors of the total $\bar{\nu}_e$-spectrum in several times (compare to reactor active zone antineutrinos). That is why this result can be considered as solution of the problem for reactor $\bar{\nu}_e$-spectrum errors.

The obtained spectrum at the detector position becomes hard and namely lithium antineutrinos ensure high count rate (>10^3 per day) in the detector with small (~ 1 m^3) volume that is very exclusively important for sterile neutrino search and another neutrino experiments.

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