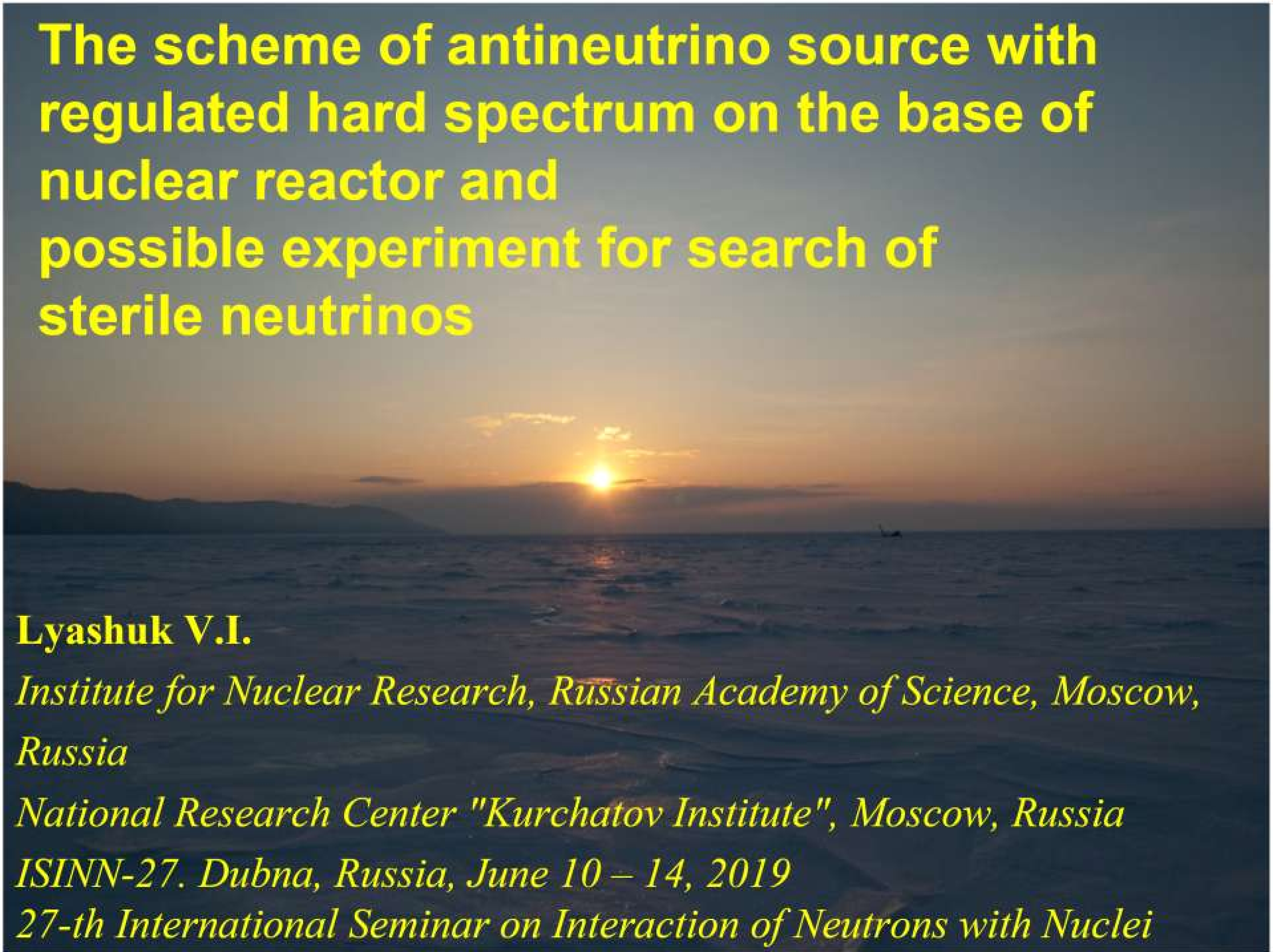

The scheme of antineutrino source with regulated hard spectrum on the base of nuclear reactor and possible experiment for search of sterile neutrinos

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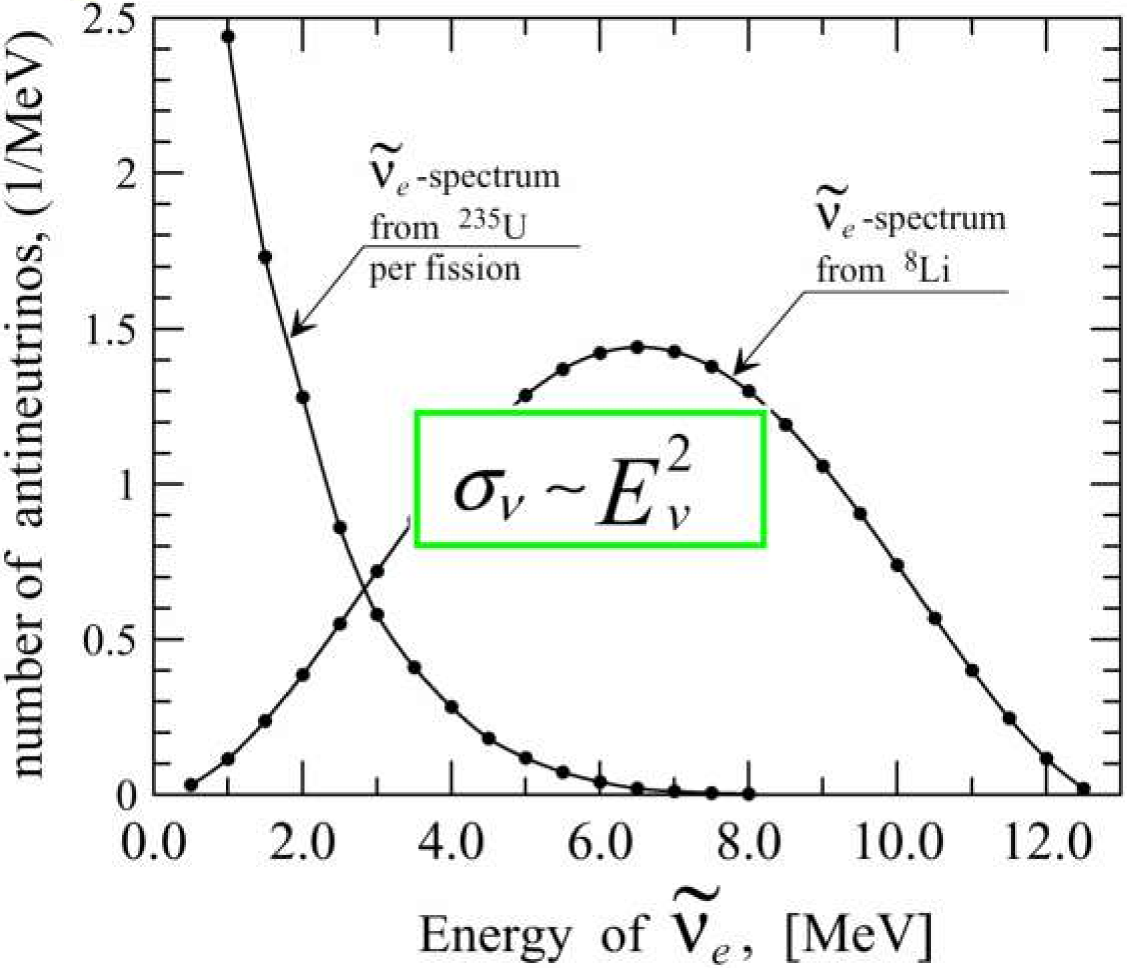
The Conception of the Lithium Antineutrino Source (1)

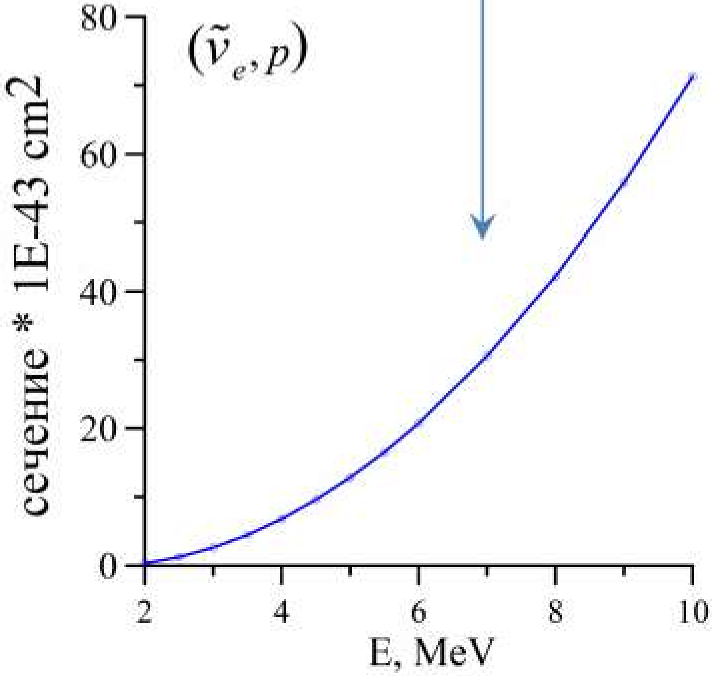
^{7}Li(n,γ)^{8}Li $T_{1/2}$ (^{8}Li) = 0.84 s $^8\mathrm{Li} \to {}^8\mathrm{Be} + e^- + \tilde{\nu}_e$

$E_{\tilde{\nu}}^{\max} \approx$ 13.0 MeV $\bar{E}_{\tilde{\nu}} \approx$ 6.5 MeV

(high energy of $\tilde{\nu}_e$!)



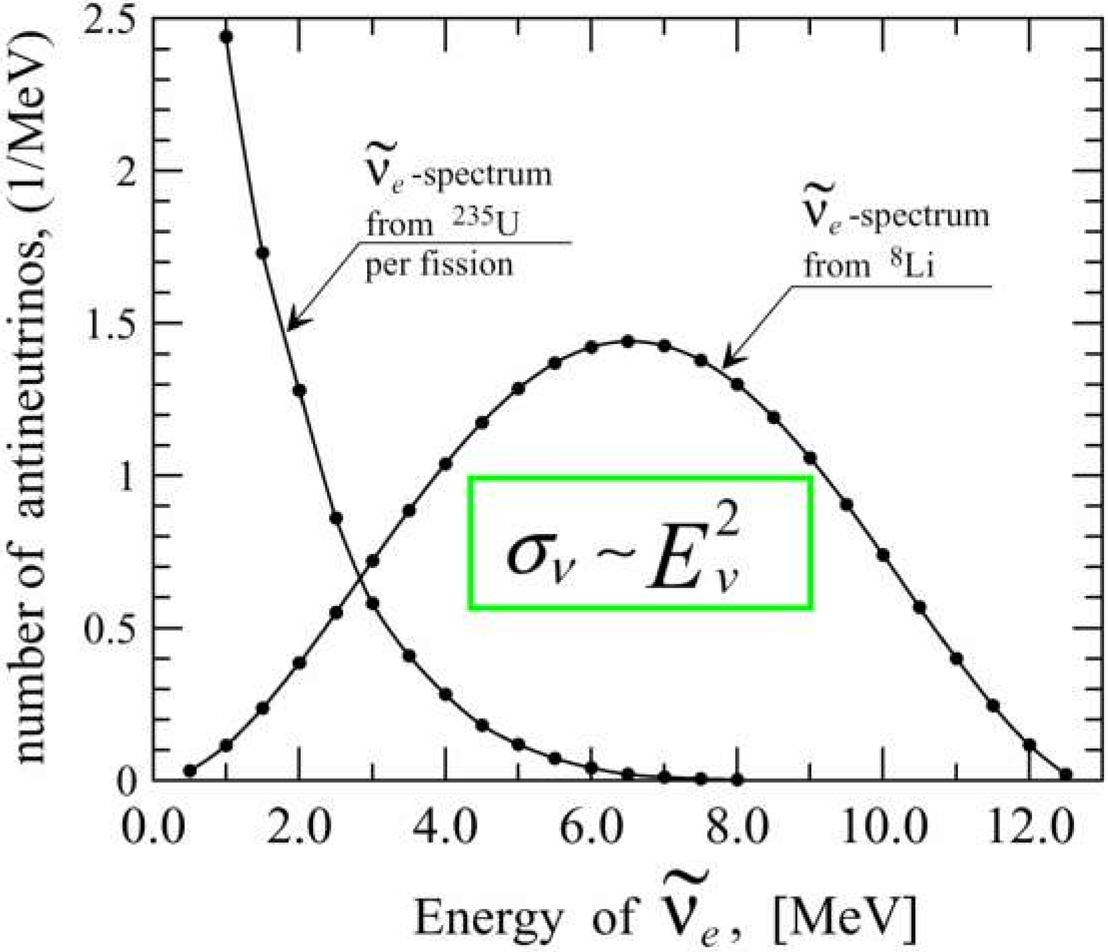
$$\sigma_\nu \sim E_\nu^2$$



The Conception of the Lithium Antineutrino Source (2)

$^{7}Li(n,\gamma)^{8}Li$ $T_{1/2}(^{8}Li) = 0.84$ s

$E_{\tilde{\nu}}^{\max} \approx 13.0$ MeV $\overline{E}_{\tilde{\nu}} \approx 6.5$ MeV



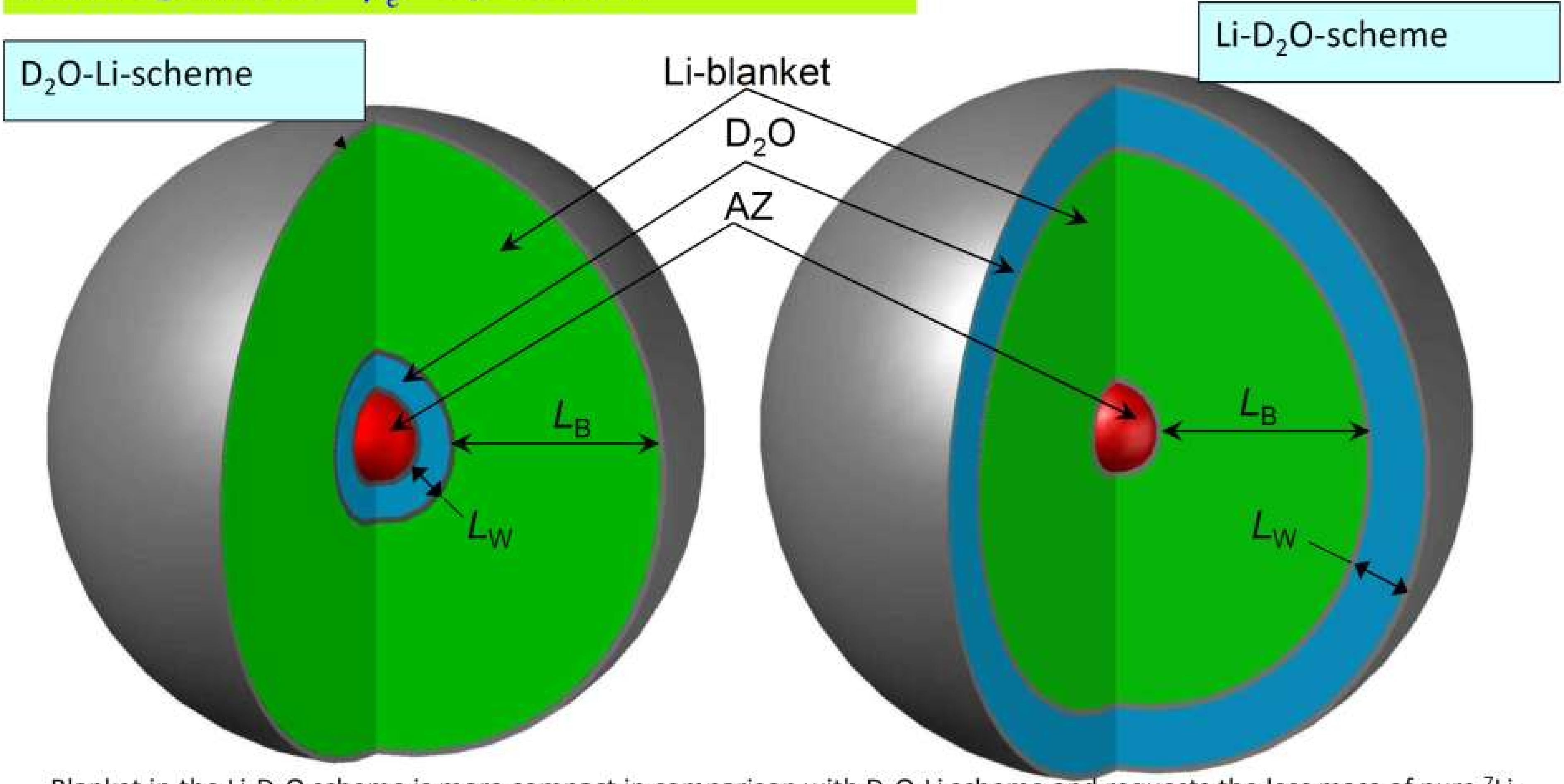
$$\sigma_\nu \sim E_\nu^2$$

Alongside with the obvious advantage on a neutrino flux the nuclear reactor has a disadvantage – 1) too-small hardness of –spectrum and 2) significant errors.

This disadvantage can be filled having realized the idea to use a high-purified isotope of ^{7}Li for engineering of a neutrons-to-antineutrino Lithium Converter.

The idea to use ^{8}Li isotope as neutrino source was originated by **L.A. Mikaelian, P.E. Spivak and V.G.Tsinoev** (L.A. Mikaelian, P.E. Spivak, And V.G, Tsinoev, Nucl. Phys, v.70, p.574 (1965).

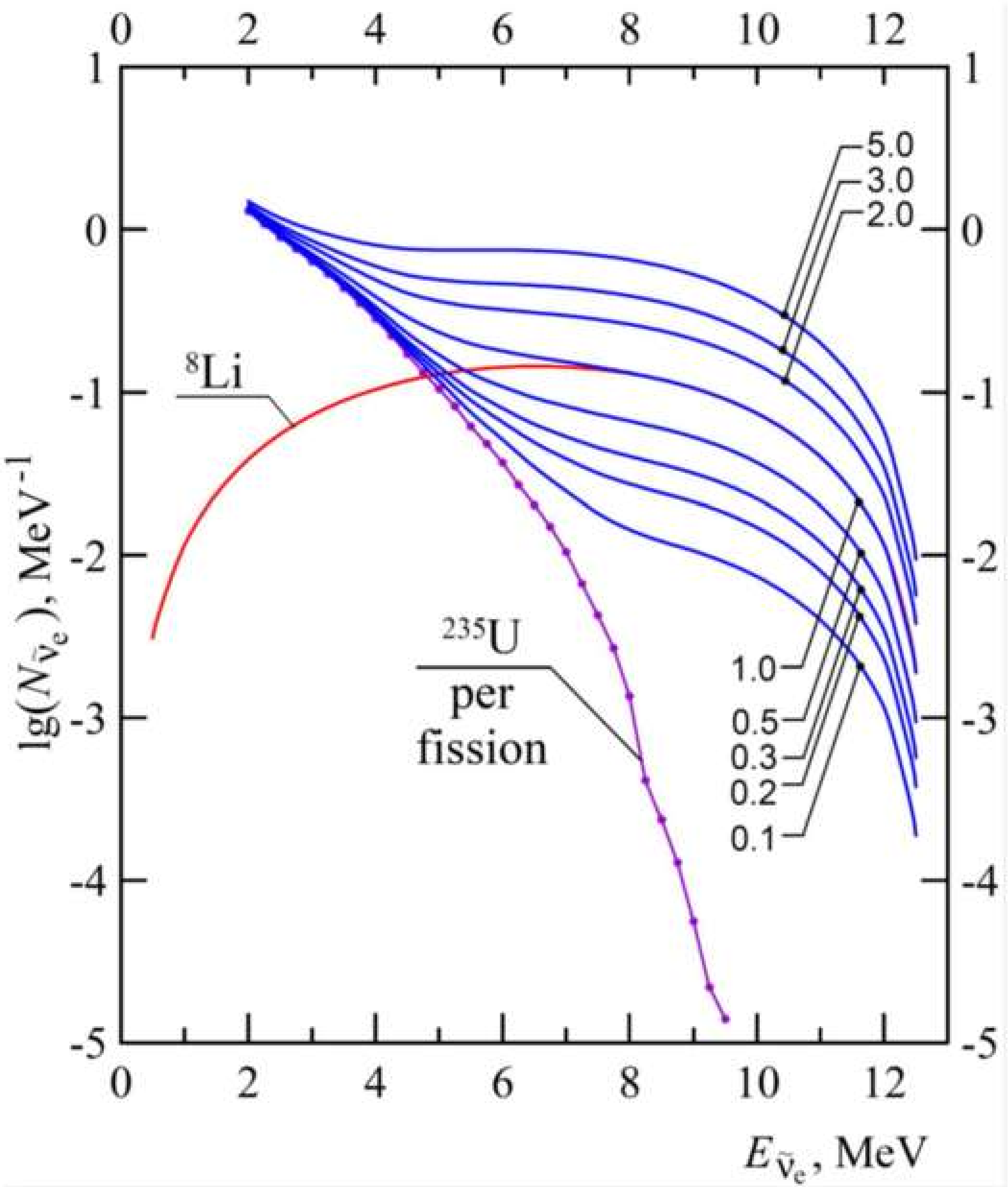
Scheme of the Antineutrino Source with Nonregulated $\tilde{\nu}_e$ – Spectrum



Blanket in the Li-D$_2$O scheme is more compact in comparison with D$_2$O-Li scheme and requests the less mass of pure ^{7}Li.
In the calculation the layer L_B was varied up to 170 cm and L_w – up to 30 cm. R_{AZ} = 23 cm (as for the reactor PIK).
It was assumed that one fission-spectrum neutron was escaped from active zone per fission in the active zone.
The D$_2$O acts as an effective moderator in D$_2$O-Li-scheme and as a reflector in the Li-D$_2$O-scheme.

In IAE in 70-th it was considered proposal to install lithium blocks into pulse reactor RING
Vorob'ev et al. The pulse reactor RING. Preprint IAE, 2384 (1974) (in russian: Воробьев Е.Д. и др. Импульсный реактор РИНГ. Препринт ИАЭ, 2384, 1974)

The TOTAL ANTINEUTRINO SPECTRUM



Efficiency of the blanket-converet is the number of ^{8}Li-isotopes produced in the lithium blanket per neutron of the source

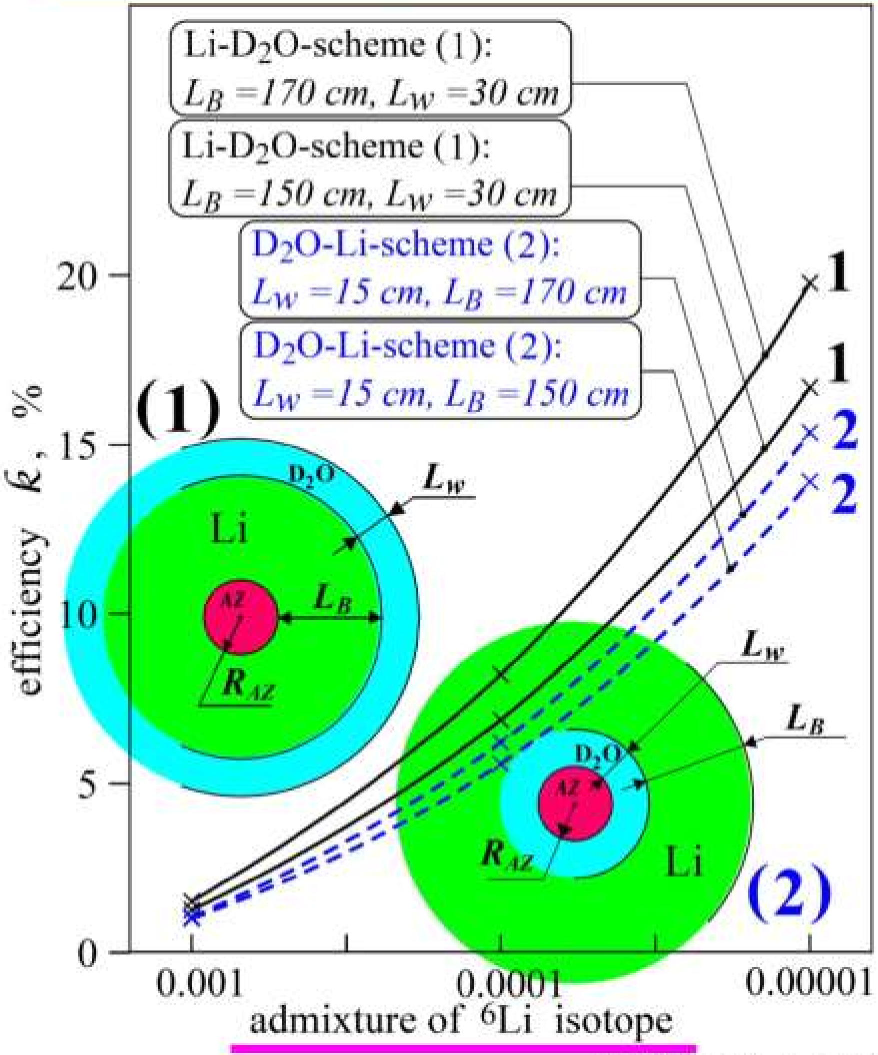
Antineutrino spectrum:

1) from ^{235}U (ponts),
2) summary antineutrino spectrum from the active zone and lithium blanket for different values of the blanket efficiency (indicated on the blue lines),
3) neutrino spectrum from the Li-blanket (red) for different blanket efficiency.

Dependence of the Lithium Blanket Efficiency *k* from ^{7}Li Purity

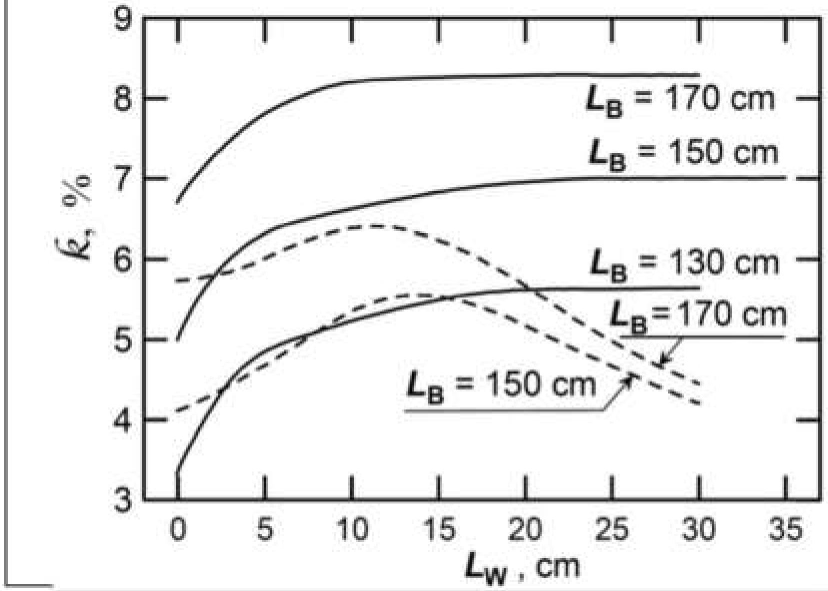
<u>efficiency *k*</u> of the lithium blanket – is the number of ^{8}Li-isotopes produced in the blanket per neutron of the source.

Dependance of the blanket efficiency *k* from the ^{7}Li-purity for Li-D_2O-scheme (solid line) and D_2O-scheme (dotted line) in case of different thickness of the blanket L_B and for different D_2O thickness L_W. (Yu.S. Lyutostansky, V.I. Lyashuk // Sov. J. Atomic Energ. 1990,v69,p696; Lyashuk V. I. and Lutostansky Yu. S. arXiv:1503.01280v2)



Contents of ^{7}Li in the nature lithium is 92,41%

Dependence of the blanket efficiency *k(%)* on D_2O layer thickness in Li-D_2O (solid line) and D_2O-Li (dotted line) for blanket thickness L_B and Active Zone of PIK reactor .



Lyashuk V. I. and Lutostansky Yu. S. 2015, JETP Letters v.103, p.293.

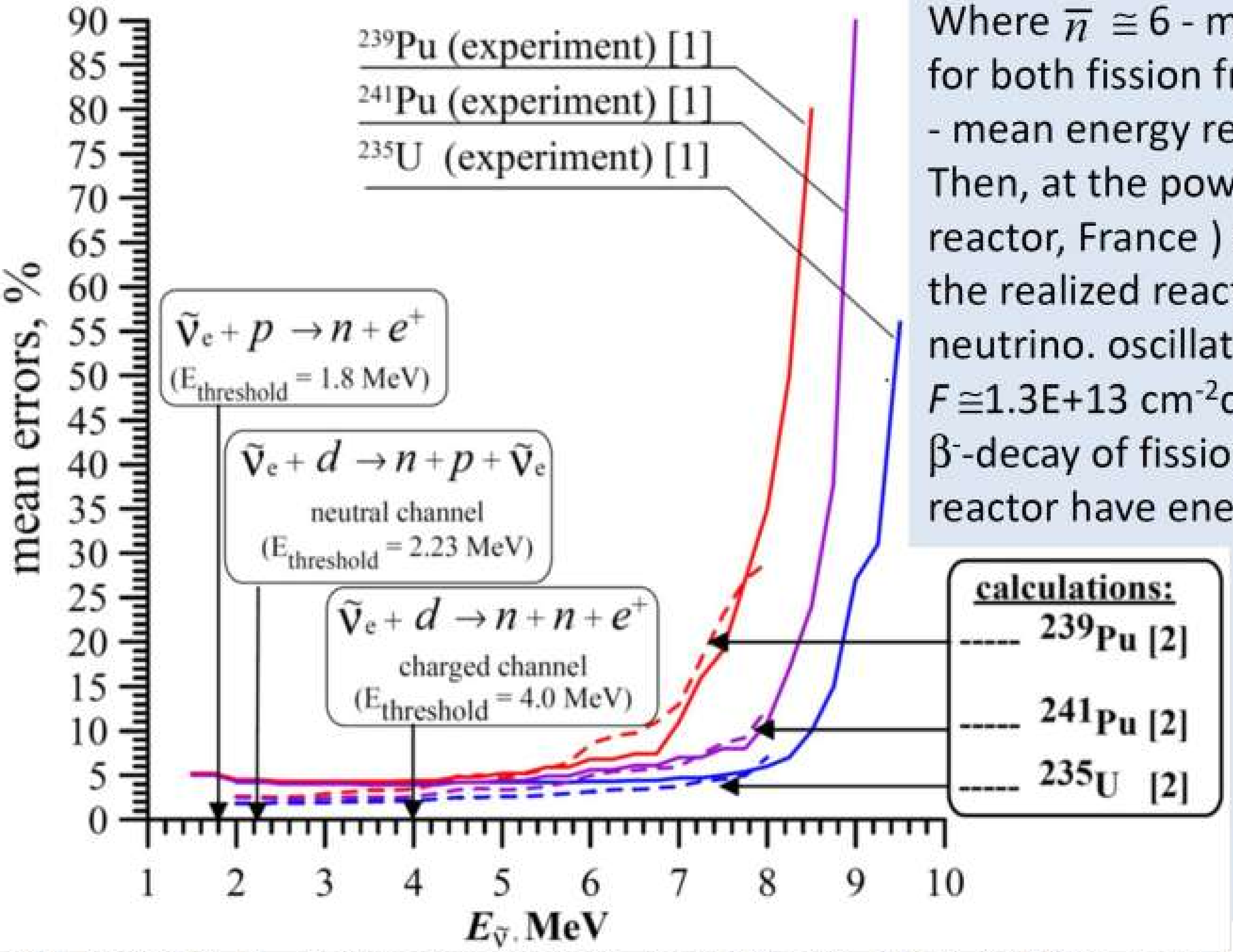
The Errors of the Reactor Antineutrino Spectrum

The density of source from a nuclear reactor Is determined by its power P and for distance R is

$$F[cm^{-2}\cdot s^{-1}] = \overline{n}\, P / 4\pi R^2 \overline{E} = 1.5\cdot 10^{12} P[MW] \;/\; R^2[m]$$

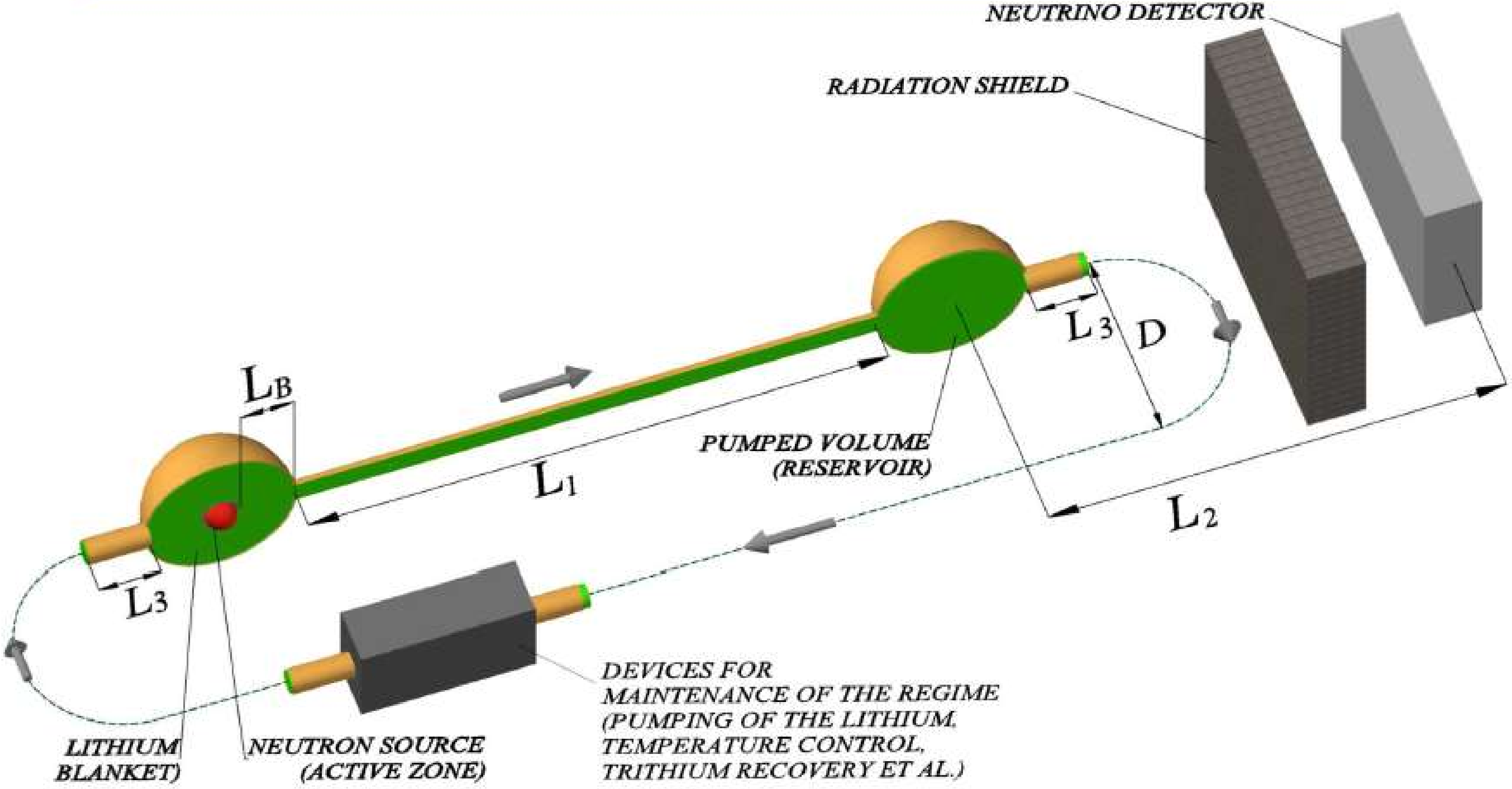
Where $\overline{n} \cong 6$ - mean number of β^--decays for both fission fragments of ^{235}U, ≅ 200 MeV - mean energy released at ^{235}U-fission. Then, at the power P = 2800 MW (the Bugeu reactor, France) and distance $R \cong 18$ m (as in the realized reactor experiments on search of neutrino. oscillations [4, 5]) the flux is $F \cong 1.3E{+}13$ cm^{-2}c^{-1}. Antineutrinos emited at β^--decay of fission fragments in a nuclear reactor have energy ≤ 10 MeV and cross sections of the interaction with protons, electrons and deuterons are in the interval 10^{-46} -10^{-43} cm^2.

Lyashuk V. I. // Particles and Nuclei, Letters. 2017. V.14. No.3. p. 465.



[1]. *Hahn A. A., Schreckenbach K., Gelletly W., et al.* // Phys. Lett. B. 1989. V. 218. P.365.
[2]. *Huber Patrick.* // Phys. Rev. C. 2011. V. 84. P. 024617.

Scheme of the neutrino source with regulated spectrum



Scheme of the neutrino source with variable spectrum. Lithium in the blanket (activated by neutrons from the source - reactor active zone) 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.

Lutostansky, Yu.S. and Lyashuk, V.I., *Bull. Russ. Acad. Sci. Phys., 2011, Vol. 75, No. 4, pp. 468.*

V. I. Lyashuk, Yu.S. Lutostansky. The Conception of the Powerful Neitrino Source..Preprint ITEP-38-97;

http://lss.fnal.gov/archive/other/itep-38-97.pdf

FLUXES of LITHIUM ANTINEUTRINOS in the SCHEME of REGULATED SPECTRUM

Let V_B - blanket volume, V_0 - volume of a whole system, **w** - volume being pumped over in a time unit (flow rate, i.e. circulation rate), then **$t_p = V_B / w$** - time of pumping over of blanket volume. In a blanket we shall allocate some spherical segment with a volume V_s and with a plane of the basis perpendicular to the axis of a delivery channel. It was obtained integral flux of lithium antineutrinos emited from this spherical segment for a time t :

$$N_S(t) = \frac{t}{t_S}\left(S_1 + \sum_{n=2}^{\infty} S_n\right) = \frac{t}{t_S}\left[S_1 + \frac{S_2}{\varphi(-\lambda_\beta V_0/w)}\right],$$

where $N_7(t)$ and $N_8(t)$ - number of nucleus ^{7}Li and ^{8}Li at the time t, $\lambda_{n\gamma}$, λ_β - rate of (n,γ)-reaction and β⁻-decay;

$$S_1 = N_7^0 - N_7(t_S) - N_8(t_S) = \lambda_{n\gamma} N_7^0 t_S - (\lambda_{n\gamma} N_7^0/\lambda_\beta)\varphi(V_S),$$

$$S_2 = \frac{\lambda_{n\gamma} N_7^0}{\lambda_\beta}\varphi(V_B)\left\{\exp\left[-\lambda_\beta(V_0 - V_B)/w\right] - \exp\left[-\lambda_\beta(V_0 - V_B + w t_S)/w\right]\right\},$$

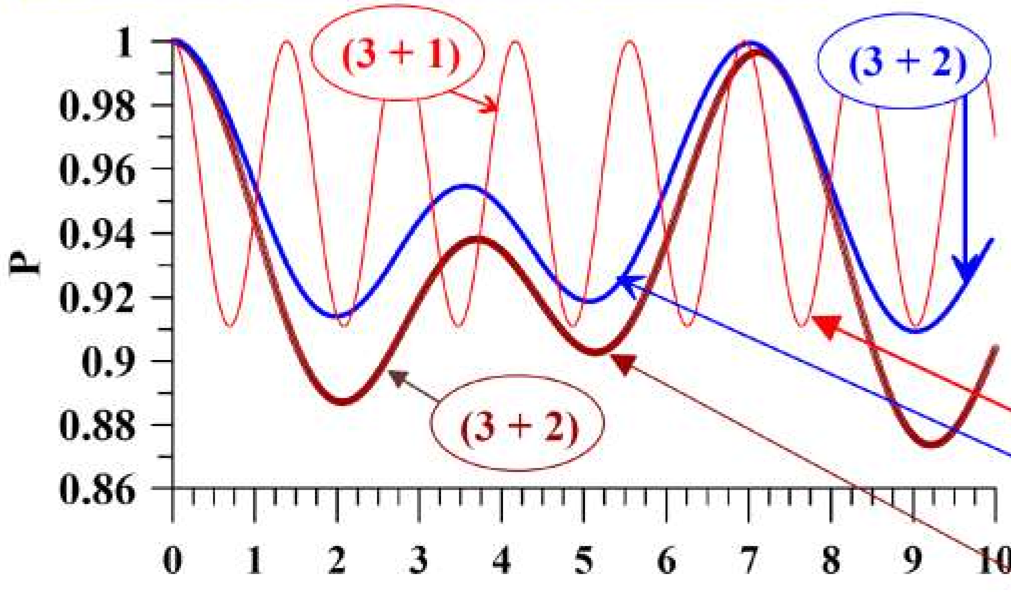
$$\varphi(y) = 1 - \exp(-\lambda_\beta y/w).$$

At a pumping over time $t_S = t_p$ the $N_S(t)$ gives an integral flux from whole volume of a blanket. In the same way it was obtained the expression for the fluxes from the delivery channel and from the pumped reservoir. So, for the flux from the reservoir is:

$$N_R(t) = N_{cd}(t_d + V_R/w) - N_{cd}(t_d) = \frac{\lambda_{n\gamma} N_7^0}{\lambda_\beta t_p} \cdot \frac{\varphi(V_B)\varphi(V_R)\exp(-\lambda_\beta t_d)}{\varphi(V_0)}.$$

The expression for fluxes from the delivery channel were obtained in the same way.

STERILE NEUTRINO MODELS (3+1) and (3+2). PROPOSED SOURCE for SEARCH of NEUTRINO at $\Delta m^2 \sim 1$ eV^2



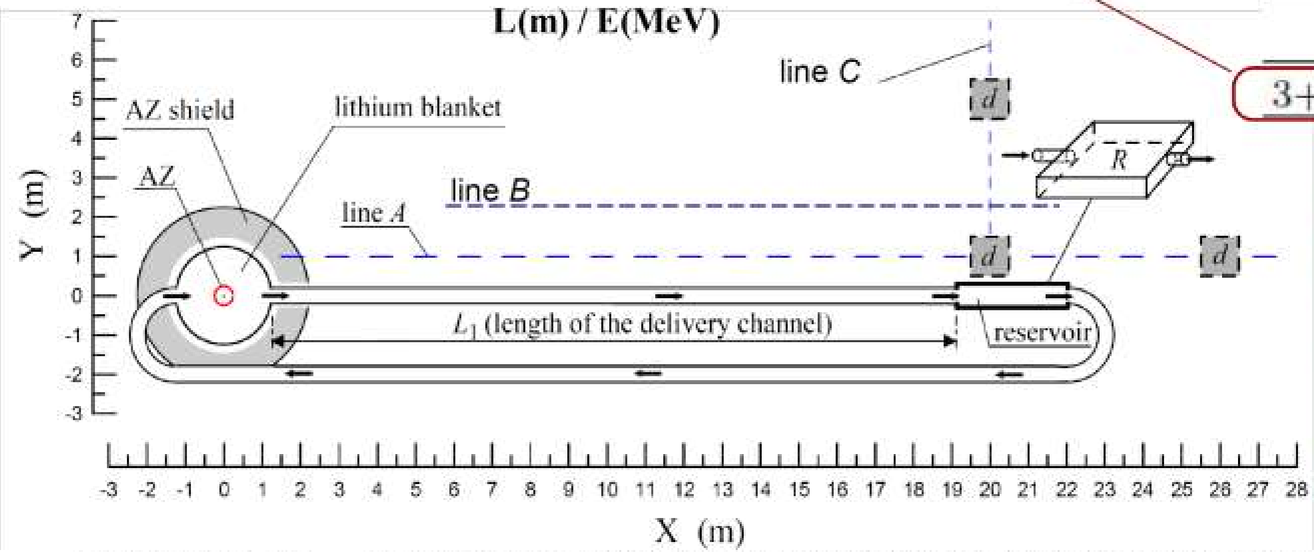
[1]. ***Joachim Kopp, Michele Maltoni, and Thomas Schwetz.*** **Are there sterile neutrinos at the eV scale? arXiv:1103.4570v2 [hep-ex];**
[2]. ***A. Bungau, et al.*** **Proposal for an Electron Antineutrino Disappearance Search Using High-Rate 8Li Production and Decay // PRL 109, 141802 (2012)**

from Table I [1]. Taking into account the reactor anti-neutrino data

	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	Δm^2_{51} [eV^2]	$\lvert U_{e5}\rvert$
3+1	1.78	0.151		
3+2	0.46	0.108	0.89	0.124

from Table II [1]. From global fit taking into account LSND, MiniBooNE

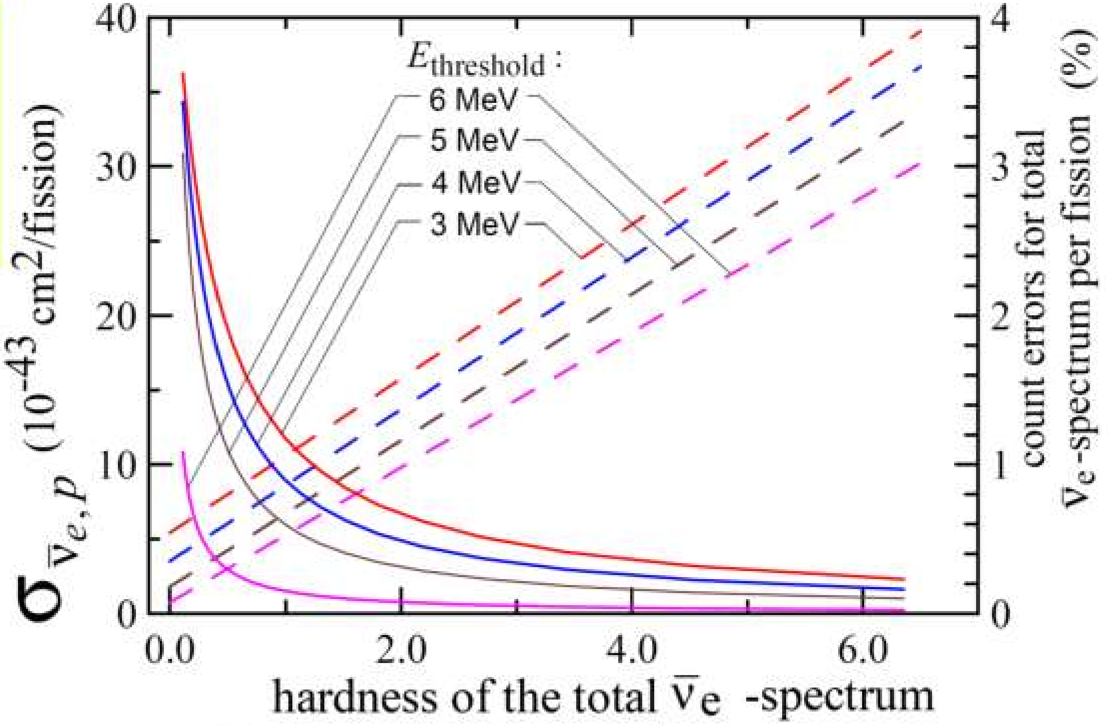
	Δm^2_{41}	$\lvert U_{e4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$
3+2	0.47	0.128	0.87	0.138



Installation:
Lithium antineutrino source with regilated spectrum. In the simulation the volume rate of pumping was $w = 2.25$ m^3/s.

The distance L_1 corresponds to the time 1 s of Li-delivery from the blanket to reservoir for appointed w rate.

CROSS SECTION and COUNT ERRORS in the TOTAL SPECTRUM with HARDNESS $H(\vec{r})$



Basing on the hardness definition

$$H(\vec{r}) = \overline{n}_\nu \frac{F_{\text{Li}}(\vec{r})}{F_{\text{AZ}}(\vec{r})},$$

it is possible to write the density of the total $\overline{\nu}_e$–flux in the point $\vec{r}$:

$$F_{\tilde{\nu}_e}(\vec{r}) = F_{\text{AZ}}(\vec{r}) + H(\vec{r}) \times \frac{F_{\text{AZ}}(\vec{r})}{\overline{n}},$$

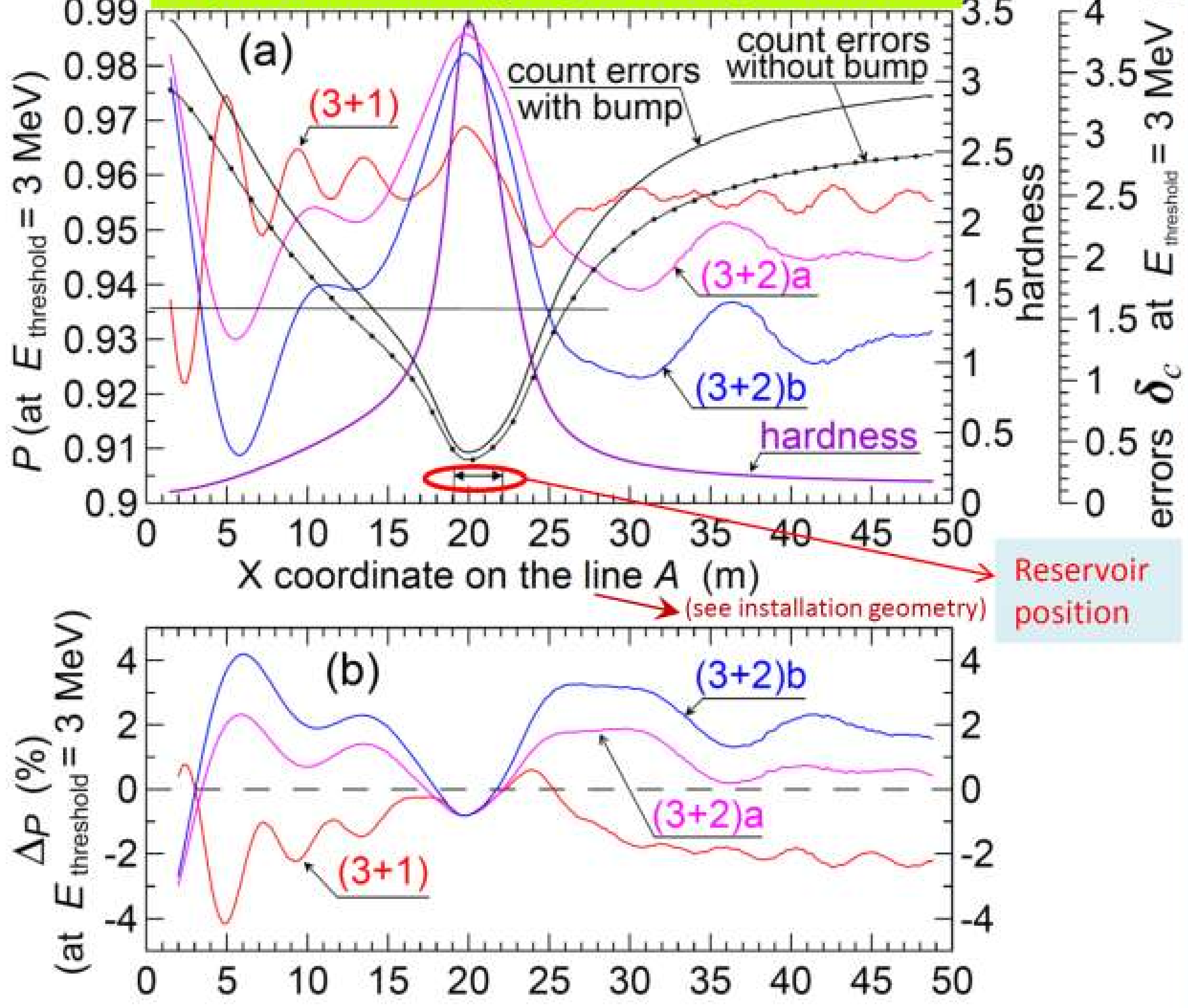
where $F_{\text{AZ}}(\vec{r})$ - density of the $\overline{\nu}_e$ -flux from AZ, *H* - generalized hardness in the point $\vec{r}$.
As the cross section is the additive value then for total -spectrum we can write:

$$\sigma_{\overline{\nu}_e \text{p}}(\vec{r}) = \sigma^{\text{AZ}}_{\overline{\nu}_e \text{p}} + H(\vec{r}) \times \sigma^{\text{Li}}_{\overline{\nu}_e \text{p}} .$$

At increase of *H*-value the strong rise of the cross section is caused by enlarged part of Li- $\overline{\nu}_e$. The cross section and count errors in the total spectrum was obtained for thresholds $E_{\text{threshold}}$ = 4, 5 and 6 MeV and it confirmed that Li yield strongly dominates the reactor part at increase the threshold. **Lyashuk V.I.** Results in Physics 7, 1212 (2017); **arXiv: 1809.0594**

Probability *P* of $\tilde{\nu}_e$ -existence for models: (3+1), (3+2)a, (3+2)b. Opportunity Δ_P of detecting.

E (threshold of $\tilde{\nu}_e$ registration) = 3 MeV

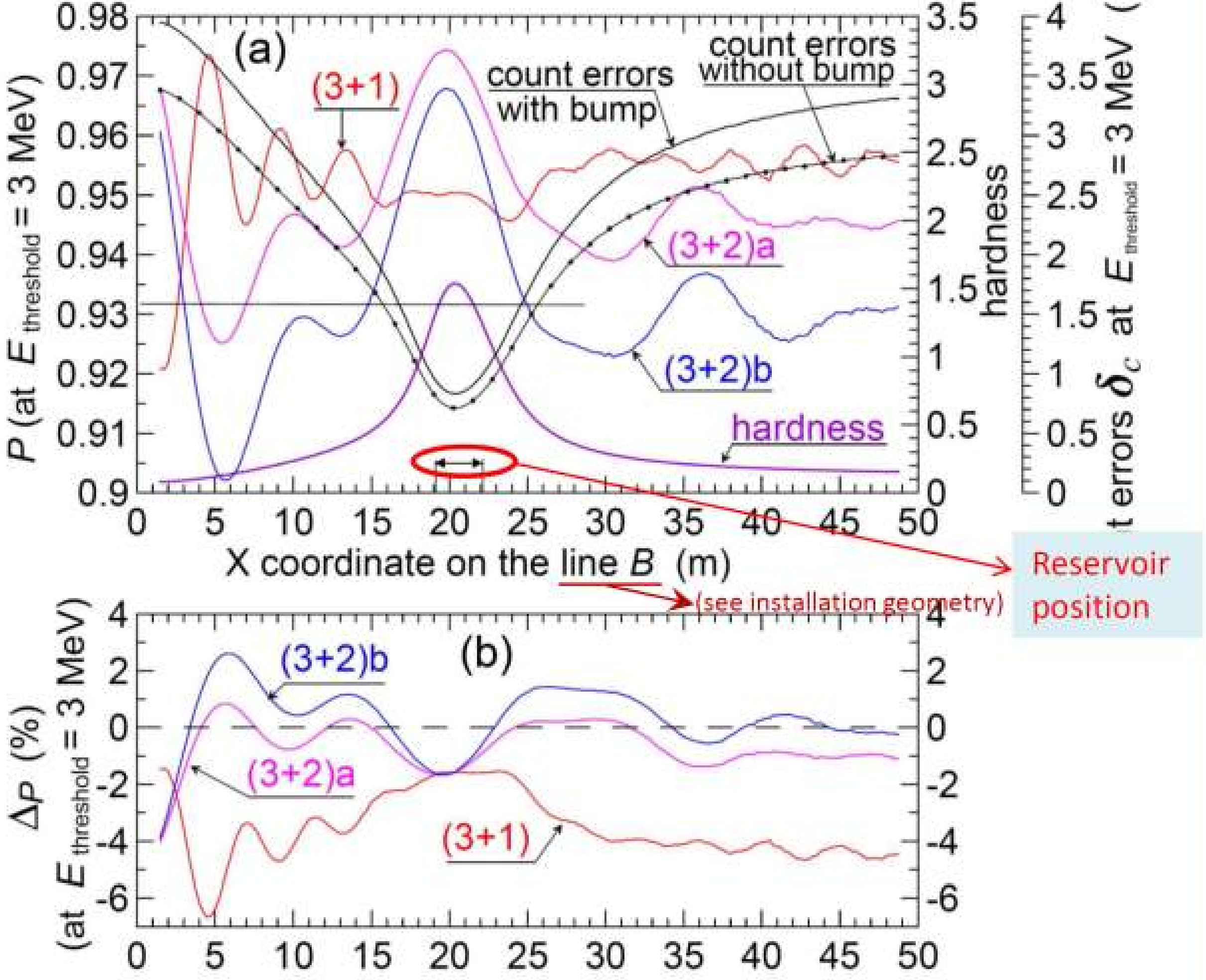


Probability *P* of -existence for three models [(3+1), (3+2)a and (3+2)b on the part (a)], hardness *H* of the total spectrum [part (a)], count errors δ_C (caused by uncertainties of AZ spectrum) [part (a)] and functional $\Delta_P(x)$ for opportunity of neutrino detecting [part (b) for models: (3+1), (3+2)a and (3+2)b] depending on the *X* coordinate **along line *A*** *(see geometry of installation)* and $w = 2.25 \text{m}^3/\text{s}$.

Probability *P*, count errors δ_C and functional Δ_P are given for the threshold of registration *E* = 3 MeV. The data are given for reactor bump taken into account. Curves with points – for case without bump.

functional $\Delta_P(x) = [1 - \delta_C(x_{\text{fix}})]\, P(x_{\text{fix}}) - [1 + \delta_C(x)]\, P(x)$ for opportunity of detecting based on comparison of the maximal *P* with the current *P*(*x*) along *A*-line (δ_C - count errors; coordinate x_{fix} corresponds to maximal *P* value close to reservoir ~ 20m

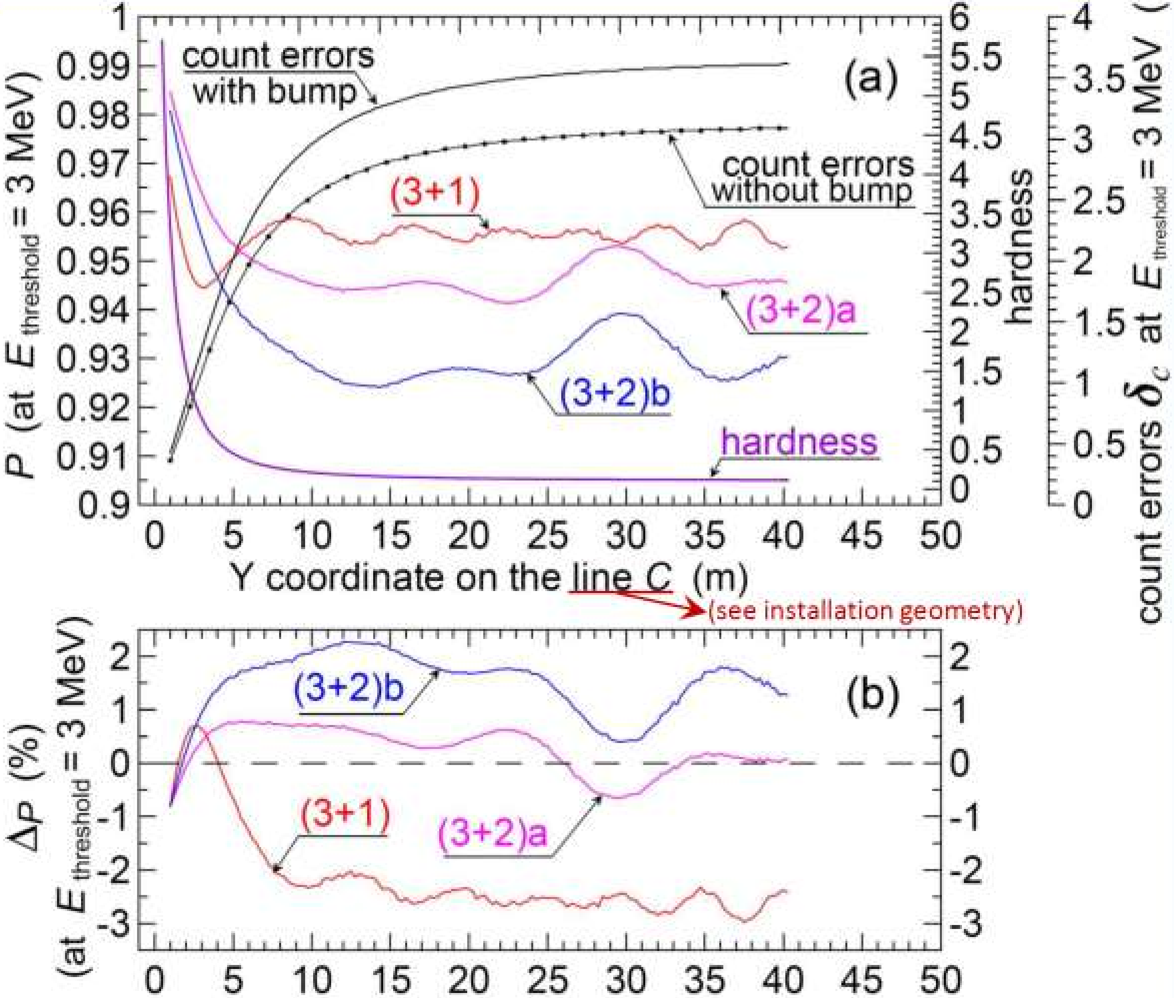
Probability *P* of $\tilde{\nu}_e$-existence for models: (3+1), (3+2)a, (3+2)b and Opportunity Δ_P of detecting along line *B*. *E* (threshold of $\tilde{\nu}_e$ registration) = 3 MeV



Probability *P* of -existence for three models [(3+1), (3+2)a and (3+2)b on the part (a)], hardness *H* of the total spectrum [part (a)], count errors δ_C (caused by uncertainties of AZ spectrum) [part (a)] and functional $\Delta_P(x)$ for opportunity of neutrino detecting [part (b) for models: (3+1), (3+2)a and (3+2)b] depending on the *X* coordinate **along line *B*** *(see geometry of installation)* and $w = 2.25\text{m}^3/\text{s}$. Probability *P*, count errors δ_C and functional Δ_P are given for the threshold of registration *E* = 3 MeV. The data are given for reactor bump taken into account. Curves with ponts – case without the bump.

functional $\Delta_P(x) = [1 - \delta_C(x_{\text{fix}})]\, P(x_{\text{fix}}) - [1 + \delta_C(x)]\, P(x)$ for opportunity of detecting based on comparison of the maximal *P* with the current *P*(*x*) along *A*-line (δ_C - count errors; coordinate x_{fix} corresponds to maximal *P* value close to reservoir ~ 20m

Probability *P* of $\tilde{\nu}_e$ -existence for models: (3+1), (3+2)a, (3+2)b and Opportunity Δ_P of detecting along line *C*. *E* (threshold of $\tilde{\nu}_e$ registration) = 3 MeV



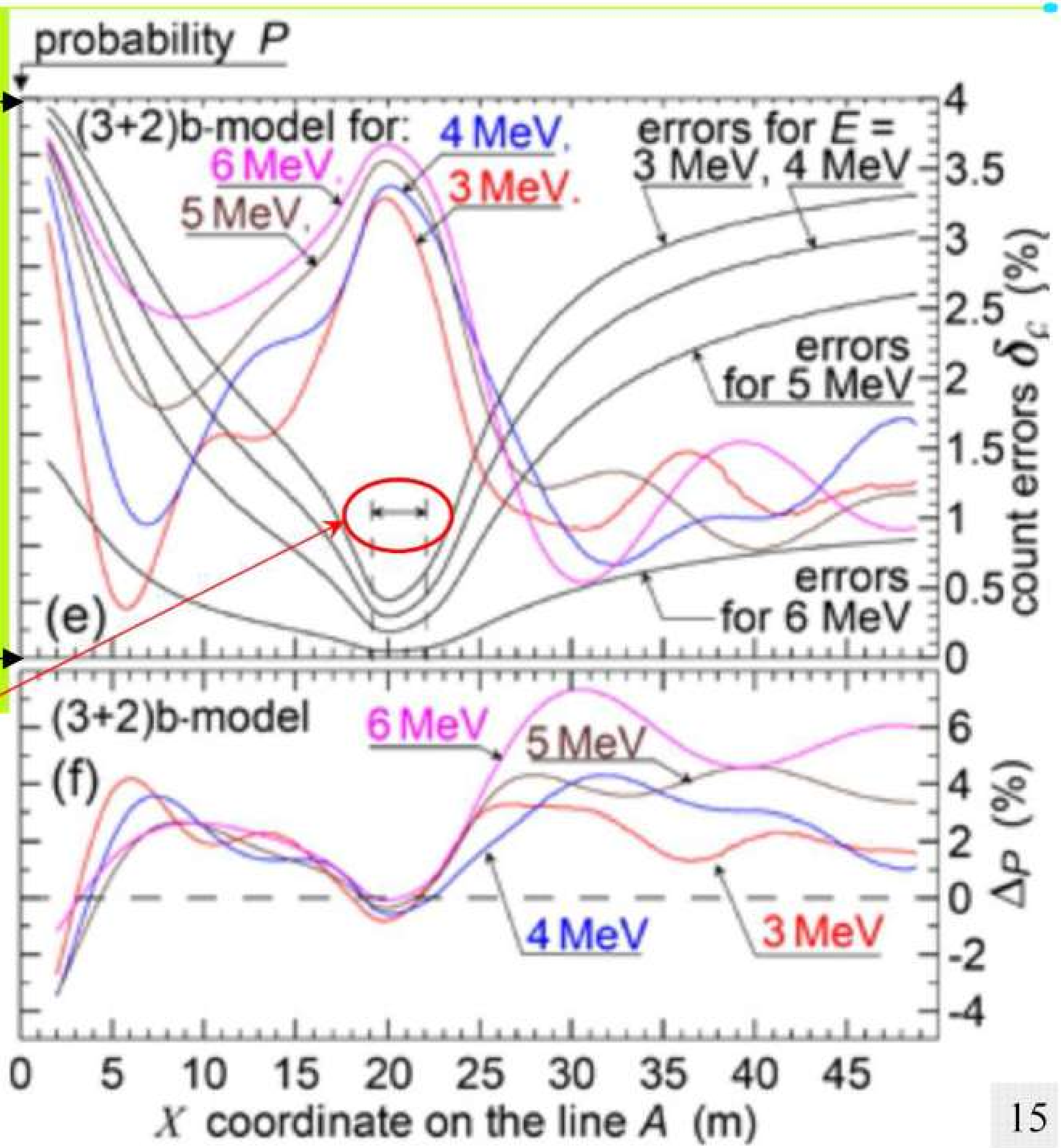
Probability *P* of -existence for three models [(3+1), (3+2)a and (3+2)b on the part (a)], hardness *H* of the total spectrum [part (a)], count errors δ_C (caused by uncertainties of AZ spectrum) [part (a)] and functional $\Delta_P(x)$ for opportunity of neutrino detecting [part (b) for models: (3+1), (3+2)a and (3+2)b] depending on the *X* coordinate **along line *C*** (*see geometry of installation*) and $w = 2.25 m^3/s$.

Probability *P*, count errors δ_C and functional Δ_P are given for the threshold of registration *E* = 3 MeV. The data are given for reactor bump taken into account.

Functional $\Delta_P(y) = [1 - \delta_C(x_{fix}; y=1m)]\, P(x_{fix}; y=1m) - [1 + \delta_C(x_{fix}; y)]\, P(x_{fix}; y)$ for opportunity of detecting based on comparison of the maximal *P* with the current $P(x_{fix}; y)$ along *C*-line (δ_C - count errors; x_{fix} corresponds to maximal $P(x; y=1)$ value close to reservoir: $x_{fix} \sim 20m$

Probability *P* of $\tilde{\nu}_e$ -existence for the model (3+2)b. Opportunity Δ_P of $\tilde{\nu}_e$ detecting.

E (threshold of registration) = 3, 4, 5 and, 6 MeV. The results are given for the A-line heometry

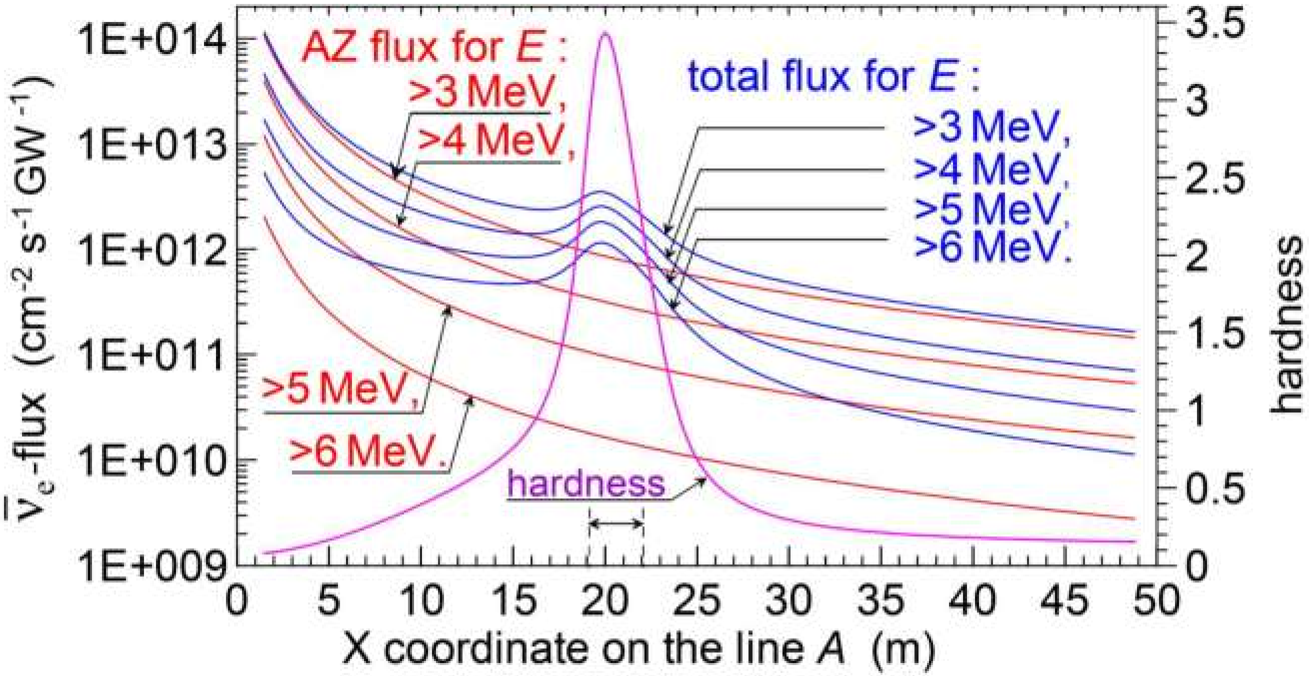


1.0

0.90

Detector position

The densities of $\tilde{\nu}_e$ fluxes



The densities of antineutrino fluxes [from antineutrinos of active zone (AZ) and from the whole mass of ^{8}Li in the installation] and hardness *H* of the total $\tilde{\nu}_e$ -spectrum depending on *X*-coordinate along line *A.*

CONCLUSION

- It was considered and simulated an intense antineutrino source with hard spectrum produced by created 8Li isotope.
- The source ensured the high flux and rate of counts ~ 10E+4 (in the detector volume ~1 m^3 per day and GW of the reactor power).
- Owing to the well defined antineutrino spectrum of 8Li the errors of the counts in the total spectrum can be decreased in order of value (up to ~ 0.5%).
- It is shown the possibility to detect sterile neutrino with $\Delta m^2 \sim 1$ eV^2 for the model (3+1) and (3+2) basing on the considered antineutrino source with regulated spectrum.

(the detailes of the proposal see in: V.I. Lyashuk, arXiv: 1809.05949.)