The possible experiment for search of sterile neutrinos

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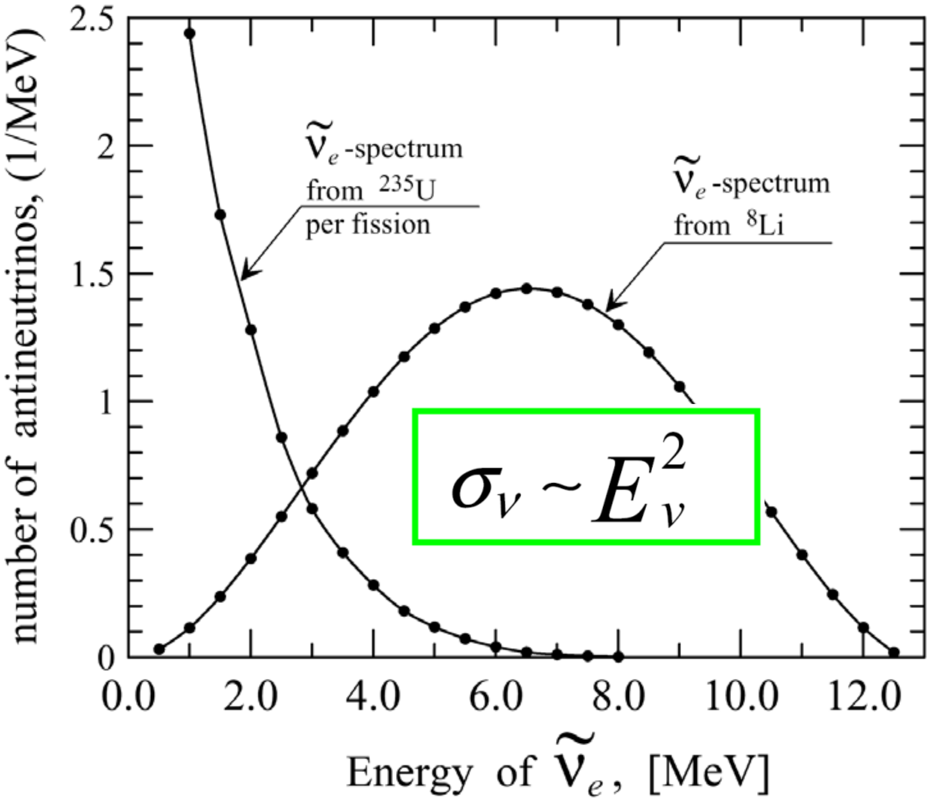
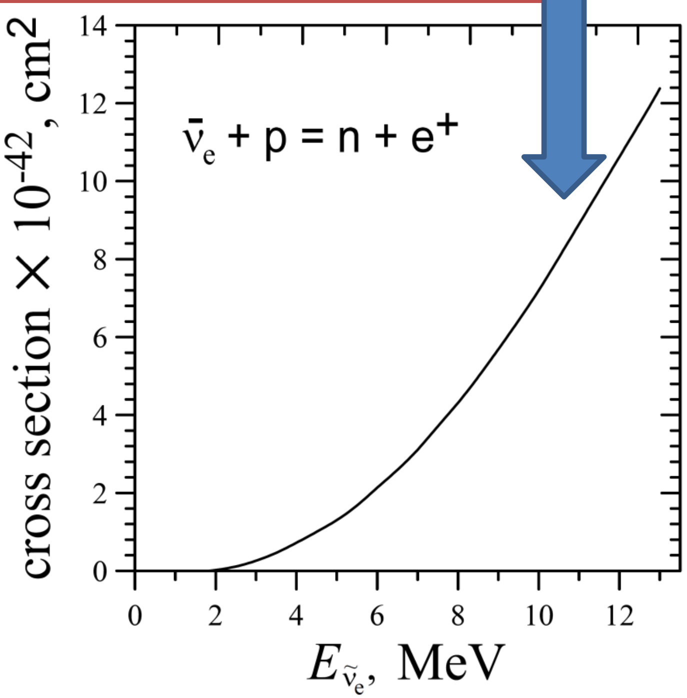
The Conception of the Lithium Antineutrino Source (1)

^{7}Li(n,γ)^{8}Li T$_{½}$ (^{8}Li) = 0.84 s $^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \tilde{\nu}_e$

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

(large high cross section for high energy of $\tilde{\nu}_e$!)





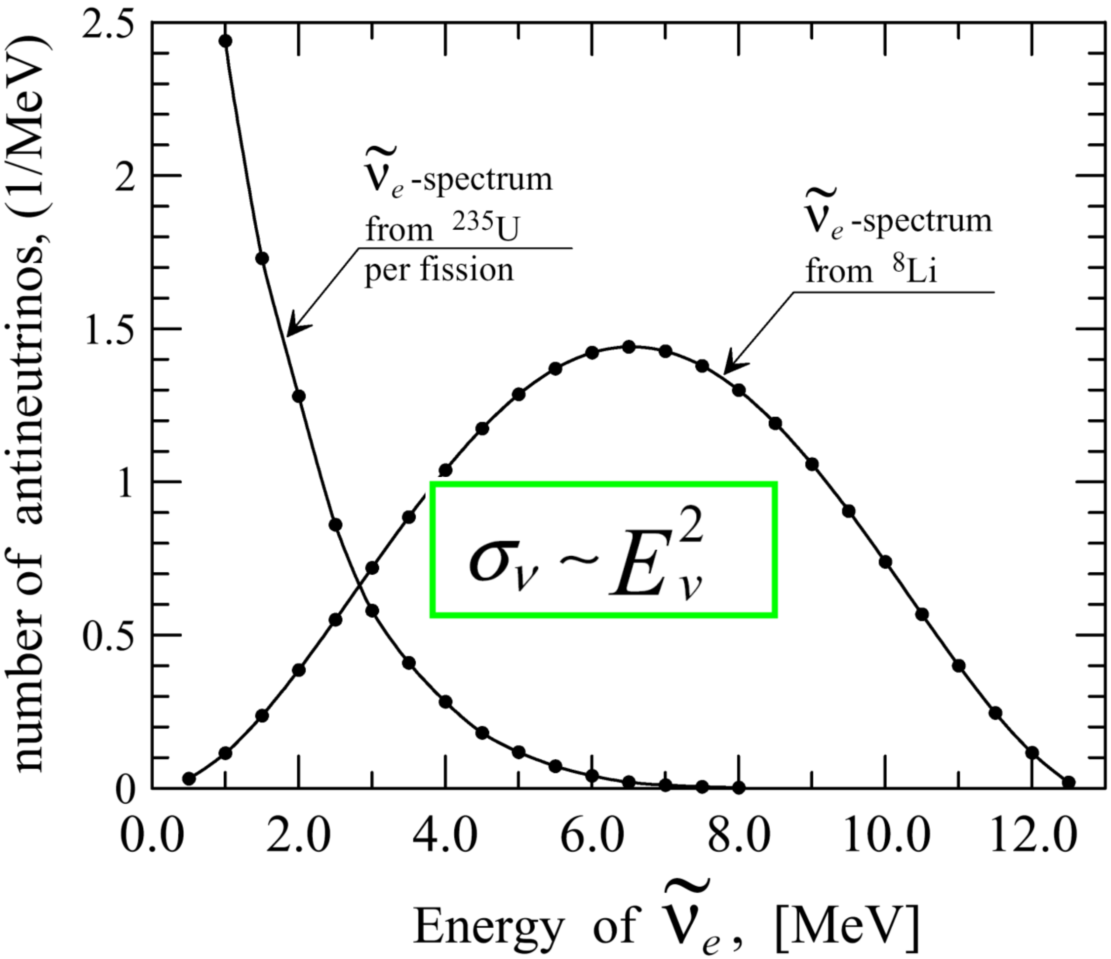
P. Vogel and J.F. Beacom, Phys. Rev. D 60 (1999) 053003

K. Schreckenbach, G. Colvin, W. Gelletly and F. Von Feilitzsch. , Phys. Lett. 160B (1985) 325.
V.G. Aleksankin, S.V. Rodichev, P.M. Rubtsov, F.E. Chukreev, Beta and antineutrino radiation from radioactive nuclei, Energoatomizdat, Moscow, Russia, (1989) ISBN 5-283-03727-4.

The Conception of the Lithium Antineutrino Source (2)

$^7Li(n,\gamma)^8Li$ $T_{½}$ (^8Li) = 0.84 s

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

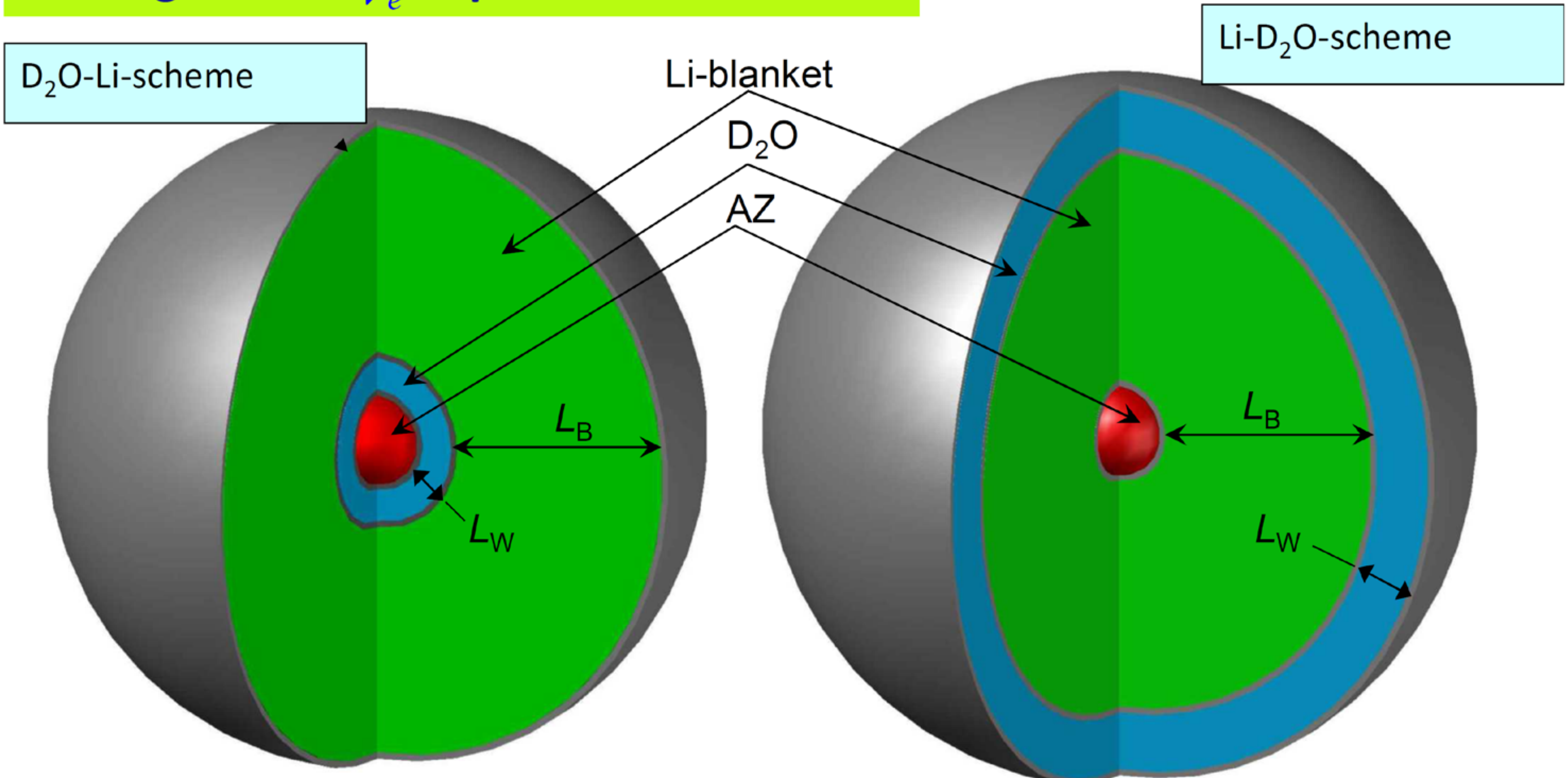


Alongside with the obvious advantage on a neutrino flux the nuclear reactor has a disadvantage – 1) too-small hardness of –spectrum and 2) significant errors.

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

The idea to use ^8Li 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_2O scheme is more compact in comparison with D_2O-Li scheme and requests the less mass of pure ^7Li.
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_2O acts as an effective moderator in D_2O-Li-scheme and as a reflector in the Li-D_2O-scheme.

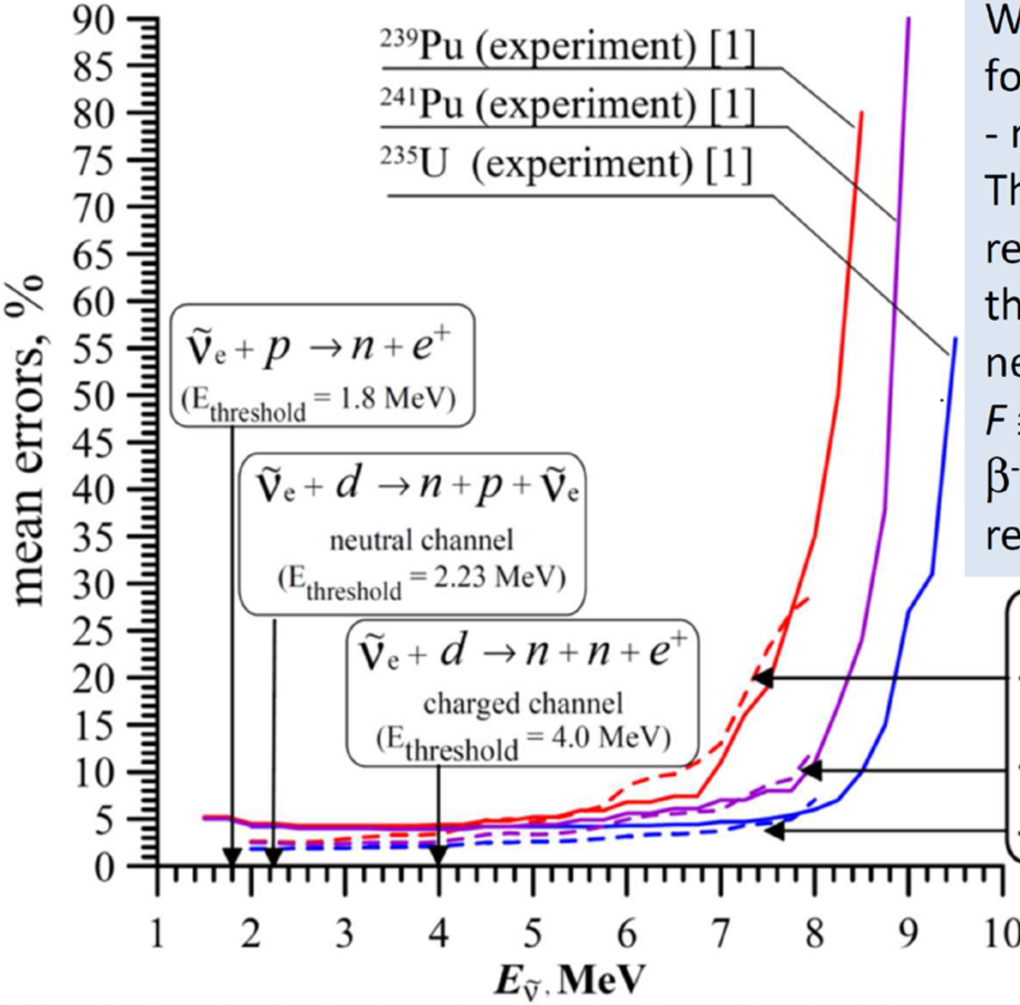
In IAE in 70-th it was considered proposal to install lithium blocks into pulse reactor RING
Vorob'ev et al. The pulse reactor RING. Preprint IAE, 2384 (1974) (in russian: Воробьев Е.Д. и др. Импульсный реактор РИНГ. Препринт ИАЭ, 2384, 1974)

The 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

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

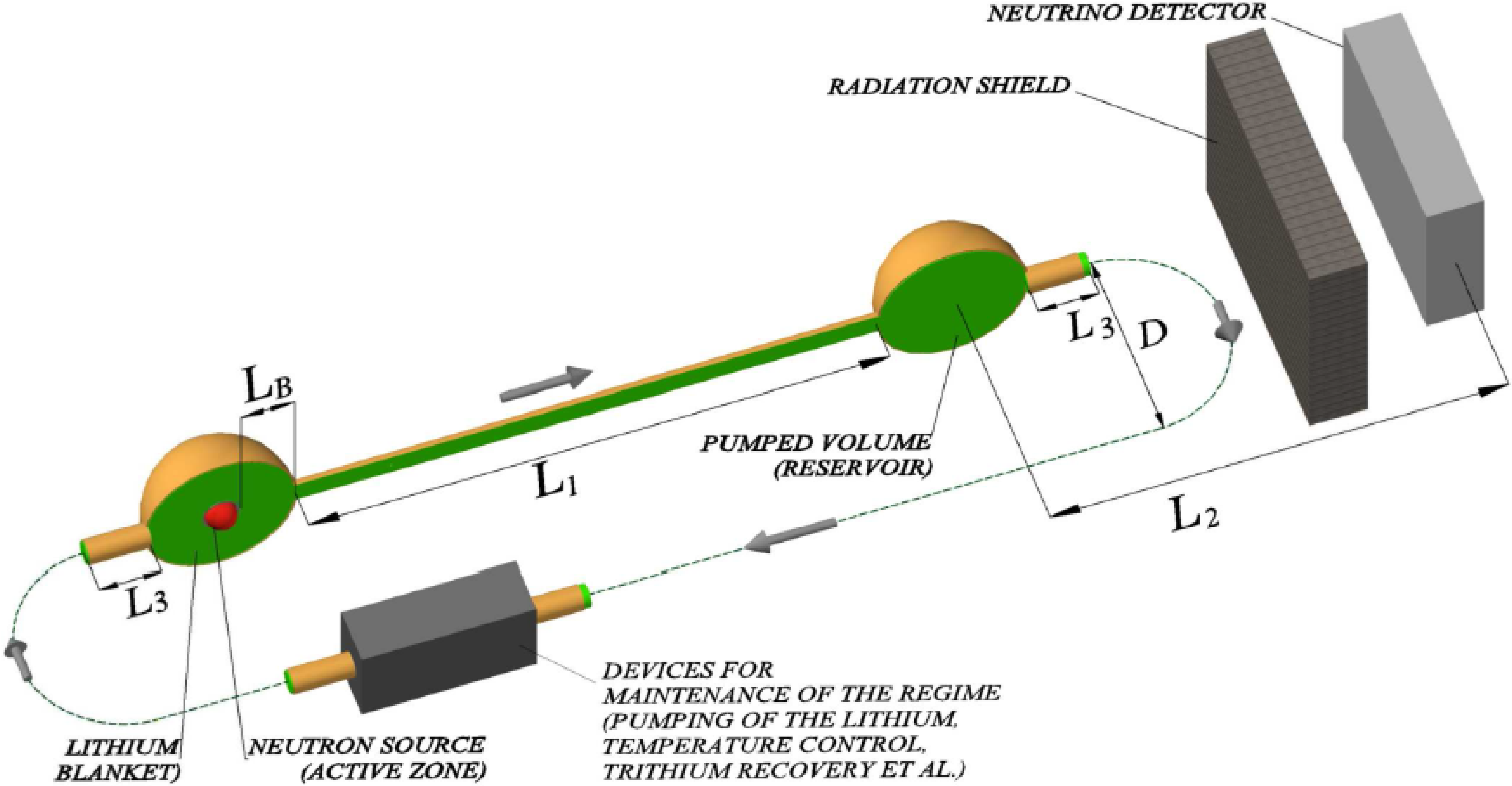
Where $\overline{n}\cong 6$ - mean number of β^--decays for both fission fragments of ^{235}U, ≅ 200 MeV - mean energy released at ^{235}U-fission. Then, at the power *P* = 2800 MW (the Bugeu reactor, France) and distance *R* ≅ 18 m (as in the realized reactor experiments on search of neutrino. oscillations [4, 5]) the flux is *F* ≅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, $\boldsymbol{w}$ - volume being pumped over in a time unit (flow rate, i.e. circulation rate), then $\boldsymbol{t_p = V_B / w}$ - 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;

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

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

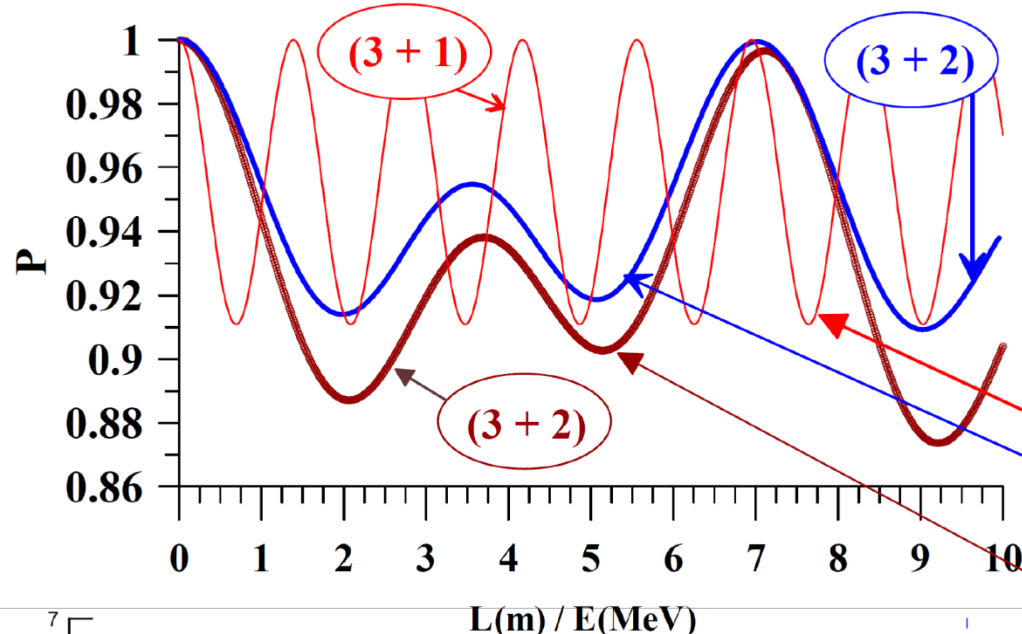
$$\varphi(y) = 1 - \exp(-\lambda_\beta y / w).$$

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 reserrvoir 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]

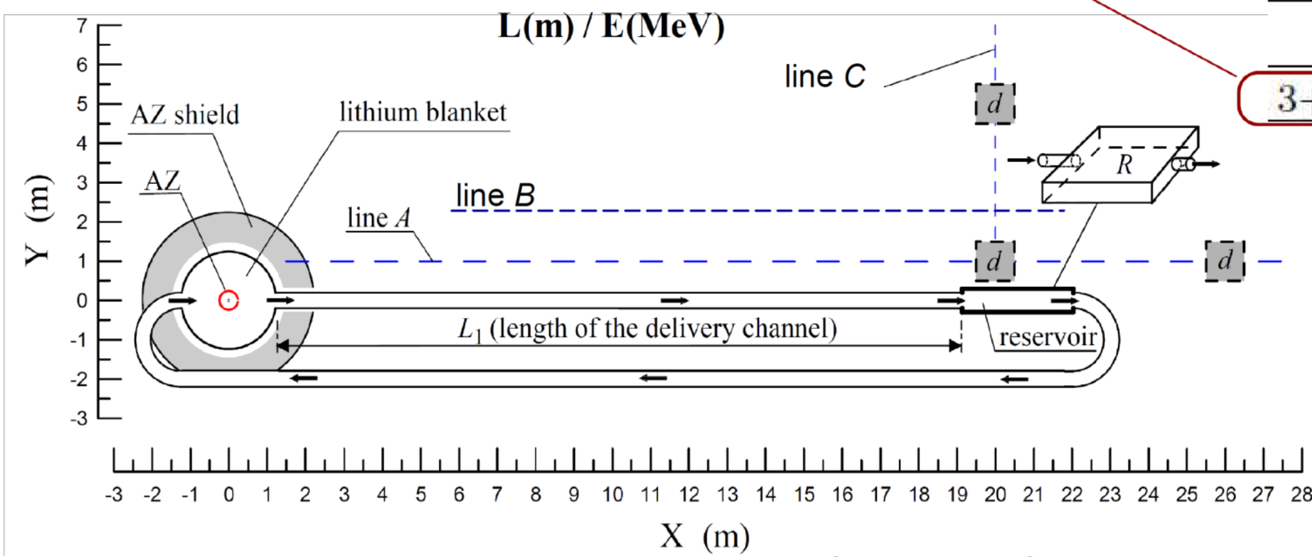
[2]. J., Kopp, M. Maltoni, T. Schwetz. Phys. Rev. Lett. 107, 091801, DOI: 10.1103/PhysRevLett.107.091801

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

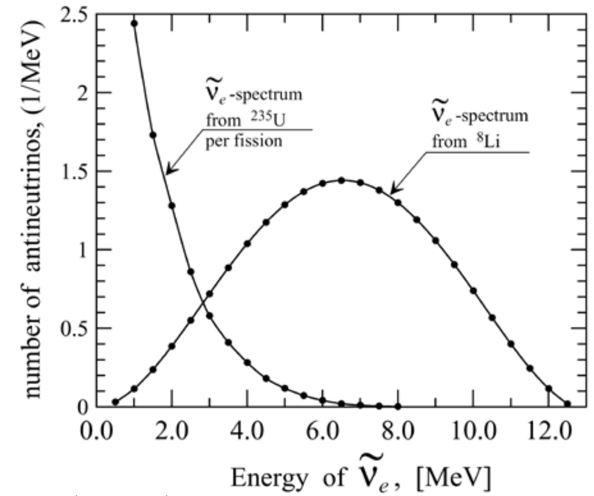


Installation:

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.

Generalized Hardness $H(\vec{r})$ of the Total Spectrum



Let $F_{\text{Li}}(\vec{r})$ and $F_{\text{AZ}}(\vec{r})$ –

- densities of lithium antineutrinos flux from the blanket and antineutrino fluxes from the active zone (AZ),

$\overline{n}_\nu = 6.14$ - number of reactor $\overline{\nu}_e$ emitted per one fission in AZ.

We admit that the hardness of the summary $\overline{\nu}_e$- spectrum at the point $\vec{r}$ **<u>equals one unit of hardness</u>** if the ratio of densities is:

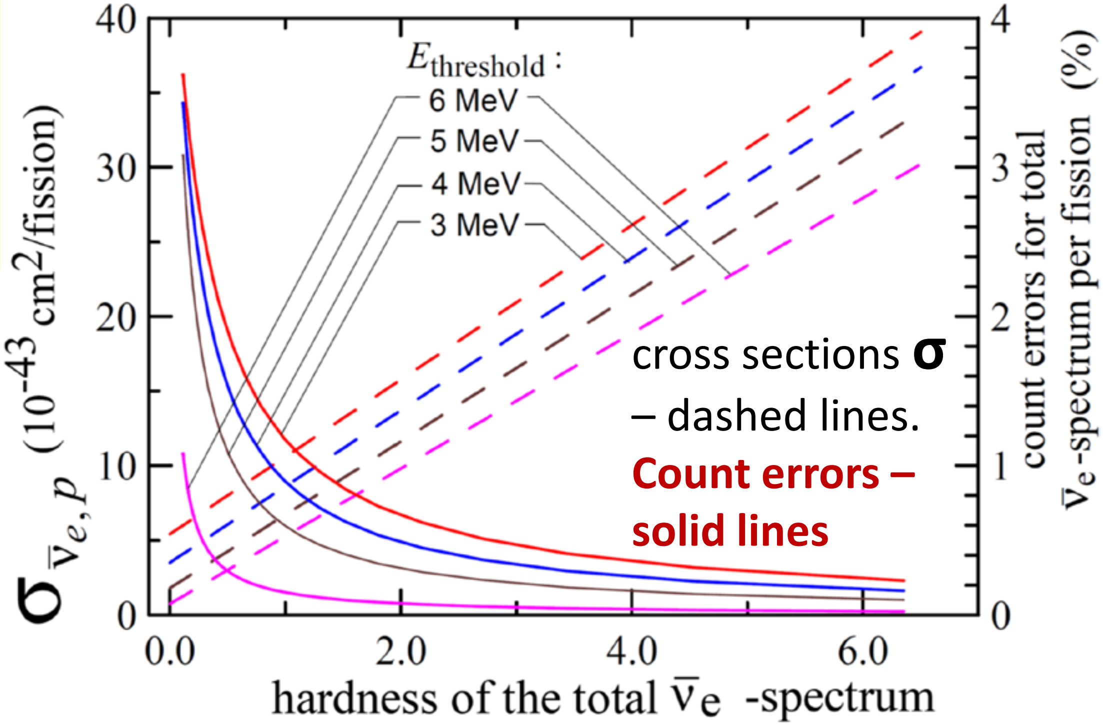
$$\frac{F_{\text{Li}}(\vec{r})}{F_{AZ}(\vec{r})} = \frac{1}{\overline{n}_\nu}$$

Then the generalized hardness of the total spectrum is:

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

This definition is convenient as in so doing the averaged (over the blanket volume) value for the total spectrum generalized hardness of steady spectrum sources is estimated by the value the efficiency *k* of the blanket.

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



Basing on the hardness definition

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

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

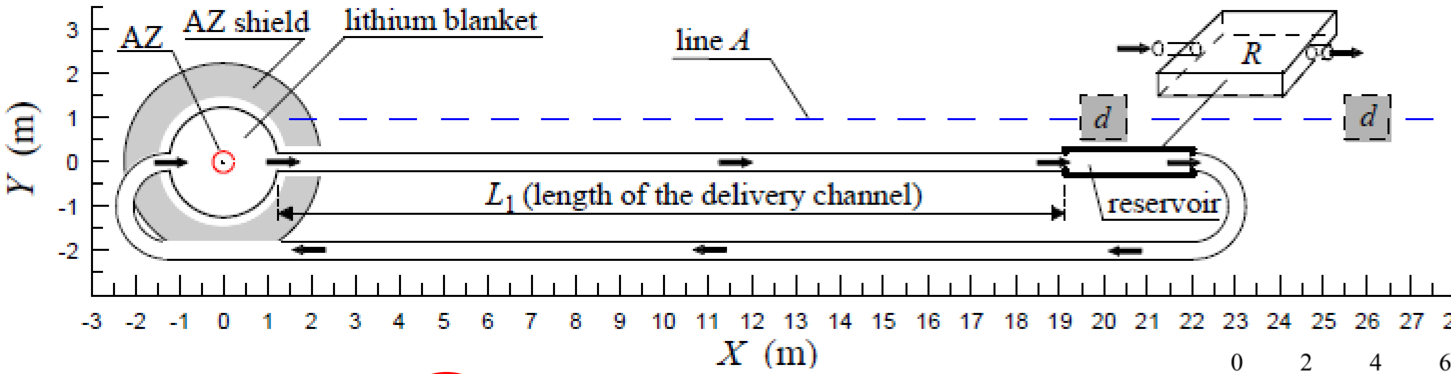
$$F_{\tilde{\nu}_e}(\vec{r}) = F_{\text{AZ}}(\vec{r}) + H(\vec{r}) \times \frac{F_{\text{AZ}}(\vec{r})}{\bar{n}},$$

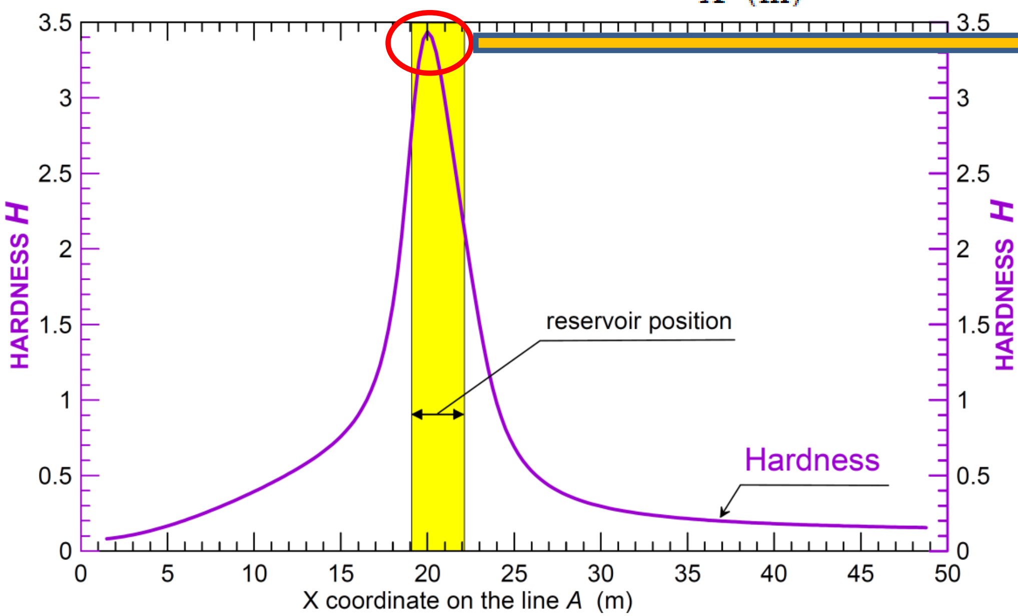
where $F_{\text{AZ}}(\vec{r})$ - density of the $\bar{\nu}_e$ -flux from AZ, *H* - generalized hardness in the point $\vec{r}$.
As the cross section is the additive value then for total -spectrum we can write:

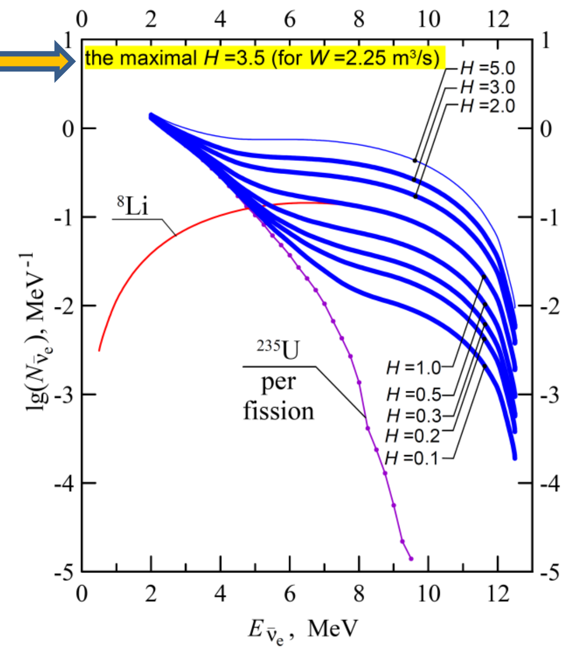
$$\sigma_{\bar{\nu}_e \text{p}}(\vec{r}) = \sigma^{\text{AZ}}_{\bar{\nu}_e \text{p}} + H(\vec{r}) \times \sigma^{\text{Li}}_{\bar{\nu}_e \text{p}} .$$

At increase of *H*-value the strong rise of the cross section is caused by enlarged part of Li- $\bar{\nu}_e$.
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: 1809.05949**

HARDNESS *H* of the total $\overline{\nu}_e$-spectrum and total $\overline{\nu}_e$-spectrum (from Active Zone and from 8Li in the dynamical system)





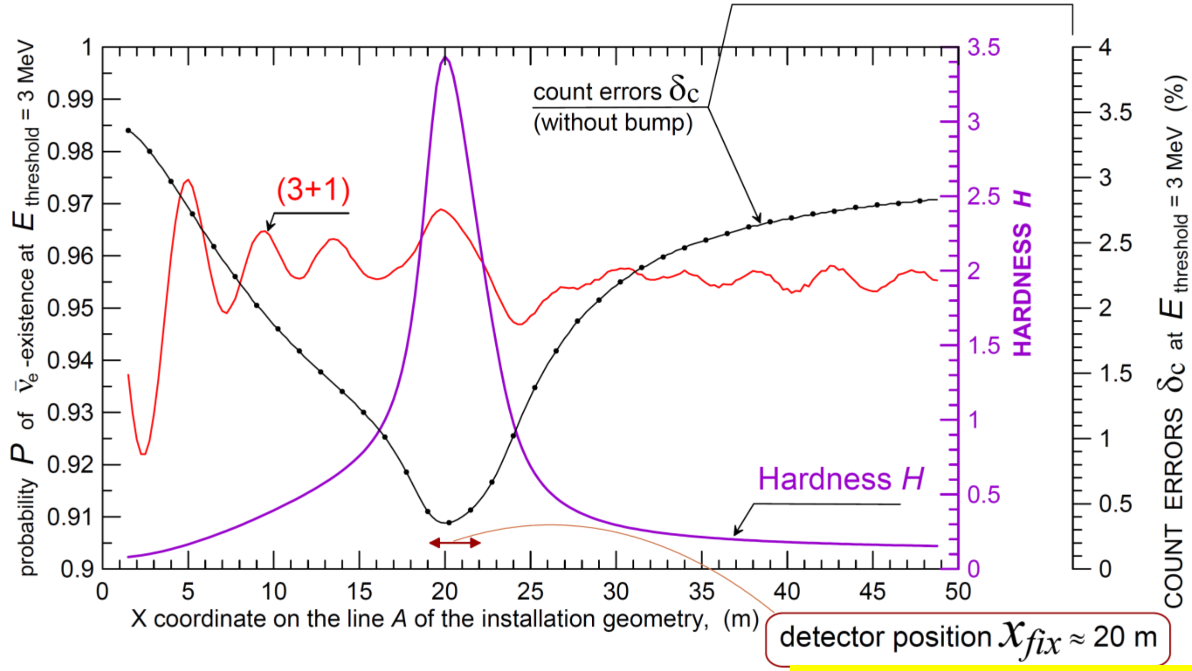


Dependence of hardness *H* from x-coordinate at shifting along the line *A*

Total $\overline{\nu}_e$-spectrum for different hardness *H* (blue lines) as sum from active Zone (AZ) and from 8Li in the installation (dynamical system)

Probability *P* of $\overline{\nu}_e$ -existence for the model (3+1), $E_{threshold}$ = 3 MeV
Opportunity Δ_p of $\overline{\nu}_e$ -detecting along A-line of the geometry

For evaluation of possibility to detect oscillation $\overline{\nu}_e$ to sterile neutrinos depending on Coordinates, let us introduce the functional $\Delta_p(x)$ for opportunity of registration. We will compare the maximal ***P*** value with the current P(x) along the indicated line (example for **A-line**) of the Installation geometry.



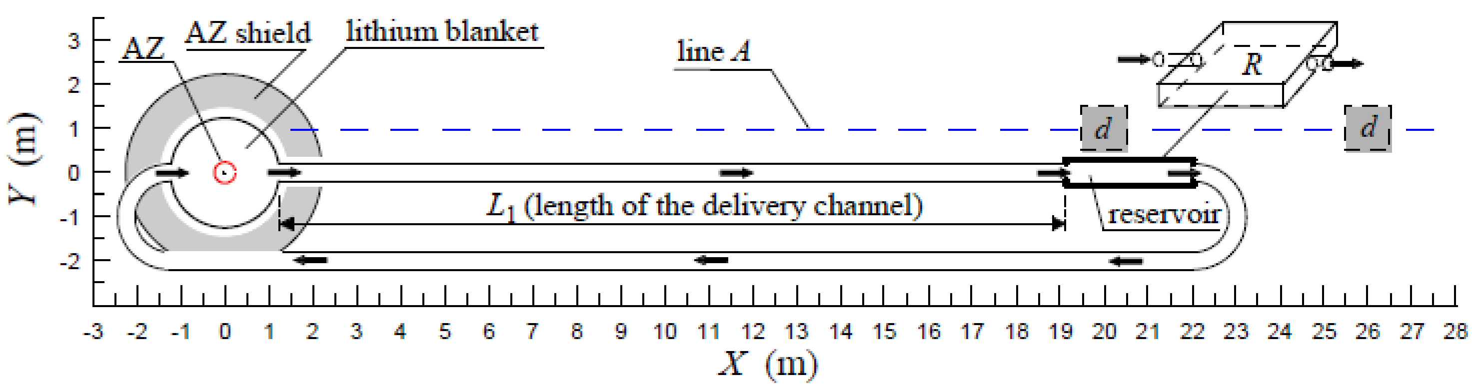
$$\Delta p(x) = [1 - \delta_c(x_{fix})] \times P(x_{fix}) - [1 + \delta_c(x)] \times P(x),$$

where δ_c - count errors; x_{fix} corresponds to maximal P-value close to reservoir position (x_{fix} ≈ 20 m).

for (3+1) model [1]:

[1] J., Kopp, M. Maltoni, T. Schwetz Phys. Rev. Lett. 107, 091801, DOI: 10.1103/ PhysRevLett.107. 091801

Best fit data for (3+1) model in Table I



Probability P of $\bar{\nu}_e$ -existence for the model (3+1), $E_{threshold}$= 3 MeV Opportunity Δ_P of $\bar{\nu}_e$ -detecting along A-line

For evaluation of possibility to detect oscillation $\bar{\nu}_e$ to sterile neutrinos depending on Coordinates, let us introduce the functional $\Delta_p(x)$ for opportunity of registration.

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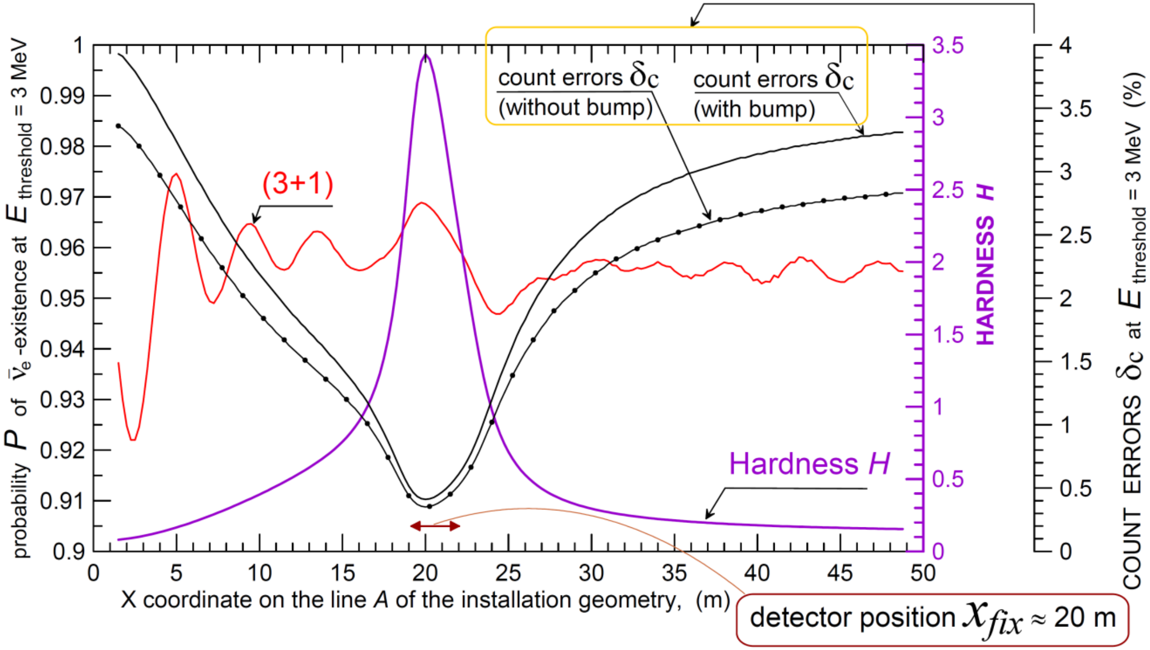

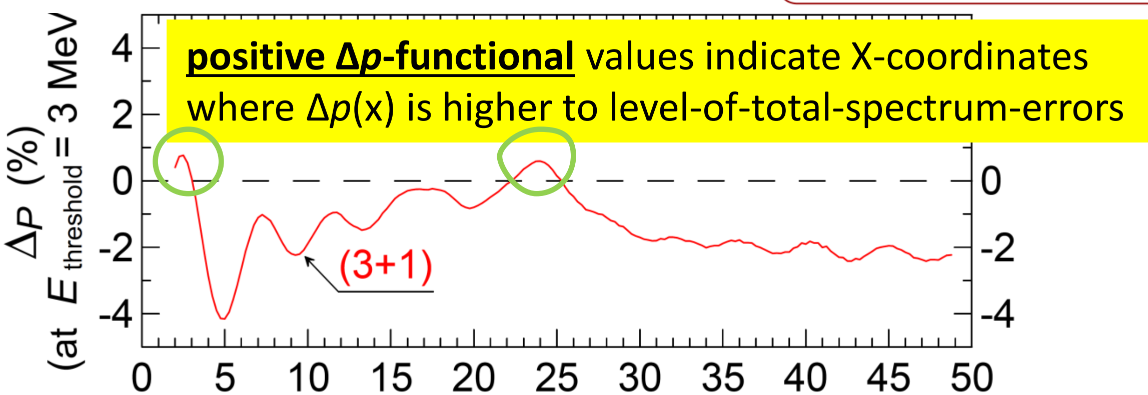

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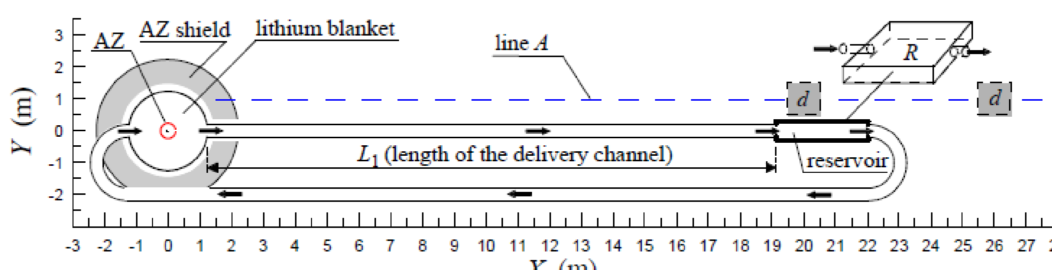
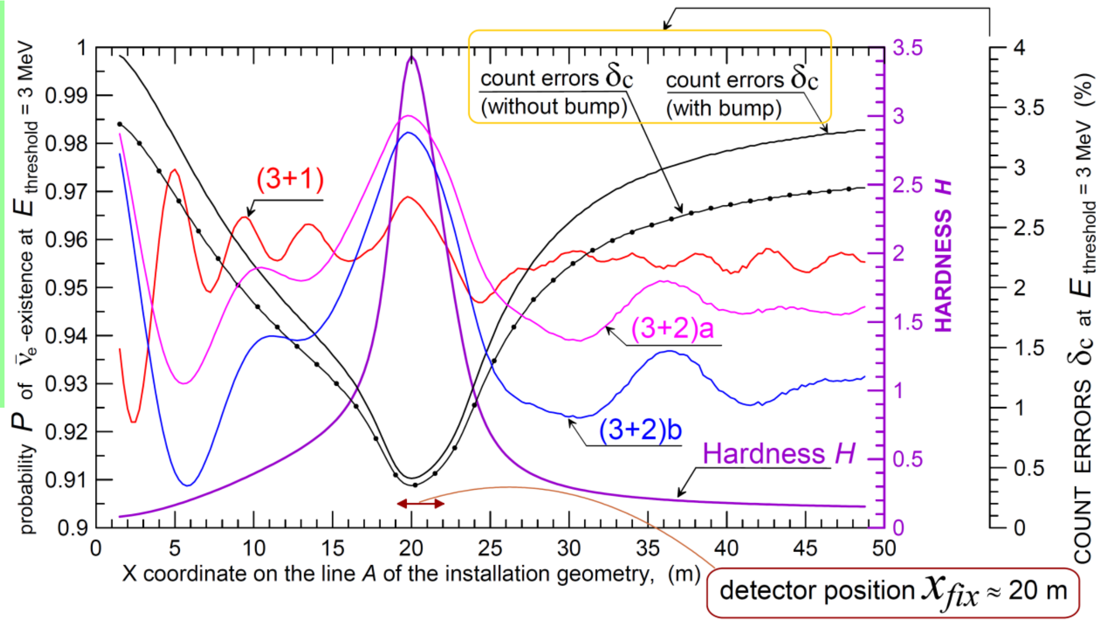
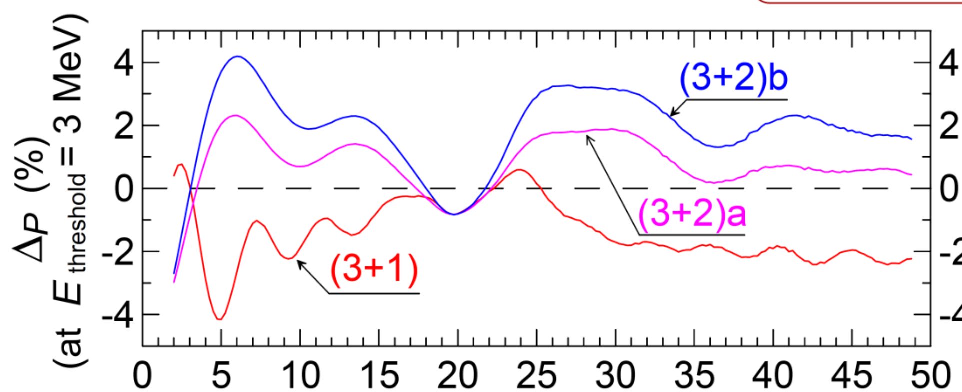


Probability P of $\bar{\nu}_e$-existence for the <u>model (3+1), (3+2)a, (3+2)b.</u> Opportunity Δ_P of $\bar{\nu}_e$-detecting along A-line

For evaluation of possibility to detect oscillation $\bar{\nu}_e$ to sterile neutrinos depending on Coordinates, let us introduce the functional $\Delta_p(x)$ for opportunity of registration.

We will compare the maximal ***P*** value with the current $P(x)$ along the indicated line (example for **A-line**) of the Installation geometry at pumpimg rate w = 2.25 m³/s.





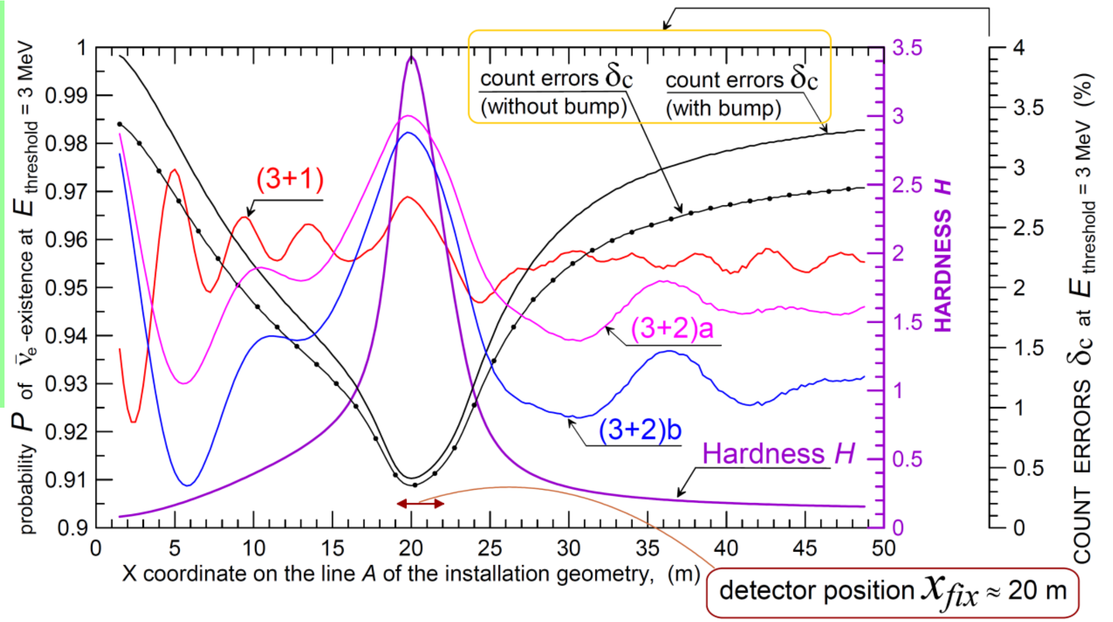
$$\Delta p(x) = [1 - \delta_c(x_{fix})] \times P(x_{fix}) - [1 + \delta_c(x)] \times P(x)$$

where δ_c - count errors; x_{fix} corresponds to maximal P-value close to reservoir position ($x_{fix} \approx 20$ m).

<u>Parameters for (3+1), (3+2) model [1]:</u>

[1] Joachim Kopp, Michele Maltoni, and Thomas Schwetz Phys. Rev. Lett. 107, 091801, DOI: 10.1103/PhysRevLett.107.091801
Best fit data for the models (3+1) and (3+2)a – see in Table I.
Best fit data for the model (3+2)b – see in Table II.

Probability P of $\overline{\nu}_e$ -existence for the <u>model (3+1), (3+2)a, (3+2)b.</u> Opportunity Δ_P of $\overline{\nu}_e$ -detecting along A-line



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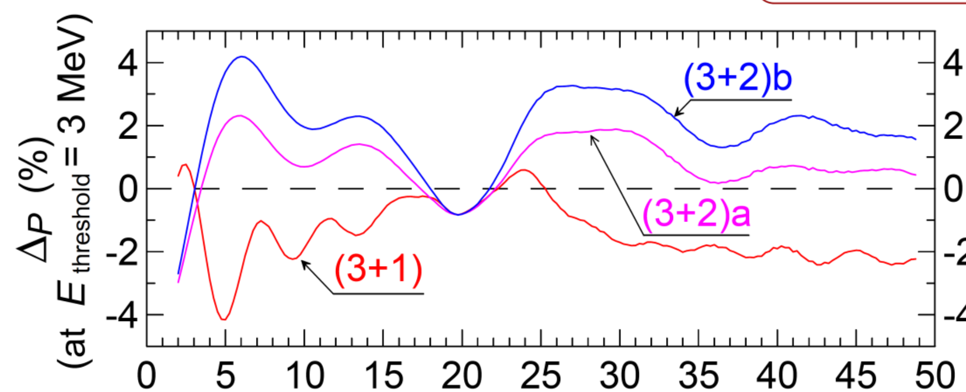

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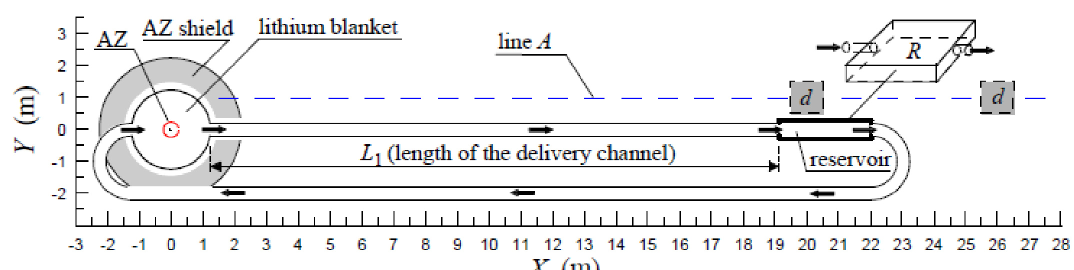
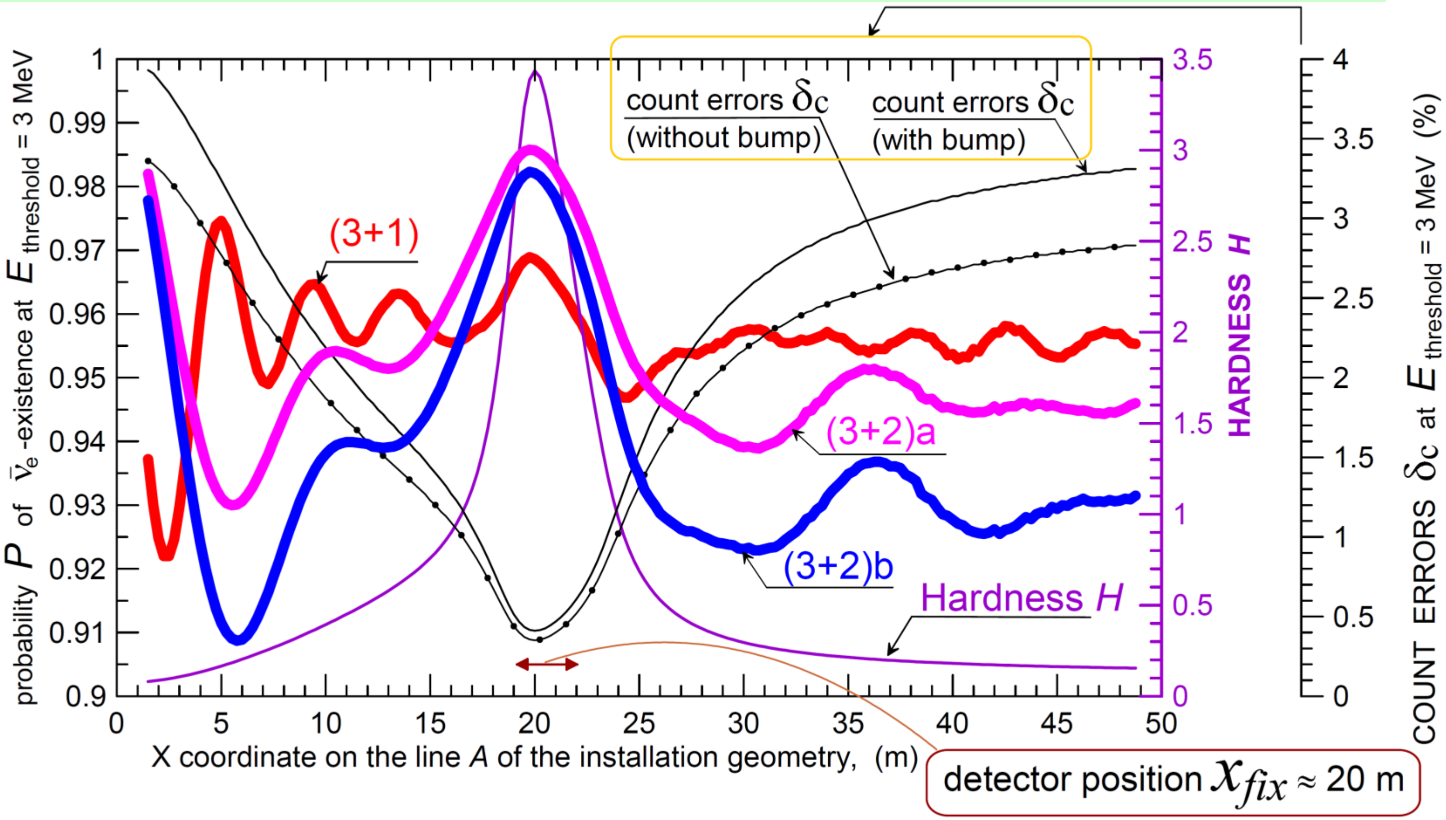
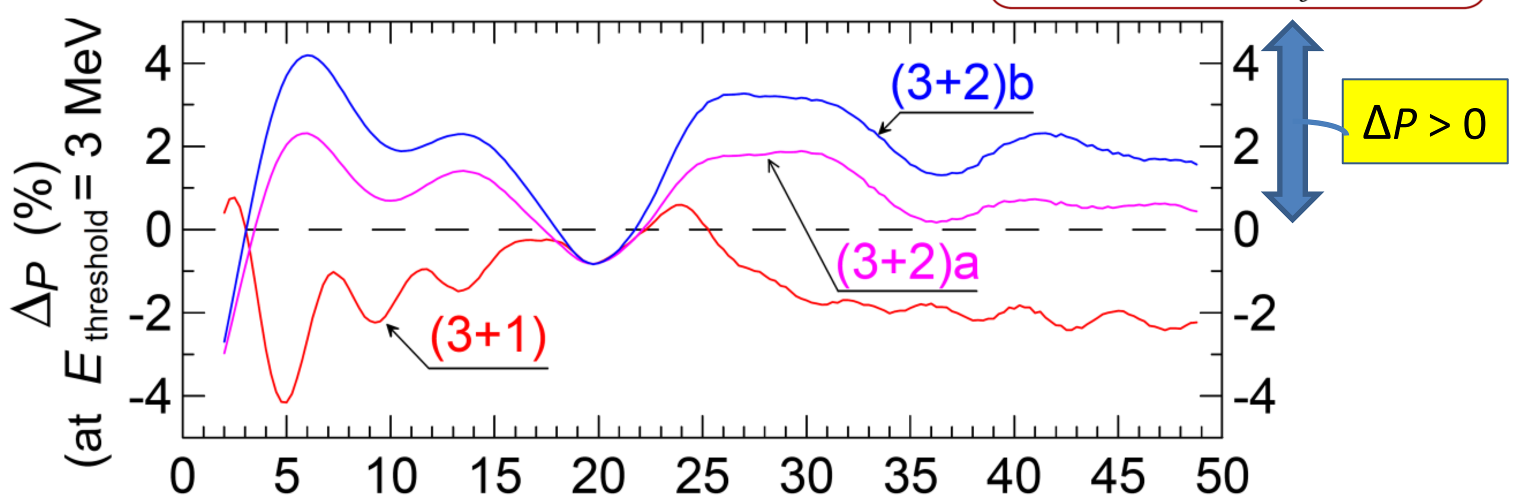


Probability P of $\overline{\nu}_e$-existence for the <u>models (3+1), (3+2)a, (3+2)b</u>. Opportunity Δ_P to detect $\overline{\nu}_e$ along A-line; $E_{threshold}$ =3 MeV



If $\Delta P > 0$,
$\overline{\nu}_e$ -detection
is
poissible

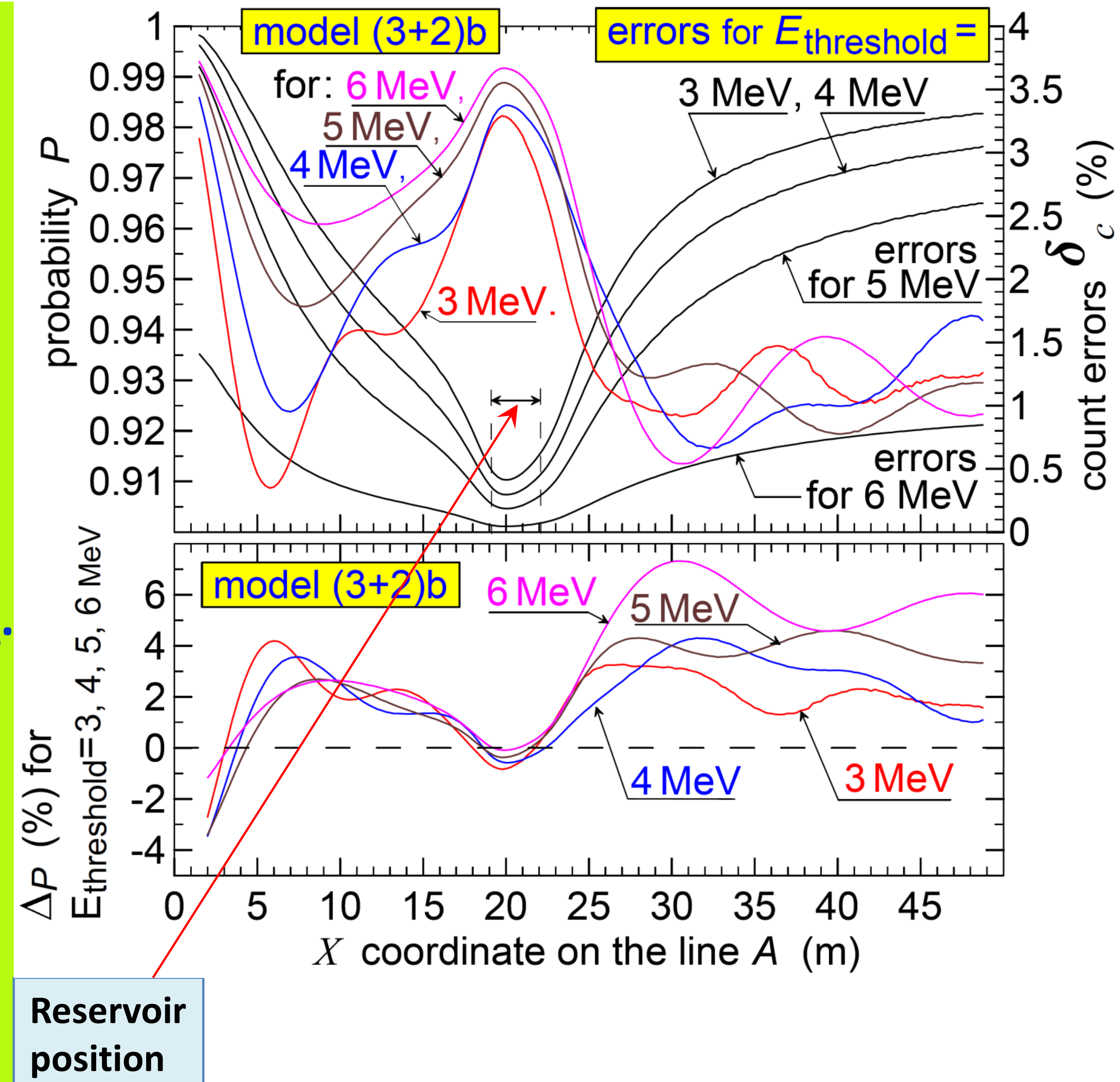


$$\Delta p(x) = [1 - \delta_c(x_{fix})] \times P(x_{fix}) - [1 + \delta_c(x)] \times P(x)$$

The "orthogonal" way to increase the OPPORTUNITY Δ_P of $\tilde{\nu}_e$ -detecting: to increase the $E_{threshold}$ of registration

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

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



The "orthogonal" way to increase the OPPORTUNITY Δ_P of $\tilde{\nu}_e$ -detecting: to increase the $E_{threshold}$ of registration

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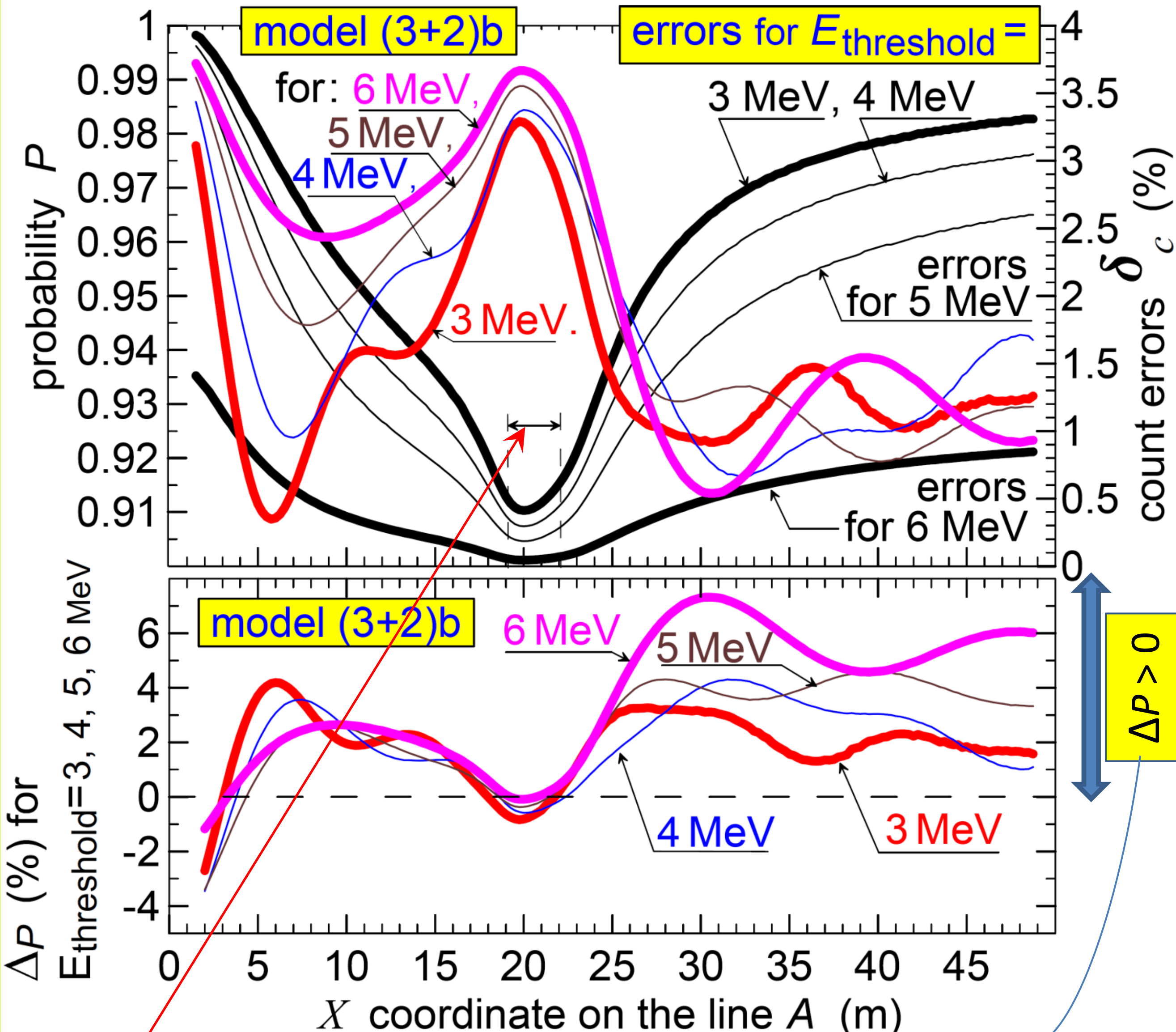
***E* (threshold of registration) = 3, 4, 5 and 6 MeV.**

The results are given for the *A*-line geometry



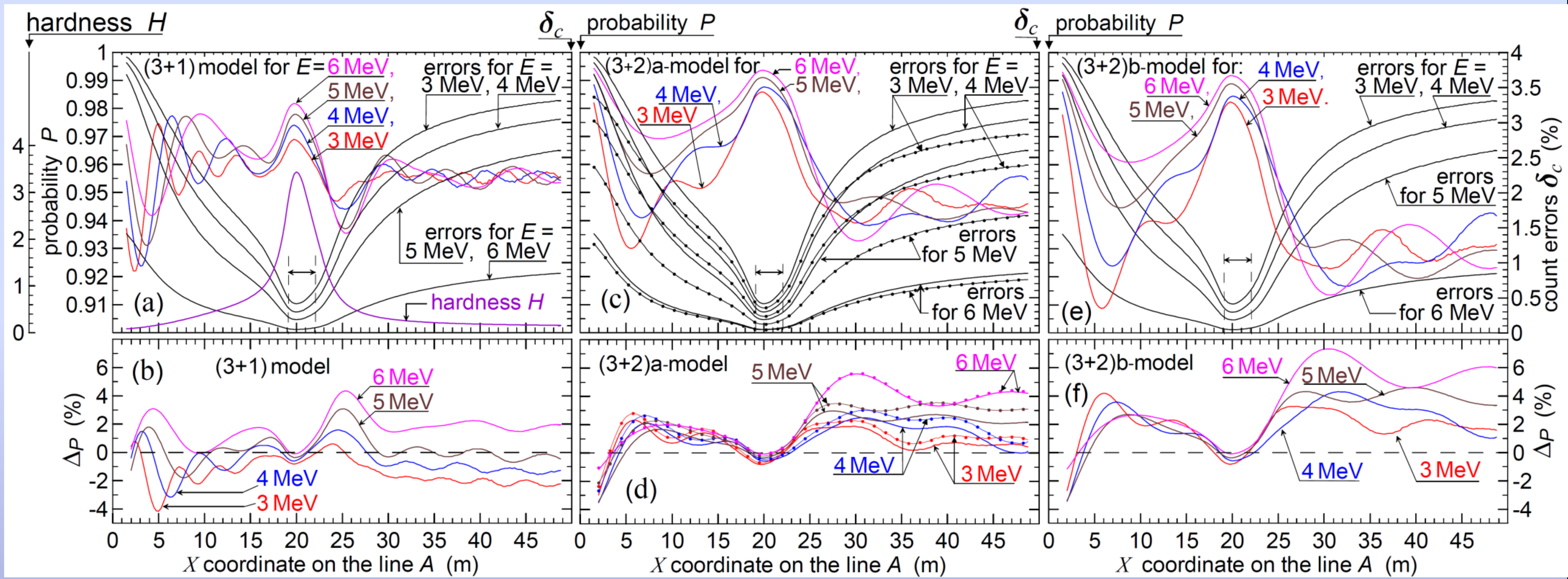
Reservoir position

If $\Delta P > 0$, then $\overline{\nu}_e$-detection is poissible

<u>Probability *P*</u> of $\tilde{\nu}_e$ -existence for models (3+1), (3+2)a, (3+2)b (top line – see figures (a), (c), (e)) and

<u>Opportunity</u> Δ_P of $\tilde{\nu}_e$ -detecting (bottom line – see figures (b), (d), (f)) for thresholds of registration *E* = 3, 4, 5, 6 MeV.

The results are given for <u>A-line</u> geometry [1]



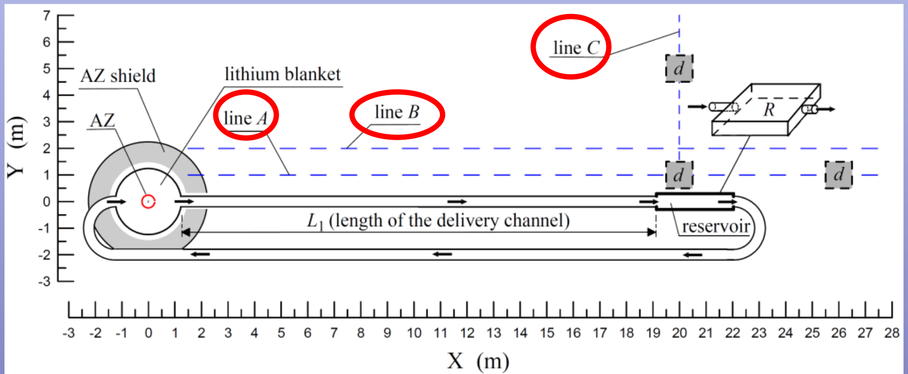
[1] V.I.Lyashuk, JHEP06(2019)135

The geometry:

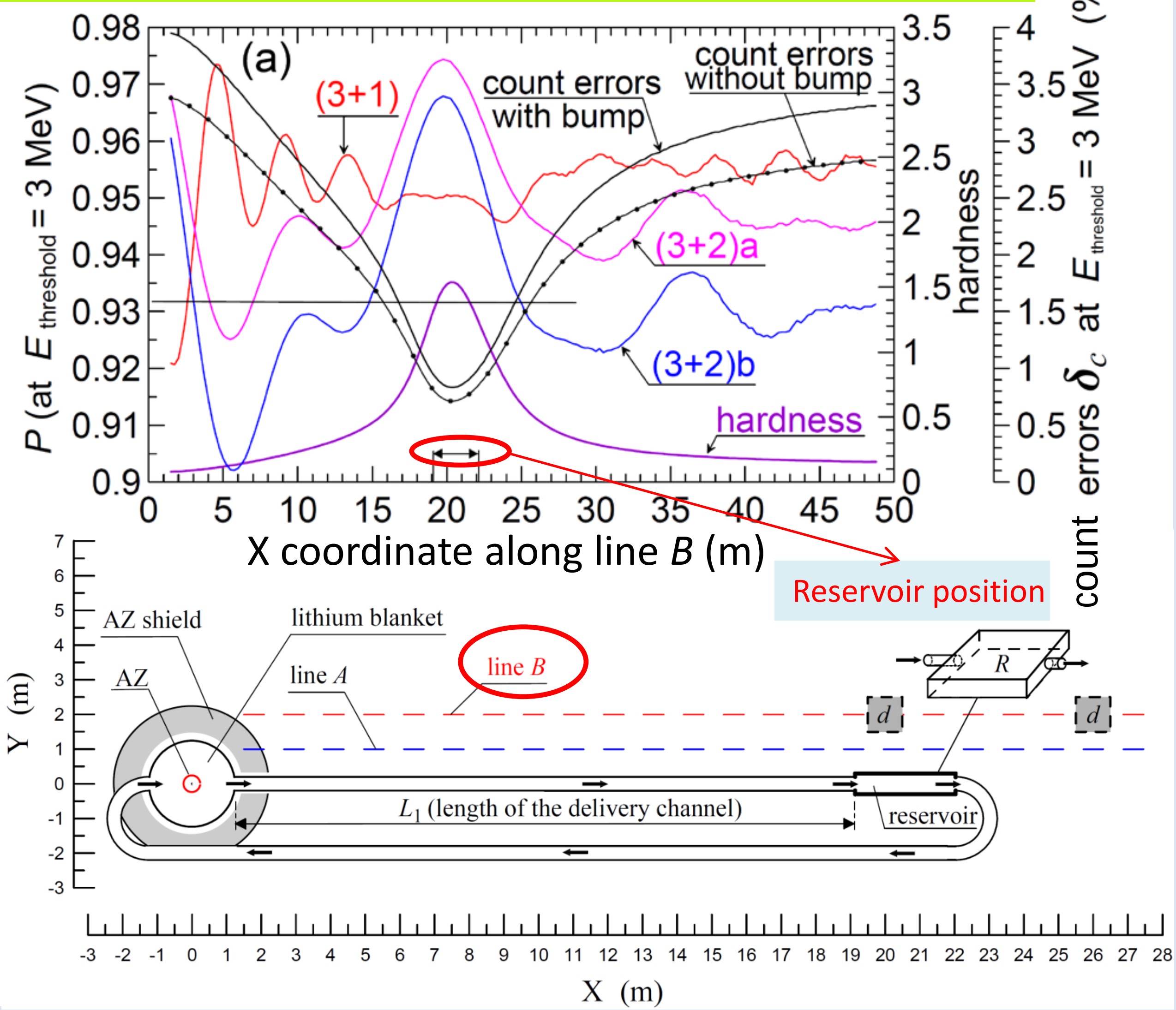
<u>A-line</u> ("d"-detector position *Y*=1 m);

<u>B-line</u> ("d"-detector position *Y*=2 m);

<u>C-line</u> ("d"-detector can be shifted ortogonal to delivery channel



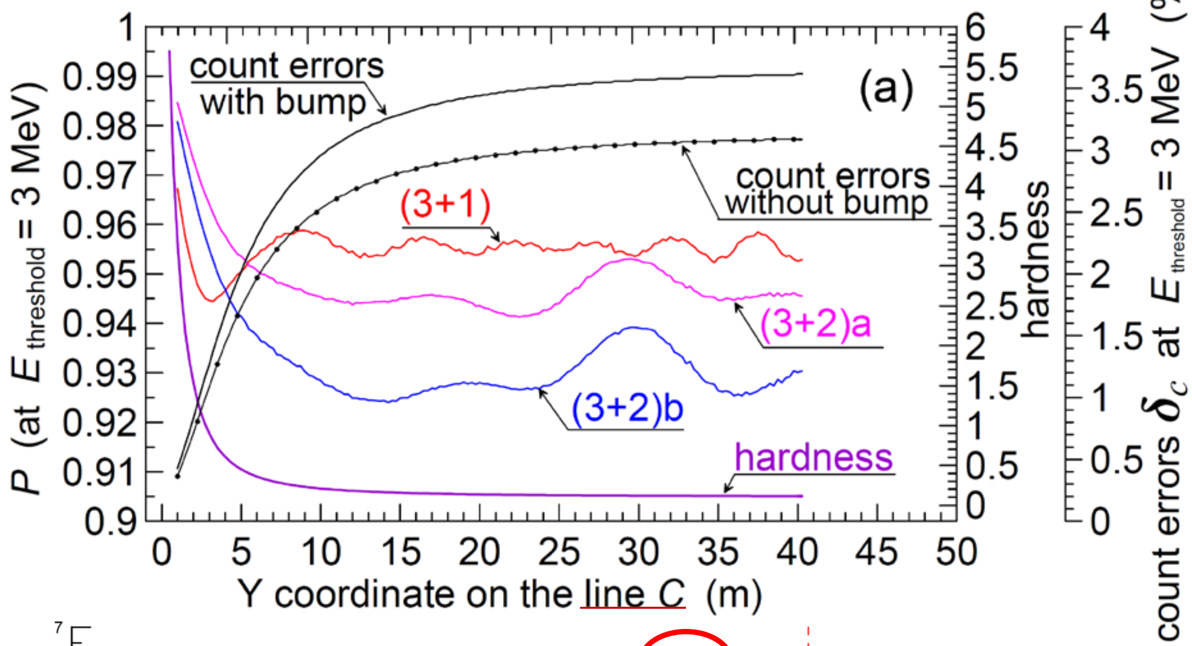
Probability *P* of $\tilde{\nu}_e$ -existence for models: (3+1), (3+2)a, (3+2)b and Opportunity Δ_P of detecting along line *B*. *E* (threshold of $\tilde{\nu}_e$ registration) = 3 MeV

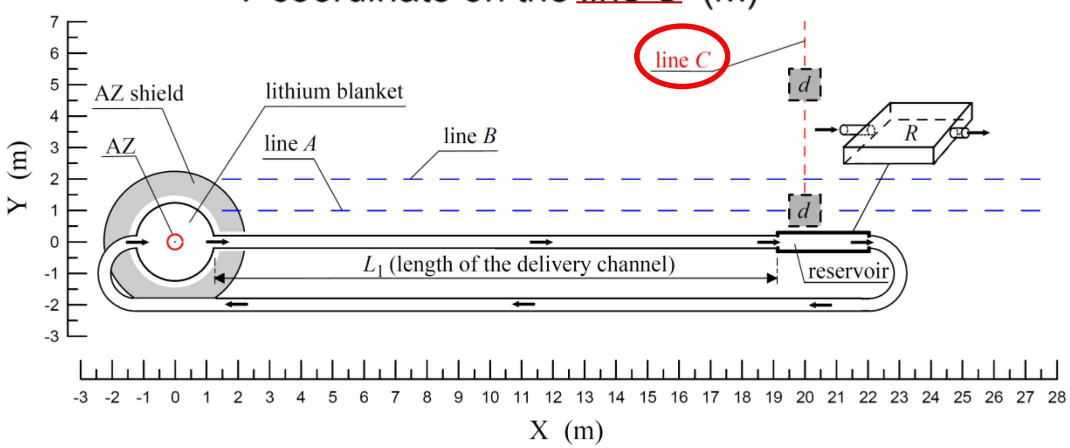


Probability *P* of -existence for three models [(3+1), (3+2)a and (3+2)b on the part (a)], hardness *H* of the total spectrum [part (a)], count errors δ_C (caused by uncerta-inties of AZ spectrum) [part (a)] and functional $\Delta_P(x)$ for opportunity of neutrino detecting [part (b) for models: (3+1), (3+2)a and (3+2)b] depending on the *X* coordinate **along line *B*** *(see geometry of installation)* and w = 2.25m³/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 $\Delta_P(x) = [1 - \delta_C(x_{fix})]\, P(x_{fix}) - [1 + \delta_C(x)]\, P(x)$ 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 = 2.25m³/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} ~20m.

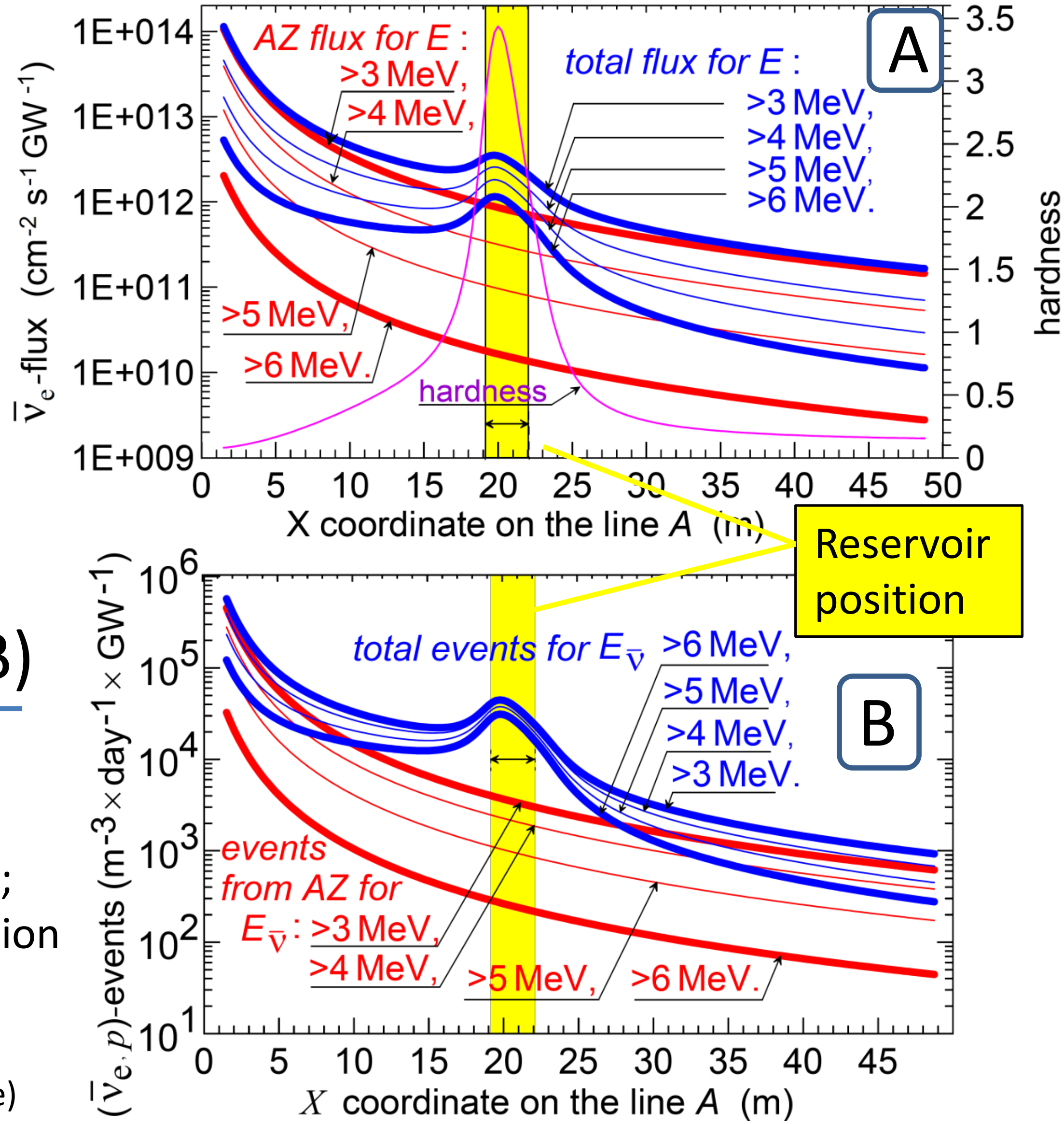
Densities of $\tilde{\nu}_e$-fluxes and number of ($\tilde{\nu}_e$,p) events in the detector

The densities of $\tilde{\nu}_e$-fluxes (A)

[from antineutrinos of active zone (AZ) and from the whole mass of ^{8}Li in the installation] and hardness *H* of the total -spectrum depending on *X*-coordinate along line *A*

and

number of events in the detector (B)



The results obtained for: detector shifted along the A-line; lithium substance – D_2O solution of LiOD, pumped at w=2.25 m^3/s; ^{7}Li purification 0.9999; proton concentration in the detector ~6.6×10^{22} cm^{-3} (as in KamLAND Detector [1]:

(80v% of normal-Dodecane + 20v% of Pseudocumene)

[1] KamLAND RCNS Group collaboration, An overview of the KamLAND 1-kiloton liquid scintillator, ArXiv 0404071

Conclusion

- It was considered and simulated an intense antineutrino source with hard spectrum owing to transfer of created 8Li isotope to the remote detector.
- The source ensures 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 neutrinos with $\Delta m^2 \sim 1$ eV^2 for the models (3+1) and (3+2) basing on the considered antineutrino source with regulated spectrum.
- For the geometry of the discussed antineutrino source it is indicated the space region for search of electron antineutrino disappearance **outside of interval of antineutrino spectrum errors**.

Thank you a lot for attention !