HIGH FLUX ELECTRON ANTINEUTRINO SOURCES BASED ON LI-8 ISOTOPE. THE POSSIBILITY TO CONSTRUCT THE COMPACT VARIANTS

V.I. Lyashuk [1,2]

1) Institute for Nuclear Research of the Russian Academy of Science, Moscow, Russia, 117312
Moscow, Russia
2) National Research Centre "Kurchatov Institute", Moscow, Russia, 123182

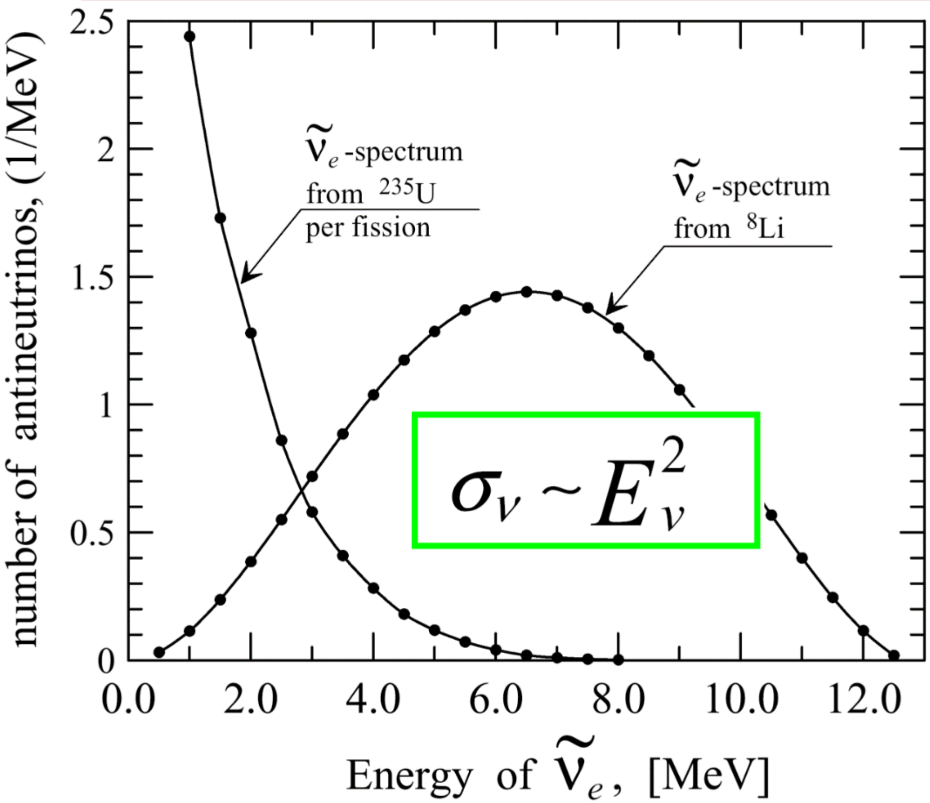
VI International Conference on Particle Physics and Astrophysics (ICPPA-2022), (from the 29th of November to the 2nd of December).
National Research Nuclear University "MEPhI", Moscow, Russia

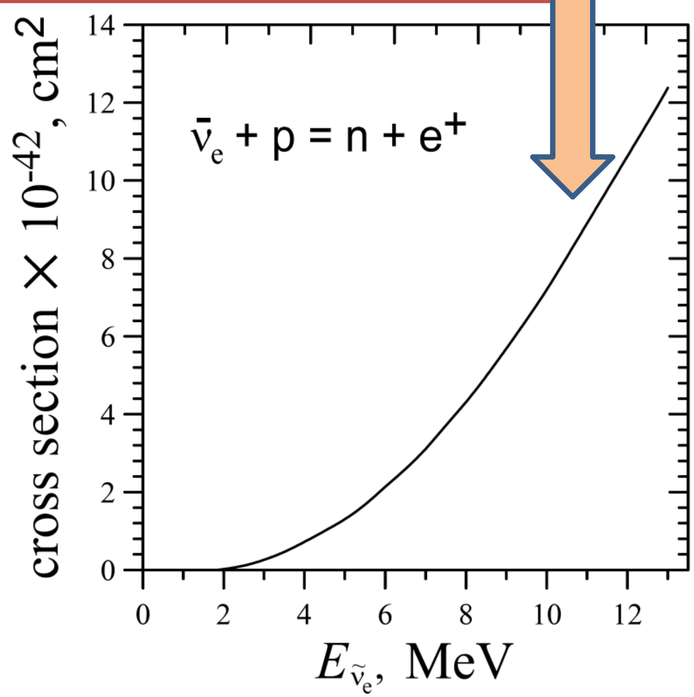
The Conception of the Lithium Antineutrino Source (1)

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

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

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





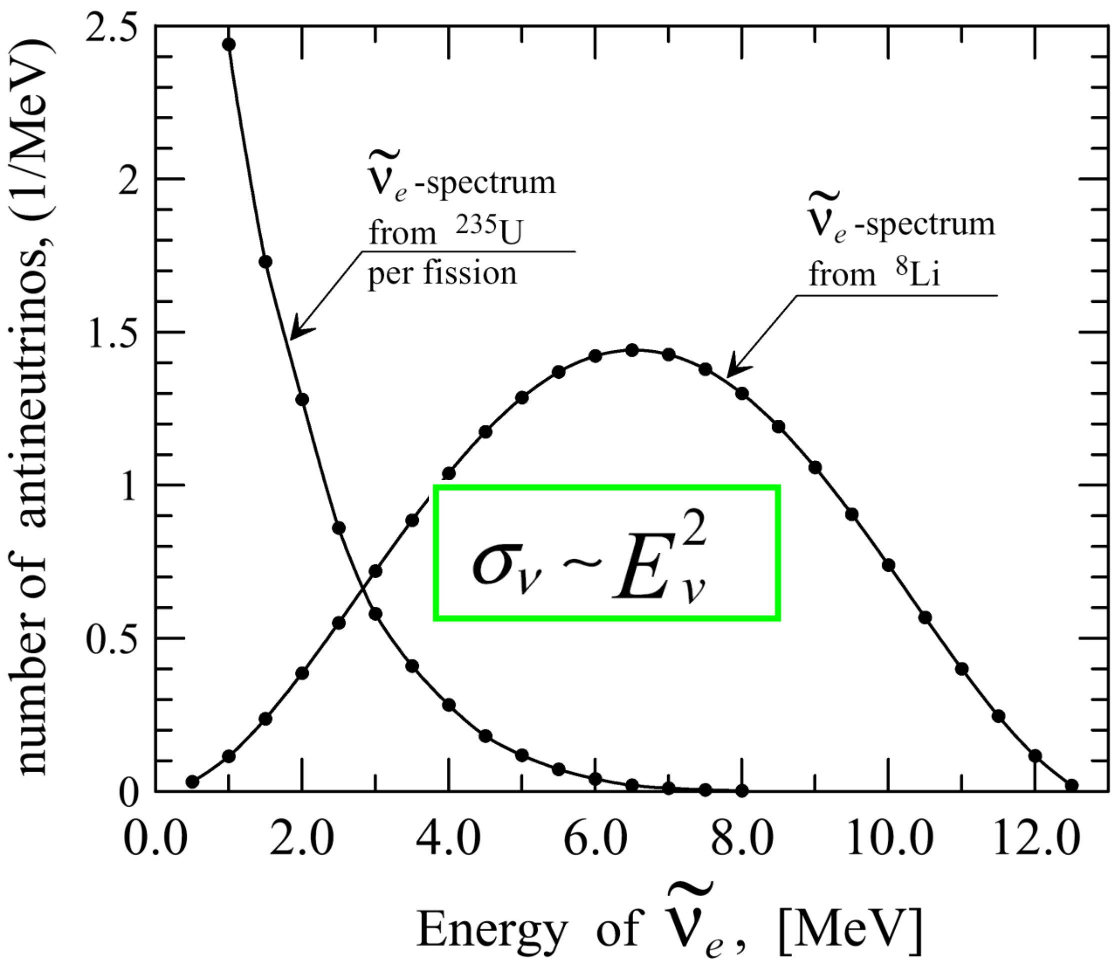
P. Vogel and J.F. Beacom, Phys. Rev. D 60 (1999) 053003

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

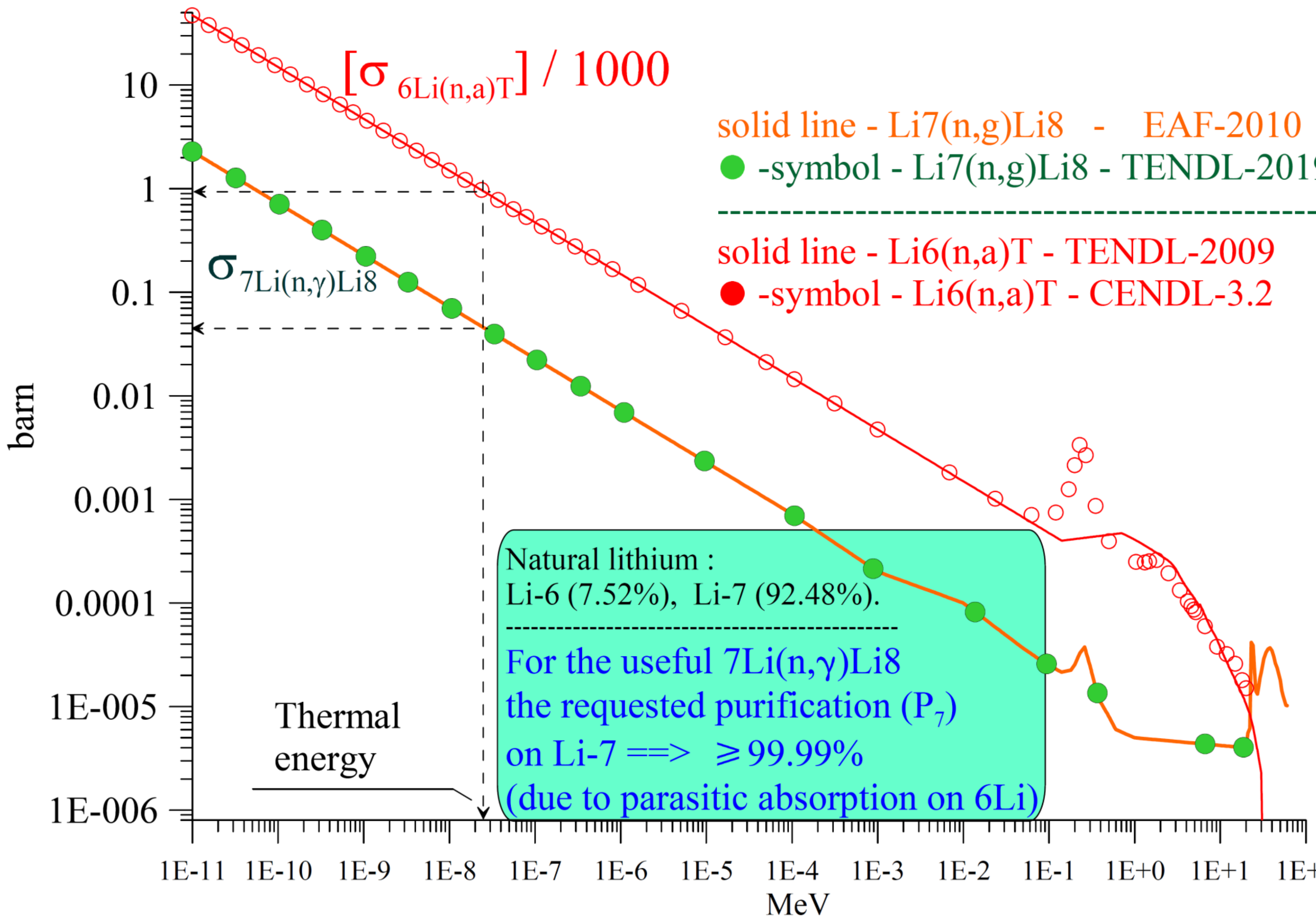


Alongside with the obvious advantage on a neutrino flux the nuclear reactor has a disadvantage – 1) too-small hardness of $\tilde{\nu}_e$ –spectrum and 2) significant errors.

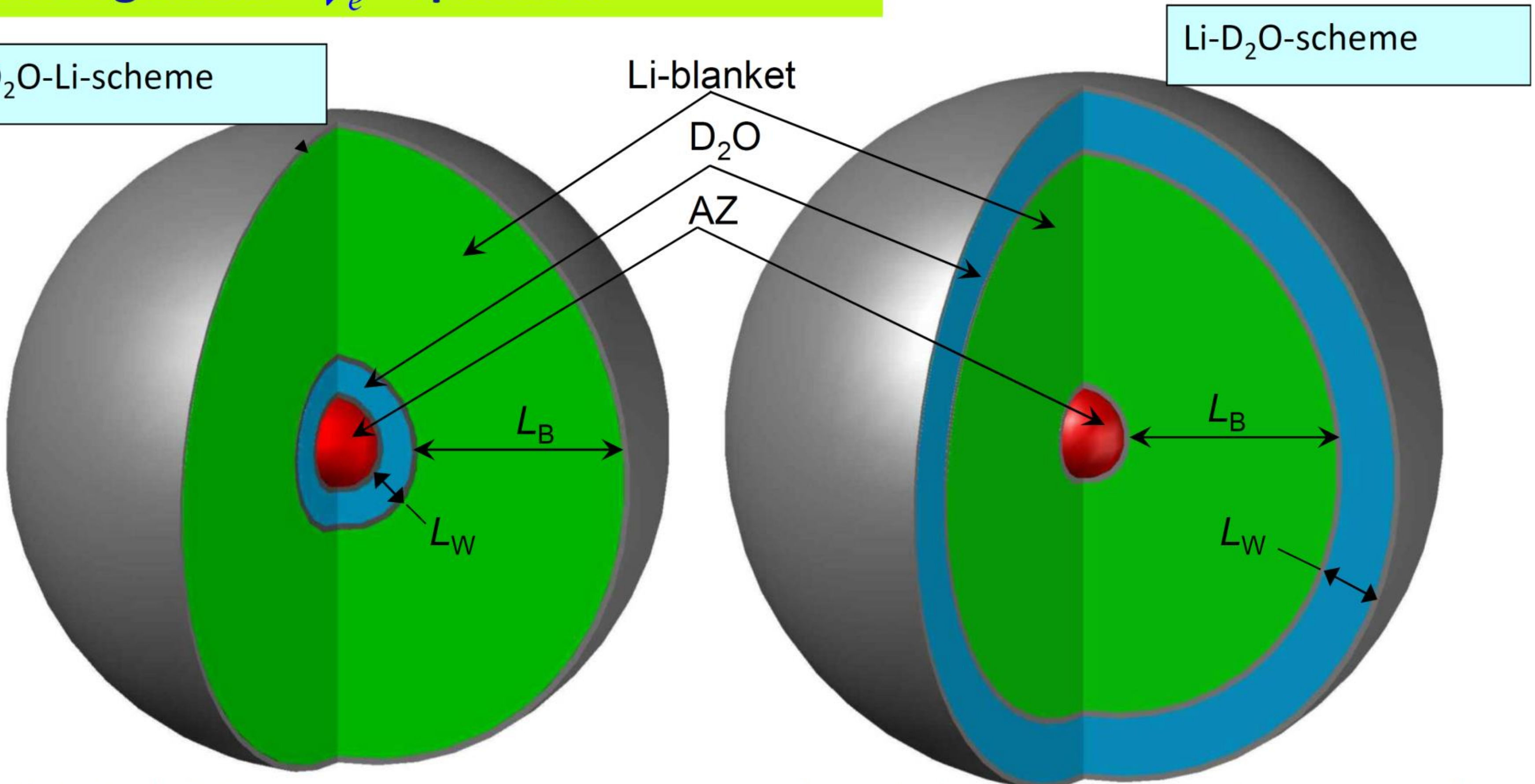
This disadvantage can be filled having realized the idea to use a high-purified isotope of ^7Li for engineering of a neutrons-to-antineutrino Lithium Converter.

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).

Cross section of Li-7 and Li-8.
Requirements for Li-7 purification



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

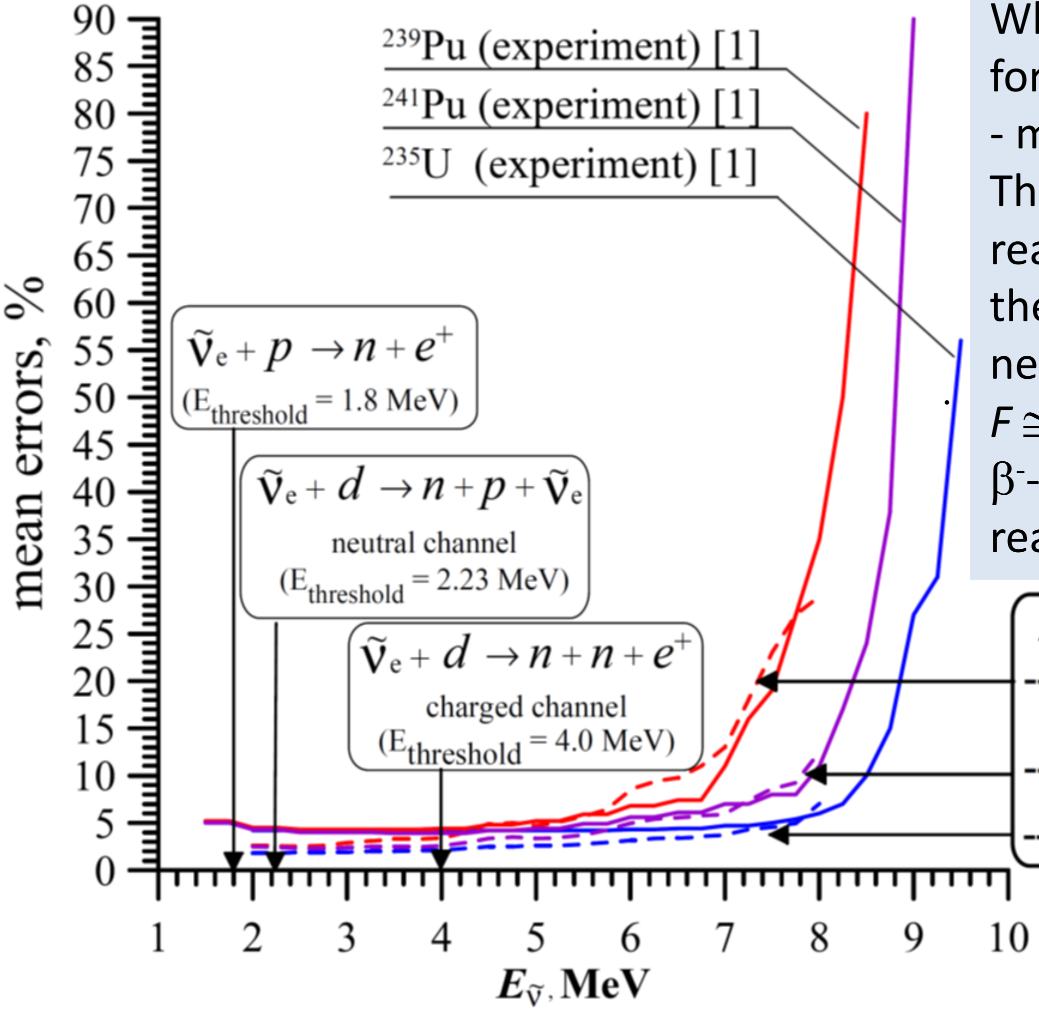
Е.Д.Воробьев, Л.А.Микаэлян, А.И.Назаров, С.М.Фейнберг, Я.В.Шевелев, И.Л.Чихладзе, М.С.Юдкевич. ИМПУЛЬСНЫЙ РЕАКТОР "РИНГ". Препринт ИАЭ, 2384б 1974)

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

$$F[cm^{-2}\cdot s^{-1}]=\bar{n}\,P/4\pi R^2\,\bar{E}=\;1.5\cdot10^{12}\,P[MW]\;/\;R^2[m]$$

Where $\bar{n}\cong 6$ - mean number of β^--decays for both fission fragments of ^{235}U, $\bar{E}\cong 200$ 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.



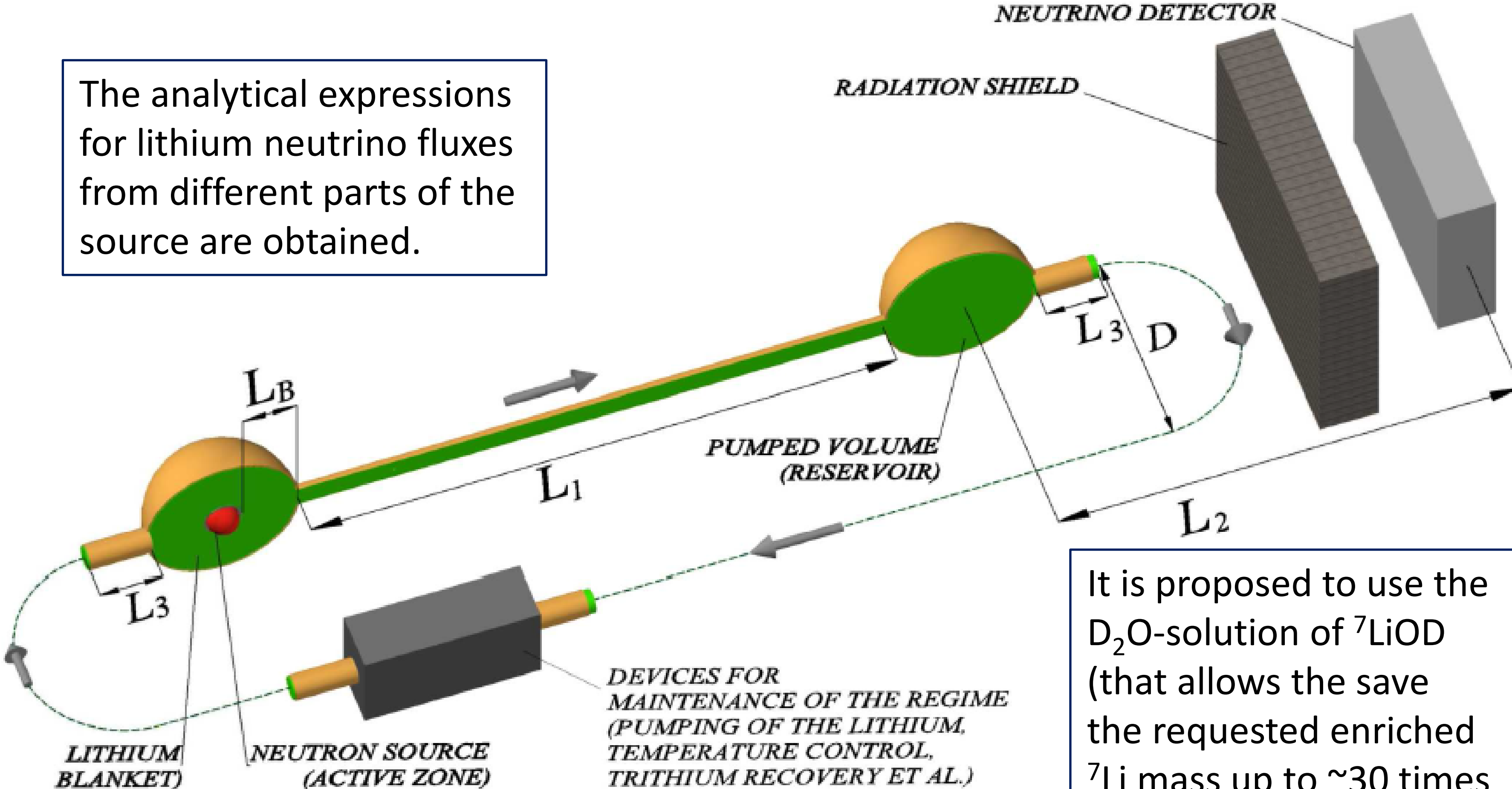
Lyashuk V.I., Lutostansky Yu.S. VarXiv:1503.01280v2

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

The analytical expressions for lithium neutrino fluxes from different parts of the source are obtained.



It is proposed to use the D_2O-solution of ^7LiOD (that allows the save the requested enriched ^7Li mass up to ~30 times

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

The Requirements to the Active Zone

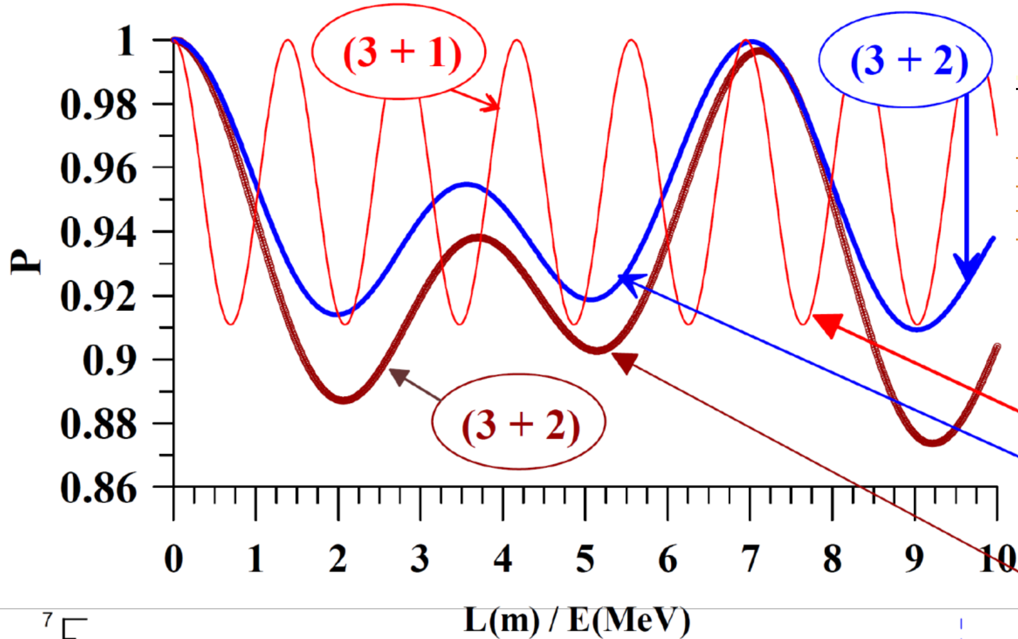
The main fuel - is enriched ^{235}U. The other main fuel isotopes (^{238}U, ^{239}Pu, ^{241}Pu) are excluded to simplify the evaluation of the total neutrino spectrum at burning of the fuel. The advantage of the enriched ^{235}U: the observed distortion of the reactor antineutrino spectrum in the 5-7 MeV can restricted by decay products only single fuel isotope [1]. The next demand to the discussed reactor is the compactness of it's active zone. In this case the the lithium blanket can be shifted more close to the reactor core. It means that the volume of antineutrino source will be more compact too that is very important for precision of oscillation search. The such solution also allows to decrease significantly the requested mass of high purified ^{7}Li.

The possible examples for the discussed reactor are SM, HFBR and PIK research reactors.

reactor	fuel	Volume of the reactor core, liters	Height of the core, cm	eeffective size of the core, cm	Max thermal power, MW	Max thermal neutron flux density	Refe ren-ces
SM	^{235}U, enrichment - 90%	50	35	42x42	100 MW	$5\times10^{15} cm^{-2}s^{-1}$	[2]
HFBR	^{235}U (9.8 kg), higly enriched	~25.4	53	48 (in diameter)	60 MW	$1\times10^{15} cm^{-2}s^{-1}$	[3]
PIK	^{235}U, enrichment - 90%	50	50	39	100 MW	$5\times10^{15} cm^{-2}s^{-1}$	[4, 5]

[1] Hayes A C, Friar J L, Garvey G T, Ibeling Duligur, Jungman Gerard, Kawano T, Mills Robert W. arXiv:1506.00583v2;
[2] http://www.niiar.ru
[3] Shapiro S M, BNL-61645. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/26/074/26074008.pdf
[4] Konoplev K.A. http://www-pub.iaea.org/MTCD/publications/PDF/P1360_ICRR_2007_CD/datasets/K.A.%20Konoplev.html
[5] Aksenov V L Reactor PIK.Present status and trends 2014 *International Workshop "Collaboration and Perspectives of Russian and Chinese Mega Projects" December 3-4, 2014, Dubna, Russia.*

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



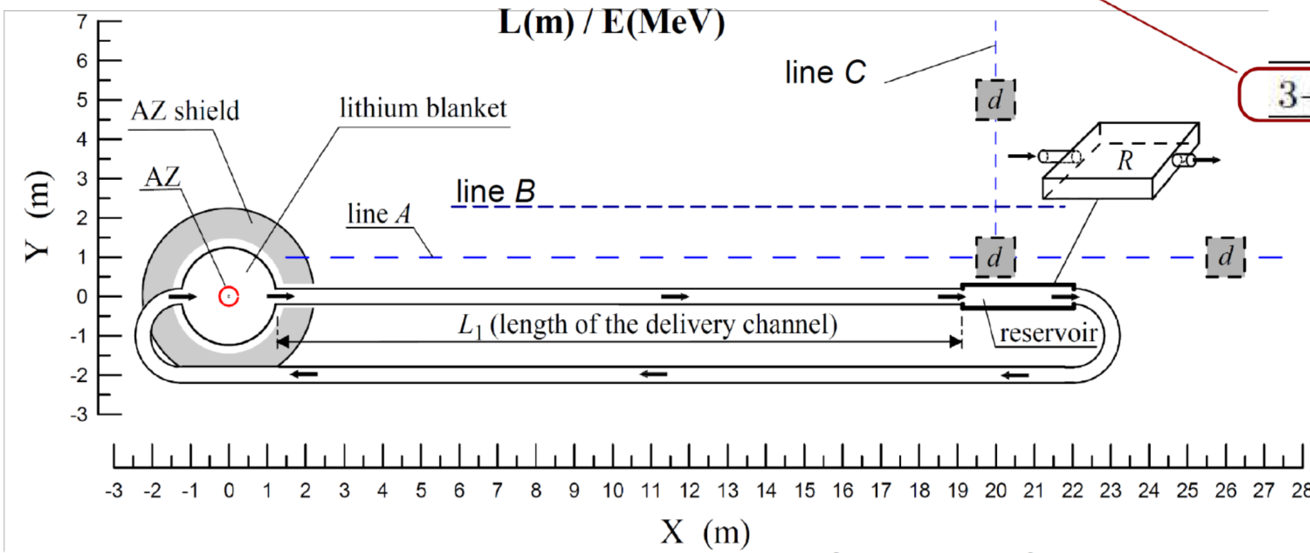
[1]. *Joachim Kopp, Michele Maltoni, and Thomas Schwetz.* Are there sterile neutrinos at the eV scale? arXiv:1103.4570v2 [hep-ex];
[2]. J., Kopp, M. Maltoni, T. Schwetz. Phys. Rev. Lett. 107, 091801, DOI: 10.1103/PhysRevLett.107.091801

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

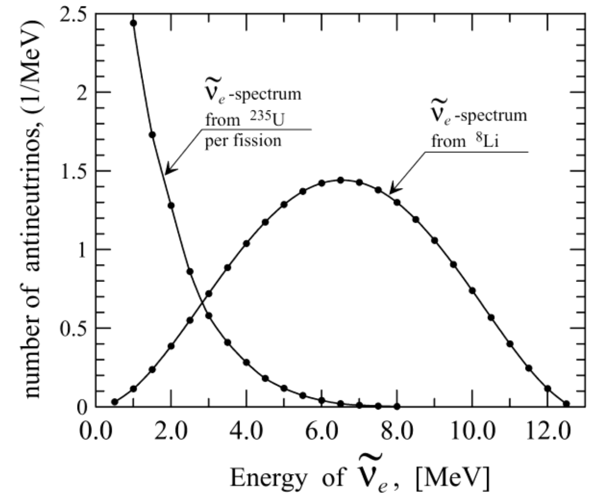


Installation:

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

- densities of lithium antineutrinos flux from the blanket and antineutrino fluxes from the active zone (AZ), $\bar{n}_\nu = 6.14$ - number of reactor $\bar{\nu}_e$ emitted per one fission in AZ.

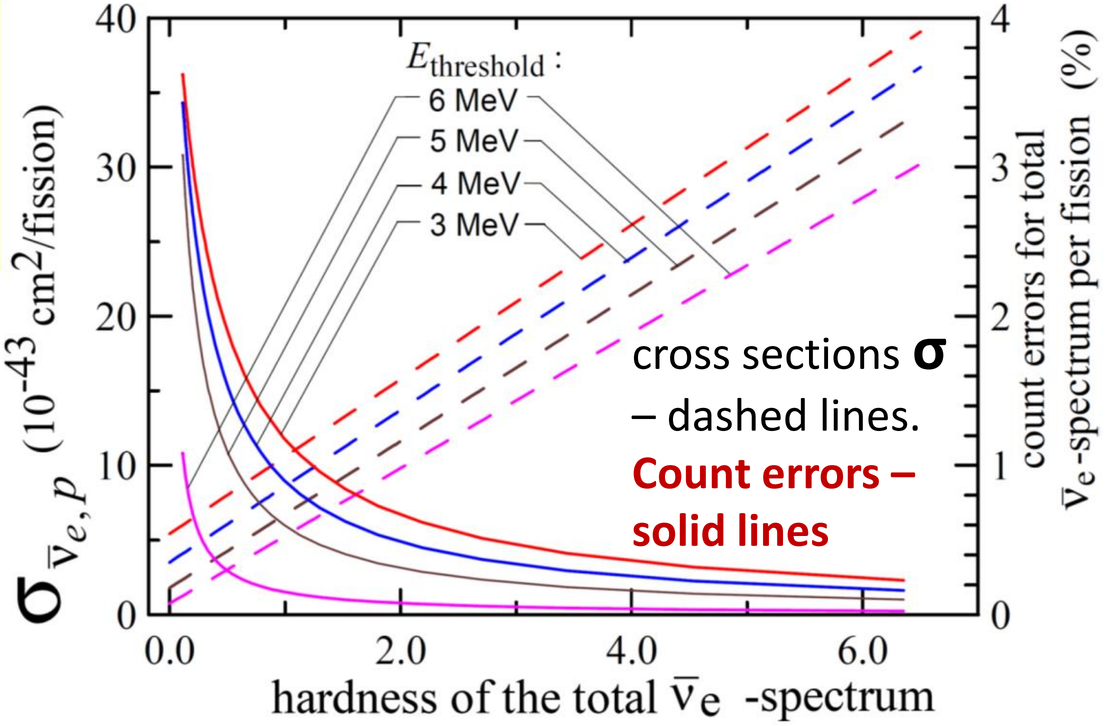
We admit that the hardness of the summary $\bar{\nu}_e$- spectrum at the point $\vec{r}$

<u>equals one unit of hardness</u> if the ratio of densities is: $$\frac{F_{\mathrm{Li}}(\vec{r})}{F_{AZ}(\vec{r})} = \frac{1}{\bar{n}_\nu}$$

Then the generalized hardness of the total spectrum is: $$H(\vec{r}) = \bar{n}_\nu \frac{F_{\mathrm{Li}}(\vec{r})}{F_{\mathrm{AZ}}(\vec{r})}.$$

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

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

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

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

where $F_{\mathrm{AZ}}(\vec{r})$ - 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:

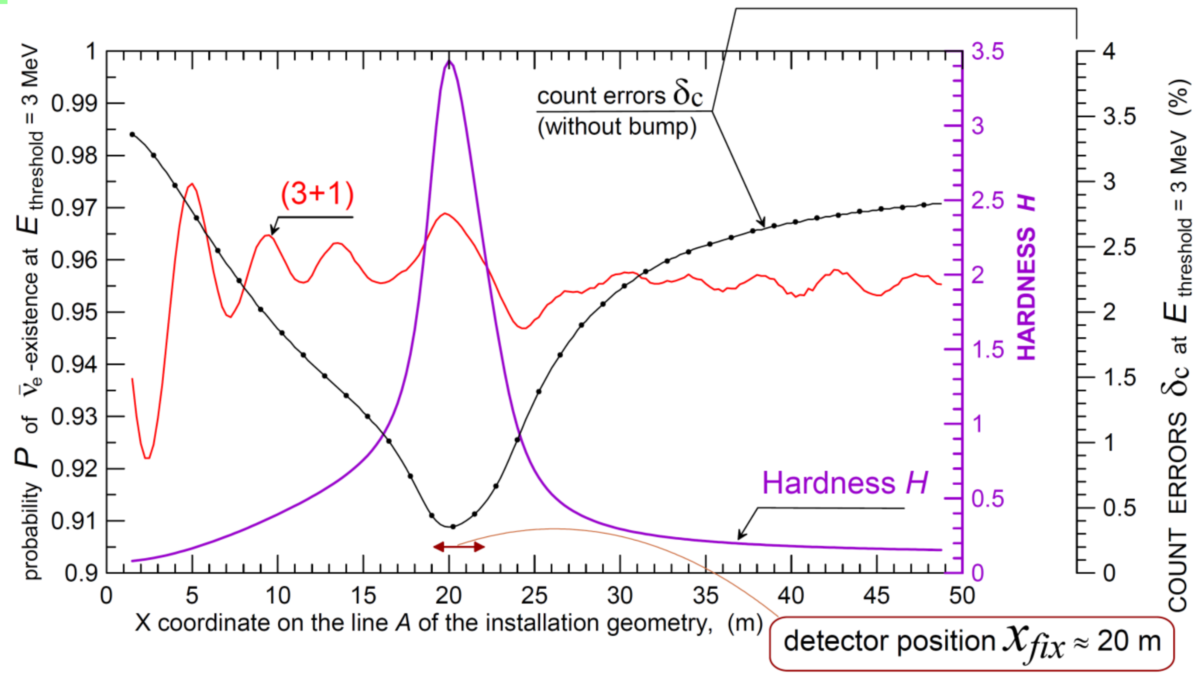
$$\sigma_{\bar{\nu}_e\mathrm{p}}(\vec{r}) = \sigma^{\mathrm{AZ}}_{\bar{\nu}_e\mathrm{p}} + H(\vec{r}) \times \sigma^{\mathrm{Li}}_{\bar{\nu}_e\mathrm{p}}.$$

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 $E_{\mathrm{threshold}}$ = 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**

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

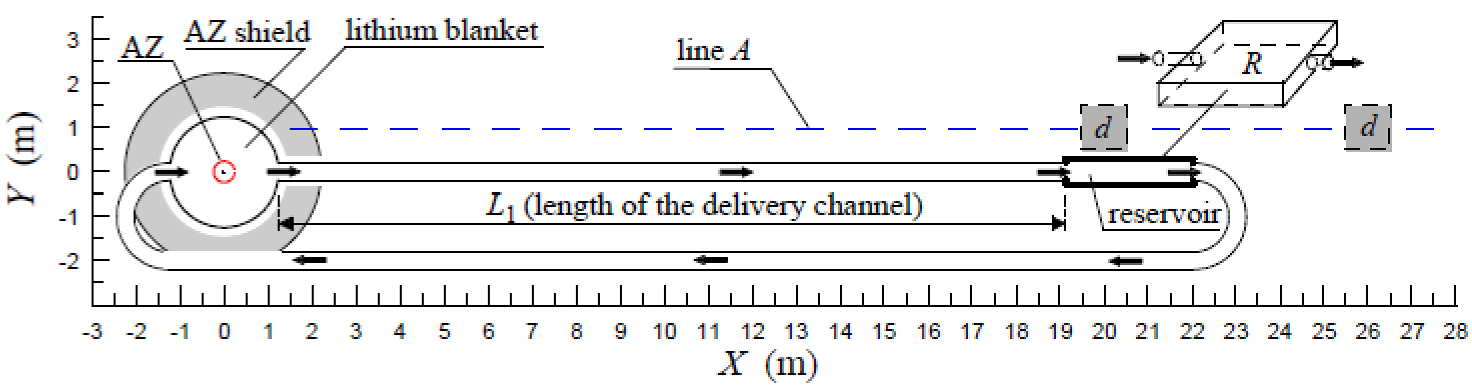
For evaluation of possibility to detect oscillation $\overline{\nu}_e$ to sterile neutrinos depending on Coordinates, let us introduce the functional $\Delta_p(x)$ for opportunity of registration.

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 ($x_{fix} \approx 20$ m).

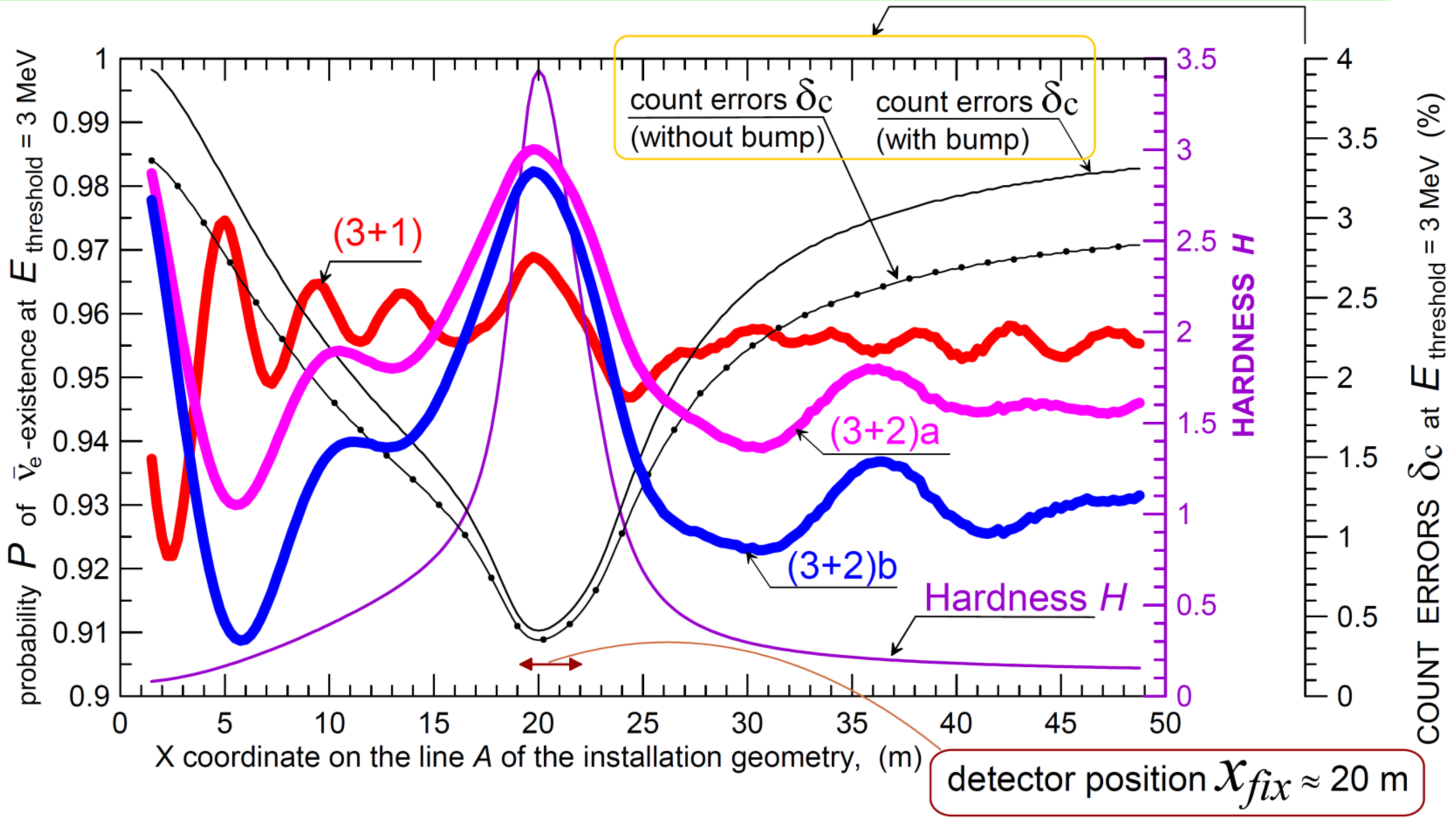


Parameters for (3+1) model model [1]:

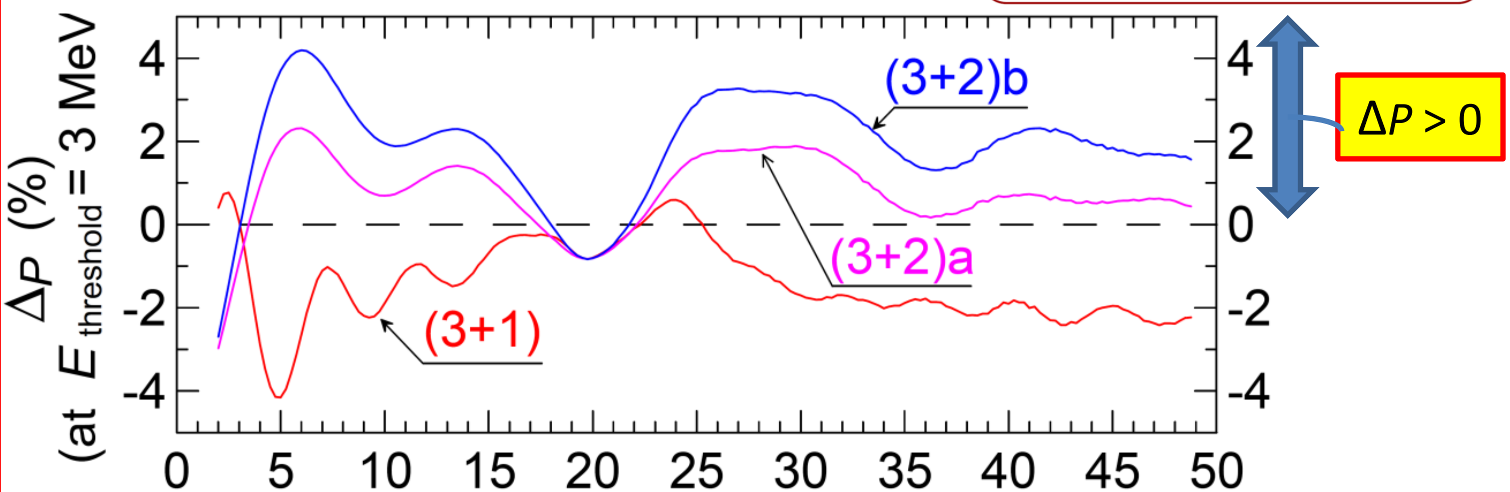
[1] J., Kopp, M. Maltoni, T. Schwetz Phys. Rev. Lett. 107, 091801, DOI: 10.1103/ PhysRevLett.107. 091801

Best fit data for (3+1) - in Table I; for (3+2)a and (3+2)b –in Table II

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. **<u>Positive Δ*p*-functional</u>** values indicate X-coordinates where Δ*p*(x) is higher to level-of-total-spectrum-errors



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

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*

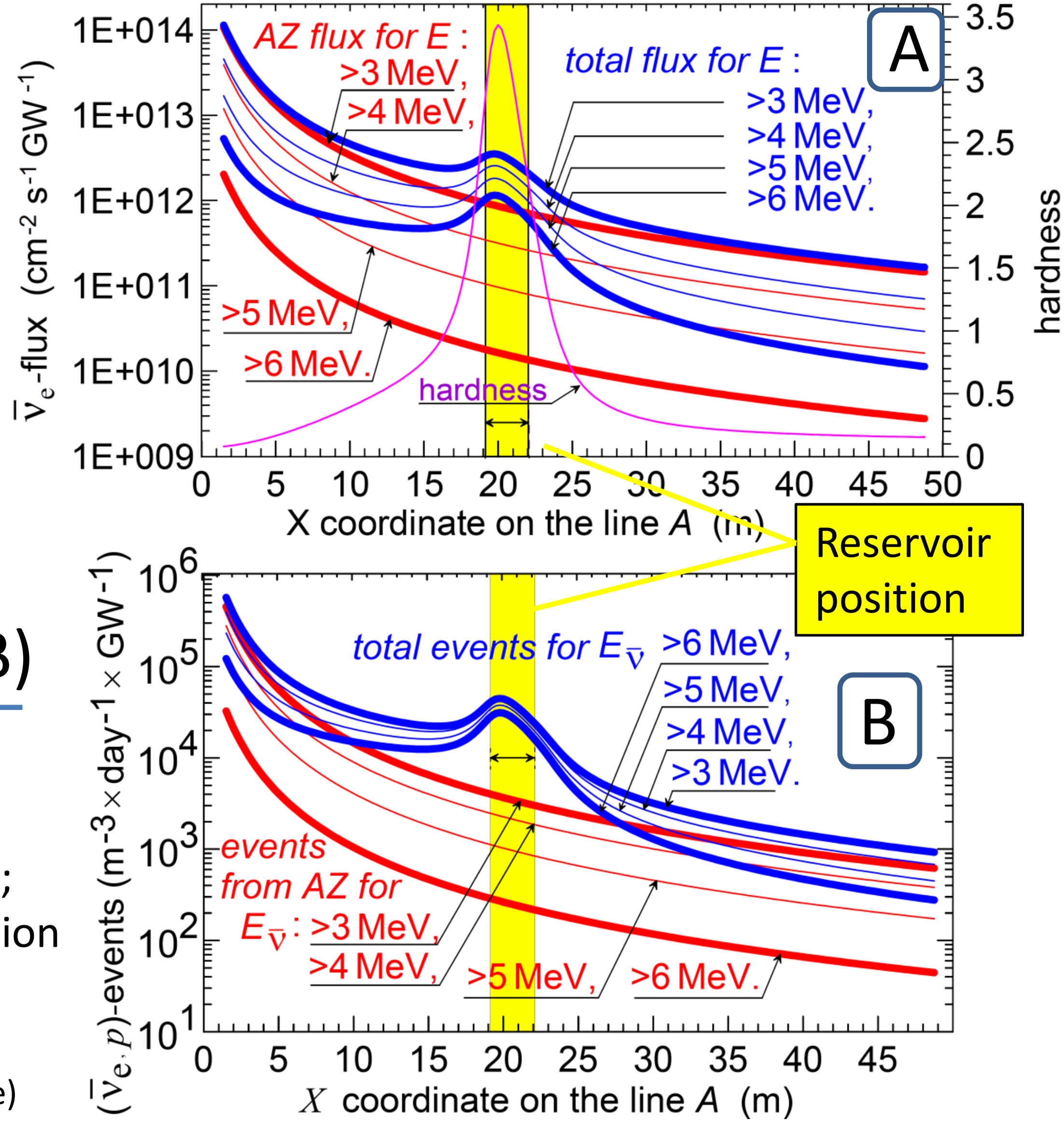
and

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

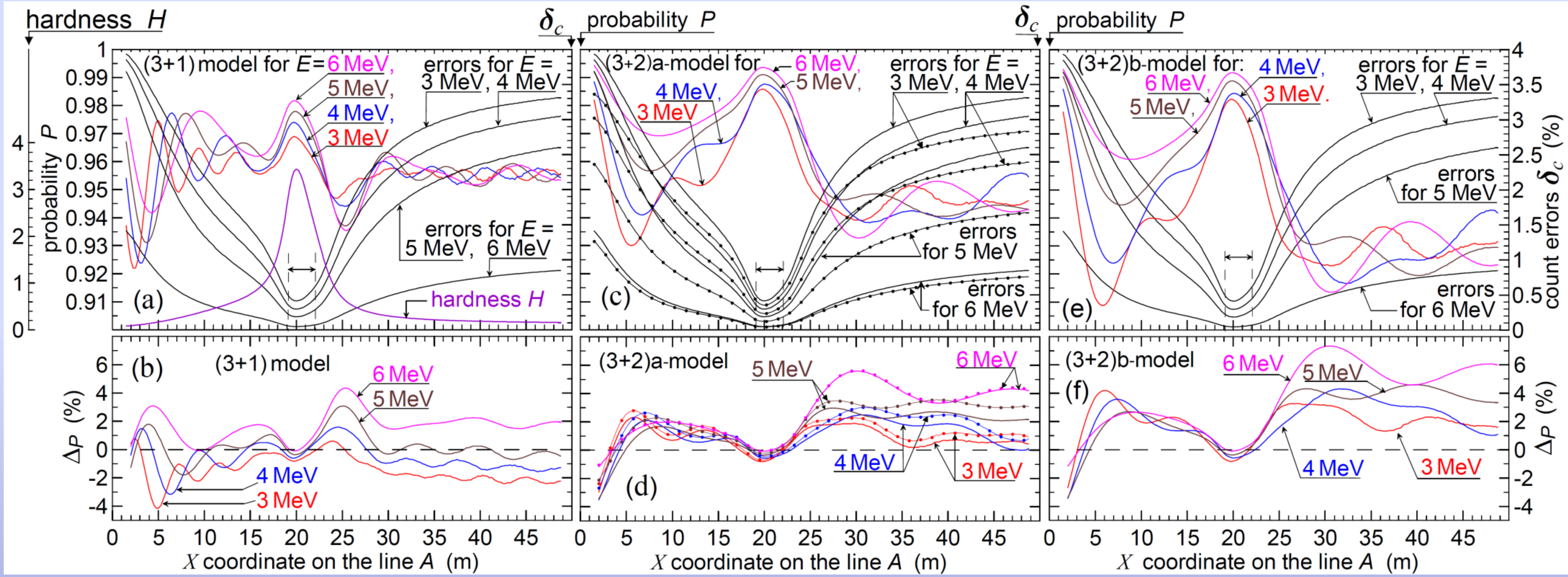


Lithium $\tilde{\nu}_e$ -flux strongly dominates over the active zone neutrinos thank to geometrical factor (detector position) and transfer of lithium in the close loop.

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

Opportunity 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 A-line geometry [1]



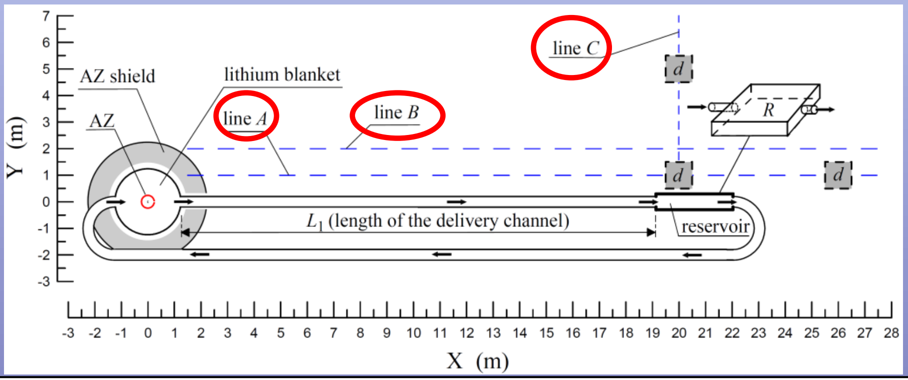
[1] V.I.Lyashuk, JHEP06(2019)135

The investigated geometry:

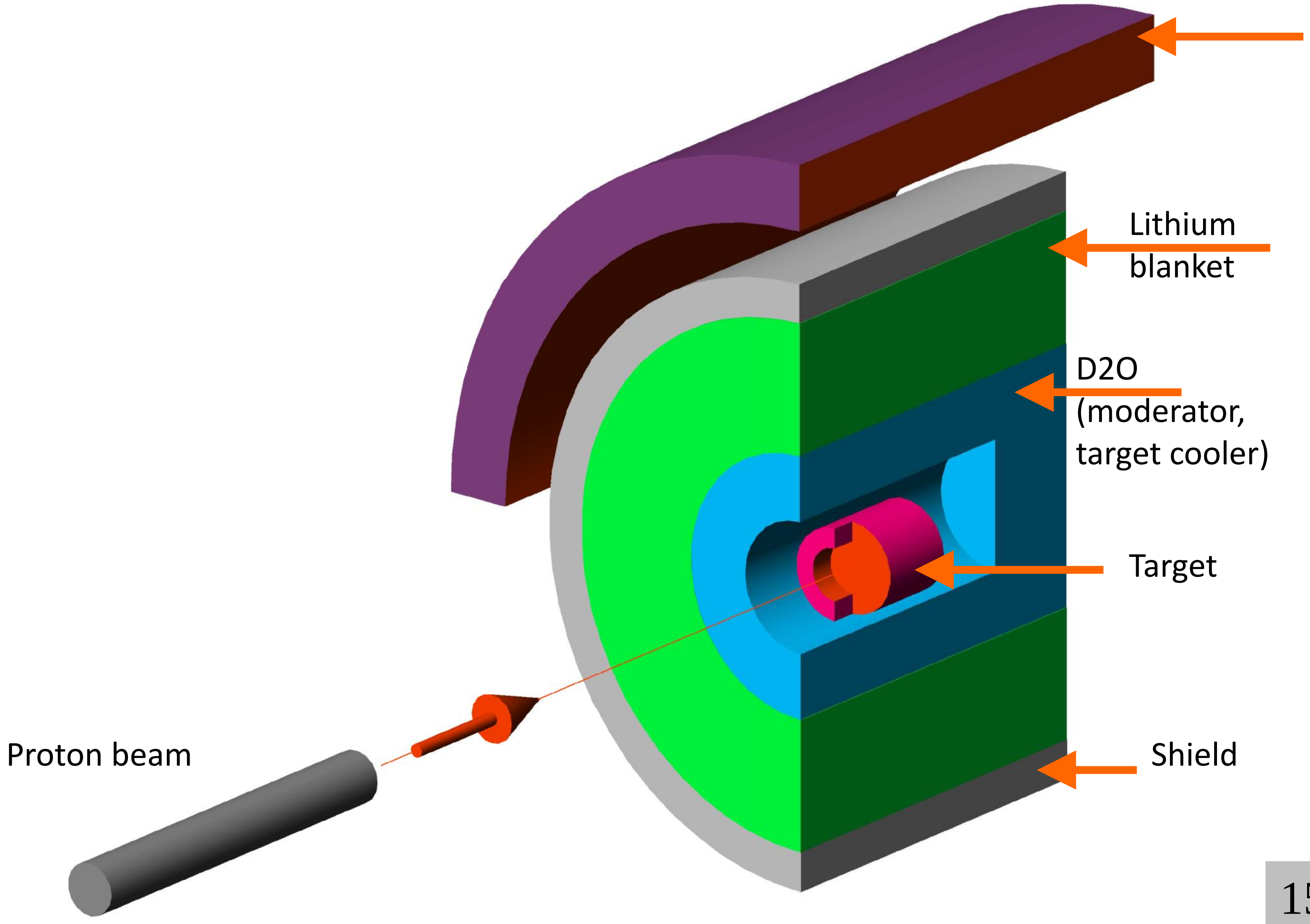
***A*-line** ("d"-detector position *Y*=1 m);

***B*-line** ("d"-detector position *Y*=2 m);

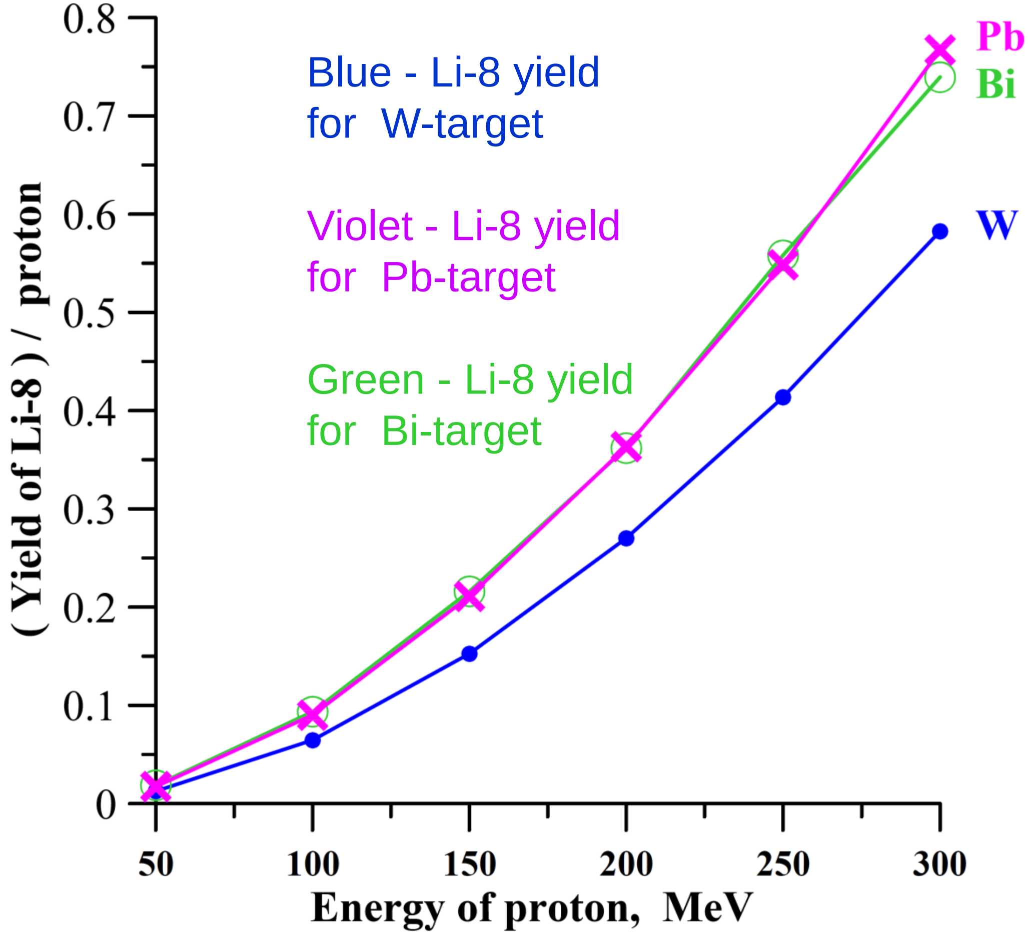
***C*-line** ("d"-detector can be shifted ortogonal to delivery channel

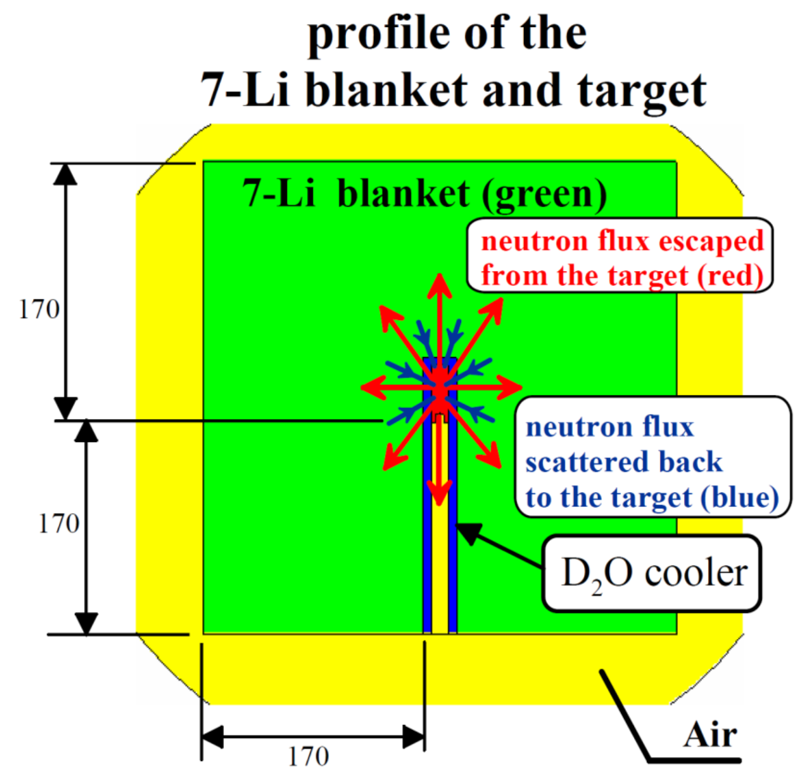


Accelerator scheme of the Li-8 antineutrino source (1).



Accelerator scheme of the Li-8 antineutrino source (2). Yield of Li-8 in case of W, Pb and Bi-targets.

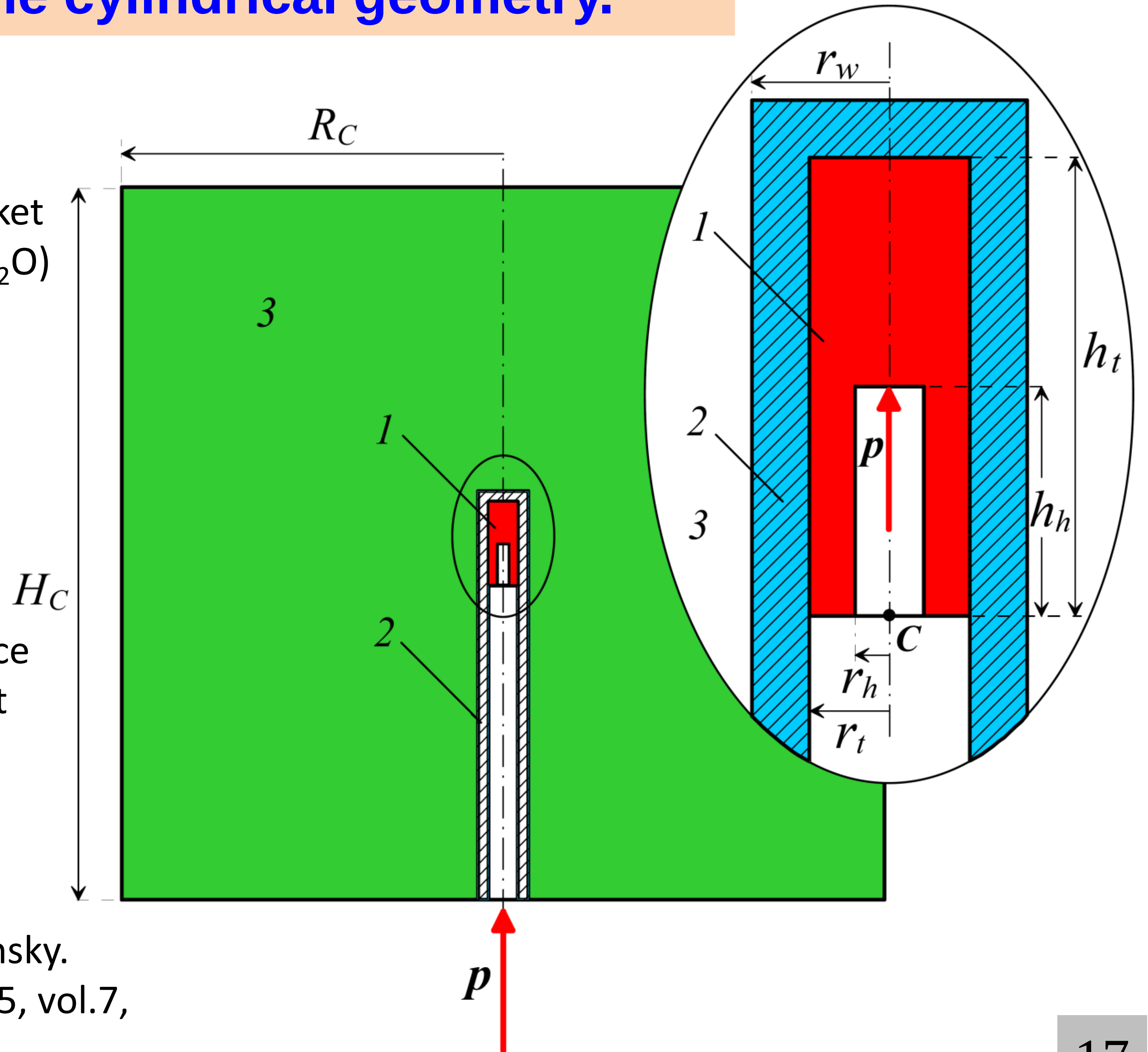




Accelerator scheme of the Li-8 antineutrino source (3). The cylindrical geometry.

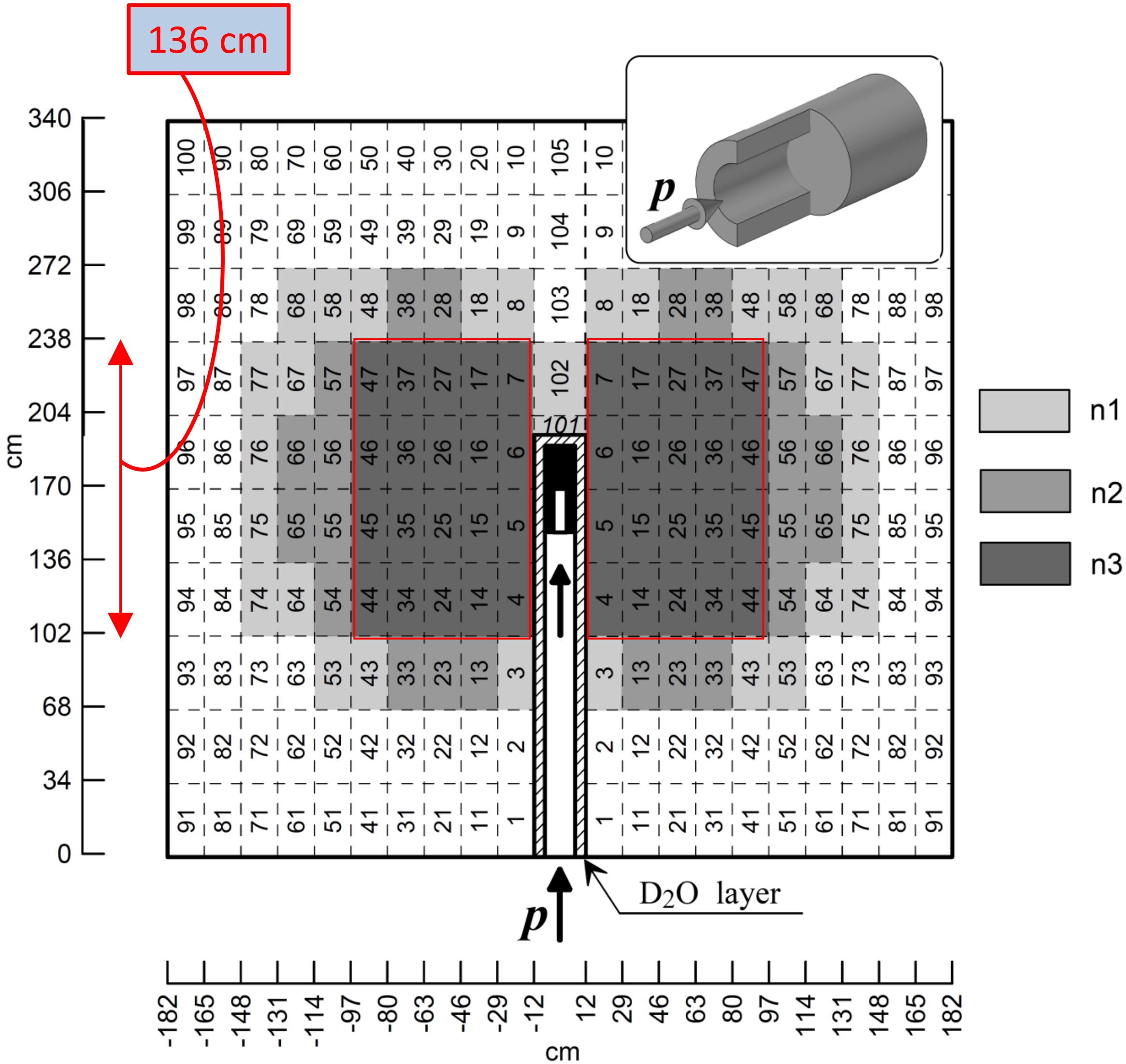
1 - W-target
2 - D_2O-channel
3 - LiOD-volume (lithium blanket with LiOD 9.46% solution in D_2O)
H_c=338 cm
R_c = 182 cm
h_t = 30-40 cm
Ep = 200 MeV

k_p ~ 0.26 (Yield of Li-8 per proton)
(2.1E+23 – antineutrino fluence during 5 years at 1 mA current and for the 80% of used time of the accelerator)



V.I. Lyashuk and Yu.S. Lutostansky. Bull. Russ.Acad. Sci. Phys, 2015, vol.7, p.431–436.

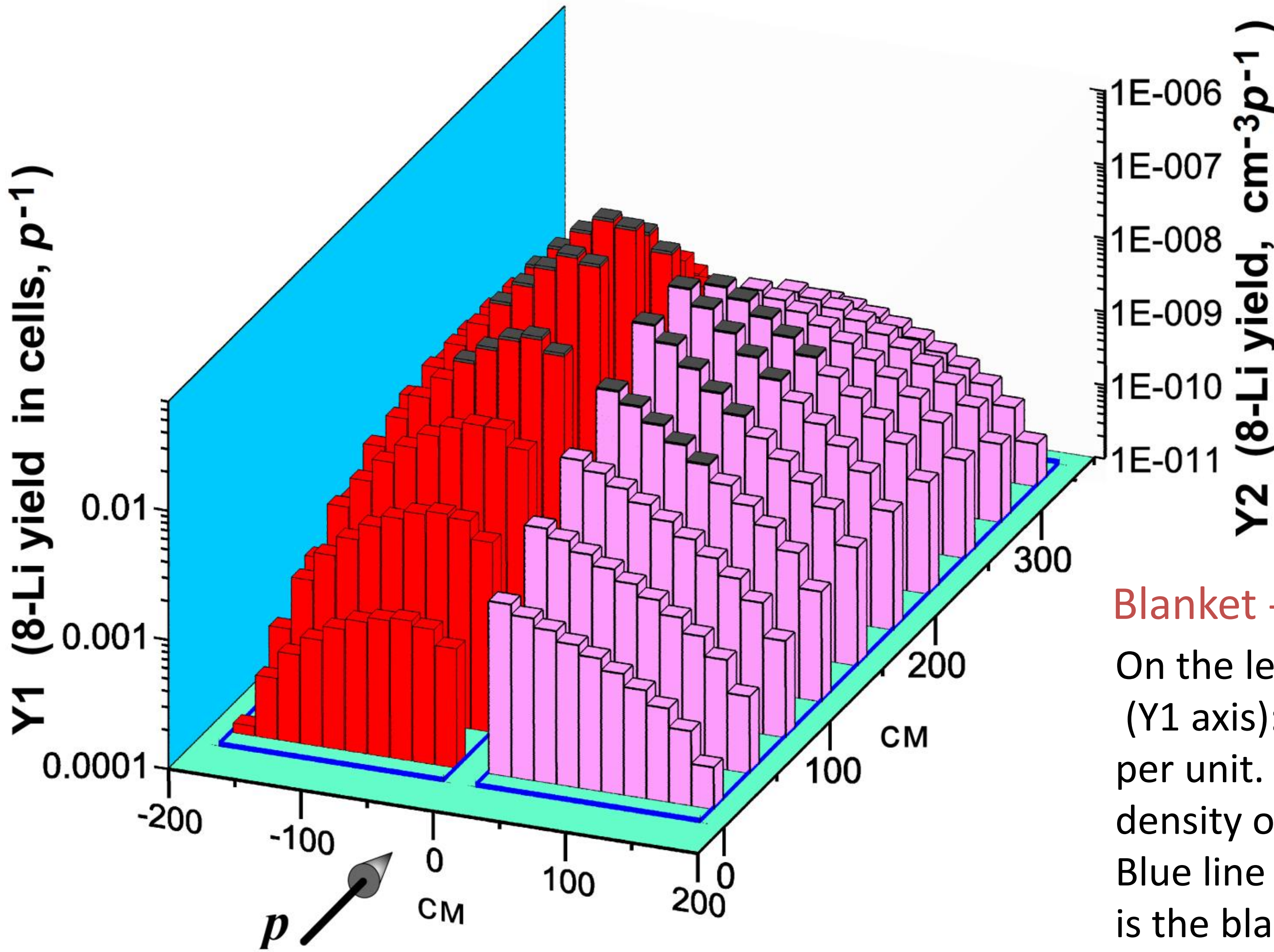
Accelerator scheme of the Li-8 antineutrino source (4). Geometry of the lithium blanket, proton beam channel and tungsten target.



The boundaries of 105-cylindrical-cells in the blanket volume are indicated as dashed lines.
The volume regions corresponding to 90%, 80% and 68% yields (of the total 8Li yield in the blanket volume) are shown by halftones (as n1, n2, n3).
The data are obtained for proton energy 200 MeV.

Lyashuk V. I. // Results in Physics, v6, 2016, p 961; Lyashuk V. I. arXiv:1609.02127. 2016

Accelerator scheme of the Li-8 antineutrino source (6).
Histograms for Density of Li-8 yield and Li-8 yield in the cells.

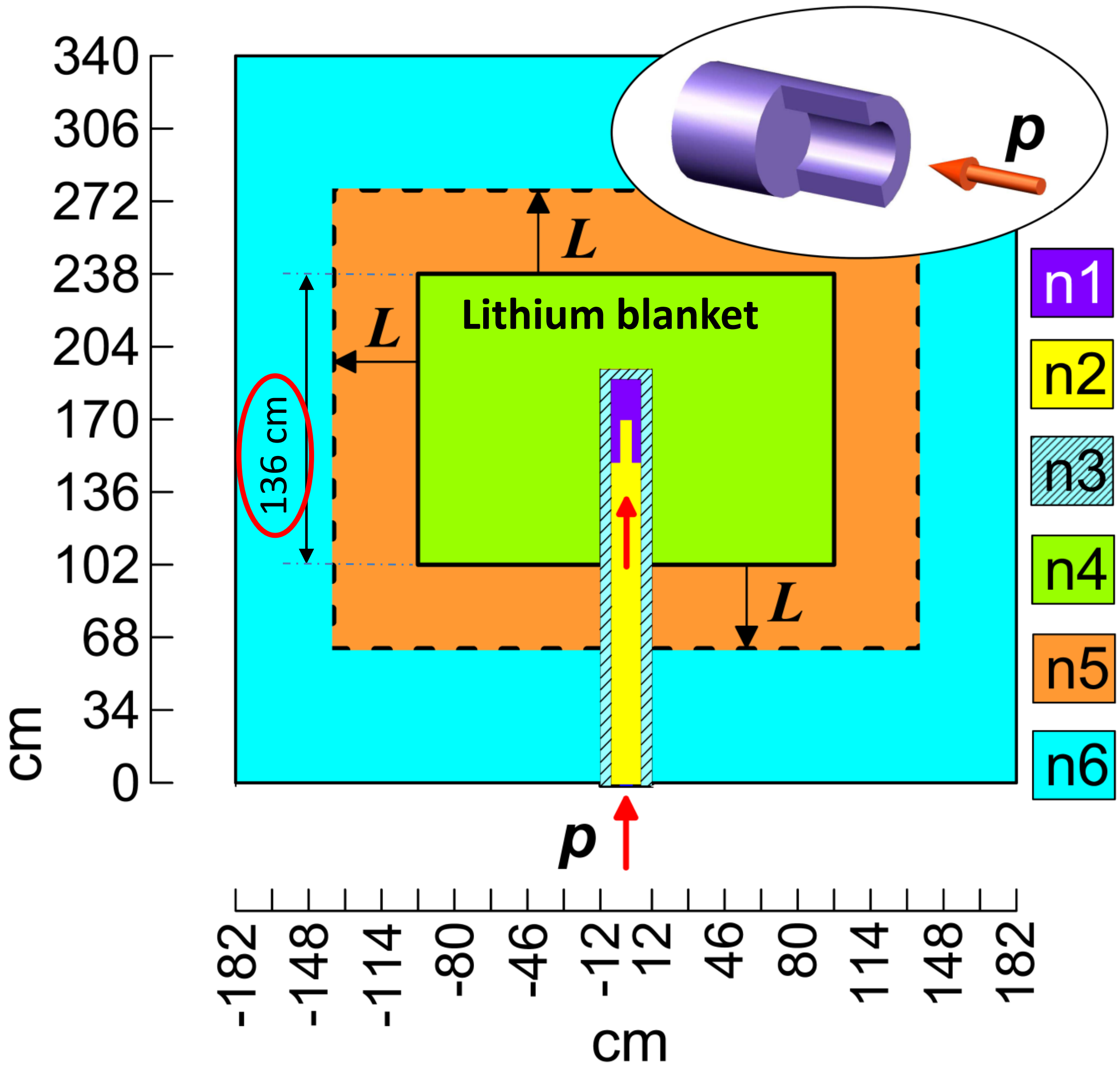


Blanket - 9.5% LiOD solution

On the left to the proton beam (Y1 axis): 8Li yield normalized per unit. On the right (Y2 axis): density of 8Li yield.
Blue line on the horizontal plane is the blanket cross section.
Histograms with black top correspond to 68% of total 8Li yield in the blanket.

Lyashuk V.I. Result in Physics, 2016. 6. 961.
Lyashuk V.I. arXiv:1609.02127 [physics.ins-det]. 2016.

Accelerator scheme of the Li-8 antineutrino source (7). Geometry for decrease of the lithium blanket dimension.



Lyashuk V. I. // Results in Physics. V.6, 2016, p. 961.

Cross section of the lithium blanket:
n1 – target,

n2 – empty channel,

n3 - D2O cooler,

n4 – lithium blanket,

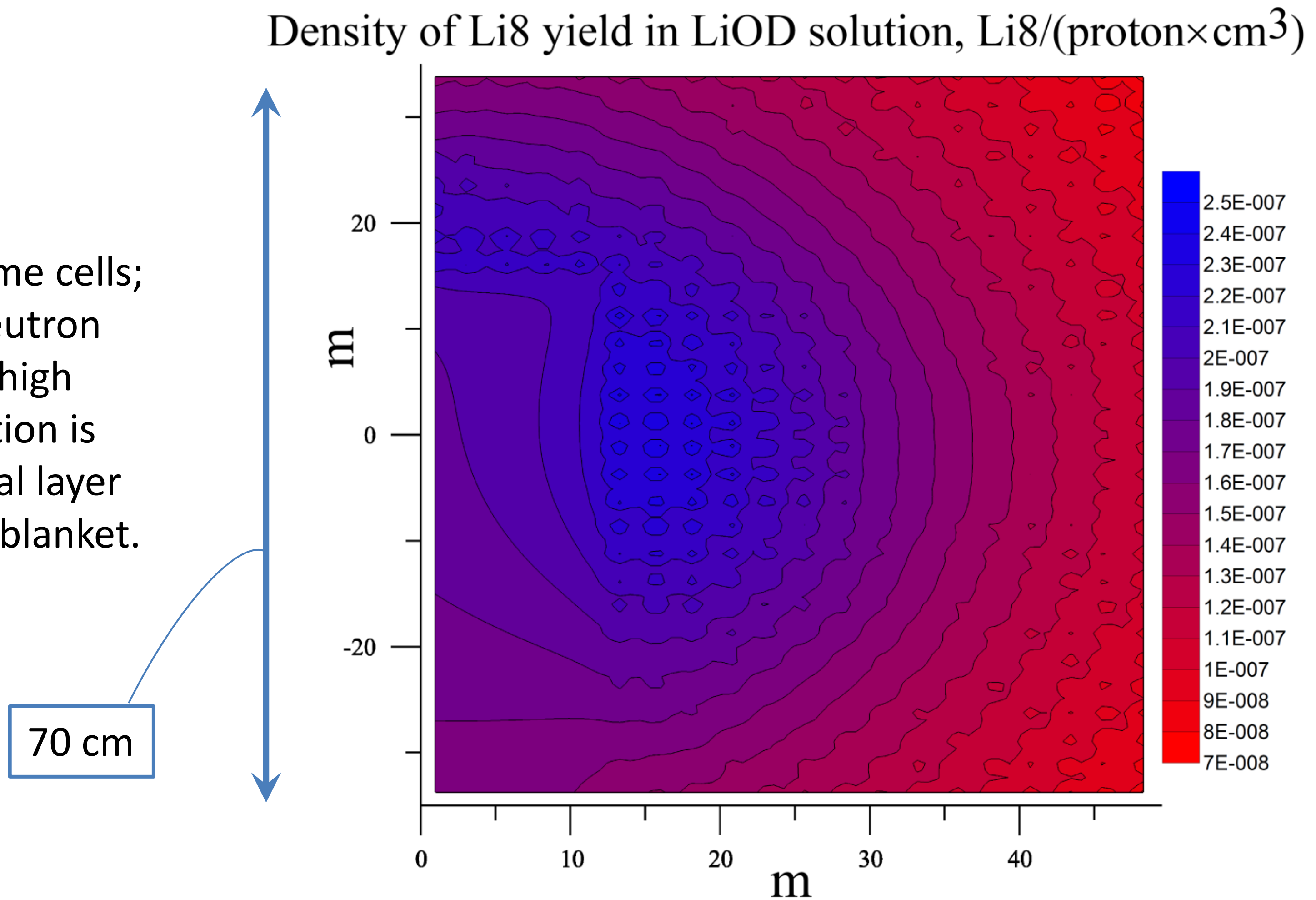
n5 – carbon layer of variable thickness *L*,

n6 – water (D2O or H2O).

For decreased dimension the k_p ~ 0.175 (Yield of Li-8 per proton at Ep=200 MeV; i.e., 65% (**<u>very close</u>** to the expected 68% of the initial efficiency k_p= 0.27)

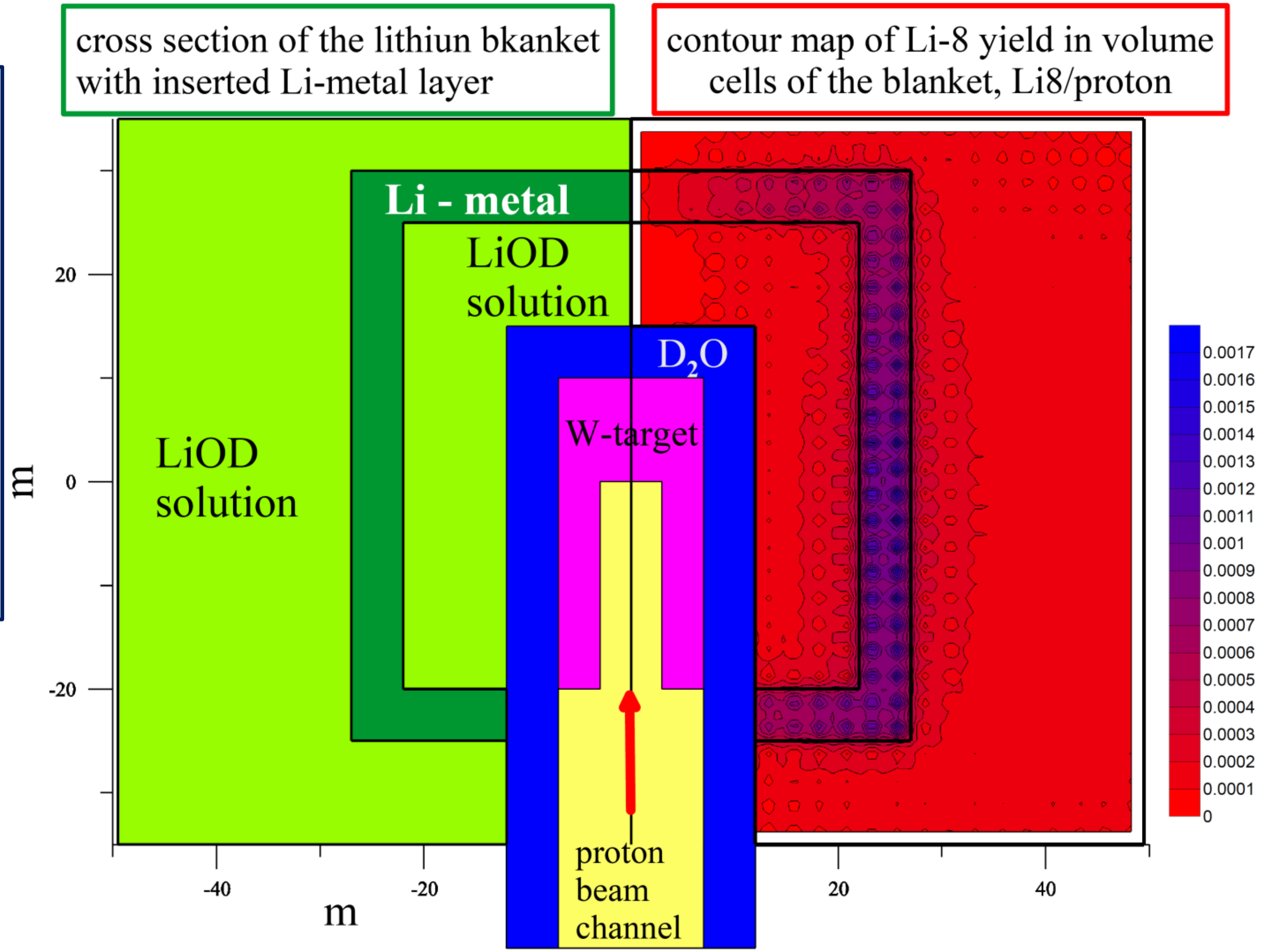
Accelerator scheme of the Li-8 antineutrino source (8). The proposed solution to create an effective Li-8 antineutrino source with diminished dimensions.

- Analysis of the Li-8 production in the volume cells;
- In case of effective neutron moderation the more high rate of $^7Li(n,\gamma)Li8$ creation is ensured by thin Li-metal layer inserted in the lithium blanket.

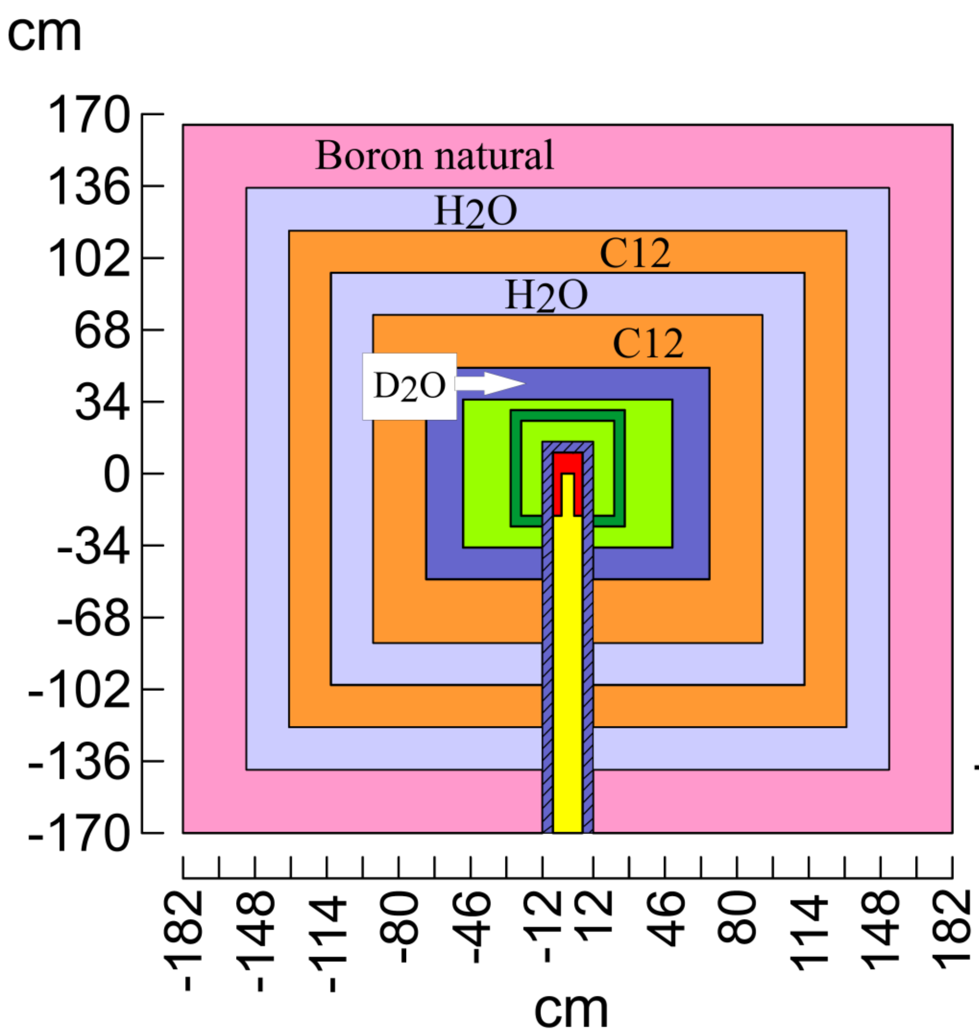


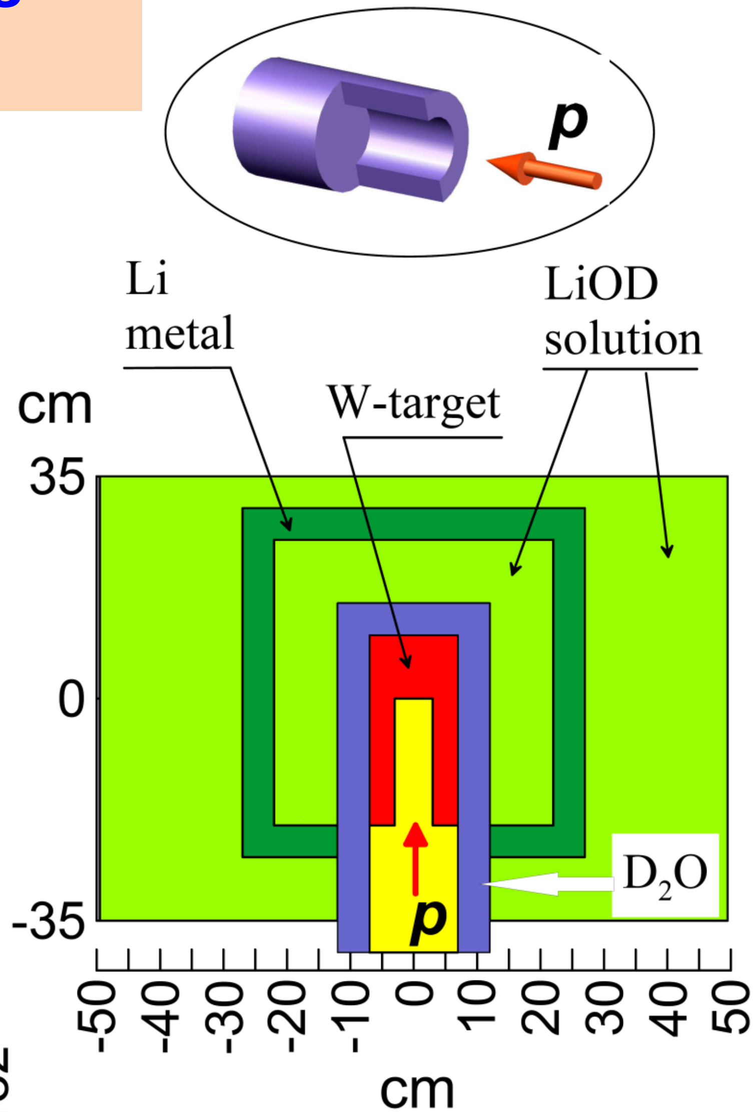
Accelerator scheme of the Li-8 antineutrino source (9). The proposed solution to diminish the dimension of the Li-8 antineutrino source (continue).

The inserted thin Li-7 layer (purification 99.99%) allows to obtain an increase of Li-8 yield more close to the target channel (see right part of the Figure)



Accelerator scheme of the Li-8 antineutrino source (10).
The geometry of the compact Li-8 antineutrino source.





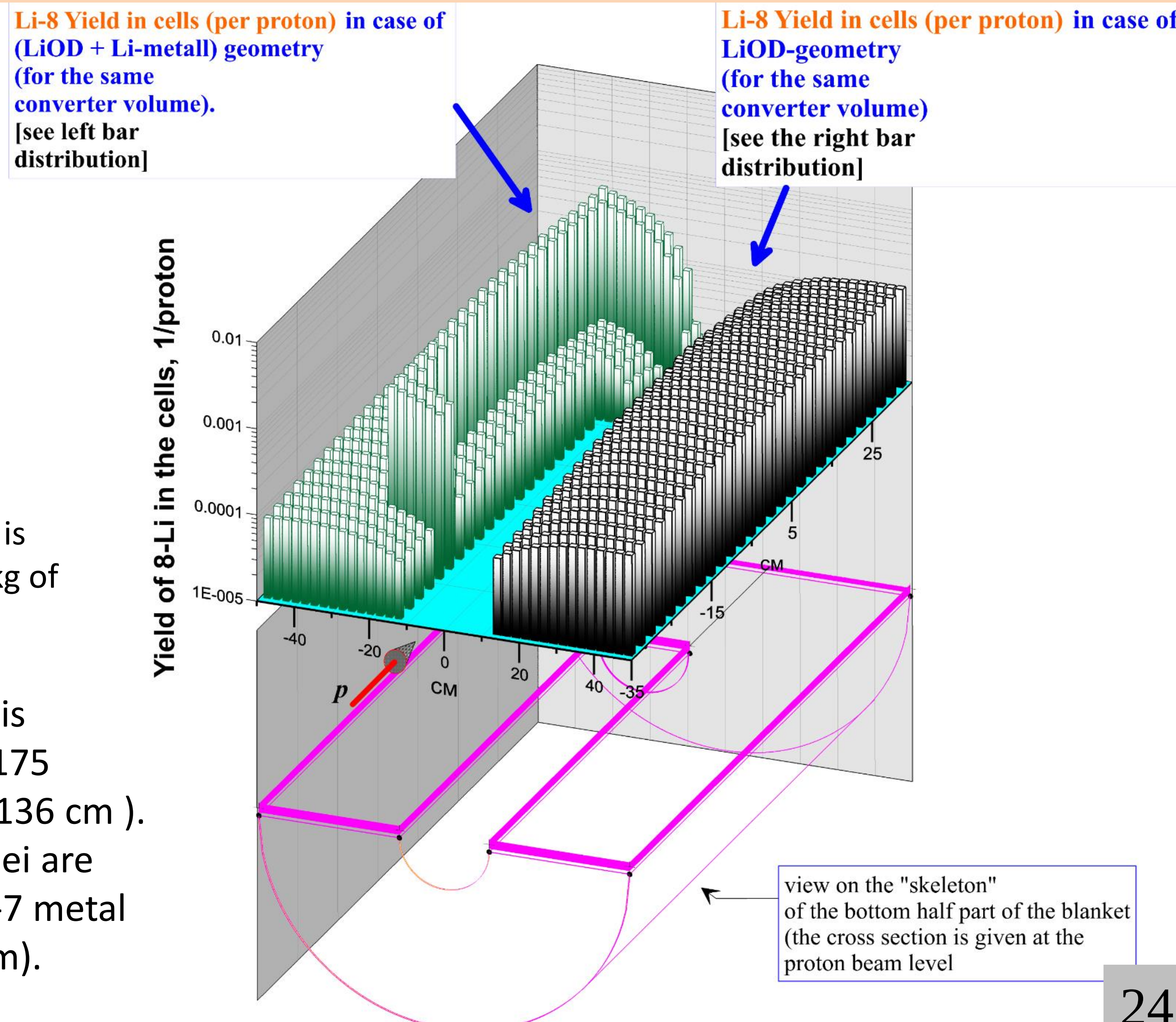
Lithium antineutrino source

Accelerator scheme of the Li-8 antineutrino source (12).

Comparison of Li-8 yield in volume cells of the lithium blankets for cases of (LiOD solution + Li-metal layer) and case of LiOD solution.

Lengh of this diminished lithium blanket is 70 cm (along the beam axis) compare to the previous geometry with L=136 cm in lenth.
The mass of the Li-7 in the diminished lithium blanket is 67.5 kg compare to 128.3 kg of The previous geometry.

The obtained Li-8 yield is k_p = 0.13 compare to 0.175 in the previous case (L=136 cm). 68% of created Li-8 nuclei are generated in the thin Li-7 metal layer (at R = < (22-27) cm).



Conclusion

- The proposed an intense antineutrino source with transfer of created 8-Li isotope to the remote detector ensure the hard spectrum and high flux in the detector volume. The expected counts in the compact detector is evaluated as ~ 10E+4 in the detector volume ~1 m^3 per day and GW of the reactor power.
- The expected count errors can be decreasd up to ~ 0.5%.
- It was proposed the method of detection for sterile neutrino (with Δm^2 ~ 1 eV^2) oscillations (**outside of interval of antineutrino spectrum errors**) in the indicated space region.

- It is proposed an effective accelerator schemes for Li-8 antineutrino sources.
- The proposed for antineutrino sources (working in tandem with accelerator) ensure high Li-8 yield. The requested mass of high purified Li-7 can be decreased up to ~ 67.5 kg.
- The Li-8 antineutrino source can be compact (~70 cm in length) that is
- exclusively important for oscillation experiments.

Thank you cordially for attention !