NEUTRON SOURCES FOR NEUTRINO INVESTIGATIONS (AS ALTERNATIVE FOR NUCLEAR REACTORS)

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Abstract: The process of (n,γ)-activation of ^{7}Li isotope leads to creation of short living isotope ^{8}Li ($T_{1/2}$ = 0.84 s), which at β^--decay emits antineutrino of hard spectrum ($E_{\tilde{\nu}}^{\max}$ = 13 MeV, $< E_{\bar{\nu}} >$ = 6.5 MeV). Owing to the hard $\tilde{\nu}_e$-spectrum and square dependence of cross section on the energy ($\sigma \sim E_{\nu}^{2}$) the ^{8}Li isotope becomes an exclusively perspective source for neutrino investigations. Today nuclear reactors are the most intensive neutrino sources. Antineutrino reactor spectrum is formed by ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu isotopes which cause large uncertainties in the summary neutrino spectrum. Use of ^{8}Li isotope allows to decrease sharply the uncertainties or to exclude it completely. An intensive neutron fluxes are requested for rapid generation of ^{8}Li isotope. The installations on the base of nuclear reactors (of steady-state or pulse neutron fluxes) can be an alternative for nuclear reactors as “traditional” neutron sources. It is possible creation of neutron sources another in principle: on the base of beam-dumps of large accelerators plus ^{7}Li converter; on the base of tandem of accelerators, neutron generating targets and lithium converter. An intensive neutron flux (i.e., powerful neutron source) is requested for realization of considered neutrino sources (neutrino factory). Different realizations of lithium antineutrino sources (lithium converter on the base of high purified ^{7}Li isotope) are discussed: static regime (i.e., without transport of ^{8}Li isotope to the detector); dynamic regime (transport of ^{8}Li isotope to the remote detector in a closed cycle); an operation of lithium converter in tandem of accelerator with a neutron-producing target on the base of tungsten, lead and bismuth. Heavy water solution of LiOD is proposed as an alternative to pure ^{7}Li in a metallic state.

1. Introduction

Antineutrino $\tilde{\nu}_e$, emitted at β^--decay of nuclear reactor fission fragments have an energy $E_{\bar{\nu}} \leq 10$ MeV and sharply decreasing spectrum. Cross sections of interactions of reactor antineutrino with proton, electron and deuteron are exclusively small – in the interval 10^{-46} –10^{-43} cm^2/fission. In fact the full $\tilde{\nu}_e$-flux of the reactor (99.8% for water-moderated reactor types) are ensured by four isotopes – ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu [1]. An experimental equilibrium $\tilde{\nu}_e$-spectrum of nucleus-fission products of these four isotopes (the spectrum are normalized per fission) are presented in the fig. 1 [2–4]. An experimental data of $\tilde{\nu}_e$-spectrum for ^{238}U isotope was published only in 2014. The yield of ^{238}U to the summary neutrino spectrum for water-moderated reactor types (according to FRM-II reactor in Garching, Germany) is evaluated as 10% [4]. As clear from fig.1 the four spectra are drop rapidly as energy increase (especially for threshold reactions).

One more complication is dependence of partial spectra from nuclear fuel composition which vary in time as in operation period as in case of reactor stops. The $\tilde{\nu}_e$-fluxes are varied too as composition changing and fluxes are recalculated by means of correction factors for

four isotopes [5, 6]. An additional unaccounted errors for $\tilde{\nu}_e$-flux evaluation appear during reactor stops between companies due to permanent presence of cooling pond for spent fuel. These errors can arise 1% [1].

An experimental $\tilde{\nu}_e$-spectrum of β^--decay nuclei-fission fragments (for ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu) are recovered from β^--spectra of these isotopes. The direct registration of β^--spectra by electrons is possible only for part of decay chains: the other chains are identified by means of γ-quantum. In case of large branching the reproduction of channel probabilities, unknown decay schemes and the final products by means of γ–spectroscopy becomes problematic. The model $\tilde{\nu}_e$-spectrum calculations have been done for solve of the problem [7–10]; the parametrization of the effective charges for fragments is considered [7], an influence of corrections (radiation and coulomb ones, weak magnetism) [8] and yield of forbidden transfers are evaluated [9].

As a results the significant uncertainties in antineutrino nuclear reactor spectra and unaccounted addition to the summary $\tilde{\nu}_e$-spectrum (up to 6%; see notes of the works [1,7–10]) do exclusively complicated the interpretation of neutrino oscillation experiments.

The nuclear reactors and isotope sources are the most widely used as intensive neutrino sources. The isotope sources have some advantages: the known characteristics, usability and availability. But isotope sources yield to reactors in fluxes [11]. The serious disadvantage is significant decrease of intensity of artificial neutrino sources in time. As example the neutrino flux of the unique source of the base of ^{37}Ar [12] (which was produced during the 133 days on the fast neutron reactor BN600 [Beloyarskaya atomic plant, the town Zarechny, Russia]; of maximal ν_e-energy up to 813 keV and $T_{1/2}$ = 35.01 days) was equal to $1.5 \cdot 10^{16}$ neutrino/s. But after 9 months the flux falls in ~300 times up to ~$5 \cdot 10^{13}$ neutrino/s.

For considered energy the cross section follows to the quadratic low: $\sigma_\nu \sim E_\nu^2$. So it is important to ensure the more hard spectrum, high flux and stability of it. The assurance of the above mentioned conditions will give opportunities to separate the neutrino effect from background.

2. Physical principles assumed as a basis for creation of antineutrino source

The weak sides of reactor antineutrino spectrum (sharp decrease of $\tilde{\nu}_e$-spectrum, significant uncertainties and time instability in neutrino spectrum of ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu) can be fill up by use of β^--decaying ^{8}Li isotope with hard $\tilde{\nu}_e$-spectrum.. The most simple way for creation of ^{8}Li antineutrino source (lithium converter) is to arrange the lithium blanket (lithium converter) close to the active reactor zone (AZ) and to ensure the effective activation ^{7}Li$(n,\gamma)^8$Li. The created short living ^{8}Li isotope ($T_{1/2}$ = 0.84 s) emits antineutrino of well defined spectrum with maximal energy $E_{\tilde{\nu}}^{\max}$ =13.0 MeV and averaged value $\overline{E}_{\tilde{\nu}}$ = 6.5 MeV. As a result the summary $\tilde{\nu}_e$-spectrum becomes more hard compare to the reactor one (see fig.1). This type of converter realization ensure the regime of operation called as static one.

The idea of a neutrino source, based on ^{8}Li decay was discussed firstly in [13] and for pulse reactors – in [14]. The questions of constructing the intensive neutrino sources with a hard spectrum, different types of lithium converters for reactors working in a stationary and

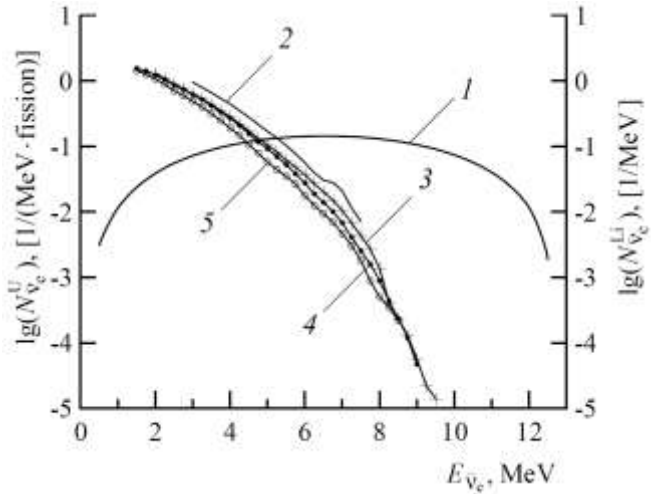

Fig. 1. $\tilde{\nu}_e$ - spectra from ^{235}U and β-decay of ^{8}Li.

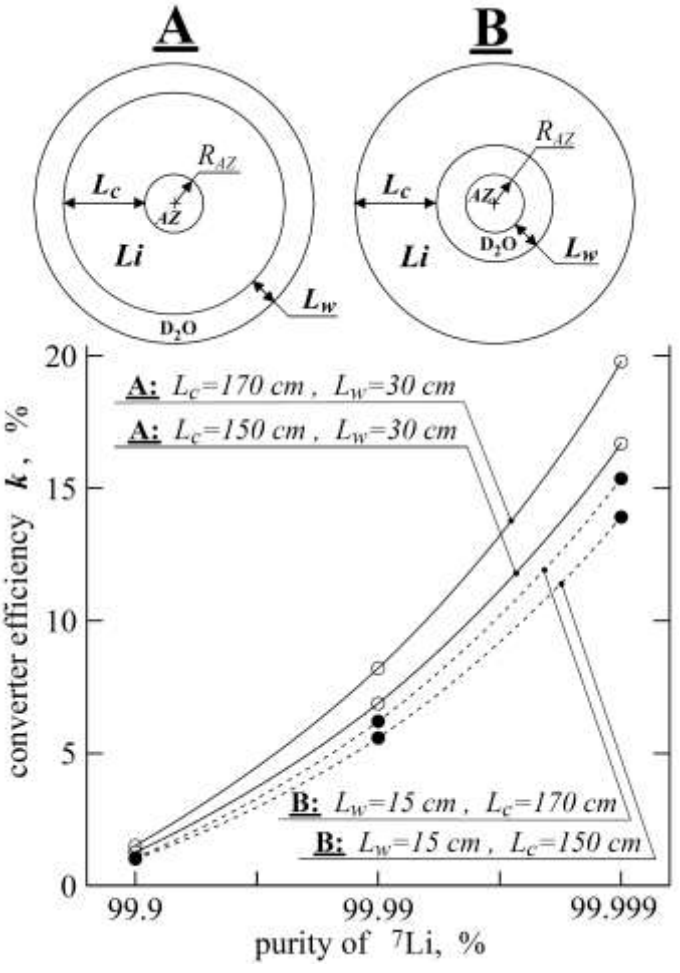

Fig. 2. Dependence of converter efficiency ***k*** on ^{7}Li isotope purity (with admixture of ^{6}Li) in the geometry ***A*** and ***B*** for lithium thickness L_C, heavy water layer L_w and reactor active zone radius R_{AZ} =23 cm.

pulse mode, applications of converters for neutrino researches are considered in Ref. [15-17]. The simple schemas of spherical construction of multi-layer converter in a static regime is presented in the fig. 2 as geometry **A** and **B**. The active zone radius R=23 cm corresponds to a 51.0-*liter* volume to that of the high-flux PIK reactor [10, 17–18].

To compare these two types of geometry the calculations were performed (using MAMONT code [10, 17–18]) for three converter thicknesses: L_C = 130, 150 and 170 cm. The thickness of iron shells was 1 cm. The D_2O acts as a reflector in geometry **A** and as an effective moderator in geometry **B.** The D_2O thickness of L_W = 30 and 15 cm are sufficient for the reflector in geometry **A** and nearly optimal for the moderator in geometry **B.** In the calculations it was assumed that one neutron with the fission spectrum escaped from the active zone per one fission. So, according to our calculations, the geometry **A** gives better results for the converter efficiency ***k***, where ***k*** is equal to the number of ^{8}Li isotopes created per one neutron escaping from AZ.

The main problem is to increase the efficiency of converter and in so way to increase the hardness of the summary $\tilde{\nu}_e$-spectrum. To increase the efficiency of converter by purification of the significant mass of ^{7}Li isotope up to the 99.999% grade is highly difficulty. The constructive way may be to use ^{7}Li isotope with realistic grade of purification (about 99.99%), but in chemical compositions instead of lithium in metallic state. The perspective candidates for use as substance in a

converter can be a heavy water solution of lithium hydroxides (LiOD, LiOD $\cdot D_2O$) and lithium deuteride – LiD [12, 19–20].

The most perspective one is the considered LiOD heavy water solution. Thus, using it permits to reduce the layer thickness L_C up to ≈1 m and to reduce sharply a required mass of a high-purified lithium: for example, for ^{7}Li purification grade 99.99% in order to ensure the efficiency level κ = 0.075 (at LiOD concentration of 9.46 % in heavy water solution) it will be necessary the lithium mass in ~350 times less compare to the converter with ^{7}Li in metallic state only.

In the work [21] the authors considered the alternative isotope for antineutrino converter – B^{12}, created by activation reaction $^{11}B(n,\gamma)^{12}B$. But it was indicated [17] that for equal isotope purification the relation of parasitic absorption on ^{10}B to beneficial one on ^{11}B is considerably worse than for respective cross section on ^{6}Li and ^{7}Li. So, to creation the neutrino source on the ^{12}B is highly difficult due to technological reasons.

Significantly more hard antineutrino spectra (from active reactor zone plus from ^{8}Li decay in the lithium converter) can be ensured in the installation of the dynamic mode of operation [22–24]: the liquid lithium is pumped (in the close cycle) through converter and further to remote neutrino detector and back to converter in a close cycle. The propose to use (see work [19–20]) the heavy water solution of lithium hydroxide LiOD instead of metallic lithium (as converter substance) is look the prime perspective as for realization of a dynamic mode the required lithium mass is increased in about 2–4 times [22–24]. I.e., the conversion of metallic lithium to LiOD solution solves the problem of strong rise in price of installation and exclude the problem of safe work with metallic lithium.

3. Neutrino source on the base of lithium converter, accelerator and the target

An intensive neutron source can be created on the base of the tandem of accelerator and neutron generating target. In this variant for creation of intensive neutrino source we need to surround the target by lithium converter [25–27]. The large benefits of neutron source on the neutron generating target is caused by the fact that as the proton energy is increasing the neutron yield Y_n (per proton) is increasing sharply: so, for energy E_p = 300 MeV the neutron yield is about $Y_n \approx$ (3–4), for E_p =500–600 MeV the yield increases up to $Y_n \approx 10$; for E_p =1, 3, 10 GeV the yield Y_n reaches the ≈ 10, 80, 150, respectively; according to the model the similar rise is continued for TeV proton energy [28].

Such neutron sources exist in Russia, USA, Europe, Japan and are developing: IREN, IFMIF, JSNS/J-Park (Japan), ESS, CSNS; project of electronuclear installation "Energy amplifier" by Rubbia C. [20, 27, 29] et. al. The used substances of neutron generating target are lead, tantalum, tungsten, uranium, mercury and beryllium (as neutron reflector and breeder). Construction of lithium (or heavy water LiOD solution) blanket around the neutron generating target will give an intensive antineutrino source.

The cylindrical target geometry (including input for beam) is considered in this work. The target substance is tungsten isotope ^{174}W. The scheme of lithium converter is presented on the fig.3. The D_2O heavy water layer (which is effective moderator) is provided for cooling. The MCNP code [30] and the code MAMONT (for reactor energies) [28, 17, 24] are used for calculations It were optimized the target size for optimization the neutron yield for the interval E_p =(50–300) МэВ. These low energies is considered with purpose to decrease the possible background of neutrino experiments and taking into account the π^0-meson production (generating the electron-photon showers) at more high energies.

For mentioned energies the ionization and nuclear tracks are not larger ~20 см. So, the

variants of lengths ($h_t - h_h$)≥ 20 cm (fig.3) [31] for decelerating of protons are considered. The length of targets h_t = (30–40) cm and channel radia r_h = 3 cm are discussed. The optimization was realized for purpose to enlarge neutron yield (per proton) and to minimize the neutron flux to back through the face plane of the target (the circle with the center in the point *C* and radius r_t on the fig.3). The optimization was realized in two stages – for variation of: 1) input length for beam in the interval h_h =(5–20) cm; 2) radius of the target in the diapason (5–12) cm. For example for 300 MeV and total neutron yield Y_n =3.61 the scattering to back fells in ~13 times up to $0.02 \cdot Y_n$. Neutron yields for optimized target (of sizes h_t = 40 см, r_t = 7 cm, h_h = 20 cm, and r_h = 3 cm) are given in the fig.4. The obtained results are in good agreement in known experimental data and calculations for extended targets [32–35].

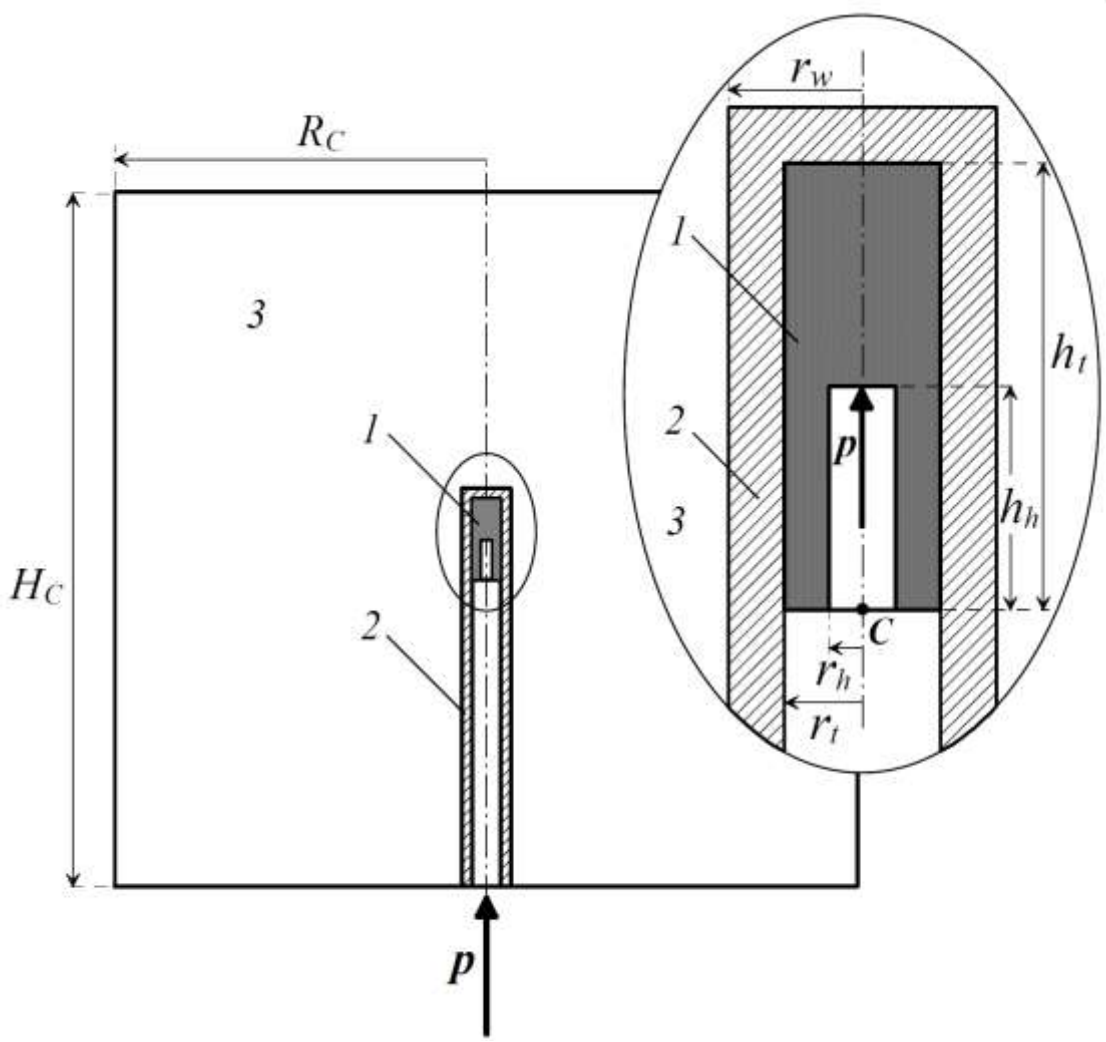

Fig. 3. The profile of the lithium converter and neutron generating target in the cylindrical geometry. *1* – tungsten (bismuth, lead) target, h_h *и* r_h – length and radius of the input channel for the proton beam; *2* – the pumping D_2O-channel for cooling; *3* – lithium converter.

The optimized target is cooling in the D_2O-channel (of 5cm in thickness) and placed in the center of the cylindrical converter (see fig.3) filled with LiOD heavy water D_2O solution (of concentration – 9.46%) [19-20]. The converter has the size: height H_c =340 cm, radius R_c = 182 cm, converter layer L_c =170 cm (as in the works [19-20]). The obtained proton efficiency

of the converter (number of ^{8}Li isotope, created in the converter per proton) is presented in the fig.5. Then converter antineutrino flux per solid angle 4π during time t and proton current I is equal to:

$$N_{\tilde{\nu}}(t) = 6.25{\cdot}10^{15} k_p(E)\, I[\text{мА}]\, t[\text{с}],$$

where: $k_p(E) = k_n(E) Y_n^{\text{eff}}(E) = k_n(E)\,[Y_n(E) - \delta Y_n(E)]$; k_n – neutron efficiency of the converter (number of ^{8}Li nuclei, created in the converter, normalized on the effective neutron yield; here $k_n \approx 0.16$); Y_n^{eff} – effective neutron yield; Y_n – total neutron yield; δY_n – correction, taking into account the loss of neutrons (mainly back scattered – to the input of the proton beam; $\delta Y_n \approx 0.02 \cdot Y_n$, see above). So, at E_p = 300 MeV and 1 мА of accelerator current the antineutrino flux during 1 s is $N_{\tilde{\nu}} = 3.6 \cdot 10^{15}$.

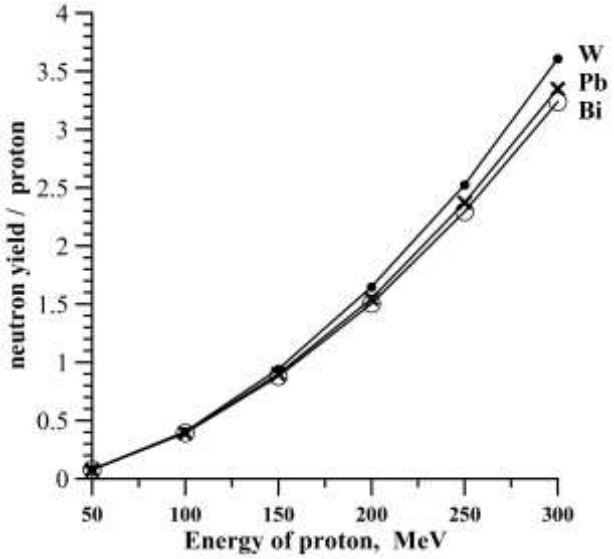

Fig. 4. Neutron yield for W, Pb and Bi-targets.

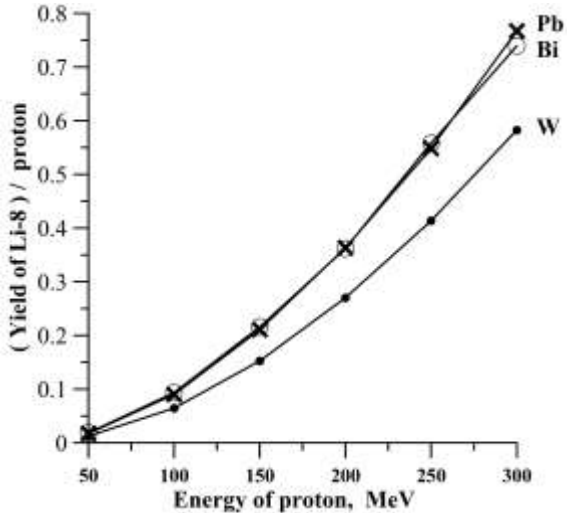

Fig. 5. Yield of ^{8}Li in the converter for W, Pb and Bi-targets.

In the articles [36–37] the authors proposed to construct $\tilde{\nu}_e$-source on the base of ^{8}Li isotope. The authors refer to the work [25–26] and considered the similar geometry, purity of the ^{7}Li, the tandem scheme of proton accelerator (E_p = 60 MeV), neutron generating ^{9}Be-target and cylindrical lithium converter (height 150 cm, diameter 200 cm) filled with metallic lithium. The expected $N_{\tilde{\nu}}$-flux from the converter during 5 years (for 90% using of time and accelerator current I =10 mA) is evaluated as $1.29 \cdot 10^{23}$. Let us compare these data with above considered $\tilde{\nu}_e$-source with W-target, lithium converter (filled with LiOD heavy water solution of concentration 9.46%), 90% time using and proton current – I =10 мА. Then for proton energy E_p =300 и 100 MeV the fluxes $1.29 \cdot 10^{23}$ $\tilde{\nu}_e$ will be obtained in 46 and 411 days respectively.

It is necessary to compare neutron yields in case different targets. Calculations were realized for lead, bismuth and tungsten (^{174}W) targets. The all three targets ensure close values for neutron yields (per proton) – see fig.4. The difference of maximal yield (^{174}W target) and

minimal one (Bi target) is not large than ~ 10%. But in case of converter (i.e., neutron generating target is placed inside the converter (LiOD heavy water solution) we have an inverse "picture": the proton converter efficiency (number of ^{8}Li isotopes created in the converter per proton) depending on proton energy $k_p(E)$ is maximal for Pb-target and minimal for W-target (fig.5).. The cause of the inversion is the converter itself: for calculations of neutron yields Y_n the "ideal" geometry is used – the target is placed in the vacuum. But in case of the real geometry the neutrons emitted from the target enter to the converter and can be scattered back to the target and be absorbed. Also it is possible the scattering back to the input channel of the proton beam. The fig.6 illustrates the neutron balance on the boundary of the W- and Pb-target. The vertical axe is the directional current through the surface: the positive value respect to the current of neutrons escaped from the target; negative values respect the current for neutrons scattered inside the target. The algebraic sum of escaped neutrons and neutrons scattered inside the target gives the number of neutrons captured out of the target. So, for Pb-target the number of events for capture out of the Pb-target (1.397) is larger compare to the similar events for W-target (1.008) and this is cause of the observed inversion phenomena.

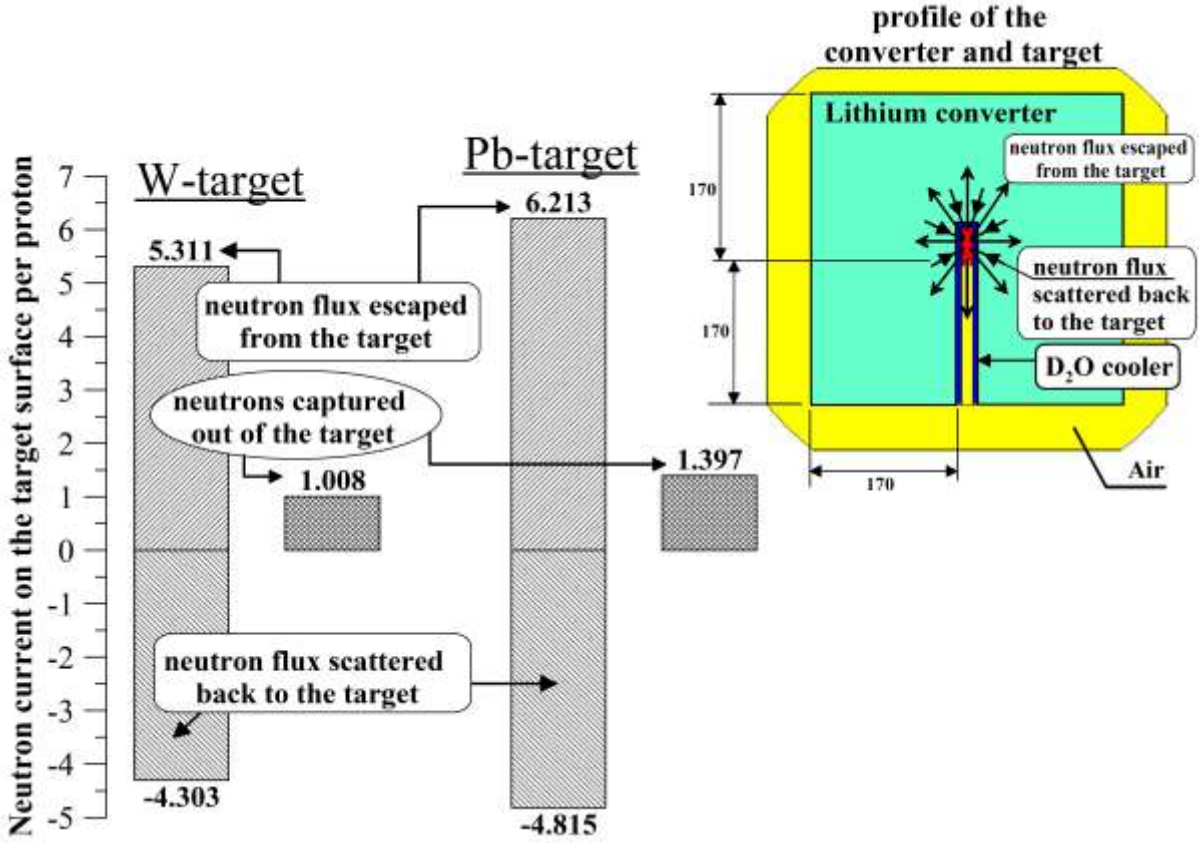

Fig. 6. Neutron balance on the boundary of the W- and Pb-target.

It is important to note that realization of the project [36-37] with lithium in metallic state will request ~ 6.1 t of lithium of purification 99.99% on the ^{7}Li isotope compare to ~ 1.1 t for the discussed here antineutrino source on the base of converter with heavy water LiOD solution (concentration 9.46%) and W-target. I.e., using of heavy water LiOD solution will

allow to decrease strongly the price of creation for expensive physical installation.

4. Conclusion

It was considered two variants of intensive $\tilde{\nu}_e$-source on the base of ^{7}Li isotope (with purity 99.99%) on the base 1) nuclear reactor (as neutron source), and 2) proton accelerator and neutron generating target (tungsten, bismuth and lead). Due to the hardness and well defined $\tilde{\nu}_e$-spectrum the ^{8}Li isotope becomes very perspective.

The reactor realization ensures the summary $\tilde{\nu}_e$-spectrum of β^--decaying nuclei (fission fragments) plus spectrum of ^{8}Li. This leads to creation of more hard spectrum [17, 20, 24-26] and allows to increase in times the cross section on protons and deuterons compare to the results in the pure reactor neutrino spectrum (which have significant uncertainties (~ 6%).

Realization of the accelerator variant of the $\tilde{\nu}_e$-source will ensure the pure lithium $\tilde{\nu}_e$-spectrum. It was discussed the variants of the tandem of proton accelerators with energy E_p =50–300 MeV and tungsten, bismuth and lead targets plus lithium converter (filled with heavy water solution of LiOD). It were calculated the neutron yields from W-, Bi-, Pb-targets, creation of ^{8}Li isotope and expected $\tilde{\nu}_e$-fluxes. The proposed $\tilde{\nu}_e$-source will ensure: 1) to decrease sharply the required mass of high purified ^{7}Li isotope (in 5.5 times compare to [36, 37]) in the installation for neutrino investigations and 2) the $1.3 \cdot 10^{22}$ $\tilde{\nu}_e$-flux for proton energy E_p =300 and 100 MeV (at the current 1 mA) in 46 and 411 days, respectively.

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