NEUTRON SOURCES FOR NEUTRINO FACTORY ON THE BASE OF LITHIUM CONVERTER

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Abstract: The powerful antineutrino source with a hard spectrum ($E_{\bar{\nu}}^{\max}$ = 13 MeV, $\overline{E_{\bar{\nu}}}$ = 6.5 MeV) can be constructed on the base of β^--decay of the short living ^{8}Li ($T_{1/2}$ = 0.84 s) isotope created in the reaction of gamma activation ^{7}Li(n,γ) ^{8}Li. Compare to the such traditional antineutrino source as a nuclear reactor the ^{8}Li. isotope has an absolute advantage taking into account that neutrino cross section depends as $\sigma \sim E_\nu^2$ at the considered neutrino energy. The creation of this type powerful neutrino source (neutrino factory) is possible by (n,γ)-activation of high-purified ^{7}Li isotope under intensive neutron flux. As a neutron source for this purpose can be used the nuclear reactors (of steady-state flux and pulsed one), neutron sources on the base of accelerators and neutron generating targets, beam-dumps of large accelerators. The capabilities and perspectives of neutron sources are considered for the purpose of creation of the 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 (pumping of activated lithium to a remote detector in a closed cycle); lithium converter on the base of (a) a pulse reactors and (b) constructed as tandem of an antineutrino source and accelerator with a neutron-producing target. Heavy water solution of LiOD is proposed as a substance for the lithium converter. The analytical expressions for lithium neutrino fluxes in the detector position are obtained.

Introduction

The experimental investigations of neutrino interaction with substance are stipulated extremely by small cross sections of the reactions. So, for the artificial neutrino source such characteristics as flux and spectrum are the most important. The smallness of cross sections extremely complicates separation of neutrino effect from background. In this case a high neutrino flux can be a decisive factor for obtaining of reliable results. On the other hand, the probability of registration strongly depends on neutrino energy. For the energy spectrum discussed in this work the dependence of the neutrino cross section is square-law: $\sigma_\nu \sim E_\nu^2$.

Nuclear reactors and accelerators and the Sun are exceptional on intensive neutrino fluxes [1 – 3]. The solar $\tilde{\nu}_e$-neutrinos fluxes are estimated as $\approx 6.6 \cdot 10^{10}$ cm$^{-2} \cdot$s^{-1}. However, the energy of ~ 98% of all solar neutrinos does not exceed 0.86 MeV. In experiments with artificial neutrino sources there is a certain freedom in specification of an energy and neutrino fluxes. The density of $\tilde{\nu}_e$-flux from a nuclear reactor [3] is determined by its power P and for distance R is:

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

where $\bar{n} \cong 6$ – mean number of β^--decays for both fission fragments of ^{235}U, $\overline{E_{\bar{\nu}}} \cong 200$ 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 $F \cong 1.3 \cdot 10^{13}$ cm^{-2} $\cdot$c^{-1}. Antineutrinos $\tilde{\nu}_e$ emitted at β^--decay of fission fragments in a nuclear reactor have energy $E_{\bar{\nu}} \leq 10$ MeV and cross sections of the interaction with protons, electrons and deuterons are in the interval $10^{-43} \div 10^{-46}$ cm^2. The interaction of neutrinos ν_μ and $\tilde{\nu}_\mu$ with energy $E_\nu \approx 10 \div 300$ MeV is studied at meson factories and at greater energy $E_\nu \approx 1 \div 200$ GeV – at high energy accelerators. The neutrino cross sections strongly grow at these energies but, however, the fluxes are on many less orders than in reactor experiments.

1. Creation of the lithium antineutrino sources. Physical aspects.

The nuclear reactors along with the obvious advantage (as intensive neutrino flux) have a serious disadvantage – too small hardness of $\tilde{\nu}_e$-spectrum. This disadvantage can be filled having realized the idea to use a high-purified ^{7}Li isotope for engineering of a reactor neutrons-to-antineutrino converter, which is located close by the active zone of a reactor. In a reactor neutrons flux a short-lived isotope ^{8}Li ($T_{1/2}$ = 0.84 s) is created in the reaction ^{7}Li(n,γ)^{8}Li and at β^--decay emits hard antineutrinos of a well determined spectrum with the maximum energy $E_{\bar{\nu}}^{\max}$ =13.0 MeV and mean energy $\overline{E_{\bar{\nu}}}$ = 6.5 MeV. As a result the summary $\tilde{\nu}_e$-spectrum from the active zone of a reactor and from decays of ^{8}Li isotope becomes considerably harder in comparison with the purely reactor spectrum (see Fig. 1). The converter constructed according this idea will realize the static regime of operation.

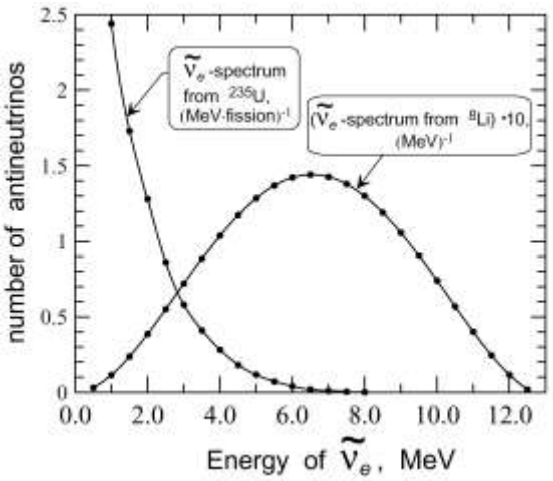

Fig. 1. $\tilde{\nu}_e$- spectra from ^{235}U and β-decay of ^{8}Li.

The idea of a neutrino source, based on ^{8}Li decay was discussed firstly in [6] and for pulse reactor in [7]. The questions of constructing the intensive neutrino sources with a hard spectrum, different types of lithium converters for reactors working in a stationary and pulse mode, applications of converters for neutrino researches are considered in Ref. [8-10].

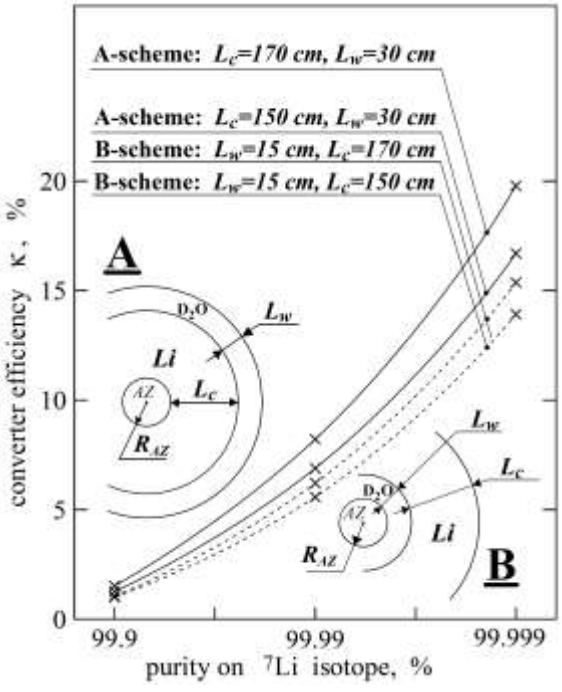

Fig. 2. Dependence of converter efficiency $\boldsymbol{k}$ on ^{7}Li purity (with admixture of ^{6}Li) in the geometry ***A*** and ***B*** for lithium thickness L_C, heavy water layer L_w and reactor active zone radius R_{AZ} =23 cm.

The simple schema of spherical construction of multilayered converter in a static regime is presented in the Fig. 2. The active zone radius R = 23 cm corresponds to 51.0 liter volume to that of the high-flux PIK reactor [10, 11]. To compare these types of geometry the calculations were performed, using Monte-Carlo method by MAMONT code [10, 11] (testing in the calculations with the thermo-nuclear spectrum [12]) for three converter thicknesses: 130, 150 and 170 cm. The thickness of iron shells was 1 cm. The D_2O thickness of 30 and 15 cm are sufficient for the reflector and nearly optimal for the moderator**.** 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 with heavy water reflector 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 the active zone. The spectrum hardness of combined active zone plus converter $\tilde{\nu}_e$-spectrum increases considerably at ***k*** ≥ 20 %. This positive effect let to increases the cross section σ_ν for many times due to $\sigma_\nu \sim E_\nu^2$ dependence.

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. This may be done in some ways: 1) to increase the ^{7}Li isotopic purity up to about 99.999% in order to reduce the strong parasitic absorption on the ^{6}Li isotope; 2) not to use ^{7}Li isotope in the metallic state, but its chemical combinations (see below); 3) to use the reactor-converter system in the dynamic regime of exploitation (see below); 4) to realize the pulse reactor-converter system [7, 8].

2. The problems of the choice for the converter matter

To increase the efficiency of converter purifying the significant mass of ^{7}Li isotope up to the 99.999% grade is difficult. 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 must have a high slowing-down power $\overline{\xi}\overline{\Sigma}_S$ and very small cross sections of absorption. For example the perspective substance for converter material can be a heavy water solution of lithium hydroxides (LiOD, LiOD $\cdot D_2O$) and lithium deuteride – LiD [13, 14].

The most perspective was considered LiOD heavy water solution. Thus, using it permits to reduce the layer thickness L_C up to ≈ 1 m and sharply to reduce 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. Other considered chemical compositions like Li_2C_2, Li_2CO_3, Li_2O, $LiDCO_3$, LiF, $LiDF_2$ and their heavy water solutions can not be so perspective for converter.

The choice of converter matter can be considered as the task of optimization for set of parameters: matter and converter geometry, lithium purity on ^{7}Li isotope, mass of lithium m_{Li} in the converter. Choosing the perspective type of converter matter, geometry and fixing the lithium purity we can consider dependence of efficiency on mass of lithium: $\kappa(m_{Li})$. The converter efficiencies κ as function of the lithium mass m_{Li} for different chemical compositions and heavy water solution of LiOD (for three concentrations) are given in the Fig.3 for two scales of mass: 0 – 50 kg, and 0 – 1000 kg.

Later it was considered the boron as an alternative material for antineutrino converter on the base of ^{11}B(n,γ)^{12}B reaction [15]. The isotope ^{12}B ($T_{1/2}$ = 20.20 ms) has a hard antineutrino

spectrum close to that of lithium with $E_{\tilde{\nu}}^{\max}$ = 13.4 MeV and mean energy $\overline{E_{\tilde{\nu}}}$ = 6.8 MeV. But at thermal energy the cross-section ratio of parasitic absorption on ^{10}B to the beneficial one

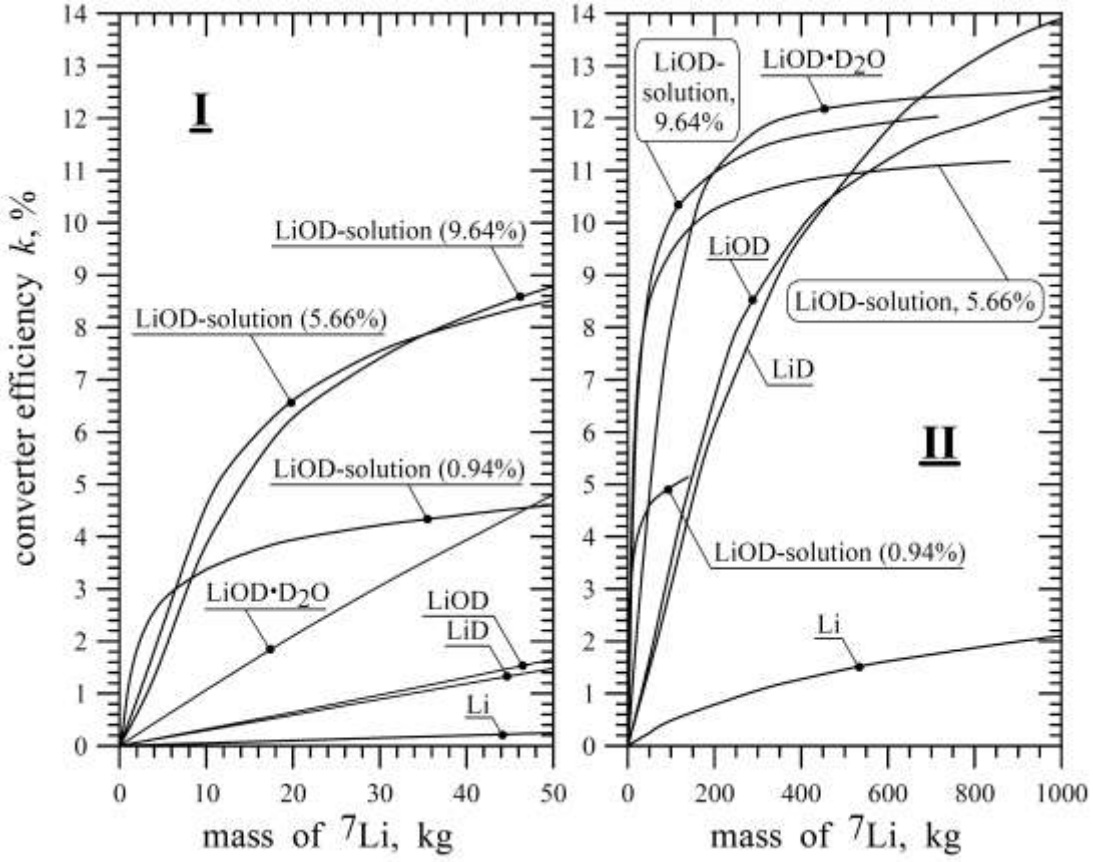

Fig. 3. Dependence of converter efficiency ***k*** on lithium mass m_{Li} (in two scales) for different chemical compositions and heavy water solution of LiOD (with LiOD concentration 0.94, 5.66 and 9.64%).

on the ^{11}B starting isotope [$\sigma_a(^{10}B)/\sigma_{n\gamma}(^{11}B)$ = 3837/0.0055] is considerably worse than for lithium [$\sigma_a(^{6}Li)/\sigma_{n\gamma}(^{7}Li)$ = 937/0.045] ratio. When for the same converter efficiencies the grade of purity required for manufacture of boron neutrino source should be ≅ 99.9997% on ^{11}B isotope compared with technologically producible 99.99% purity of ^{7}Li in a lithium neutrino source.

For the thermonuclear and more hard neutrons it is possible the antineutrino production in the ^{11}B(n,α)^{8}Li-reaction. But in here will be the same problems with the parasitic absorption on ^{10}B and the isotope purification of ^{11}B.

3. Realization of the antineutrino source in the dynamic regime of operation

It is possible to supply powerful neutrino fluxes with considerably greater hardness in a facility with a dynamic mode of operation [16 – 18] where liquid lithium is pumped over in a closed cycle through a converter and further to a remote neutrino detector (Fig. 4). For increasing of a part of lithium antineutrinos a being pumped reservoir is constructed near the $\tilde{\nu}_e$-detector, or the detectors enclose the reservoir (Fig.4). Such type of the facility will ensure not only harder spectrum in the location of a detector but also an opportunity to investigate $\tilde{\nu}_e$-interaction at different spectrum hardness varying a rate of lithium pumping over.

However, the development of such a facility with lithium in metallic state comes across

serious problems connected with necessity of a temperature regime maintenance ($t_{melting}$(Li) = 180.5°C) and requirement in a large mass of a high-purified lithium. So, for fill up of the converter with lithium layer L_C = 1.5 m the required mass of lithium reaches 11.9 t. For realization of dynamic mode the required lithium mass is increased in about 2 – 4 times [16]. For a facility with a dynamic mode of operation the heavy water solution of lithium hydroxide LiOD look as the most perspective for converter substance, taking into account the price of high-purified lithium and questions of safety (lithium in metallic state is inflammable).

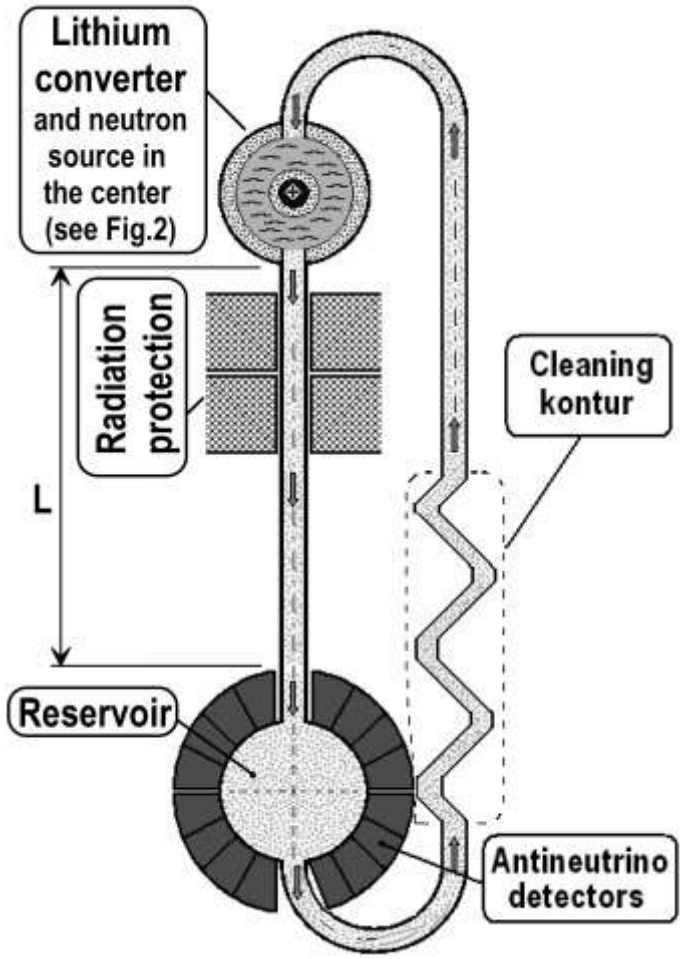

Fig. 4. Dynamic regime of the lithium antineutrino source.

Let us denote the values and assume: N_7^0 and N_8^0 – number of ^{7}Li (starting isotope) and ^{8}Li nuclei at time t = 0; N_8^0 = 0 at the start (t = 0) of (n,γ)-activation; $N_7(t)$ and $N_8(t)$ – number of ^{7}Li and ^{8}Li nuclei at the time t; $\lambda_{n,\gamma}$, λ_β – rate of (n,γ)-reaction and of β^--decay. We will denote (see Fig. 4): V_c – lithium volume in the converter (see also Fig.2), V_0 – lithium volume of a whole system, w - volume being pumped over in a time unit (flow rate), then $t_p = V_c/w$ – time of pumping over of converter volume.

It was obtained the expressions for number of lithium antineutrinos emitted from different parts of the facility (see Fig. 4). So, the integral flux N_C of lithium antineutrinos emitted from the converter for the time t [16 – 18]:

$$N_C(t) = \frac{t}{t_p}\left[S_1 + \frac{S_2}{\varphi(-\lambda_\beta V_0 / w)} \right] , \qquad (2)$$

where

$$S_1 = \lambda_{n,\gamma} N_7^0 t_p - (\lambda_{n,\gamma} N_7^0/\lambda_\beta)\varphi(V_C),$$

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

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

The integral flux $N_r(t)$ of lithium antineutrinos emitted from the pumped reservoir (Fig. 4):

$$N_r(t) = \frac{\lambda_{n,\gamma} N_7^0 t}{\lambda_\beta t_p} \cdot \frac{\varphi(V_C)\varphi(V_r)\exp(-\lambda_\beta t_d)}{\varphi(V_0)} \ , \qquad (3)$$

where: V_r – lithium volume in the pumped reservoir, t_d is the time requested for lithium delivery from the converter to the pumped reservoir.

In order to reach rapid pumping over of a converter and to provide the lithium delivery (on the distance $L \approx 15 \div 25$ m in the time $t_d \leq 1$ s) it will be necessary to ensure a very significant flow rate w and linear speed V of moving in the channel. Examples of rapid pumping of the cooler we can see at the reactors [19]: ATR (Idaho, USA) – flow rate of water coolant – 170 ÷ 200 m^3/min, GHFR (Grenoble, France) – linear speed of D_2O-coolent - 15.5 m/s, SRHFD (Savannah River, USA) – flow rate of D_2O-coolent – 5.65 m^3/s at linear speed 19.8 m/s.

The other very important advantage of a dynamic regime of operating is a possibility to modify a spectrum shape and investigate neutrino reactions at different hardness of the summary $\tilde{\nu}_e$ - spectrum varying flow rate w from a zero up to maximum.

4. Operation of the neutrino source in the tandem: lithium converter plus accelerator

The conception of intensive antineutrino source can be realized in another effective way if the neutron source will be constructed on the base of proton accelerator and target for neutron production [20, 21]. Such neutron sources exist in Russia, USA, Europe, Japan and are developing (IREN (Russia), IFMIF (Italy), JSNS/J-Park (Japan), ESS (European project), CSNS (China) (see Table 1); project of electronuclear installation "Energy amplifier", proposed by Rubbia C. [22] et. al.) for neutron investigations, for construction of electronuclear reactors, incineration of radioactive materials and waste [21]. The targets are manufactured from lead, tantalum, tungsten, uranium, mercury and also beryllium (as reflector and neutron multiplicator). Lithium (or heavy water solution of LiOD) blanket placed around of such neutron generating target will be the intensive source of hard antineutrino. Realization of the dynamic regime will allow transporting the decaying ^{8}Li isotope more close to the neutrino detector [20].

At the end of 1970-th Yu. Ya. Stavissky (JINR, Dubna, Russia) [23] proposed to utilize dump of TeV-energy protons for generation of short giant neutron pulse and suggested to develop the neutron source at Large Hadron Collider (LHC) complex in CERN. The feature of the protons accumulation in the accelerator ring is accumulation of beam defects due to loss of focusing. So, in LHC all these accumulated protons are dumped presumably every ten hours into the beam dump (which is a graphite cylinder with 1 m in diameter and 15 m in length. In order to create the neutron source it was proposed the idea to install the neutron generating target at the graphite beam dump. The suggested target (with zirconium hydride moderator inside of it) can be manufactured from tungsten and titanium elements. According to the simulation [23] the flux of thermal neutrons in the moderator cavity can be up to 6×10^{19} neutron/(cm^2s) and about 10^{20} neutron/(cm^2s) on the neutron channel surface; specific duration of the thermal pulse ~100 μs. If to cover the beam dump of LHC with the lithium blanket we will have an intense antineutrino source with hard spectrum. If the converter efficiency is about 20 – 30%, then in the beam dump for neutron yield per pulse as 6×10^{18} the lithium antineutrino flux will reaches about $(1 – 2)\times10^{18}$ per pulse. The possible scheme of the neutrino factory is given in the Ref. [21, 24] in the dynamic regime on the base of the beam dump of the Large Hadron Collider (LHC) complex in CERN .

Table 1. Neutron sources on the base of accelerator and neutron producing target

Facility (Country, site, laboratory)	**Beam parameters: particles, energy, current, frequency (Hz)**	**Neutron yield, flux**	**Target; status of the facility**
IN-6 (Russia, Troitsk, INR RAS)	protons, 600 MeV, 0.5 mA (average), 100 Hz (project parameters)	~$1\cdot10^{16}$ s^{-1}	tungsten (target in the block 1). first run in 1998 year
IREN (Russia, Dubna, JINR)	electrons, 200 MeV, 3 A (in the pulse), 150 Hz	$1\cdot10^{15}$ s^{-1}	plutonium (K_{eff} <0.98); under construction: (tungsten-target at 1st stage)
SNS (USA), ORNL	protons, 1 GeV, 1.4 mA (average), 60 Hz	$(1.8 - 2.7)\cdot10^{17}$ s^{-1}	mercury; work since 2006 year
SINQ Swisserland, Paul Scherrer institute	protons, 590 MeV, 1.8 mA, steady-state flux	$1\cdot10^{14}$ $cm^{-2}s^{-1}$	lead; work since 1998 year
n-TOF Switzerland, Geneva, CERN	protons, 20 GeV, 4 Hz	$0.4\cdot10^{15}$ s^{-1}; at the distance 185 m from the target : $4\cdot10^{5}$ $cm^{-2}s^{-1}$	lead; work since 2000 year
IFMIF Italy, Frascati	deuterons, 40 MeV, 125 mA, steady-state flux	$(4.5\div10)\cdot10^{17}$ $m^{-2}s^{-1}$	Moltem ^{7}Li; under construction
LANSCE USA, Los-Alamos	protons, 100-800 MeV, up to 1mA; 20 Hz	$1\cdot10^{16}$ s^{-1}; for MTS(material test facility): $2\cdot10^{15}$ $cm^{-2}s^{-1}$ (2012 year plan)	tungsten; work since 1985 year
KENS (Japan, Tsukuba, KEK)	protons, 500 MeV 10 μA, 20 Hz	$3\cdot10^{14}$ $cm^{-2}s^{-1}$	tungsten (tantalum clad); work since 1980 year
ESS Sweden,Lund	protons, 2.5 GeV, 14 Hz	$40\cdot10^{15}$ $cm^{-2}s^{-1}$ (peak flux);	tungsten; normal operation in 2019; 44 neutron instruments in 2025 year
CSNS China, Dongguan	protons, 1.6 GeV, 62.5 μA, 25 Hz; $1.63\cdot10^{13}$ proton/pulse (according to Project phase 1)	~ $5\cdot10^{15}$ $cm^{-2}s^{-1}$	tungsten; normal operation in 2018 year

Conclusion

The creation of the powerful antineutrino source (neutrino factory) with a hard spectrum is possible on the base of lithium converter and intensive neutron source. This problem can be solved in a dynamic system where the high-purified ^{7}Li isotope (or lithium-containing substance, for example, heavy water solution of LiOD) is pumped cyclically through a converter close by the active zone of a reactor and further over a channel to a remote voluminous reservoir near to the $\tilde{\nu}_e$-detector. The dynamic system allows to locate β^--decays of ^{8}Li isotope near the detector and it is basic difference and advantage (the possibility to investigate neutrino interactions at different hardness of the spectrum) in comparison with a lithium converter operating in a static mode. The dynamic scheme gives the possibility to increase cross sections of ($\tilde{\nu}_e$,d)-reaction in the (n,n)-channel in tens times and in the (n,p)-

channel – up to to orders in comparison with cross sections of these channels in the purely reactor $\tilde{\nu}_e$-spectrum [17, 18]. The extremely powerful neutrino source with pure lithium antineutrino spectrum can be created in case of neutron flux from an experimental nuclear explosion. In reality to construct the powerful neutrino source with pure lithium antineutrino spectrum is possible on the base of intensive neutron sources like pulse nuclear reactors, on the base of tandem of accelerator with neutron producing target and (above discussed) beam dumps of large accelerators.

During the work were approved some methods of neutron transport calculations in case of thermonuclear source for the pulse nucleosynthesis.

The idea of the powerful neutrino source for investigation have gained large interest and activity directed on the development and simulation of the powerful neutrino source based on the lithium converter [25 – 27]. At this time a large team of physicists from Europe, USA and Japan are cooperated in the effort for development of the international project on creation of the intencive neutrino source on the base of tandem of lithium converter and accelerator with neutron producing target and it was proposed the program for neutrino investigations in inverse beta decay interaction $\tilde{\nu}_e + p \rightarrow e^+ + n$ and existence of zero, one, and two sterile neutrinos. The authors refer to the works [20, 24] and propose to build the lithium (with 99.99% purity on ^{7}Li) cylinder of large volume (of 2 m in diameter and 1.5 m in length) and to install the neutron producing ^{9}Be target (embedded 40 cm into the upstream face of the cylinder) for 60 MeV proton beam. The authors named the neutrino source as IsoDAR (Isotope Decay At Rest) and evaluate the efficiency of antineutrino production as 14.6 $\tilde{\nu}_e$ per 1000 protons (i.e. 1.46%). The obtained efficiency is smaller by order in value compare to the efficiency ***k***, that is about (10-15)%, which discussed in this work and can be reach on the proposed lithium substances.

So that is positive the growing interest and international activity in direction of creation of the neutrino source on the base of lithium converter that can help in understanding of neutrino nature.

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