NEUTRON SOURCES FOR NEUTRINO INVESTIGATIONS WITH THE LITHIUM CONVERTER

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Creation of the powerful antineutrino source with a hard spectrum ($E_{\tilde{\nu}}^{max}$ = 13 MeV, $< E_{\tilde{\nu}} >$ = 6.5 MeV) is possible on the base of β^--decay of the short lived ^{8}Li ($T_{1/2}$ = 0.84 s) isotope formed in the reaction ^{7}Li(n, γ) ^{8}Li. The ^{8}Li. isotope is a prime perspective antineutrino source taking into account that neutrino cross section depends as $\sigma \sim E_\nu^2$. at the considered 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 expressions for neutrino fluxes in the detector position are obtained.

1. Introduction

The difficulties on research 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 the square-law: $\sigma_\nu \sim E_\nu^2$.

In earthly conditions the Sun, nuclear reactors and accelerators 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:

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

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

2. Physical basis for creation of the antineutrino sources

Alongside with the obvious advantage on a neutrino flux the nuclear reactor has a 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 $E_{\tilde{\nu}}^{max}$ =13.0 MeV and mean energy $\overline{E}_{\tilde{\nu}}$ = = 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 (Fig. 1). The converter constructed according this idea will realize the static regime of operation.

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].

The simple schema 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, 11].

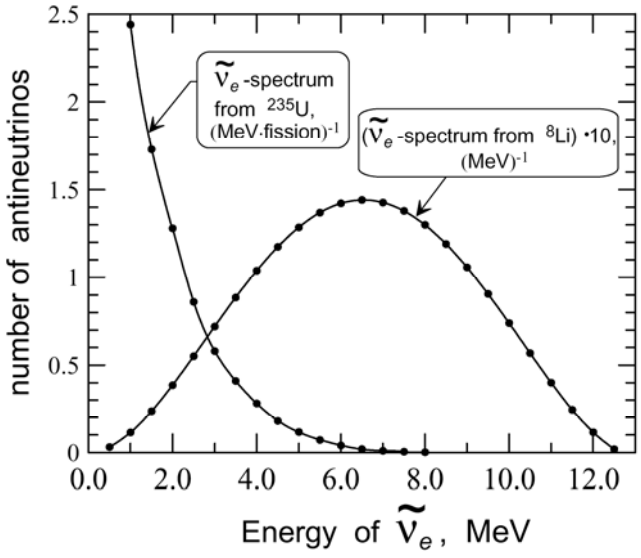

Fig. 1. $\tilde{\nu}_e$ - spectra from ^{235}U and β-decay of ^{8}Li.

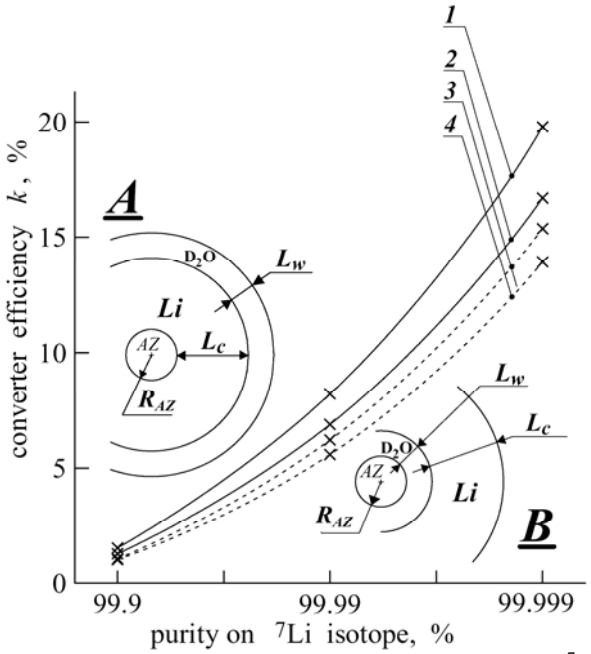

Fig. 2. Dependence of converter efficiency ***k*** on ^{7}Li isotope purity (with admixture of ^{6}Li) in the geometry ***A*** and ***B*** for lithium thickness L_C, heavy water layer L_w and reactor active zone radius R_{AZ} = 23 cm.

To compare these two types of geometry the calculations were performed (using MAMONT code [10, 11]) 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 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].

3. Choice of 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 can be a heavy water solution of lithium hydroxides (LiOD, $LiOD \cdot D_2O$) and lithium deuteride - LiD [12, 13].

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, $LiDF_2$ are not so perspective.

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

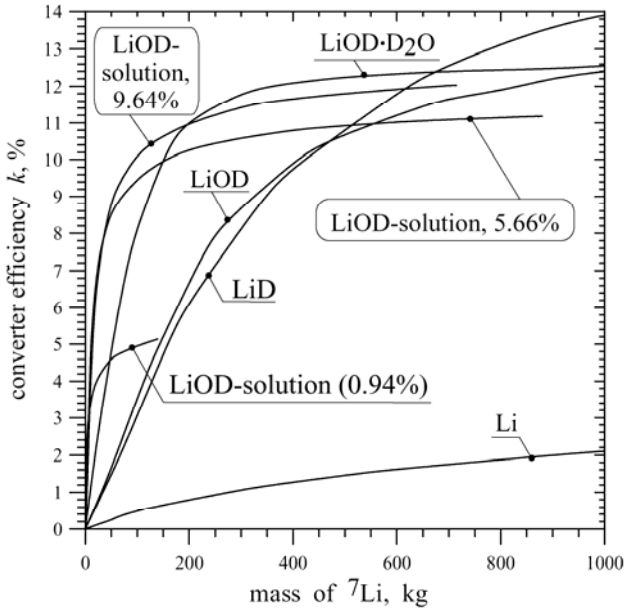

Fig. 3. Dependence of converter efficiency $\boldsymbol{k}$ on lithium mass m_{Li} for different chemical compositions and heavy water solution of LiOD (with LiOD concentration 0.94, 5.66 and 9.64 %).

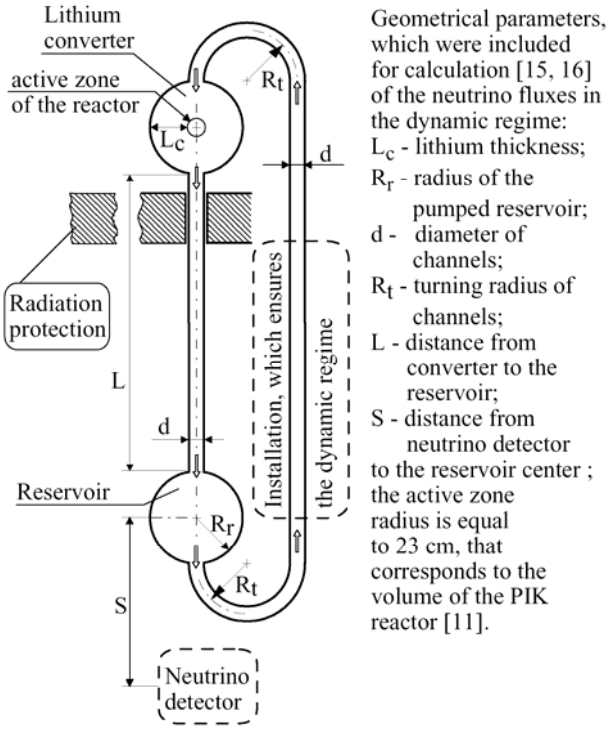

Fig. 4. Dynamic regime of the lithium antineutrino source on the basis of the nuclear reactor.

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(in persents) as function of the lithium mass m_{Li} for different chemical compositions and heavy water solution of LiOD are presented in the Fig.3. The results were obtained in the geometry $\boldsymbol{A}$ for ^{7}Li purification – 99.99 %.

Later it was considered the boron as an alternative material for antineutrino converter on the base of $^{11}B(n,\gamma)^{12}B$ reaction [14]. But at thermal energy the cross-section ratio of parasitic absorption on ^{10}B to the beneficial one 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.

4. Dynamic regime of the antineutrino source

It is possible to supply powerful neutrino fluxes with considerably greater hardness in a facility with a dynamic mode of operation [15 - 17]: liquid lithium is pumped over in a closed cycle through a converter and further in a direction to a remote neutrino detector (Fig. 4). For increasing of a part of hard lithium antineutrinos a being pumped reservoir is constructed near the $\tilde{\nu}_e$-detector. Such type of the facility will ensure not only more hard 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 fillup of the converter with thickness L_C = 1.5 m the required mass of lithium reaches 11.9 t. For realization of a dynamic mode the required lithium mass is increased in about 2 - 4 times [15].

For a facility with a dynamic mode of operation the heavy water solution of lithium hydroxide LiOD is 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).

For 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 $\boldsymbol{V}$ of moving in the channel. Examples of rapid pumping of the cooler (up to 5.65 m^3/s at linear speed 19.8 m/s) we can see at the reactors [18]: ATR, SRHFD (USA), GHFR (France).

5. Idea of the tandem: lithium converter plus accelerator

The conception of 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 [19, 20]. Such neutron sources exist in Russia, USA, Europe, Japan and are developing: IREN, IFMIF, JSNS/J-Park (Japan), ESS, CSNS (Table); project of electronuclear installation "Energy amplifier" by Rubbia C. [20, 21] et al. 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 such neutron generating target will be the powerful source of hard antineutrino. Realization of the dynamic regime will allow to transport the decaying ^{8}Li isotope more close to the neutrino detector [19].

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)	~$1 \cdot 10^{16}$ 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	$1 \cdot 10^{15}$ 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	$(1.8 - 2.7) \cdot 10^{17}$ s^{-1}	mercury; work since 2006 year
SINQ Swisserland, Paul Scherrer institute	protons, 590 MeV, 1.8 mA, steady-state flux	$1 \cdot 10^{14}$ $cm^{-2}s^{-1}$	lead; work since 1998 year
n-TOF Switzerland, Geneva, CERN	protons, 20 GeV, 4 Hz	$0.4 \cdot 10^{15}$ s^{-1}; at the distance 185 m from the target : $4 \cdot 10^{5}$ $cm^{-2}s^{-1}$	lead; work since 2000 year
IFMIF Italy, Frascati	deuterons, 40 MeV, 125 mA, steady-state flux	$(4.5 \div 10) \cdot 10^{17}$ $m^{-2}s^{-1}$	Moltem ^{7}Li; under construction
LANSCE USA, Los-Alamos	protons, 100-800 MeV, up to 1mA; 20 Hz	$1 \cdot 10^{16}$ s^{-1}; for MTS(material test facility): $2 \cdot 10^{15}$ $cm^{-2}s^{-1}$ (2012 year plan)	tungsten; work since 1985 year
KENS (Japan, Tsukuba, KEK)	protons, 500 MeV 10 μA, 20 Hz	$3 \cdot 10^{14}$ $cm^{-2}s^{-1}$	tungsten (tantalum clad); work since 1980 year
ESS Sweden, Lund	protons, 2.5 GeV, 14 Hz	$40 \cdot 10^{15}$ $cm^{-2}s^{-1}$ (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; $1.63 \cdot 10^{13}$ proton/pulse (according to Project phase 1)	~ $5 \cdot 10^{15}$ $cm^{-2}s^{-1}$	tungsten; normal operation in 2018 year

At the end of 1970-th years Yu.Ya. Stavissky [22] 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 ~ (1 · 15) m). 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 can be manufactured from tungsten and titanium elements. According to the simulation [22] the flux of thermal neutrons in the moderator cavity can be up to $6 \cdot 10^{19}$ 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 $6 \cdot 10^{18}$ the lithium antineutrino flux will reaches ~$(1 - 2) \cdot 10^{18}$ per pulse. The possible scheme of the proposed installation is given in the Ref. [20, 23].

6. Conclusions

The work is dedicated to the development of the powerful antineutrino source with a hard spectrum 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 compounds) 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 to a 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 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. It was obtained the expressions for lithium antineutrino fluxes from different parts of the facility operating in the dynamic regime [15 - 17].

The dynamic scheme allows 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 two orders in comparison with cross sections in the purely reactor $\tilde{\nu}_e$-spectrum [16, 17]. The extremally powerful source with pure lithium $\tilde{\nu}_e$-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 $\tilde{\nu}_e$ - spectrum is possible if to base on intensive neutron sources as pulse nuclear reactors, the tandem of accelerator with neutron producing target and (above discussed) beam dumps of large accelerators.

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