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ANTINEUTRINO SPECTRUM FROM POWERFUL REACTOR AND NEUTRINO CONVERTER SYSTEM

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Antineutrino spectrum for a powerful reactor–converter system based on ^{8}Li β^{-} decay is discussed. This neutron-to-antineutrino converter contains high-purified ^{7}Li isotope in chemical composition and β^{-} decaying ^{8}Li from $^{7}\mathrm{Li}(n,\gamma)^{8}\mathrm{Li}$ reaction. Many chemical compositions were analyzed and the most perspective is found to be LiOD heavy-water solution, which minimizes the converter lithium mass. Static, dynamic and pulse regimes are discussed for some types of converter constructions. The most interesting is powerful antineutrino source on the basis of accelerator-driven system (booster) used for incineration of nuclear waste.

Обсуждается спектр реакторных антинейтрино, производимый специальной системой конвертирования нейтрино, основанной на бета-распаде ядер ^{8}Li. Предлагаемый нейтрон-в-нейтрино конвертер содержит высокоочищенные изотопы ^{7}Li и β^{-}-распадающиеся ядра ^{8}Li от реакции захвата нейтрона $^{7}\mathrm{Li}(n,\gamma)^{8}\mathrm{Li}$. Проанализированы многие возможные химические составы такого конвертера и найдено, что наибольшие перспективы имеются у раствора LiOD в тяжелой воде, использование которого минимизирует общую массу лития. Для ряда возможных реализаций данного конвертера обсуждаются статические, динамические и импульсные режимы работы. Наиболее интересным является мощный источник антинейтрино на базе специального бустера, используемого для сжигания ядерных отходов.

1. LITHIUM CONVERTER AS A POWERFUL ANTINEUTRINO SOURCE

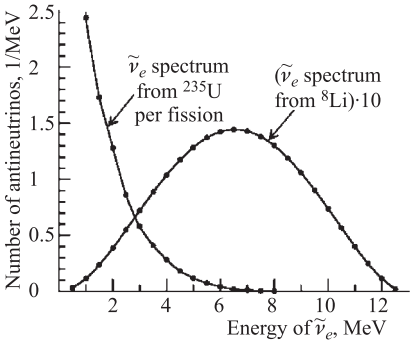

Fig. 1. Neutrino spectra from ^{235}U and β decay of ^{8}Li

Nuclear reactors, as powerful $\tilde{\nu}_e$ sources, are used for experimental study of neutrinos during 50 years, beginning from first observation of neutrinos at the Savannah River reactor by Cowan and Reines. Alongside with the obvious advantage of a neutrino flux, the nuclear reactor has a disadvantage. It is too small hardness of the $\tilde{\nu}_e$ spectrum. This disadvantage can be bypassed with realization of the idea of using a high-purified ^{7}Li isotope for construction of a reactor neutron-to-antineutrino converter, which is located close to the active zone of a reactor [1]. The neutron flux from the active zone creates in this converter a short-lived isotope ^{8}Li ($T_{1/2} = 0.84$ s) by means of the reaction $^{7}\mathrm{Li}(n,\gamma)^{8}\mathrm{Li}$. In subsequent

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β^- decay of ^{8}Li, hard antineutrinos with well determined spectrum (the maximum energy $E_\nu^{\max} = 13.0$ MeV and mean energy $\overline{E}_\nu = 6.5$ MeV) are emitted. As a result, the total $\tilde{\nu}_e$ spectrum from the active zone of a reactor and from ^{8}Li decays becomes considerably harder in comparison with a purely reactor spectrum (Fig. 1). The idea of a neutrino source based on ^{8}Li decay was discussed firstly in [2] and for the pulse reactor in [3]. The construction of intensive neutrino sources with a hard spectrum, different types of Li converters for reactors working in a stationary mode, applications of converters for neutrino research are considered in [1, 4, 5].

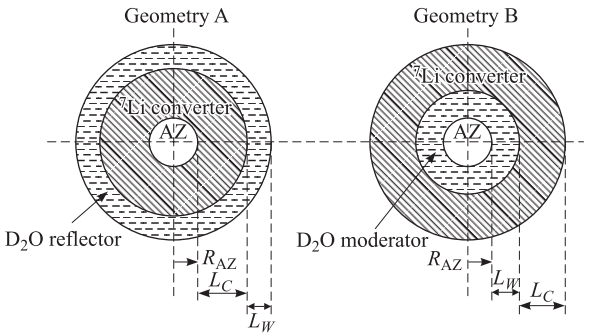

Fig. 2. Geometry of the multilayer converter

The simple scheme of spherical construction of the multilayer converter is presented in Fig. 2. The radius $R_{\rm AZ} = 23$ cm of the active zone (AZ) corresponds to a 51-liter volume of the high-flux PIK reactor [6]. To compare these two types of geometry, the Monte-Carlo simulations with MAMONT code [1] were carried out, 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 is sufficient for the reflector in geometry A and nearly optimal for the moderator in geometry B. 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 efficiency k, which is equal to the number of ^{8}Li isotopes created per one neutron escaping from the active zone. The hardness of the total $\tilde{\nu}_e$ spectrum from the active zone and from the converter increases at $k \geqslant 20\%$. Due to the $\sigma_\nu \sim E_\nu^2$ dependence, this positive effect allows one to obtain significantly larger σ_ν cross section. Therefore, the main problem is to increase the efficiency of the converter and hence to increase the intensity and hardness of the total $\tilde{\nu}_e$ spectrum. There are four ways to do this: 1) to increase the purity of ^{7}Li up to no less than 99.999%; 2) to use chemical combinations of ^{7}Li isotope as the converter material; 3) to use the reactor–converter system realizing the dynamic regime of operation, and 4) to realize the pulse reactor–converter system.

2. CONVERTER MATERIAL

It is difficult to increase the efficiency of the converter by increasing the purity of ^{7}Li to required very high value. The promising way is to use the different chemical compositions

of ^{7}Li as the converter material instead of the pure ^{7}Li isotope. For example, a perspective substance is a heavy-water solution of lithium hydroxide LiOD, $\mathrm{LiOD \cdot D_2O}$ and LiD [1, 6]. The estimations of the Li mass for different chemical compositions and some other information are given in table. The LiOD heavy-water solution can be considered as the most perspective. It allows one to reduce the layer thickness L_C down to 1 m and sharply reduce a required mass of high-purified lithium. For example, to achieve the efficiency $k = 0.077$ with the concentration of 9.46%, one needs 300 times smaller lithium mass than in a converter with pure lithium. Other chemical compositions like $\mathrm{Li_2C_2}$, $\mathrm{Li_2CO_3}$, $\mathrm{Li_2O}$, $\mathrm{LiDCO_3}$, LiF, $\mathrm{LiDF_2}$ and their heavy-water solutions were less perspective.

Comparison of lithium different chemical compositions as converter material

Converter material	Density, g/cm^2	Temperature of melting t, °C	Li mass (in kg) for $k = 9\%$ (^{7}Li = 99.99%)
^{7}LiD (lithium deuteride)	0.89 (crystal) 0.80 (pressed)	686 ± 5	> 300
^{7}LiOD (lithium hydroxide)	1.495	$462 \div 471$ (for LiOH)	250
$^7\mathrm{LiOD \cdot D_2O}$ (monohydrate of lithium hydroxide)	1.965	> 600 (for $\mathrm{LiOH \cdot H_2O}$)	115
$^7\mathrm{LiOD \cdot D_2O}$ + ^{7}Li (6%)			70

As an alternative material for $n - \tilde{\nu}_e$ converter, boron [7] from $^{11}\mathrm{B}(n,\gamma)^{12}\mathrm{B}$ reaction may be used. Isotope ^{12}B ($T_{1/2} = 20.20$ ms) has a hard antineutrino spectrum close to that of Li with $E_\nu^{\max} = 13.4$ MeV and mean energy $\overline{E}_\nu = 6.8$ MeV. But at thermal energy, the cross-section ratio of parasitic absorption on ^{10}B (abundance = 19.8%) to the beneficial one on the starting isotope ^{11}B [$\sigma_a(^{10}\mathrm{B})/\sigma_{n\gamma}(^{11}\mathrm{B}) = 3837/0.0055$] is considerably worse than for lithium [$\sigma_a(^6\mathrm{Li})/\sigma_{n\gamma}(^7\mathrm{Li}) = 937/0.045$]. When the isotope composition is accounted for and the same converter efficiencies assumed, the grade of purity required for manufacture of the boron neutrino source should be $\cong 99.9997\%$ on ^{11}B isotope compared with technologically producible 99.99% purity of ^{7}Li in a lithium neutrino source.

3. DYNAMIC REGIME

In the dynamic system, liquid lithium or its chemical composition is pumped over in a closed cycle through a converter close to the active zone of a reactor and further close to a reservoir located nearby the $\tilde{\nu}_e$ detector. Such a facility will ensure not only harder $\tilde{\nu}_e$ spectrum near the detector but also an opportunity to investigate $\tilde{\nu}_e$ interaction at different spectrum hardness varying a rate of lithium pumping-over. The maximal effect is reached at small distance from the reservoir and at maximum flow rate. As an example of particular dynamic systems, it is shown [8] that, owing to a large growth of hardness of the total $\tilde{\nu}_e$ spectrum, the cross section of neutrino interaction with a deuteron can be ten times increased

in the neutral channel ($\tilde{\nu}_e + d \to n + p + \tilde{\nu}_e$) and two-order-of-magnitude increase is possible in the charged channel ($\tilde{\nu}_e + d \to n + n + e^+$).

4. PULSE REACTOR-CONVERTER

The efficiency and hardness of the total $\tilde{\nu}_e$ spectrum must be much higher for a $\tilde{\nu}_e$ source based on a pulse reactor surrounded by a n–$\tilde{\nu}_e$ converter. Neutron outgoing flux is much higher, but one needs larger D_2O mass and also lithium for thermalization of the fast neutrons.

It is constructively difficult to use a standard pulse reactor [9] surrounded by a converter because the reactivity and operation control should be changed strongly. For the neutrino investigations the special pulse reactor RING was proposed [10]. But it is rather difficult to realize the scheme of the reactor and converter with moving constructions.

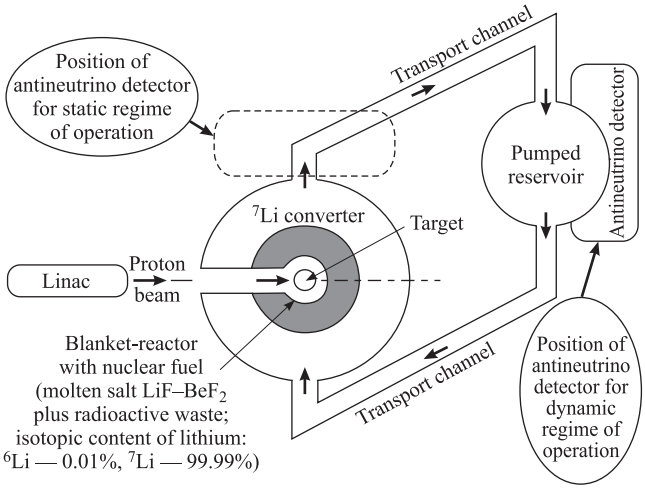

Fig. 3. Scheme of the lithium antineutrino source on the basis of the booster-type neutron source. Variants for the static and dynamic regimes of operation

We propose to use a powerful booster-type neutron source surrounded by a converter. This scheme is used in projects for incineration of nuclear waste in the framework of national Russian, European and USA programs. The scheme of a facility based on a linear proton accelerator is presented in Fig. 3 for static and dynamic regimes of the converter operation. Hard-spectrum neutrinos from ^{8}Li (accumulated in $^7\mathrm{Li}(n,\gamma)^8\mathrm{Li}$ process) will be detected by an antineutrino detector situated close to the converter (static regime of operation). In the installation with lithium pumped over the cycle (from the converter to the remote reservoir and back to the converter) the converter operates in the dynamic regime. In the dynamic regime the antineutrino detector will be situated near the pumped reservoir. This scheme will allow one to increase the part of the hard neutrino spectrum from ^{8}Li and to decrease the soft part of the neutrino spectrum (from fission processes in the blanket-reactor) in the total neutrino spectrum. For this scheme, LiOD heavy-water solution is the most promising

converter material from the standpoint of the efficiency k and requested mass of high-purified ^{7}Li isotope.

In such an installation one can use molten-salt LiF–BeF_2 composition together with radioactive waste and the LiOD heavy-water solution as the neutrino converter and cooling material simultaneously. The linac could be more preferable than a synchrotron accelerator, because 1) it is cheaper, 2) the facility ensures harder and more stable (in time) $\tilde{\nu}_e$ spectrum (important for precision measurements), 3) more intensive $\tilde{\nu}_e$ flux is possible with low-energy particle beam.

There are two intensive fast neutron fluxes falling on the converter. One is from the target and the other is from the pulse blanket-reactor. The first flux of photoneutrons has harder spectrum than the second one of the prompt neutrons, and in this situation one needs larger mass of the heavy-water moderator for neutron thermalization.

CONCLUSION

Today, when big national projects of very intensive neutron sources for nuclear waste incineration are in progress, it becomes more realistic to engineer an antineutrino plant for scientific research. The $\tilde{\nu}_e$ flux of 10^{13}–10^{14} $(\mathrm{cm}\cdot\mathrm{s})^{-1}$ in the dynamic regime of operation will be comparable with the flux from the powerful reactor at a distance of 10–15 m [11]. The $\tilde{\nu}_e$ spectrum from such a facility will be much harder than the one from the simple reactor–converter system, and in this case the efficiency depends on the construction of the target–reactor–converter system and its cooling devices.

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