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Investigation of a Possibility of Chromium-51 Accumulation in the SM-3 Reactor to Fabricate a Neutrino Source

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Abstract. Compact high intensity neutrino sources based on ^{51}Cr isotope are demanded for very short baseline neutrino experiments. In particular, a 3 MCi ^{51}Cr neutrino source is needed for the experiment BEST on search for transitions of electron neutrinos to sterile states. The paper presents the results of the analysis of options of the irradiation of highly enriched ^{50}Cr in the existing trap of thermal neutrons of high-flux reactor SM–3, as well as using the most promising variants of the trap after upcoming reconstruction of the reactor. It is shown that it is possible to to obtain the intensity of ^{51}Cr up to 3.85 MCi at the end of irradiation of ^{50}Cr enriched to 97% in the high-flux reactor SM–3 of the JSC "SSC NIIAR".

1. Introduction

One of the most important tasks in study of composition of the Universe is to obtain complete information about neutrino sector. The priority task in this direction is to verify the hypotheses about the existence of sterile neutrinos - hypothetical particles, which, according to modern ideas, can be a part of dark matter [1]. For direct test of this hypothesis, an experiment has been required to measure with high accuracy the neutrino flux as a function of distance from the source. Attention to solution of this problem is so great, that in the recent years, dozens of projects with use of nuclear reactors, accelerators, and high-intensity artificial sources of neutrinos and antineutrinos were proposed and widely discussed [2 – 5].

Of particular interest is the proposed experiment BEST on search for sterile neutrinos based on investigation of interactions of neutrino from a powerful compact artificial ^{51}Cr source with nuclei of metal gallium target of the Gallium-Germanium neutrino telescope of the Baksan Neutrino Observatory INR RAS. In the experiment, it is planned to place the neutrino source ^{51}Cr with activity 3MCi in the center of Ga metal target of the telescope divided into two concentric zones, internal and external, with equal average path length of neutrinos and to measure the neutrino capture rate on gallium in each zone. The statistically significant differences between the values of neutrino capture rate in the zones will give a direct proof of transitions of active neutrino into sterile states.

To date three high-intensive artificial neutrino ^{51}Cr sources with the intensity of 19.13 PBq (0.517 MCi) in the experiment SAGE [6, 7], 63.42 PBq (1.714 MCi) and 69.12 PBq (1.868 MCi) in the GALLEX experiment [8, 9] have been produced for the calibration of gallium detectors of solar neutrinos.

To achieve a sensitivity to disappearance of electron neutrinos of a few percent in the BEST experiment, the activity of a source based on the ^{51}Cr isotope should be not lower than 111 PBq (3 MCi). In this paper, we investigate the possibility of fabricating such a source using the research reactor SM-3 at the JSC "SSC RIAR".

2. Input data and computational models

The ^{51}Cr-based neutrino source under development must be compact enough. One of its design modifications under consideration implies that the source represents itself a welded stainless steel capsule with overall dimensions of about 100 mm. There are thin-walled stainless steel tubes inside the capsule. These tubes comprise irradiated chromium metal bars, which are manufactured as rods with 8.5 mm diameter and a height of 9.5 cm (there are eighty-one (81) chromium bars in total). A total mass of starting material will be 3000 g of chromium enriched in ^{50}Cr up to 97%.

As evidenced by the preliminary results, target activities of ^{51}Cr (at least 3 MCi) can be achieved in the SM-3 reactor in the position with the highest flux of thermal neutrons that the central neutron trap. It is the main and the most demanded irradiation position in the reactor that is occupied by 100% at the moment.

The present paper discusses the following modifications of the SM-3 central trap (channel) arrangement:

- "Separator"-type that is the present-day separator-type design modification comprising twenty-seven (27) zirconium tubes with dimensions $\varnothing 15\times1.25$ mm to accommodate targets under irradiation in water moderated conditions (figure 1);
- "Separator-free" design modification. It is similar to the above-described design but it does not have a separator;
- "Module-type" design modification. There will be four reloadable modules with neutron moderator and absolutely new design of the central shim rod in the neutron trap (figure 2);
- Neutron trap without the central shim rod. In this case the SM-3 neutron tarp will not have the central shim rod (figure 3).

High-precision calculations of neutronic parameters were performed with the use of the MCNP code [10]. It implements a computational algorithm of neutron spatial and energy distribution in three-dimensional geometry with the use of Monte Carlo method. The composition of materials zones in the computational model was the same as in a standard model of the reactor used for irradiation simulations. As to the fuel assemblies (FA) in the reactor core, the computational model provided for their burnup of 15%. The positions of shim and control rods corresponded to the mid position during the reactor operation cycle.

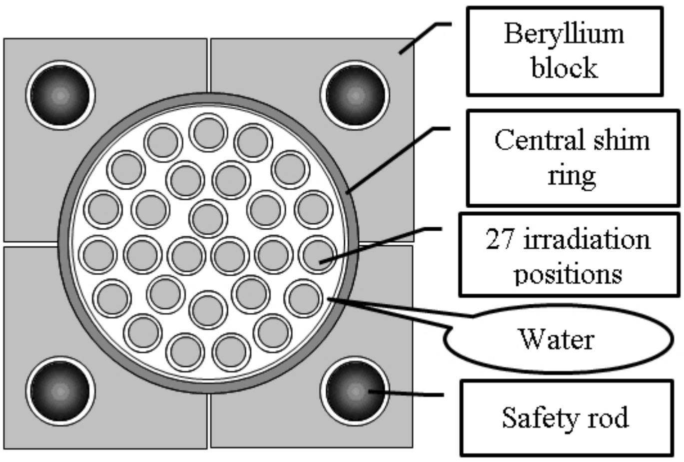

Figure 1. "Separator-type" design modification of the SM-3 neutron trap.

When calculations were performed, neutron flux functions were registered in the volumes of chromium bars provided that the target had one, two or three bars (the number depends on the computational model) and they are placed symmetrically relative to the SM-3 mid-core plane. A rate of radiation neutron capture reaction occurred on the ^{59}Co (to obtain a temperature of neutron gas) ^{50}Cr and ^{51}Cr nuclei, was also considered in calculations. Functionalities of neutrons were registered in energy groups with the uppermost energies of 0.5 eV, 100 eV, 0.1 MeV, and 20 MeV.

The “separator-type” (figure 1) and “separator-free” modifications provided for twenty-seven (27) targets with three chromium bars and zirconium cladding with dimensions ∅10×0.4 mm. The “module-type” design modification (figure 2) provides for fifty-two (52) zirconium tubes with dimensions ∅14×0.5 mm but the cross-shaped absorber of the central shim rod is removed from the core. The tubes accommodate targets with chromium bars and zirconium cladding (∅10×0.4 mm). In computational simulation consideration was given to three (3) chromium bars in each twelve (12) central irradiation positions and two bars in each twenty-four (24) middle irradiation positions. Moreover, the remaining positions were occupied with aluminum dummies (it is a dummy target with an aluminum rod). The modules were filled with water.

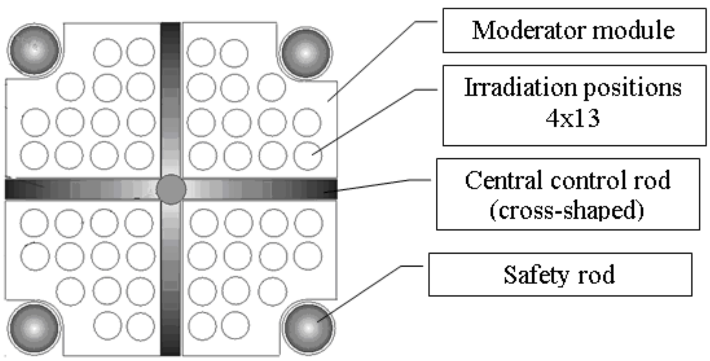

Figure 2. “Module-type” design modification of the SM neutron trap.

The computational model of the neutron trap without the central shim rod (figure 3) includes fifty-seven (57) irradiation positions which are occupied with the following: three chromium rods are placed in each twenty-five (25) irradiation positions in the central region, one chromium rod is placed in each six (6) irradiation positions in the 4th row and dummies are placed in the remaining irradiation positions. The neutron trap is filled with water.

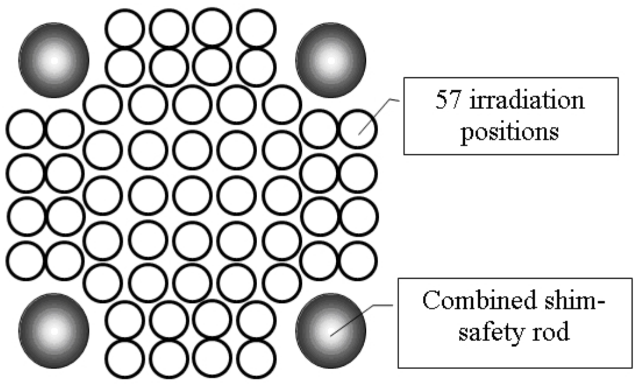

Figure 3. The SM-3 neutron trap design modification without the central shim rod.

The most suitable layout of chromium bars and dummies for the “module-type” design modification of the neutron trap and its design modification without the central shim rod was chosen based on the analysis of neutronic parameters with reference to unperturbed states when all the irradiation positions were occupied with aluminum dummies in a model. The regions where the thermal neutron flux density is the highest were chosen to accommodate chromium.

3. Results of calculations

Given in table 1 are the calculated irradiation parameters averaged over all the chromium bars (computational simulation data).

Table 1. Neutronic parameters of chromium irradiation.

Neutron trap modification	Neutron flux density averaged over the Cr bars, $cm^{-2}s^{-1}$, with the following energies:				Neutron gas temperature, K
	0 ÷ 0.5 eV	0.5 ÷ 100 eV*	0.1 ÷ 100 keV	Higher than 0.1 MeV	
“Separator-type”	3.76E+14	1.00E+14	7.77E+14	1.04E+15	720
“Separator-free”	4.29E+14	9.28E+13	6.86E+14	9.23E+14	680
“Module-type”	4.87E+14	8.80E+13	6.59E+14	1.01E+15	650
Neutron trap without the central shim rod	4.41E+14	8.75E+13	6.38E+14	9.39E+14	676

* – per unit interval of lethargy

To perform computational simulation of nuclei transmutations, the ChainSolver code from the ORIP_XXI [11] code package was used. The considered schedule of the SM-3 reactor operation during chromium irradiation is almost to be the same as a standard one: a reactor operation cycle of 10 days takes turns with short-term (1 day) and long-term (5 days) reactor outages. The reactor thermal power was taken to be equal to 100 MW. Figure 4 represents the ^{51}Cr activity as a function of irradiation time with reference to different design modifications of the neutron trap.

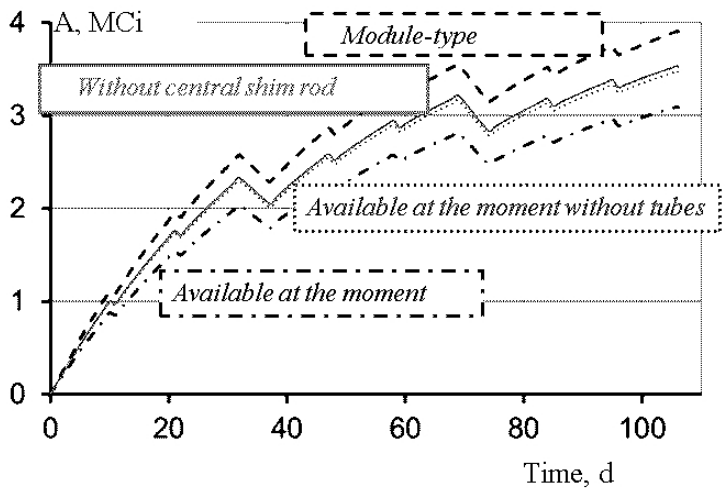

Figure 4. Calculated total activity of ^{51}Cr in irradiated bars.

As it is shown in figure 4, the module-type design modification of the central neutron trap is the most promising one for the ^{51}Cr accumulation (provided that it is filled with water). At the same time, the “separator-free” design modification is very easy to use and it allows the target activity to be achieved.

4. Conclusion

The completed research in support of ^{51}Cr production suggests that the active part of the neutrino source with the target parameters could be produced with the use of the SM-3 reactor.

The further research and development work will be focused on studying new design modifications of the SM-3 central neutron trap (in view of the SM core refurbishment in 2019) as well as on design engineering of the source itself capable of necessary biological shield from emission of radionuclides formed under irradiation including activation of impurities in the material.

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