Fabrication of reactor target from enriched $^{50}$Cr for artificial neutrino source

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Abstract. The fabrication of the enriched $^{50}$Cr target for the artificial $^{51}$Cr neutrino source with activity $> 3$ MCi for the experiment BEST is presented. The processes of obtaining a target in the form of disks with a thickness of 4 mm and a diameter of 84 and 88 mm required to achieve the necessary activity using the reactor SM-3 are considered, including: enrichment of natural chromium in the form of oxyfluoride by gas centrifugation, electrolytic reduction and refining of metallic chromium, as well as the formation of chromium disks by spark plasma sintering.

1. Introduction
For the first time intense artificial neutrino sources were employed by SAGE and GALLEX in order to test all experimental procedures. SAGE used $^{51}$Cr [1] and $^{37}$Ar [2] sources and GALLEX twice used a $^{51}$Cr source [3, 4]. The weighted-average result of these four experiments, expressed as the ratio R of the measured neutrino capture rate to the expected rate, based on the known neutrino capture cross section gave $R = 0.87 \pm 0.5$, more than two standard deviations less than unity, named the Gallium anomaly [5]. The Gallium anomaly can be explained as $\nu_{e}$ oscillations into sterile states at very short baselines with $\Delta m^2$ about 1 eV$^2$ [6]. For solution of this problem the experiment BEST has been proposed [7].

In BEST an artificial $^{51}$Cr neutrino source with initial activity of $\sim 3$ MCI will be placed in the center of a 50-tonne target of liquid Ga metal that is divided into two zones (an inner 7.5 t zone and an outer 42.5 t zone), that provide the same neutrino pass length of 55 cm in each zone. The direct evidences of nonstandard neutrino properties can be: 1) a significant difference between the capture rates in the two zones and/or 2) considerably low average rate in both zones in comparison with the expected rate.

One of the main stages in realizing of the project BEST is production of a compact high-intensive artificial neutrino source based on $^{51}$Cr of high radionuclide purity.

2. Stages of $^{51}$Cr source fabrication
The $^{51}$Cr source emits neutrino with energy 0.75 MeV (90.1 %) and 0.43 MeV (9.9 %) according to reaction: $^{51}$Cr + e$^{-} \rightarrow ^{51}$V + $\nu_{e}$. Both lines can be detected by gallium-germanium telescope. However, since 96% of captures on Ga are from neutrino with energy 0.75 MeV, the source can be considered with a good approximation as monochromatic one.
a) $^{50}$Cr enrichment

$^{51}$Cr can be produced by neutron capture on $^{50}$Cr. However, $^{50}$Cr content in the natural chromium is only 4.35%. Therefore, the first step in source fabrication is the $^{50}$Cr enrichment. The gas centrifugation of chromyl fluoride CrO$_2$F$_2$ was chosen due to its rather high efficiency and low cost. Chromyl fluoride is an appropriate volatile compound due to its chemical and physical properties: 1) reasonably high saturation vapor pressure at room temperature (> 5-10 mm Hg); 2) inactivity to equipment materials; 3) existence of the only one stable isotope of oxygen and fluorine; 4) thermal and chemical stability (no transition in nonvolatile substances).

370 kg of chromyl fluoride (99.97%) was synthesized in the National Research Center "Kurchatov Institute" by the technology based on the reaction of molecular fluorine with chromium trioxide at elevated temperature in the flow system.

The 98% $^{50}$Cr enrichment was carried out in The Joint Stock Company “Production Association “Electrochemical Plant” (JSC “PA ECP”, Zelenogorsk, Krasnoyarsk region). After gas centrifugation the chromyl fluoride CrO$_2$F$_2$ was hydrolyzed in chromic anhydride form with the total CrO$_3$ mass 8875 g and the chromium mass 45000 g.

b) Metal Cr electrolytic reduction

The next technological procedure was the electrolytic reduction of metal chromium from aqueous solution CrO$_3$ and H$_2$SO$_4$. The electrolyzer was constructed in INR RAN and corresponds the water-cooled titanic cell with lead anode and steel cathode. The operating parameters of electrolysis were followed: I - 200 A, U – 5.5-6.5 V, T - 18-23 ºC with the average efficiency of metal chromium about 25 g/h.

We carried out the electrolysis of natural chromic anhydride and analyzed its chemical composition by ICPMS technique. The chromium flakes after electrolysis were annealed in high-purity hydrogen atmosphere at 1540 ºC. The appearance of the electrolytic chromium flakes before and after annealing are shown in figure 1.

![Figure 1](image1.png)

**Figure 1.** The chromium flakes after electrolysis of natural chromic anhydride a) before and b) after thermal annealing.

The main metallic impurity elements are displayed in table 1.
Table 1. The chemical composition of metal chromium flakes from the natural chromic anhydride.

| Elements | Na  | Ti  | Mn  | Fe   | Ni   | Cu  | Zn  | Sn  | Ba  |
|----------|-----|-----|-----|------|------|-----|-----|-----|-----|
| Concentration, ppm | 12.0 | 2.5 | 1.0 | 90   | 10.3 | 1.2 | 2.1 | 0.5 | 2.6 |

Mainly these impurity elements got into the chromium during the electrolysis: Fe, Ni and Mn from the stainless-steel cathode, Na from the natural chromic anhydride. So, we had to apply another refinement procedure of electrolytic chromium flakes after electrolysis in solution of the nitric acid.

c) Metal Cr compaction

There are different techniques of metal powder compaction. At first, we proposed to use the hot isostatic pressing (HIP) at high isotropic pressure and elevated temperature. After HIP procedure we planned to apply the electrical discharge machining of Cr bar with the aim to get the chromium hexagonal rods and irradiate them by thermal-neutrons in the atomic reactor [8].

But HIP technique involves using the mechanical operation of chromium bars which can result in rather high losses of expensive material. So, we decided to apply the spark plasma sintering (SPS) that uses pulsed high electrical current to rapidly heat a conductive powder under simultaneous uniaxial pressure. With no heating elements extremely rapid heating and cooling of the sample is possible, enabling high density materials to be sintered with ultra-fine or even nano-sized grain structures.

Before SPS the electrolytic chromium flakes were grinded in FSUE “IREA” using a mechanical mortar RM200 to a powder with a particle size of up to 315 microns (figure 2). This powder was compacted in MSTU “STANKIN” by SPS technique to test the mechanical properties of compressed material. The specific density of the compacted species is 7.1 g/cm³, the porosity – 0%, the flexural strength – 170 MPa, the chromium loss is less 3%. These mechanical properties of metal chromium fulfil requirements to the irradiation target.

Figure 2. Chromium powder with a particle size of up to 315 microns.

d) Design of irradiative $^{50}$Cr target.

The new form of chromium pieces and an irradiation fitment were offered by JSC «SSC RIAR» (figure 3). Neutrino source will enclose 26 chrome disc assembly with a thickness of 4 mm and a diameter of 84 and 88 mm (with inner hole diameters of 6 and 22 mm, respectively) in sealed steel container and biological tungsten shielding.
Figure 3. (a) Neutrino source scheme with 26 chrome disc assembly in sealed steel container and biological tungsten shielding; (b) Part of irradiation fitment with chrome discs.

The design of the irradiation fitment provides acceptable cooling conditions and simplifies the process of assembling the source.

3. Conclusions

The design of the artificial neutrino source based on $^{51}$Cr for the BEST project was developed. The neutrino source will be consisted of 26 chromium disks in sealed steel container and biological tungsten shielding. Technology of the $^{51}$Cr source production includes the stages of natural chromium enrichment, production of metal chromium target and irradiation with thermal neutrons. Currently, the gas centrifugation of CrO$_2$F$_2$ was carried out and $^{50}$Cr enrichment is 98%. Technology of metal chromium target fabrication (electrolytic metal chromium reduction, thermal refinement in hydrogen, chips grinding, spark plasma sintering of metal chromium powder) is developed and tested.

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