Proposal of experiment for Very Short Baseline $\nu_e \rightarrow \nu_x$ Oscillation Search with a Dual Metallic Ga Target at Baksan and a ^{51}Cr Neutrino Source (BEST experiment)

BEST

(**B**aksan **E**xperiment on **S**terile **T**ransitions)

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Abstract

At the Gallium-germanium neutrino telescope at the Baksan Neutrino Observatory INR (Russia) there is a unique opportunity for research aimed at solving the most pressing problems of basic science - the absence of antimatter in the universe and the nature of dark matter. In the attempts to find solutions of these problems the attention of the world scientific community is focused on the hypothesis of the existence of sterile neutrinos - hypothetical particles whose interaction with matter is carried out through small admixtures of conventional (i.e. active) neutrinos. Now in the world, more than fifty possible approaches to its experimental solution are actively being discussed.

We propose an experiment to search for sterile neutrinos through using neutrino from a powerful compact artificial source interacting on nuclei of gallium in the gallium-germanium neutrino telescope. Unique supersensitive gallium-germanium neutrino telescope with 50 tons of metallic gallium is located in the low-background conditions, deep under the earth's surface and is successfully operating for more than 20 years in the experiment SAGE. The highly qualified research team at the telescope has experience with powerful artificial sources of neutrinos, and Russia has a unique experience and technical capabilities of their manufacture.

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 can give a direct proof of a real physical effect, the disappearance of electron neutrinos, the possible transitions of active neutrinos into sterile states. The oscillation signature coming from the ratio of events in the near and far gallium volumes is largely free of systematic errors such as cross section or source strength uncertainties.

This project, in comparison with other projects, has several advantages: a well-known neutrino spectrum, the large value of the signal- to-background ratio, ease of interpretation of the results. The proposed experiment has a sensitivity of a few percent to the disappearance of electron neutrinos and has the potential to search transitions of active neutrinos into sterile states with oscillation parameters Δm^2 >0.5 eV^2 and $\sin^2 2\theta$ >0.1.

I Introduction

The discovery of neutrino oscillations has provided a direct challenge to the completeness of the Standard Model of particle physics. Cosmology provides two other pieces of evidence for this lack of completeness: these are the mystery of dark matter and the baryon asymmetry of the Universe. It is noteworthy that all these phenomena can be explained by modification of just the neutrino sector of the Standard model [1]. Therefore studies of neutrino sector are important not only for building a complete model of particle physics, but for understanding the evolution of the Universe and for refining its present composition [2].

In the proposed experiment we plan to study the hypothetical sterile neutrino of mass greater than 0.5 eV and moderate mixing angles with active neutrinos. Interest in such models has increased greatly in the last few years due to announcements of new experimental results, which do not fit the standard scheme with just three light (active) neutrinos.

Recently there have been indications from cosmology to the possible presence of light sterile neutrinos in the primordial plasma in the early Universe. In the early Universe light sterile neutrinos with moderate mixing are in thermal equilibrium with Standard Model particles and after decoupling continue to contribute to the expansion rate of the Universe, along with the usual neutrinos. Modern cosmological data exhibit better agreement with theoretical predictions, if we assume the presence of one additional light fermionic component (sterile neutrino) at the epoch of primordial nucleosynthesis [3] and at the epoch of recombination [4]. In the course of further expansion of the Universe sterile neutrinos of masses about 1 eV become non-relativistic and at present they form a constituent part of the dark matter.

There is evidence from experiments directly studying neutrino oscillations. For many years, all direct experimental data well fit into the scheme with three active neutrinos [5]: there are two non-zero differences of squared neutrino masses, two large and one small mixing angle. The only exception was the LSND experiment, which announced the discovery of oscillations between the muon and electron antineutrinos, which imply a moderate mixing angle and squared mass difference of about 1 eV^2 [6]. This result does not fit into the standard pattern of three neutrinos, and suggests at least one light sterile neutrino needs to be introduced to the theory. There were attempts to verify the existence of oscillations with such parameters in various experiments (NOMAD [7], KARMEN [8]). The experiments results obtained were rather controversial; they failed to exclude entirely the region of parameter space claimed by the LSND experiment.

The problem of existence and nature of sterile neutrinos of mass about 1 eV has been emphasized in the last few years, because of both announcement of new anomaly results in experiments on observation of neutrino oscillations and some refinement of cosmological data. Firstly, the MiniBooNE experiment at the first stage of studying oscillations $\bar{\nu}_\mu \to \bar{\nu}_e$ has received the result [9], which agrees with the result of the LSND. At the same time the oscillations $\nu_\mu \to \nu_e$ are consistent with the standard 3-neutrino pattern, and for low-energy events (MiniBooNE experiment works with a wide beams of neutrinos and antineutrinos) the anomalous behavior is exhibited in both channels [10], which does not resemble the oscillation signal at all. Secondly, the evaluations of reactor antineutrino fluxes have been revised [11], so that the results of corresponding experiments began to point to some deficit (unfortunately, the uncertainties of the estimates are quite large), which supports the hypothesis of oscillations of $\bar{\nu}_e$ with parameter $\Delta m^2 \lesssim 1$ eV [12]. The combined analysis of the whole experimental data set shows that it is possible to explain the results with two sterile neutrinos of masses $\lesssim 0.5$ eV [13]. Possibly the same physics is responsible for the result of the calibration experiments of SAGE and GALLEX with artificial sources of neutrinos [14,15].

In light of foregoing, the direct verification of the hypothesis about the oscillations into sterile neutrino with $\Delta m^2 \lesssim$ 1eV is of great value. The neutrino sector differs significantly from the quark sector, and here, probably, a lot of mysteries are still hidden being relevant not only for particle physics, but for astrophysics and cosmology also. Neutrinos are produced in thermonuclear reactions and the details of their interactions have impact on stellar evolution. An understanding of the light neutrino physics is crucial for developing reliable systems for monitoring thermonuclear processes in the inner parts of the Sun and nuclear processes in the center of the Earth [16], and for adopting neutrinos to study the internal structure of the Earth [17]. Determination of the complete set of light neutrino and their masses and mixings, will allow a reduction in the degeneracy between cosmological parameters [2], which is important for understanding the nature of dark energy.

II SAGE and Ga experiments with neutrino sources

1. Short overview of experiment SAGE

SAGE (Soviet American Gallium Experiment) [18,19] was created with a goal to solve the problem of the deficit of solar neutrino observed in the Cl experiment where the detected rate of Solar neutrinos was one third of the value predicted by the Standard Solar Model. Only a radiochemical experiment based on reaction of neutrino capture on ^{71}Ga nuclei could give the possibility to get information about the low energy part of the solar neutrino spectrum, and, most importantly, about *pp* neutrino.

The feature of the experiment that distinguishes it from all other already performed or currently operating solar neutrino experiments is its sensitivity to the reaction of proton-proton fusion $p + p \rightarrow d + e^+ + \nu_e,$ in which the overwhelming part of the solar energy is generated, and which almost independent of the parameters of the solar models. At the present time SAGE is the only experiment that provides direct measurement of the current rate of this reaction.

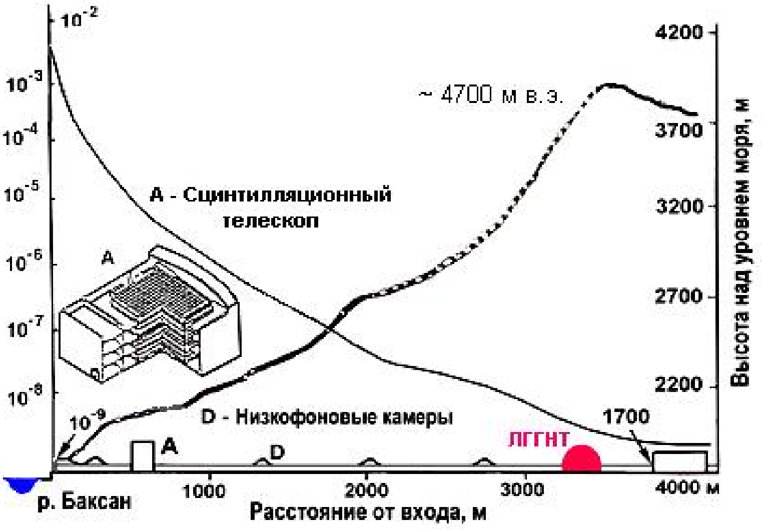


Fig. 1. Mountain profile, muon flux curve and layout of location of the BNO underground laboratories.

1.1. Laboratory of the Gallium-Germanium Neutrino Telescope

The measurements in SAGE are carried out on the Gallium-Germanium Neutrino Telescope (GGNT) that is situated in a dedicated deep-underground laboratory of the Baksan Neutrino Observatory of the Institute for Nuclear Research of the Russian

Academy of Sciences in the northern Caucasus mountains in Elbrus region. The underground GGNT facility is located at a distance of 3.5 km from an entrance of a horizontal tunnel leading to the interior of Mt. Andyrchi (Fig.1). The rock overburden in the laboratory is equivalent to 4700 m of water and the measured muon flux at the location of the GGNT is $(3.03\pm0.10)\mathrm{x}10^{-9}/(\mathrm{cm}^2\mathrm{s})$. The GGNT laboratory ranks second in the world on the depth among operating underground laboratories.

The main experimental hall of the GGNT laboratory is a cylindrical chamber of 60 m long, 15 m diameter, 12 m wide on the ground and 10 m high. To reduce neutron and γ-backgrounds from the rock, the laboratory is entirely lined with 600 mm low radioactivity concrete with an outer 6 mm steel shell. Bearing metal structures are assembled in the laboratory at different levels to arrange workrooms, technology equipment, shield chambers, etc. The underground facility has rooms for analytical chemistry, for the registration system of ^{71}Ge decays and for a low-background semiconductor Ge detector. Auxiliary equipment of engineering systems is located in separate chambers adjacent to the laboratory. Some part of auxiliary production rooms is situated in the laboratory buildings on the surface.

Fig. 2. The main experimental hall of the SAGE Gallium Germanium Neutrino Telescope

1.2. The experimental layout

In the SAGE experiment, the neutrino flux is determined by measurement of solar neutrino capture rate with gallium metal target of the GGNT based on reaction $^{71}Ga(\nu_e,e^-)^{71}Ge$. The reaction threshold of 233 keV allows measurement of neutrino flux from all reactions that generate neutrinos in the Sun according to Standard Solar Model (SSM), including neutrinos from *pp*-reactions whose end point energy is 420 keV.

The Ga target of the telescope contains approximately 50 tons of gallium metal located in 7 chemical reactors (Fig.2). The gallium in reactors is in the form of liquid metal under temperature ~ $31^{o}C$ (the gallium melting temperature is $29.8^{o}C$). Measurements have a cyclical character. Each measurement of the solar neutrino capture rate (run) begins by adding to the Ga target a carrier – stable Ge in the form of a solid Ga-Ge alloy with known Ge content (~ 250 μg). Ge is then carefully stirred to thoroughly disperse it in the reactors throughout the whole Ga mass. After the exposure (approximately 4 weeks) the Ge carrier and any additional Ge atoms produced by reactions of solar neutrino capture and by background reactions are chemically extracted from the Ga.

Fig. 3. The counters in the well of the NaI detector (on the left), the large passive shield (on the right).

The extracted Ge (the carrier and ^{71}Ge atoms) is then transferred into a gaseous form GeH_4 (Germane) and, after measuring its volume, is placed into proportional counter.

Chemical properties of Ge isotopes are identical, therefore the total efficiency of the extraction of the ^{71}Ge atoms is equal to the efficiency of extraction of stable Ge, which is determined as a ratio of Ge mass content in the germane to the added mass of Ge-carrier and is usually 95 ± 3%.

The counter containing the GeH_4 obtained in the extraction is then placed into the well of the NaI active veto detector, located inside the large passive shield (Fig.3), where the registration of events from ^{71}Ge decays in the counter continues during 5 months. The procedures of extraction and counting of the extracted atoms were described in detail in [18, 20-22].

2. Ga experiments with artificial neutrino sources

Even the first results of measurements, which started in 1990th in SAGE [23] and in GALLEX [24], showed a lowered flux of neutrinos, which could not be explained in the frames of the SSM. Because of importance of the conclusions based on these results, that neutrino change their flavor and have a mass, there has been required evidence that we know the efficiencies of all experimental procedures correctly.

To completely check all experimental procedures, including neutrino cross sections, chemical extraction, counting of ^{71}Ge, and analysis technique, SAGE and GALLEX have used artificial neutrino sources. Ga targets of both experiments have been irradiated in different times with artificial sources of electron neutrino based on isotopes produced in nuclear power plants with activity close to 1 MCi. Two independent experiments have been performed on each of the detectors.

Table 1. Results of four Ga experiments with artificial neutrino sources. $P_{meas.}$ – measured rate of ^{71}Ge production from sources. R – ratio of the expected production rate p_{meas} to the production rate expected in the absence of oscillations – p_{meop}.

	SAGE^{51}Cr	SAGE^{37}Ar	GALLEXCr1	GALLEXCr2
Activity, kCi	516.6±6.0	409±2	1714^{+30}_{-43}	1868^{+89}_{-57}
$p_{изм}$, atoms^{71}Ge/d	14.0±1.5±0.8	$11.0^{+1.0}_{-0.9}$±0.6	11.9±1.1±0.7	10.7±1.2±0.7
Ga mass (t)	13.1 (metal)	13.1 (metal)	30.4 ($GaCl_3$:HCl)	30.4 ($GaCl_3$:HCl)
$R=p_{изм}/p_{meop.}$	0.95±0.12	0.79±0.10	0.953±0.11	0.812±0.11

In SAGE approximately 25% of the target have been irradiated with sources based on the isotopes^{51}Cr [25] and ^{37}Ar [26]. In GALLEX the source based on ^{51}Cr isotope was used twice to irradiate its entire target [27,28]. Both sources emit practically monoenergy neutrinos with energy close to the energy of solar ^{7}Be neutrino: 0.75 MeV for ^{51}Cr and 0.81 MeV for ^{37}Ar. Table 1 gives results for each of these experiments. As opposed to solar measurements the interaction rate of neutrinos from sources is proportional to the target density. In SAGE the target is in the form of metal Ga, whose density is significantly higher than that of GALLEX, whose target was in the form of $GaCl_3$ solution. Therefore though the activities of the sources differed 3-4 times and the masses of target - 2.3 times, the results are consistent within the statistical errors.

The weighted-average result of these experiments, expressed as the ratio R of the measured neutrino capture rate to the expected rate, based on the measured source intensity and the known neutrino capture cross section, calculated by J. Bahcall [29], gives $R = 0.87 \pm 0.05$, more than two standard deviations less than unity.

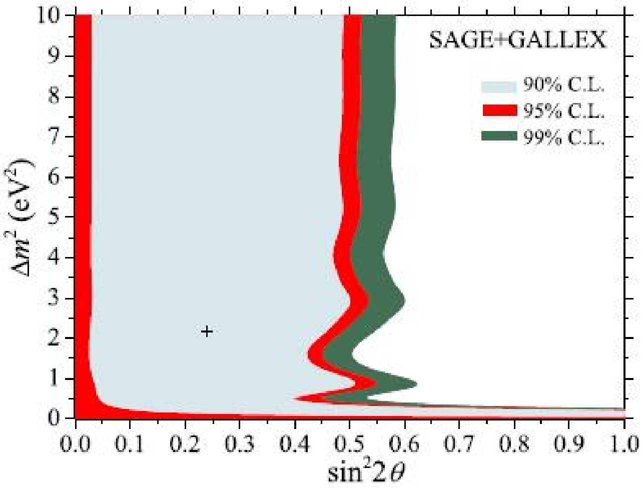


Fig. 4. Region of allowed mixing parameters inferred from gallium source experiments assuming oscillations to a sterile neutrino. The plus sign at Δm^2= 2.15 eV^2 and $\sin^2 2\theta$=0.24 indicate the best-fit point

Possible explanations of such a low result are considered in detail in [20]. One of the hypotheses about an overestimated value of cross section of neutrino capture to the two lowest excited levels in ^{71}Ge [30] was not confirmed. On our initiative, measurements of the charge exchange reaction ^{71}Ge(^{3}He, t)^{71}Ge have been performed at the RCNP (Osaka, Japan) to determine with high precision, the contribution of excited levels in ^{71}Ge to the cross section of neutrino capture on ^{71}Ga nuclei [31]. The results of measurements have shown, that the value of contribution of these levels agrees well with the value calculated by J. Bahcall [29]. Thus, the reason of deficit of neutrino in calibration Ga experiments can be statistical fluctuation, the probability of which is small, about 5%, or real physical effect, possibly transition of active neutrino into sterile states at very short baselines with large Δm^2[15]. The region of allowable oscillation parameters, obtained from the results of four Ga source experiments, in the assumption that transitions in sterile neutrino occur, is shown in Fig.4.

The proposed new experiment with artificial 3 MCi ^{51}Cr neutrino source will confirm or exclude the hypothesis about transitions of electron neutrino into sterile states with large Δm^2.

III New 2-zone Gasource experiment

1. Main features of the proposed experiment

We propose an experiment to search for the short baseline disappearance of electron neutrinos from a radioactive source. The scheme of the proposed experiment on search of oscillation transitions of active neutrino to sterile states is presented in Fig. 5.

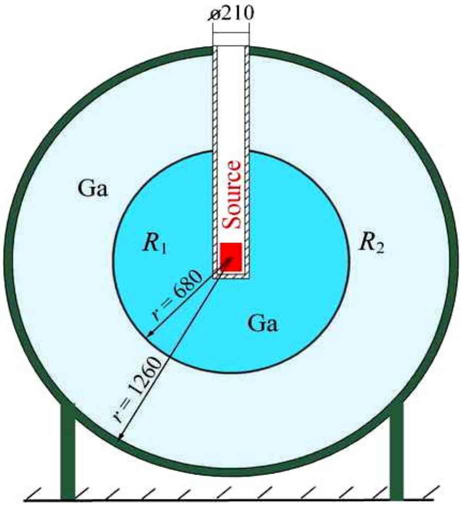


Fig. 5. Schematic drawing of the proposed experiment. R_1 and R_2 are the ratios of measured capture rate to predicted rate in inner and outer zones, correspondingly.

Our plan is to place an intense 3MCi ^{51}Cr source at the center of a 50 t target of liquid Ga metal divided into two independent inner and outer zones with 7,5 t and 42,5 t of Ga, which will provide equal pass lengths of neutrino, and to measure neutrino capture rates simultaneously in each zone.

The ^{51}Cr source emits neutrino with energy 0.75 MeV (90 %) and 0.43 MeV (10 %). Since 96% of captures on Ga is from neutrino with energy 0.75 MeV, the source can be considered with good approximation as monochromatic (the correction to non-monochromacity is accounted in numerical estimations).

If oscillations to sterile neutrino occur, the neutrino wave function which describes a pure ν_e state at the source, will contain an amplitude which oscillates into sterile neutrinos as the distance from the source increases. This sterile component will not interact with the gallium, and the measured capture rate will differ from the expected value in the absence of oscillations. In a model with just the electron neutrino and one sterile neutrino, the probability that neutrino with energy E will survive after passing the distance L from the source i.e. survival probability, is described by the expression:

$$P_{ee} = 1 - \sin^2 2\theta \cdot \sin^2(1.27\frac{\Delta m^2(eV^2)\cdot L(m)}{E_\nu(MeV)})$$

where Δm^2 is squared mass difference of neutrino eigenstates and θ is mixing angle. The apparatus shown in Figure 5 is sensitive to this type of oscillation as the two gallium regions are at different distances from the source. The probability of interaction of the neutrinos in each region is shown in Figure 6 together with the ratio of event rates. The ratio is particularly sensitive to any oscillation because it is independent of both the source strength and the cross section thus eliminating the major systematic errors.

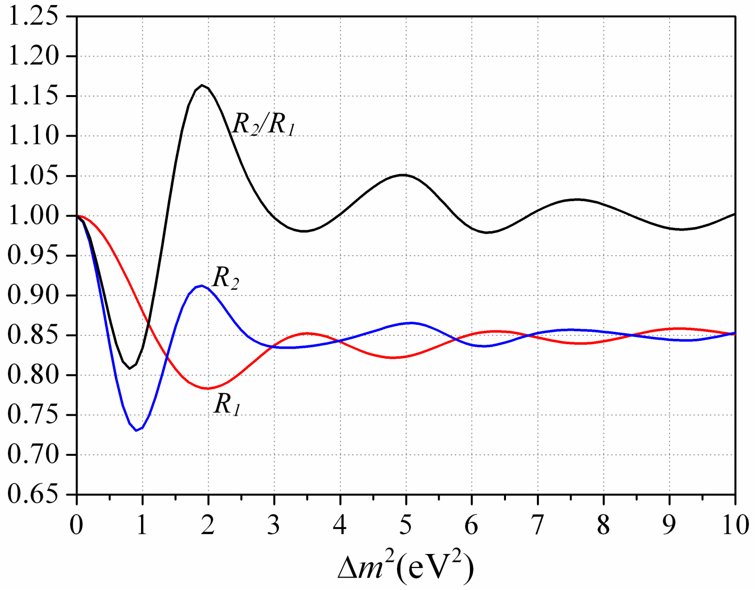


Fig. 6. Ratio of measured capture rate to predicted rate in the inner (R_1) and outer (R_2) zones and their ratio R_2/R_1 as a function of Δm^2 for the case of $\sin^2 2\theta = 0.3$.

A statistically significant departure of the either the rates R_1 or R_2, or their ratio, would provide direct evidence of non-standard properties of neutrino. The obtained ratio of the rates would provide guidance to new neutrino properties and these can be further constrained by including the results of the earlier gallium experiments. The sensitivity region of new 2-zone Ga experiment with 3 MCi ^{51}Cr source combined with previous Ga experiments would provide the constraints indicated in Figure 7.

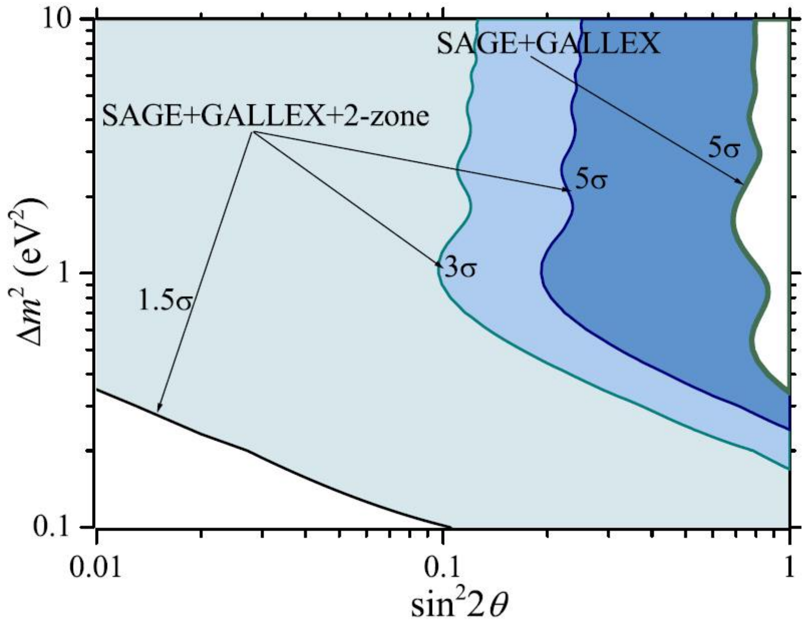


Fig. 7. Region of mixing parameters to which proposed new ^{51}Cr source experiment, in combination with previous source experiments, is sensitive with various levels of confidence. The white region in upper-right corner has been already excluded with 5σ confidence by previous SAGE and GALLEX source experiments. As indicated, the new 2-zone experiment has the capability to greatly expand this exclusion region with high confidence.

The proposed experiment has significant advantages in comparison to other projects. These advantages come from the use of a compact, nearly monochromatic neutrino source of well known activity; the use of a metallic Ga target, where the density ensures high interaction level; the special geometry of the target, that gives the neutrino interaction rate at two distances, as well use of the well established procedure of measurement of neutrino capture rate on gallium developed for the Gallium-Germanium Neutrino Telescope.

The obvious advantage of this experiment is the significant value of ratio signal/background and the simplicity of interpretation of the results. The main contribution to the background will in fact be neutrinos from the Sun, whose flux is known well from many years of measurement on the telescope, and in fact, the activity of the source should provide the number of interactions in the detector several times higher as the Sun.

The simplicity of interpretation of results is assured by use of the ^{51}Cr source that emits nearly monochromatic neutrino flux, and the absence of systematic uncertainties connected with inaccurate knowledge of neutrino spectrum.

The proposed new experiment on electron neutrino disappearance with intense artificial source of electron neutrino and optimized geometry of Ga target gives the opportunity to search transitions of active neutrino to sterile states with $\Delta m^2 > 0.5$ eV^2 with sensitivity to disappearance of electron neutrino of several percent.

Along with the confirmation of or exclusion of the sterile neutrino hypothesis a direct verification of the neutrino capture cross-section on ^{71}Ga nuclei will be done.

2. Stages and methods of preparation of the experiment

Stages of preparation:

1. Production of 3.5 kg ^{50}Cr enriched up 97%
2. Preparation of the artificial neutrino source:
   a) neutron-physical calculations and calculations of nuclei transmutation, planning and analysis of experimental results, leading to issuing of technical documentation;
   b) design and preparation of irradiating assembly and reactor targets with enriched chromium;
   c) test irradiation of the reactor target with enriched chromium to determine the contents of admixture of nuclides;
   d) optimization of design and of dimensions of biological shielding of the source;
   e) full scale experiment on physical model of reactor SM to test results of calculations as well as of the optimization of irradiation conditions;
   f) experiment-calculated substantiation of irradiation safety of reactor targets with chromium;
   g) development and preparation of components and devices inside the chamber, which are necessary for the source assembly;
   h) full scale irradiation of the enriched chromium in central channel of the reactor SM;

i) assembly and preliminary certification of the neutrino source;

j) transportation of the neutrino source to the Customer.

3. Preparation of source shielding.
4. Preparation of calorimeter for measurement source activity.
5. Development of method of determination of the source activity using measurement of spectra of the internal Bremsstrahlung (IB).
6. Preparation of a handler for the source.
7. Preparation of concentric zones for irradiation of 50 t of Ga target,
8. Upgrading of the extraction system,
9. Preparation of the second counting system.
10. Preparation of ~20 new proportional counters of the YCT-type.

In the next sections we discuss our preliminary works and methods to realize each of these stages.

2.1. Production of 3.5 kg ^{51}Cr

Natural chromium consists of 4 stable isotopes ^{50}Cr, ^{52}Cr, ^{53}Cr, ^{54}Cr. The isotope of interest, ^{50}Cr, represents only 4.35% of natural chromium. Neutron activation of ^{52}Cr and ^{53}Cr produces stable isotopes, while activation of ^{54}Cr produces radioactive ^{55}Cr. Since ^{55}Cr has a half-life of 3.5 min. the ^{51}Cr is the only radioactive isotope of chromium that is present in the source.

Production of the 3.5 kg of the chromium-50 isotope with enrichment of not less than 97% in the form of chromium anhydride (CrO_3) will be carried out using centrifugal separation of the isotopes at the JSC “PA “Electrochemical Plant” (Russia).

Gas kinetic methods of separation including centrifugation can be applied only if the working substance is in a gaseous state. In addition to natural gaseous chemical elements, modern chemistry is aware of many compounds with volatility.

The main requirement for use of centrifugation is a chemical compound containing the element be found with vapour pressure at room temperature greater than 5-10 mm Hg. Otherwise the proper pressure and flux for the centrifuge will not be possible . The working substance should not interact with materials used in manufacturing of the rotor centrifuge, gas track and communications of the centrifugal separation facility. Chemical and temperature stability of the compounds used have to be sufficient, i.e. they should not transform into volatile form (oxides, elementary, etc.).

To generate the enriched chromium-50, it is necessary to:

1. Produce the volatile chemical compound of chromium CrO_2F_2 in the amount of many tens of kilograms (special and non-industrial technology).

2. Carry out the separation at the centrifugation cascade and to collect the light fraction $^{50}CrO_2F_2$ enriched to the needed level of concentration.

3. Hydrolize the enriched gas $^{50}CrO_2F_2$ and to obtain the oxide - $^{50}CrO_{3.}$

At all stages it is important to provide the proper chemical purity so that the final metal will have the impurity levels low enough to allow activation of the ^{51}Cr in the reactor.

The first large scale enrichment of ^{50}Cr was performed at the “Kurchatov Institute» for the SAGE experiment in the Baksan Neutrino Observatory [32, 33]. 0.8 kg of material at 90% enrichment were produced. Later the «Kurchatov Institute» produced about 40 kg of chromium-50 enriched to more than 38% for the West European Collaboration GALLEX [34].

The accumulated experience of production of the sources for SAGE and GALLEX has shown that the it is important to have optimal requires a combination of the reactor opportunities as well as the features of the irradiated chromium target. The main feature is the amount of the chromium-50 isotope containing in the target. This can be achieved with different content of chromium-50 as well as of the different mass of target. The major part of physical and technical parameters of the neutrino source as well as its cost depend on the value of combination “mass-enrichment”.

For example, the volume of the irradiated chromium is limited by geometry of the active zone of the reactor providing the required neutron flux.

The peculiarity of this project is that it is necessary to get 3,5 kg of chromium-50with high enrichment up to 97%, and this in significant measure distinguishes the given task from that ones performed earlier. The required enrichment of chromium-50 cannot be reached with single run of enrichment on the separation cascade. In the preliminary stage there will be necessary to carry out calculations of the separation procedure, to realize its optimization on parameters work time/expenditures of the initial chromium fluoride, to take into consideration the influence of «isotope memory» of the equipment, to estimate possible losses at the stage of separation to obtain the chromium anhydride. This gives basis for choice of a number of the needed separation stages, parameters of the cascade assembling providing the needed levels of flows of power with initial gas and separation of the valuable fraction.

The elaborated solutions will be realized technically for the following technological process of the enrichment of chromium-50 in the needed amount, with proper enrichment and chemical purity.

2.2. Neutrino source

In the previous experiments with artificial neutrino sources the isotopes ^{51}Cr and ^{37}Ar were used. The SAGE experiment with ^{37}Ar source showed, that this source has advantages in comparison to ^{51}Cr source: the absence of radioactive impurities, the opportunity of application of several independent methods of measurement of activity, higher neutrino energy which provides more high capture rate, etc. Unfortunately in the present time the production of ^{37}Ar source with activity of 1 MCi or higher doesn't seem to be possible. Therefore in the experiment there will be used the ^{51}Cr source, which can be produced using method of capture of thermal neutrons on stable ^{50}Cr isotope.

The decay of ^{51}Cr with half life 27,7 days is via electron capture to ^{51}V with neutrino energies of 751 keV (90.12%) and 426 keV (9.88%), Fig.8. The 90% branch decays directly to the ground state of ^{51}V, and the 10% branch decays to the first excited state of ^{51}V, which promptly decays with the emission of 320 keV gamma ray to the ground state.

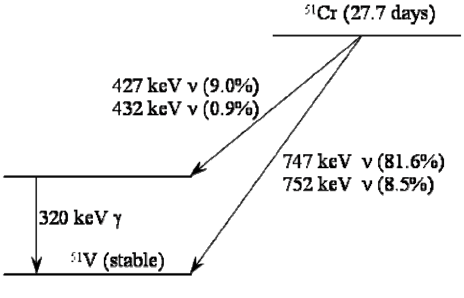


Fig. 8. Decay scheme of ^{51}Cr to ^{51}V through electron capture.

Taking into account the atomic levels to which the transitions can occur, the source will radiate neutrinos with energies 752 keV (9 %), 747 keV (81 %), 432 keV (1 %), and 427 keV (9 %). Since 96% of decay on Ga occur with energy 0.75 MeV, the source can be considered with good approximation as monochromatic.

The capture rate of neutrino from the ^{51}Cr source with activity 3 MCi in the 50-ton gallium target/day will be ~130 times higher than the solar neutrino capture rate.

2.2.1. Manufacturing of the source

The chromium in the amount of 3.5 kg with 97% enrichment by ^{50}Cr isotope in the form of chromium oxide of ultrahigh purity will be produced at the JSC «PA "Electrochemical Plant». At the INR powdery metal chromium of high purity will be produced from the chromium oxide obtained in the electrochemical procedure. At the JSC "Kompozit" this powder will be used to prepare intermediates of compact metal chromium that is necessary for preparation via electro spark way the targets for irradiation. The target will have the form of hexagonal rods with a diameter of circumscribed circle 9.3 mm and a length of 95 mm with a total number of 81 and the mass 3015 g.

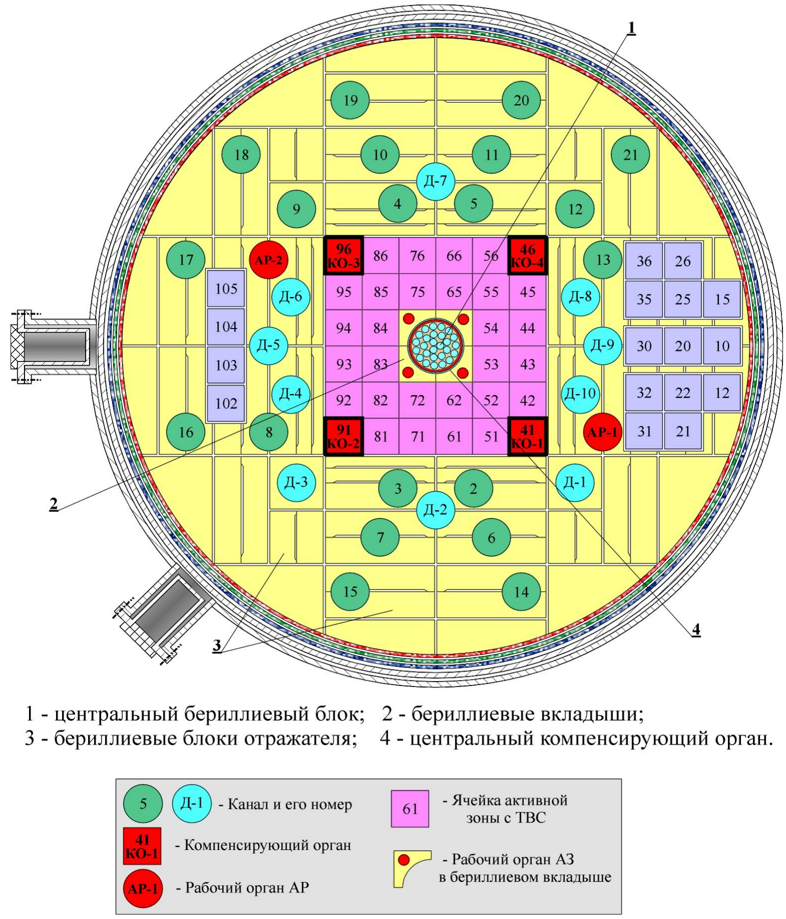
The ^{51}Cr neutrino source will be produced at the JSC"SSC Research Institute of Atomic Reactors". The irradiation of the ^{50}Cr will be carried out on reactor SM-3. The chromium rods will be placed in 27 cells of the central neutron trap where the neutron flux is 5.0×10^{14} neutron/(cm^2 s), and the irradiation will continue within 58.9 eff. days (69 calendar days). In accordance with calculations of experts, at the end of irradiation the specific activity of the target should reach the value of 1016 Ci/g, and its total activity should be 3.20 MCi. The irradiated rods will be placed in separator, which is a honeycomb structure made using selective laser melting, located in a sealed cylindrical hermetic shell made of stainless steel Ø91×101 mm.

2.2.2. Proposal of the JSC "SSC Research Institute of Atomic Reactors" (RIAR) on manufacturing of the ^{51}Cr neutrino source with activity 3 MCi

For irradiation of the total mass of chromium it is proposed to use the high flux research reactor SM (Fig. 9).

The irradiation of reactor targets with enriched chromium is to be carried out in the most high flux channel of the reactor SM – the central neutron trap [35].

Taking into account the reactor features (first of all, the energy intensity and high pressure of water heat carrier) it is proposed to use for irradiation of the start material the devices that correspond to the assemblies of cylinder targets. The precision version neutron-physical calculations were carried out using the MCNP program [36] that realizes an algorithm of determination of space-energy distribution of neutrons in 3D model of reactor using Monte Carlo procedure. For this calculation the model of the SM reactor was used which is at most approximated to the real reactor geometry. The calculations were performed for different positions of the compensatory parts of the reactor.



1 - центральный бериллиевый блок; 2 - бериллиевые вкладыши;
3 - бериллиевые блоки отражателя; 4 - центральный компенсирующий орган.

Fig. 9. The cartogram of reactor SM.

The accumulation of ^{51}Cr was calculated on the Chain Solver program that realizes the algorithm of numerical integration of the system for differential equations describing the change of concentration of nuclides in the process of irradiation. The rates of nuclear reactions were calculated in a three-group approximation. The initial data were the parameters of neutron field in the volume of irradiating material obtained on results of neutron-physical calculations.

Effective cross sections of neutron reaction were preliminary determined using the MCNP program.

Initial data:

Mass of chromium, enriched on ^{50}Cr up to 97% - 3015 g;

The total of 27 cells of the central channel were occupied with chromium targets;

Each chromium target had D=8,5mm, and the summarized height was h=28.5cm.

Result:

σ_{50} = 15.9 b, RI_{50} = 6.38 b

σ_{51} = 10.2 b, RI_{51} = 4.1 b

The parameters of the most effective version of irradiation of targets with chromium are given below:

- Chromium is placed in the targets made of zirconium ∅10 × 0,4 mm.
- Regular separator of the central channel (beam of the 27 zirconium guide tubes) should not be installed. This permits an increase the density of the thermal neutron flux.
- Averaged over the chromium volume the neutron flux density is as follows:

thermal - $4.57\cdot10^{14}$cm^{-2}c^{-1}

resonance - $9.55\cdot10^{13}$cm^{-2}c^{-1} (for an interval of lethargy)

fast - $9.46\cdot10^{14}$cm^{-2}c^{-1}

Temperature of neutron gas T_{ng} = 674 K.

- Regime of reactor SM operation at the power of 95 MWt on the following timetable (day -power):

(10- 95)+(1- 0)+(10- 95)+(1- 0)+(11- 95)+(3- 0)+(10- 95)+(1- 0)+(10- 95)+(1- 0)+(11- 95).

Total 69 calendar days (58.9 eff.days).

Immediately following the irradiation, the activity of chromium-51 should be **3.2 MCi.**

For the moment of start of exposure of a two-zone detector at BNO the activity of the source should be **3.01 MCi.**

The summarized duration of assembly of the source at the RIAR, its transportation to BNO and inserting it in the detector should be not more than 60 hours (2.5 days).

2.2.3 Stages of work to be performed at the RIAR:

1. Neutron-physical calculations and calculations of transmutation of nuclei, planning and analysis of experimental results, issue of technical documentation.
2. Development and manufacturing of the irradiation assembly and reactor targets.
3. Irradiation of reactor target with enriched chromium to determine the contents of

impurity radionuclide.

4. Optimization of design and size of biological protection of the source.

5. Full-scale experiment on the physical model of reactor SM to test results of calculations and of the optimization of irradiation regime.

6. Experiment-calculated substantiation of safety of irradiation of reactor targets with chromium.

7. Development and manufacturing of the components and in-chamber devices necessary for the source assembly.

8. Full-scale irradiation of the enriched chromium in the central channel of reactor SM.

9. Assembly and preliminary certification of the neutrino source.

10. Transportation of the neutrino source to the Customer.

Preliminary calendar plan of works

Number of stage	Calendar month												Preliminary cost of the stage, thous. rub	Preliminary cost of the stage, thous. $*
	1	2	3	4	5	6	7	8	9	10	11	12		
1	■	■	■	■	■	■	■				■	■	4 000.0	114.3
2	■	■	■										2 000.0	57.1
3			■	■									4 000.0	114.3
4					■	■	■						4 000.0	114.3
5					■	■	■						5 000.0	142.9
6						■	■	■					3 000.0	85.7
7									■	■	■		32 000.0	914.3
8					■	■	■	■	■	■			7 000.0	200.0
9											▐	■	10 000.0	285.7
10												▌	4 000.0	114.3
Total:													75 000.0	2 142.9

* Calculation for rate: 1USD = 35 rub

2.3. Preparation of the shield for the source

The source will be supplied with its own biological shield 30 mm thick, prepared of tungsten alloy of the BHM-type. The size of the biological shield will be: Ø145×151 mm. The mass of the tungsten shielding will be ~ 39 kg, the mass of the source assembly ~ 45 kg.

All operations with ^{51}Cr artificial neutrino source will be carried out in accordance with requirements of Federal Authority on Safety, which will assure the safety of all operations with source. A certificate of this Authority will be issued for the works with such source.

2.4. Preparation of calorimeter for measurements of activity of the source.

The activity of the source will be measured using calorimetric and other methods. With each ^{51}Cr decay there is emitted an average of 36 keV of thermal energy, i.e. the energy which doesn't leave with neutrino. So, the source of 3 MCi should emit about 640 W of heat. The source activity will be measured after each exposure using calorimeter and by measurement its gamma-rays using a Ge semi-conductor detector. After all exposures will finish, the value of activity will be additionally determined by measurement of a number of accumulated ^{51}V – the product of ^{51}Cr decay. In the previous experiment with ^{37}Ar source the activity was determined with accuracy of 0.5%. The presence of radioactive admixtures that influence the accuracy of calorimetric measurements will be estimated using a Ge semi-conductor detector, as it was done in the first ^{51}Cr experiment.

2.5. Manufacturing of a handler for the source

To ensure the necessary conditions of safety during operations with source, at the company UNIMET there will be designed and manufactured a special pick-and-place system – the remote handling system. This device will be used in the proposed experiment to carry out the following operations:

1) handling of the source from a lead shield through a special adapter into the center of reactor containing 50 t of Ga target;
2) fixing and removal of the shield and adapter at the moment of inserting (extraction) of the source;
3) handling of the source after each irradiation into calorimeter for measurement of activity of the source;
4) handling of the source into collimator after the experiment will finish to measure the level of impurities by means of measurement of gamma irradiation from the source using a Ge semiconductor detector.

2.6. Manufacturing of concentric tanks for irradiation of 50 t of Ga

The inner Ga zone will have a form of spherical tank with radius 660 mm, the cylindrical channel ø203 mm and height 1196 mm (100 mm below the center) to insert the source into the center of the target. This zone will contain 7.5 t of Ga.

From the technical point of view the construction of the outer Ga target zone in the form of the sphere with large diameter is much more complicate and expensive than preparation of this tank in the form of cylinder. Therefore we propose to prepare the outer zone in the form of cylinder with a dished (elliptical) bottom. Analytical calculations and Monte Carlo modeling have shown that results of the experiment will not change significantly: i.e. in the absence of oscillations the counting rate in the outer zone will change for 2% only in the case if its spherical form will change to cylindrical. The change of the target form will have negligible influence on the sensitivity of the experiment search for oscillations. All numerical estimations and graphs in this paper were performed for the outer zone in form of cylinder with a dished bottom.

Outer cylindrical zone with diameter of 2192 mm and height of 2192 mm will contain 42,5 tons of Ga, Fig. 10.

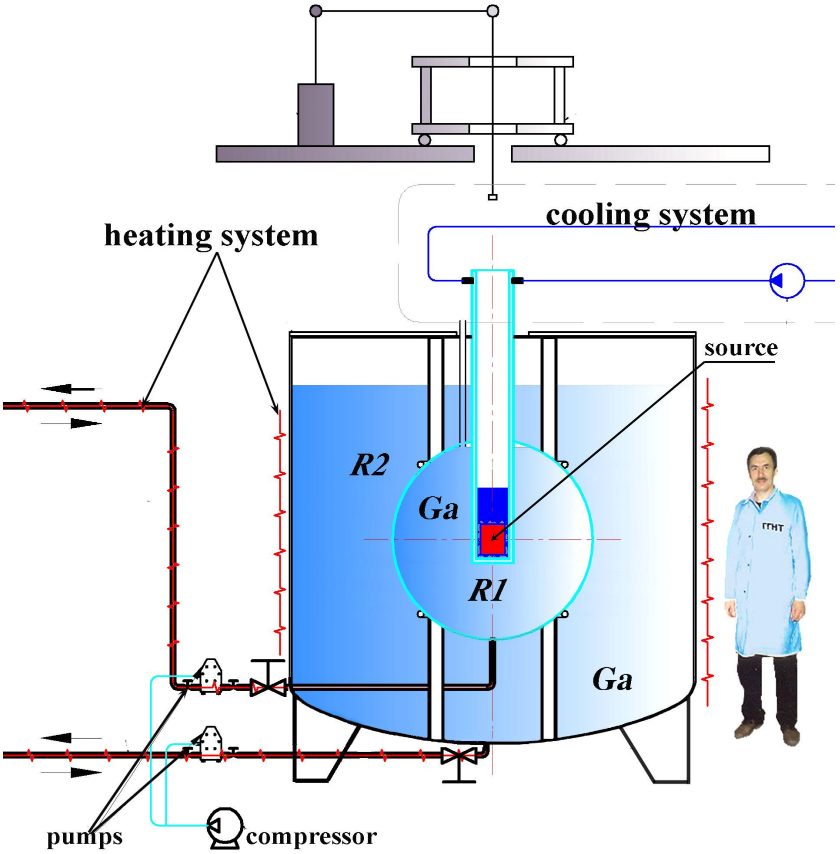


Fig. 10. Layout of the 2-zone facility

Geometric sizes of both tanks provide equal average neutrino pass length in Ga target zones, ⟨L⟩ ~ 550 mm.

Technological and electrical schemes of a 2-zone facility are completely developed and designed including the choice of auxiliary equipment.

Design of concentric tanks will assure the safety for conditions of the experiment. Because of small dimension of tunnel (gate: width of 2.8 m, height of 2.94 m) leading to the laboratory, the tanks will be made of prefabricated units. The assembly of the 2-zone reactor will be carried out in the place of installation without welding. The design of the junctions of prefabricated units will ensure the leak tightness of the whole tank.

The surfaces of tanks will be lined with polypropylene to exclude the contact of Ga and hydrochloric acid with material of walls and of the tank bottoms. The outer tank will contain a system for supporting and fixing the inner tank. In both tanks a brunch pipe for inside and outside pumping of liquid Ga with necessary shutoff fittings is foreseen. The surface of all elements of tanks contacting with Ga will also be lined with polypropylene.

To sustain the temperature of liquid Ga at the level not lower than 35°C an electrical heating of the tanks with a heating resistance cable is foreseen.

The pumping of liquid Ga in/out the proposed facility will proceed with use of a system of piping and branch. During the filling of the inner spherical tank the level of liquid Ga should increase parallel with the level of filling in the outer tank to prevent the emergence of lift of spherical (cylinder) tank that is assured via regulation of pumping feed and level meters installed in both tanks.

2.7. Upgrading of the extraction system

For this experiment with an artificial neutrino source, the same technological scheme of Ge extraction, which is used in the GGNT experiment on measurement of solar neutrino flux will be employed. This scheme includes the following stages:

1) Extraction of Ge from metal Ga using method of selective oxidation of Ge by a weekly acidic H_2O_2 solution.
2) Concentration of Ge in the solution by vacuum evaporation.
3) Sweeping of germanium from the solution in the form of $GeCl_4$ by a gas flow with consequent Ge absorption in small amount of water.
4) Concentration of Ge by extraction of carbon tetrachloride.
5) Synthesis of a volatile junction of germanium GeH_4 (germane) and its purification.

The process provides independent extraction of ^{71}Ge atoms from each zone of the Ga target with maximal use of the existing technological equipment used in the GGNT.

In the first stage of Ge extraction, which results in extraction of Ge from Ga target in the form of metal Ga alloy and its transfer into water solution, the chemical reactors of the GGNT will be used. To realize this opportunity, a system for Ga pumping was developed and tested that permits transfer in the short time, the Ga from each zone of the facility for irradiation of Ga target with neutrino source, to chemical reactors of the GGNT. The Ga pumping is realized by membrane pumps adapted to operations with liquid Ga.

The concentration of Ge in solution by vacuum evaporation proceeds in glass vacuum steamers. For this stage we plan to use generally the equipment of the GGNT. To increase the efficiency of the evaporation system components of borosilicate glass have been purchased and installed for an additional vacuum evaporation system.

To realize the process of $GeCl_4$ sweeping from a solution in the Ga target zone, containing 42,5 tons of Ga there will be used the existing system of sweeping. For the Ga target with mass 7,5 tons an independent system of sweeping was designed and purchased. Main elements of this system are: a tank made of borosilicate glass with volume of 150 l, and a valve-ejector that disperses gas into solution.

For concentration of Ge via extraction and synthesis of germane there will be mainly used the same equipment that is used for the same goals in SAGE.

2.8. Preparation of the second counting system and manufacturing of new proportional counters

To assure the simultaneous counting of extraction samples from two zones of Ga target, the second counting system will be prepared with 8 counting channels and there will be manufactured additionally 20 proportional counters of the YCT–type (Yants-Carbon-Thin).

2.8.1 Counting system

The counting system of SAGE [18] has 8 counting channels that permit to simultaneously register the ^{71}Ge decay in the regions of L and K peaks (0.4-15 keV) with total efficiency up to 75%. Uninterrupted running during the period of the experiment (more than 20 years) has shown its reliability and competency. In the new experiment along with the existing system there will be used new counting system with 8 counting channels, whose main features will not be worth than existing ones and which has to have data format compatible with the existing standard procedure of SAGE data analysis.

Table 2. Main features of the SAGE counting system

Number of counting channels	8
Energy range, keV	0.37-15
Bandwidth, MHz	100
Rise time, ns	3.5
Digitizing frequency, GHz	1
Digital resolution, bit	8 (two independent channels)
Dead time (normal acquisition mode),s	0.34
Dead time (calibration mode), s	0.3
Energy range of the NaI channel, keV	60-3000
Energy range of the NaI coincidence channel, keV	190-3000
Width of hardware coincidence, μs	4
Width of coincidence in the TDC channel, ns	70
Energy equivalent of noise (2.35σ), keV	<0.324
Counting efficiency (counters of the YCT-type), %	≈75

Taking into account these requirements for the second counting system the best and the most simple way seems to be the maximal reproduction of the existing counting system. Such approach to creation of a new counting system increases the level of unification of the equipment in the system and its reliability. Table 2 shows the main features of the existing counting system of SAGE.

2.8.2 Proportional counters

High precision measurements in the experiment require miniature proportional counters with volume of ~ 0.5 cm^3 for counting of pulses from decay of ^{71}Ge atoms, which should have high volume and peak efficiency and stability of gas amplification. The final result and total efficiency of the experiment depend on perfection of design of the counter and its background. With use of an advanced technology, new low background miniature proportional counters (Fig. 11) with high stability of gas amplification and energy resolution will be prepared.

In the counters of this type a thin layer of a carbon laid on the inner surface of a quartz body using thermal decomposition of isobutene serves as cathode that gives an advantage to exclude dead volume behind the cathode. The special design with the walls rounded inwards in the places where the cathode comes to an end ensures small edge effect. Contactor ends of cathode and anode made of molybdenum band, provide leak tightness of the counter and guarantee perfect stability of amplification. The counters volume efficiency is 96% ± 1% with efficiency of registration in K-, L –peaks of 40% ± 1%, and 35% ± 1% correspondingly.

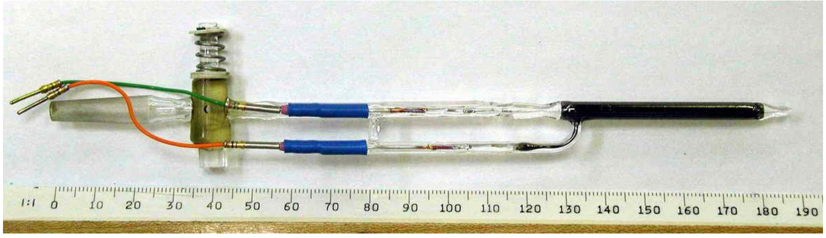


Fig. 11. Low background proportional counter

For manufacturing of the counters only materials with very low content of radioactivity can be used. The counter body is fabricated of synthetic quartz (Suprasil). Small (about 200 μm) thickness of the wall of the body is reached using method of etching in hydrofluoric acid. Because of small thickness the number of own background counts from decays of elements of natural radioactive chains in quartz is small enough, that gives an advantage to carry out low background measurements. The average background of the counters is: for K-peak - 0.028±0.037 and for L-peak - 0.057±0.073 events/day.

The counters of this design were used in all solar measurements in SAGE beginning 2001 till present time. Different test measurements of their counting features were performed in the course of their operation. The results of these measurements have shown that this design of the counter ensures more high volume efficiency and efficiency of registration of signals in the energy ranges for K-and L –peaks in comparison to the previously used counters with other design. A possibility of the whole volume irradiation through the thin walls of the counter during calibrations doesn’t polymerize the anode and significantly decreases the time of calibration. During the period of operation all used counters showed very stable and approximately equal features.

3. Extractions’ schedule and statistics

In the proposed experiment with a ^{51}Cr source of activity of 3 MCi, and the 2-zone Ga target, both zones will be irradiated simultaneously, and in the absence of oscillations the predicted number of ^{71}Ge atoms generated in the zones will be equal. In this section we consider the needed number of irradiations and their duration to obtain the maximal number of registered captures of neutrino.

The number of ^{71}Ge atoms, generated in neutrino interactions in the target for time *t,* N_{Ge}:

$$N_{Ge}(t) = \frac{n_{Ge}}{\lambda_1 - \lambda_0} \cdot (e^{-\lambda_1 t} - e^{-\lambda_0 t}) \qquad (1)$$

where n_{Ge} – the rate of generation of ^{71}Ge atoms at the start of measurements. In case the value of activity of the ^{51}Cr sources will be 3 MCi, then n_{Ge}= 65 day^{-1} for Ga metal target with an average neutrino pass length 55 cm. The λ_0 and λ_1 are the values of ^{51}Cr and ^{71}Ge decay: λ_0=ln(2)/27.7 day^{-1} and λ_1=ln(2)/11.43 day^{-1}. Fig. 12 shows the value N_{Ge}(t) for initial source activity of 3 MCi.

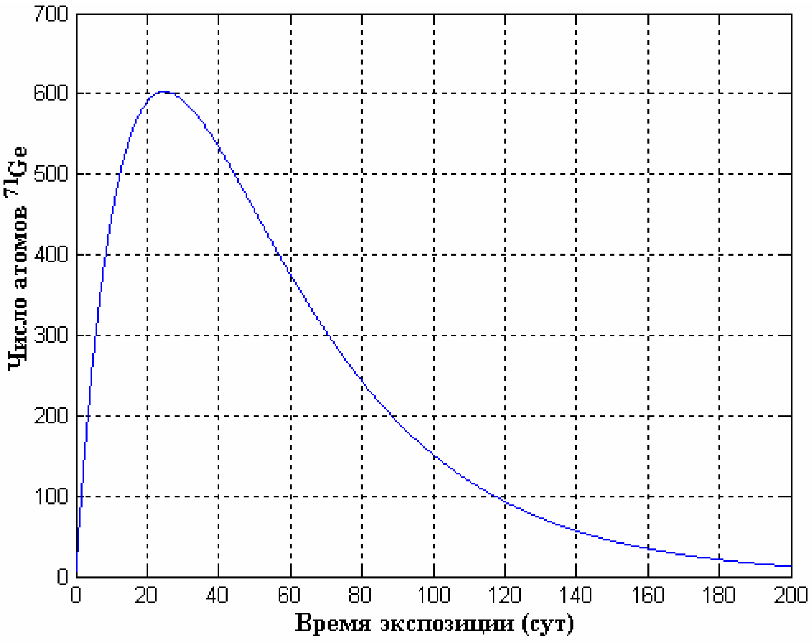


Fig. 12. The number of ^{71}Ge atoms in the target with average pass length in metal Ga of 55cm by irradiation with ^{51}Cr source with activity 3 MCi.

A number of the registered events can be increased by increasing of a number of extractions. As one can see from Fig. 12, the maximal number of registered events can be obtained if the time of irradiation is infinitely short, but this doesn't have practical application as the extraction procedure cannot be shorter than one day. With equal intervals of irradiation the maximal summarized amount of neutrino captures in the absence of oscillations can be reached with irradiation time of 9.5 days. Consequently our choice for schedule of extractions is as following. There will be carried out 10 irradiations with equal duration of 9 days each and with one day «dead time» for extraction of the generated ^{71}Ge atoms from the target. With such schedule ~1647 ^{71}Ge atoms are predicted in each zone of the target. Taking into account the total efficiency of extraction and the efficiency of counting 53% [26], the total number of pulses from registered ^{71}Ge decays in the counters should be ~873. The data on the expected number of events are presented in Table 3.

Table3. The expected neutrino capture rates in each zone of the target from a 3 MCi source in the absence of transitions to sterile neutrino. The second column gives a number of neutrino captures/day in each zone of the target in the beginning of each exposure. The third column shows the expected number of ^{71}Ge atoms accumulated in each zone at the end of exposure by the source. The fourth column presents a number of pulses from ^{71}Ge atoms decay produced by the source and registered in proportional counter. The fifth and the sixth columns give the ratio of a number of captures in the target from the source and from the Sun. The solar neutrino capture rate was taken 66.1 SNU, i.e. 0.0197 interaction/day in one ton of Ga.

№ of exposure	**Production rate at.^{71}Ge/d**	**Number of ^{71}Ge at. at the end of exposure**	**Number of ^{71}Ge at. in counter**	**^{71}Ge at.-$\nu_{\text{и}}$/^{71}Ge at. - ν_C, inner zone**	**^{71}Ge at.-$\nu_{\text{и}}$/^{71}Ge at. - ν_C, outer zone**
1	**64.6**	**397.2**	**210.5**	**336.6**	**64.1**
2	**50.3**	**309.3**	**164**	**262.1**	**49.9**
3	**39.1**	**240.9**	**127.6**	**204.1**	**38.8**
4	**30.5**	**187.5**	**99.4**	**158.8**	**30.3**
5	**23.7**	**146.0**	**77.4**	**124**	**23.5**
6	**18.5**	**113.6**	**60.2**	**96.3**	**18.4**
7	**14.5**	**88.5**	**46.9**	**75**	**14.3**
8	**11.2**	**68.9**	**36.5**	**58.4**	**11.1**
9	**8.7**	**53.6**	**28.5**	**45.4**	**8.7**
10	**6.8**	**41.8**	**22.1**	**35.4**	**6.8**
Σ		**1647.3**	**873.1**	**139.6**	**26.6**

Note. After 10 days 1.18 atoms ^{71}Ge generated by solar neutrino are assumed to be in 7,5 tons of Ga and 6.20 atoms in 42,5 tons.

For a 3 MCi source the value of statistical uncertainty of a set of exposures obtained using Monte Carlo modeling based on the proposed schedule of irradiations, efficiencies of extraction and counting, background rate and the rate of production from solar neutrino are ± 3.7% in each zone and ± 2.6% for the total target.

4. Systematic uncertainties

In the proposed 2-zone experiment we expect a much lower value of statistic uncertainty than in the previous source experiments. To decrease the value of total systematic uncertainty expected in the experiment we investigated in detail possible sources of systematic uncertainties.

Table 4. Systematic uncertainties in % for a 2-zone experiment with 3 MCi source (5th column). Systematic uncertainties for experiment with ^{37}Ar source (3rd column) and for solar extractions (4th column).

Source of uncertainty	**Sign**	**Ar-06 [19]**	**Solar-09 [13]**	**Cr-2-zone**
1				
Eff. Chemical extractions				
Mass of Ge carrier	δ_{G1}	±2.1	±2.1	±2.1
Mass of the extracted Ge	δ_{G2}	±3.5	±2.5	±0.8
Residual Ge carrier	δ_{G3}	±0.5	±0.8	±0.3
Mass ofGa	δ_{G4}	±0.5	±0.3	±0.5
Total (extraction)		±4.1	±3.4	±2.3
2				
Counting efficiency				
Volume efficiency	δ_{C1}	±0.5	±1.0	±0.4
End effects	δ_{C2}		±0.5	
Efficiency of registration in peaks	δ_{C3}	±2.5		±0.4
InterpolationM-C	δ_{C4}	±1.7	±0.3	0
Centering	δ_{C5}	±0.1		
Resolution	δ_{C6}	±0.3	-0.5 +0.7	±0.3
Cutting on rise time	δ_{C7}	±0.6	±1.0	±0.6
Variations of amplification	δ_{C8}	+0.5	+1.1	0
Time of exposure and extraction	δ_{C9}		±0.8	
Total (counting)		+3.2 -3.1	+1.8 -2.1	±0.9
3				
^{71}Ge of non-solar origin				
Fast neutrons			$<-3\cdot10^{-2}$	
^{232}Th			$<-6\cdot10^{-2}$	
^{226}Ra			<-1.0	
Cosmic ray muon			<-1.0	
Total (besides the Sun)	δ_{N1}		<-1.5	<-0.07
Background , mimic ^{71}Ge				
Internal ^{222}Rn	δ_{N2}	-1.7	<-0.3	<-0.01
External ^{222}Rn			0.0	
Internal ^{69}Ge	δ_{N3}		<-0.9	<-0.03
Background from solar neutrinos	δ_{N4}	±0.4		±0.16
Residual ^{71}Ge after extraction		0.0		
Total (background)		+0.4 -1.7	<-0.9	±0.16
4				
Weight factors	δ_{W1}		±0.15	±0.15
Source activity	δ_{W2}			±0.5
Total		**+5.2 -5.4**	**-4.3 +4.0**	**±2.6**

In Table 4 sign "-" indicates the values of systematic uncertainties connected with processes, leading to increase of results of the measured value (for instance, the processes, connected with background sources of production of Ge isotopes in Ga target, as well as Rn decay inside and outside of a counter which mimic a signal from Ge decay in the counter), therefore these systematic uncertainties are one-sided.

The systematic uncertainties in Ga measurements can be logically divided in several groups: 1 – uncertainties that concern to the procedure of extraction of Ge from Ga target (δ_G), 2 – uncertainties connected with counting of ^{71}Ge decay in proportional counters (δ_C), 3 – uncertainties arising from background events (δ_N), and 4 – another uncertainties, which include uncertainties in analysis and measurements of activity of the source. Table 4 shows our calculated values for all these systematic uncertainties for the 2-zone experiment and, for comparison, the systematic uncertainties of solar measurements and measurements performed with ^{37}Ar source.

4.1. Uncertainty of extraction efficiency

The largest contribution to the systematic error is from extraction efficiency, which is the sum of uncertainties of the introduced mass of Ge carrier, used for measurements, of the extraction efficiency, δ_{G1}, and the uncertainty of measurement of its extracted amount δ_{G2}. Estimation made by mass-spectrometry analysis of composition of the extracted Ge gives an average value $\delta_{G2(1)}=\pm 2\%$ of single measurement. For a set N of independent measurements the total relative uncertainty decreases in accordance with $\delta_{sum} = \frac{\sigma_{sum}}{N} = \frac{\sqrt{\sum_i \sigma_i^2}}{\sum_i N_i}$. One can expect that in ten irradiations there will be registered $N \approx N_0 \cdot \sum_{i=0}^{9} e^{-\lambda t_i}$ events. Here N_0 – a number of expected events in the first measurement; λ – the ^{51}Cr decay constant; and $t_i = \Delta t \cdot i$ - start time of the i-st irradiation. With choice of time interval Δt=10 days for each irradiation we obtain $\delta_{G2} = \delta_{G2(1)} \cdot 0.38 = 0.8\%$.

Any residual Ge after each extraction will influence the efficiency of measurement of the subsequent extraction. To determine the amount of this residual Ge we propose to carry out second extractions after each first extraction. Taking into account the efficiency of each extraction ε = 95%, the amount of residual Ge should not exceed $(1-\varepsilon)^2 \sim 0.3\% = \delta_{G3}$.

The uncertainty δ_{G4} of Ga mass in the target is expected to be the same as it was in measurements with ^{37}Ar, i.e. 0.5%.

4.2. Uncertainty of counting efficiency

Uncertainties of the second group δ_C take into account the features of proportional counters.

The values of uncertainties connected with measurements of counter volume efficiency ε_v and with a number of events registered in ^{71}Ge peaks $\varepsilon_{p,}$ which were obtained in result of direct measurements of characteristics of all counters of the YCT-type, used in solar measurements, are $\varepsilon_v = \pm1.0\%$ и$\varepsilon_p = \pm1.1\%$. Because in each measurement there will be used different counters, the contribution of uncertainties of each measurement will be independent, and the uncertainty summarized on all measurements can be found using method described above (for δ_{G2}): $\delta_{sum}=\delta_1\cdot0.38$. i.e. $\delta(\varepsilon_v)=0.4\%$ and$\delta(\varepsilon_p)=0.4\%$.

The value δ_{C4} matches the uncertainties connected with Monte Carlo simulations, used for calculation of counter efficiency for different filling parameters. As the precise measurements of counter efficiencies will be carried out for the whole set of the filling parameters, one can consider the value $\delta_{C4} = 0$.

For 75 solar runs (beginning April 2001) the average change of window position of counter during the first months of counting was ±2 channels only and did not influence significantly the result of solar measurements, so, we set $\delta_{C8}=0$.

One can expect that with use of counters of the YCT-type in new experiment the uncertainty in determination of counter resolution (δ_{C6}) as well as in choice of limits of pulse rise time (δ_{C7}) will be the same as the values, which we used for experiment with Ar source.

4.3. Background

Background events can produce the pulses indistinguishable from ^{71}Ge decay in the counters. A sample of background of such type is ^{222}Rn, which decays inside the counters (δ_{N2}). If the average number of Rn atoms in the counter doesn't exceed this number in solar runs, this uncertainty should have the value $\delta_{N2}=0.3\cdot\frac{3\cdot10}{917}\sim 0.01\%$, where 0.3% - the uncertainty of Rn in solar runs. Thereby we can estimate the influence of ^{69}Ge (δ_{N3}), and the background production of ^{71}Ge, which is not connected with the Sun (δ_{N1}).

The estimation of the uncertainty, connected with solar neutrino, was made in the assumption that the capture rate of neutrino from the Sun is constant and corresponds to the value, measured in Ga experiment, namely 66.1±3.1 SNU [2]. The expected number of pulses from solar background will be subtracted from the result of measurements of each irradiation. The relative uncertainty of the subtracted value will be $\delta_{N4}=\frac{6.20\cdot 0.53\cdot \frac{3.1}{66.1}\cdot 10}{873}$=0.16% for an outer zone of target (42.5 t) and 0.03% for an inner zone (7.5 t). In this expression 6.20 is the expected number of ^{71}Ge atoms, produced by solar neutrino in a 10-day period of irradiation in Ga target with mass of 42 t, 0.53 – efficiency of registration, 10 – the number of irradiations, and 873 – the expected number of ^{71}Ge pulses generated from the source in one zone of the target.

4.4. Another uncertainties

The fourth group of the uncertainties consists of the uncertainty, obtained from use of weight coefficients in the maximum likelihood analysis and of the uncertainty in measurements of activity of the source. Based on the estimation of solar data the uncertainty of weight coefficients gives the value δ_{W1}=0.15%.

As it was with previous sources we intend to use several methods for measurement of the ^{51}Cr source activity. The activity of our first ^{51}Cr source was measured with uncertainty ±1.2%, and the uncertainty of our ^{37}Ar source was ±0.5%.

4.5. Total systematic uncertainty of the experiment

The quadratic sum of all systematic uncertainties gives the value ±2.6% for each zone as well as for the total target.

Combining this value with the expected statistical uncertainty ±3.7% for each zone and ±2.6% for the total target will give the uncertainty of ±4.5% for each zone and ±3.7% for the total target.

Taking into account the theoretical uncertainty of the cross section of neutrino capture from Cr source on Ga +3.6/-2.8% [29] the total uncertainty of the experiment should be ±5.5 % for each zone and ±4.8 % for the total target.

IV Limits for parameter of oscillations

Oscillations decrease the probability of neutrino capture in target. For the point source and for target at a distance from r_1 to r_2 from the source the capture rate will be proportional to the value $\int_{r_1}^{r_2} \frac{S(r)}{4\pi r^2} \cdot P_{ee} dr$, where $S(r)$ – the area of intersection of a sphere with radius r with Ga target, and $P_{ee} = 1 - \sin^2 2\theta \cdot \sin^2(1.27 \frac{\Delta m^2 r}{E_\nu})$ - survival probability, function of parameters of oscillations. For a spherical tank (if neglect the connector (reentrance tubing) containing the source), we have $S(R) = 4\pi R^2$ and the expected capture rate proportional to the average value of the value of survival probability P_{ee}.

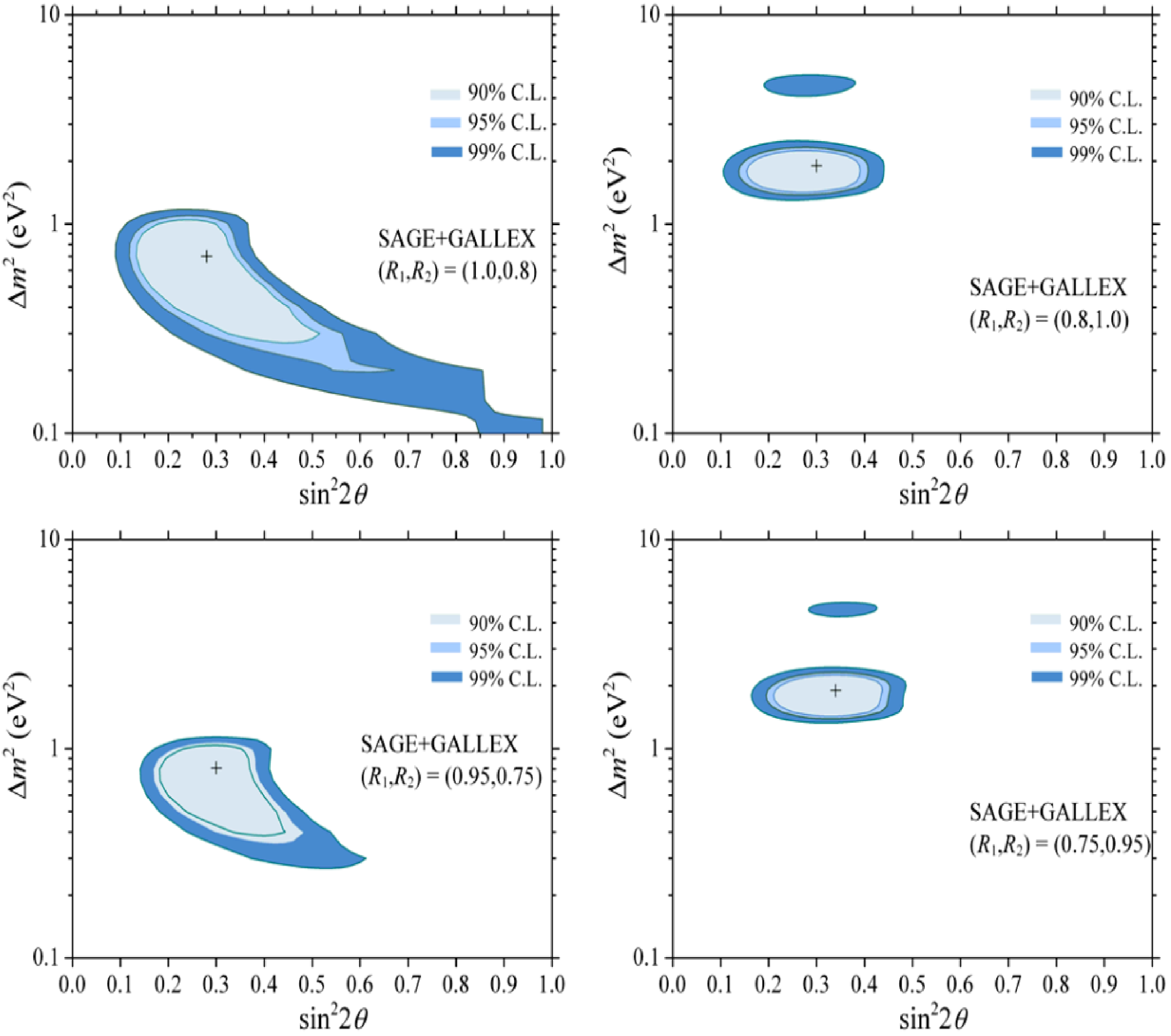


Fig. 13. Regions of allowed parameters of oscillations for four possible results of a 2-zone experiment combined with results of four previous experiments with sources SAGE and GALLEX. Sign "+" indicates the best fit point. R_1 and R_2 are the ratios of measured rate to predicted rate in the inner and outer zones, respectively. Plus sign indicates the best-fit point.

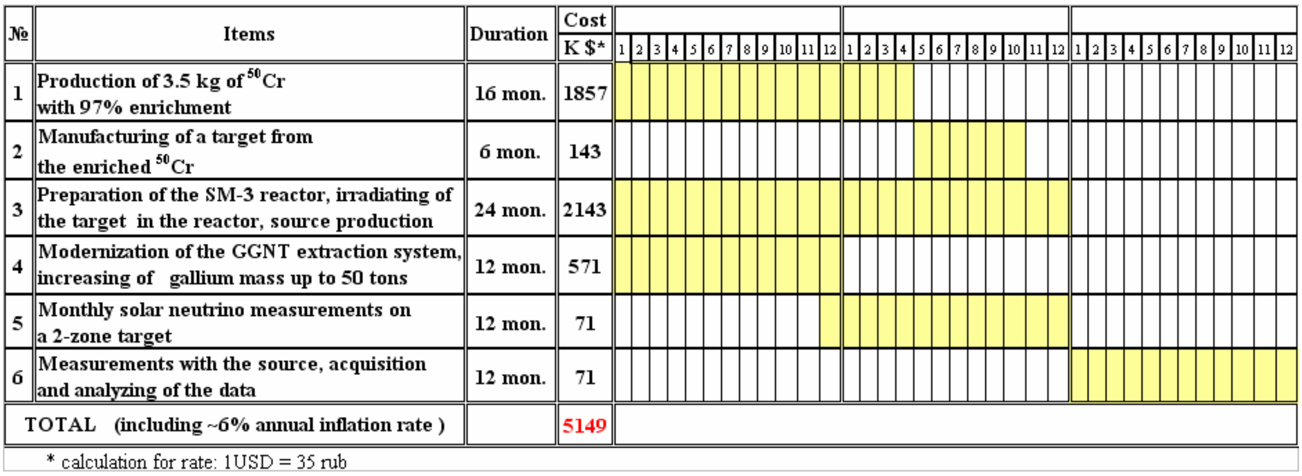
Based on this expression, the region of the allowed parameters of oscillation transitions of electron neutrino to sterile states for some possible outcomes of a new 2-zone Ga experiment were calculated taking into account the results of four previous Ga experiments with sources in SAGE and GALLEX, Fig.13.

V Cost and time schedule

The estimated cost of the whole experiment adjusted for 6% annual inflation rate is \$5.15M of which \$4.4M is the cost of the neutrino source.

Table 5 shows the preliminary time schedule and cost estimation of the experiment with ^{51}Cr neutrino source with activity ~3 MCi on a two-zone Ga target of the Gallium-Germanium Neutrino Telescope.

Table 5. Time schedule of works and the experiment cost estimate



№	Items	Duration	Cost K $*	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1	Production of 3.5 kg of ^{50}Cr with 97% enrichment	16 mon.	1857	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨																				
2	Manufacturing of a target from the enriched ^{50}Cr	6 mon.	143																	🟨	🟨	🟨	🟨	🟨	🟨														
3	Preparation of the SM-3 reactor, irradiating of the target in the reactor, source production	24 mon.	2143	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨												
4	Modernization of the GGNT extraction system, increasing of gallium mass up to 50 tons	12 mon.	571	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨																								
5	Monthly solar neutrino measurements on a 2-zone target	12 mon.	71												🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨												
6	Measurements with the source, acquisition and analyzing of the data	12 mon.	71																									🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
TOTAL (including ~6% annual inflation rate)			5149																																				

* calculation for rate: 1USD = 35 rub

References

1. A. Boyarsky, O. Ruchayskiy, M. Shaposhnikov, Ann. Rev. Nucl. Part. Sci. **59**, 191, 2009, arXiv:0901.0011v2 [hep-ph].
2. R.A. Burenin, A.A. Vikhlinin, Astron. Lett., **38**, 1, 2012, arXiv:1202.2889v1 [astro-ph.CO].
3. Y.I. Izotov, T.X. Thuan, Astrophys. J. **710** (2010) L67, [arXiv:1001.4440 [astro-ph.CO]].
4. E. Komatsu et al. [WMAP Collaboration] Astrophys. J. Suppl. **192** (2011) 18, [arXiv:1001.4538 [astro-ph.CO]].
5. C. Amsler *et al.* (Particle Data Group), Phys. Lett. B**667**, 1 (2008).
6. A. Aguilar et. al. (LSND Collaboration), Phys.Rev. D **64** (2001) 112007, [hep-ex/0104049].
7. P. Astier et al., [NOMAD Collaboration], Phys. Lett., **B570** (2003) 19 [hep-ex/0306037].
8. K. Eitel et al., [KARMEN Collaboration], Nucl. Phys. Proc. Suppl. **77** (1999) 212 [hep-ex/9809007]; B. Armbruster et al., [KARMEN Collaboration], Phys. Rev. D **65**,112001,2002 [hep-ex/0203021v1].
9. A.A.Aguilar-Arevalo, C.E.Anderson, S.J.Brice, et al., arXiv:1007.1150 [hep-ex]; A.A. Aguilar-Arevalo et al. [MiniBooNE Collaboration], Phys. Rev. Lett. 103, 111801 (2009); A.A. Aguilar- Arevalo et al. [MiniBooNE Collaboration], Phys. Rev. Lett. 105, 181801 (2010); Z. Djurcic [MiniBooNE Collaboration], arXiv:1201.1519.
10. A.A. Aguilar-Arevalo et al. [MiniBooNE Collaboration], Phys. Rev. Lett. 98, 231801 (2007); A.A. Aguilar-Arevalo et al. [MiniBooNE Collaboration], Phys. Rev. Lett. 102, 101802 (2009).
11. T.A. Mueller et al., Phys. Rev. C 83, 054615 (2011); arXiv:1101.2663, arXiv:1103.2452.
12. G. Mention et al., Phys. Rev. D 83, 073006 (2011); [arXiv:1101.2755].
13. J. Kopp, M. Maltoni and T. Schwetz, Phys. Rev. Lett. **107** (2011) 091801 [arXiv:1103.4570 [hep-ph]].

14. M.A.Acero, C.Giunti, M.Laveder, Phys. Rev. **D78** (2008) 073009 [arXiv:0711.4222 [hep-ph]]; C.Giunti, M.Laveder, Phys. Rev. **D82** (2010) 053005 [arXiv:1005.4599 [hep-ph]].
15. B.T. Cleveland, H. Ejiri, S.R. Elliott, V.N. Gavrin, et.al, arXiv:1204.5379v1 [hep-ph]; V.N.Gavrin, V.V.Gorbachev, E.P.Veretenkin, and B.T.Cleveland, arXiv:1006.2103 [nucl-ex].
16. G.Domogatski, V.Kopeikon, L.Mikaelyan, V.Sinev, Phys. Atom. Nucl. **68** (2005), 69 [hep-ph/0401221].
17. S. Razzaque and A. Yu. Smirnov, JHEP **1107** (2011) 084 [arXiv:1104.1390 [hep-ph]]; V. Barger, Y. Gao, D. Marfatia, Phys. Rev. **D85** (2012) 011302 [arXiv:1109.5748v1 [hep-ph]]; S. Razzaque and A. Yu. Smirnov, arXiv:1203.5406 [hep-ph].
18. J.N. Abdurashitov, V.N. Gavrin, (SAGE Collaboration) et al., Phys. Rev. C **60** (1999), 055801 [astro-ph/9907113];
19. В.Н. Гаврин, УФН. 2011, Т.181, №9.
20. J.N.Abdurashitov, V.N.Gavrin, V.V.Gorbachev, etal., Phys. Rev. C**80**, 015807 (2009)
21. J. N. Abdurashitov et al. (SAGE coll.), J. Exp. Theor. Phys. **9**5, 181 (2002); Zh. Eksp. Teor. Fiz. 122, 211 (2002); Preprint No. 0204245, astro-ph (2002).
22. B. T. Cleveland, Nucl. Instr. Methods Phys. Res. **214**, 451 (1983).
23. Abazov A I et al. Phys. Rev. Lett. 67 N 64 3332 (1991)
24. Anselmann P et al. (Gallex Collaboration) Physics Letters B 285 376 (1992)
25. J.N.Abdurashitov, V.N.Gavrin, S.V.Girin, et al., Phys.Rev. C59, 2246 (1999)
26. J.N.Abdurashitov, V.N.Gavrin, S.V.Girin, Phys.Rev. C 73, 045805 (2006)
27. W.Hampel, G.Heusser, J.Kiko, et al. Phys. Lett. B **420**, 114 (1998).
28. F.Kaether, W.Hampel, G.Heusser, et al., Phys. Lett. B **685**, 47 (2010), arXiv:1001.2731 [hep-ex].
29. Bahcall J N Phys. Rev. C 56 3391 (1997); hep-ph/9710491
30. Naoya Hata, Wick Haxton, Physics Letters B **353**, 422 (1995).
31. D. Frekers *et al.*, Phys. Lett. B**706**, 134 (2011).

32. PopovG.E., PrusakovV.N., RudnevA.I., TikhomirovA.V., VoroninA.V., "Centrifugalenrichmentofchromium-50 forexperimentsondetectingsolarneutrinos", Nucl. Instr. and Meth., A **362** (1995), pp. 532-537.
33. Tikhomirov A.V., “Practice of centrifugal stable isotope separation for experiments in neutrino physics”, Proceedings of the IV Int. Symp. on Weak and Electromagnetic Interactions in Nuclei, Osaka, Japan, June 12-16, 1995, World Scientific, pp. 208 - 211.
34. Cribier M., et al., “Production of a 62 PBq ^{51}Cr low energy neutrino source for GALLEX”, Nucl. Instr. and Meth., A **378** (1996), pp. 233-250.
35. VakhetovF.Z., Romanov E.G., TarasovV.A. Kompleksprogramdlyaraschetatransmutatsiynuklidov, // Sb. Trudov (in Russian), Dimitrovgrad: GNC NIIAR, 2003, Vyp.3, S.53-57
36. MCNP^{TM}-A General Monte Carlo N-Particle Code. Version 4B / EditorJudith F. Briesmeister. Report LA-12625-M. Los Alamos, 1997.