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The Russian-American gallium experiment SAGE

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1. Introduction

Ever since W Pauli postulated in 1933 the existence of the neutrino, it remains one of the most interesting particles in nuclear physics. The concept of a neutrino in the beta-decay theory, which was developed by E Fermi a year later, proved to be so fruitful that the neutrino was confidently introduced to the family of elementary particles long before its discovery [1].

By 1956, when C Cowan and F Reines with coworkers succeeded to detect the free neutrino for the first time, the characteristics of this particle had been already established for the most part from indirect data obtained in many preceding experiments with natural and artificial beta-decay and K-captured isotopes and in studies of meson–neutrino reactions in accelerators.

The notion of the neutrino based on these studies was in good agreement with all experimental observations until the 1970s–1980s, although the questions of the existence of the neutrino mass and its nature (the Dirac or Majorana neutrino) remained open. In this period, the results of the first solar neutrino experiments were obtained, which led to changing the view of the neutrino and thereby of a number of phenomena in the modern physical picture of the world.

2. The solar neutrino problem

The aim of the first solar neutrino experiment started in the late 1960s was to verify the theory of the structure and evolution of stars, which forms the basis of the Standard Solar Model (SSM) [2].

It was believed that energy in the Sun is produced due to thermonuclear transformation of four protons to an α particle in reaction chains where two positrons and two neutrinos are created. It was also assumed that weakly interacting neutrinos pass through the Sun and reach Earth without any changes.

Thus, the recording of the energy spectrum of neutrinos should give information on conditions under which thermonuclear reactions proceed in the Sun. M A Markov pointed out in 1964: “It is widely accepted that the energy balance of stars like the Sun is supported by nuclear reactions proceeding in the depths of a celestial body. Although this hypothesis looks very plausible, nevertheless, the existence of such processes in the Sun has not been experimentally confirmed to date, and surprises with far-reaching consequences are possible, in principle, here” [3].

Indeed, the first solar neutrino flux measurement in the USA with a chlorine detector containing a 610-t chlorine-containing target revealed a considerably smaller number of neutrinos than that predicted by the detailed models of physical processes in the Sun [4]. This experiment was started in the late 1960s and continued until the mid-1980s. In it researchers realized B Pontecorvo’s remarkable idea of detecting solar neutrinos by the radiochemistry method by measuring the production rate of ^{37}Ar isotopes in the reaction of neutrino capture by ^{37}Cl nuclei in a chlorine target [5]. Although various SSMs predicted somewhat different rates for the chlorine experiment, the capture rates in all these models considerably exceeded the values observed. This discrepancy became the widely known ‘solar neutrino problem’, which existed for more than 30 years.

For 20 years, the chlorine experiment remained the only one for detecting solar neutrinos. The chlorine target utilized in this experiment was sensitive solely to the highest-energy neutrinos in the solar spectrum, produced in the decay of ^{8}B nuclei and to a fraction produced in the decay of ^{7}Be. The reactions in which these neutrinos are created make an insignificant contribution to the energy produced in the Sun, while the intensity of these neutrino fluxes strongly depends on the temperature at the center of the Sun. The very low intensity of neutrino fluxes observed in experiments cannot be explained within the framework of the SSM.

As a result, a great number of so-called nonstandard models were constructed in which agreement with the chlorine-experiment result was achieved by introducing some temperature lowering mechanisms at the center of the Sun. However, most of these models encountered problems in describing other measured parameters of the Sun.

An alternative explanation of the discrepancy of the chlorine-experiment results with SSM predictions could be the existence of neutrino oscillations. In the chlorine experiment, neutrinos are detected by the reaction of inverse β-decay and, therefore, the chlorine detector is only sensitive to electron neutrinos. If neutrinos oscillate during their motion from the central regions of the Sun to Earth (and, hence, change their flavor), the chlorine detector can detect only a fraction of their flux.

The idea that neutrinos may oscillate was proposed by Pontecorvo [6] already in the early 1960s, but was not generally accepted because it led to a strong mixing of neutrinos, which was inconsistent with the concepts existing at that time.

In the mid-1980s, measurements of a solar neutrino flux were started in Japan by using a large water Cherenkov detector (the Kamiokande experiment) sensitive to recoil electrons created in elastic collisions of solar ^{8}B-neutrinos with target electrons. As in the chlorine experiment, the measured flux proved to be lower than that predicted by the SSM, and so the existence of the neutrino deficit in the high-energy part of the solar neutrino spectrum was confirmed in the second independent experiment.

To understand whether this deficit is related to solar physics or neutrino physics, the gallium solar neutrino experiment was required. This experiment differs from all other solar neutrino experiments in its high sensitivity to the proton–proton (pp) reaction $p + p \rightarrow d + e^{+} + \nu_e$ in which most of the solar energy is generated.

The rate of the p-p reaction is directly related to the solar luminosity and, therefore, it is virtually independent of the model, while the capture rate of the pp-neutrino by Ga nuclei

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can be predicted very accurately. Thus, the gallium experiment is the only one providing a direct measurement of the rate of energy generation in the Sun.

3. Gallium experiments

The use of gallium in the radiochemical solar neutrino experiment was proposed by V A Kuzmin back in 1963 [7], even before the first solar neutrino experiments were performed. However, the high cost of gallium, the small amount of its global production, and the absence of reliable technology for extracting and counting single atoms of the germanium ^{71}Ge isotope produced via the capture of neutrinos by a large-tonnage gallium target significantly prevented carrying out the gallium experiment at that time.

Laboratory investigations on the design process of the gallium experiment at the Institute for Nuclear Research (INR) of the Academy of Sciences of the USSR and at the Brookhaven National Laboratory (BNL) in the USA were started almost simultaneously in 1975. Methods for extracting germanium from liquid metal gallium and from the solution of gallium chloride in hydrochloric acid were developed. Considerable advances were achieved in the development of these two methods for a few years. Methods for counting single ^{71}Ge atoms were developed, and the production rates of ^{71}Ge nuclei were calculated and measured in different background processes caused by muons of cosmic rays, α particles from internal radioactive impurities, and fast neutrons from external sources.

The American group chose the method utilizing a gallium chloride solution as the simplest to realize, and made a pilot facility containing 1.3 t of gallium in the gallium chloride solution in hydrochloric acid. In 1981, a proposal to perform a large-scale 50-t gallium experiment was directed to the US Department of Energy. The proposal was considered at a high level and recommended for realization, but was unfunded. Fifteen years later, G T Garvey, Director of the Los Alamos Meson Physics Facility, commented on this financial mishap in the following way: “This happened mainly because, as was found out, a Federal Agency for financing studies of this type was nonexistent, which is a true flaw in the USA system.”

At the department headed by G T Zatsepin at INR, laboratory studies on the development of the gallium experiment were also started by using the gallium chloride solution. But when it became clear that our industry could not provide the required purity of 50 t of this solution, it was decided to begin to develop a method for extracting germanium directly from metal gallium because metal gallium is considerably less sensitive to radioactive impurities.

The possibility of extracting extremely small amounts of germanium from metal gallium was first demonstrated by R Davis. Based on the Davis idea, we developed the technology of extracting single ^{71}Ge atoms from many tons of metal gallium. Our first paper in which this method was applied to extracting single ^{71}Ge atoms from 300 kg of metal Ga was published in 1980 [8].

In 1984, G T Garvey sent a proposal to the INR, USSR Academy of Sciences to combine the efforts of the Los Alamos National Laboratory (LANL) in the USA and the INR in investigations of solar neutrinos, in particular, in conducting the gallium experiment. An agreement on the performance of the joint Soviet–American Gallium Experiment using the gallium–germanium neutrino telescope (GGNT) at the Baksan Neutrino Observatory was signed by V A Matveev in 1986. The experiment was called SAGE (Soviet–American Gallium Experiment). The American participants of the experiment were LANL and Pennsylvania State University. Later on, the University of Washington and the National Institute of Standards and Technologies (Gaithersberg) were also involved in the experiment.

In 1986, a pilot facility containing 7.5 tons of metal Ga was created at the INR in Troitsk, at which the procedure of extracting single ^{71}Ge atoms was fine-tuned. The American team was engaged in the development and production of a system for detecting the decay of extracted ^{71}Ge atoms.

In 1984, a German group at the Max-Planck-Institut (Heidelberg) headed by T Kirsten presented a project on the gallium experiment with the use of a gallium chloride solution at the underground Gran Sasso Laboratory in Italy and began to create, with the participation of BNL, the Western-European Collaboration, which was called GALLEX (GALLium EXperiment).

Thus, two independent gallium experiments appeared, in fact, simultaneously: GALLEX, based on the Ga chloride solution, at the underground Gran Sasso Laboratory, and SAGE, based on metal Ga, at the underground laboratory at the Baksan Neutrino Observatory of the INR.

4. Gallium–germanium neutrino telescope laboratory at the Baksan Neutrino Observatory of the Institute for Nuclear Research, RAS

Solar neutrino experiments were some of the first initiating a new direction of investigations in astrophysics and the physics of elementary particles. These studies required the establishment of underground laboratories providing a considerable lowering of the muon background of cosmic rays (by a few million times), and special low-background materials for protecting detectors from the radiative emission of the environment. The Baksan Neutrino Observatory was founded for the development of these investigations in the USSR.

The Baksan Neutrino Observatory is located in the upper reaches of the Baksan River in the Northern Caucasus at an altitude of 1700 m above the sea level. The underground parts of the observatory are located in the depths of the Andyrchi Mountain massif (3937 m in altitude), which is part of the side branch of the Large Caucasian Ridge. The construction of the observatory was initiated in 1967.

The initial project of the Baksan Neutrino Observatory assumed the construction of a deep underground laboratory containing, according to the program of solar neutrino spectroscopy proposed by G T Zatsepin, a unified complex of three radiochemical neutrino telescopes based on Cl, Li, and Ga and having different sensitivities to neutrinos created in different reactions proceeding in the Sun.

It was proposed that this complex be placed at a distance of 4200 m from the entrance of a horizontal adit where the intensity of cosmic-ray muon fluxes in the depths of the massif reaches its minimum.

Because the acquisition of experimental data in the low-energy part of the spectrum of solar neutrinos became very urgent, it was decided in 1977 to begin first of all with establishing a separate gallium–germanium neutrino telescope laboratory, not waiting for the termination of the adit sinking over the entire projected length.

Because the gallium neutrino experiment can be performed at smaller depths than those required for chlorine

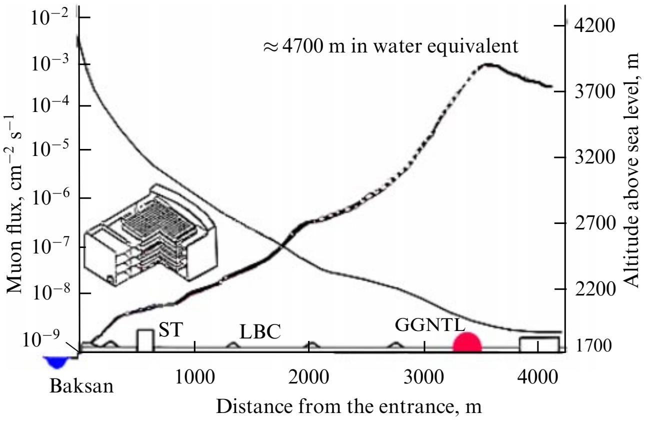

Figure 1. Profile of a mount, the dependence of the muon flux on the adit length, and the schematic arrangement of underground laboratories at the Baksan Neutrino Observatory: ST — scintillation telescope, LBC — low-background chambers, GGNTL — gallium–germanium neutrino telescope laboratory. The insert in the left part of the figure shows the schematic view of the scintillation telescope.

experiments [9, 10], the GGNT laboratory facility was placed at a distance of 3600 m from the entrance of an adit (Fig. 1). The thickness of cover rocks over the laboratory is 2100 m, corresponding to 4700 m of the water equivalent. The GGNT laboratory is now second in the world in site depth.

The GGNT laboratory comprises a cylindrical chamber shaft 60 m in length, 15 m in diameter, 12 m in base width, and 10 m in height. To organize work rooms, control panels, and sites for the technological equipment, support metal structures are mounted in the laboratory at different levels. The auxiliary equipment of engineering systems (electric substation, air-conditioning system, air vent aggregate, etc.) is placed in separate rock shafts adjacent to the laboratory (Fig. 2). The temperature of the surrounding rock reaches 38.3 °C.

The laboratory has a forced ventilation system taking fresh air from the adit, and an air vent discharge setup directing the exhaust air to its air line. Laboratory rooms are cooled with an air conditioner. The incoming air is purified in two stages: in the first filter chamber (with FL-1.8 filtering material), the air is purified of dust, and in the second chamber with Petryanov FPP-1.5 filters, it is purified of aerosols contained in air (in particular, the decay products of ^{232}Th and ^{238}U nuclei). Air is directed to each room through separate air lines. A ventilator of the air-flow system produces excess pressure in the laboratory rooms. The exhaust air arrives at the main ventilator placed at the entrance of the auxiliary adit.

Personnel, materials, and equipment are transported by rail using electric battery locomotives, passenger cars, and special platform cars.

The muon flux in the GGNT laboratory was measured with a small telescope of scintillation polystyrene detectors 4 m^2 in area [11]. The global intensity of muon fluxes in the GGNT laboratory was measured to be [11]

$$N_{\text{measured}} = (3.03 \pm 0.10) \times 10^{-9}\ \text{cm}^{-2}\ \text{s}^{-1}\,.$$

Calculations of the production rates of germanium isotopes in Ga for this muon flux [9] showed that the rate of the ^{71}Ge production at the laboratory location depth was less than 0.01 atoms per day, i.e., lower than 1% of the value predicted by the SSM (in the absence of attenuation of the electron neutrino flux due to, for example, oscillations or other effects).

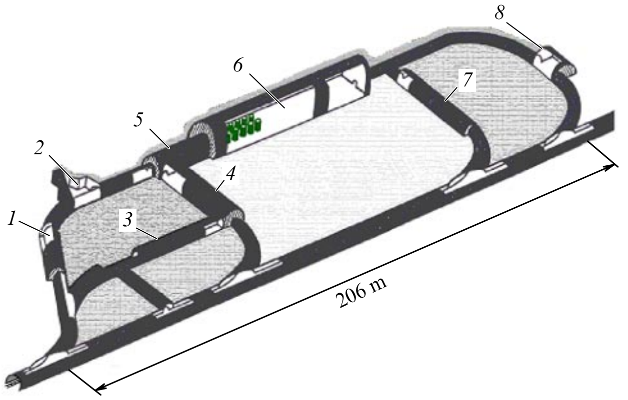

Figure 2. Schematics of the underground compartments of the GGNT laboratory: *1*, *2*, *5*, *7*, *8* — auxiliary compartments; *3* — electric substation compartment; *4* — air-conditioning compartment, and *6* — reactor hall of the GGNT.

Metal gallium is considerably less sensitive to fast neutrons than is the solution of its chloride in hydrochloric acid. According to estimate [12], the contribution of fast neutrons from surrounding rocks to the production rate of ^{71}Ge, even without shielding, in experiments with metal Ga is less than 1% of the contribution expected from solar neutrinos by neglecting their oscillations.

However, to maximally realize the potential of this unique arrangements for performing experiments requiring an extremely low radiation background, it was decided to reduce significantly the neutron flux in the gallium laboratory by applying for its construction special low-background concrete, which, apart from its direct function of strengthening rocks, can serve as a radiation shield. In addition, we took into account that the low-energy solar neutrino flux, to which the gallium experiment is primarily sensitive, can be suppressed and considerably lower than the expected flux, as had been found in the chlorine experiment for high-energy neutrinos.

The content (g g^{-1}) of radioactive elements in rocks surrounding the laboratory is as follows: ^{238}U — $(1.5-3.8) \times 10^{-6}$, ^{232}Th — $(1.9-2.5) \times 10^{-5}$, and ^{40}K — 3.4×10^{-6}.

The GGNT laboratory was embedded in concrete based on dunite, silica sand, and Portland cement, which was developed at the Central Research Laboratory of Orgproekt in cooperation with INR, USSR Academy of Sciences [13]. The average contents of uranium and thorium impurities in the basic concrete components were 1.58×10^{-7} and 6.73×10^{-7} g g^{-1}, respectively.

In December 1987, the laboratory was put into operation and work was started on GGNT adjustment. The first measurements of a solar neutrino flux in SAGE were performed in December 1989.

5. Soviet-American gallium experiment (SAGE)

The neutrino flux in SAGE is determined by measuring the rate of neutrino capture reaction $^{71}\text{Ga}(\nu_e, e)^{71}\text{Ge}$ on metal Ga in the GGNT. The reaction threshold, which was 233 keV, allows the detection of neutrinos produced in all neutrino-production reactions proceeding in the Sun according to the SSM, including neutrinos produced in pp reactions (pp-neutrinos). The maximum energy of the pp-neutrino is 420 keV. The number of pp-neutrinos with energies exceeding the capture threshold by ^{71}Ga nuclei is more than half the total number of pp-neutrinos, and their contribution to the expected capture rate in experiments is about 54%.

The telescope target consists of approximately 50 t of metal gallium uniformly distributed in seven chemical reactors. Gallium is contained in reactors in the liquid form at a temperature of 31 °C (the melting point of gallium is 29.8 °C). Measurements are performed cyclically.

Each measurement of the capture rate of solar neutrinos begins with the addition of a carrier (≈ 250 µg of stable germanium) to the Ga target. The carrier is added in the form of tablets containing the gallium alloy with the known amount of germanium (about 2×10^{-4} mass percent). Germanium is uniformly distributed in the reactors over the entire gallium mass.

The neutrino capture rate in radiochemical experiments is expressed in SNU (Solar Neutrino Units): 1 SNU corresponds to one neutrino captured per second in a target containing 10^{36} atoms of isotope (in our case, ^{71}Ga) capturing neutrinos. The expected capture rate of solar neutrinos by gallium atoms amounts to 128 SNU [14]. For natural gallium containing 39.9% of ^{71}Ga isotopes, the capture rate of 128 SNU corresponds to the production rate of ^{71}Ge atoms in the 50-t target of about 1.9 atoms per day. Thus, for a long exposure time (the half-life of ^{71}Ge decay is $T_{1/2} = 11.43$ days), the average number of ^{71}Ge atoms in the target can be about 32.

Exposures used in the experiments lasted for 4 to 6 weeks. Then, the ^{71}Ge atoms produced are chemically extracted together with the germanium carrier from gallium by the method described in Ref. [15]. Germanium extracted from gallium (the carrier and ^{71}Ge atoms) is converted to the gaseous form GeH_4 (germane) and, after measuring its volume, is placed into a proportional counter.

The chemical properties of germanium isotopes are identical, and therefore the total extraction efficiency for ^{71}Ge atoms is equal to the extraction efficiency for stable germanium, which is defined as the ratio of the germanium mass in germane to the introduced mass of the germanium carrier. Germanium enriched with ^{72}Ge or ^{76}Ge isotopes is used as the carrier. After completing each extraction, the final extraction solution sample is analyzed with a mass spectrometer to determine the fractional composition of different Ge isotopes.

Molecules of germane are highly symmetrical and are not polarized, and therefore they can be used as a quenching addition in proportional counters. The main counting gas in counters is xenon having a large atomic number ($Z = 54$) and, consequently, a large enough cross section for interaction with soft X-rays produced upon the recovery of electron shells during the decay of ^{71}Ge nuclei.

The counting of ^{71}Ge decays extends over 5–6 months, which is related to the method of selecting pulses generated by the ^{71}Ge decay from all the pulses detected by the counter, a considerable fraction of them being background pulses. The pulses are analyzed after the termination of counting by the developed method of event selection and time analysis.

The capture rate of solar neutrinos by gallium is determined by the number of detected ^{71}Ge decays, taking into account the extraction and counting efficiencies.

Figure 3. GGNT chemical reactors.

Figure 4. General view of the GGNT reactor hall.

5.1 GGNT chemical reactors

The GGNT comprises ten chemical reactors (Figs 3, 4) connected with each other by a heated Teflon pipe with a Teflon liquid pump providing the circulation of metal gallium between reactors. The reactor (Fig. 5) represents a 2-m^3 Teflon tank with 40-mm-thick walls, which is heated with band heaters. The Teflon tank is placed inside a stainless steel tank. Gallium is mixed with a special mixer with the maximum rotation speed of 80 rpm. To provide the efficient mixing of reagent solutions (density of ≈ 1 kg l^{-1}) with metal gallium (density of 6.1 kg l^{-1}), the reactor has special cutters fastened on the inner side of the reactor lid. The cutters are made of Teflon, and the mixer and the inner side of the lid are also covered by a Teflon layer.

Reagents are fed into reactors by means of a system of controllable valves and pumps made of Teflon and borosilicate glass. The system allows one to feed the measured amounts of reagents to any of these reactors. The solution obtained after completing the extraction (the extraction solution) is decanted with the help of a vacuum system whose components are made of glass, Teflon, and zirconium. The reagent dosing and mixing processes are completely automated.

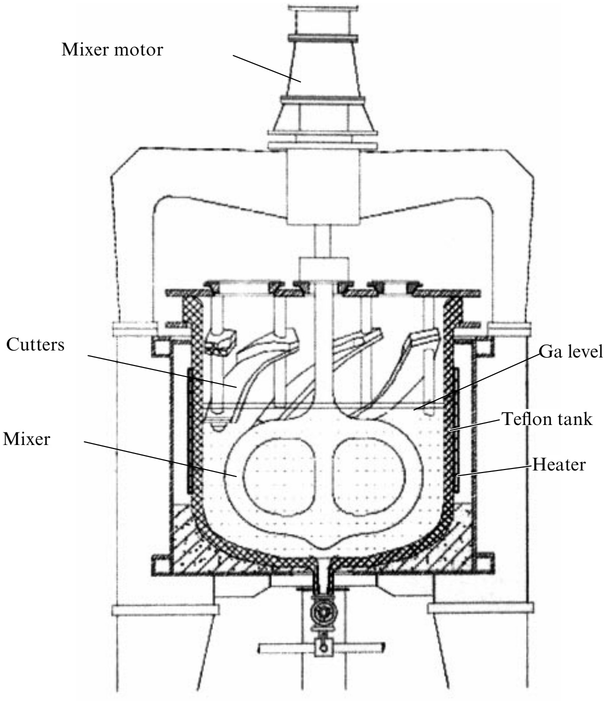

Figure 5. Chemical reactor for extracting germanium from gallium.

The germanium extraction efficiency depends on many parameters, and increases upon increasing the amount of oxidizer (hydrogen peroxide solution) added; at the same time, the amount of gallium dissolved during the oxidation reaction increases proportionally to the amount of hydrogen peroxide added. The extraction efficiency also depends on the aqueous phase volume, which determines the duration of the subsequent concentration of germanium — the longest stage of the entire extraction process.

Taking into account all the factors considered above, an extraction procedure was developed which provides a total extraction efficiency reaching $(95 \pm 3)\%$ for an amount of dissolved gallium smaller than 0.1%.

5.2 Counting ^{71}Ge atoms

The ^{71}Ge nuclei decay back into ^{71}Ga nuclei due to purely electron capture with a half-life period of 11.4 days. A proportional counter gives two peaks: the K peak at 10.4 keV, and the L peak at 1.2 keV.

Beginning from April 2001, completely reconstructed proportional YCT (Yants–Carbon–Thin) type counters [16] have been used in the experiment. These counters were developed by V E Yants at the Laboratory of Radiochemical Methods for Neutrino Detection at the INR, RAS. Unlike the solid cathode used in counters earlier, a cathode in new counters represents a thin carbon layer deposited onto the inner surface of a quartz flask upon thermal decomposition of hexane or acetone vapor. This excluded the ‘dead’ volume behind the cathode. The dead volume was also diminished by eliminating edge effects due to the specific design of these counters.

The contacts of the cathode and anode are brought out from the counter with the help of a molybdenum band, which provides air tightness and a high stability of the counter. The cathode is so thin that the counter walls are transparent, allowing the visual observation of its internal structure. The measured volume efficiency of all new counters reached 96%, with a spread in values of only 1%. The increase in the volume efficiency resulted in a considerable increase in the efficiency of counters: by approximately 25% in the K peak, and 10% in the L peak.

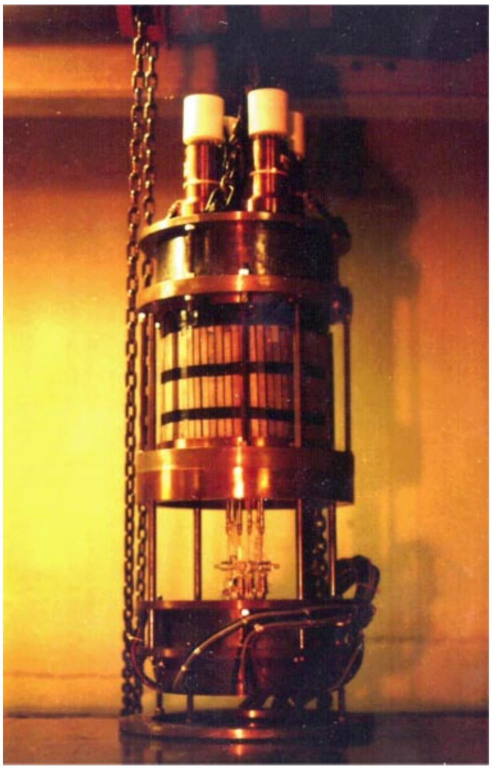

Figure 6. Part of the active shield of the detection system with an NaI detector and proportional counters inside it.

The output pulses of a proportional counter are fed into a digital oscilloscope, where they are digitized in the 800-ns interval after the pulse onset with two different amplifications for the K and L peaks. The digital oscilloscope is used to separate fast rising ^{71}Ge pulses from (predominantly) slowly rising background pulses.

Proportional counters filled with a gas mixture are set up in the GGNT detection system, which is designed so that the detection of the ^{71}Ge decays in counters is provided with maximum efficiency. For this purpose, a number of measures were taken for suppressing noise and background pulses. The detection system is placed in a specially equipped room of the underground laboratory. The external walls of the room are made of 10-mm-thick sheet steel and a 70-cm-thick low-radioactive concrete layer protecting from fast neutrons and γ-radiation of the surrounding rocks. The inner walls are coated with 1-mm-thick sheets of zinc-plated iron for screening from radio interference.

A counter containing GeH_4 obtained from gallium-extracted germanium is placed into an NaI detector well (Fig. 6) located inside a large passive shield, and decay pulses from ^{71}Ge are detected with the counter for 5–6 months. The NaI detector well can simultaneously accommodate up to eight counters.

To reduce the action of ^{223}Ra nuclei, the volume inside the shield around the counters is blown out with liquid nitrogen evaporated from a Dewar. The shield consists of successive iron, lead, copper, and tungsten layers. All the components of

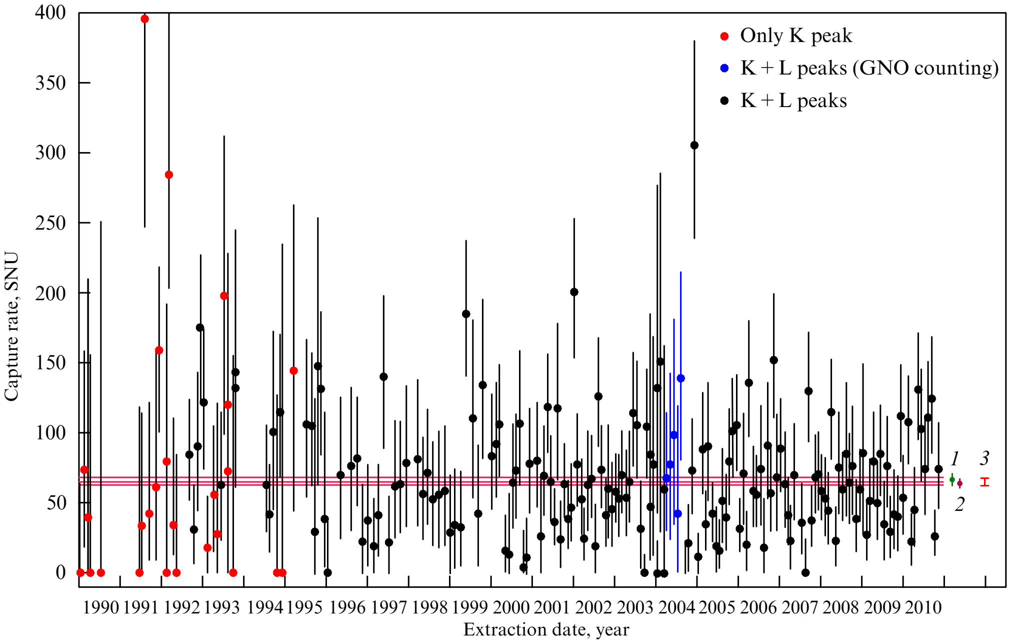

Figure 7. Neutrino capture rate for all SAGE extractions as a function of time. The vertical bars at each point correspond to a statistical error of 68%. Results of processing with the L peak (*1*), the K peak (*2*), and the combined result for all data (*3*). The horizontal bars correspond to the combined SAGE result (65.4 ± 2.7 (stat.)) SNU.

the shield are made of low-radioactive materials which were preliminarily selected with the help of a low-background germanium semiconductor detector.

5.3 Data analysis and SAGE results

Based on selection criteria described in Ref. [15], candidate events from ^{71}Ge nuclei decays are selected from the counter data for each germanium extraction. The time distribution of these selected events is approximated by the maximum likelihood function [17], assuming that they occur from the unknown background constant in time and from decays of ^{71}Ge atoms whose number exponentially decreases.

The measurement of the capture rate of solar neutrinos on a metal gallium target in SAGE was started in December 1989. Since then, the measurements have been performed mainly monthly, with only a few short interruptions. The results of 200 individual measurements performed between January 1990 and August 2010 are presented in Fig. 7. Because only a few decays of ^{71}Ge nuclei are detected in each extraction, the results of individual measurements have a large statistical uncertainty and, therefore, a small significance. The results of analysis of the SAGE data combined over years for the same period are given in Fig. 8.

The neutrino capture rate obtained from the analysis of 200 measurements is (65.4 ± 2.7) SNU. If the data obtained for the L and K peaks are analyzed separately, the results will be (66.9 ± 4.1) SNU and (64.2 ± 3.6) SNU, respectively (here and above, only statistical uncertainties are indicated). The agreement between the results of the independent analysis of data in the two peaks well confirms the reliability of the criteria for selecting events. As another argument that we are counting namely ^{71}Ge atoms, we introduce into the likelihood function, along with the combined production rate of ^{71}Ge atoms and all background counting rates, the decay constant as a free variable. The half-life period found in such a way for all events selected in the L and K peaks amounts to (11.5 ± 0.9 (stat.)) days, in good agreement with the half-life period of (11.43 ± 0.03) days for ^{71}Ge decays measured in Ref. [18].

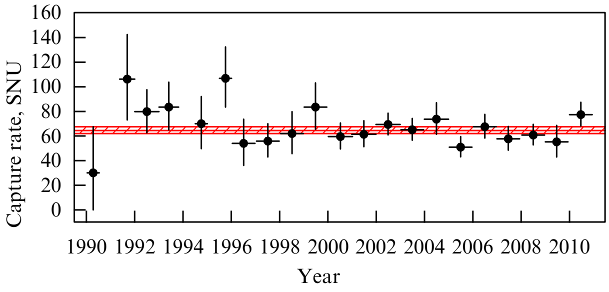

Figure 8. Results of measurements combined by years. The shaded region corresponds to the combined SAGE result (65.4 ± 2.7 (stat.)) SNU. The vertical bars at each point correspond to a statistical error of 68%, and the horizontal bars correspond to the time interval of the combined analysis of measurements.

The combined analysis of the SAGE data for the entire measurement period, taking into account the statistical and systematic uncertainties, gives a capture rate of solar neutrinos by gallium at [65.4 ± 2.7 (stat.) ±2.7 (sist.)] SNU or (65.4 ± 3.8) SNU, where the statistical and systematic errors are combined quadratically. The systematic uncertainties of the experiment were considered in detail in papers [15, 19, 20].

5.4 Results of gallium experiments

The measurements of solar neutrinos in the GALLium EXperiment (GALLEX) at the underground laboratory in Gran Sasso [21] were performed with a 103-t target consisting of a GaCl$_3$ solution in hydrochloric acid containing 30 t of gallium. For 5.4 years, from May 1991 to January 1997, 65 measurements were performed, the final analysis of which gave the capture rate of (73.1 ± 7.2) SNU.

After some interruption, the experiment was continued under the new name GNO (Gallium Neutrino Observatory);

from May 1998 to April 2003, 58 measurements were performed which gave the capture rate of (62.9 ± 5.1) SNU.

The combined result of solar neutrino measurements in two Gran Sasso experiments gives the neutrino capture rate in gallium equal to (67.6 ± 5.1) SNU, which is in excellent agreement with the SAGE result of (65.4 ± 3.8) SNU. The agreement between the results of two independent gallium experiments using Ga targets of different shapes considerably increases their reliability.

The weighted-mean neutrino capture rate obtained from SAGE and GALLEX/GNO experiments is (66.1 ± 3.1) SNU, which is about 50% of the value predicted by the SSM. Thus, gallium experiments have demonstrated a considerable suppression of the solar neutrino flux over the entire energy range, which excluded the possibility of solving the solar neutrino problem within the framework of solar physics only, and proved the change in the flavor of neutrinos traveling from the center of the Sun to Earth.

6. The pp-neutrino flux from the Sun

As mentioned above, the radiochemical gallium experiment with its low energy threshold (233 keV) is sensitive to all the components of the solar neutrino spectrum — from low-energy pp-neutrinos to high-energy neutrinos produced in the ^{8}B nucleus decay. Thus, the neutrino capture rate measured in gallium experiments, which is the sum of capture rates from all the components of the solar neutrino flux, can be expressed in the form

$$[\mathrm{pp} + {}^{7}\mathrm{Be} + \mathrm{CNO} + \mathrm{pep} + {}^{8}\mathrm{B}|\mathrm{Ga}] = 66.1(1 \pm 0.047)\ \mathrm{SNU},$$

where the left-hand side presents the capture rates in gallium from the components of the solar neutrino flux. Here, we neglected the insignificant contribution of the *hep*-neutrino and combined neutrino fluxes from the ^{13}N, ^{15}O, and ^{17}F decays into one component of the solar neutrino flux, denoted CNO.

By using the results of measurements of neutrino fluxes in the Borexino [21] and SNO (Sudbury Neutrino Observatory) [23] experiments and the neutrino capture rates obtained in the chlorine experiment [24], we determined the contribution from each component of the solar neutrino flux to the capture rate measured on Ga targets [20]:

$$[{}^{7}\mathrm{Be}|\mathrm{Ga}] = 19.1(1 \pm 0.12)\ \mathrm{SNU},$$

$$[{}^{8}\mathrm{B}|\mathrm{Ga}] = 3.6(1^{+0.32}_{-0.16})\ \mathrm{SNU},$$

$$\left[(\mathrm{CNO} + \mathrm{pep})|\mathrm{Ga}\right] = 3.68(1 \pm 1.0)\ \mathrm{SNU},$$

$$[\mathrm{pp}|\mathrm{Ga}] = 39.7(1 \pm 0.14)\ \mathrm{SNU}.$$

The capture rate of the pp-neutrino on Ga equal to $39.7(1 \pm 0.14)$ SNU corresponds to the pp-neutrino flux $\Phi_{\mathrm{pp}} = 3.38(1 \pm 0.14) \times 10^{10}$ cm^{-2} s^{-1}. This is a fraction of the flux of pp-neutrinos with the electron flavor that falls on Earth.

The magnitude of the pp-neutrino flux obtained for the first time in experiments directly demonstrates the existence of the proton–proton chain in the thermonuclear fusion reactions proceeding in the Sun.

Taking into account the survival factor $\langle P^{\mathrm{ee}} \rangle = 0.561(1^{+0.030}_{-0.042})$ for neutrino oscillations with a large mixing angle (LMA solution), the total pp-neutrino flux arriving on Earth from the Sun is $\Phi_{\mathrm{pp}} = 6.01(1 \pm 0.14) \times 10^{10}$ cm^{-2} s^{-1} [20]. This value agrees well with the pp-neutrino fluxes predicted by the two existing solar models differing in the concentrations of heavy elements in the Sun: $\Phi_{\mathrm{pp}} = (5.97 \pm 0.04) \times 10^{10}$ cm^{-2} s^{-1} and $\Phi_{\mathrm{pp}} = (6.04 \pm 0.03) \times 10^{10}$ cm^{-2} s^{-1} [14].

7. Experiments with artificial neutrino sources

The first SAGE [25] and GALLEX [26] measurements performed in 1990 already revealed the low neutrino flux which could not be explained by the SSM. Because this result leads to the important conclusions that the neutrino changes its flavor and has mass, it was necessary to confirm that we correctly estimated the efficiency of all the procedures followed in experiments.

The total verification of the SAGE and GALLEX measurements as a whole (i.e., the chemical extraction efficiency, the counting of ^{71}Ge atoms, and the data analysis technique) was performed by utilizing artificial neutrino sources. Gallium targets were irradiated by artificial neutrino sources based on isotopes produced in atomic reactors with the activity close to 1 MCi. In SAGE, approximately 25% of the target was irradiated by the ^{51}Cr [27] and ^{37}Ar [28] sources. In GALLEX, the ^{51}Cr source was twice used for irradiating the entire target [29]. The weighted-mean ratio R of the measured production rate of ^{71}Ge isotopes to the expected rate, calculated from the source power, proved to be unexpectedly low for all four experiments, $R = 0.87 \pm 0.05$, less than unity by more than two standard deviations.

To prove the correctness of the efficiencies of all the procedures followed in running SAGE and GALLEX, numerous investigations were performed [15]. The extraction efficiency was determined from various chemical and volume measurements based on the introduction and subsequent extraction of the known amount of the carrier of stable Ge. Also, the verification was performed by adding to a Ga target the Ge carrier in a mixture with a known number of ^{71}Ge atoms in SAGE and ^{71}As atoms in GALLEX. As a result, it was shown that the extraction efficiencies of the stable carrier and ^{71}Ge isotopes are very close.

The results of all auxiliary verifications, especially those of the GALLEX experiment with ^{71}As [16], showed that all the efficiencies were most likely determined correctly, and it was concluded that the low neutrino capture rate observed in gallium experiments with different sources is not caused by erroneous experimentation.

The possible reasons for such a low neutrino capture rate were considered in detail in paper [20]. One of the hypotheses is that the cross sections for neutrino capture into the two lowest excited levels in ^{71}Ge nuclei, which can be reached when using the ^{51}Cr or ^{37}Ar source, are overestimated [31]. Other possible reasons can be a statistical fluctuation, which has a low probability (about 5%), or a real physical effect of an unknown nature, such as the hypothetical transition of active neutrinos to the sterile state.

8. The potential of SAGE in the investigation of oscillation transitions of active neutrinos into sterile states

The most relevant issues in neutrino physics at present are whether sterile neutrinos exist and whether there are *CP* and *CPT* violations in the neutrino sector of physics? The question of the existence of sterile neutrinos with $\Delta m^2 \sim 1$ eV^2 appeared in the analysis of results obtained in the LSND (Liquid Scintillator Neutrino Detector) and MiniBooNE (Booster Neutrino Experiment) accelerator experiments, in a number of reactor experiments, and in gallium experiments with artificial neutrino sources [32].

The question of the existence of sterile neutrinos has aroused considerable interest in the last few years. This is explained by both some refinement of cosmological data and the appearance of new 'anomalous' results obtained in experimental studies of neutrino oscillations. New estimates of reactor antineutrino fluxes have confirmed the hypothesis about the oscillations of neutrinos with a mass of ~ 1 eV. On the other hand, the absence of specific features in the spectrum of atmospheric neutrinos with energies of about 1 TeV in the first data from the IceCube neutrino telescope suggests the absence of neutrino transitions with large Δm^2.

To study the oscillation transitions of active neutrinos to sterile states, it is planned at present to perform, along with known experiments, new experiments by using both existing and specially projected atomic reactors and accelerators.

We propose using the unique possibilities of the GGNT for studying the oscillation transitions of active neutrinos to sterile states. For this purpose, a ^{51}Cr source with an activity of 3 MCi is placed at the center of a metal Ga target of the 50-t telescope divided into two independent, internal and external, zones containing 8 and 42 t of Ga, respectively (Fig. 9), with equal neutrino mean free paths, and the neutrino capture rates are measured simultaneously in each zone. During transitions to sterile states with the oscillation parameter $\Delta m^2 > 0.5$ eV^2 (it is these transitions that are of special interest at present), the capture rate in one of the zones or in both zones of the target should be suppressed (Fig. 10). In the case of the statistically ensured difference between neutrino capture rates in each zone or the statistically ensured difference between the mean capture rate in both zones and the expected value, we obtain direct confirmation of the existence of unusual properties of the neutrino. The ratios of capture rates measured in zones to the expected values will give the allowed regions of parameters of the observed oscillations.

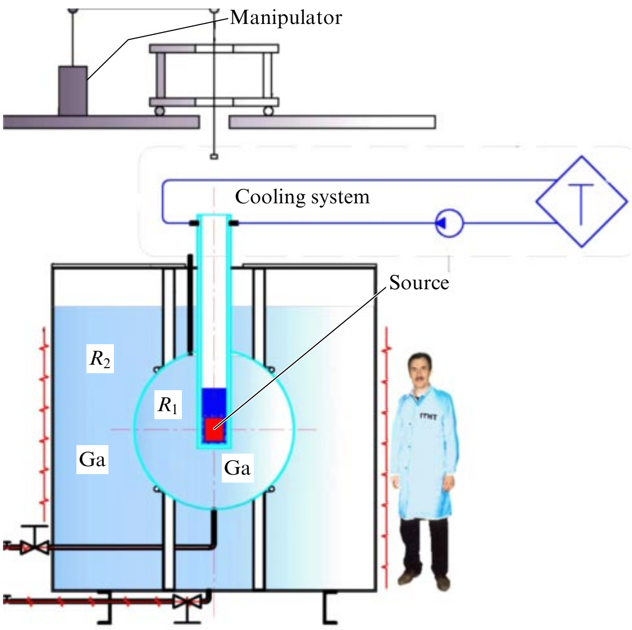

Figure 9. Schematics of the proposed experiment with an artificial neutrino source. R_1 and R_2 are the ratios of the capture rates measured in the internal and external zones, respectively, to the expected capture rate.

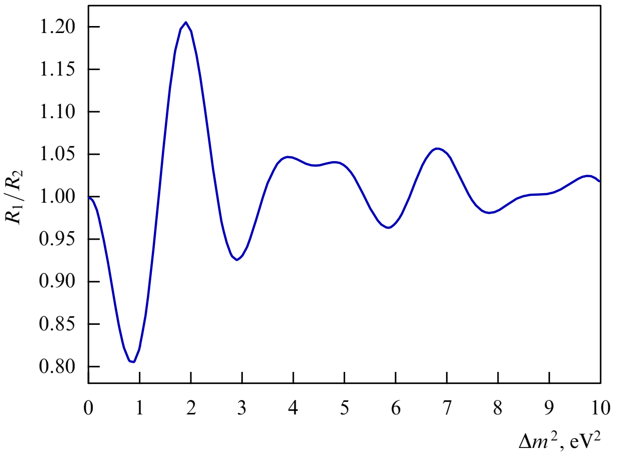

Figure 10. Ratio of neutrino capture rates in the external and internal zones as a function of Δm^2 for $\sin^2 2\theta = 0.3$.

The experiment on Ga with an artificial electron neutrino source offers significant advantages compared to other projects. These advantages are provided due to the employment of: a compact, almost monochromatic neutrino source with a well-known activity; a metal Ga target with a density providing a high interaction rate; targets with a special geometry allowing the study of the dependence of the neutrino capture rate on the distance to the source, and a well-developed method for measuring the neutrino capture rate on gallium target in the GGNT.

Another obvious advantages of such experiments are a large signal-to-noise ratio and the simplicity of the interpretation of results. The point is that the main contribution to the background will be made by solar neutrinos whose flux is well known from GGNT measurements performed for many years, while the source activity should provide the number of interactions in the detector exceeding by a few dozen times that which can be caused by solar neutrinos. The results can be simply interpreted because the artificial source emits a monochromatic neutrino flux and, therefore, systematic uncertainties related to the uncertainty in the neutrino spectrum are absent.

Taking into account the cross section for neutrino capture on Ga calculated by Bahcall [33], we determine that, in the absence of oscillations to sterile neutrinos, the production rate from the source at the beginning of the first irradiation will be ~ 65 ^{71}Ge atoms per day in each zone. We plan to perform 10 irradiations of Ga, for 9 days each, with the 1-day interruption between irradiations. The standard procedure for extracting and counting ^{71}Ge atoms, which was well developed in solar measurements, will be used. ^{71}Ge decays from each zone will be detected in individual counters. The production rate of ^{71}Ge atoms at the beginning of the first irradiation by the source will be higher than that from solar neutrinos by approximately 64 times for the external zone, and by almost 340 times for the internal zone.

The statistical uncertainty for the irradiation series, obtained by the Monte Carlo method based on the proposed program of irradiations, the extraction and counting efficiencies, the background rate, and the production rate from solar neutrinos is equal to 3.7% in each zone and ±2.6% for the entire target.

Thus, the expected total number of ^{71}Ge atoms accumulated over ten exposures in such experiments will be ~ 840 (±4.5%) in each zone, and ~ 1680 (±3.7%) on the entire target (the statistical and systematic uncertainties are combined quadratically).

9. Conclusion

The capture rate of solar neutrinos on a Ga target obtained in SAGE is (65.4 ± 3.8) SNU. The weighted average capture rate of neutrinos on Ga in three gallium experiments (SAGE, GALLEX, and GNO) is (66.1 ± 3.1) SNU, where the statistical and systematic uncertainties are combined quadratically.

By using the results of other solar neutrino experiments and the theory of large-mixing-angle (LMA) neutrino oscillations, we obtained in SAGE for the first time the value of pp-neutrino flux reaching $(3.40 \pm 0.46) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for neutrinos with the electron flavor arriving on Earth, and the value of total pp-neutrino flux amounting to $(6.0 \pm 0.8) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

The gallium solar neutrino experiments have shown for the first time that most of the solar neutrinos arriving on Earth are low-energy neutrinos created in the proton–proton reaction and directly confirmed the correctness of the SSM and the LMA solution for solar neutrino oscillations.

To elucidate the reasons for the unexpectedly low neutrino capture rate on Ga in experiments with artificial sources, we developed the concept of a new experiment with a high-intensity neutrino source and the optimized geometry of a Ga target [34].

Up to now, SAGE remains to be the sole experiment in which the pp-neutrino flux has been measured. We plan to pursue the monitoring of solar neutrino fluxes and to make preparations for a new experiment with a high-intensity neutrino source and the optimized geometry of a Ga target.

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BAIKAL neutrino experiment

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1. Introduction

The Baikal neutrino experiment is rooted in 1959–1960, when M A Markov [1] proposed the idea of large-scale underground and deep-sea experiments for studying the properties of neutrinos and the natural sources of their origin. The idea proved to be extremely fruitful. Investigations performed under conditions of the drastically reduced background of penetrating cosmic radiation, when huge volumes of the surrounding soil or water themselves serve as targets for high-energy neutrinos, made it possible to achieve a fundamentally new sensitivity level of experiments, allowing the study of rare processes which cannot be virtually detected in ground-based laboratories. The underground investigations

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